The Sustainable Concrete Guide

Applications

Andrea J. Schokker, Editor

U.S. GREEN
CONCRETE COUNCIL

The Sustainable Concrete Guide

Applications

Andrea J. Schokker, Editor

U.S. GREEN
CONCRETE COUNCIL

U.S. GREEN
CONCRETE COUNCIL

Staff

President
Ron G. Burg

Technical
Rex C. Donahey
Kevin P. Mlutkowski
Khaled Nahlawi
Douglas J. Sordyl
Michael L. Tholen

Production
Marie L. Fuller

Design
Ryan M. Jay

Editing
Kelli R. Slayden
Denise E. Wolber

Cover photo credits
Clockwise from upper left, cover photos courtesy of Cast Stone Institute, American Shotcrete Association, American Concrete Institute, Tilt-Up Concrete Association, kennyknickers@hotmail.com, and American Concrete Pressure Pipe Association

U.S. Green Concrete Council
38800 Country Club Drive,
Farmington Hills, MI 48331 USA

First Edition

Library of Congress catalog card number: 2010914869
ISBN: 978-0-87031-401-8

U.S. GREEN CONCRETE COUNCIL

Dedication
November 2010

The transformation toward sustainable development provides the concrete industry with a tremendous opportunity and responsibility to inform stakeholders about our material's ability to not only enhance the built environment for people and communities but also to protect our planet as well. The longevity of service of concrete structures continues to be a critical environmental asset, with beneficial impact on natural resource conservation, landfill use, and CO_2 reduction. In addition, such long-serving structures contribute positive social and economic benefits. And, when safeguarding against the devastation caused by natural or man-made disasters, the resilience of concrete structures becomes essential for protecting people, protecting communities, and protecting our planet's resources.

I extend my gratitude to the Editorial Review Panel of Michael Deane, Kevin MacDonald, Aris Papadopoulos, Michael Paul, Richard Stehly, and Wayne Trusty for the countless hours they spent providing direction, content, and editorial support for this guide, after the completion of the first "Strategies and Examples" guide just months before. My dear friend and colleague, Richard Stehly, who passed away just prior to the publishing of this book, was a visionary and inspired each of us to embrace the opportunity for using concrete in sustainable development. He will be missed, and his contribution to this guide is one of the many legacies he leaves for us all.

In compiling this book, the Editorial Review Panel worked with associations, institutes, and organizations that represent concrete materials, products, and construction to qualify and quantify concrete applications in regards to sustainable development. It is to these associations, institutes, and organizations that have invested so much time, effort, and knowledge to this industry-wide resource that I dedicate this book; their knowledge and experience will provide designers and constructors with the information and understanding necessary to transform the built environment. For that, I am grateful. Our industry is grateful.

Florian G. Barth
President, U.S. Green Concrete Council

TABLE OF CONTENTS

INTRODUCTION

Photo courtesy of Essroc Cement Corp.

Concrete is the most used construction material in the world with over 25 billion tons (22.7 billion metric tons) placed each year (World Business Council for Sustainable Development 2009). This book is the second in a series of guides on sustainable concrete. The first book, *The Sustainable Concrete Guide—Strategies and Examples* (Schokker 2010), provides an overview of the aspects for potential contributions to sustainability of concrete used in buildings. While the two books can serve as stand-alone references, the *Strategies and Examples* book provides a base of knowledge about using concrete to achieve more sustainable buildings. This book, *Applications*, focuses on integrating sustainable strategies into the selection of concrete materials, constructing with concrete, and identifying uses for a multitude of concrete applications.

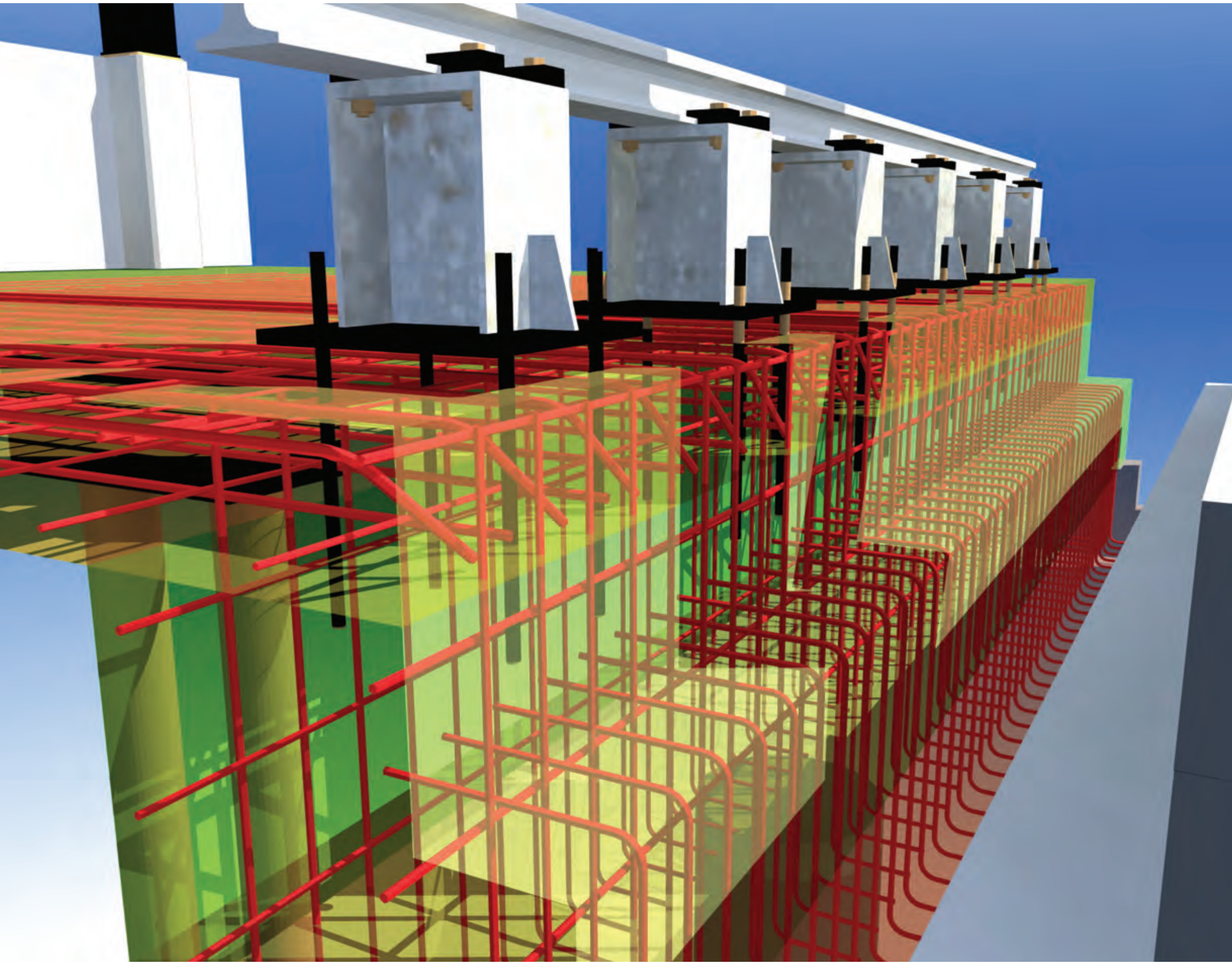
The book is divided into five parts: 1) materials, 2) construction, 3) applications, 4) concrete in sustainable structures, and 5) codes. Part 1 addresses the material components and their sustainable benefits when used in the production of concrete. Part 2 covers the construction team's role from production, waste stream management, scheduling through quality control, and commissioning. Part 3 describes the sustainable attributes of various concrete systems and products highlighted by a list of sustainable attributes for each application. Part 4 provides a summary of how concrete structural elements can be integrated into overall building design, as well as solutions to meet typical building needs. Part 4 also covers detailed information on maintenance, repair, preservation, and adaptive reuse. Part 5 provides an overview of how sustainable recommendations are migrated from voluntary acceptance to mandatory considerations in codes and standards. Case studies and examples are used throughout to demonstrate how sustainable benefits have been achieved in practice. The information presented in this book is based on referenced material from the individual organizational members of the Concrete Joint Sustainability Initiative (discussed below) with expertise in the various materials, production, construction, and applications.

After a number of years of addressing sustainability individually, numerous stakeholders in the concrete industry agreed to advance the sustainable benefits of concrete by forming the Concrete Joint Sustainability Initiative (Concrete JSI) in 2009. Concrete JSI member organizations agree to contribute to a unified vision focused around the social values provided by concrete structures. Concrete structures as defined by the Concrete JSI include "all vertical and horizontal applications and all concrete products." This focus on concrete structures moves the Concrete

Photo courtesy of Post-Tensioning Institute

JSI members toward an integrated systems approach to sustainability and is centered on the key values of concrete structures:

- **Stewardship of Nature's Resources** – Concrete can play a vital role in the way we conserve and protect natural resources in the structures we create with it and the processes by which we produce it. Concrete offers long-lasting service with minimal maintenance, along with recycled content and end-of-service recyclability. In its many forms, uses, and styles, concrete can reduce the need for additional building materials, operating energy in buildings and transportation, conversion of undeveloped land, retention ponds, and other traditional storm-water management systems.
- **Stewardship of Financial Resources** – In the case of concrete, the length of service that results



Rendering courtesy of Virtual Design & Construction Dept., KLORMAN Construction from its durability, the versatility of its design and applications, the speed of construction, and the in-place performance all contribute to a return on the investment. Concrete structures provide long-term savings in operating cost and service life. In addition, their durability, their resistance to damage from harsh weather, pests and natural disasters, and their low maintenance requirements are beneficial to future owners and users.

- **Durability, Safety, and Stability** – Concrete is a lasting material that provides shelter to get through disasters with less damage, less loss, and less waste. It connects people to each other through transportation corridors, gathering places, and monuments. It also helps ensure that critical services like roads, hospitals, communications, data transmission, and emergency services can remain in operation.
- **Aesthetics** – Aside from the basic functionality, the look and feel of a place influences how successfully it serves its purpose. Concrete is strong and functional, yet its fluidity lets the designer adapt it to whatever form, scale, shape, surface, and texture he can imagine. Beyond a visual aesthetic, designers can use concrete to affect sound—either through amplification or dampening between spaces.

Nearly 30 organizations are members of the Concrete JSI, showing a commitment to a unified systems approach to improving sustainability of concrete structures and in educating engineers, architects, owners, contractors, and the general public. This book includes educational information from members of the Concrete JSI to help these decision-makers in understanding the various sustainable attributes of the many concrete systems that are available.

This book, *The Sustainable Concrete Guide—Applications*, its companion book *The Sustainable Concrete Guide—Strategies and Examples*, and the Concrete JSI Web site, **www.sustainableconcrete.org**, provide hundreds of strategies, resources, and case studies on the use on concrete in sustainable development.

Photo courtesy of Portland Cement Association

Photo courtesy of Cast Stone Institute

PART 1—
MATERIALS

Introduction

Part 1 addresses the materials (water, cement, supplementary cementitious materials [SCMs], aggregates, reinforcement, admixtures, and other materials) that are used in the applications presented later in the book. Each of the seven materials chapters provides (as applicable): definitions, primary sustainable attributes, contributions to longevity and life cycle, opportunities to reduce/reuse/recycle, industry initiatives, and sources for additional information.

Chapter 1—Water

Sustainable attributes

Water is the most consumed resource in the world. Human life depends on it for drinking water, personal hygiene, and irrigation of crops. Beyond these basic needs, water is used in abundance by industry—including the concrete industry. To accommodate a world population with increasingly precious potable water, our industry continues to address standards that allow greater use of nonpotable water alternatives. Water shortages increasingly affect more people and more countries. Water shortages are not limited to third-world countries—droughts, limited water supplies, and increasing populations have brought the issue to the forefront in many parts of the U.S.

The concrete industry uses large quantities of water in the concrete mixture itself, as well as for other processes,

Fig. 1.1—Based on the world's population, the worldwide production of concrete, and an assumed water-cementitious material ratio (*w/cm*), approximately 50 gallons of water per person are used annually in the production of concrete.

Fig. 1.2—Concrete trucks returning to deposit wash water: (a) trucks returning from a delivery have used self-contained washout. They are given wash water from the standpipe above the door and discharge into the weir system in the facility; (b) standpipe above doorway; and (c) not only is wash water treated, but also any water used to clean vehicles and rainwater is directed into the facility.
Photos courtesy of Cemstone

such as washing out mixers. To get a feel for the magnitude of water used in concrete, consider:

- 2.5 billion tons (2.3 billion metric tons) of cement is used annually worldwide;
- An assumed 0.50 *w/cm*;
- There are approximately 6 billion people worldwide.

This leads to *50 gal. (189 L) of water per person worldwide each year* for the water that goes into concrete as a mixture ingredient.

Wash water and storm water collected on site at a ready mix facility must be treated before discharge. The reuse of this water in concrete production can transform

Fig. 1.3—On-site water treatment at a ready mix facility in Burnsville, MN: (a) the first three stilling basins are shown herein. The fourth runs along the rear of the structure transverse to the others. Note the berm used to direct site runoff into the first basin; (b) view into the facility showing the froth on the water in the first basin. This material will break up overnight. Solids need to be removed frequently; (c) cleaning is readily done with a front-end loader. Solids are reclaimed as fill; (d) water passing the weir from Basin 1 to Basin 2. The weir is baffled to hold back the froth. Note the lack of froth in Basin 2; and (e) the finished water in Basin 4. The material on the surface is calcium carbonate, resulting from CO_2 sequestration from the air. The water at this stage has a pH of 12.5 but very low suspended solids.
Photos courtesy of Cemstone

a ready mix plant into a zero-discharge facility rather than a large producer of contaminated water from potable water. This change in operation is a positive step in reducing the environmental impact of concrete construction. Admixtures (as discussed in Chapter 6) and optimal mixture proportioning can significantly reduce water demand while achieving more durable concrete.

Water used in concrete mixtures was governed by ASTM C94/C94M until 2004, when water standards were separated into a new specification that governs the use of mixing water (ASTM C1602/C1602M-06 [ASTM International 2006]) along with a new test method (ASTM C1603). ACI 318-08 (ACI Committee 318 2008) references ASTM C1602/C1602M-06 (ASTM International 2006). ASTM C94/C94M has permitted the use of wash water as mixing water in concrete since 1978, but the standard for wash water was prescriptive rather than performance-based, and was not practical for many ready mix facilities. Increasing environmental pressure led to a new approach that allowed the use of reclaimed water for use in mixing water based on performance. The use of reclaimed water is often frowned upon by agencies and owners based on the colloquial notion that new water is better, and that all water needs to be potable. This notion is outdated, as we have learned much more about the requirements for water for use in concrete. The main components in water for use as a reagent are chlorides, sulfates, and suspended solids. Contaminants such as carbohydrates are not likely to be encountered in reclaimed concrete water in concentrations that would be a problem.

ASTM C1602/C1602M-06 (ASTM International 2006) sets limits on sulfates, chlorides, and suspended solids because of their potential for complications when used in mixing water. Sulfates interfere with the action of many high-range water-reducing admixtures and may affect the setting of the concrete. Chlorides affect the setting of the concrete and may cause corrosion of embedded reinforcing steel. Suspended solids can act as nucleation sites and accelerate the setting of the concrete, and may cause some staining depending on their nature. Large quantities of suspended solids may also significantly decrease the surface durability if the particles are less dense than the aggregate particles and create large amounts of laitance.

The requirements set by ASTM C1602/C1602M-06 (ASTM International 2006) are specific to the needs for water used as mixing water in concrete. Requirements for mixing water to be potable are wasteful and unnecessary. Most concrete plants will discharge approximately 50 ft^3 (1.4 m^3) of water per load in combined wash and washout water. This water can be readily reclaimed and used as reagent water or reused as wash water.

Admixtures can also have a significant impact on water use in the concrete mixture. Water-reducing admixtures allow more efficient water use for cement hydration while retaining workability. Depending on the mixture proportion, this can reduce water demand to one-half of what would be needed without the admixture.

The abbreviation *w/cm* (water-cementitious material ratio) is used throughout this book as the generalized term to express the ratio of mass of water to mass of cementitious materials (either cement alone or with SCMs). If a distinction is needed between a concrete mixture that includes cement versus one with cement in addition to other cementitious materials, the cement-only mixture will use the abbreviation of *w/c* (water-cement ratio).

Reduce, reuse, recycle

The changes in ASTM standards described in the previous section are a move in the right direction to use reclaimed water. The concrete industry is also aware of the need to act, and has set targets on reducing potable water usage. The National Ready Mixed Concrete Association (NRMCA) includes potable water reduction in the list of key performance indicators in their "Sustainable Concrete Plants Guidelines" (National Ready Mixed Concrete Association 2010). Their target levels (as compared with a 2007 baseline) are to reduce potable water use by 10% by 2020, and by 20% by 2030. As sustainability becomes even more of a factor, ready mix facilities will need to invest in new equipment and train their personnel on water usage reduction issues.

Figures 1.1 and 1.2 show the process of water treatment and collection at a ready mix facility in Burnsville, MN. Trucks have a self-contained washout system that is used at the construction site so that no wash water is left on site. The water is returned to the Burnsville facility for treatment.

Definitions

The definitions that follow are from ASTM C1602/C1602M-06 (ASTM International 2006). These four definitions categorize water that can be used in concrete as per ASTM C1602/C1602M-06 (ASTM International 2006).

Potable water—Water fit for human consumption.

Nonpotable water—Water from sources that are not potable, that might have objectionable taste or smell, but not related to water generated at concrete plants. This is often water from wells, streams, or lakes.

Water from concrete production operations (reclaimed water)—Water recovered from processes of hydraulic cement concrete production that includes wash water from mixers or that was a part of a concrete mixture; water collected in a basin as a result of stormwater runoff at a concrete production facility; or water that contains quantities of concrete ingredients.

Combined water—Mixture of two or more sources of water blended together—before or during introduction into the mixture—for use as mixing water in the production of concrete.

Chapter 2—Cement

Sustainable attributes

Society expects cements that will make concrete strong, durable, safe, long-lasting, versatile, and economical in all forms of construction—from homes to infrastructure. In addition to these benefits, the raw materials for cement manufacture are widely available, which reduces the need for long-distance transport. The quarries that supply the necessary raw materials should have a mitigation/restoration plan so that they have limited impact on land use. Quarries can also be restored to create parks and small lakes. In addition, modern cement plants often use by-products from other industries as a portion of their raw materials, thereby reducing the use of virgin materials and processing fuels and reducing the amount of material that is sent to landfills. Modern cement plants generate a relatively small quantity of by-products. This chapter focuses on the sustainable attributes of hydraulic cement, many of which have been demonstrated in practice for decades.

Carbon footprint

The positive sustainability attributes that concrete provides are accompanied by an environmental investment. Cement contributes approximately 96% of the carbon footprint of concrete, and 85% of the embodied energy. Figure 1.4 shows the breakdown of the various component contributions to carbon footprint and embodied energy (Portland Cement Association 2006). The manufacture of cement is an energy-intensive process. The raw ingredients are mined or recovered from other industries, then ground and blended. This raw feed is then heated to approximately 2600°F (1450°C), where the chemical reactions to form hydraulic cement take place. The primary environmental impact is typically considered to be carbon dioxide (CO_2) emissions. CO_2 is classified as a greenhouse gas that is naturally found in the atmosphere, and is an emission of virtually all life forms as well as the product of the burning of fossil fuels. In addition to CO_2 from fuel used to heat raw ingredients of cement, the cement manufacturing process releases CO_2 from limestone (a primary raw material) as an integral part of the subsequent chemical reactions to take place in the kiln. This process is known as calcination. Approximately 65% of the CO_2 from manufacturing cement is from calcining, and the remaining 35% is generated from burning fuel to heat the kilns.

Recent manufacturing improvements in North American plants have significantly reduced the amount of CO_2 generated from the heating process (37% in North America since 1972 [Portland Cement Association 2008]). The CO_2 generated by calcining, however, is fixed by the chemical nature of limestone. Manufacturers are reducing this impact through efforts to reduce the clinker portion of finished cement. Designers should allow this improvement to be realized through performance-based concrete specifications and the increased use of blended cements.

The vast majority of plants in the U.S. are dry kiln plants, which are more efficient than wet kiln plants. A dry kiln process uses dry, ground materials that are sent to the kiln. A wet kiln process grinds the materials with the addition of water to form a slurry, and the slurry is sent to the kiln; this requires additional fuel to evaporate the water.

The numbers and percentages quoted for the amount of CO_2 generated from cement manufacture can vary greatly. The generally accepted statistic for global production is 5% from the World Business Council for Sustainable Development (2009). This is reflective of the ubiquitous use of concrete worldwide. In the U.S., the cement industry is currently responsible for less than 1.5% of total man-made CO_2-equivalent greenhouse gas emissions (U.S. Environmental Protection Agency 2006).

In comparison, electric power generation and transportation sources in the U.S. account for approximately 33% and 27%, respectively, of CO_2 produced annually. Figure 1.5 shows a comparison of CO_2 emissions for nine major industries from 2008 data. This figure uses the units of million metric tons of CO_2 equivalents ($MMTCO_2E$) to illustrate the relative comparison.

An important distinction that is often overlooked for CO_2 numbers is that buildings are built with concrete—not cement. Cement is only a small portion of concrete (approximately 11% in an average mixture), and this portion can be further reduced with the use of supplementary cementitious materials (SCMs) (as discussed in Chapter 3). Many U.S. cement plants have substituted 5 to 10% of their limestone and shale raw materials with fly ash and slag. This not only prevents the landfilling of these by-products by other industries, but also provides environmental and cost benefits in cement manufacturing. These materials specifically reduce both calcination CO_2 (by reducing calcining materials), as well as fuel CO_2 (by reducing energy consuption).

A significant benefit to using concrete is in the operational energy savings over the life of the structure, which reduces the carbon footprint. In a life-cycle analysis (LCA), the materials and construction phase typically range from 2 to 15% of the total carbon

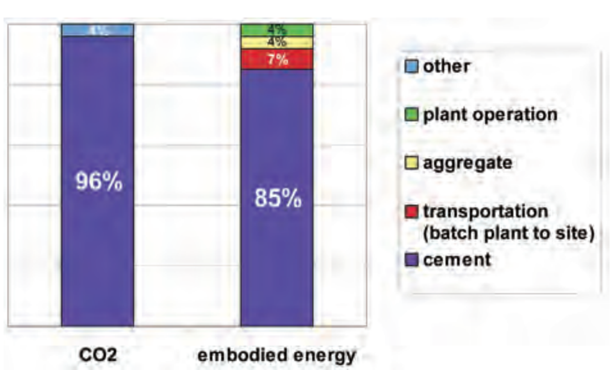


Fig. 1.4—Contribution of materials in concrete to the total CO_2 and embodied energy (Portland Cement Association 2006).

footprint, whereas the operation of the building is approximately 85 to 97%. In other words, the operational energy tends to dwarf the embodied energy for a building. While all manufacturers have a responsibility to improve their products, designers have a far greater role in using them to optimize performance in areas such as energy efficiency and durability.

Greener cement specifications

The primary specifications for hydraulic cements are:

- ASTM C150/C150M, "Standard Specification for Portland Cement" (first introduced in 1940 with the current edition published in 2009 [ASTM International 2009]);
- ASTM C595/C595M, "Standard Specification for Blended Hydraulic Cements" (first introduced in 1967 with the current standard published in 2010 [ASTM International 2010]); and
- ASTM C1157/C1157M, "Standard Performance Specification for Hydraulic Cement" (first adopted in 1992 with the current standard published in 2010 [ASTM International 2010]).

Following similar trends in other parts of the world, recent changes to cement specifications have enabled reductions in the carbon footprint of cement as well. Changes in ASTM C150/C150M-09 (ASTM International 2009) have had a significant impact by permitting the use of up to 5% by mass of limestone (uncalcined) to be used in cement, and permitting up to 5% of inorganic processing additions (often fly ash or slag). Although chemical requirements and performance limits in the cement specifications limit the amount of these nonclinker materials to less than 10%, estimates for the potential reductions in CO_2 are significant (Nisbet 1996). There is extensive data that demonstrates that the equivalent strength and durability performance can be readily achieved with these changes (Hawkins et al. 2005).

The use of blended cements (ASTM C595/C595M-10 [ASTM International 2010]) helps reduce the carbon footprint of the final concrete product. These blended cements contain blast-furnace slag and pozzolans; thus, the amount of pyroprocessed materials and calcined limestone in the cement are reduced. Blended cements are often believed to result in slower strength gain and setting characteristics in concrete. In practice, these materials can be manufactured to be comparable to Type II portland cement (Bhatty and Tennis 2004), as shown in Fig. 1.6 and 1.7. Concrete made with blended cements (as opposed to portland cement concretes with supplementary cementitious materials [SCMs]) can have better control of chemical and physical properties of the overall cementitious material composition. While some concrete producers feel they have more flexibility when using SCMs instead of blended cements, this flexibility can be obtained by using blended cement with additional SCMs.

In 2009, ASTM International adopted revisions to ASTM C595/C595M-10 (ASTM International 2010) to create a ternary blended cement designation (Type IT). This type provides options for cements that contain two SCMs. Transparency in communicating both the amount and the type of SCMs in blended cements is another benefit with this cement designation. Combining blended cement with an additional SCM to form a ternary concrete mixture (as opposed to a ternary blended cement) also presents an attractive option.

ASTM C1157/C1157M-10 (ASTM International 2010) provides even greater flexibility in producing cements with lower carbon footprints. Specification requirements for these cements are based on performance testing rather than indirect (prescriptive) limits.

Tables 1.1 and 1.2 show an estimate of emission reductions based on the amounts of limestone, inorganic processing additions (IPAs), or SCMs used in cements, based on the approach of Nisbet (1996) and U.S. Environmental Protection Agency (EPA) factors (U.S. Environmental Protection Agency 2009).

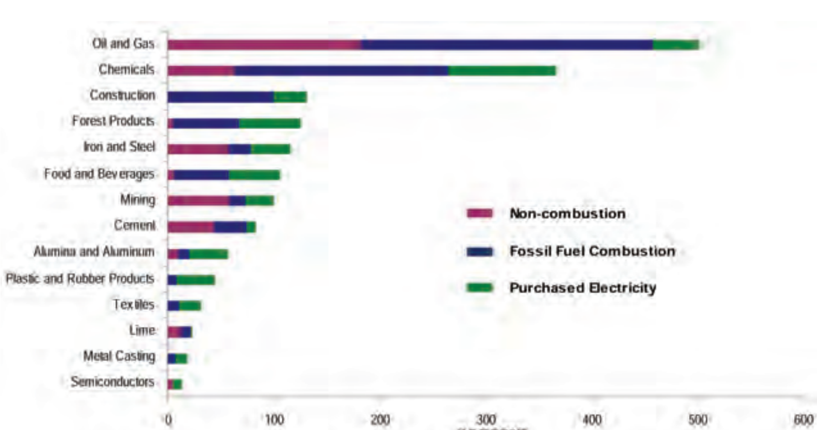


Fig. 1.5—2002 noncombustion, on-site fossil fuel combustion, and purchased electricity greenhouse gas emissions from key industrial sectors in $MMTCO_2E$ (millions of metric tons of CO_2 equivalents). *Quantifying Greenhouse Gas Emissions from Key Industrial Sectors in the United States, U.S. EPA, May 2008, Chapter 1, page 7*

CO_2 readsorption

During the life of a concrete structure, hydrated cementitious materials react to absorb CO_2 from the atmosphere through a process called carbonation, which makes concrete a "CO_2 sink" over time. The carbonation of concrete is a natural phenomenon (roughly the opposite of calcining). Carbonation decreases the durability of concrete by lowering the pH, which in turn permits increased rates of corrosion of reinforcing steel. Over time, the amount of CO_2 adsorbed by this process is approximately equal to the amount of CO_2 generated by the calcination of limestone during the manufacture of cement. The process, however, takes place very slowly. Current estimates place the amount of CO_2 adsorbed by this process at approximately 86% (of that generated during calcination) after 100 years (Engelsen et al. 2005). It is important to note that for high-quality concrete, CO_2 adsorption rates are very low, and thus relatively insignificant. However, when that concrete is crushed for recycling or disposal, more surface area is exposed and the rates increase.

Longevity and life cycle

Durability

When considering sustainability issues, one attribute of paramount importance is durability and the resulting longevity of structures. Durability affects all three pillars of sustainability:

- **Environmental**—Long-lasting construction reduces the need for additional materials, energy demand, and waste due to replacement;
- **Economic**—Long-lasting, low-maintenance concrete buildings and pavements offer better economic value through a lower annual cost of ownership; and
- **Social**—Less frequent replacement of buildings and pavements reduces the downtime and inconvenience associated with repairs and replacement.

Concrete is an extremely durable material. Concrete durability is a function of mixture proportioning, mixing, placement, and curing. Deficiencies in these areas increase concrete permeability and create a corresponding decrease in concrete durability. The cementitious material content and water content of a concrete mixture are particularly critical because they directly influence permeability. Cement and other cementitious materials, however, can also affect durability. ACI 318-08 (ACI Committee 318 2008) and ACI 301-05 (ACI Committee 301 2005) refer to specific cements for specific environments. The use of appropriate cementitious materials can improve the durability of concrete by providing—among other attributes—sulfate resistance, freezing-and-thawing durability, deicer scaling resistance, and enhanced corrosion resistance.

Life-cycle evaluations

In its plainest sense, a life-cycle assessment (LCA) is a study of the environmental impacts of a given product from its beginnings, through its life, and up to its ultimate demise. Typically, the goal of an LCA is to compare the full range of environmental impacts assignable to products and services. An LCA provides a basis for choosing the solution with the least impact. The term "life cycle" refers to an assessment of raw material acquisition and production, manufacture, distribution, use, and disposal, including all transportation steps necessary or caused by the product's existence. The sum of all of these steps is

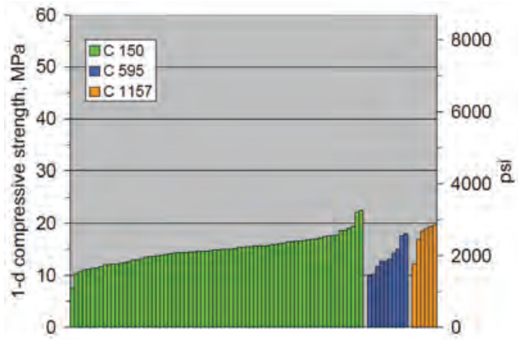


Fig. 1.6—One-day strengths of ASTM C150 Type II, and ASTM C595 and C1157 cements from a 2004 survey (Bhatty and Tennis 2004). Although commonly perceived to have slower strength gain characteristics, ASTM C595 and C1157 cements are designed to be competitive with portland cement properties.

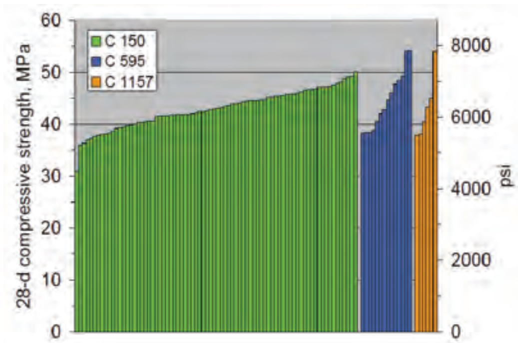


Fig. 1.7—Twenty-eight-day strengths of ASTM C150 Type II, and ASTM C595 and C1157 cements from a 2004 survey (Bhatty and Tennis 2004).

Table 1.1—Estimated U.S. kiln emissions savings potential, (lb/ton [0.49 kg/metric ton])

Level,* %	5	20	35
SO_2	0.30	1.06	2.04
NO_x	0.30	1.06	2.04
CO	0.06	0.22	0.40
CO_2	94.3	377	660
THC	0.00	0.02	0.06

(Following the approach of Nisbet [1996] and EPA emissions factors.)

*Percent cement replaced with SCMs, IPAs, or limestone.

Table 1.2—Estimated U.S. kiln emissions savings potential (tons/year [0.91 metric tons/year])

Level,* %	5	20	35
SO_2	13,560	54,344	95,240
NO_x	13,560	54,344	95,240
CO	2425	9700	16,976
CO_2	4,417,500	17,669,900	30,939,200
THC	331	1323	2315

(Using data in the previous table and assuming 97 million metric tons per year portland cement production.)

*Percent cement replaced with SCMs, IPAs, or limestone.

the life cycle of the product. A life-cycle inventory (LCI) is a review of the environmental details of all aspects of a product, and is a primary input into an LCA. Detailed LCI data for portland cement manufacturing (Marceau et al. 2006) and portland cement concrete (Marceau et al. 2007) are available. These inventories include consideration of raw material inputs; energy usage; and particulate, liquid, and gaseous emissions over the entire duration of portland cement and concrete production. The inventory includes effects from the mining, transportation, pyroprocessing, and delivery of raw materials. These data are useful in producing LCAs of concrete products for a more complete comparison against other construction materials.

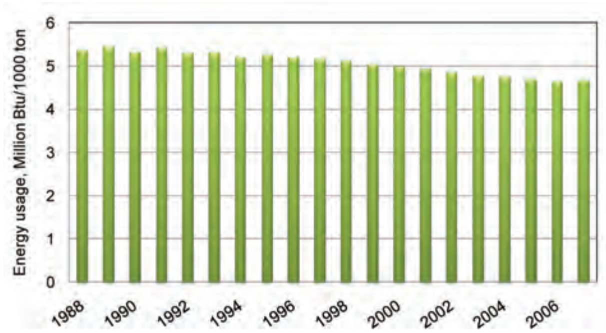


Fig. 1.8—Energy consumption data (1988 to 2007) for the cement industry in the U.S. *(Portland Cement Association 2008)*

Fig. 1.9—Portland cement plants that used blast-furnace or iron slag as a raw material in 2008. (*Portland Cement Association 2009)*

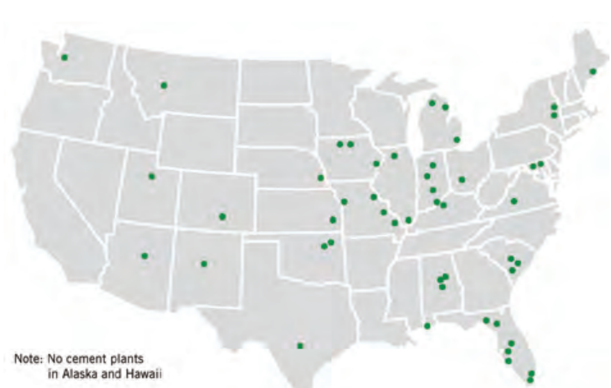


Fig. 1.10—Portland cement plants that used fly ash and/or bottom ash as a raw material in 2008.

Human factors and living/working environment

Potential health concerns

This section is not intended to be a comprehensive resource on the safe use of cement, but rather a highlight of some potential health concerns and safety precautions. Cement is highly alkaline, and wet concrete can cause severe chemical burns to eyes and exposed skin. Eye protection, such as safety glasses and skin protection (gloves, boots, and clothes that cover arms and legs) are necessary. Cement particles are very fine, so precautions (such as a dust mask) should be taken to avoid inhaling cement when opening bags.

Heat island effect: white cement

White cement clinker is manufactured with select raw materials so that it contains less than 1% ferric oxide (Fe_2O_3). It can be an integral part of innovative sustainability strategies in two ways. First, white cement concrete can deliver architectural benefits that replace less durable cladding or coating materials. White cement is essentially the same as gray cement with the exception of its color, so concrete made with white cement retains all of the durability and benefits of standard gray concrete. Because it facilitates a broad pallet of architectural colors and finishes difficult to achieve with ordinary gray cements, it is an aesthetic choice for architects and designers.

The second innovative, sustainable application for white cement is its bright color and reflectivity. These characteristics can be used to reduce lighting needs and unwanted heat gain. Concretes that use white hydraulic cements have significantly higher reflectance than gray cement concrete. This reflectance can reduce lighting needs by more than 30%, thereby saving the electrical power for the light itself and reducing a building's cooling load. In exterior applications, white cement concrete's higher reflectivity reduces solar heat gain and thermal heat islands. It should be noted that, although white cements are significantly lighter colored than gray cements, all concrete does a very good job of reflecting solar energy. Marceau and VanGeem (2007) found that a wide range of concrete mixtures were eligible for LEED sustainable sites credit.

Reduce, reuse, recycle

Reducing energy usage and emissions

The cement industry has been actively engaged in improving manufacturing efficiency to reduce CO_2 (and other greenhouse gases) and energy consumption for decades. Figure 1.8 shows the energy required to produce 1 ton of clinker and how process improvements have led to a 13% drop in energy usage since 1988. Since 1972, the energy usage has dropped an additional 37% (Portland Cement Association 2008).

Recycling by-products

Cement manufacture uses by-product materials from other industries. Waste oils, medical waste, and scrap tires are commonly used as fuels in cement manufacturing. Fly ash and blast-furnace slag are commonly used as raw materials in cement manufacturing (as well as their use as ingredients in blended cements). Considering 115 operating plants in 2008 (Portland Cement Association 2006), 36 plants used blast-furnace or iron slag as a raw material, and over 50 plants used fly ash or bottom ash from electric power plants, as illustrated in Fig. 1.9 and 1.10. Other materials used in cement manufacturing include copper slag, foundry sand, mill scale, sandblasting grit, and synthetic gypsum. The detailed chemical analysis of raw materials used to make cement allows for the chemically efficient and beneficial use of large volumes of these industrial by-products that would otherwise be placed in a landfill. Their beneficial use in cement manufacturing reduces the volume of wastes, the use of natural raw materials and, in some cases, the energy required for manufacturing.

Reducing materials usage

The previous sections provide details on the beneficial reuse of by-product materials from other industries and noncalcined materials. The use of portland cements with limestone and blended cements has the benefits noted previously and also serves to reduce the amount of virgin materials that are used to produce concrete. Efficient mixture proportions with these materials are discussed in Chapter 3.

Cement industry initiatives

The U.S. cement industry has voluntarily committed to several goals toward sustainability (Portland Cement Association 2008):

- **CO_2**—adopted a voluntary target of reducing CO_2 emissions by 10% (from a 1990 baseline) by 2020 per ton of cementitious product produced or sold.
- **Cement kiln dust (CKD)**—adopted a voluntary target of a 60% reduction (from a 1990 baseline) by 2020 in the amount of CKD landfilled per ton of clinker produced.
- **Environmental management systems (EMS)**—adopted a voluntary target of at least 40% of cement plants in the U.S. having implemented an auditable and verifiable EMS by 2006, with 75% of the plants implementing an EMS by the end of 2010, and with 90% by the end of 2020. The 2006 target of 40% was met and, by 2008, 54% of plants had an EMS.
- **Energy efficiency**—adopted a voluntary target of 20% improvement (from 1990 baseline) energy efficiency by 2020—as measured by total Btu-equivalent per unit of cementitious product.

Associations and resources

The cement industry participates in multiple organizations devoted to improving the sustainability of cement manufacture (and, therefore, concrete). These are described as follows.

Asia-Pacific Partnership (APP)

The Asia-Pacific Partnership (APP) has the goal of accelerating the development and deployment of clean energy technologies. APP addresses increasing energy needs and associated challenges, including air pollution, energy security, and greenhouse gas intensities. The seven member countries (Australia, Canada, China, India, Japan, Republic of Korea, and the U.S.) constitute one-half of the world's population, and more than one-half of the world's economy and energy use. In total, 61% of global cement production is represented by APP. The Portland Cement Association (PCA) joined the U.S. Department of State and the EPA in this organization (**www.asiapacificpartnership.org**).

U.S. Environmental Protection Agency (EPA) Sector Strategies Program

Through this program, the EPA fosters a collaborative approach to address drivers and barriers to better manufacturing performance. Program staffers create partnerships with Portland Cement Association (PCA) member companies, state and local officials, and others. Sector strategies include targeted regulatory changes, sector-based environmental management systems, and easier links to assistance services. The program also tracks performance with a more strategic allocation of resources by all stakeholders. (**www.epa.gov/ispd/**)

Climate VISION

PCA joined the Climate VISION program to voluntarily reduce greenhouse gas emissions. This program includes the U.S. Department of Energy, the U.S. Department of Transportation, the U.S. Enviromental Protection Agency, and the U.S. Department of Agriculture. The program assists industry efforts to accelerate the transition to practices, including improved processes and energy technologies that are cost-effective, cleaner, more efficient, and more capable of reducing, capturing, or sequestering greenhouse gases. Climate VISION links these objectives with technology development, commercialization, and commercial use activities supported by the private sector and the government. (**www.climatevision.gov**)

Climate Leaders

Climate Leaders is an industry-government partnership in which companies voluntarily commit to reduce greenhouse gas emissions and report their progress to the EPA. Companies develop comprehensive climate change strategies, including a corporate-wide inventory of their greenhouse gas emissions. These efforts create a credible record of a company's accomplishments, and the EPA recognizes outstanding efforts. Currently, over 25% of the clinker-producing cement plants are members of this program. (**www.epa.gov/climateleaders/**)

ENERGY STAR cement manufacturing focus

The U.S. Department of Energy and the EPA sponsor the ENERGY STAR Industrial Focus Program. One aspect of this program is to assist businesses in overcoming barriers to energy efficiency by developing industry-specific energy management tools and resources. The cement manufacturing focus began in 2003 and currently includes over 65% of the clinker-producing cement plants. (**www.energystar.gov/index.cfm?c=in_focus.bus_cement_manuf_focus**)

Concrete Sustainability Hub

The Concrete Sustainability Hub (CSH), established in 2009 with the goal of accelerating emerging breakthroughs in concrete science and engineering and transferring that science into practice, will provide $10 million of sponsored research funding initially organized around three focus areas: concrete materials science, building technology, and the econometrics of sustainable development. The CSH, expected to run through at least 2013, includes researchers from MIT's School of Engineering, School of Architecture and Planning, and Sloan School of Management. Additional details can be found at **http://web.mit.edu/cshub/about/index.html**.

World Business Council for Sustainable Development (WBCSD) Cement Sustainability Initiative (CSI)

WBCSD is an association of companies that deal exclusively with business and sustainable development. They support companies in the exploration of sustainable development and the transfer of knowledge, experiences, and best practices. WBCSD focuses on four areas:

- Energy and climate;
- Development;
- Business roles; and
- Ecosystems.

The Cement Sustainability Initiative (**www.wbcsdcement.org**) is a subgroup of cement companies dedicated to addressing the sustainable development of cement. Approximately 70% of the clinker-producing cement plants in the U.S. participate in the WBCSD. (**www.wbcsd.org**)

Calcination (calcining)—(In the case of cement production) the pyroprocessing (heating to high temperatures) of limestone (calcium carbonate) that results in the decomposition of limestone into lime (calcium oxide) and CO_2.

Clinker—The solid material that is produced within a cement kiln. The material in the kiln fuses into nodules under high temperature (this process is called sintering). These nodules are known as clinker, which is then ground with gypsum to form cement.

Hydraulic cement—The ingredient in concrete that provides binding capacity, durability, and strength to the material. A hydraulic cement reacts chemically with water to develop strength and other properties. Two primary types of hydraulic cements are portland cements and blended cements.

Portland cement—A calcium silicate-based hydraulic cement produced by heating materials that contain calcium, silicon, aluminum, and iron. Portland cement provides the binding capacity that gives concrete its strength and durability.

Blended cement—A hydraulic cement typically produced by intergrinding portland cement with SCMs (as discussed in detail in Chapter 3).

Inorganic processing addition (IPA)—A material that is interground or blended in limited amounts in hydraulic cements to aid in the manufacturing process. Materials such as slag (from electrical arc furnaces [EAFs] or basic oxygen furnaces [BOFs]), fly ash (from coal-fired power plants), or CKD (from the cement manufacturing process) can be qualified as IPAs. These materials are also used as SCMs.

Limestone—A type of rock that primarily consists of calcium carbonate or calcium and magnesium carbonates. Limestone is used as a source of calcium in the raw kiln feed for portland cement manufacture. In this case, the limestone is calcined. Uncalcined limestone, ground to the proper fineness and used in appropriate amounts as an ingredient in finished portland or hydraulic cements, can reduce the generation of CO_2, while retaining its cement efficiency.

Pozzolan—A siliceous (or siliceous and aluminous) material that chemically reacts with calcium hydroxide to form compounds that have cementitious properties.

Chapter 3—Supplementary cementitious materials (SCMs)

Sustainable attributes

Beneficial properties to concrete

Most of today's high-performance concrete mixtures use one or more supplementary cementitious materials (SCMs) to enhance workability, strength, durability, service life, and other performance characteristics. While there are a number of potential SCMs that have been used in concrete (including volcanic ash, metakaolin, and rice husk ash), this chapter focuses on the three most common: fly ash, silica fume, and slag cement. The process that produces these materials influences their properties, so a basic introduction to each is given below.

Fly ash

Fly ash is a by-product of coal-fired plants that generate electricity. The fly ash is transported through the boiler by flue gases and captured. The particles are spherical, and are sized on the order of 2×10^{-5} to 4×10^{-3} in. (0.5 to 100 μm). Class F fly ashes are typically produced from anthracite and bituminous coal, and Class C fly ashes are typically produced by lignite or subbituminous coal. Class F fly ash is pozzolanic, but is less reactive than Class C fly ash. Some Class C fly ashes alone will harden and gain strength with the addition of water. The specification for fly ash is ASTM C618-08a (ASTM International 2008).

Fly ash: Class C and Class F

Class F ash is predominantly produced in the Eastern U.S., while Class C ash is produced in the Midwest and Western U.S. Class C ash contains minimal residual carbon, whereas Class F ash can contain high and varying levels of residual carbon. This is caused by incomplete combustion at power plants, due to NOx emissions controls, and can cause quality problems in concrete. However, since the mid-1990s, beneficiation processes are being commercially employed to reduce carbon in fly ash to low consistent levels, thus converting an uncontrolled by-product to a specified manufactured product.

Silica fume

Silica fume a very fine, dust-like material generated during silicon metal and ferrosilicon production (also referred to as microsilica or condensed silica fume). Specifically, it is produced by the reduction of high-purity quartz with coal or coke and woodchips in an electric arc furnace during silicon metal or ferrosilicon alloy production. The glassy, spherical fume particles are extremely small, measuring less than 1 μm in diameter, with an average diameter of approximately 4×10^{-6} in. (0.1 μm). Silica fume particles are composed primarily of amorphous silicon dioxide (usually more than 85%). The silica fume is collected from electric arc furnace stack filters and recovered for reuse as a pozzolan in high-performance concrete (HPC). Silica fume is sold in the U.S. in powder form, and is often made denser by tumbling it in a silo, which leads to the buildup of surface charges and an agglomeration of particles, producing what is referred to as densified silica fume, the most widely used form of silica fume used in concrete. The densification of silica fume increases the loose-fill bulk density, which reduces the volume of the material and makes it more economical to transport and handle in conventional concrete operations. Silica fume can also be shipped as a slurry, but this is typically not done due to the increased cost of transport. The specification for silica fume is ASTM C1240-05 (ASTM International 2005).

Slag cement

In the production of iron, the blast furnace is continuously charged from the top with iron oxide (ore, pellets, and sinter), fluxing stone (limestone or dolomite), and fuel (typically coke). Two products are obtained from the furnace: molten iron that collects in the bottom of the furnace (hearth), and liquid iron blast-furnace slag floating on the pool of molten iron. Both are periodically tapped from the furnace at a temperature of approximately 2732°F (1500°C). The composition of blast-furnace slag is determined by that of the ores, fluxing stone, and impurities in the coke charged into the blast furnace. Typically, silica, calcium, aluminum, magnesium, and oxygen constitute 95% or more of the blast-furnace slag.

To maximize cementitious properties, the molten slag is chilled rapidly as it leaves the blast furnace. Rapid quenching or chilling minimizes crystallization and converts the molten slag into fine-aggregate-sized particles composed predominantly of glass. This product is referred to as granulated blast-furnace slag. The potential reactivity of a granulated blast-furnace slag depends, to a large extent, on the chemistry and the glass content.

Other types of blast-furnace slag can be used as aggregates, and are discussed in Chapter 4. The specification for slag cement is ASTM C989-09a (ASTM International 2009).

Performance

Many years of widespread use have demonstrated that these SCMs can, when used appropriately, enhance both fresh and hardened properties of concrete. In addition to the environmental benefits provided by using these industrial by-products, SCMs can significantly improve the quality of the concrete. Some of the benefits are highlighted in this section; each type of SCM affects these items to a different degree.

- **Increased compressive strength**—Higher strengths allow more efficient sections that are useful in applications such as structural columns in high-rise buildings, piles and girders in HPC bridges, and heavily loaded pavements or floors. The impact of

SCMs on increased strength is most prevalent at ages beyond 7 days;

- **Reduced bleeding**—While fly ash and slag decrease bleeding to some degree, silica fume reduces bleeding most significantly. Excessive bleeding in concrete can lead to the formation of capillary channels that can increase concrete permeability;
- **Reduced heat during curing (heat of hydration)**—SCMs can reduce the heat generated in concrete due to their impact on early-age chemical reactions as well as the reduced amount of portland cement, which is the primary contributor to heat evolution. This is particularly useful in mass concrete applications where reducing heat is crucial;
- **Reduced permeability**—SCMs reduce the permeability of concrete because they react with cement hydration products to reduce capillary pores and thus the permeability of the concrete paste system. In addition, their fineness also contributes to reduced permeability. While fly ash and slag cement can be finer than cement particles, silica fume is approximately 100 times finer than cement. The reduced permeability of concrete due to SCMs means better resistance to intrusion of chloride ions from deicing chemicals and attack from chemicals, such as sulfates and acids that affect concrete durability;
- **Corrosion resistance**—Reduced chlorine ion intrusion protects the reinforcing steel from corrosion and helps extend the life of steel-reinforced concrete structures;
- **Mitigation of alkali-silica reaction (ASR) (fly ash)**—Marginal quality sand and gravel can contain reactive forms of silica. Sodium and potassium alkalis in the portland cement can react and cause expansion of the concrete. In extreme cases, the useful life of the concrete will be shortened. Some sources of fly ash are powerful mitigators of ASR. Fly ash usually costs much less than portland cement; therefore, fly ash may provide an inexpensive method that allows marginal aggregates to be used in concrete. More information can be found in ACI 201.2R-08 (ACI Committee 201 2008) and ACI 221.1R-98 (ACI Committee 221 1998);
- **Electrical resistivity (silica fume)**—A large increase in electrical resistivity limits the passage of electrical current through concrete containing silica fume, an important attribute capable of suppressing corrosion current (macrocell) within the concrete matrix. High electrical resistivity is known to increase the period after corrosion starts until repairs are necessary (often called the propagation period); and
- **Workability**—The nature of silica fume as a mixture ingredient in concrete acts to increase the viscosity of concrete by reducing the mobility of water, an effect often visually witnessed as having little or no bleeding. Fly ash and slag cement can significantly add to the workability of concrete by allowing easier placement while keeping the water content low.

Carbon footprint

The EPA (U.S. Environmental Protection Agency 2008) has calculated the environmental impact of fly ash, silica fume, and slag cement and expressed the result in energy efficiency savings and corresponding levels of reduced CO_2 emissions. Table 1.3 summarizes energy savings and avoided CO_2 emissions for each of the three common SCMs. A row in the table is included based on reasonable rates of SCM substitution by type. These rates can vary significantly depending on the application, and many times a ternary mixture (using two SCMs along with portland cement in the same mixture) may be the preferred alternative to achieve the desired properties. Different grades of SCMs also use different replacement rates. For instance, very high replacement percentages of cement with Class C fly ash may be appropriate for specific applications.

Longevity and life cycle

SCMs play a critical role in increasing the longevity of concrete structures, and this has been a major reason for their widespread use for many years. The low permeability that SCMs provide extends the time-to-corrosion initiation period of steel reinforcement in uncracked concrete. Once corrosion in the steel begins, the increased volume occupied by the resulting corrosion product (rust) can crack the concrete cover, resulting in quicker access of chlorides and other aggressive agents to the steel.

In addition, if sufficient chlorides are present to initiate corrosion of the steel reinforcement, the substitution of portland cement with silica fume delays the propagation of corrosion. This is due to an increased electrical resistivity of silica fume concrete that slows down the corrosion rate (Smith et al. 2004), thus extending the period between first corrosion and time to replacement.

Table 1.3—Energy savings and reduced CO_2 emissions per ton of SCM used (adapted from Bühler [2010])

	Fly ash (Class F)	Slag cement	Silica fume
Energy savings (Btu)	10,425,000 (At 30% substitution: 3,128,000)	4,409,000 (At 50% substitution: 2,205,000)	34,382,000 (At 10% substitution: 3,438,000)
Energy savings, USD	302	128	997
Reduced CO_2 emissions (lbs)	3621	1625	1697

Note: 1 Btu = 1.055 kJ; 1 lb = 454 g; 1 ton = 0.9 metric tons.

Once corrosion is initiated, the electrical current that feeds the anode and cathode at the level of reinforcing steel through the concrete matrix (macrocell corrosion) is highly suppressed in silica fume concrete, as shown in the widely used evaluation method, ASTM C1202-10 (ASTM International 2010). This characteristic is an important consideration to the life cycle of the structure, but should not be considered as a "time to corrosion test" because many other factors contribute to the corrosion of reinforcement in concrete in place.

Human factors and living/working environment

Heat island effect

Urban areas can reach temperatures up to 10°F (6°C) higher than surrounding undeveloped areas. In summer, 99% of this temperature increase is due to dark surfaces such as roofs and pavement (Rosenfeld et al. 1997). The heat island effect has multiple consequences that affect all three aspects of the triple bottom line. Higher temperatures mean that more energy is used for cooling in buildings. The additional energy required to counteract this increased air temperature results in more cost as well as CO_2 release and pollution. These higher heat levels and pollution are ideal conditions for the creation of smog, which causes respiratory distress and allergies for many people.

Strategies to reduce heat island effect include "cool" roofs and pavements, along with vegetation. Light-colored materials reflect heat instead of absorbing it, whereas porous materials have a lower storage capacity for heat due to their large void percentage, and allow cooling through moisture evaporation.

Materials are quantified for their potential as a cool surface through a solar reflective index (SRI). The SRI combines the effect of albedo (solar reflectance) and emittance (portion of energy radiated from the material surface). Materials with high SRI values result in much cooler roofs and pavements, thus reducing the heat island effect. SRI values typically range from 1 to 100, but very dark absorbing materials can have negative SRI values, and some white materials can be above 100. Because the SRI value is dependent on both reflectivity and emissivity, materials of the same type with different colors can have a wide range of SRI values. The use of a light-colored coating is often an option to achieve a high SRI value when concrete is not used. Concrete (particularly the lighter shades of concrete) generally has a high SRI value. Slag cement and some fly ashes are light in color, and thus produce a more reflective concrete that reduces the heat island effect. Details on SRI values are available in *The Sustainable Concrete Guide—Strategies and Examples* (Schokker 2010).

Potential health concerns

As with use of cement, proper respiratory, eye, and skin protection are needed when using SCMs. This section is not intended as a comprehensive resource on the safe use of SCMs, but rather as a general overview.

Fly ash

In 1980, the U.S. Congress enacted the Bevill exclusion, which excludes fly ash and other solid waste from the extraction, beneficiation, and processing of ores and minerals from regulation. In 1993 and 2000, the EPA determined that fly ash did not warrant regulation under Subtitle C of the Resource Conservation and Recovery Act (RCRA) and that it retains that exemption under RCRA Section 3001(b)(3)(c). In 2009, the EPA began considering regulations to manage the disposal of fly ash, maintaining that beneficial use of fly ash would still be encouraged and would remain exempt from regulation.

Fly ash of any composition that is incorporated into concrete is, to a high degree, sequestered; and its environmental interaction is significantly reduced. Such sequestering remains even if the concrete is subsequently ground into aggregate-sized particles and recycled.

Silica fume (Silica Fume Association 2005)

As a result of its formation, silica fume is an amorphous form of silica. Silica fume is not associated with any severe health concerns. In contrast to respirable crystalline silica, which was reclassified as a human carcinogen by the International Agency for Research on Cancer (IARC) in 2009, amorphous silica was not associated with silicosis or lung cancer. Amorphous silica is considered a PNOC (particulates not otherwise classified), and is therefore a nuisance dust. As with all types of dusts, however, there is a risk of chronic obstructive lung disease upon chronic exposure to silica fume in concentrations that exceed the occupational exposure limit value. It is therefore recommended in the material safety data sheet to avoid dust-generating activities and to wear dust masks when handling silica fume. Traces of crystalline silica may be present in silica fume from carry-over of the raw materials into the off gas. Specific studies to the European regulation REACH (Registration, Evaluation, Authorization and Restriction of Chemical substances (European Parliament 2006), however, have shown that the amount of respirable crystalline silica in silica fume is only marginal (<0.1%), and does not necessitate any hazardous classification.

Because a fraction of silica fume is a nanomaterial (<100 μmm)—as per ISO/TS 27687 (American National Standards Institute 2008)—the hazardous properties have been assessed accordingly. Dustiness tests according to EN 15051 (British Standards Institution 2006) have shown that the amount of airborne silica fume in nanosized particles is extremely low due to the agglomeration of the particles. As a result, silica fume has been characterized as a material that does not release nanosized particles in air.

Slag cement

Slag cement contains trace amounts of crystalline silica, so the prolonged inhalation of respirable crystalline silica from slag cement can cause silicosis. Slag is not listed as a carcinogen by the IARC or the National Toxicity Program (NTP), but crystalline silica and hexavalent chromium (both found in trace amounts in slag cement) are classified as known human carcinogens. It should be noted that the trace amounts of these materials are the same as or lower than other cements. The Occupational Safety and Health Administration (OSHA) (2010) states that slag cement can be used to reduce impacts of hexavalent chromium.

Reduce, reuse, recycle

As by-products of major industrial markets, fly ash, silica fume, and slag cement are produced in mass quantities. Before viable uses were developed for these materials, they had to be stockpiled or disposed of by various means. The use of these SCMs takes an industrial by-product out of the waste stream and turns it into a beneficial additive for sustainable construction. SCMs greatly improve concrete quality, lower its carbon footprint, and provide economy to structures.

Compatibility with other innovative sustainability strategies

Research has shown a synergistic effect when using two or more SCM materials in the same concrete mixture (Bouzoubaa et al. 2004; Thomas et al. 1999; Smith et al. 2004). Reduced permeability, reduced cracking, improved alkali-silica reaction (ASR) control, and controlled heat of hydration are a few properties that benefit from incorporating multiple SCMs into concrete mixtures. Because each reacts differently in concrete due to chemical and physical differences, using SCMs in optimized combinations can produce unique properties. This optimization leads to the creation of high-performance concretes where performance properties are selected precisely for the environment to which the concrete will be exposed during the structure's service life.

Case studies

Hanford Site (Hanford, WA)

The use of SCMs played an important role for the canister storage facility at the Hanford Site nuclear facility. The concrete was required to have a minimum strength of 7500 psi (51.5 MPa) while limiting the maximum in-place temperature to 100°F (38°C) to control thermal cracking. This is difficult to achieve because high strength and low heat are typically at odds for mixture proportioning. Through the use of a ternary mixture with silica fume and fly ash, both properties were achieved, along with the other sustainability benefits related to the use of these materials discussed previously in this chapter. Table 1.4 summarizes the cementitious materials in the mixture and the benefits in energy savings and reduced CO_2 emissions.

Four Seasons Hotel and Tower (Miami, FL)

At 750 ft (229 m), the Four Seasons Hotel and Tower is the tallest building in Florida, designed with concrete strengths up to f_c' = 10,000 psi (69 MPa). Modulus of elasticity requirements ranged from 4 to 6 million psi (28 to 42 GPa). The dense reinforcement configurations (Fig. 1.12), particularly in the core of the building, required that the concrete maintain high workability even with temperatures close to 100°F (38°C) for up to 2 hours from the time of batching.

The various concrete mixtures employed a 6% silica fume addition rate to a 50/50 blend of slag and portland cements, each contributing to specific mixture proportion requirements. In 2002, slag cement was recently introduced to the local marketplace, and had shown great advantages in reducing total water demand and maintaining workability of a self-consolidating concrete (SCC) under hot weather conditions. Originally, all high-strength concrete on the project was to receive imported coarse aggregate, as the local limestone aggregate had shown limitations in its capacity to consistently attain modulus of elasticity values in excess of 4 million psi (28 GPa). During the pre-bid concrete evaluations, it became evident that this project's modulus of elasticity requirements could be achieved with the locally available limestone aggregate when silica fume was part of the mixture. As a result, 15,000 yd^3 (11,500 m^3) of concrete could forgo the imported granite aggregate at an overall concrete mixture savings of approximately $150,000, along with a significant reduction in energy use and CO_2 emissions from the long transport. These concrete mixtures employed 10 to 15% less total cementitious material than similar HPC

Table 1.4—Hanford Site mixture components

Material	Amount, lb/yd^3	Substitution, %	Energy savings*, USD/yd^3	Avoided CO_2 emissions,* lbs/yd^3
Cement, Type I	391	—	—	—
Fly ash, Class F	150	25	$12.00	146
Silica fume	60	10	$73.80	126
Total cementitious	601	35	$85.80	272

*Based on average performance characteristics of a conventional mixture with f_c' = 4000 psi (27.6 MPa) at 28 days, 500 lb (227 kg) cement, 30 gal. (114 L) water

Note: 1 lb/yd^3 = 0.593 kg/m^3.

produced in the area. The sand-to-total aggregate ratio was 0.36, which was highly desirable for high-strength concrete maximizing coarse aggregate content, but less than ideal for SCC proportioning that typically has higher fines. Silica fume's viscosity-modifying properties enhanced the SCC consistency in controlling segregation even under situations of free fall heights up to 20 ft (6.5 m) and pumped delivery up to the top of the building. Table 1.5 shows a mixture summary. Figure 1.11 shows the reinforcement congestion and Fig. 1.12 shows the SCC being pumped into place.

Solid Waste Authority (Palm Beach Gardens, FL)

Although the floors are made with specialty components such as iron aggregates, impact from garbage trucks unloading and abrasion from heavy equipment moving trash can shorten the average transfer floor life to only 1 to 3 years, as shown in Fig. 1.13. For the Solid Waste Authority, the downtime of any plant and the logistics of diverting continually accumulating trash are paramount. Floor rehabilitation typically averages 2 months of construction time before the floor goes back into operation. The average cost of the rehabilitation at the time of this project (1993) would have been approximately $17/ft^2 ($183/m^2). A ternary mixture with silica fume and fly ash allowed easy application and rapid strength gain that reduced the typical downtime for this project to only 1 month from the start of demolition to the reopening of the facility. The total construction cost approached $9/ft^2 ($97/m^2) for a topping twice as thick, at a project savings of a reported $250,000 (1993 U.S. dollars). Life expectancy more than doubled, as the new floor was still in service after 6 years. Table 1.6 shows a mixture summary and Fig. 1.14 shows the floor under construction.

Indianapolis International Airport Parking Garage (Indianapolis, IN)

The Midfield Terminal at the new Indianapolis International Airport opened in 2008, and includes a massive 7000-car parking garage. Each of the five parking levels is approximately 500,000 ft^2 (46,500 m^2). The two-way post-tensioned concrete design for the garage maximized the benefit from the chosen HPC mixture.

Longevity with minimal maintenance was a key concern for the Airport Authority. They recognized that next to airfield revenues, the parking garage is the second largest revenue generator for the airport.

The Airport Authority had a design service-life requirement of 70 years (equivalent to the airport service life). To achieve a 70-year service-life design in the parking decks, the designer chose an HPC mixture that was previously used to construct other local parking garages. The HPC mixture incorporated both fly ash and silica fume as SCMs. The silica fume and fly ash,

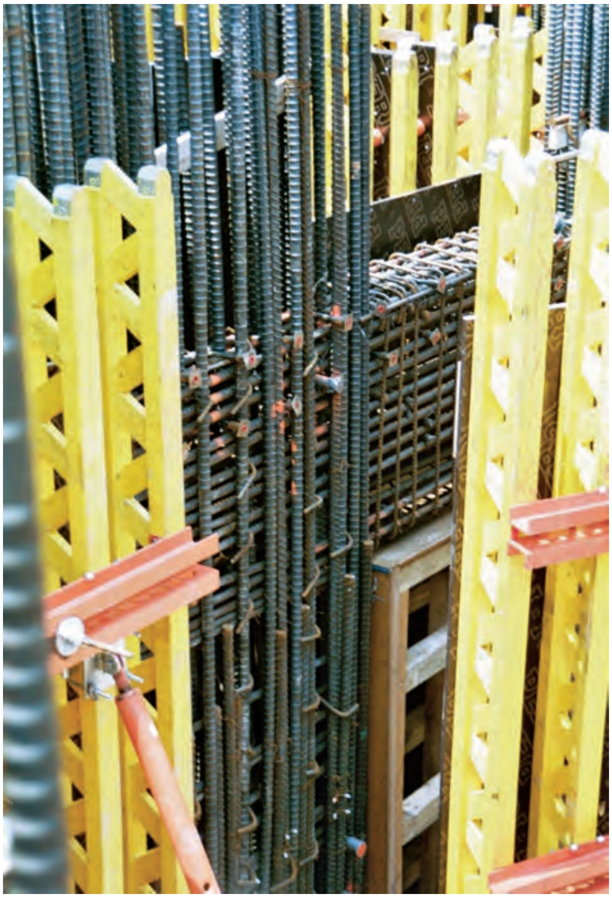


Fig. 1.11—Massive structures receive low heat of hydration concrete. *Courtesy of Silica Fume Association*

Fig. 1.12—SCC flowing into the reinforcing cage. *Courtesy of Silica Fume Association*

Table 1.5—Four Seasons Hotel and Tower mixture components

Material	Amount, lbs/yd³	Substitution, %	Energy savings, USD/yd³	Avoided CO_2 emissions, lbs/yd³
Cement, Type I	450	—	—	—
Slag cement	450	47.4	$22.50	270
Silica fume	50	5.2	$61.50	105
Total cementitious	950	52.6	$84.00	375

*Based on average performance characteristics of a conventional mixture with f_c' = 4000 psi (27.6 MPa) at 28 days, 500 lb (227 kg) cement, and 30 gal. (114 L) water.
Note: 1 lb/yd³ = 0.593 kg/m³.

Table 1.6—Solid waste authority site mixture components

Material	Amount, lbs/yd³	Substitution, %	Energy savings,* USD/yd³	Avoided CO2 emissions,* lbs/yd³
Cement, Type IP	578	—	—	—
Fly ash, interground	127	18	$10.16	123
Silica fume	141	16.7	$173.43	296
Total cementitious	846	34.7	$183.59	419

*Based on average performance characteristics of a conventional mixture with f_c'= 4000 psi (27.6 MPa) at 28 days, 500 lb (227 kg) cement, and 30 gal. (114 L) water.
Note: 1 lb/yd³ = 0.593 kg/m³.

Table 1.7—Indianapolis Airport Parking Garage mixture components

Material	Amount, lb/yd³
Cement	611
Fly ash, Class F (100% preconsumer waste)	100
Silica fume (100% preconsumer waste)	50
Water	289
Water-cementitious material ratio (*w/cm*)	<0.375
Coarse aggregate, 3/4 in. (19 mm)	1800
Fine aggregate	1150
CA + FA	Minimum 65% volume
High-range water reducer (HRWR)	6 to 8 oz per cwt
Air-entraining admixture (AEA)	4 to 6%
Strength	3000 psi at 20 hrs; 9000 to 10,000 psi at 28 days
Permeability	<1000 coulombs at 28 days

Note: 1 lb/yd³ = 0.593 kg/m³.

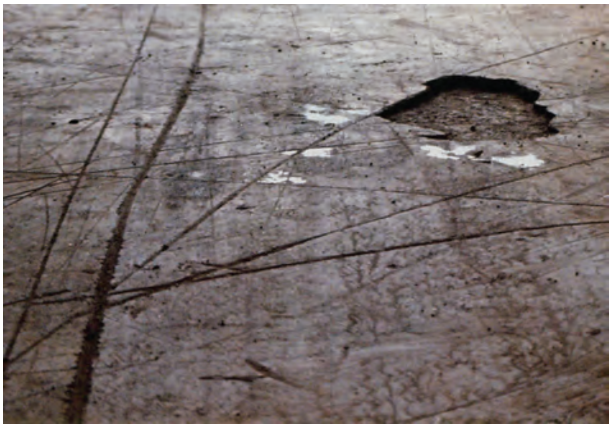


Fig. 1.13—Transfer floor wear after 1 to 3 years. *Photo courtesy of Silica Fume Association*

Fig. 1.14—Finishing the new transfer floor. *Photo courtesy of Silica Fume Association*

as 100% preconsumer waste materials, contributed to the LEED credit for use of recyclable materials. The local sourcing of all concrete materials contributed to a LEED credit for use of local materials, and the use of the SCMs as recycled materials contributed an additional LEED credit.

The number-one priority of any parking garage design is public safety for the user/consumer. Confronted with a design that called for four of the parking levels to have a virtual 500,000 ft^2 (46,500 m^2) roof over the floor, the designers knew they did not want to design a conventional parking garage with columns approximately every three parking spaces (as shown in Fig. 1.15(a)). A more open layout would have less of a cavernous feeling, and less of a perception of a "forest" of columns across the large floor space.

The HPC mixture detailed in Table 1.7 was used throughout the structure, and simplified the construction schedule. The combination of post-tensioning and the HPC mixture reduced the concrete thickness in the slab to 5.5 in. (140 mm). The higher strength, thinner deck, and large girders allowed for greater column spacing (approximately six parking spaces between columns, as shown in Fig. 1.15(b)). The column dimensions were also reduced through the use of HPC.

The contractor used the early-strength gains of the HPC to post-tension decks typically within 20 hours after casting. By post-tensioning at early ages, the concrete is placed under compression before the greatest shrinkage period, which virtually eliminates concrete deck cracking. The project called for 163 individual deck placement days,

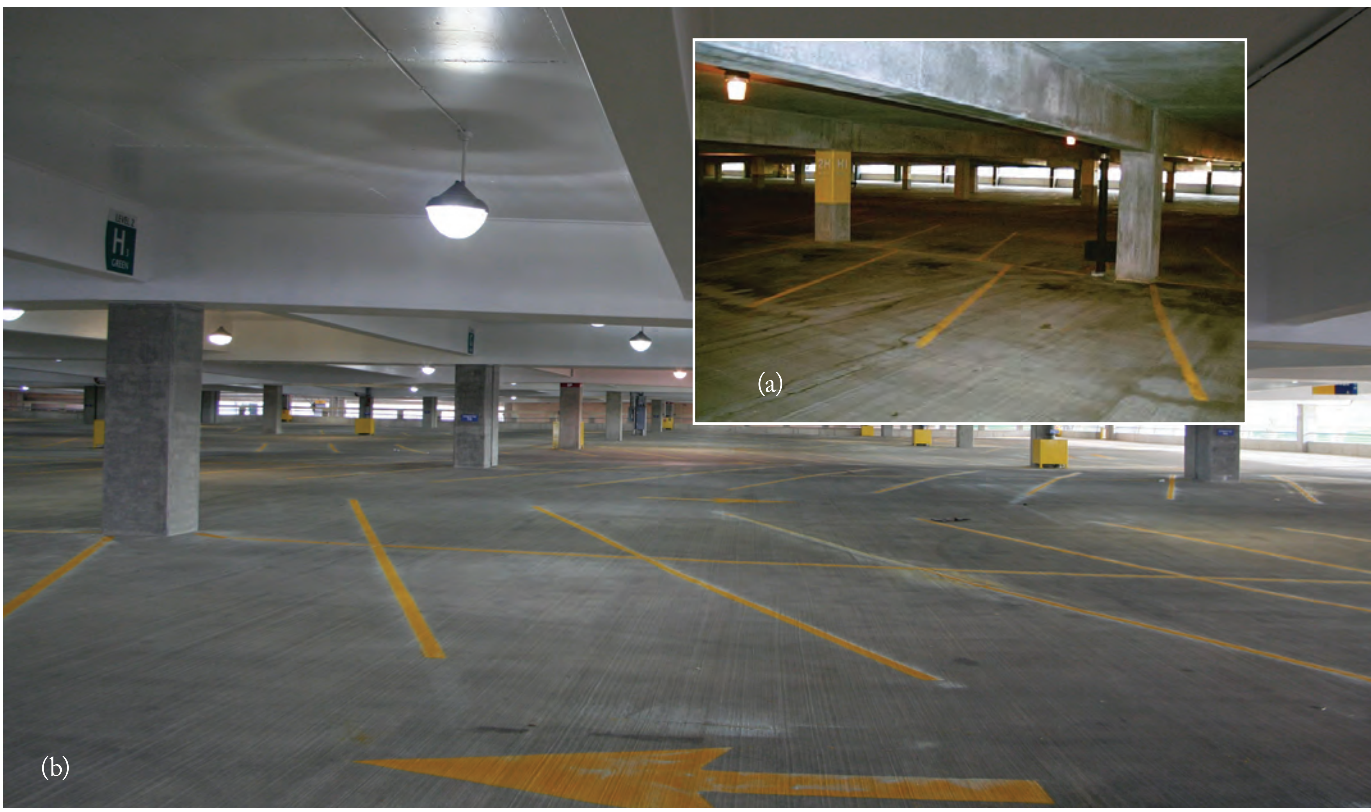


Fig. 1.15—(a) Conventional parking garage column spacing; and (b) column spacing on the Indianapolis Airport Parking Garage. *Photos courtesy of Silica Fume Association*

Fig. 1.16—Finishing operation. *Photos courtesy of Silica Fume Association*

Fig. 1.17—Indianapolis Airport Parking Garage. *Photo courtesy of Silica Fume Association*

and continued uninterrupted for 16 months. Being able to reuse forms quickly proved to be an economical advantage to the contractor. Another economical advantage for the contractor was the ability to rapidly finish and cure the HPC parking decks. HPC mixtures with sufficient amounts of SCMs will have virtually no bleed (free) water. Without bleed water, the contractor can place, consolidate, bring to grade, close the surface, texture, and cure the concrete in a single pass (one-pass finishing operation). Figure 1.16 shows photos of the progression of the finishing operation, and Fig. 1.17 shows the completed garage.

Beneficiation—(As used in reference to fly ash) the process of separating the by-product of electricity generation (fly ash) into a consistent lower carbon content fly ash product suitable for cement substitution and a carbon-rich material that can be returned as fuel.
Blast-furnace slag (BFS)—Formed when iron ore, coke, and a flux (limestone or dolomite) are reduced together in a blast furnace.
Blended cement—A hydraulic cement typically produced by intergrinding portland cement with SCMs.
Fly ash—The finely divided residue that results from the combustion of ground or powdered coal and is transported by flue gases from the combustion zone to the particle removal system.
Metakaolin—A calcined kaolinite (a clay mineral). High reactivity metakaolin has potential advantages for concrete that include increased strength and durability, reduced permeability and shrinkage, and enhanced workability.
Natural pozzolans—Naturally occurring reactive materials such as volcanic ash, diatomaceous earth, pumice, and pumicite. With processing, these materials can serve as SCMs.
Pozzolan—A siliceous (or siliceous and aluminous) material that chemically reacts with calcium hydroxide to form compounds possessing cementitious properties.
Recovered mineral components (RMCs)—Recycled industry materials that are able to substitute for conventionally used ingredients, such as cement (primarily) or aggregates. The definition for RMC was introduced by the EPA (U.S. Environmental Protection Agency 2008b).
Rice husk ash (RHA)—A by-product from the burning of rice husks/hulls that has been used as an SCM.
Silica fume—A very fine, dust-like material generated during silicon metal and ferrosilicon production (also referred to as microsilica or condensed silica fume).
Slag—A broad term covering all nonmetallic by-products resulting from the separation of a metal from its ore. Only granulated blast-furnace slag is used as an SCM. Steel-furnace slag is not used in the production of concrete, but can be used as an additive in the production of portland cement, as discussed in Chapter 2.
Slag cement—Also called ground-granulated blast-furnace slag (GGBFS). GGBFS is dewatered and then screened and ground to form slag cement.
Supplementary cementitious materials (SCMs)—Inorganic materials such as slag cement, fly ash, or silica fume, metakaolin, rice husk ash, volcanic ash, pumice, pumicite, and others that react pozzolanically or hydraulically. SCMs substitute for a portion of cement content in a concrete mixture and, for a given set of performance requirements, can reduce the portland cement content. Silica fume, fly ash, and slag cement meet both RMC and SCM characteristics, and have a proven track record in concrete.

Chapter 4—Aggregates

Sustainable attributes

Aggregates are an essential component of concrete, and contribute to durability and a number of related properties. ACI E1-07 (ACI Committee E-701 2007) provides an excellent primer for understanding aggregate types and uses. Aggregates are typically classified as natural (sands and gravel that are used at the size that nature produces through weathering) or manufactured (fine and coarse aggregate produced from crushing larger stone). Aggregates can also be by-products or co-products of certain industries: blast-furnace slag (discussed as a supplementary cementitious material in Chapter 3, and as an aggregate in this chapter) is one example. Other aggregates are specifically manufactured to achieve certain properties (such as being lightweight). Rotary kiln-produced expanded shale, clay, and slate (ESCS) aggregate is specifically produced to be lightweight. This aggregate typically has a higher initial cost (both monetary and in embodied energy) per unit volume than standard normalweight aggregate. However, the benefits provided in-place to the building users, particularly related to energy savings and reduction in the amount and weight of material used, usually offset the initial cost premium or result in a net savings (Ries et al. 2010). Some natural lightweight aggregates, such as pumice, are also available. The maximum strength of the concrete with lightweight aggregate may depend on the aggregate itself. Increasing cement amounts in the mixture can increase strength up to a point when a "strength ceiling" is reached. At that point, the aggregate is the controlling factor and significant additional strength cannot be attained with increasing cement content. (ACI Committee E-701 2007).

The type of rock used for aggregates can also influence properties such as durability and strength. For instance, a hard rock, such as granite, will typically be difficult to fracture within the concrete, whereas a softer rock, such as limestone, is more likely to fracture. The porosity of the aggregates can also have an influence. It is important to note, however, that rock type alone does not indicate aggregate performance for a specific situation; testing must be done to ensure the proper quality of aggregate.

Carbon footprint

Transportation

Different regions have different types of locally available aggregate. Rather than trucking certain aggregate long distances, making the best use of local sources is preferable for saving fuel and reducing CO_2 emissions. Concrete mixture proportions can be adjusted accordingly to accommodate for the differences.

Lightweight aggregate can reduce transportation costs and environmental impact through reduced weight. This may or may not be true for the transportation of lightweight aggregate from its source, because sources can be long distances from local markets. On the other hand, transportation cost and environmental impact can be lowered in cases where precast construction is used as the final product. Table 1.8 shows an example of how weight contributes to trucking cost from a study conducted at a precast plant in the U.S. Costs shown are the trucking costs for transporting the precast panels from the precast facility to the site. The transportation cost savings in this case was seven times greater than the additional cost of the lightweight aggregate (Ries et al. 2010). The number of truck loads was reduced by over 30%, providing a significant contribution to reducing the carbon footprint from transportation.

Thermal transmission

Concrete with lightweight aggregate has better insulating properties than standard concrete due to the reduced concrete density (and corresponding increased thermal resistance). Figure 1.18 shows the relationship between the *R*-value per 1 in. (2.5 cm) thickness for varying concrete weights. The insulating properties of the lighter-weight concrete provide a reduction in energy use from heating (or cooling) losses that can become substantial over the life of the building. Details about the thermal mass and thermal transmission—along with examples and calculations—can be found in *The Sustainable Concrete Guide—Strategies and Examples* (Schokker 2010).

Longevity and life cycle

Aggregate is tested for abrasion resistance, impact resistance, soundness, chemical stability, and a number of other tests of the aggregate itself or as part of a concrete specimen. This testing helps to ensure a durable end-product. Normalweight aggregate concrete has a proven track record of durability.

Table 1.8—Reduction in transportation costs with lightweight precast concrete (adapted from Ries et al. 2010)

Shipping cost per truck load, USD		$1100
Number of loads required	Normalweight concrete (145 lb/ft^3 [2320 kg/m^3])	431 loads
	Lightweight concrete (114 lb/ft^3 [1830 kg/m^3])	287 loads
	Reduction in loads required	**144 loads**
Transportation savings	Shipping cost per load × cost reduction in truck loads	$1100 × 144
	Total savings	**$158,400**

Table courtesy of Big River Industries

Lightweight concrete also has a history of good performance. Versions of lightweight concrete were used as early as 126 A.D. in the dome of the Pantheon (still in good condition today) and also in 75 to 80 A.D. for the Roman Coliseum. After the fall of the Roman Empire, lightweight concrete only saw limited use until the twentieth century (Expanded Shale Clay and Slate Institute 1971). Today, lightweight concrete and masonry is widely used.

The addition on the Southwestern Bell Telephone Company office in Kansas City, MO, was one of the first major building projects in the U.S. to use lightweight concrete. The 14-story addition was completed in 1929. Had normalweight concrete been used, a bigger foundation would have been required because the foundation of the original building, as designed, could only have taken the weight of eight floors. After more than 80 years, this building remains in service (Ries et al. 2010).

Storm water management

Rounded and crushed, coarse, single-size aggregate of grading between 3/4 and 3/8 in. (19 and 9.5 mm) is typically the only aggregate component of pervious concrete. Normalweight aggregate is typically used, although both normal and lightweight aggregate have been used to make pervious concrete.

While the use of lightweight concrete does not have specific benefits in pervious concrete, ESCS lightweight aggregate is a tool for storm-water management through on-site water filtering and use in rain gardens and bioswales. Lightweight aggregate is also used as part of the soil mixture for green roofs to support plant growth and provide drainage.

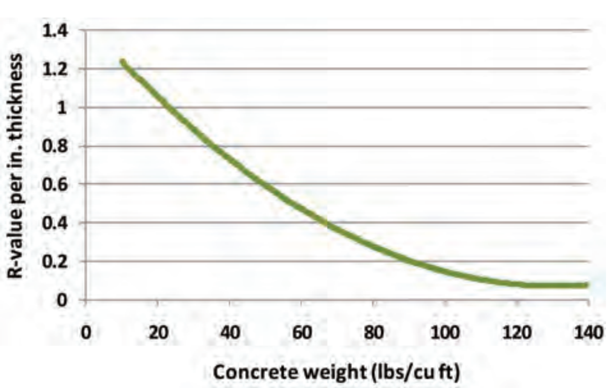


Fig. 1.18—*R*-value versus concrete weight (data from Prestressed Concrete Institute 2007). (Note: 1 in. = 2.5 cm; 1 lb/ft^3 = 16 kg/m^3)

Human factors and living/working environment

Ergonomics

A good example of the benefit of the use of lightweight aggregate for the work force is lightweight masonry blocks. With a weight up to 40% lighter than traditional concrete masonry units, the physical demands and injury risk for workers is significantly decreased. Masons can work more comfortably and efficiently. As an example, a mason can place approximately 20% more wall area during a year, but still lift approximately 15% less weight (94 fewer tons [85 metric tons]) per year (Ries et al. 2010).

Security and safety

Fire resistance

The fire resistance of concrete is well-established, and depends on the aggregate type. Table 1.9 shows the minimum cover thickness requirements for different types of aggregate for different fire durations for design as per ACI 216.1-07 (American Concrete Institute 2007).

Lightweight concrete has lower thermal conductivity and a lower coefficient of thermal expansion than normalweight concrete. Additionally, the ESCS aggregate has already been heated to above 2000°F (1090°C) during its manufacture, and is stable at high temperatures. The minimum thickness of supported concrete slabs may be controlled in some cases by the fire rating rather than standard loads. In these cases, lightweight concrete can reduce the slab thickness needed and the corresponding concrete volume for the building.

Shielding

Normalweight aggregate concrete can be an effective barrier for blast loading or other types of extreme loading, such as from hurricanes and tornados. Lightweight aggregate can also be incorporated in layers or in graded density walls for energy dissipation under blast loading.

Table 1.9—Fire resistance of single-layer concrete walls, floors, and roofs (Joint ACI-TMS Committee 216 2007)

	Minimum equivalent thickness for fire-resistance rating, in. (mm)				
Aggregate type	1 hour	1-½ hours	2 hours	3 hours	4 hours
Siliceous	3.5	4.3	5.0	6.2	7.0
Carbonate	3.2	4.0	4.6	5.7	6.6
Semi-lightweight	2.7	3.3	3.8	4.6	5.4
Lightweight	2.5	3.1	3.6	4.4	5.1

Note: 1 in. = 25 mm.

Heavyweight aggregates are used in concrete for specialty applications—such as radiation shielding—at a lower cost than lead or composite shields.

Reduce, reuse, recycle

Using recycled concrete aggregate for new concrete reduces the demand for virgin aggregate (such as the aggregate stockpiles shown in Fig. 1.19), conserving natural resources, while minimizing the waste stream by diverting demolished material from landfill. Recycled normalweight and lightweight concrete can also be used for a variety of applications where virgin material (whether natural or manufactured gravel) has been traditionally used, such as aggregate base coarse under pavement and water drainage areas. When crushed concrete is reused on site, transportation costs are also avoided twice—shipping demolished material to disposal and virgin material to the site.

Air-cooled blast-furnace slag is an example of an aggregate that comes as a by-product from another industry. Slag cement is discussed in Chapter 3 as an SCM, but air-cooled blast-furnace slag can also be processed for use as an aggregate. Air-cooled blast-furnace slag has noninterconnected voids that can result in a structural aggregate with a relatively low bulk density and good freezing-and-thawing durability. Air-entraining agents are recommended for use with slag aggregate to help with workability, even if the concrete will not need freezing-and-thawing resistance (ACI Committee E-701 2007).

ACI 555R-01 (ACI Committee 555 2001) provides details on recycled aggregate starting with removal through mixture proportioning and concrete production. Working with recycled aggregate versus virgin aggregate requires knowledge of the potential changes in properties expected in concrete with recycled aggregate. A few examples are listed as follows for recycled coarse aggregate concrete (summarized from ACI 555R-01 [ACI Committee 555 2001]):

- Concrete strength
  - Reduction of 5 to 25% found in research
  - A good rule of thumb is to anticipate a one-third reduction in strength when compared with the use of similar virgin material sources
  - Higher variation in strength test results
- Concrete modulus of elasticity
  - Lower (research showed 25 to 40% reduction)
  - More variation
- Concrete creep
  - Higher (research showed 30 to 60% increase due to the paste content in the recycled aggregate)
- Concrete drying shrinkage
  - Higher (research showed 20 to 50% increase)
- Concrete permeability
  - Higher (research showed two to five times higher at water-cementitous ratios [*w/cm*] between 0.5 and 0.7; effects can be offset by lowering the *w/cm* of the recycled aggregate concrete)
- Concrete freezing-and-thawing resistance
  - No significant change

The property changes noted do not preclude the use of recycled aggregate in a large number of applications; these changes simply must be known to choose the proper mixture proportions for the application. The initially used quarried materials can be reused multiple times through a range of applications. The aggregates may first go into a high-strength structural member, then be used for a lower-strength member, then a pavement, and then as a base layer. In each case, the material is diverted from the waste stream and beneficially reused in place of virgin material.

Some tips for mixture proportioning are as follows (summarized from ACI 555R-01 [ACI Committee 555 2001]):

- Use a higher standard deviation (700 psi [4.83 MPa]) for required compressive strength if recycled aggregates are of variable quality;
- Assume the same water-cementitious material ratio (*w/cm*) when designing the mixture for recycled coarse aggregate concrete as for conventional concrete. If trial batches indicate a strength reduction, lower the *w/cm*;
- Use 5% more free water for recycled coarse aggregate concrete than for conventional concrete to attain the same slump;
- Determine specific gravity, unit weight, and absorption of aggregates before mixture proportion studies;
- Base the mixture proportions on the measured density of the recycled aggregates that will be used in the concrete;
- Use the same sand-aggregate ratio for recycled-aggregate concrete; and
- Perform trial mixtures, as they are absolutely necessary for proper mixture proportioning of recycled aggregate concrete. If the placement will include confined spaces and irregular form shapes, trial placements should also be included.

Production (batching, mixing, transporting, and placing) of recycled aggregate concrete and conventional concrete are similar. Two items, however, need special attention for the use of recycled aggregate in concrete: 1) presoak the recycled aggregates to offset the higher water absorption; and 2) eliminate materials smaller than the No. 8 (2 mm) sieve before production.

A premier example of aggregate recycling on a large scale is at the site of the former Stapleton Airport in Denver, CO. The project included demolition, removal, and recycling of 1400 acres (5.7 km^2) of concrete runways and other paved surfaces, for a total of 6.5 million tons (6 million metric tons) of aggregate (Construction Materials Recycling Association 2010). Figure 1.20 shows the on-site concrete recycling operations. The aggregate was used throughout the redevelopment of Stapleton for road base, erosion control, and also in

Fig. 1.19—Aggregate stockpiles. *Photo courtesy of BASF*

new concrete. Enterprise Park, which was built on the former Stapleton site, includes three buildings that are made with ready mix concrete containing recycled aggregate from the Stapleton site. The project highlights the use of recycled materials in very large quantities while also nearly eliminating transport impacts because the recycled materials stayed on site.

Economic impact

In addition to the economy through reduction in transportation costs, lightweight concrete can optimize structural efficiency for specific applications. These include thinner fire-resistant slabs, longer spans, taller buildings, adding building stories onto an existing building, and building on sites with poor soil conditions. The dead load reduction reduces foundation loads (and thus, foundation sizes, which saves materials) and decreases inertial seismic forces (Ries 2010).

Compatibility with other innovative sustainability strategies

Internal curing

Internal curing is essentially the continued curing in concrete from water released from the aggregate. As shown in Fig. 1.21, porous lightweight aggregate can hold water in the pores that can continue to be available for curing. The water in the pores is from pre-wetting the aggregate before mixing. The porous surface of lightweight aggregate also allows an exchange between the aggregate and paste at the interface so there is no potential for a weak layer of high water content paste.

Internal curing helps reduce early-age cracking, and is particularly beneficial in concretes with low *w/cm* and where high volumes of pozzolans are used. This makes lightweight aggregate particularly compatible with materials used in sustainable mixtures.

Associations and resources

Guiding principles for sustainable aggregate operations

The National Sand, Stone & Gravel Association (NSSGA) members have a set of resources to encourage sustainable practices in their operations. Their sustainability Web site (**http://www.nssga.org/sustainability/index.html**) has information that describes sustainable approaches, including a guiding principles document and an online quiz for aggregate producers to gauge how they are doing with respect to sustainable practices. The overarching sustainable practices for NSSGA include a commitment to health and safety; community improvement; product reuse; minimization of life-cycle impacts from aggregate extraction, delivery, and use; proper land use and development; and ethical and transparent business practices.

Fig. 1.20—Concrete from Denver's former Stapleton International Airport was recycled and reused on site. *Photo courtesy of Recycled Materials Company, Inc.*

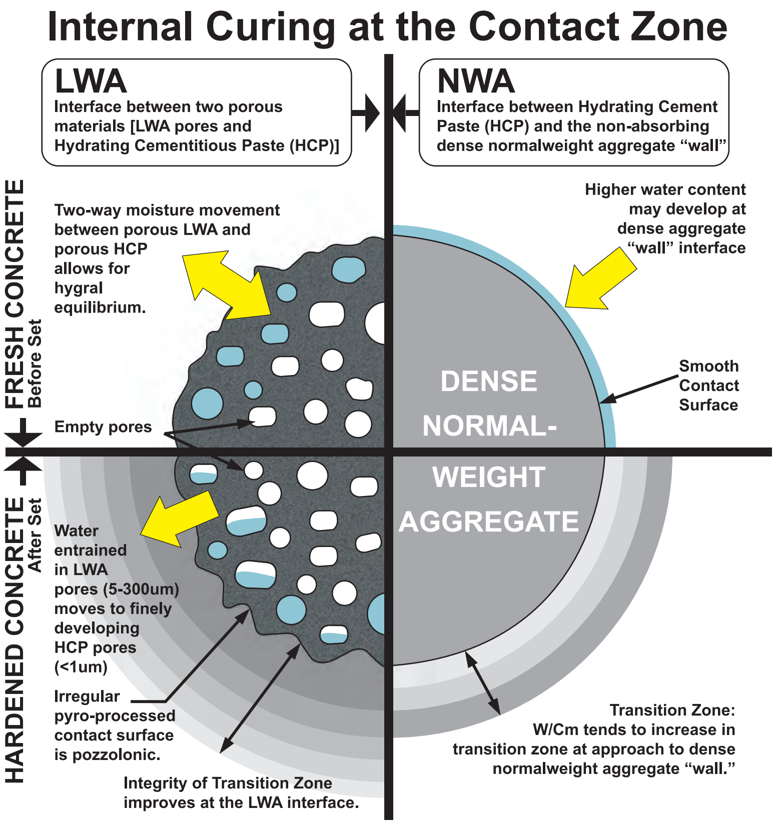


Fig. 1.21—Internal curing at the aggregate paste interface.

Aggregates—The inert materials used in concrete such as sand, gravel, crushed stone, or even less-typical fillers such as chopped rubber, wood chips, and glass beads.

Air-cooled blast-furnace slag—The material resulting from the solidification of molten blast-furnace slag under atmospheric condition. The material is processed through a screening and crushing plant, and is used for aggregate in concrete.

Coarse aggregate (CA)—The coarse granular material (such as crushed stone or gravel) used in concrete. CA is defined by the percentage of material passing a certain sieve size (ASTM C33/C33M-08 [ASTM International 2008]).

Fine aggregate (FA)—The finer granular material (such as sand) used in concrete. FA is defined by the percentage of material passing a certain sieve size (ASTM C33/C33M-08 [ASTM International]).

Heavyweight aggregate (HWA)—Ranges in specific gravity from approximately 3.5 to 7.5 and can produce concretes in a range of unit weight from approximately 180 to 350 lb/ft^3 (290 to 560 kg/m^3). Heavyweight aggregates are used for applications such as radiation shielding or as a counterweight. Examples of heavyweight aggregate include barite, magnetite, iron, and steel (ACI 221R-96 [ACI Committee 221 1996]).

Insulating aggregate—A nonstructural lightweight aggregate that includes ultra-lightweight aggregates such as vermiculite with a bulk density between 5.5 and 10 lb/ft^3 (88 and 160 kg/m^3) (ACI 213R-03 [ACI Committee 213 2003]). ASTM C330/C330M-08, C331-05, and C332-09 (ASTM International 2008, 2005, and 2009) cover lightweight aggregate, masonry lightweight aggregate, and insulating aggregate, respectively.

Structural lightweight aggregate (SLA)—A strong, stable aggregate that is appropriate for structural concrete applications. It can come directly from materials, such as pumice and scoria, that are mined from volcanic deposits, or can be produced from clays, slates, shales, fly ash, and blast-furnace slag.

Lightweight aggregate—The name given to the group of aggregates with a relative density lower than standard (normalweight) aggregates. These include structural lightweight aggregate and masonry lightweight aggregate, both with a bulk density of less than 70 lb/ft^3 (1120 kg/m^3) for fine aggregate, and less than 55 lb/ft^3 (880 kg/m^3) for coarse aggregate.

Normalweight aggregate—Ranges in density of approximately 75 to 110 lb/ft^3 (1200 to 1750 kg/m^3). This aggregate is the aggregate commonly used in normalweight concrete.

Recycled concrete aggregate—Aggregate produced from crushing concrete that is no longer in service. The process includes crushing, removal of foreign materials (such as steel reinforcement or wood), washing, and grading. Recycled aggregates tend to have a higher water absorption than virgin aggregates, and the resulting concrete may have lower strength because the aggregate strength is based on the original concrete (Hansen 1986).

Chapter 5—Reinforcement

Sustainable attributes

Reinforcement plays an important role in structural concrete for a number of reasons: handling tensile stresses (due to direct tension, bending, shear, etc.), crack bridging, ductiliy, confinement, and many others. Reinforcement includes a wide range of materials used in concrete including bars, mesh, strand, and sometimes fiber. This chapter focuses on reinforcing bar (rebar), prestressing steel (including pretensioning and post-tensioning), and welded wire reinforcement. Fibers are included in Chapter 7.

Carbon footprint reduction

Steel reinforcing bars in current practice are typically Grade 60 (yield stress of 60 ksi [414 MPa]). Typical bar sizes and dimensions are given in Tables 1.10 and 1.11. High-strength reinforcing steel products are becoming more readily available: Grade 80 (yield stress of 80 ksi [550 MPa]) was adopted into the ASTM specifications for both ASTM A615/A615M-09 band A706/A706M-09b (ASTM International 2009) in 2009 (for ASTM A615/A615M-09b, Grade 80 will replace ASTM A615/A615M-09b Grade 75 after a transition period). ACI 318, "Building Code Requirements for Structural Concrete," has adopted the limited use of Grade 100 (yield stress of 100 ksi [690 MPa]) as specified by ASTM A1035/A1035M for use as confinement reinforcement (ties or spirals) in compression members. Higher-strength reinforcing products can, in some instances, provide a proportional replacement for lower-strength materials. Such replacement can reduce reinforcing material, and can aid in the reduction of structural mass if members can be reduced in size. Transportation energy, emissions, and cost savings will result from the need to transport a lesser quantity of material. Figures 1.22 and 1.23 show placement of reinforcing bars in the Trump International Hotel & Tower, Chicago, IL. Bars are bent by the fabricator into the necessary shapes, and then tied in place in the field to form the reinforcement cages.

Wire and welded wire reinforcement is fabricated to high yield strengths, up to 100 ksi (689 MPa), in accordance with ASTM A1064/A1064M-09 (ASTM International 2009), thus using less steel material in the design of reinforced concrete structures for many applications. This results in a lowered carbon footprint from both production and transportation. Figure 1.24 shows the placement of welded wire reinforcement before the addition or placing of concrete in a footing in the Ice Mountain Project. Figure 1.25 shows the placement of welded wire reinforcement in a typical tilt-up panel. As mentioned previously, wire reinforcement, much like bars, are bent by a fabricator into the necessary shapes and tied in place in the field. Welded wire reinforcement is welded by the fabricator then is placed flat or can be bent into specific shapes to form reinforcement cages.

Prestressed concrete structures can further reduce the amount of material used due to the precompression provided to the concrete that allows for longer spans and thinner structural members. This efficient use of concrete reduces the amount of cement needed, reduces transportation weights, and thus reduces the overall carbon footprint. Reduced weight in building components also means a reduction in foundation materials and cost. Two standard prestressed applications have shown

Table 1.10—Reinforcing bar designations, in.-lb units

ASTM standard reinforcing bars in.-lb units			
Bar size designation	Area,* in.^{2}	Weight, lb/ft	Diameter,* in.
No. 3	0.11	0.376	0.375
No. 4	0.20	0.668	0.500
No. 5	0.31	1.043	0.625
No. 6	0.44	1.502	0.750
No. 7	0.60	2.044	0.875
No. 8	0.79	2.670	1.000
No. 9	1.00	3.400	1.128
No. 10	1.27	4.303	1.270
No. 11	1.56	5.313	1.410
No. 14	2.25	7.650	1.693
No. 18	4.00	13.600	2.257

*Nominal dimensions.

(1 in.^{2} = 6.5 cm^2; 1 lb/ft = 1.5 kg/m; 1 in. = 2.5 cm)

Courtesy of the Concrete Reinforcing Steel Institute

Table 1.11—Reinforcing bar designations, metric units

ASTM standard reinforcing bars metric units			
Bar size designation	Area,* mm^2	Weight, kg/m	Diameter,* mm
No. 10	71	0.560	9.5
No. 13	129	0.994	12.7
No. 16	199	1.552	15.9
No. 19	284	2.235	19.1
No. 22	387	3.042	22.2
No. 25	510	3.973	25.4
No. 29	645	5.060	28.7
No. 32	819	6.404	32.3
No. 36	1006	7.907	35.8
No. 43	1452	11.38	43.0
No. 57	2581	20.24	57.3

*Nominal dimensions.

Courtesy of the Concrete Reinforcing Steel Institute success in this area for many years: precast pretensioned structural members, and unbonded post-tensioned slabs.

A post-tensioned slab can reduce the floor-to-floor height (and building height) compared with a steel structure of similar bay sizes. This, in turn, reduces the material needed for all vertical elements (concrete, mechanical and electrical systems, elevators, and curtain wall systems). The reduction comes from not only the reduction in slab thickness from post-tensioning versus nonprestressed reinforcement, but also through a reduction in floor-to-floor height once the building systems are incorporated. The amount of interior space to heat and cool is also lowered, which results in a lower carbon footprint for energy use. The energy required to vertically transport liquids, gases, cooled air, and people is also reduced. In very tall buildings, evacuation times can be reduced for tenants on the upper floors.

Fig. 1.22—Bar placement in the foundation of the Trump International Hotel & Tower. *Photo courtesy of Jack Gibbons, Concrete Reinforcing Steel Institute*

Fig. 1.23—Bar placement (Trump International Hotel & Tower). *Photo courtesy of Skidmore, Owings, and Merrill LLP*

Longevity and life cycle

By enhancing the corrosion resistance properties of the reinforcing materials in the structure, the potential exists to substantially enhance the durability of the concrete structure. Reinforced concrete structures that use conventional reinforcing steel bars have proven their ability to provide long-lasting, nearly maintenance-free service lives. In applications where the structure is exposed to chlorides, moisture, and oxygen, however, corrosion of the steel in the concrete is more likely. The concrete provides a high pH environment that protects the steel from corrosion through a passive film layer on the steel. If chlorides reach the steel level, the passive film on the steel can be breached, and corrosion can begin.

There are many ways to help protect the steel from corrosion; some are discussed in Chapter 3. This chapter will focus on the reinforcement itself. The reinforcement can have a coating that provides a protective barrier such as in the case of epoxy-coated reinforcement, governed by ASTM A775/A775M-07b (ASTM International 2007) for straight bars, or ASTM A934/A934M-07 (ASTM International 2007) for prefabricated bars. Galvanization, governed by ASTM A767/A767M-09 (ASTM International 2009), provides both a protective barrier and a sacrificial coating that protects the underlying steel. Zinc and epoxy dual-coated steel reinforcing bars, governed by

Fig. 1.24—Welded wire reinforcement placement in footing (Ice Mountain). *Photo courtesy of ACI Committee 439 volunteers*

Fig. 1.25—Welded wire reinforcement placement in tilt-up panel. *Photo courtesy of ACI Committee 439 volunteers*

ASTM A1055/A1055M-08ae1 (ASTM International 2008), use a thermally sprayed zinc coating method followed by an epoxy coating. ASTM A884/A884M-06 (ASTM International 2006) addresses epoxy-coated steel wire and welded wire reinforcement. Bars made from more corrosion resistant metals, such as stainless steel (governed by ASTM A955/A955M) and wire/welded wire reinforcement conforming to ASTM A1022/A1022M [ASTM International 2010], are also used. Other products, such as stainless steel clad reinforcing bars, have recently been introduced to the market. These products are not currently covered by ASTM specifications, and due to limited availability and transportation distances, should be considered carefully before use (some are only produced outside the U.S.). Nonmetallic reinforcement, such as fiber-reinforced polymer (FRP) reinforcement, is another option for long-term durability. FRP has been in use for decades (ACI Committee 440 2007), but is primarily used in the bridge industry.

The level of protection chosen for reinforcement (such as epoxy coating the steel) depends on the severity of the environment of the structure. Bridges, marine structures, parking garages, and manufacturing facilities with corrosive by-products are examples of environments in which additional protection should be considered. Members in a standard building not located in a severe environment typically do not need an aggressive corrosion protection system.

Prestressed reinforcement is typically designed at a level of force so that the structural members are uncracked at service levels. When combined with low, permeable, high-quality concrete, the reinforcing steel is protected from corrosion. In post-tensioned systems, either grout or a grease-like coating provides an additional layer of corrosion protection for the strand. The unbonded, greased monostrand systems have improved over the years to increase protection of the tendon. The encapsulated nonmetallic sheath and anchorage protection can provide a very robust layer of protection for the post-tensioned strand.

Human factors and living/working environment

The judicious use of repetition can reduce placement effort and speed construction, which reduces the impact on surrounding areas. For example, the Aqua Building in Chicago (Fig. 1.26) incorporated a unique architectural design in which no two floor plates were the same geometric shape as the exterior balcony edges wander around the building. This design created a challenge for the contractor in terms of the relative lack of repeatability from floor to floor. To accommodate the constant change in dimension of the floor plate, the contractor chose to use standard steel reinforcing bar details (all bars were fabricated to the same length) for the exterior balcony reinforcing. This approach alleviated the logistics of individually fabricating each piece of reinforcing steel by simply field adjusting the lap length to accommodate the additional length of the reinforcing bar.

On The Park, a 62-story unbonded post-tensioned building, was built at a rate of one floor every 3 days. It became the first residential tower in the Midwest U.S. to achieve LEED Silver certification. The construction team shaved off more than 2 months from their schedule using a combination of post-tensioning, specialized forming, and high-performance concrete, while keeping construction time (and noise emission) to a minimum. The speed of construction and reduced labor through the use of welded wire reinforcement and unbonded post-tensioning contributed to an improvement for the surrounding environment. Conventional steel reinforcement can be preassembled to also reduce construction cycle times on site, along with other methods (such as efficient forming, concrete pumping, and others discussed in later parts of this book).

In nonurban areas, particularly in environmentally sensitive areas, a reduced construction schedule can be very important for the surrounding ecosystem. While there is the obvious political, social, and economic pressure for constructing structures, it is still important to protect the ecosystem and reduce the impact of the construction industry on the environment.

Security and safety

High-strength (Grade 80) and very-high-strength (Grades 100 and 120) steel reinforcing bars and welded wire reinforcement are ductile materials with high yield and ultimate strengths. In blast-resistant structures, concrete can absorb some of the blast, whereas the reinforcing steel retains the core concrete and minimizes the flying debris. The concrete wall system can serve to stop flying debris from other parts of the building. The elongations of the reinforcement steel before breaking also provide energy absorption to reduce blast effects.

Reduce, reuse, recycle

The following statement has been prepared and approved by the Concrete Reinforcing Steel Institute's (CRSI) Technical Committees regarding the percentage of recycled materials content for steel reinforcing bars (based on an August 2010 announcement from CRSI):

The vast majority of domestically produced, conventionally available reinforcing steel (i.e. ASTM A615 and A706) has recycled material content typically greater than 97 percent. Specialty reinforcing steel products, such as ASTM A1035 low-carbon, chromium steel and ASTM A955 stainless steel, have a recycled content typically greater than 75 percent.

Wire and welded wire reinforcement is typically produced with 92 to 97% recycled material content.

Reinforcing steel (bars, strand, and wire) is also 100% recyclable at the end of the useful service life of the structure. This recycling loop keeps material from the waste stream.

Fig. 1.26—The Aqua Building in Chicago, IL.

Economic impact

The material reductions (and associated reduction in transportation costs) described in the previous sections contribute heavily to the reduced economic impact of building construction. For higher-strength steel reinforcement, savings from labor expense can result from a reduced number of reinforcing bars to be fabricated and placed into the project. The purpose of this point is to encourage the use of local materials, thus reducing transportation emissions and cost while contributing to the local economy. In the case of post-tensioned slab systems, the use of the post-tensioning tendons can significantly reduce the amount of reinforcement that has to be tied in place on site, and thus reduce on-site labor costs.

Case study

2201 Westlake (Seattle, WA) (Maingot 2009)

This Seattle structure provides an excellent case study for the efficient use of both traditional high-strength conventional reinforcing steel and post-tensioning. Figure 1.27 shows a two-tower, 450,000 ft^2 (41,800 m^2) reinforced concrete mixed-use development in downtown Seattle at 2201 Westlake. One tower is a seven-story office building, and the other is a 12-story office/condominium over a five-level podium with retail and restaurants. While other structural systems were evaluated early in the design process, reinforced concrete proved to offer the best design flexibility, construction economy, and local availability. The sustainability advantages of cast-in-place reinforced


Fig. 1.27—2201 Westlake. *Photo courtesy of Benjamin Benschneider*

concrete also helped the project to achieve the LEED Gold certification for innovative environmental design.

Post-tensioned slabs with wide shallow beams were chosen to provide more open space through minimizing columns and maximizing span lengths. Typical span slabs in the building are 28 ft (8.5 m) for the 8 in. (200 mm) thick post-tensioned slab. A unique drop head system helped to maximize slab spans at the condominium core, which permitted spans of nearly 40 ft (12 m) without interior columns. The subterranean parking levels were post-tensioned to achieve a typical 9 ft (2.7 m) floor height. This reduction in floor height resulted in lowered costs associated with reduced excavation, temporary shoring, and basement wall requirements.

High-strength reinforcing bar of 100 ksi (690 MPa) yield was used in the lower levels of the structure for seismic confinement in the core and at wall boundary elements to increase boundary element tie spacing and dramatically enhanced constructibility of the project. The innovative reinforced concrete systems used in the project helped achieve all of the original design objectives. The building was delivered on time, and below the original budget with a low environmental impact. This project was awarded an Honorable Mention in the 2010 Concrete Reinforcing Steel Institute's Design Awards competition.

Prestressed reinforcement—Reinforcement that is used to precompress a hardened concrete member to resist loading. The precompression can maximize the efficiency of concrete by counteracting tensile forces that cause cracking. The reinforcement is typically high-strength steel seven-wire strand, bar, and, in some cases, wire or bundles of wire. Standard seven-wire prestressing strand is Grade 270 (with a guaranteed ultimate tensile strength of 270 ksi [1862 MPa]), and standard prestressed bar is Grade 150 (with a guaranteed ultimate tensile strength of 150 ksi [1034 MPa]). Seven-wire strands in sizes of 0.5 or 0.6 in. (13 or 15 mm) diameter are most common.

Pretensioned concrete—A form of prestressed concrete where the steel is stressed before casting the concrete. After the concrete hardens, the anchorage points are released, allowing transfer of the strand force through the concrete section.

Post-tensioned concrete—A form of prestressed concrete where the strand is in a duct or sheath and is tensioned after the concrete has hardened. The transfer of force to the concrete occurs at end anchors. Seven-wire strands (single or in groups within a duct) and bars are most common. A post-tensioned tendon includes the steel reinforcement, duct or sheath, and anchorage, in addition to any material inside the duct (such as grout or corrosion inhibiting post-tensioned grease).

Bonded post-tensioning—Uses grout in the duct to bond the strand to the concrete member after stressing. The grout also provides corrosion protection for the strand. Bonded systems are most commonly multi-strand tendons used in bridges; however, they may also be used in buildings.

Unbonded post-tensioning—Relies on the anchorage for transferring the strand force to the member throughout its life. Unbonded tendons are typically single strands in a sheath filled with a corrosion inhibiting grease. The tendons include an encapsulated anchorage that is also filled with grease. External grouted tendons used in bridges and for repairs for both buildings and bridges are also considered unbonded tendons because they are only attached to the structural member at the anchorages and at other discrete points such as deviators (where there is a change in tendon profile).

Reinforcing bars—Bars that are embedded in concrete members to resist tensile stresses. Conventional reinforcement is a steel bar with deformations to increase bond between the bar and the surrounding concrete. Reinforcing bars can be coated with epoxy or other types of approved coatings to provide a barrier to corrosion. Other types of bars are available, including various corrosion-resistant metals and nonmetallic reinforcement (such as fiber-reinforced polymers).

Welded wire reinforcement (WWR)—A prefabricated reinforcement consisting of a parallel series of high-strength, cold-drawn, or cold-rolled steel wires welded together in square or rectangular grids. Each wire intersection is electrically resistance-welded by a continuous automatic welder. Pressure and welding fuse the intersecting wires into a homogeneous section, and fix all wires in their proper position. Plain wires, deformed wires, or a combination of both may be used in WWR.

Chapter 6—Admixtures

Admixtures (Fig. 1.28) are materials added to concrete (other than cement, water, aggregate, reinforcement, or fibers) to obtain a desired characteristic in fresh or hardened concrete. Admixtures are added to the concrete batch just before mixing or during mixing, either at the batch plant or on site. ASTM C494/C494M-10 (ASTM International 2010) covers the basic types of admixtures: air-entraining, set-retarding, set-accelerating, water-reducing, and high-range water-reducing (also known as superplasticizers). Industry continues to produce new admixtures that are not yet covered under ASTM specifications, such as corrosion-inhibiting, shrinkage-reducing, workability-enhancing, and others.

Fig. 1.28—A sample of concrete admixtures.

Sustainable attributes

Admixtures are produced to improve specific concrete properties during placement and/or use in service. Different brand names and types of admixtures are introduced frequently. ACI Education Bulletin E4-03 (ACI Committee E-703 2003) provides an overview of the types of admixtures available, along with a discussion of the associated standards, testing, and information for their use. ACI Education Bulletin E4-03 lists the following types of admixtures:

- Air-entraining;
- Water-reducing and set-controlling (including set retarders and set accelerators);
- Corrosion-inhibiting;
- Shrinkage-reducing;
- Controlling alkali-silica reactivity; and
- Underwater concreting (sometimes referred to anti-segregation or thixotropic).

Carbon footprint reduction

Admixtures provide carbon footprint reduction for buildings in different ways, depending on the properties that the admixture imparts to the concrete. The environmental or CO_2 cost in making the admixture itself can be more than offset in the sustainable qualities it imparts to the concrete end product. Some examples:

- Admixtures that improve workability can reduce the labor needed to place concrete and also reduce the energy used by the equipment during placing and finishing.
- Water-reducing admixtures can significantly reduce the amount of water that is needed in a batch of concrete by improving cement efficiency.
- Reducing the water content also lowers the water-cementitious material ratio (*w/cm*), thus decreasing permeability.
- A number of other admixtures can also enhance durability—these are discussed in the next section. The construction of concrete structures with very long service lives helps conserve natural resources while reducing the embodied energy and carbon footprint of the structure and life-cycle costs.

Longevity and life cycle

In the quest for a long service life and sustainable construction, the durability of concrete can be further enhanced through the use of durability-enhancing chemical admixtures, such as corrosion inhibitors that prevent oxidation of steel reinforcement, shrinkage reducers that reduce cracking of concrete, and air-entraining admixtures that increase the resistance of concrete to repeated cycles of freezing and thawing in cold climates.

Alkali-silica reactivity (ASR) is a harmful expansion that can occur in concrete when alkalis in the pore solution of the paste react with aggregates containing reactive forms of silica, and the resulting gel subsequently expands in the presence of moisture. Potential for ASR can be effectively mitigated through the use of SCMs, such as fly ash, slag cement, and silica fume. While use of SCMs is a common approach, admixtures such as lithium have also been used to mitigate ASR. A number of industry guides and model specifications are available to design against potential ASR (PCA Guide Specification 2007).

Reduce, reuse, recycle

Hydration control admixtures are used to effectively manage construction waste by extending the mixing and/or transit time, thus enabling the reuse of returned leftover concrete and concrete wash water. The reuse of returned leftover concrete promotes the judicious and economical use of concrete component materials, thereby helping to conserve natural resources. As discussed previously, water-reducing admixtures can also have a significant role in water reduction.

Resources

PCA (Portland Cement Association) admixtures Web page: **http://www.cement.org/basics/concretebasics_chemical.asp**

BASF Construction chemicals: **http://www.construction-chemicals.basf.com/en/Pages/default.aspx**

Energy efficiency: **http://www.energyefficiency.basf.com/ecp1/EnergyEfficiency/en/content/index**

The Euclid Chemical Company: **http://www.euclidchemical.com/**

Sika Corporation: **http://www.sikaconstruction.com/**

W.R. Grace & Co.: **http://www.grace.com/**

Chapter 7—Other materials and technologies

The materials covered in this chapter do not fit directly into the standard categories used for Chapters 1 through 6. These materials include fibers, filler material (such as wood chips, chopped tires, and other by-products), and lightweight synthetic particles. Numerous types of materials have been used in concrete to gain specific properties (such as energy absorption or extreme light weight). Concrete is also used as an inert material (when hardened) to encapsulate waste materials, such as radioactive waste from reactor decommissioning.

Sustainable attributes: other materials

Fiber-reinforced concrete

Fibers in the concrete mixture contribute to the longevity of a concrete structure primarily through crack control and apparent reduction. Short standard fibers help reduce plastic shrinkage cracking during placement and curing. Some long fibers can bridge structural cracks, and can help spalling resistance (particularly under fire or blast loads). Many of the fiber types are made of recycled materials from other industries. Carpet waste, recycled steel, tire cord, and many others have been used.

A specific type of fiber-reinforced concrete, known as engineered cementitious composites (ECCs), can replace some reinforcement and provide a lighter-weight member. These fibers also help the concrete exhibit strain hardening with increased ductility. Cracks are distributed among the fibers, and ECC maintains very low crack widths (which helps corrosion resistance and long-term durability).

Fillers in concrete

Materials such as wood chips and chopped/shredded tire can be used as a filler material in concrete. The addition of these materials can also have benefits for certain applications. For instance, concrete made with rubber from tires can be beneficial in applications requiring vibration damping (such as foundations for machinery or equipment) and in applications with impact loads (such as barriers).

Photocatalytic materials

A relatively novel tool in the effort to combat air pollution is the use of photocatalytic materials (Van Hampton 2007; Portland Cement Association 2009). These chemicals, most notably titanium dioxide (TiO_2) particles, can be mixed with cement (or added as a separate ingredient in concrete), which then provides the concrete with an inherent ability to convert some pollutants (for example, NOx to nitrate, SOx to sulfate, and oxidation of some organics) when exposed to sunlight (or other ultraviolet light sources). The process is somewhat analogous to photosynthesis. Because the photocatalytic materials are catalysts, they are not consumed in the reactions, and will continue to work at reducing pollution.

These agents also help maintain the light-colored (and often brilliant white) appearance of concretes (Fig. 1.29), and are often referred to as "self-cleaning concretes". The breakdown of organic materials decreases staining of the concrete, which reduces maintenance and maintains reflectance in supporting heat island mitigation.

Lightweight synthetic particles

Expanded polystyrene spheres (Fig. 1.30) can be used as an ultra-lightweight additive. The Elemix® concrete additive business (**www.elemix.com**) has produced a specific type of this aggregate known as Elemix® XE additive that has negligible water absorption (the particles are hydrophobic) and negligible chloride contribution. The spheres have a maximum diameter of 1/8 in. (3 mm), with an average bulk density of 1.45 lb/ft^3 (23.2 kg/m^3). The thermal resistance of the concrete produced with this additive is improved due to the lower density. Additionally, lab and field performance was improved in a number of other areas as well: freezing-and-thawing resistance, cracking resistance, and pumping. A new acceptance criteria sets forth the testing to evaluate the use of lightweight synthetic particles in structural concrete.

Waterproofing concrete

Waterproofing agents of various types have been added as a surface layer for many years. A new take on this concept from Hycrete, Inc. (**www.hycrete.com**) is to use an admixture to the concrete that makes the concrete hydrophobic while also forming a protective barrier around reinforcement. The combination of keeping the water out and protecting the reinforcement can provide a very effective way to inhibit the corrosion of metal in concrete.

Sustainable attributes: other technologies

CO_2 sequestration

Innovative methods for CO_2 sequestration in concrete and for reducing the amount of CO_2 from cement production are gaining ground. The projects are based on the concept of CO_2 reduction through lowered emissions, by sequestration, or both. Innovative technologies, such as CO_2 sequestering cement and aggregate, are also coming into the market.

One sequestration method is an accelerated concrete curing that uses CO_2 in precast plants (refer to **www.cleantech.com** for more information). The plants can use the CO_2 they produce to divert to the curing, or could be situated near a large CO_2 source such as a power plant. The process essentially carbonates the concrete, but this is not appropriate for every type of concrete member. For the right application, however, this method can provide more than a tenfold reduction in curing time, resulting in large energy savings (and reducing CO_2 emissions), along with providing a potentially CO_2-negative precast plant.

Fig. 1.29—Photocatalytic concrete was used at the Dives en Misericordia Church in Rome, Italy. *Photo courtesy of Essroc Cement Corp.*

Fig. 1.30—A loose pile of Elemix® XE concrete additive. *Photo courtesy of Syntheon, Inc.*

A new technology can use brines, waste water, and flue gas in a process to produce a limestone aggregate, capture CO_2, and provide fresh water (refer to **www.calera.com** for more information). The process uses pollutants and salt water to make a calcium carbonate material that can replace a portion of cement in concrete. For every 1 ton (0.9 metric ton) of material made, there is potential to sequester 0.5 tons (0.45 metric tons) of CO_2. Several companies are continuing to develop this new technology by using waste materials for the partial replacement of cement while sequestering CO_2 or in producing alternate binders.

Another potential technology being explored by the cement industry to capture and reduce CO_2 is algae bioprocessing. Pilot testing is under way at one North American plant and several others are in discussions with multiple technology companies active in this field. Plant stack gases would be directed to closed algae bioreactor vessels where CO_2 is converted to biofuels and biomass. This fuel could be recycled as plant fuel, used to replace diesel in mobile equipment, or as a feedstock for bioethanol (in lieu of agricultural feedstocks).

CO_2 sequestration—Long-term or permanent storage of CO_2 (in this case, within concrete).
Fiber-reinforced concrete—A concrete containing short (typically 3/4 to 2 in. [19 to 51 mm]) discrete fibers of various materials that are distributed randomly throughout the concrete member. Fiber materials include synthetics, steel, carbon, glass, and natural fibers such as wood cellulose, jute, and bamboo.

PART 2—CONSTRUCTION

Introduction

Part 1 discussed the various material constituents used in concrete. Teamwork that incorporates good planning, design, engineering, and execution is required to formulate, produce, and place these materials.

Part 2 will highlight items particular to the construction phase, including specifics for the construction team, planning processes, management of construction, and testing. Two principal ways to produce concrete structures are: 1) on-site construction; or 2) remotely in plants. Whether concrete is produced at the construction site (ready mixed concrete), remotely (precast plants), or through synergistic methods such as site-cast tilt-up, or specialized installation such as shotcrete, there are many common elements of production and construction—planning, production, forming, testing. Other areas are relatively unique, depending on whether the concrete is site- or plant-produced concrete. These principally include transport, installation, finishing, and waste stream considerations. In Part 2, the focus is on ready mixed concrete for on-site placement; similarities and differences with precast concrete will be noted where applicable.

Chapter 8—Construction team

The construction team includes the owner and the entire group of professionals who see the project through from start to finish, as well as the owner and facility operations team. The team encompasses professionals who are knowledgeable in the following areas (with other areas added as needed for a specific project):

1. Architecture, structural engineering, mechanical engineering, electrical engineering, controls engineering, site development, and landscaping;
2. Estimating, scheduling, procurement, installation, and placement; and
3. Testing (quality control) and commissioning.

Item 1 is handled by the design professional, Item 2 is handled by the contractor, and Item 3 is handled by the testing service. Specifically considering concrete construction, a concrete producer/material supplier will have an important role in Item 2. For all three of these roles, subcontractors are often involved. Figure 2.1 shows the integration of the team members.

A multidiscipline approach to building has always been essential to a successful project that meets the needs of the owner. A multidiscipline approach is especially critical to ensure building sustainability by thoughtfully integrating systems and materials in an efficient manner and considering the various opportunities for the inclusion of sustainable materials, means, and methods, as discussed in *The Sustainable Concrete Guide—Strategies and Examples* (Schokker 2010).

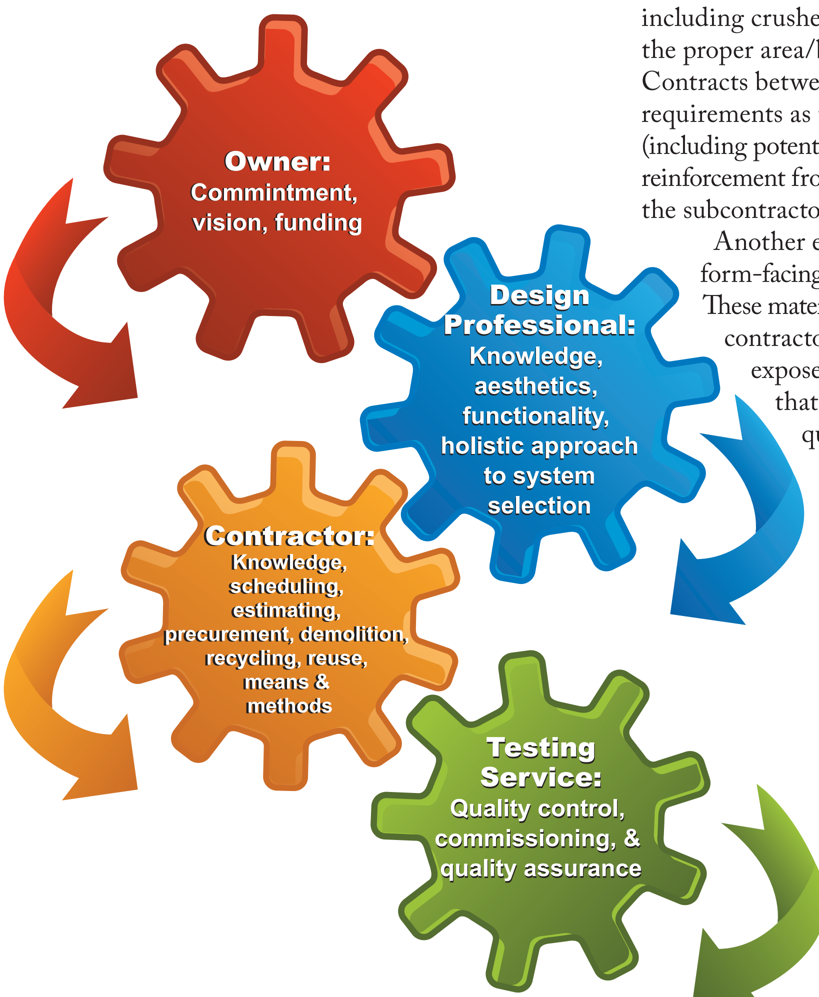


Fig. 2.1—Construction team.

Subcontractors

Often, the principal players on the design and construction team are knowledgeable and experienced in sustainable strategies, design, and construction operations. Indeed, owners are more often considering individuals experienced in sustainable building when selecting their construction team. However, there may be some subcontractors on the project who do not share this knowledge and expertise. It is imperative that the principal players provide the leadership and education as needed to ensure that all participants properly execute the work using materials, means, and methods that do not compromise the sustainable design and construction practices.

For example, all subcontractors should be clearly instructed as to the segregation of construction wastes, including crushed concrete and disposal of wastes in the proper area/bins to facilitate recycling or reuse. Contracts between parties should include such requirements as they could result in additional costs (including potential items such as the removal of reinforcement from the concrete before disposal by the subcontractor) to comply.

Another example would be the selection of form-facing materials and form-release agents. These materials should be chosen by the forming contractor to meet designated finishes in exposed areas and avoid excessive emissions that could affect indoor air quality or water quality after construction.

Chapter 9—Planning and building information modeling

Decisions

While this book focuses on the use of concrete in sustainable structures, it is important to realize that all materials should be selected to provide the best solutions for the particular project. Bias exists in the minds of owners, designers, and contractors that certain materials should be used for certain applications based simply on the fact that "it's always been done that way." The desire for improvement and the move toward sustainability challenges the industry to look for innovative uses of materials to provide solutions. Caution, however, should be exercised when new, innovative material uses and systems are implemented. Past practice can be a predictor of future success, and while improvement requires change, not every change will result in improvement.

For example, the selection of plywood as an exterior building face may appear to be a sustainable selection; it uses more renewable materials. But if used in an area near the ocean or in an area of high humidity, the material may not last as long or perform as well, resulting in future maintenance and replacement.

Building information modeling

Building information modeling (BIM) is the use of detailed, intelligent, data-rich building information models in three-dimensional (3D) geospatial representation to coordinate and capture the various facets of architecture, engineering, and human knowledge. The 3D building model is only a part of BIM; data such as energy modeling, lighting, design parameters, concrete mixture proportions, fabrication information, tolerances, quantity data types, testing, commissioning, equipment information, sustainable material, and labor use are stored as part of the model to coordinate information from design to construction to operations and facilities management. Additionally, BIM can incorporate software to calculate embedded carbon in materials and can be used as a tool to select low carbon material options.

BIM combines tools already available separately in the building industry and those being developed to provide an integrated model for buildings and structures. The move toward sustainable building and structures is helped by BIM because the entire building system and all data related to it can be contained within one location and accessed by the various stakeholders for specific information, coordination, and use. Some of the ways this benefits the move toward a sustainable building are as follows:

- **Visualization**—A full BIM model includes 3D representations of the proposed building design, including finishes and equipment inside and outside the building. Owners can be shown various concepts such as daylighting, open spaces, furnishings, fixtures, equipment layout and operations/maintenance space, surface textures, and the overall look of the building. This type of visualization (along with the associated data on energy savings and carbon footprint) can educate and convince an owner to consider sustainable alternatives, and can also give confirmation and confidence in expectations for the final product. The visualization component of BIM not only assists the owner in making sustainable decisions, but also helps all of the project participants to better understand the final product, including its performance requirements, and ensure optimum participation through better coordination and maximum sustainability reviews. BIM can be used to site a structure to take advantage of thermal mass, passive solar, etc.;
- **Energy modeling**—BIM models can be linked to and include databases with information that provides energy modeling of the given building system. Incorporation of this information in the model leads to quicker evaluation of different potential solutions that involve various materials, amounts of insulation, and heating, ventilating, and air conditioning (HVAC) scenarios such as operable windows and flow-through ventilation to determine the most efficient energy systems for the building;
- **Coordinated effort among all building teams**—The BIM model serves as the unified database for all teams working on the project, and is used from the conceptual design phase, through construction, and then by the owner for maintenance and facilities operations. Information related to everything associated with the project (for example, schedule, budget, and performance modeling) is centralized. With all those involved in the building design and construction basing information (and inputting information) into the same model, there are fewer chances for discrepancies and errors and the team works more efficiently. This can result in significant savings in time, materials, labor, and money;
- **Speed of analysis**—If an actual prototype of the finished structure is contained in the BIM, complex analysis programs can quickly compare, evaluate, and rate the project for sustainability issues;
- **Temporary and permanent construction (durability and impact)**—BIM allows for analysis and review for the selection of both temporary and permanent construction materials and systems that will maximize sustainability. Consistent with the ultimate goal to reduce the impact on society and the local community at all points along the life cycle of a building, BIM allows the construction team to systematically reduce the material and labor required to construct, maintain, and ultimately recycle the building or structure. Consideration of the concrete structure as a system is an ideal way to achieve reductions in cost, materials, and/or CO_2 emissions through the selection of such items as formwork for the cast-in-place elements of the building,

concrete mixture proportions, substitute materials (SCMs, recycled aggregate, etc.), and reinforcement. For example, by modeling several form systems, the optimum reuse of material can be predetermined. This reuse reduces the amount of materials needed, which thereby reduces the impact of generating the material, reduces debris, and reduces labor associated with the construction and disposal. Formwork for all portions of a project can efficiently and effectively be modeled to reduce impact and allow selections of materials that have greater benefits. An efficiently planned BIM model can quickly generate bills of material so various alternatives can be adequately reviewed, including the equipment required to erect, dismantle, move, and remove materials from the site, as well as the fuel used in the equipment. The same applies to the actual construction materials to be left in place. Concrete mixture proportions can be reviewed by, among other things, the location of the structure and time constraints, which may or may not have impact. For example, areas of the building where elements do not need rapid strength gain to allow construction to continue can reduce cement usage by using mixtures containing pozzolans such as fly ash. The addition of pozzolans reduces the carbon footprint of the concrete and adds durability. In other cases, admixtures for mid- and high-range water-reducing admixtures can be added to increase workability and durability. There are numerous scenarios that can be considered from the building model that will allow all project participants to minimize consumption rates for material and labor, greatly improving sustainability; and

- **Maintenance**—The building model provides a basis for the continued monitoring of building operations and helps with maintenance planning. A facilities manager or owner has a full 3D model that contains pertinent information about the building systems, design, components, furnishings, and fixtures to use for future maintenance and facilities management.

Figures 2.2 through 2.8 present some of the visuals that are produced through BIM to aid the entire construction team.

Fig. 2.2—Rendering of completed structure regarding sustainability impact model. *Rendering courtesy of Virtual Design & Construction Dept., KLORMAN Construction*

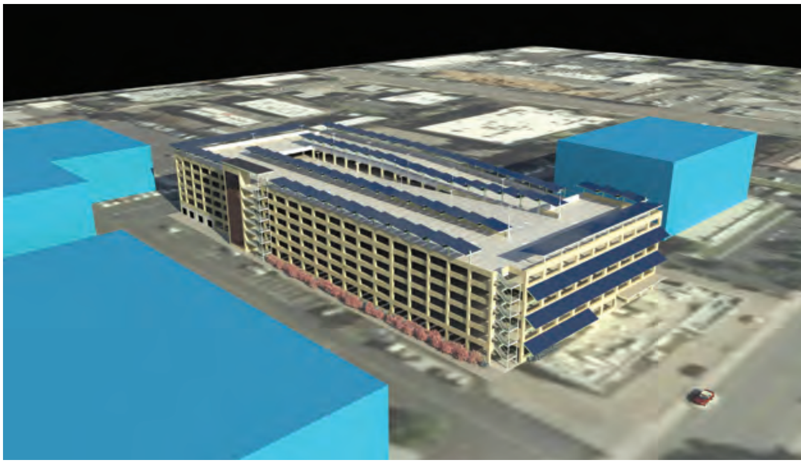


Fig. 2.3—Rendering of completed structure with sighting to other structures on site. *Rendering courtesy of Virtual Design & Construction Dept., KLORMAN Construction*

Fig. 2.4—Rendering of suspended slab formwork systems used during construction. *Rendering courtesy of Virtual Design & Construction Dept., KLORMAN Construction*

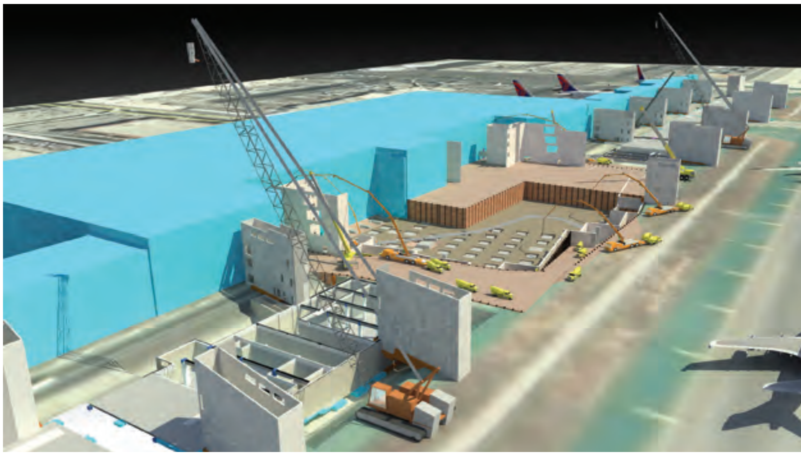


Fig. 2.5—Construction activity logistics rendering. *Rendering courtesy of Virtual Design & Construction Dept., KLORMAN Construction*

Commission Building

The San Francisco Public Utilities Commission (SFPUC) Building (illustrated in Fig. 2.9) provides an excellent case study for the integration of BIM to achieve a sustainable building. This building required carbon accounting for construction materials and construction activities, and is LEED Platinum certified. Figures 2.10 through 2.12 show various views of the core walls of the building that incorporate vertical post-tensioning. This building was used as a case study for sustainable construction in *The Sustainable Concrete Guide—Strategies and Examples* (Schokker 2010), where more detailed information can be found. Highlights of the many sustainable aspects of the building include:

- Net-zero energy building
  - 60% energy reduction, and 40% on-site energy generation (wind, solar)
  - High-performance concrete with the following reductions based on a standard building as a baseline:
    - 40% less CO_2 from steel reinforcement
    - 49% less CO_2 from concrete
    - 63% less CO_2 from framing and drywall
- Operable windows
- Lighting controls
- Raised access floors

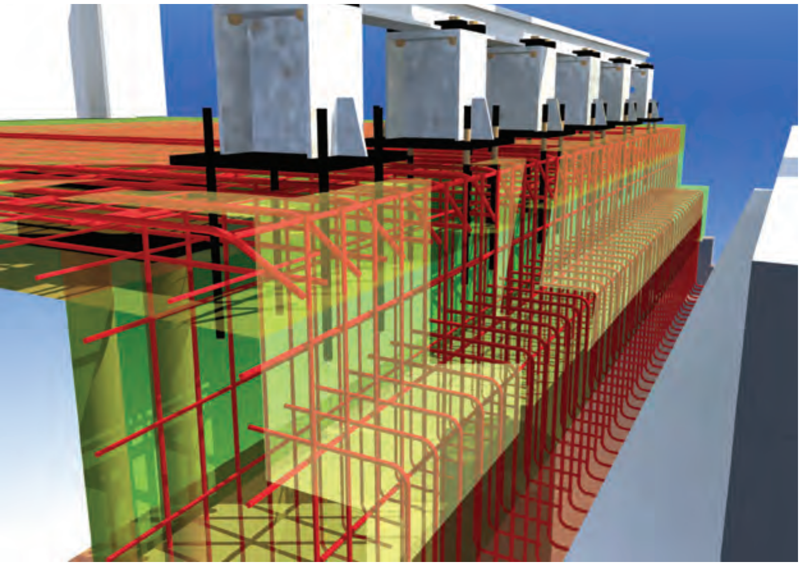


Fig. 2.6—View of reinforcement and detailing. *Rendering courtesy of Virtual Design & Construction Dept., KLORMAN Construction*

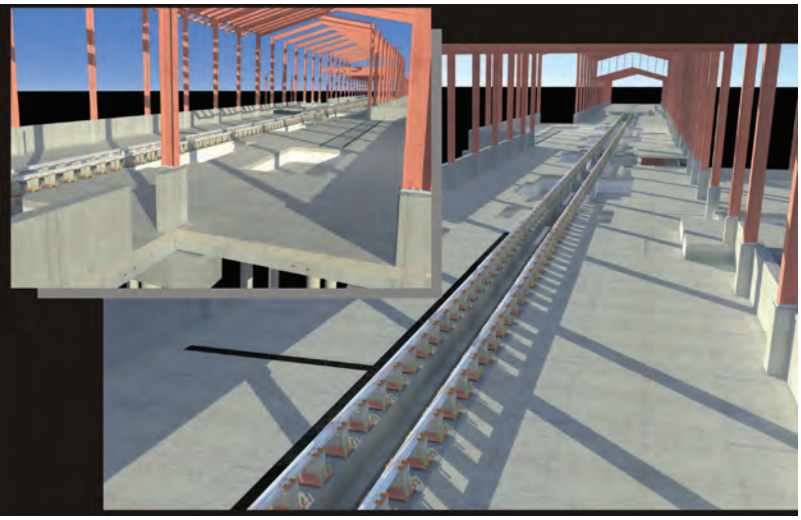


Fig. 2.8—Concrete and steel tolerance model. *Rendering courtesy of Virtual Design & Construction Dept., KLORMAN Construction*

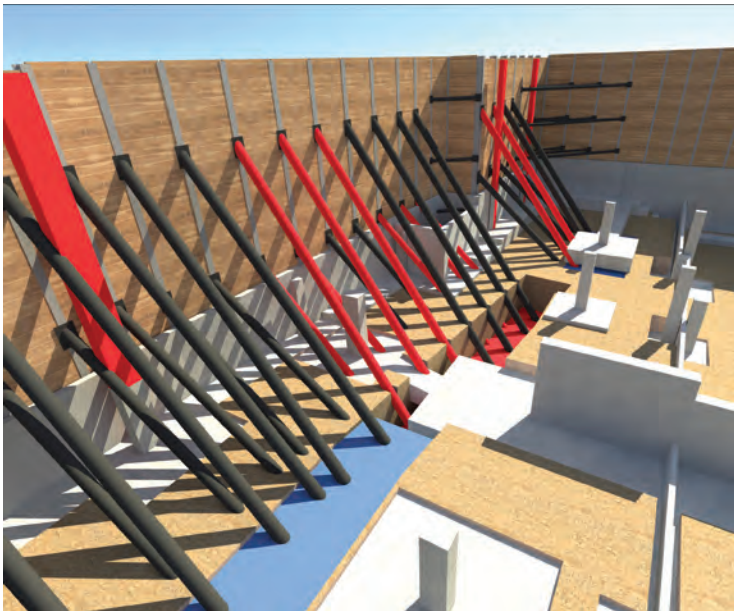


Fig. 2.7—Sample BIM rendering of below-grade clash detection. *Rendering courtesy of Virtual Design & Construction Dept., KLORMAN Construction*

Fig. 2.9—Rendering of the San Francisco Public Utilities Commission (SFPU) Building (net-zero energy building modeled using BIM). *Rendering courtesy of KMD Architects*

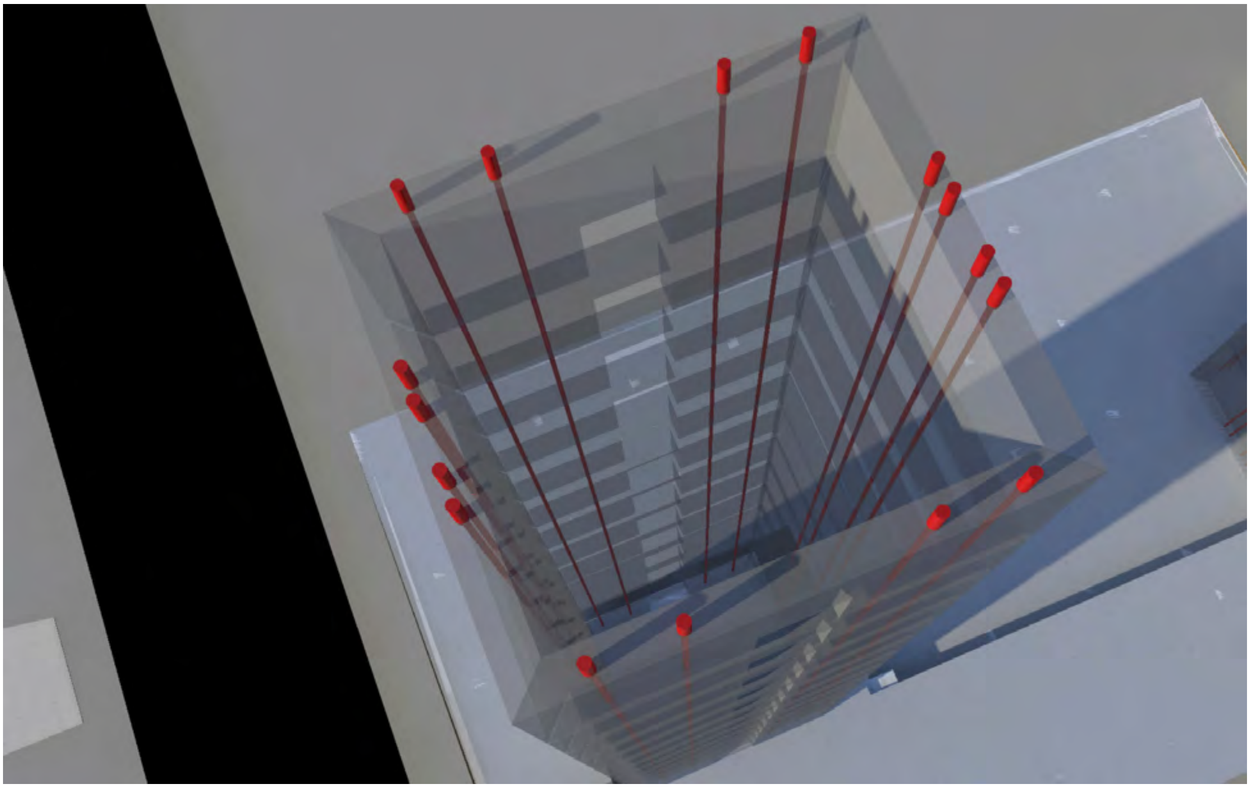


Fig. 2.10—Vertical post-tensioning used in core walls. *Rendering courtesy of Webcor Builders*

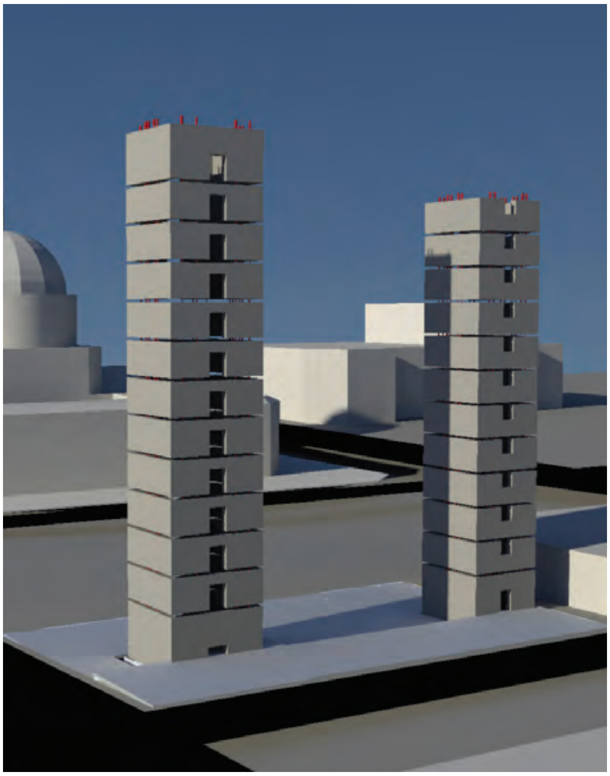


Fig. 2.11—Core walls. *Rendering courtesy of Webcor Builders*

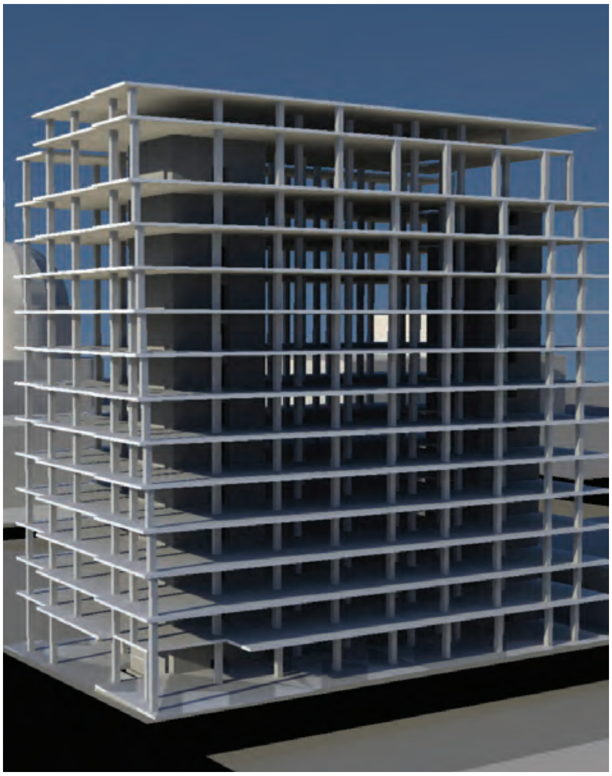


Fig. 2.12—Core walls within full structural system. *Rendering courtesy of Webcor Builders*

Chapter 10—Managing construction

Production of concrete

Concrete production is a process that takes the materials discussed in Part 1 and combines them to form concrete. Concrete production can be accomplished at a ready mixed concrete facility, on the job site, or at a precast or pipe plant.

A central batch plant is a stationary mixer that mixes the concrete and then discharges the concrete into a truck or directly into a conveyance system for delivery on site or to a casting bed in a remote precast concrete plant. Central plants can be located temporarily on the project site, or located permanently as part of a ready mixed operation or precast concrete plant. Concrete produced at a ready mixed concrete facility is typically mixed in a truck or can be mixed in a central batch plant and then discharged in the truck, or can be a combination of both. For truck-mixed or transit-mixed concrete, ingredients are placed in the truck and mixed in the yard, in transit, or at the job site. When in transit, the truck drum continues to revolve at low speeds (agitating speed) when not mixing.

On small or remote projects, mobile volumetric proportioning plants (mixture mobiles) are often used. Mixture mobiles are essentially small concrete plants on wheels that may be used for on-site mixing for some small-volume pours. Basic concrete ingredients are carried in bins on the truck. The materials are then fed into the mixer (also on the truck) and mixed on site. Mixture mobiles have an advantage when small loads are all that is needed (which reduces waste). They can avoid lost loads and project delays, and may be needed for some specialty mixtures (such as fly ash binder mixtures) with fast set times, as the mixing is done on site.

Mixture proportions

Mixture proportions should be optimized for the project requirements, such as strength and durability, while considering the opportunities for reducing the carbon footprint based on the information discussed in Part 1 of this book. A typical yd^3 (m^3) of concrete produced in 2007 had a carbon footprint of 865 lb/yd^3 (520 kg/m^3). Many mixtures in 2007 still used primarily virgin materials and had a much higher carbon footprint than this average. Through the use of supplementary cementitious materials (SCMs), recycled materials, admixtures for water reduction, and improved cement plants, an average yd^3 (m^3) of concrete today has lower carbon footprint, with the goal of continued reduction of both CO_2 and virgin materials. NRMCA (the National Ready Mixed Concrete Association) is targeting a 20% reduction in carbon footprint from the 2007 values by 2020, and a 30% reduction by 2030.

Case study: X-ray vault

American Engineering Testing Inc. (St. Paul, MN) used the design and construction of a new X-ray vault to reduce a concrete mixture's carbon footprint and the potential for a reduction of virgin material. The vault is entirely concrete, with a plan section of 30 x 20 ft (9.1 x 6.1 m), 12 ft high (3.7 m), and 3 ft (1 m) thick walls. The target strength was 4000 psi (27.6 MPa) at 56 days.

The mixture, as designed, weighed approximately 3875 lb/yd^3 (1758 kg/m^3) of which 3547 lb/yd^3 (1609 kg/m^3)—that is, 98%—was recovered by-products (including slag, fly ash, coarse aggregate, and sand). Only 82 lb/yd^3 (37.2 kg/m^3) of cement was used in combination with other SCMs (with zero carbon emissions), which resulted in an 80% reduction in CO_2 and a 75% reduction in embodied energy (based on a normal mixture with 562 lb/yd^3 (255 kg/m^3) of cement). Specifying the target strength at 56 days rather than 28 days allowed for a slower maturity of strength in the concrete, and thus the need for a lower cement content. Extending target strengths to 56 days is important when using many SCMs so that the full benefit of the material can be used. The required values for temperature gain, resistance to alkali-silica reaction (ASR), and shrinkage were all met in concrete tests.

Figure 2.13 shows a picture of the completed X-ray vault. This mass concrete bunker provided insight on using high levels of recycled content in concrete mixtures, and served as the basis for the concrete mixtures used on the I-35W replacement bridge in Minneapolis, MN, in 2009.

Fig. 2.13—Concrete X-ray vault consisting of 98% recycled materials.
Photo courtesy of American Engineering Testing

Transportation

Whether concrete is cast-in-place or precast, producers have an opportunity to reduce the carbon footprint. By purchasing from sources with a commitment to sustainability, concrete producers can support these sources and encourage other companies to follow suit to contribute to a sustainable environment and remain competitive. Materials suppliers can have a significant influence on the carbon footprint of concrete through their choice of fuel usage for material production, transportation methods, and other factors, such as their sources of raw materials. Using recycled materials, such as those described in Part 1, can also be encouraged by producers.

Ready mixed concrete plants have a fleet of concrete trucks and other vehicles. The CO_2 emissions from these vehicles can be reduced through optimized routing, fuel choice and efficiency, and maintenance. Installation of global positioning systems (GPS) can optimize travel routes and provide details on mileage (and thus, fuel usage). Diesel flow meters can directly track fuel usage. Vehicles that are not performing as well with fuel economy may need to be repaired or replaced. Reduced fuel usage for concrete transport decreases the carbon footprint for ready mixed concrete plant operations.

Precast operations have the advantage of not transporting concrete in the plastic state over a long distance, but rather a relatively short distance in-plant via a truck or conveyance system. Of course, the final product must still be shipped to the site, typically via truck, but rail or ship is another possibility as the product may be produced at a greater distance from the final site of installation.

Community presence

Concrete production facilities (whether ready mixed operations or precast plants) should strive to be good neighbors in their community. Beneficial influences on the community and region that positively reflect on the local concrete industry include:

- Purchasing materials and equipment from local suppliers;
- Providing local employment; and
- Operating clean, well-maintained trucks that drive at appropriate speeds.

Noise from operations of material transport, mixing operations, vibrator beds, and concrete truck or delivery truck traffic can be managed with:

- The use of self-consolidating concrete (SCC) in precast placement operations to reduce or eliminate the need for vibrating beds, thus reducing the plant noise footprint; and
- Well-maintained trucks that are driven at appropriate speeds and that are turned off when not in use (no-idle policy) are not only economical, but also reduce noise and the carbon footprint.

Resources

Green-Star Concrete Plant Certification Program

The Green-Star Plant Program from NRMCA recognizes efforts by plants to move toward sustainability. The program uses an Environmental Management System (EMS) to track progress and formally recognizes plants of excellence in sustainability through a rigorous certification process. Detailed information is available at **http://www.nrmca.org/operations/ENVIRONMENT/certifications_greenstar.htm**

Formwork

Formwork is required for nearly all types of concrete, including cast-in-place, precast, and shotcrete applications. Figure 2.14 shows how waffle forming was used to achieve an efficient structural system that doubles as an architectural feature in the highly recognizable Washington Metropolitan Area Transit Authority's rail stations. The types of formwork available are extensive, depending on the type of construction and final building use.

- Full formwork
  - Traditional forms that are stripped and removed
  - Stay-in-place forms
- Minimized formwork
  - One-sided wall forms (such as that used for shotcrete)
  - No forms (such as the case of earthen-formed foundations)
- Specialty formwork
  - Integral insulating forms
  - Fabric forms

Some of the many characteristics that should be considered for formwork include:

- **Quality**—Reflects the aesthetics of exposed finishes because formwork imparts surface characteristics to the finished concrete. Quality also relates to the ability to reuse the forms;
- **Safety**—Always a consideration during construction and should be considered for formwork as well;
- **Economy/reuse**—Forms can be 60% or more of the cost of the concrete structure (ACI Committee 347 2004), so considerations about their economy and sustainability are significant. Forms should be designed and planned for maximum reuse, including efficient form assembly and disassembly (refer to Figure 2.15);
- **Strength and stiffness**—Relate to the safety of forms, the safe height and extent for concrete placement, and the ability to maintain tolerances in finished construction;
- **Release agents**—Ensure that forms can be easily removed from the concrete. These agents should be environmentally friendly, nontoxic materials instead of petroleum-based products that were commonly used in the past;

Fig. 2.14—Using waffle-formed concrete to form an architectural feature at the Washington, DC Metro. *Photo courtesy of Kenneth C. Zirkel*

- **Decorative features**—Can be achieved through textured form liners or as part of the form itself;
- **Absorptiveness or drainage**—For excess water from the concrete surface;
- **Resistance to mechanical damage**—Vibrators used as part of the placement process, or abrasion from slip forming are examples of the types of resistance forms may need;
- **Workability**—For cutting, drilling, and attaching fasteners;
- **Adaptability to weather and extreme field conditions**—Forms must be able to perform properly in a variety of site and weather conditions, such as temperature, mositure, wind, and other elements, which can vary tremendously; and
- **Handling**—Ease of handling should be considered for forms. If forms are lifted by hand or with small equipment, lightweight form pieces are necessary.

Some of the many types of formwork available are shown in Fig. 2.1 to 2.20, which describes some of the advantages and disadvantages of various types of materials used in forming concrete. Forming related to shotcrete and insulated concrete forms are discussed in their specific chapters in Part 3. Precast concrete (also covered in Part 3) does not require forming on site, but almost any of the form types listed as follows can be used in precast construction.

Fig. 2.15—In addition to the environmental benefits of reusing forms, substantial cost savings may be realized. Shown here are forms being reused between multiple job sites. *Photo courtesy of Daniel Kourey*

Wood forms

Advantage	Disadvantage
• Lightweight—wood forms are lighter in weight than most commonly used metallic forms • Renewable—can be made from certified forests • Some reuse—maximum reuse will vary greatly depending on proper stripping, removal, and handling of forms • Flexibility, easy to cut/drill—wood forms can be adjusted in the field with standard tools • Materials available without special order—plywood, 2x members, nails, etc., are available in most hardware stores	• Limited number of reuses—after several times of stripping and erecting, wood forms will lose their surface smoothness and stiffness • Feasibly limited to basic shapes—atypical shapes will result in waste and complicated construction • Deformation and damage—if not properly stored, may bow or twist permanently, which will reduce its load capacity and result in disfigured concrete shapes • Limited spans—requires frequent vertical shores limiting space at the lower level • High labor cost—forming, stripping, cleaning, and storing is labor intensive • High waste—forming to specific dimensions and shapes could result in high waste

Metallic forms

Advantage	Disadvantage
• Can be made from recycled metals—scrap metal can be used to produce metal forms • Nonabsorbent—does not absorb water from concrete and therefore does not require special treatment • Smooth finish surface—metal surface remains smooth even after multiple usage resulting in smooth concrete surfaces • Long spans—allows for wide range of uses and reduces the need of excessive inventory, and less congested lower level • Although minimal, contraction and expansion can occur due to temperature, metal formwork does not experience shrinkage • Durable for multiple reuse • Efficient for standard shapes • Easy to clean • Robust assembly	• Heavy—steel forms are relatively heavy and may require a crane or other type of equipment for delivery and handling • High upfront cost—cost of metal forms is relatively high compared to other types of form material • Requires relatively large area for storage—metal members are rigid • Care during handling to prevent damage—dents and deformation from improper usage and handling affects the final appearance of cast concrete • Relatively expensive—Some types of metallic forms require skilled labor

Metal deck forms

Advantage	Disadvantage
• Composite or noncomposite floors—provides a choice to the engineer • Easy to maintain and can be erected in almost any weather • Ease and speed of installation—quicker project completion, saving on crane time and site costs • Stay-in-place—form becomes part of floor system, and is included in the structural capacity for composite systems; reduces required reinforcement • Lightweight and minimal waste—steel sheets arrive on site cut to length; sheets can be handled without equipment, saving installation time • Reduced construction time—quicker project time resulting in site saving	• Requires tag welding or fastening of metal deck to main supporting members • Cost—Relatively expensive compared to other form types • Easily damaged and dented • Exposed metal deck can rust • Limited construction weight allowed before concrete is cast and up to strength

Cardboard forms

Advantage	Disadvantage
• Very lightweight—can be easily handled by one person • Easy to cut and drill on site—does not require special tools for cutting and modification • Biodegradable, and waste is recyclable • Made from recycled material • Can be left in place or stripped quickly • Displaces concrete, can be used to reduce concrete weight by creating voids in the member • Skilled labor not required	• No reuse—cardboard once in contact with water is damaged and cannot be reused • Easily damaged—a tear can lead to form failure • Limited to specific uses (most often used as tubes for columns) • Damaged by prolonged water contact

Fiberglass reinforced plastic forms

Advantage	Disadvantage
• Lightweight—relatively light compared to metal and wood forms • Customization of shapes—can be molded in unique and complex shapes • Durable—high number of reuses • Skilled labor not required—forms are molded and erected in the field with typical tools • Displaces concrete—can be used to reduce concrete weight by creating voids in strategic locations in member; can be permanent or removable • Easily installed and stripped by workforce—due to light weight of forms special equipment for lifting and moving are not required • High-quality concrete finishes—due to smooth surface contact area and fewer joints in the forms	• Not a recycled product and not biodegradable • Limited experience by contractors—fiberglass forms are not widely used and many contractors are not familiar with the system • Can deform and warp—exposure to heat and improper usage • Long lead time—fiberglass forms requires building forms to shape the fiberglass form • Attack of alkalies in the concrete and from expansion because of exposure to hot sun • Limited span lengths—long spans require strengthening • Easily damaged • Upfront cost—cost of molding the forms and not being readily available

Fabric forms

Advantage	Disadvantage
• Extremely lightweight—approximately 1/10th the weight of cardboard • Reusable—can be reused as long as it does not tear • Little or no waste—can be cut to the desired length and shape • Flexible—allows forming of unusual shapes that are difficult and expensive to produce by other methods; allows the construction of higher efficiency structures by varying the cross section of a member to follow the path and distribution of forces • Inexpensive—1/10th the cost of plywood formwork • Requires simple skills—does not require skilled labor for erection and stripping • Reduced storage area—fabric does not take much volume • Underwater forms—heavy fabric forms are suited for underwater construction • No need to refinish—depending on the type of fabric used • Permeable membrane—filters excess water and air bubbles, improving finish durability and appearance	• Limited experience—most contractors are not familiar with the system • Fabric form works in tension only—cannot handle bending or torsion, limiting their use to certain shapes • Limited reuse—tears and holes will render the forms unusable

Fig. 2.16—Sample of concrete forms (wood). *Photo courtesy of Ranplett*

Fig. 2.17—Sample of concrete forms (metal). *Photo courtesy of Jeff Wilkinson*

Fig. 2.18—Sample of concrete forms (metal deck forming, normally used for steel framed buildings, is shown here with a portion of the slab blocked out for later placement).

Fig. 2.19—Sample of concrete forms (fiberglass reinforced plastic).

Fig. 2.20—Sample of fabric concrete forms (showing variations in circumference, height, and capital design). *Photo courtesy of Mark West*

Installation (placement/finishing/curing)

The erection of formwork, installation of reinforcement, and placing of concrete on site or the use of delivered precast elements consumes energy, labor, and money. Reduction in these areas contributes to sustainability. Many of the materials described in this book, such as insulating concrete forms or precast units, can reduce labor and energy on site. Materials such as self-consolidating concrete (SCC) can reduce labor for placing concrete, particularly when heavy reinforcing cages are needed.

SCC can flow easily without vibration and is excellent at reaching tight places in the formwork, including areas of architectural detail. SCC is formulated to retain enough viscosity to avoid segregation of the aggregate from the mixture while remaining highly flowable. Figure 2.21 shows SCC during placement in a double-tee form.

Installation and placement requires specific knowledge about materials and construction methods. Part 3 of this book provides details about specific applications, including their installation and placement. On-site installation of hardened concrete includes tilt-up and precast applications, in addition to the installation of specific concrete products such as pipe and masonry block. On-site placement of ready mixed concrete typically involves traditional methods, such as the use of crane and bucket, conveyor, and direct discharge. Special means to deposit fresh concrete on site includes shotcreting and pumping. Shotcrete placement is described in detail in Chapter 21, and pumping is discussed in the following section.

When evaluating various alternatives, flexibility, adaptability to the local site, and required specialized resources and training should be considered.

Fig. 2.21—Self-consolidating concrete during placement in a double-tee form.

Concrete pumping

Concrete is a relatively heavy material, and is difficult to handle when fresh due to its semi-liquid state and alkaline nature. Concrete pumps were developed in the first half of the last century to aid in the placement of concrete. The first pumps were rudimentary, with small capacities and limited reach. Many developments have been introduced in the last 50 years to create the pumps that are available today. Modern concrete pumps can easily pump up to 200 yd^3 (153 m^3) per hour, which is much more concrete than what a typical single concrete plant can produce.

Concrete pumps are divided in two main groups: boom pumps and line pumps. Boom pumps are attached to a truck chassis, and the engine used to move the truck is used to operate the pump. Boom pumps can reach as much as 220 ft (67 m), vertically or horizontally, to discharge the concrete. Line pumps, also known as trailer pumps, do not have placing booms; instead, a 4, 5, or 6 in. (10, 13, or 15 cm) diameter specialized line is attached to the pump for conveying the concrete. Line pumps can readily convey concrete horizontally up to 2500 ft (762 m).

Safe access to construction sites is important, but space may be very limited (Fig. 2.22), particularly in urban areas. In remote areas, standard construction equipment may have limited reach to the site. With a pumping operation, concrete trucks can be sent repeatedly to the same location rather than congesting the site by sending trucks to various areas for direct discharge into the forms as shown in Fig. 2.23, reducing the amount of site disturbance.

Line pumps have been used to move concrete in areas where there is limited equipment access. In extraordinary circumstances, one pump can be used to pump to another pump to reach a remote area. A Florida sidewalk within the Yamato Scrub Natural Area in Boca Raton, FL, was completed with this special pump-to-pump operation.

Likewise, concrete pumps have excellent accuracy and can ensure proper placement of the concrete without spills. Pumps can also convey concrete across water, mud, creeks, and riverbeds without spilling material or damaging the environment.

The Skelton Dam project (Fig. 2.24) in Maine required pumping with a truck-mounted concrete boom pump to deliver concrete to a deteriorated portion of the spillway without having any concrete reach the environmentally sensitive waters of the Saco River, home to salmon and other fish.

The direct discharge of concrete from the concrete truck chute is simple and easy, but is limited in reach to approximately 10 to 15 ft (3.0 to 4.6 m) from the point of access. Use of a bucket and crane increases the reach but is time consuming. Pumping can significantly speed up the placement process, reducing labor, construction time, site disturbance, traffic congestion on site, and

Fig. 2.22—Limited construction site space during construction of the Trump International Beach Resort in Sunny Isles Beach, FL. *Photo courtesy of the American Concrete Pumping Association*

Fig. 2.23—Delivery location for concrete trucks (in red) to pumps (Peninsula II Condos, Aventura, FL). *Photo courtesy of the American Concrete Pumping Association*

Fig. 2.24—To reach the furthest point of concrete placement, Northeast Concrete Pumping positioned their boom pump on land's edge, then fully extended the 151 ft (46 m) long boom to the ground below and finally connected the pump's end hose to 340 ft (104 m) of four-inch delivery system. *Photo courtesy of Putzmeister*

provides an efficient use of resources. The volume of concrete placed by pumping is estimated as 20 to 30% greater than other methods, and it requires 20 to 30% less labor per yd^3 (m^3) (RSMeans 2008).

The American Concrete Pumping Association (ACPA) has developed safety programs for its members, and has trained thousands of operators in safe use of the equipment. In addition to learning about the safe operation of the pumps, operators should also learn about the hazards on job sites, and have the ability to train and teach coworkers about safe and sustainable work practices around concrete pumps.

Concrete finishing

The use of concrete as a durable, finished surface allows the use of its thermal mass characteristics and reduces the need for finishes such as paints or carpets that may contain volatile organic compounds (VOCs). If the concrete is to serve as the finished surface, the contractor should ensure that the finishers take appropriate measures during finishing and curing operations so that the exposed surface is aesthetically pleasing. Polished concrete floors or form liners for vertical surfaces can also produce a pleasant aesthetic effect. For floor placement, vibrating screeds, lasers for leveling, and specialized finishing equipment may also be needed.

Waste stream

Waste materials are generated at many different points during the construction process. This section focuses on the waste materials generated on site from construction with concrete, including formwork (wood), wash water, leftover concrete, and concrete and reinforcement leftover from demolition of existing structures or pavement. Washwater should be diverted to special bins and treated before disposal or reuse. Leftover concrete should be used on site if possible, or recycled with concrete waste. Concrete waste from demolition can preferably be used on site as described in Chapter 4, but can also be sent off site for recycling and used in a different project.

The amount of waste from a construction site that enters landfills can be very large if opportunities for diversion are not used. Contractors should have a site waste management plan in place that includes separation of recyclable materials. On-site separation is a common method used, but is not a good solution for every job, particularly if space on site is limited. Off-site separation can also be effective and can achieve higher diversion rates. A hybrid of on-site and off-site diversion is an excellent choice where possible because it often yields the highest diversion rates.

Water

As discussed in Chapter 1, water is a resource that must be managed wisely to ensure that it is available for basic human needs. A producer can minimize the use of potable water for the many activities at the plant: batch water, wash water, heating and cooling water for the concrete, and water for dust management. Storm water can preferably be reused on site for concrete operations rather than be discharged into the sewer system.

Excess concrete

Ready mixed concrete is returned to the plant for many reasons, including excess from an over order, or rejection at the job site for quality. Ideally, this concrete can return directly to be used in another batch of concrete, but this can be difficult due to the limited window of time during which the fresh concrete is still usable. The same is true for precast plant operations, but the fresh concrete has not left the casting yard, so more time is typically available before the concrete becomes unusable.

The concrete can be used for needs on site at the plant (such as paving or barricade) or cast into blocks or other shapes for resale. Hardened concrete with no resale value in its cast form can be crushed and used as recycled aggregate. The returned concrete should not be added to the waste stream.

Chapter 11—Quality control and commissioning

Quality control through testing is important to ensure that the materials specified meet their performance requirements. A significant reduction in a project's carbon footprint can be achieved by simple adjustments in the concrete requirements specified by the designer. This chapter discusses several ways that the designer can influence the economy, durability, and lowered carbon footprint of a structure through testing requirements.

Overdesign

Variations in compressive strength test results are normal, and come from variations in materials, variations in concrete production, and variations in testing. All have a significant impact in the prescribed overdesign needed to meet ACI 318-08 acceptance requirements (ACI Committee 318 2008). The criteria are set by calculating an average compressive strength (f'_{cr}) that is higher than the specified compressive strength (f'_c), as shown in the two equations for concrete of less than 5000 psi (34.5 MPa) strength. A reduction in standard deviation of 250 psi (1.7 MPa) reduces the required average compressive strength by 335 psi (2.3 MPa)

$$f'_{cr} = f'_c + 1.34S_s$$

$$f'_{cr} = f'_c + 2.33S_s - 500$$

where S_s is the standard deviation.

All technicians involved in concrete sampling and testing should be certified to execute the tests that they run. Proper testing also helps reduce waste through ensuring that acceptable materials are not erroneously rejected.

ACI 318-08 (ACI Committee 318 2008) and ACI 211 (ACI Committee 211 2001) documents contemplate only one level of reliability. These documents set acceptance requirements for the buyer's risk that 1 in 100 strength tests will fail 95% of the time, and that the average of any three consecutive tests will not fall below the required strength 95% of the time. It is easy for people to understand that a minimum strength is required, but often more difficult to understand why there would be a problem with an excessively higher strength than needed. As a consequence, mixture proportions in common use may be overdesigned.

Design decisions should be made to address the fact that durability and strength in concrete are not completely independent of one another. Cases still exist where the strength requirement is performance-based (a minimum f'_c), while the durability requirement is prescriptive (a maximum water-cementious material ratio [*w/cm*]). *W/cm* alone is not a measure of durability; and a performance-based requirement is more appropriate. The strength resulting from a mixture of a prescriptive low *w/cm* may be considerably higher than specified (particularly in elements that have lower strength requirements). This excess strength requires additional cement to meet the durability design criteria and therefore increases the carbon intensity of the design mixture. It also does not take into account other important ways of increasing the durability, such as through the use of supplementary cementitious materials (SCMs). The designer should address durability and strength requirements with an eye for performance and with an understanding of the relationship between the two.

Acceptance age

ACI 318-08 requires that the design strength (f'_c) be based on 28-day cylinder tests unless otherwise specified. Traditionally, the time to acceptance for concrete strength has been set as 28 days, and provisions may be included that if the minimum strength is met before this time, the concrete is accepted. This practice leads to a desire for early strength gains. For specific applications, there may be a need for early strength gain so that the construction schedule is not compromised. On most projects, however, a significant portion of the structure can achieve the specified design strength at a later age without compromising the construction schedule or safety.

It is well accepted that concrete continues to gain strength beyond 28 days given favorable temperatures and moisture. In mixtures containing lower cement contents, the strength gain may be slower but still achieve the same strength as a higher cement content mixture over time. The mixtures with lower cement content and that use SCMs can be beneficial to long-term durability, so their potentially slower strength gain should be taken into consideration.

Figure 2.25 shows a plot of test data for concrete mixtures with 0% (baseline mixture), 15%, and 35% fly ash (Headwaters Resources 2006). As the amount of cement replaced with fly ash (Class F) is increased, the rate of strength gain is slowed, but the long-term strength is higher than that of the mixtures with lower percentages of fly ash. Considering the strength values of the 0% mixture and the 35% fly ash mixture between 28 and 56 days, the 0% fly ash mixture could be used to satisfy a 28-day design strength of 5000 psi (34.5 MPa). However, with the inclusion of the standard deviation, the 35% fly ash mixture could not be used (even though it achieves a strength of over 6500 psi [44.8 MPa] at 56 days, which is higher than the 0% fly ash mixture).

Consider the following example to illustrate the benefit of extending the acceptance age from 28 to 56 days for a concrete footing. Assume the concrete has a design compressive strength of 3000 psi (20.7 MPa) and contains fly ash. Assume the variability of the producer is moderate, resulting in a standard deviation of 450 psi (3.1 MPa) for this mixture. The required average

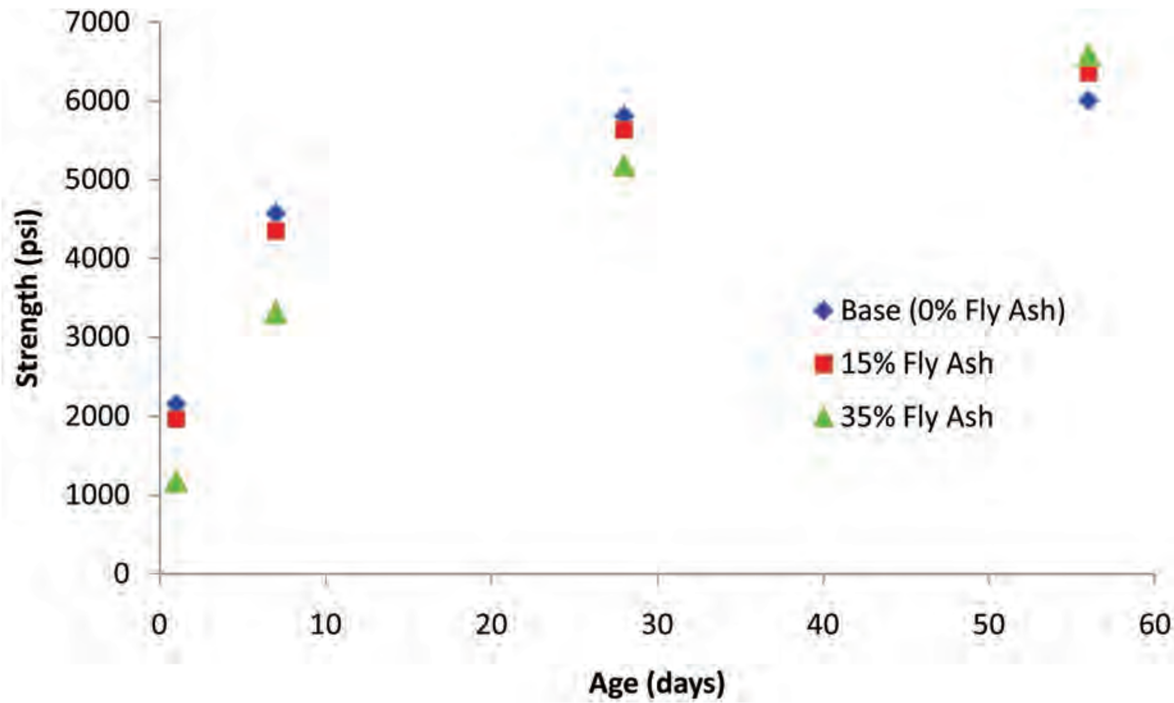


Fig. 2.25—Strength gain comparison between a standard concrete mixture and with increasing percentages of fly ash (adapted from data from Headwaters Resources [2006]). (Note: 1 MPa = 145.03 psi.)

compressive strength, f'_{cr}, is 3603 psi (24.8 MPa), derived from formulas prescribed previously in the chapter. Assuming a modest cementitious efficiency of 7 psi/lb per yd^3 (0.14 MPa/kg per m^3) of concrete, the mixture needs approximately 514 lb/yd^3 (305 kg/m^3) of cementitious material. Given a 10% increase in strength from 28 to 56 days, the mixture would deliver an average compressive strength of 3969 psi (27.4 MPa). If the acceptance criteria are changed to a required compressive strength of 3603 psi (24.8 MPa) at 56 days, cementitious material could be reduced by approximately 50 lb/yd^3 (30 kg/m^3), which is a significant reduction.

Building commissioning

Concrete is not used directly for the types of systems that are typically commissioned (such as HVAC and lighting), but commissioning is briefly discussed in this chapter because it is an important part of the construction process. A sustainable building should be built with a whole-building approach to be truly successful, and commissioning is part of this process. Commissioning verifies that the systems in the building are functioning as they were intended. This includes verification of proper design, installation, calibration, and operation. The commissioning authority for a project should be a third party that is not involved directly in the design or construction of the building. The scope of the commissioner's responsibility is wide, and includes, but is not limited to:

- Heating, ventilating, and air conditioning (HVAC), including ducts, equipment, and controls;
- Piping;
- Lighting;
- Any special systems for energy production;
- Training for the users of the building systems;
- Operation and maintenance manuals for all systems; and
- Documentation of all parts of the process.

Any performance requirements that were included for the building are also verified during building commission. A truly effective sustainable structure will include monitoring and future evaluation of system performance.

PART 3—
APPLICATIONS

Introduction

Parts 1 and 2 of this book focused on materials and construction. Part 3 looks at the specific applications in concrete that are used to build sustainable structures. While there is necessarily some overlap in applications, Part 3 has been organized to provide content to the architect, engineer, or owner on specific types of concrete applications/systems. Each association/institute that provided content was asked to provide a list of the top sustainable attributes from their perspective. The chapters are organized in alphabetical order.

Chapter 12—Architectural precast

Sustainable attributes

This chapter will discuss sustainable attributes that apply to both of the two basic forms of architectural precast concrete (unless otherwise noted): load bearing standard architectural precast concrete, and glass fiber-reinforced concrete (GFRC) cladding systems.

Carbon footprint

Materials

As with any concrete, the carbon footprint associated with architectural precast should be considered from two perspectives. The first is how much embodied energy and carbon are linked with putting a finished product in place, along with any further treatments to meet a project's aesthetic requirement and the maintenance that product requires throughout the service life of the structure. The second, more significant, consideration is how a product contributes to the energy efficiency of the building or project as a whole.

The carbon footprint of architectural precast will depend on material selection and transportation, manufacturing procedures, distance from the ultimate project site, the construction method used to put the precast member in place and, finally, the maintenance procedures required to sustain the item through the life of the project.

Architectural precast typically uses materials selected for their durability and aesthetics. This means fine and coarse aggregate, cement, and coloring agents are selected for their ability to give the final product the appearance desired by the specifier/owner. Aggregates and other raw materials extracted from or manufactured at local and regional sources have less embodied energy due to their proximity to the producer's manufacturing facility. Naturally occurring gravels take slightly less energy to produce than manufactured aggregates (crushed stone).

As discussed in Part 1, supplementary cementitious materials (SCMs) can replace a portion of the portland cement in a given mixture, which lowers the embodied CO_2 and energy associated with the mixture. Other potential benefits of SCMs include reduced alkali-silica reaction, permeability, and efflorescence, and increased long-term concrete strength, durability, and resistance to chemical attack.

Consultation between the architectural precast producer and the specifier/owner can have a big impact on the ultimate material selection process. The architectural precast producer should advise specifiers/owners on color schemes and finishes that can be produced with locally and regionally extracted aggregates. They should also provide advice on the maintenance needs of different finishes and architectural features or details that will reduce or defer cleaning cycles.

When possible, specifiers/owners should compare finishes in terms of their relative carbon footprints. For instance, is it better to achieve an architectural effect through raw materials that have a higher carbon footprint due to manufacturing processes or transportation distances versus the alternative of having to cover or coat concrete designed to have a lower carbon footprint? In most cases, the carbon footprint and energy required to produce, apply, and maintain a coating or covering material for architectural purposes is significantly higher than could have been achieved by using raw materials imported from outside the region and then incorporated into a durable architectural precast finish. Local raw materials provide the best of all scenarios when they are available. The architect and owner may want the look of stone without the added costs associated with stone. Precast can provide this look without the thickness and added weight of natural stone. This ultimately uses fewer natural resources, and also reduces the material used for foundations due to the weight reduction. Additional information is available in the Cast stone and Precast chapters (Chapters 14 and 20, respectively).

The material selection process is impacted by the type of concrete being produced. For instance, if the precast member is a sandwich panel constructed using standard architectural precast concrete where only the exterior (face) of the panel is exposed, the interior (backup) mixture is produced without regard to its appearance. In this case, the most efficient mixture in relation to its energy and carbon footprint can be used. Likewise, the GFRC backing mixtures, which are not exposed, can be made with materials selected for minimum environmental impact, regardless of appearance. This can also be achieved with architectural thin shell precast or other precast products that use less concrete by creating a thinner panel with high-performance design.

In architectural precast operations, process or washout water can be reclaimed and used on site. Uses include incorporating reclaimed water into new concrete mixtures in accordance with ASTM C1602/C1602M-06 (ASTM International 2006), dust mitigation, and equipment cleanup. Precast operations can reduce the amount of washout water associated with a project when compared with site-cast concrete because a concrete truck is not used on site. Any washout water is handled at the precast yard rather than the job site.

GFRC contains a mixture of cement, fine aggregates, and alkali-resistant glass fibers. In architectural applications, building components are produced with an exposed layer or "facing" that contains no reinforcing glass fiber. Face mixtures can incorporate aggregate up to 3/8 in. (9.5 mm) in size, and use raw materials selected for appearance and their compatibility with the backing mixture materials. Face mixtures are constructed to be 1/8 in. (3 mm) thicker than the largest aggregate size. Backing mixtures that incorporate glass fiber reinforcement are usually 1/2 to 5/8 in. (13 to 16 mm) in thickness, not including the facing mixture.

Typically, the resulting GFRC precast skin is anchored to a frame of steel studs by means of a flexible anchor (steel rod) embedded in a bonding pad on the skin's backing layer. The stud frame is then mechanically connected to the structure. This application produces a fascia or cladding panel that is indistinguishable from standard architectural precast on its visible surface. The one limitation to the architectural finish is the smaller maximum exposed coarse aggregate size. As a result of this unique construction, GFRC panels have less concrete material than standard architectural precast. Standard architectural precast, however, does not need the steel framing system employed with GFRC.

Manufacturing

Architectural precast concrete is manufactured with very little waste. It uses repetitive patterns and forms to generate uniform concrete items with a high degree of quality control and precision. Required concrete volumes are accurately established, and batches are created to meet known requirements. Because of the high degree of control, precasters are able to reduce strength variation and optimize cement/cementitious material use, which is the most energy- and CO_2-intensive portion of the mixture.

The vast majority of forming materials are used again and again in precast concrete operations, thereby decreasing the need for nonreusable form materials. Precasters construct forms out of steel, plastic, or wood, which are often from recycled materials and have an almost unlimited practical service life.

Transportation

As with any concrete operation, architectural precasters must transport raw materials into their production facility. The environmental and societal impact of this raw material transportation when producing standard architectural precast concrete is similar to that of a typical regional ready mix operation. Because there is so little waste, however, fewer raw materials need to be brought into the production location to put a finished product in service.

Forming materials, equipment, and labor required to produce the finished architectural concrete stay at the precast manufacturing plant. Only the finished item is shipped to the project. Impact to the environment due to the mobilization of equipment, labor, and materials is minimized because the equipment used to produce concrete components supplied to the project does not move from place to place.

GFRC architectural precast panels feature thin concrete sections and less total mass than cast-in-place concrete. The resulting architectural cladding product requires fewer raw materials to produce than standard concrete, resulting in less transportation impact. GFRC panels are much lighter than standard concrete assemblies. This equates to energy savings in transportation because more panels can be shipped per truckload. Depending on the mixture, glass fiber, aggregate and polymer content, compaction rates, and spray techniques, GFRC has a dry density between 120 and 140 lb/ft^3 (1920 to 2240 kg/m^3).

GFRC's lower density, coupled with its very thin concrete thickness, means that GFRC panels typically weigh approximately 20 lb/ft^2 (100 kg/m^2) compared with approximately 48 lb/ft^2 (230 kg/m^2) panel weight for 4 in. (100 mm) of standard concrete, or 73 lb/ft^2 (350 kg/m^2) weight for a 6 in. (150 mm) thick standard concrete panel. As a result, trucks can haul 2-1/2 to 3-1/2 times more architectural GFRC cladding per load than standard architectural concrete cladding. Additional structural materials, however, will also need to be transported to the site if GRFC panels are used.

Thermal transmission

The thermal transmission values for standard architectural precast are essentially the same as structural concrete of the same dimensions. Depending on the *w/cm*, glass fiber, aggregate and polymer content, and compaction and spray techniques, GFRC thermal conductivity is 3.5 to 7.0 BTU/in./h/ft/°F (0.5 to 1.0 W/m/°C).

For the best energy performance, architectural precast panels should be combined with traditional rigid insulation, such as expanded polystyrene (XPS). For standard architectural precast panels, insulation can be applied to the back of the panel or incorporated into the wall section. This latter method of producing sandwich panels sets rigid insulation between exterior and interior concrete layers or wythes. In standard architectural precast concrete, 2 to 4 in. (50 to 100 mm) of rigid insulation is commonly combined with exterior concrete wythes approximately 2 in. (50 mm) thick and interior concrete wythes 2 to 6 in. (50 to 150 mm) thick.

Standard architectural precast concrete sandwich panels should incorporate nonconductive ties between the wythes and insulation. This will prevent thermal bridging that can conduct heat or cold through the insulation to the interior wythe. Likewise, it is important that layers of insulation cover the entire cross section of the panel. For a more detailed discussion on thermal transmission and thermal bridging, refer to *The Sustainable Concrete Guide—Strategies and Examples* (Schokker 2010). Sandwich panels are typically engineered to deliver the added advantage of being effective vapor barriers, which can contribute to significant energy savings. Another advantage of sandwich panels is the flexibility of using different mixtures for the inside and outside wythes. The exterior or visible section can have an architectural finish using materials selected for their aesthetic appeal, whereas the interior section that will not be visible can contain materials selected solely for their sustainable and economic value.

GFRC assemblies are most often insulated with 4 to 6 in. (100 to 150 mm) of traditional mineral fiber batt insulation. Less common are surface-applied or spray-on foam insulations that can be combined with traditional batt insulation. Sandwich panels are not typically used in GFRC systems, as they are not as economically efficient at insulating the panels as systems that employ batt insulation. GFRC panels use a frame and anchor system that creates a minimum 1 in. (25 mm) air gap between the concrete skin and the supporting frame and insulation. This air barrier creates a buffer to prevent moisture transmission and reduce thermal bridging. The skin is anchored to the stud frame of the assembly most commonly by means of smooth, round steel rods that are typically 3/8 in. (10 mm) in diameter.

Thermal mass and operational energy

Standard architectural precast concrete has the potential for the same thermal mass benefits as other concrete applications. For a more detailed discussion on thermal mass, refer to *The Sustainable Concrete Guide—Strategies and Examples* (Schokker 2010). Designers can engineer architectural features, details, and finishes for passive solar design by anticipating environmental exposures. Precast concrete items can incorporate energy-conserving design features such as overhangs, recesses, and vertical struts or ribs to provide shade and reduce solar heat gain, thereby reducing cooling loads and saving energy. GFRC panels are particularly beneficial in this regard because their lighter weight offers designer panel shapes without much added weight. Passive solar design strategies for architectural precast elements can also incorporate openings and glazing layouts that deliver natural light to living and work spaces.

Longevity and life cycle

Architectural precast panel longevity will depend on the durability of the concrete and the architectural details developed by the precast producer and project designer. In climates where architectural precast concrete is exposed to freezing-and-thawing cycles, it should feature the same freezing-and-thawing durability strategies as any concrete.

In addition to standard recommendations for concrete durability, designers of architectural concrete should pay special attention to materials selection. In almost all cases, the visible finish of architectural concrete is literally the materials that make up the mixture. Exposed aggregates and paste components should be selected and designed to resist the elements and ultraviolet (UV) exposure. Nonabsorptive aggregate and iron oxide-based pigments have the best track records for retaining their appearance.

In a study by the Portland Cement Association (Panarese et al. 2005), 60 architectural precast panels were prepared using a wide variety of mixtures and placement techniques, and were then inspected after long-term exposure to the elements. The panels were placed on display outdoors in suburban Chicago, IL, where they stayed from 1963 to 2001. The average annual precipitation at the site was 33 in. (840 mm), with an added average snowfall of 35 in. (890 mm). Depending on their orientation to the sun, the average panel experienced 15 to 55 freezing-and-thawing cycles each year. Before their removal from the site to make way for development in 2001, all of the panels were inspected and found to be intact and structurally sound.

In 2000, the panels were cleaned, visually inspected, and given ratings of excellent, good, fair, and poor for their appearance. Over 90% of the panels were rated as "excellent" or "good," which means they had minor or no color change in the surface aggregate or pastes and no noticeable or only a minor loss of surface paste or exposed aggregate. These results demonstrate the long-term durability of architectural precast concretes and their finishes.

Five panels received "fair" or "poor" ratings due to changes in their appearance. These panels used pigments and, in one case, aggregates that were subject to fading. To ensure aesthetic durability, pigments should be evaluated for their conformity to ASTM C979-05 (ASTM International 2005).

Quality control

Architectural precast concrete is a highly specialized product that requires a level of expertise beyond what is typically expected for cast-in-place concrete. In recognition of this fact, the architectural precast industry has developed standards of practice and rigorous certification programs. This is especially useful to sustainability professionals because it establishes quality standards, codes of conduct, and documentation that are easily verified and referenced. Examples of acceptable certification programs are those that require annual, unannounced inspections conducted by professional engineers with experience in the precast industry. During inspections, plants are subject to a meticulous list of checkpoints that span all facets of the production facility, including storage and administrative areas. These practices ensure a constant commitment to quality that is documented and verifiable. As modern certification programs that are standard in the concrete industry, they include quality-control procedures that address the sustainable practices within the manufacturing process.

Maintenance

<u>Concrete design:</u> The raw materials and production methods are selected to produce concrete with the appropriate density, compressive and flexural strengths, and air content for the service environment. Nonabsorptive materials and concretes are less likely to stain and

require cleaning. Likewise, concrete that has been designed to be durable in the face of exposure to moisture, freezing-and-thawing, and other environmental factors will require the least amount of maintenance.

Almost all GFRC mixtures use polymeric admixtures that greatly reduce the concrete paste absorption rates, making them very resistant to stains. Aggregates that will be exposed should have low absorption rates to ensure they do not increase the need for cleaning.

Architectural detailing: Architectural precast concrete is impervious to wind and rain, and will resist the effects of even the most severe weather. The precast concrete panel will not be damaged if moisture does get behind the building's concrete skin. In curtain wall construction, panel sizes can be maximized to reduce the number and length of joints. Good joint material installation and maintenance will ensure that they do not leak.

The service environment where a concrete element will be exposed has a significant impact on its need to be cleaned and/or maintained. First and foremost, detailing should address how water will be handled by the structure. For simple architectural elements such as wall caps, water can be managed by the addition of a drip notch or groove on the underside of the cap. In this way, waterborne soot and grime are carried to the underside of the overhang where they can drip straight down without staining the face of the material below (Fig. 3.1 and 3.2).

Architectural detailing can also direct water to locations of transition between finishes to highlight those transitions. This is especially effective where it is desirable to create a framing effect from the patina lent by the runoff and the associated staining. To be successful, this type of detailing should ensure that water will be directed to specific locations where its

Fig. 3.1—Use of overhangs (Renner Corporate Center I, Lenexa, KS). *Photo courtesy of Architectural Precast Association*

Fig. 3.2—Use of water diversion, architectural details, and overhangs (Potomac Yard – Land Bay A, Alexandria, VA). *Photo courtesy of Architectural Precast Association*

effects will contribute to the aesthetics of the structure as a whole and not compromise the weatherproofing.

In contrast, water can be channeled away from the face of architectural details by gutters and/or drains. Surface areas and expected levels of precipitation should be calculated so the gutter detail is not overwhelmed in heavy storm events. In most regions of North America, detailing must also manage accumulated ice and snow. Understanding how to handle the elements is a key factor in reducing the need for cleaning and maintenance of architectural precast concrete.

In standard architectural precast concrete applications, details that eliminate sharp corners should be employed to prevent impact damage. Architectural elements in areas where impacts are expected should be protected or designed with sacrificial thicknesses to extend the component's service life.

Fig. 3.3—Color and texture to match traditional finishes (Frisco Square Town Center, Frisco, TX). *Photo courtesy of Architectural Precast Association*

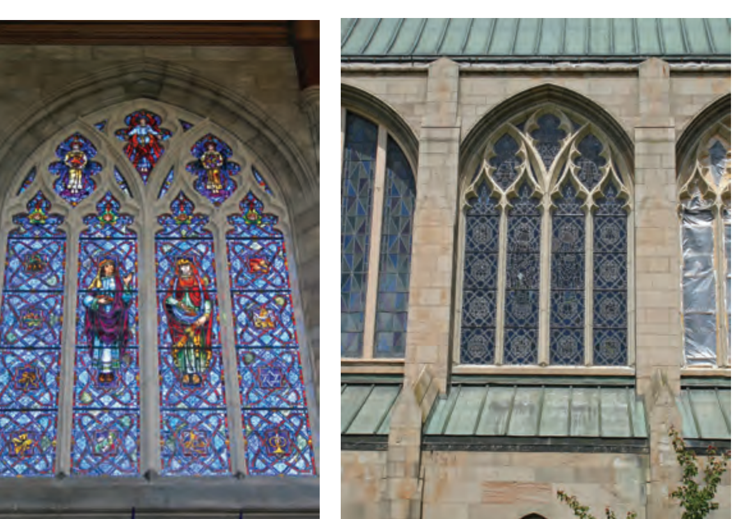


Fig. 3.4—Use of concrete in place of natural stone (Cathedral of St. John the Evangelist, Spokane, WA). *Photos courtesy of Architectural Precast Association*

GFRC panel edges typically feature a return of a minimum of 1.5 in. (40 mm) to accommodate sealing the joints between panels or between panels and other materials. This return distance is important to ensure that a good seal is achieved, promote long-term durability, and reduce the need for maintenance.

Finish: Finish selection affects maintenance and cleaning cycles. Dense, smooth finishes are less susceptible to deposits of soot and grime than rough textures. Their uniform appearance, however, can make any staining more noticeable. The most common architectural finishes (such as those achieved by medium sandblasting or acid etching) yield an exposed aggregate surface that reveals the concrete matrix including the paste, fine aggregate and, to a lesser extent, limited portions of the coarse aggregate. This varied texture and resulting slightly varied appearance makes common stains less noticeable. It is advantageous to select aggregates and finish techniques that will not contrast with prevailing staining elements. For instance, selecting aggregates that approximate the prevailing soil color will help hide windblown deposits of dirt.

Human factors and living/working environment

Standard architectural precast concrete buildings have the advantage of safety, security, and comfort. Architectural precast can act as a very good barrier to unwanted noise, whether the application is a highway sound wall or the skin of a precast building. In addition to being excellent sound barriers, architectural concrete's durable finish minimizes the need for maintenance and cleaning so building occupants have less disruption to their work and lives.

The social benefits of aesthetics are an often underappreciated attribute when sustainable design is considered. Panels can be made to complement the architectural characteristics of a given setting. They can appear light and intricate or solid and bold, and come in a large range of colors and textures, as shown in Fig. 3.3 through 3.5. Architectural precast or cast stone elements can be used in details such as quoins, sills, lintels, and arches that were once constructed from natural stone. In some cases, regional sources of the stone used by past generations for these items no longer exist, so architectural precast concrete or cast stone may be the best practical way to sustain the character of a neighborhood or district.

Architectural precast operations tend to employ a steady workforce. The production operation does not have to move to follow the project, which creates a more stable workforce that can make informed choices about where to live, thereby reducing the social impact of traffic- and transportation-related emissions. It also encourages more investment in the community by the labor force, as they are more likely to be from the local region.

Likewise, precast manufacturers have a much higher incentive to invest in the communities than if they were only present long enough to complete a given project before moving on to the next job. Architectural precasters can afford to invest in more efficient equipment and methods because they are more assured that the cost of such equipment will be amortized over many projects.

Security and safety

Fire resistance

Like other concrete products, architectural precast concrete will not burn, thus providing protection to building occupants from fires, and keeps fires from spreading from one structure to the next. Standard architectural precast concrete panels do not require fireproof coatings or special measures. They often go through fire events with little or no damage, and can be reused to rebuild the structure.

Blast resistance

The cladding and exterior building skin is often the first line of defense against blast loads. Blast design does not seek to leave the panel intact. Instead, cladding materials are expected to absorb and deflect energy by cracking and flexing. Appropriately designed architectural precast systems can give occupants enough time to safely evacuate the structure in a blast event. It is expected that damaged panels will need to be replaced; or, depending on the size of the blast, the entire structure may need to be reconstructed.

Reduce, reuse, recycle

Architectural precasters are in the business of producing highly engineered mixtures optimized to make effective use of raw materials and minimize waste. Precast concrete is prepared to precise standards in a controlled environment by highly trained professionals.

Unlike site-cast concrete, the batch plant is in the same location as the crew placing the concrete. This prevents inefficient ordering practices that can occur on job sites, such as when the placement crew places excessive orders to ensure that they don't run short and need to order another load. Precasters typically produce approximately 2% overage. This "waste" product can be reused to produce other products, or can be reclaimed by washing and separating the aggregate for use in another batch or operation.

If an owner prefers a true brick or stone look, precast concrete can be combined with a veneer to achieve an exterior surface of stone or brick, with only a fraction of the thickness of the material that would be used with full brick or stone construction. Figures 3.6 through 3.9 show some examples.

The key to profitability for precast operations is tied to the ability to produce repeated or standardized shapes and items, as shown in the building in Fig. 3.10. Because one-of-a-kind pieces are rare, precasters

Fig. 3.5—Customized detailing (Southern Methodist University Parking Garage No. 7, Dallas, TX). *Photos courtesy of Architectural Precast Association*

achieve dramatically higher reuse efficiencies with their forms than are possible for typical site-cast applications. Architectural precast items are produced ready for project installation, so there is little or no job-site cutting or modification.

Standard architectural concrete's inherent strength allows it to be cast in large sections that can span several floors and between columns. Exterior panel loads are carried directly by the columns, and need not be transferred to perimeter beams or floors; thus, the floor/beams can be made lighter as they do not need to carry the load of the cladding. This strategy allows the panel to transfer loads to the foundation, as illustrated in the building in Fig. 3.11. It also reduces the number of connections and limits the need for joint sealants.

Architectural precast is ideally suited for the ultimate reuse application where panels or precast items are disassembled for reuse as part of a new building or structure. This scenario is especially useful in multi-building campus situations, where expansion and retrofitting are common. Precast panels can be removed from one project and moved to a different location for incorporation into a new project. Few, if any, building systems have this same level of flexibility.

Compatibility with other innovative strategies

Architectural precast concrete is often on the cutting edge of innovation for sustainable strategies. Innovative sustainable strategies include: recycled materials for aggregate, photocatalytic cement applications, lightweight composites, and specialized SCMs, such as ground low-alkali-content glass.

Architectural precasters have long produced stepping stones and hardscape items that are light in color to

Fig. 3.6—Precast form with thin brick installed in a form. *Photo courtesy of National Precast Concrete Association*

Fig. 3.8—Installation of thin veneer precast on the Mariachi Plaza subway station in East Los Angeles, CA. *Photo courtesy of National Precast Concrete Association*

Fig. 3.7—The completed architectural precast panel with all the components included window sills, quoins, and coping. *Photo courtesy of National Precast Concrete Association*

Fig. 3.9—The centerpiece of the plaza is a gazebo created with Mexican cantera stone and donated by the city of Guadalajara in honor of the mariachi bands who congregate in the always-lively plaza. *Photo courtesy of National Precast Concrete Association*

Fig. 3.10—Repetition of precast elements (Devon Energy Hall and Rawl Practice Facility, University of Oklahoma, Norman, OK). *Photo courtesy of Architectural Precast Association*

Fig. 3.11—Column-to-column span with precast units (One Sugarloaf Centre Duluth, GA). *Photo courtesy of Architectural Precast Association*

Fig. 3.12—University of North Florida Social Sciences Building. *Photo courtesy of Architectural Precast Association*

Fig. 3.13—Domus residential complex in Philadelphia, PA. *Photo courtesy of National Precast Concrete Association*

mitigate heat gain. As environmental studies have progressed, the benefit of reflective concrete for roofing and hardscapes has become even more evident. The use of white or light-colored raw materials can also be used in architectural panels to increase reflectance.

Architectural Precast Top Sustainability Benefits

- Plant-controlled manufacturing provides opportunity for reduced construction waste.
- Material optimization/conservation: structural and architectural dual use eliminate need for interior finishes (paint, drywall, etc.).
- Reduced heat island effect.
- Indoor air quality: opportunity for no/low volatile organic compounds (VOCs).
- Durability: provides economic benefit over building life cycle.
- Thermal mass: energy efficiency.
- Resilient: particularly against terrorist attacks and natural disasters such as fires, hurricanes, tornadoes, and floods.
- Materials efficiency: can use regional and recycled materials.

Case studies

University of North Florida Social Sciences Building, Jacksonville, FL

The University of North Florida (UNF) is set in a nature preserve, and administrators felt that the new Social Sciences building (Fig. 3.12) should blend with its green environment while also being sustainable. The building is three stories tall, and is 70,600 ft^2 (6600 m^2). The building has many environmentally friendly features, including waterless urinals, an emphasis on natural light, energy-efficient heating and mechanical systems, and an irrigation system that uses recycled water.

Designers chose a precast concrete insulated sandwich-panel wall system for the exterior, providing an increased *R*-value, elimination of thermal breaks, and enhanced energy efficiency. The walls were made with colored, sand-blasted concrete as well as intricate form liners and thin brick. The thin brick was only 1/2 in. (12.5 mm) thick rather than the standard full depth brick of 3-5/8 in. (92 mm), which saved on raw materials, brick firing costs, and fewer truck loads to move the brick material. The form liners' thin brick was made of 100% post-industrial recycled content. The insulation (XPS) in the sandwich panels contained up to 40% post-industrial recycled content, and scrap materials were taken to a polystyrene recycling center for use in other products. Waste concrete from the precaster was crushed and used as road fill.

Site disturbance was minimized with the use of crawler cranes for panel erection that were kept within 30 ft (9.1 m) of the project perimeter. The heat island effect was counteracted with the use of white-cement concrete at the faces of the wall panels.

School administrators were so pleased with the outcome that they intend to follow similar sustainable construction methods in the future. The building uses 20% less energy than the baseline requirements of ANSI/ASHRAE Standard 90.1-2007 (American Society of Heating, Refrigerating and Air Conditioning Engineers 2007) and is 30% more efficient than required by code, resulting in $28,210 in annual energy savings.

Domus Residential Complex, Philadelphia, PA

This eight-story residential complex (Fig. 3.13) in Philadelphia, PA, incorporates 414,000 ft^2 (38,500 m^2) of premium residential and retail space in addition to 108,000 ft^2 (10,000 m^2) of parking. Domus covers a large city block, and its vast exterior surfaces were initially designed for masonry, including a wealth of visual details to harmonize with the brick façades of the adjacent University of Pennsylvania. When construction documents were 65% completed, the Houston, TX-based developer accelerated construction. Groundbreaking was scheduled for December 2005, and the company wanted to enclose the structure before the coming winter. The developers wanted the speed of precast erection, but they did not want to increase the loads on the structure and force a major reengineering of the project so late in the plan. Thin-shell precast concrete was the answer.

The developer brought in an engineering firm with expertise in thin-shell construction. The Metal Stud Crete system (Fig. 3.14) was recommended, which the engineering firm had used previously with positive results. Metal Stud Crete uses the same type of concrete as conventional precast, though in an unconventional way. The heart of the system is a proprietary galvanized steel shear-transfer strip with Y-shaped flanges. The strip is screwed to light-gauge steel studs. The panelized steel is placed in the precaster's forms with the shear-transfer strip's flanges projecting downward so that they become embedded as the concrete is placed. Other than the addition of the steel framing, the casting form is set up in the usual way, including welded-wire mesh reinforcement in accordance with design requirements, but the entire mold is only 2 in. (50 mm) deep (Fig. 3.15).

As the project developed, it became apparent to all parties that they had gained more than time. The space gain achieved by eliminating an interior furring wall was impressive: 3 to 4 in. (75 to 100 mm) all the way around the perimeter of the building. In an urban project where the building footprint is strictly limited, this space can be very important.

Domus also used a special Metal Stud Crete option that maximizes thermal performance. The thermal standoff version of the sheer transfer strip separates the face of the steel studs from the concrete surface by 1/2 in. (13 mm), improving thermal resistance and reducing potential for condensation. Combined with larger panel sizes to minimize the number of joints where air can leak, this creates a residence that's well adapted for both the cold winters and hot summers of the East Coast.

Through innovative precasting, the engineering firm maintained fire resistance of the panels and saved on construction costs. The company designed an integrated fire stop, a horizontal beam cast in the interior surface of the panels. Normally, this would have been added

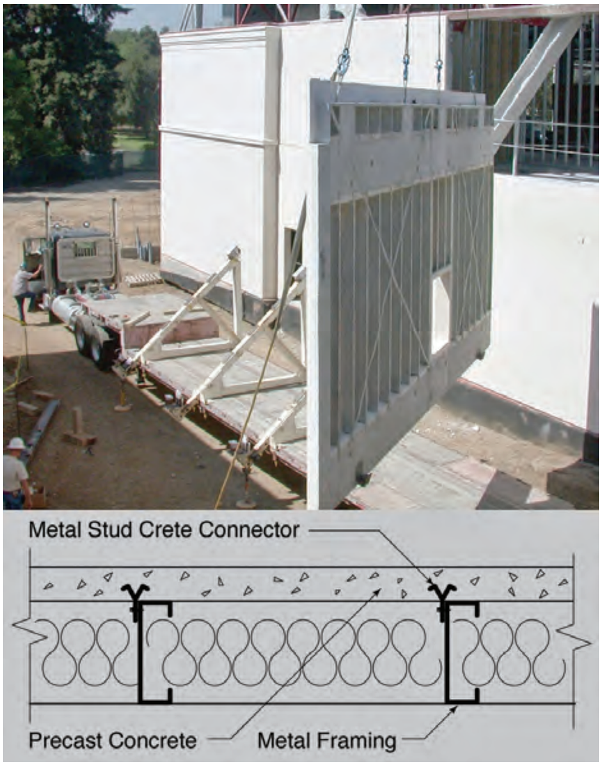


Fig. 3.14—Metal Stud Crete connector detail. The back side of the precast Metal Stud Crete panels shows the cold-formed steel stud framing used to support the 2-1/2 in. (65 mm) thick precast concrete face. Metal framing provides space for utilities and insulation. *Photo courtesy of National Precast Concrete Association*

Fig. 3.15—A mock-up for the Domus project illustrates how color, texture, and special details can be combined in thin-shell precast concrete construction. *Photo courtesy of National Precast Concrete Association*

by the contractor after erection to seal the wall against floor-to-floor fire migration. The integral fire stop did double duty: the weld plates were placed within the fire cavity for connection to the slab.

Perhaps most impressive, the architectural finish was produced cost effectively using thin-shell precast. The architect knew that large façades need a lot of detail to relieve the eye, but the expense of hand-placed masonry would have allowed decorative detailing only on the two most visible façades. With thin-shell precast, detail was affordable on all of the sides through repeatability in the forms. The project boasts four colors with varying textures, including a buff limestone effect around the base, gray sandblast, medium sandblast to reveal aggregate, and an acid-etch terra cotta color.

Architectural precast concrete—A variation on standard concrete that incorporates specialized materials and architectural surface finishes. Architectural precast concrete in this form is both structure and finish.

Architectural thin shell precast—A thin precast wall with a wood or metal stud frame attached. This product provides all of the natural benefits of precast while still allowing construction flexibility. Stud framing enables changes to be made in the future, for items such as electrical wiring and data boxes.

Efflorescence—The white dust-like deposit that is sometimes found on the surface of concrete. As water brings soluble compounds to the surface, the moisture evaporates, leaving the precipitate.

Glass fiber-reinforced concrete (GFRC)—A cementitious composite consisting of alkali-resistant glass fibers in a mortar or cement paste matrix that is used in architectural precast concrete applications. Typically, GFRC is used in thin members as cladding or fascia with no structural load-bearing resistance. GFRC, however, can be incorporated as a part of a load-bearing panel with other materials.

Precast concrete veneer (PCV)—A relatively thin layer of precast concrete used as a nonstructural facing or overlay, usually for aesthetic purposes. Veneers are adhered or attached by a mechanical means to a substrate.

Sandwich wall panel—A wall system consisting of a rigid insulation layer between two layers of concrete. Mechanical connections are used between the interior and exterior layers of concrete.

Veneered precast concrete (VPC)—Enables architectural precast panels to provide the look of masonry and stone products. VPC is created by attaching a thin layer of material to a precast concrete backing. This is typically done during casting of the precast. The attachment may be through direct bonding with concrete (common with clay products), or by mechanical anchorage with a bond breaker between the precast backer and the veneer (common with stone products). The precast units can be made into almost any shape (flat panels, column covers, curved sections, angled, or more detailed shapes). The thickness and final design of the units are based on the properties of the veneer material.

Chapter 13—Cast-in-place

Sustainable attributes

Cast-in-place concrete is deposited in forms on site, where it remains. Fresh, fluid concrete is transported as a ready mix product. It may also be mixed on site. Cast-in-place concrete has the advantages associated with all concrete, such as thermal mass, durability, and use of recycled materials. It can be used for nearly all types of concrete elements, including foundations, slabs-on-ground, walls, beams, columns, floors, and roofs. Additionally, cast-in-place concrete is an excellent solution for free forming concrete into a variety of shapes, spans, and forms. Cast-in-place concrete also provides a solution when a site has limited access and space for crane placement, staging, and storage. In the U.S., approximately 75% of the concrete used is cast-in-place concrete made in ready mixed concrete plants and delivered in concrete trucks to the construction site.

Because the concrete is placed on site, considerations need to be made for casting and curing in relation to the weather and environmental conditions. A team should be on site to rapidly place the concrete and perform jobs such as screeding, finishing, and curing. The concrete cures in-place until it is self-supporting and able to take additional building loads. Therefore, construction schedules accommodate in-place strength gain as opposed to delivery schedules of concrete cast in manufacturing plants. Slabs-on-ground are almost exclusively the domain of cast-in-place concrete, as are many foundations.

Concrete is a sustainable building material due to its many eco-friendly features. The production of concrete is resource efficient and the ingredients require little processing. Most materials for concrete are acquired and manufactured locally, which minimizes transportation energy. Concrete building systems combine insulation with high thermal mass and low air infiltration to make homes and buildings more energy efficient. Concrete has a long service life for buildings and transportation infrastructure, thereby increasing the period between reconstruction, repair and maintenance and the associated environmental impact. Concrete, when used as pavement or exterior cladding, helps minimize the urban heat island effect, thus reducing the energy required to our homes and buildings. Concrete incorporates recycled industrial byproducts such as fly ash, slag and silica fume, which helps reduce embodied energy, carbon footprint, and waste.

Embodied energy of cast-in-place concrete

Embodied energy is an accounting method that aims to find the sum total of non-renewable energy necessary to produce a product or service from raw material extraction, transport, manufacturing, assembly, installation, operations and, finally, its disassembly, deconstruction and/or decomposition. There are two aspects to embodied energy: the initial embodied energy of a material or system and the recurring embodied energy. The initial embodied energy is the energy necessary to acquire raw materials and to process, manufacture, transport and install these materials for a project. For cast-in-place concrete, the initial embodied energy includes the energy required to extract limestone and other raw materials for cement, extract aggregates for concrete, manufacture cement, produce concrete, transport concrete to the site, and place concrete for the project. Recurring embodied energy is the energy required to maintain, repair, restore, refurbish or replace materials during the life of a project. When properly designed and constructed, cast-in-place concrete is a durable material that requires minimal maintenance over time, thus limiting the recurring embodied energy.

Thermal mass

Thermal mass is the term used to describe a material that absorbs and stores heat energy. In a building system, it is the mass of the building elements that stores heat during the hottest periods of the day and releases the heat during the cooler evening hours. Concrete is one of several building materials that possess thermal mass properties. In the winter season, high thermal mass concrete walls and floors absorb radiant heat from the sun and gradually release it back into the occupied space during the night when the outdoor temperature drops. Cast-in-place concrete is an ideal building material for commercial, residential, and educational facilities due to its high specific heat, high density, and low thermal conductivity.

The distinct benefits of high thermal mass buildings are:

- Moderate shifts in peak loads of energy requirements due to the reduction in high fluctuations between indoor and outdoor temperatures.
- Heat transfer through a high thermal mass wall is reduced. Therefore, less energy is used to heat and cool the interior space.
- The thermal mass of concrete delays peak temperatures, and reduces and spaces out peak energy loads, therefore shifting the energy demand to off peak periods when utility rates may be lower.

Post-tensioned cast-in-place concrete

The advantages of post-tensioned cast-in-place concrete for building green are the same as for cast-in-place concrete structures, with additional benefits from the post-tensioning force. Post-tensioning allows smaller, more efficient members with precompression to counteract tensile forces. Part 1 covers the basics for post-tensioning and the associated sustainability benefits. In buildings, the most common cast-in-place post-tensioned component is a floor slab or slab-on-ground that uses unbonded monostrand tendons. Unbonded (and to a lesser extent, bonded) post-tensioning, however, has widespread use in a variety of structural members and structure types, including parking structures, storage structures, stadiums, and as transfer members in staged construction or tension members such as tension rings or tie-beams.

Unbonded post-tensioning has made it possible for owners, designers, and builders to see their projects come to life with exceptional design flexibility and aesthetics, fast construction, and long design life with low maintenance. The construction benefits that unbonded post-tensioning provides in structures include:

- Significant reduction of concrete and reinforcing steel quantities;
- Superior structural integrity provided by continuous framing and tendon continuity;
- Permanent compressive forces that result in greater control of cracks, deflection, and camber;
- Thinner structural members that allow lower structure heights, reduced foundation loads, and longer spans when compared with conventionally reinforced structures;
- Monolithic connections between slabs, beams, and columns that eliminate troublesome joints between elements;
- Profiled tendons that result in balanced gravity loads, significantly reducing total deflections; and
- Reduced overall building mass, which can be important in zones of high seismicity.

Construction advantages of unbonded post-tensioned structures compared with steel, nonprestressed concrete, and precast construction include:

- Faster floor construction cycle: use of standard design details for post-tensioning elements, minimal congestion of prestressed and nonprestressed reinforcement, use of high-strength concrete (HSC), and earlier stripping of formwork after tendon stressing can significantly reduce the floor construction cycle;
- Lower floor weight: greater span-depth ratios are allowed for post-tensioned members as compared with nonprestressed members, which results in a lighter structure;
- Lower floor-to-floor height: greater span-depth ratios are allowed for post-tensioned members as compared with nonprestressed members, which results in a reduction in story height while maintaining required headroom;
- Reduced exterior shell costs: by reducing the individual floor-to-floor heights, the overall building height is decreased. Thus, the costs for the exterior building treatment are reduced;

Fig 3.16—Cast-in-place concrete frame with post-tensioned flat-plate slabs are used in construction of the Mosler Lofts in Seattle, WA. *Photo courtesy of Post-Tensioning Institute*

- Larger spans between columns: the reduced weight and structural integrity of a post-tensioned member allows greater spans between support points;
- Reduced foundations: the reduced weight of the post-tensioned structure allows a reduction in the size of the foundations; and
- Increased flexibility for space planning: increasing the column spacing and the use of flat soffits allows greater flexibility of space for tenants and mechanical and electrical services.

The Mosler Lofts in Seattle, WA, (Figure 3.16) is built with a cast-in-place concrete frame with 7-½ in. (19 cm) thick post-tensioned flat-plate slabs at the residential levels, and 18 x 24 in. (450 x 600 mm) columns. The shear wall core incorporates 24 in. (600 mm) thick walls to carry seismic loads. Subterranean parking levels use post-tensioned slabs as well. The highest concrete level is a post-tensioned transfer slab that supports the dramatic steel-framed penthouse and cantilevered roof canopy. Without post-tensioning, it would have been very difficult to achieve a flat-plate slab to support this steel structure.

Cast-In-Place Concrete Top Sustainability Benefits

- Flexibility: free-forming cast-in-place concrete can be placed into a variety of shapes, spans, and forms.
- Peace and quiet: concrete's mass dampens sound transmission.
- Indoor air quality: opportunity for no/low volatile organic compounds (VOCs).
- Ability to control on-site waste stream.
- Opportunity to use local labor.
- Durability: provides economic benefit over building life cycle.
- Thermal mass: energy efficiency.
- Resilient: particularly against terrorist attacks and natural disasters such as fires, hurricanes, tornadoes, and floods.
- Materials efficiency: can use regional and recycled materials, allows the use of high-volume pozzolans, and can be comprised of essentially 100% post-industrial waste and reclaimed water.

Unbonded post-tensioning—Post-tensioning tendons consist of single strands protected by PT coating against corrosion and with extruded plastic sheathing to prevent bond with the surrounding concrete. External tendons attached to the concrete at anchorage and deviators only are also unbonded tendons.

Bonded post-tensioning—Post-tensioning tendons consist of strands or bars in plastic or corrugated galvanized metal ducts that are grouted after stressing to provide bond with the surrounding concrete and corrosion protection.

Chapter 14—Cast stone

Cast stone products are available in virtually any color, and will give the appearance of a variety of natural building stones including, but not limited to, limestone, granite, slate, travertine, and marble. Applications for cast stone range from the simplest windowsills to the most complicated architectural elements, including use as a masonry veneer product; for sills, caps, and copings; and for stair treads and balustrades. Cast stone is distinguished by its fine surface texture. According to ASTM C1364-10 (ASTM International 2010), all surfaces intended to be exposed to view should have a fine-grained texture similar to natural stone, with no air voids in excess of 1⁄32 in. (0.8 mm) with the density of such voids less than three occurrences per any 1 in.^{2} (625 mm^2) and not obvious under direct daylight illumination from a 5 ft (1.5 m) distance, unless otherwise specified.

Fig. 3.17—This private residence incorporated a large amount of cast stone, which included a custom designed ornate door entry, window surrounds, water table, clad columns, roof coping, and site wall coping (Lewisburg Residence, PA). *Photo courtesy of Cast Stone Institute*

Fig. 3.18—Cast stone allowed the main entrance to become an intricate focal point. Structurally, the columns served as the load-bearing members, and the cast stone was voided out to allow an anchoring system to attach the stone in addition to allowing room for plumbing, electrical, and other mechanical systems. *Photo courtesy of Cast Stone Institute*

Specific benefits when compared with natural limestone include:

1. Recycled materials may be used in cast stone production;
2. Greater flexibility in meeting regional requirements in code and rating systems;
3. Greater ability to customize cast stone helps limit energy use and waste on site;
4. Reduces dust from grinding of natural stone (easier on masons and laborers and less disruption near the site);
5. Ability to match existing material colors makes cast stone a good candidate for historic restoration projects;
6. Facilitates incorporation of items such as handling inserts and anchor slots, reducing labor and energy required to set product on the job site; and
7. Higher compressive strength and lower absorption levels makes cast stone durable and helps contribute to a longer building life cycle.

Sustainable attributes

Cast stone manufacturing is not an energy-intensive process in itself (although the same types of carbon footprint items discussed in other chapters for concrete applications still apply). Steam curing is often used to maintain a consistent curing temperature, though in many southern climates, steam curing is not necessary. Most manufacturers that use steam curing use natural

Fig. 3.19—Cast stone is used on the main entry porch of this grand residence and as wall capping (Green Residence, Mansfield, TX). *Photo courtesy of Cast Stone Institute*

gas or liquid propane gas (LPG). Waste heat from combustion may be captured and used as a beneficial part of the curing process. In addition, many manufacturers have improved the energy efficiency of the manufacturing facility itself by adding insulation, which results in a reduction of energy required for heat.

Cast stone, like other masonry and concrete products, has high thermal mass that helps provide an energy efficient envelope with excellent longevity. Cast stone is very durable, has a high compressive strength, and is subject to freezing-and-thawing tests and standards. It is manufactured throughout the U.S., often from materials that are locally available.

Reduce, reuse, recycle

The cast stone manufacturing process efficiently uses raw materials, which minimizes waste. Most wooden forms used in production may be recycled or disassembled and used repeatedly to create new molds, which conserves materials. Manufacturing plants certified by the Cast Stone Institute adhere to a rigorous 86-step program designed to ensure quality control and minimize waste through efficient processes and proper storage of materials and finished products. Cast stone is manufactured and delivered to the job site in the exact quantities needed for the project, which results in almost no construction waste.

Many cast stone elements can be reused with care. Copings, sills, and other shapes that can be cleaned of mortar can be reused. All cast stone is recyclable. Cast stone discards are often crushed and used as aggregate in other concrete products or as fill in roadbeds. In addition, cast stone can also contain recycled materials, such as certain supplementary cementitious materials (SCMs), recycled glass, or other recycled aggregates, coloring pigments made from post-consumer recycled materials, synthetic fibrous reinforcement made from 100% post-consumer recycled materials, and steel reinforcement with a high recycled material content.

Cast stone is typically manufactured with white portland cement, resulting in an assumed solar reflective index (SRI) of 86 for a nonpigmented mixture. As a result, cast stone used in hardscapes (such as caps, copings, and steps) helps mitigate the heat-island effect. Figures 3.17 through 3.24 show examples of uses of cast stone for new construction and also for the restoration of historic structures.

Fig. 3.20—Cast stone used in this collegiate-gothic style building with ornate window and door surrounds at The Taft School in Watertown, CT; and integration of new cast stone into the existing Joule Hotel, Dallas, TX, designed to appear as if it had always been an architectural element (Joule Hotel, Dallas, TX). *Photo courtesy of Cast Stone Institute*

Fig. 3.21—Restoration (before and after): cast stone was used to replicate the entire original exposed aggregate structure, while maintaining the historical integrity of the intricate architectural details (Naples Central School District Naples, NY). *Photo courtesy of Cast Stone Institute*

Fig. 3.22—Restoration of decorative detail at Robertson County Courthouse, Springfield, TN. *Photo courtesy of Cast Stone Institute*

Cast Stone Top Sustainability Benefits

- Requires minimal to no maintenance or repair—conserves resources.
- Numerous/local production locations reduce transportation impacts.
- Custom nature of cast stone minimizes on-site construction waste.
- Higher SRI of light colored cast stone helps reduce heat retention and urban heat-island effect.
- Low volatile organic compound (VOC) emissions support indoor air quality strategies.
- Durability: provides economic benefit over building life cycle.
- Thermal mass: properties help optimize energy performance.
- Resilient: particularly against terrorist attacks and natural disasters such as fires, hurricanes, tornadoes, and floods.
- Materials efficiency: can use regional and recycled materials.

Architectural cast stone—An architectural precast concrete building unit intended to simulate natural cut stone, used in unit masonry applications.

Chapter 15—Foundations

Sustainable attributes

Foundations come in a large number of varieties that are covered elsewhere in this book: cast-in-place (traditional poured walls or insulated concrete forms and slabs), prestressed (most typically post-tensioned slabs-on-ground), precast (often as a wall unit that includes insulation for basements), and block. Each type has similar advantages for sustainability, as covered in the respective sections for these various applications. Water tightness (either from a reduction in the number of joints or from properly sealed joints) is extremely important for basement walls.

Basements can provide a temperature-moderated environment for additional living areas or storage. The thermal mass of the concrete, along with the soil outside the wall, can keep basement areas extremely cool in the summer without the energy needed to cool other levels of a building or house. Additionally, basements provide an additional level of safety during tornados and major storms, or can be used as a safe room. Figure 3.23 shows a cast-in-place post-tensioned foundation and Fig. 3.24 shows a precast foundation.

Fig. 3.23—Placing a cast-in-place post-tensioned foundation. *Photo courtesy of Post-Tensioning Institute*

Concrete Foundations Top Sustainability Benefits

- Low environmental impact: residential basements offer a unique green strategy to add significant square footage in the same footprint.
- Reduced energy consumption: below-grade living space has a significantly lower energy use per ft^2 (m^2) than above-grade. The concrete in residential foundations provides a home with enough thermal mass to dramatically reduce temperature fluctuation and energy use.
- Local resources: residential concrete for basements and foundations has a high percentage (nearly 100%) of local materials (500 mile [800 km] radius).
- Air quality improvements: foundation/basement concrete does not provide a food source for pests such as termites, and controls temperature when insulated properly for the elimination of mold and mildew development.
- Durability: provides economic benefit over building life cycle and achieves a finished, durable state without the need for additional cladding or finish systems.
- Longest use life: residential concrete walls provide a life span endurance of more than 100 years.
- Resilient: particularly against terrorist attacks and natural disasters such as fires, hurricanes, tornadoes, and floods.
- Materials efficiency: can use regional and recycled materials.

Fig. 3.24—Precast foundation. *Photo courtesy of National Precast Concrete Association*

Associations and resources

For poured walls: Concrete Foundation Association (CFA) (**www.cfawalls.org**)

For post-tensioned foundations: Post-Tensioning Institute (PTI) (**www.post-tensioning.org**)

For Precast Foundations: **http://www.solutions.precast.org/concrete-foundations**

Foundation—An element or system that supports a structure (such as a building). Concrete foundations can be cast-in-place or precast (including standard reinforcement and/or post-tensioned reinforcement), precast, or block. In residential construction, it is often both practical and economical to increase these foundations to enclose living space as basements or lower-level living.

Slab-on-ground—A foundation type that is essentially a slab poured without foundation walls below to transfer load to footings. A thickened edge portion of the slab serves as a footing. Post-tensioning is often used for this type of foundation. Slab-on-ground is appropriate only for areas where the ground does not freeze (unless used with a heated structure and proper insulation to prevent freezing).

Foundation wall systems—Support the floor slab above so the slab does not provide the entire support for the building. Foundation walls run underground to a footing below the frost line. This type of foundation is used in areas where the ground freezes. Foundation wall systems are also used in conjunction with basements.

Pier and grade beam—An option in heavily sloped areas or areas with particularly poor soil. Piers can provide the load distribution down to competent soil for a stable foundation system.

Chapter 16—Hardscape/pavement

Sustainable attributes

Hardscape is the nonvegetative areas of the landscaping, including paved areas, walls, patios, and foundations. *The Sustainable Concrete Guide—Strategies and Applications* (Schokker 2010) provides background and overview information on various types of hardscaping, such as cast-in-place concrete, precast open grid pavers, pervious concrete, decorative concrete, and permeable interlocking concrete pavements. As with other concrete applications, recycled materials, such as supplementary cementitious materials (SCMs), can be used. The primary sustainable attributes for hardscape/pavement are in the areas of storm-water management, heat-island effect, and improving the visual character of living/working environments.

Storm-water management

Pervious concrete and interlocking concrete pavers provide a significant contribution to managing storm-water quality and quantity. A detailed discussion on both of these applications is available in *The Sustainable Concrete Guide—Strategies and Examples* (Schokker 2010). Pervious concrete is essentially a filter made with concrete; the concrete contains large interconnected voids that help filter particulates and organics from storm water. The water filters down through the sub-base, where it can return to the aquifer. This diminishes storm-water runoff quantities, while improving the quality of runoff going to the aquifer. In large storm events, the pervious concrete and underlying base layers can store a large quantity of runoff without leaving standing water on the surface of the pavement. The water can then infiltrate at a slower rate through the ground. Pervious concrete (Fig. 3.25) can be used for parking lots, streets, sidewalks, and any other hardscape paving applications.

Permeable interlocking concrete pavers (PICPs) have similar benefits for storm-water management to that of pervious concrete. The joint spaces among the pavers are highly permeable (consisting of small aggregate), and the pavers are placed over a highly permeable aggregate base. These allow storm water to infiltrate through the ground to the aquifer. PICP is typically used for parking lots, sidewalks, driveways, plazas, and some low-speed streets.

Both systems can also eliminate the need for detention ponds, and thus result in less cleared land with more green space. Like pervious concrete, PICP offers substantial reduction of storm-water runoff and pollutants. In addition, both can be used for water harvesting. PICP is well suited for coatings that reduce air pollution and integration with horizontal ground source heat pumps to conserve building energy for heating and cooling.

Fig. 3.25—Working on a pervious concrete sidewalk in Atlanta, GA. *Photo courtesy of American Concrete Institute*

Interlocking Concrete Pavements Top Sustainability Benefits

- Recharges water table.
- Improves storm-water discharge quality.
- Reduces the need for storm-water treatment facilities and the cost to operate/maintain them.
- Reduces the requirements for storm-water detention and retention features along with maintenance and liability for the owner.
- Urban heat-island reduction is supported with products that exceed the solar reflective index (SRI) of >29.
- Immediately ready for traffic upon completion, minimizing disruption.
- Americans with Disabilities Act (ADA) compliance: complies; narrower openings, regular interlocking pavers, or both can be used if desired.
- Repairs: units and aggregate can be easily removed and reinstated.
- Winter durability: high freezing-and-thawing and deicing salt-resistant concrete; water in base does not cause heaving; complete saturation when frozen will not damage pavement; accepts snowplowing equipment.
- Materials efficiency: can use regional and recycled materials.

Fig. 3.26—Whitemarsh Park pervious pavement parking lot. *Photo courtesy of Portland Cement Association*

Fig. 3.27—The porous nature of pervious concrete allows water to drain through and recharge aquifers, helping to replenish groundwater supplies. *Photo courtesy of Portland Cement Association*

Human factors and living/working environment

Heat-island effect

Dark surfaces, such as roofs or hardscape (for example, asphalt parking lots), contribute to the heat-island effect that raises temperatures in highly urbanized areas. Concrete hardscape in light colors (natural concrete or stained/colored) reflects some heat rather than absorbing it, thus lowering the heat-island effect. Porous materials, such as pervious concrete, also tend to store less heat.

Aesthetics

Concrete pavers and decorative concrete are also popular choices for aesthetic reasons. The patterns, colors, and customized shapes provide endless opportunities to provide beautiful hardscape that contribute to the character of a place. Two case studies are presented at the end of this chapter that illustrate some of the different looks that can be achieved.

Case studies

Whitemarsh Park, MD—First Eastern Shore community to choose pervious concrete

Centreville's Bloomfield Farm, once home to a working farm, now includes Whitemarsh Park, an active recreation facility that houses many attractions for this Eastern Shore community in Maryland that is within the Chesapeake Bay watershed. Surrounding the original nineteenth century homestead, Whitemarsh Park includes fields for soccer, lacrosse, and baseball; a driving range, and a fishing pond, among other points of interest. Located on nearly 300 acres (120 hectares) of pristine farmland, Whitemarsh Park is home to forest and meadows unique to Maryland's Eastern Shore. When considering parking facilities for the new park, Queen Anne's County officials wanted to take the delicate balance of the environment into account through every phase of planning to ensure that Whitemarsh Park could be enjoyed for generations to come.

The Board of Commissioners was resolute in preserving the surrounding environment and educating the public about the importance and benefits of sustainable development. After much consideration and study, pervious concrete was chosen as the material to construct the site's first of three parking areas (Fig. 3.26 and 3.27). Parking lots constructed with pervious concrete provide a filtration system that helps prevent oil, grease, and other contaminants from entering groundwater. Additionally, the porous nature of pervious concrete allows water to drain through and recharge aquifers, helping to replenish groundwater supplies. Using this technology also helps prevent harmful erosion and unnecessary deposits of sediment into rivers and streams. Construction with pervious concrete is recognized by the EPA as a Best Management Practice (BMP) for storm-water management.

A great deal of planning, preparation, and education went into the development of the Whitemarsh Park parking lots. Queen Anne's County Department of Public Works (DPW) engineers conducted field investigations to be certain the conditions of the site would be appropriate for the use of pervious concrete, and considered several parameters and specifications necessary to achieve a working design for the lots. Installation of the concrete was contracted to a National Ready Mix Concrete Association (NRMCA) certified pervious concrete installer.

In addition to careful planning and research, the DPW, the Maryland Ready Mix Concrete Promotion Council, and Chaney Enterprises hosted a pilot project to gain Pervious Concrete Certification and participate in an installation demonstration. The certification workshop was the first NRMCA installer certification testing held in the state of Maryland, and more than 30 contractors attended.

"The Chesapeake Bay and her tributaries are an invaluable resource on a national scale, while her protection remains here at the local level. Public outreach is a key component and we're delighted with the interest and enthusiasm the project has received," said County Commissioner Carol Fordonski.

Autumn Trails (Moline, IL)

Autumn Trails pioneers PICP in streets

George Bialecki Jr. takes green building seriously. As developer of age 55+ communities, environmentally responsible design saves his projects money and sells his energy-saving units more quickly. For example, PICP saved thousands of dollars by eliminating conventional storm-water drainage at Autumn Trails, an independent living community with 32 homes located in Moline, IL, as shown in Fig. 3.28. The savings was so great that it made PICP cost-competitive with conventional asphalt and concrete pavements. Figure 3.29 illustrates the plan for Autumn Trails.

At the invitation of the Chinese government, Bialecki was chosen to represent the U.S. in the first International Sustainable Energy Demonstration community in the world before the 2008 Olympics located in Beijing, China. This "Future House" community brought 10 nations together to showcase their country's best energy-saving building practices. Future House USA not only introduced PICP within their driveway and walkways, but also worked to assist the Chinese Ministry of Construction to incorporate PICP throughout the streets of the entire community.

Even as an infill project in an older area of Moline, Autumn Trails sold out before construction began because operating costs for buyers were reduced as much as 85%, compared with conventional building designs. Features such as geothermal heating made the highest winter monthly heating bill $40 (in 2008 dollars). The designs also included reduced water consumption, improved indoor air quality, and the extensive use of recycled materials in addition to PICP to reduce runoff.

Part of the development's success is that buyers are introduced to housing as a living organism that breathes, absorbs environmental elements, and produces waste. Global environmental concerns are taken seriously by designing low-energy and low-consumption lifestyles into the homes.

Fig. 3.28—Autumn Trails in Moline, IL, demonstrates the cost savings of permeable interlocking concrete pavement to developers, cities, and homeowners. *Photo courtesy of Interlocking Concrete Pavement Institute*

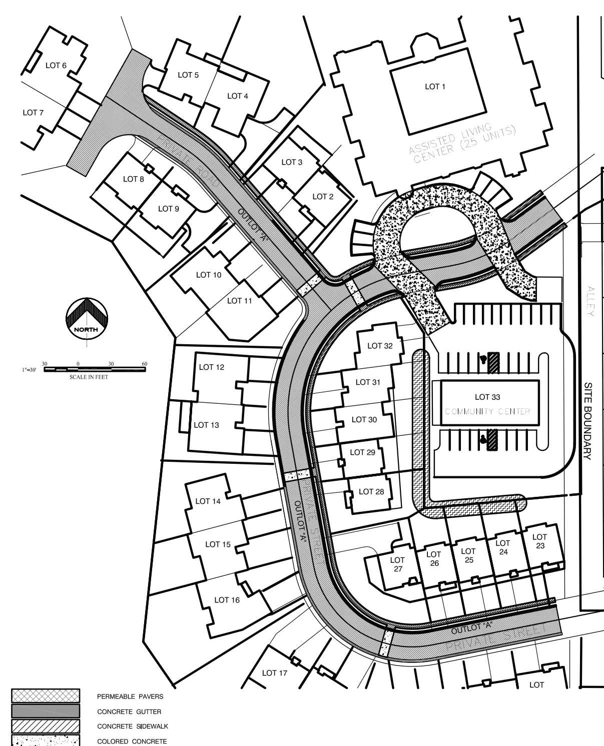


Fig. 3.29—Autumn Trails includes independent and assisted living units tied together with PICP streets. *Photo courtesy of Interlocking Concrete Pavement Institute*

Cost savings from PICP

PICP was chosen for several reasons. First and foremost, PICP was a great fit into the environmentally responsible approach, and yielded significant cost savings. These savings included the elimination of storm-water runoff fees and the burden on Moline's aged storm sewer system. By eliminating a detention pond, more land was available for income-generating housing units at Autumn Trails. PICP met the municipal requirements for pervious-impervious ratio cover. Thanks to pervious soils, PICP eliminated storm sewer inlets and pipes. The cost comparison in Table 3.1 for the 39,000 ft^2 (3,900 m^2) or 2500 ft (762 m) street portion of the Autumn Trails project demonstrates the savings that made PICP cost-competitive with asphalt (in 2008 costs). City officials approved of using PICP and eliminating drainage inlets and pipes. Because the PICP street is privately owned and maintained by the community, it was difficult for city officials to object.

Table 3.1—Dollar cost comparison of pavement systems for autumn trails (Moline, IL), 2008 costs

Item	PICP	Concrete	Asphalt
Paving, ft^2 (m^2)	2.25	8.00	3.00
Excavating, ft^2 (m^2)	1.00	1.00	1.00
Stone, ft^2 (m^2)	2.00	1.50	1.50
Installation, ft^2 (m^2)	4.00	(in paving cost)	1.50
Curbs	1.50	1.50	1.50
Maintenance	0.20	0	Not known
Replacement	None	None	Every 12 years
Detention, retention required	None	Yes	Yes
Storm sewer system, ft^2 (m^2) paving	None	3.00	3.00
Total, ft^2 (m^2)	10.95	14.00	11.50
Total, linear ft (linear m)–municipal street	171	218	179
Total, linear ft (linear m) for 30 ft (9 m) wide street	230	280	230

Table courtesy of Interlocking Concrete Pavement Institute

Autumn Trails features 39,000 ft^2 (3900 m^2) of 3.125 in. (80 mm) thick PICP units over a 2 in. (50 mm) thick bedding of Illinois Department of Transportation (IDOT) coarse aggregate CA-16. CA-16 was also used to fill the paver openings. This material has an infiltration rate of over 500 in./h (12,700 mm/h). When placed in the openings, the material yields an approximate effective infiltration rate of at least 50 in./h (1270 mm/h). Even with a worst-case estimate of 90% reduced surface infiltration after decades of use, the CA-16 stones in the PICP openings are expected to maintain at least a 5 in./h (127 mm/h) surface infiltration rate, well above most rainfall events for Moline, IL.

The open-graded crushed stone base and subbase act as a reservoir to store and infiltrate water into the soil subgrade. The base consists of 8 in. (200 mm) of Illinois DOT CA-7 over a subbase of 8 in. (200 mm) of CA-1. The CA-1 has perforated pipe running through both sides of its cross section to facilitate movement of excess water to French drains. The subbase sits on geotextile to separate it from the adjacent soils. Figure 3.30 shows a typical cross section.

The gradation of the CA-16, CA-7, and CA-1 enable each to filter into the layer beneath, thereby providing a stable base for the pavers and vehicles. The gradation

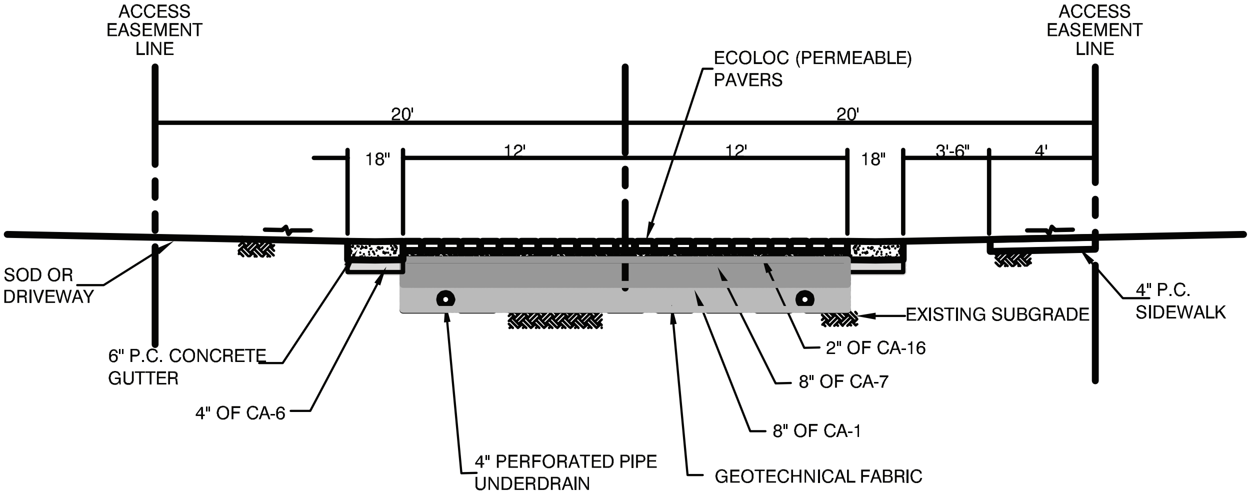


Fig. 3.30—Typical PICP cross section includes a substantial base thickness for water storage and infiltration. The water and sanitary sewer lines run under the street. (Note: 1 in. = 2.54 cm; 1 ft = 0.3048 m.) *Courtesy of Interlocking Concrete Pavement Institute*

of each aggregate type is shown in Table 3.2. The base and subbase together have an estimated storage volume (void space) of approximately 40%. Therefore, their total thickness of 16 in. (400 mm) can store approximately 6-1/2 in. (165 mm) of rainfall coming from roofs, sidewalks, and driveways. This storage volume accommodates both common and most heavy rainstorms. The pavement is designed to overflow and drain at one end should there be saturated soil and base conditions during heavy rains. There is a small retention pond to catch overflows, and the water collected is used for irrigating lawns.

Construction

An unusual construction aspect was that the pavement was built in winter. Precast concrete units were manufactured in a factory off site, and were ready for installation regardless of the outside temperature. A source of unfrozen aggregate was available nearby, and the open-graded pavement base layers and pavers were placed in the winter months. This reduced the construction schedule by months, positively affecting financing costs and accelerating the opening date. This would not have been possible with most other paving methods.

The base layers were placed and compacted with a 10 ton (9.1 tonne) roller. Figure 3.31 shows the compaction process. After the CA-1 and CA-7 layers were compacted, the CA-16 was spread and screeded. The start of this process is illustrated in Fig. 3.32. After the 2 in. (50 mm) thick CA-16 bedding layer was in place, the units were supplied to the project in a ready-to-install laying pattern. Layers of pavers were brought to the site stacked on pallets, and each layer was clamped and placed by a mechanical installation machine, as shown in Fig. 3.33 through 3.35.

Once the pavers were in place, their openings were filled with the small CA-16 stones. Figure 3.36 shows this process. Excess stones were removed from the paver surface, and the pavers were compacted with a plate compactor. No curing was needed, so the PICP surface was ready for vehicles immediately after compaction.

An essential aspect of PICP construction is keeping the open-graded base materials free from sediment during placement and construction. This was addressed by building a temporary gravel road around the rear of the development for use by construction vehicles.

Snow melts more quickly on PICP because the water can drain directly into the pavement. The impact of this feature on reducing snowplowing costs is likely to be positive, and slip hazards from ice are definitely reduced. There has been no problem with pavement heaving or settlement because the water does not freeze in the base. The heat from the earth helps keep the water flowing. Snowplowing is done as with any other pavement.

While there are many PICP parking lot projects across the U.S. and Canada, Autumn Trails is one of the first successful PICP street projects. PICP has the

Table 3.2—IDOT coarse aggregate in percent passing

	CA-16	CA-7	CA-1
Function	Bedding layer	Base reservoir	Subbase reservoir
Sieve size:	—	—	—
3 in. (76 mm)	—	—	100
2-1/2 in. (63 mm)	—	—	95 ± 5
2 in. (50 mm)	—	—	60 ± 15
1-1/2 in. (38 mm)	—	100	15 ± 15
1 in. (25 mm)	—	95 ± 5	3 ± 3
1/2 in. (13 mm)	100	45 ± 15	—
3/8 in. (10 mm)	97 ± 3	—	—
No. 4 (4.75 mm)	30 ± 15	5 ± 5	—
No. 16 (1.18 mm)	2 ± 2	—	—

Table courtesy of Interlocking Concrete Pavement Institute

Fig. 3.31—Compaction equipment completes the base surface before placing the bedding layer. *Photo courtesy of Interlocking Concrete Pavement Institute*

Fig. 3.32—Screeding smooth to receive the permeable pavers. *Photo courtesy of Interlocking Concrete Pavement Institute*

structural capacity for low-volume streets and heavier loads under stabilized bases. As with Autumn Trails, PICP is part of a sustainable building solution that works toward saving money for the developer and residents. Moreover, this street project, along with city-owned projects in Portland, OR, and Waterford, CT, sends a unique challenge to municipalities to use PICP in city streets as a means to comply with national, provincial, state, and local storm-water regulations while reducing drainage costs.

Marine Way Market (Burnaby, BC, Canada)
Do something beautiful

Aesthetics is what moved Westbank Projects Corporation to use approximately 350,000 ft^2 (3.2 ha) of PICP at Marine Market Way (Fig. 3.37). The project, completed in Spring 2007, boasts nearly 100% occupancy. By combining parking and detention under the 1161-space parking lot, permeable pavement created a bit more rentable space and matched unique building entrances and light fixtures. The finished project projects an invitation to customers to come, park on environmentally responsible pavement, and shop at their favorite stores housed in exciting architecture and lighting. The development lifts customer expectations above the dullness of many shopping centers to new visual and environmental horizons.

The roofs deliver storm water into the permeable pavement base in addition to water falling directly on the permeable pavers and into narrow, stone-filled joints (Fig. 3.38 and 3.39). The open-graded stone base and subbase detain and filter runoff before

Fig. 3.33—The permeable interlocking concrete pavers are supplied and installed in layers on the screeded bedding material (pea-sized aggregate—bedding sand is never used in PICP). Note the snow on the pavers doesn't interfere with installation, and the border coarse against the concrete curb provides a finished edge. *Photo courtesy of Interlocking Concrete Pavement Institute*

Fig. 3.34—Mechanical installation equipment places ready-made layers of the concrete pavers. *Photo courtesy of Interlocking Concrete Pavement Institute*

Fig. 3.35—The equipment generally reduces paver installation time by 50 to 70% compared with manual installation. *Photo courtesy of Interlocking Concrete Pavement Institute*

Fig. 3.36—The paver openings are filled with the small stones (CA-16), and excess stones are removed from the paver surface before compaction. *Photo courtesy of Interlocking Concrete Pavement Institute*

being released at lower rates into the drainage system. Because the entire parking surface is one large drainage inlet, there are no catch basins on the site. As the rainfall passes through the paver joints and into the open-graded stone base, 6 in. (150 mm) diameter perforated pipes placed on a slope at the bottom of the open-graded subbase convey water and direct flows to a central 24 in. (600 mm) diameter storm sewer.

The combined drainage and pavement structure includes 3-1/8 in. (80 mm) thick concrete pavers over 2 in. (50 mm) of ASTM No. 8 stone. The pavers and bedding layer rests over 4 in. (100 mm) of No. 56 stone over 12 in. (300 mm) minimum thickness of ASTM No. 2 stone subbase (generally stone sizes 3 in. down to 3/4 in. [75 down to 20 mm]). The base and subbase provide a storage reservoir that consists of more than 30% of the total volume of the stone. The runoff storage is at least 128,000 ft^3 (3,625 m^3), or approximately 957,000 gal. (3.62 million L).

The soil subgrade was imported as engineered fill and compacted. While soil compaction is not recommended in most permeable pavement applications, the designers recognized that fill soil would require compaction for stability. In the hydrological design, compaction was assumed to render the soil impervious. Hence, perforated drain pipes were used to restrict and direct outflows. This satisfied the design approach of filtering the water slowly through the stone base, allowing some nutrient digestion and reduction of oils via microbial activity.

After filling, grading, and compacting the soil, geotextile was placed under 12 in. (300 mm) of large-sized open-graded No. 2 subbase stone, as shown in Fig. 3.40. Smaller-sized base stone, ASTM No. 56, provided a 4 in. (100 mm) thick transition layer over the larger stone and the bedding coarse above it. Large trucks transported and spread the subbase and base, as shown in Fig. 3.41. After placing and screeding a 2 in. (50 mm) thick bedding layer of No. 8 stone, mechanically installed pavers provided the structural wearing surface.

Fig. 3.38—With no space for a separate detention pond, the permeable interlocking concrete pavement parking lot becomes the detention facility for roof and parking lot runoff. *Photo courtesy of Interlocking Concrete Pavement Institute*

Fig. 3.39—Post-modern architecture, unique lighting, and permeable interlocking concrete pavement transformed Marine Market Way into a visually exciting place that minimizes environmental impacts. *Photo courtesy of Interlocking Concrete Pavement Institute*

Fig. 3.37—Permeable interlocking concrete pavement manages roof and parking lot runoff at the Marine Market Way in Burnaby, BC, Canada. *Photo courtesy of Interlocking Concrete Pavement Institute*

The project used paver layers manufactured in a 45-degree herringbone pattern (Fig. 3.42). Layers were stacked and bound together for transport to the site. Mechanized equipment with a specially fitted clamp enabled the installation of each layer, covering approximately 1 yd^2 (m^2). Paver installation productivity averaged approximately 6000 ft^2 (600 m^2) per day. This included screeding the bedding material, placing the pavers and permeable jointing material, sweeping, and compaction. Figure 3.43 illustrates only one person positioning the paver layers into place.

Figure 3.44 shows how the jointing material transported in large sacks was moved and dispersed into the joints. The jointing material was 1/8 in. (3 mm) in size (similar

Fig. 3.40—Large stone similar to railroad ballast in size created a stable subbase and ample water storage under the parking lot. *Photo courtesy of Interlocking Concrete Pavement Institute*

Fig. 3.41—A base layer of No. 56 stone enables a transition between the subbase and bedding layer, causing all stone layers to interlock and "choke" into each other. The No. 56 layer also provides runoff storage capacity. *Photo courtesy of Interlocking Concrete Pavement Institute*

Fig. 3.42—A unique 45-degree herringbone paving pattern eliminated removal and replacement of half-stones, thereby saving labor expense and reducing paving time. The layers arrived at the site in a 45-degree pattern with no shift or misalignment during transport. *Photo courtesy of Interlocking Concrete Pavement Institute*

to ASTM No. 9 stone). Not shown are sweeping the joints full and compacting the pavers to begin the interlocking process among the paving units.

Two different-colored pavers were used: one to mark parking spaces, and another for the moving lanes. Charcoal gray pavers in the parking spaces help disguise oil drippings. Instead of spraying paint, parking stalls are marked with small white, flat delineators. This eliminated ongoing maintenance of repainting the parking stalls. The narrow joints between the pavers resulted in a shopping-cart-friendly and ADA-compliant surface.

Marine Market Way Shopping Center represents a paradigm shift. For decades, shopping centers treated runoff as a waste product that was dumped off the site as quickly as possible, only to pollute downstream waters and damage property. By using PICP that works with nature, shopping center developers can dedicate more site space to revenue-generating buildings rather than to detention ponds. Storm sewer costs and related maintenance are eliminated. Customers never stand in or dodge puddles. For the paver industry, using 45-degree herringbone patterns made at the factory reduces labor expenses by eliminating one or two extra persons working at the laying face. Over the coarse of a large project like Marine Market Way, this labor savings can represent thousands of dollars. This savings offsets additional paver cutting expenses to close the 45-degree pattern along curbs.

Fig. 3.43—Nearly all permeable interlocking concrete pavements are mechanically installed to reduce construction time. This shopping center contractor used such equipment to place 3-1/8 in. (80 mm) thick pavers over a 2 in. (50 mm) thick layer of screeded No. 8 stone. *Photo courtesy of Interlocking Concrete Pavement Institute*

Fig. 3.44—After placing the pavers, the joints were filled with fine washed stone, and the pavers compacted. The pavers have notched sides that create sufficient open area on the surface to infiltrate rainstorms. *Photo courtesy of Interlocking Concrete Pavement Institute*

Chapter 17—Insulated forms

Sustainable attributes

Carbon footprint

The upfront investment for insulating concrete forms (ICFs), in terms of CO_2 emissions, comes from the materials used, production, and transportation. The plastic foams in ICFs are typically expanded polystyrene foam (EPS), extruded polystyrene foam (XPS), or polyurethane, with EPS currently being the most commonly used. Each has different properties, including *R*-value, density, moisture resistance, and others. Individual manufacturers of ICFs determine the most appropriate foam for their system. All of these plastic foams are petroleum-based, so their manufacture depletes fossil fuels. For years, these types of foams (used in many other applications) have taken up space in landfills after being discarded. Each of the foams used in ICFs, however, can now be recycled rather than disposed of in a landfill. The foam forms are lightweight, so transportation costs are lower than for traditional formwork. The system provides efficiency of materials because the formwork stays in place to provide insulation to the building system.

Table 3.3—Comparison of plastic foam properties

	EPS	XPS	Polyurethane
R-value, per in.	4.17 to 4.35	5.00	5.90
Density, lb/ft^3	1.35 to 1.80	1.60 to 1.80	2.00
Compressive strength, psi	15 to 33	25 to 40	30
Tensile strength, psi	18 to 27	45 to 75	30
Water absorption, %	<3.0	<0.3	2.0

Note: 1 in. = 25.4 mm; 1 lb/ft^3 = 16.02 kg/m^3; 1 psi = 6.89 kPa.

Insulated Forms Top Sustainability Benefits

- High *R*-values are readily achieved, with less potential for installation problems.
- Excellent thermal performance due to very low infiltration rates.
- Extreme durability of both the insulation and structural components.
- ICFs are very lightweight, reducing fatigue of installation crew.
- Will not rot or rust.
- Versatility: ICF homes can be designed in any style, and will accept any traditional exterior finish including vinyl, wood siding, stucco, and brick.
- Peace and quiet: in sound transmission tests, ICF walls allowed less than one-third as much sound to pass through over ordinary frame walls filled with fiberglass insulation.
- Greater comfort and lower energy bills: a combination of high R-values, low air infiltration, and high thermal mass accounts for the 25 to 50% energy savings of ICFs versus traditional wood or steel-framed homes.
- Resilient: particularly against terrorist attacks and natural disasters such as fires, hurricanes, tornadoes, and floods.
- Materials efficiency: can use regional and recycled materials (both in the concrete and steel reinforcing).

The energy savings from using ICFs is their biggest contribution as a sustainable building system. The combination of a high *R*-value insulating material over a continuous concrete wall can provide significant energy savings for heating and cooling. With a traditional frame home, insulation is provided between wall studs, so insulation is not continuous because the studs provide a thermal bridge from the interior of the house directly to the outside. With ICF construction, the insulation is continuous over the concrete wall, and air leakage is minimized. While the amount of energy savings for heating and cooling differ depending on the climate where a building is located, a report by VanderWerf (1997) found a 44% reduction in energy costs for heating, and a 32% reduction for cooling in ICF homes compared with traditional wood frame homes.

Thermal transmission (*R*-values)

Not only are the *R*-values provided by the plastic foam in ICFs high, but because the actual *R*-value of the system also depends on the continuity of the insulation, ICF concrete walls reach high *R*-values as a system. Table 3.3 shows *R*-values and other properties for each of the three plastic foams discussed (EPS, XPS, and polyurethane). EPS tends to be the least expensive, followed by XPS, and then polyurethane.

Thermal mass

Thermal mass reduces the effects of temperature spikes outside a building on the temperature inside the building. Concrete walls provide storage of energy with delayed release (more information is available in *The Sustainable Concrete Guide—Strategies and Examples* [Schokker 2010]). Exposed concrete surfaces are most effective for use with passive solar designs. These surfaces can be provided by floors, interior walls, or mass elements such as a concrete fireplace. The ICF walls still provide a contribution from thermal mass to delay temperature spikes for heat or cold that passes through the insulating layer.

Longevity and economy

The materials used in ICFs (concrete and EPS or other plastic foam) have a proven track record of durability over many years of service. Because the yearly energy savings from ICFs have the greatest impact on their use toward a sustainable structure, the return on the original investment increases each year the building is in service. In colder areas, savings are more substantial for heating; and in warmer areas, the savings are more substantial for cooling. ICFs are for residential construction as well as large commercial buildings. The lower demand on the heating, ventilating, air conditioning (HVAC) systems means that their sizes may also be reduced.

Examples of ICF structures under construction (Fig. 3.45 to 3.48)

Case study

City of Philadelphia: revitalization of the East Parkside Community using insulating concrete forms

Philadelphia Mayor Michael Nutter is on a mission to turn his city into one of America's greenest. Beginning in the fall of 2008, Habitat for Humanity Philadelphia and BASF Corporation partnered with the East Parkside Community Revitalization Corporation (EPCRC) on a restoration project to transform the blighted historic neighborhood into a revitalized and sustainable

Fig. 3.45—Residence with ICF. *Photo courtesy of Insulating Concrete Form Association*

Fig. 3.46—Commercial building under construction with ICF. *Photo courtesy of Insulating Concrete Form Association*

Fig. 3.47—Stone being laid directly over ICF. *Photo courtesy of Insulating Concrete Form Association*

community. The focal point of the project is a group of seven, tri-level residential buildings featuring insulating concrete forms (ICFs) for the exterior walls and firewalls between the units (Fig. 3.49 and 3.50). The project team chose ICFs for energy efficiency, durability, and safety. Because the homes will use less energy, the affordability of living in the homes will be sustained, and the homeowners can continue to afford to heat their homes even as energy prices dramatically increase.

Other green features of the homes include daylighting, a south-facing thermal wall, ENERGY STAR® rated appliances, and dual flush toilets, leading to a 65% reduction in total utility costs for the homeowners. The ICFs also deliver fire safety and sound insulation. A labor force made up of community residents can stack ICF blocks, and are able to help build their neighbors' homes.

The first phase of homes in the East Parkside restoration achieved a Silver certification under the LEED for Homes rating system by the U.S. Green Building Council. As Philadelphia's first LEED-certified affordable housing project, the restoration was featured on the Discovery's Planet Green channel during the program "Renovation Nation" in the spring of 2009.

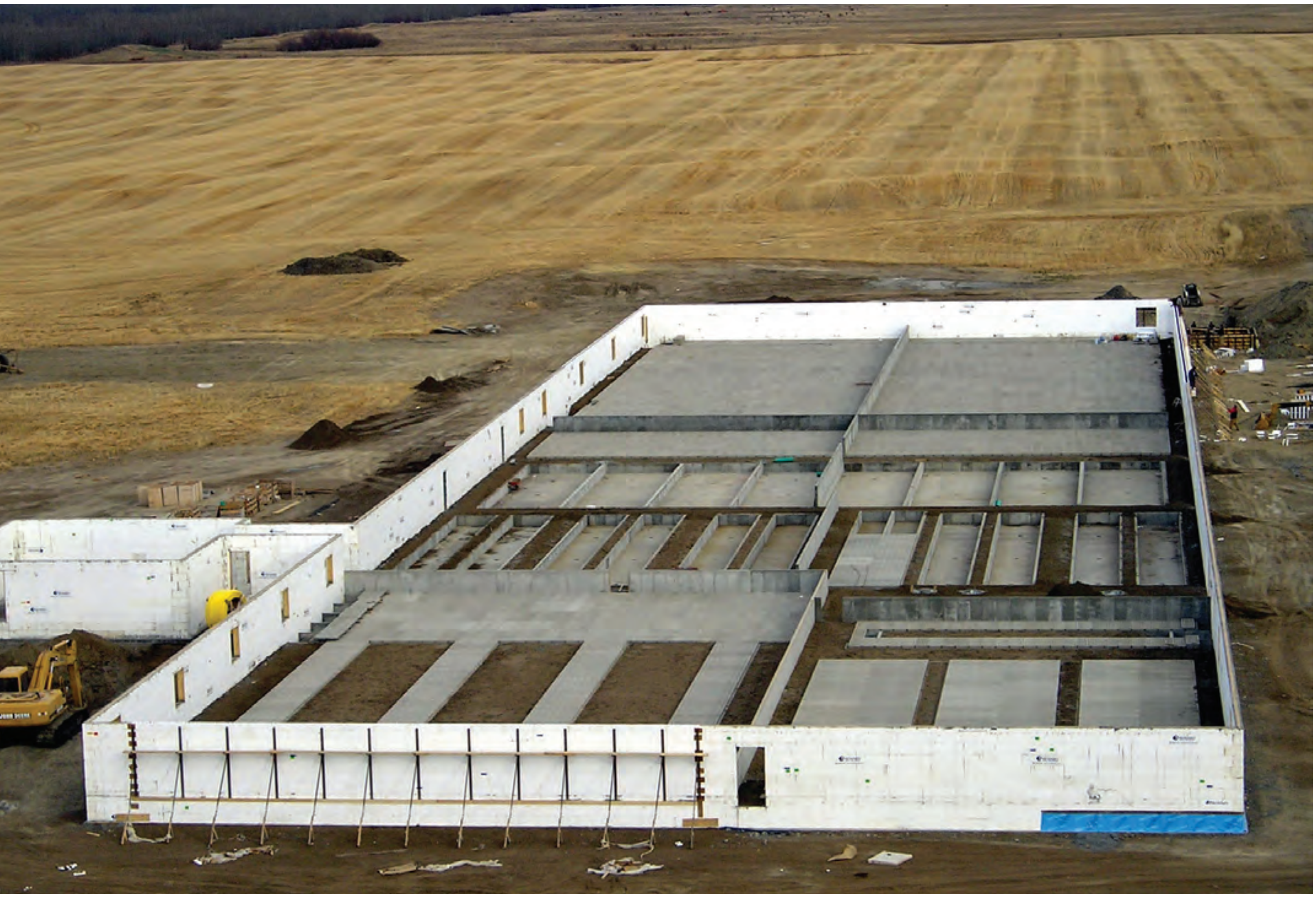


Fig. 3.48—Hog barn with ICF walls. *Photo courtesy of Insulating Concrete Form Association*

Insulating concrete forms—Stay-in-place forms used with poured concrete walls. The forms are made of foam insulation material and come in a variety of shapes and sizes, including block, panel, and plank systems.

Expanded polystyrene foam (EPS foam)—A closed-cell plastic foam made of pre-expanded polystyrene beads. It is made from a liquid hydrocarbon that is made from petroleum.

Extruded polystyrene foam (XPS foam)—Similar in composition to EPS, but is stiffer, denser, and has a lower thermal conductivity.

Polyurethane foam—A thermoset plastic with a base composition material derived from a by-product of the oil-refining process.

Fig. 3.49—East Parkside residential units. *Photo courtesy of Portland Cement Association*

Fig. 3.50—Insulating concrete forms (ICFs) were selected for this project for their energy efficiency, durability, and safety. *Photo courtesy of Portland Cement Association*

Chapter 18—Masonry

Sustainable attributes

Carbon footprint

The manufacturing process used to produce concrete masonry products lends itself to optimizing mixture proportions for specific applications and affords the flexibility to incorporate high replacement volumes of supplementary cementitious materials (SCMs). Concrete masonry is typically produced locally, using locally available materials, which thereby reduces energy demands and emissions associated with the transportation of raw materials to the manufacturing plant and the finished product to the job site. The hollow cells of concrete masonry also permit design optimization by efficiently using materials through partial grouting and prestressed masonry design techniques.

Masonry Top Sustainability Benefits

- The variety of finishes, textures, and colors eliminates the need for additional wall coverings.
- Better resale value: masonry buildings are aesthetically pleasing and maintain their beauty.
- Masonry walls can be easily adjusted at any time to suit job-site conditions, even after construction has started, and without production delays.
- Material optimization/conservation: structural and architectural dual use.
- Reduced sound transmission.
- Environmentally safe: prefinished masonry units such as split face, colored, glazed, and units with integral waterproofing provide additional benefits of safety through environmental health because they do not emit VOCs into the air.
- Indoor air quality: opportunity for no/low volatile organic compounds (VOCs).
- Durability: provides economic benefit over building life cycle; in addition, the color of the masonry won't fade, rust, or discolor from the weather, which eliminates painting and maintenance.
- Better insulation and energy performance: the thermal mass of concrete masonry walls keeps inside temperatures more constant, therefore reducing heating and cooling costs. There is an array of insulation options for high *R*-values in cavity walls.
- Resilient: particularly against terrorist attacks and natural disasters such as fires, hurricanes, tornadoes, and floods.
- Materials efficiency: can use regional and recycled materials.

Thermal mass and operational energy

The thermal mass of concrete masonry walls significantly influences heat transmission. For most applications, the effectiveness of thermal mass is determined by construction material properties, climate, building type, and the position of the insulation within the wall (relative to the masonry). Due to concrete masonry's inherent thermal mass, concrete masonry buildings can provide similar performance to buildings constructed of lightweight framing materials while using less added insulation. The benefits of thermal mass have been incorporated into sophisticated programs for modeling building performance. Prescriptive energy code compliance methods currently account for the benefits of thermal mass. While the thermal mass benefits in the prescriptive tables tend to be overly simplified (and thus conservative), energy codes and standards permit concrete masonry walls to have less insulation than frame wall systems to meet the code requirements.

When a concrete masonry wall requires additional thermal resistance, concrete masonry lends itself to many strategies that allow the design to provide the necessary thermal envelope without jeopardizing the other performance criteria for the project. Foam inserts, foamed-in-place, or granular fill insulation may be inserted in the cores of the concrete masonry units. Rigid board insulation may be adhered to the interior or exterior of the masonry, or the interior can be furred or studded. Rigid board, foamed-in-place, or batt insulation is placed between studs or furrings. In addition, multi-wythe construction lends itself to placing insulation between two wythes of masonry when the wythes are separated to form a cavity. With this form of construction, the resulting *R*-value is limited only by the desired thickness of the wall cavity.

Placing insulation between two wythes of masonry offers maximum protection for the insulation. The means to meet or exceed model building code requirements are easily obtainable, because the cavity installation allows a continuous layer of insulation to envelop the masonry. Thus, this continuous insulation layer can also reduce heat loss due to air infiltration. Cavity walls are also sometimes built with interior insulation only, leaving the entire cavity open for drainage.

Cavity walls, as well as single-wythe masonry with core insulation, also provide hard, durable surfaces on both sides of the wall, efficiently using the inherent impact resistance and low maintenance needs of concrete masonry. While these needs are most commonly associated with multi-family dwellings, hospitals, schools, and detention centers, the benefits of resistance to damage from hail, shopping and loading carts, gurneys, motorized chairs, and even sports make cavity wall construction ideal for many other applications.

Longevity and life cycle

Concrete masonry has been an integral part of the built environment for more than a century. When properly designed and constructed, concrete masonry products perform virtually maintenance free for 100 years or more. To the new and prospective owner of a building, one of the most attractive features of constructing with concrete masonry is its low cost of maintenance. The characteristic wear and tear that all buildings are subjected to, however, necessitates periodic repair and restoration to preserve and maintain the original integrity and appearance of the structure. Preventive maintenance conserves the value, appearance, and integrity of the building.

Design and construction methods greatly affect the required maintenance needs of a building. Accordingly, maintenance issues should be considered during the design and construction processes. Where possible, accepted industry practices should be followed to avoid cracking and spalling, preclude efflorescence, minimize staining and dirt buildup, and prevent the penetration of water into the structure (NCMA TEK 8-1A, Maintenance of Concrete Masonry Walls).

Human factors and living/working environment

Key features offered by concrete masonry include:

- Addresses indoor air quality issues by eliminating the need for paints with exposed concrete masonry walls, thereby reducing the potential for volatile organic compound (VOC) emissions;
- Improves indoor air quality with concrete masonry due to the reduced potential for mold growth (concrete masonry is not a food source for mold) and concrete masonry's ability to be cleaned instead of being replaced in the event of a mold incident; and
- Concrete masonry has superior acoustical characteristics, minimizing unwanted noise transmitted from adjacent rooms or from the outside.

Security and safety

Concrete masonry has long been considered an excellent material for building secure structures, from the backyard bomb shelters of the 1950s, to today's high-security prisons and seismic resistant buildings. In recent years, protection from terrorist attacks has become a higher priority for many buildings.

While the type and size of a terrorist attack cannot be predicted, guidelines for improving building performance are available. The mass of concrete masonry is beneficial for blast resistance. Masonry walls also protect against ballistics and shrapnel (flying debris from a bomb). Properly designed concrete masonry products provide protection for both people and properties across a broad array of applications and conditions.

Bullet resistance can also be a high priority for many buildings, often more so than blast resistance. Most ballistic testing on concrete masonry walls was carried out during World War II to make sure that adequate protection was provided for transformers, switching stations, and other installations subject to sabotage.

Recommended constructions for bullet resistance are 8 in. (203 mm) solid or grouted concrete masonry walls, or 12 in. (305 mm) hollow units with sand-filled cores. Both walls provide equal protection under test conditions. In no case did bullets penetrate the opposite face shell of the masonry when tested with high-powered rifles, revolvers, and machine guns (NCMA TEK 14-21, Blast and Bullet Resistant Concrete Masonry Buildings).

Communities across the nation rely on concrete masonry for their prisons and detention centers. In addition to its strength and durability, the layout of concrete masonry walls and cells can be cost-effectively tailored to meet the facility's needs. Concrete masonry is a proven product for correctional facilities, providing secure construction with minimal long-term maintenance.

Concrete masonry walls designed as security barriers are most often fully grouted and reinforced. Typically, vertical grouted cells with steel reinforcing in every cell are provided, although reinforced horizontal bond beams may also be specified. This type of construction is found in prisons, secure facilities, or other areas where the integrity of the building envelope or wall partition is vital to secure an area. Vertical post-tensioning may be provided in concrete masonry to enhance lateral stability.

When tested in accordance with ASTM F2322-03 (ASTM International 2003), solidly grouted 8 in. (203 mm) concrete masonry walls with and without window openings have been shown to meet the highest security rating (Grade 1) with a representative barrier duration time of at least 60 minutes (National Concrete Masonry Association 2003).

Reduce, reuse, recycle

As previously mentioned in this chapter, the design of concrete masonry systems can be optimized for each specific application and set of design variables by varying the assembly thickness, reinforcement spacing, and grout placement, thereby using materials to their fullest advantage. The zero-slump mixture and controlled curing process permits the flexibility to alter mixture proportions to incorporate waste by-products and recycled materials. The inherent durability of concrete masonry also permits existing construction to be rehabilitated to new uses while reusing much of the original core structure. In the event that a concrete masonry structure has reached the end of its intended purpose, it can be crushed to create aggregate and used in other applications.

Concrete masonry (Fig. 3.51 and 3.52) is used in a broad array of applications—from residential foundations to commercial structures, to hardscapes. The uses of manufactured concrete products, such as concrete masonry and segmental retaining wall units, are limited only by the vision of the designer. The modular configuration of these products facilitates their use with other construction materials and in areas of limited access. While the basic configuration of concrete masonry was perfected decades ago, the manufacturing technology and applications continue to evolve dynamically with market demands.


Fig. 3.51

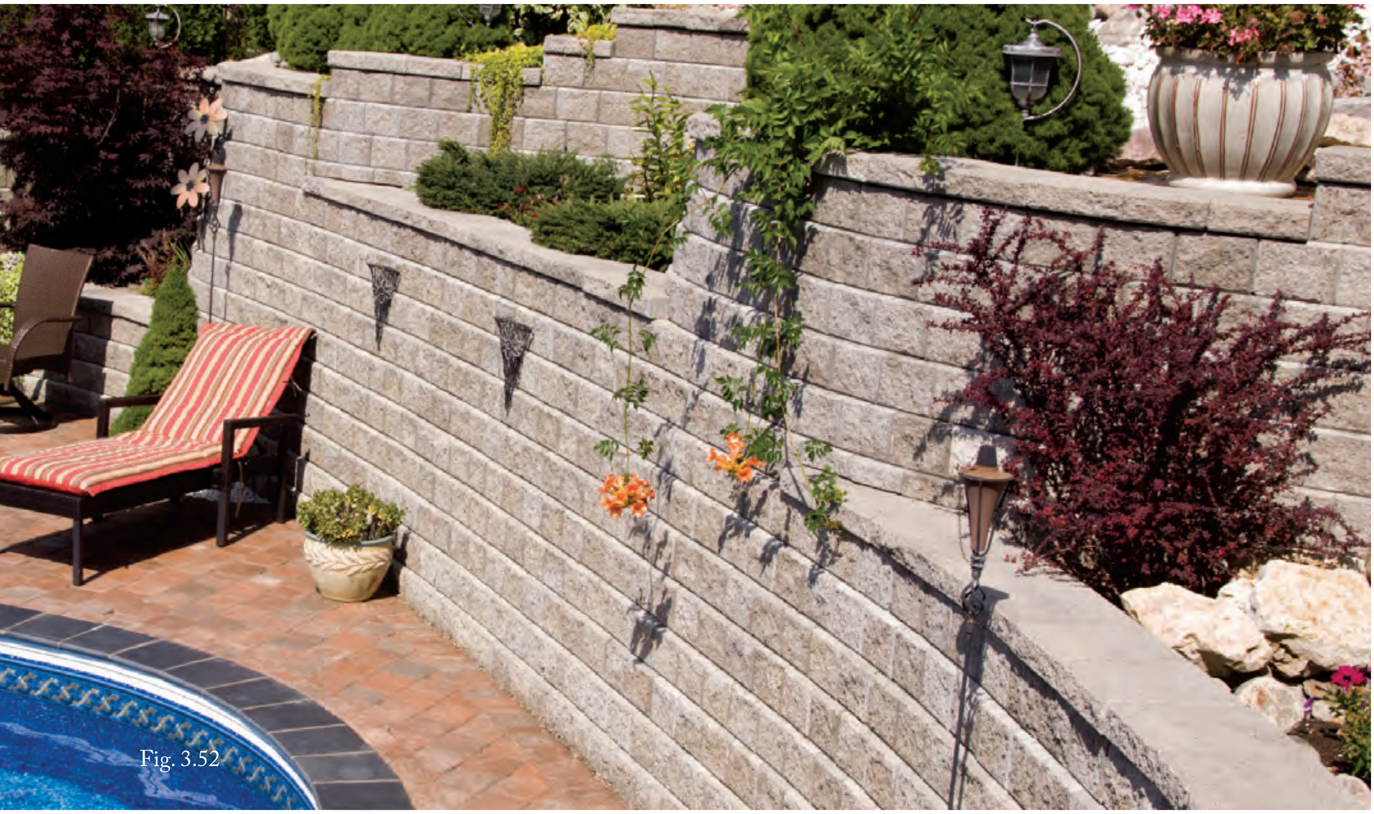


Fig. 3.52

Chapter 19—Pipe

Sustainable attributes

Concrete is the predominate solution for culverts and pipes due to its long life cycle and durability.

Carbon footprint

Concrete pipe and box culverts are products that can either be precast or cast-in-place; both of these methods have advantages. While unreinforced concrete pipe is still manufactured, most of the concrete pipe produced today is precast and contains recycled steel as reinforcement, which greatly increases its strength. The long life of concrete pipe and box culverts reduces the necessity for replacement, thereby eliminating construction zones and associated traffic congestion. Energy savings are realized, vehicle pollutants are eliminated, and the public's health and safety is improved. Properly installed concrete pipe reduces pavement subsidence because the concrete pipe itself does not deflect, which saves maintenance costs and energy.

Concrete pipe and box culvert components (cement, water, aggregate, and steel) are extracted and manufactured locally, thereby reducing economic and environmental costs associated with transporting pipe to distant sites. Concrete pipe and box culverts are usually backfilled with native soil and do not require large amounts of imported material.

Thermal mass and operational energy

Due to the Earth's near-constant temperature, precast concrete pipe can be used as earth tubes and buried at depths of approximately 5 to 10 ft (1.5 to 3.0 m). It is possible to use this constant temperature of the Earth to moderate air temperature for the purpose of ventilating a building. Earth tubes refer to this system of pipes that are placed below the ground and are used to heat and cool buildings. Concrete pipe is an ideal material for use as earth tubes which, unlike plastic pipe, will not release gas chemicals into the air when it travels through the tubes. The air intake is at a certain distance from the building, and the air circulates in the concrete pipe before arriving in the building's ventilation. In summer, the air cools before arriving inside the building, and the energy requirements for air conditioning are reduced. In winter, the cold air has time to be heated before entering the building, and the heat energy requirements are reduced. Because heating and air conditioning are two significant energy requirements of a building, the reduction of heating and cooling loads with concrete pipe earth tubes is an important method of energy conservation.

Example of a geothermal system

Nine 65 ft (19.8 m) long rows of concrete pipe were placed under the Earth Rangers Centre in Woodbridge, ON, Canada. The Centre, completed in 2004, is used for the treatment and the rehabilitation of wild animals and as an education center for youth. In addition to the geothermal system created by the nine rows of concrete pipe, a system for heating and cooling the concrete floor by radiation was installed. This system consists of a concrete floor with integrated concrete pipes through which heated or cooled water is circulated. These two systems, combined with an effective insulation medium, allow substantial energy savings to be realized.

Longevity and life cycle

The durability of a pipe material is equally important. The capability of pipe to perform as expected for the design life of a project is a fundamental engineering consideration, especially in today's economic environment where life-cycle cost analysis and asset management requirements have been set in place to ensure sustainable buried infrastructure.

Compressive strengths for concrete pipe typically range from 4000 to 6000 psi (27.6 to 41.4 MPa). It is not uncommon for 28-day tests to substantially exceed the specified design strengths. Quality concrete pipe densities typically range from 145 to 155 lb/ft^3 (2323 to 2483 kg/m^3).

Absorption is primarily used to check the density and imperviousness of the concrete. As with compressive strength, the absorption can be greatly influenced by both the aggregates and the manufacturing process. ASTM C76-10a (ASTM International 2010) specifies a maximum allowable absorption of 8.5 or 9%—depending on the test method used—for concrete pipe.

Cementitious materials content, which has always been a concern to engineers and manufacturers, includes both cement and supplementary cementitious materials (SCMs), such as fly ash or slag cement. The key to a proper cementitious materials content is proper proportioning of the mixture, with consideration of all material properties, manufacturing, and curing processes. All types of cement have been used in the manufacture of concrete pipe, but Type II cement is typically used. The water-cementitious material ratio (*w/cm*) is typically between 0.33 and 0.53.

Both natural and manufactured aggregates are suitable for use in concrete pipe. Aggregates are a key element in producing quality concrete and, in turn, quality pipe. With regard to strength, durability, and performance, all aspects of the aggregates should be considered. These include gradation, absorption, specific gravity, hardness and, in some cases, alkalinity.

Storm-water management

Concrete pipe and box culverts are favored for storm sewers that service large tracts of land because concrete pipelines can reduce adverse impacts on water resources. Concrete pipelines fit within storm-water management plans because they can drain landscapes where excess runoff cannot be accommodated by percolation into the native soils and where constructed surfaces become impervious, inhibiting or limiting infiltration.

Similarly, precast concrete box culverts have become standard options for buried storm-water detention and retention systems that treat, control, and sometimes provide storm water for reuse for both neighborhood and new site construction. It is now commonplace for designers of storm-water management systems to include reinforced concrete box culverts because of the speed of installation and versatility of design to reduce the construction footprint and provide a structure that will last for the full design life of the project. Both concrete pipe and box culverts, along with pretreatment systems such as oil-sediment separators and energy dissipaters, are being used for a wide range of storm-water management applications. They can mimic the natural hydrology of an area while reducing pollutant loadings from storm-water discharges, reducing peak flow rates to minimize downstream channel erosion, and maintaining or restoring chemical, physical, and biological integrity of downstream waterways. For instance, concrete pipe is used widely in the Rio Grande Valley of Texas for irrigating croplands and conserving water that could be lost through evaporation from open channels.

Precast concrete pipe and box culverts are commonly used for underground storage of runoff that can be used for irrigation or part of a retention system of treated storm water and snow melt connected to oil sediment separators using precast concrete pipe, manholes, and box components. Concrete detention and retention systems are used to reduce pollutant loadings in surface water bodies and to help restore local hydraulic regimes to pre-urban development. Specially designed concrete pipe and boxes with internal baffles can reduce the energy of storm-water flow for discharge into streams, rivers, and lakes with reduced or no erosion near the outfall. Concrete pipe and box culvert producers have manufactured perforated concrete pipe and three-sided box culverts to help recharge aquifers with storm water channeled from urban areas with impervious streetscapes and parking areas.

Pipe joints

Concrete pipe and box culverts offer a variety of joints, from soil-tight to pressure joints. They are not affected by the type of backfill used for the installation. Joint performance should be demonstrated in the plant before pipe installation, and joint integrity can be field tested in a variety of ways. With concrete pipe, deflection will not compromise field joint test capability. The cross-sectional rigidity of concrete pipe makes joint assembly a simple operation. Rigid joint integrity will minimize the likelihood of embedment intrusion and subsidence of overfill, often referenced as infiltration.

Contamination and potential leaks are controlled by proper joints. The following details are provided as information for the specifier:

- Gasketed, leak-resistant reinforced concrete pipe joints that withstand a minimum hydrostatic internal head of 13 psi (90 kPa) (ASTM C443-05ae1 or C1628-06 [ASTM International 2005, 2006]); and
- The types of concrete pipe joints, including O-ring gaskets, profile gaskets, and mortar and mastic joints:
  - O-Ring gaskets are used on all sanitary and some storm-reinforced concrete pipe where leak-resistant joints are required. These gaskets may be used in joints following ASTM C443-05ae1, C1628-06, or C361-08 (ASTM International 2005, 2006, 2008) for low-head pressure applications.
  - Profile gaskets are used on storm-water culverts and reinforced concrete pipe storm and sanitary sewers. Pipe is produced with a single offset spigot joint according to ASTM C443-05ae1 or C1628-06 (ASTM International 2005, 2006).
  - Mortar or mastic joints are used for storm sewers, culverts, and horizontal elliptical reinforced concrete pipe. Mortar or mastic is applied to the bottom half of the bell end and to the top half of the adjoining spigot. Mastic and butyl sealants are applied in accordance with ASTM C990-09 (ASTM International 2009).
  - In some applications, a quality joint may be a wrap applied to the external surface of the joint. These may be specified in accordance with ASTM C877-08 (ASTM International 2008).

Human factors and living/working environment

Sustainable development places emphasis on the design and construction elements that bring buildings together into a neighborhood, and relate the neighborhood to its larger region and landscape. Developers are required to evaluate where they build, and how they build to preserve environmentally sensitive areas and accommodate pedestrian traffic that involves jobs, education, services, amenities, and public transit. Concrete pipelines and buried storm-water management and treatment systems have a significant place in determining construction elements and best practices.

Projects may constitute whole neighborhoods, fractions of neighborhoods, or multiple neighborhoods. Smaller infill projects that are single use, but complement existing neighboring uses, should be able to earn certification as well as larger and mixed-use developments. All of these development types are ideal for concrete pipe and box culvert applications. Reinforced concrete pipe and box culverts offer a complete solution for comprehensive storm-water management plans to meet infiltration, water reuse, detention, and evapotranspiration criterion that is required for sustainable development. Once properly installed, these sewers require little maintenance until they reach the end of their service life, which may extend well beyond the design life of a neighborhood development.

Unlike plastic products or products that need to be coated, concrete does not give off volatile organic compound (VOC) emissions.

Security and safety

Fires do occur in sewers and storm drains. Unlike thermoplastic conduits, concrete pipe and box culverts will not burn or melt. This is important for the planning of road and highway cross drains in urban areas and remote locations that are heavily forested. Concrete pipe and box culverts are a wise choice for construction site safety, public safety (fire and toxic fumes hazard), and homeland security.

In addition to the possible loss of the pipe and the associated infrastructure, the owner and designer should consider the danger of flames and hazardous fumes to the general public and firefighters. The inconvenience suffered by the public and the loss of revenue to businesses during roadway repair are also major concerns, not to mention the liability facing the owner, contractor, and design engineer that chooses flammable pipe. The flammability of buried pipelines and culverts is a serious issue. Besides vandalism, fuel spills, brush fires, and other means of ignition should be considered. The examples that follow show how specifying concrete pipe can limit liability in the case of fire:

- In October 2000, in Fort Worth, TX, an 8000 gal. (30,000 L) gasoline tanker exploded. According to the Fort Worth Star-Telegram, "A gasoline tank truck toppled over and exploded during morning rush hour… shooting flames two stories high into the sky, dumping a burning river of gasoline into city storm sewers." If this pipe had been a flammable pipe, such as HDPE (high-density polyethylene) or bituminous/polymer-coated metal pipe, it could have destroyed the pipe, along with the neighborhood. Luckily, the pipe was concrete, and no damage occurred;
- On a construction site in Washington County, PA, a fire started in a 48 in. (1.2 m) HDPE pipe at an outfall near the edge of the property. The fire damaged 135 ft (41 m) of pipe, and was extinguished when the pipe collapsed and cut off the air supply. The fire did not affect a 48 in. (1.2 m) reinforced concrete pipe upstream from the HDPE pipe;
- Children near Tucson, AZ, found themselves in a dangerous situation while playing with fire in an HDPE pipe. Not only was the pipe destroyed by fire, but the sidewalk, roadway, and other surrounding structures were devastated as a result of the pipe failure. The blazing HDPE pipe was near a 4 in. (100 mm) diameter gas main that could have ignited, causing a devastating and potentially lethal explosion; and
- In Blytheville, AK, children found themselves in a similar situation when they discovered an accessible end to an HDPE pipe, and started a fire. The fire destroyed 10 ft (3 m) of the 54 in. (1370 mm) diameter pipe. The fill above the pipe collapsed and extinguished the fire. Fortunately, the children were not inside. This pipe was repaired with concrete collars around the joints.

Concrete pipe and box culverts do not burn or rust, are not affected by ultraviolet (UV) light, gain strength over time, and have an estimated service life of 100 years or more. The cost in time, money, and resources to dig up and replace deteriorated pipe is very high, so the extended service life from concrete is extremely beneficial.

Reduce, reuse, recycle

Like other concrete discussed in this part, concrete pipes use SCMs and recycled steel reinforcement. Pipelines, and particularly culverts, are often used in temporary applications to facilitate drainage during construction. While designers often try to minimize the cost of these facilities, one of the overlooked components is the salvage value of the pipe. The salvage value of pipe is closely related to its inherent strength and ability to survive the abuse of installation and removal.

The rigid nature of concrete pipe and box culverts makes them ideal for removal and replacement. In terms of life-cycle costs, it is prudent to account for the salvage value of the pipe when planning a temporary line for drainage. The benefit of salvaging concrete pipe does not stop on the construction site. There are projects where concrete pipe and box culverts have been excavated in industrial areas after decades of use, cleaned, and reinstalled to continue performing as storm sewer pipe.

Economic impact

A comparison of the initial hard cost of materials is only the first step to determine where the greatest value lies. There is an array of costs that arise after the initial purchase that can profoundly affect a project's bottom line. Selecting pipe materials best suited for service as a storm sewer, culvert, sanitary sewer, or small bridge replacement is of primary importance to the design engineer. Selection is based on hydraulic efficiency, structural integrity, durability, and cost. On many projects when alternate materials are bid, selection is too often based on initial cost. The pipe material with the lowest first cost, however, may not be the most economical selection for the design life of the project. A design engineer should consider the pipe service life and installation requirements, including bedding and backfill.

The application of least (life cycle) cost analysis to road and drainage projects has increased dramatically in recent years. Local and state governments have increasingly included some type of analysis in their material selection process. The importance of considering the future of a facility during the design phase has been made clear by the multitude of problems many authorities are facing as our infrastructure deteriorates. In many instances, engineers and executive officers need to repair and replace integral sections of infrastructure that have experienced premature degradation. According to the U.S. Army Corps of Engineers, selection of all systems, components, and materials for civil works projects are based on their long-term performance, including a life-cycle cost analysis. It is policy that the design engineers are responsible for implementing life-cycle design concepts into the project development process.

ASTM C1131-95(2007) (ASTM International 2007) covers procedures for using life-cycle analysis (LCA) techniques to evaluate alternative pipeline materials, structures, or systems that satisfy the same functional requirement. The LCA technique evaluates the present value constant dollar costs to install and maintain alternative drainage systems, including planning, engineering, construction, maintenance, rehabilitation and replacement, and cost deductions for any residual value at the end of the proposed project design life. The decision maker, using the results of the LCA, can then readily identify the alternative with the lowest total cost based on the present value of all initial and future costs. The American Concrete Pipe Association (ACPA) has used ASTM C1131-95(2007) (ASTM International 2007) to develop a comprehensive LCA practice that eliminates unreliable assumptions, resulting in a readily usable and accurate design aid. The practice uses the well-established economic principles of present value that have been used by economists and other professionals for decades. The method does require certain assumptions, however, regarding future interest and inflation trends.

First cost is only one of the nine factors that influence a proper economic analysis, and first cost may be the least important factor if there are high-maintenance costs or if the pipe material or system ever has to be replaced during the design life of the project. The effective cost of a material is its total cost, in today's dollars, that includes first cost, any replacement costs during the project design life, and any residual value at the end of the project design life.

Project design life

In regard to project design life, a review of all published culvert surveys and current state practices published in the National Cooperative Highway Research Program (NCHRP) *Synthesis* 254, "Service Life of Drainage Pipe," (NCHRP 1998) defines service life by the number of years of relatively maintenance-free performance. The synthesis states that a high level of maintenance may justify replacement before failure occurs. The synthesis also offers guidelines to determine required project service lives for culverts under primary and secondary highways. Based on the guide recommendations, up to 50 years of relatively maintenance-free performance should be required for culverts on secondary road facilities, and up to 100 years for higher-type facilities, such as primary and interstate highways and all storm and sanitary sewers.

Material service life

Once the project design life is established, the proven service life of the pipe material or system should be evaluated. Service life is the number of years of service a material, system, or structure will provide before rehabilitation or replacement is required. Numerous culvert condition surveys, dating back more than 75 years, have been conducted in the U.S. by major, impartial specifying agencies such as the Federal Highway Administration, Soil Conservation Service, Bureau of Reclamation, U.S. Army Corp of Engineers, and several state DOTs. Sewer condition surveys have also been conducted by local jurisdictions, municipalities, consulting engineers, and universities.

According to the U.S. Army Corps of Engineers, concrete pipe has a service life of 70 to 100 years. Corrugated metal pipe may obtain up to a 50-year service life with the use of coatings. HDPE pipe is categorized as plastic pipe, and according to the U.S. Army Corps of Engineers, the designer should not expect a material service life greater than 50 years for any plastic pipe. HDPE pipes share the same characteristics as other plastic pipes: they are lightweight and flexible. Their service life greatly depends on the installation and surrounding soil of the embankment, which will add to the initial cost of the pipe. Other factors that affect the service life of HDPE pipe include the flammability of polyethylene and UV sensitivity. The U.S. Army Corps of Engineers states that the long-term performance of aluminum pipe is difficult to predict because of a short history of use. The designer should not expect a material service life greater than 50 years. The residual value of the pipe should also be considered in the LCA.

Concrete pipe and box culverts cost less than plastic or metal pipe to install, inspect, and test. Concrete also provides lower ongoing maintenance costs, and reduces risk of failure, early replacement, or liability to the public. Costs for crews to repair and replace failed pipelines are enormous, and puts an undue burden on the public. Concrete pipe and box culverts are the strongest drainage product available, the most hydraulically efficient, and have great current and future value as an infrastructure asset.

Compatibility with other innovative strategies

Concrete pipe and box culverts, as well as other concrete products, are environmentally friendly, do not leach harmful VOCs or other chemicals into the soil, are noncombustible, and have no off-gassing. Properly designed concrete storm water systems control flooding and the spread of water-borne diseases.

Concrete pipe and box culverts have been used successfully to conserve habitat, wetlands, and water bodies with the casting of internal baffles or dissipaters to reduce the energy of flowing water before it discharges into receiving lakes and streams. Such systems have been used for storm sewers, intermittent streams, and creeks enclosed in culverts for road crossings. Precast concrete culverts can be three-sided, leaving the natural ecosystems of the stream intact and accommodating aquifer recharge, or cast with artificial bases to facilitate the movement of aquatic life through the culverts so that migration and spawning characteristics of an ecosystem can be maintained. Quick installation of precast concrete pipe and box culverts reduces the impact on the habitat during construction, and ensures long service life with little maintenance to avoid disturbing habitat, wetlands, and water bodies for periods of 100 years and more. Precast boxes have been used successfully for constructing aquatic habitat in harbors while providing structures for piers, walls, or jetties to manage currents.

Reinforced concrete pipe and box culverts have been used successfully in brownfield development in deep buries or in an environment of contaminated soils. Concrete mixtures and the long service life of precast concrete products ensure low maintenance of a sewer, and minimal disturbance of soils for the design life of a project. Concrete pipe and box culvert installations located within brownfields have been tested for continued performance and left in the installed condition for the redevelopment of the site. Reinforced concrete pipe and box culverts are a compatible infrastructure material for the redevelopment of brownfield sites.

Figures 3.53 to 3.58 show various concrete pipe applications.

Fig. 3.53

Fig. 3.54

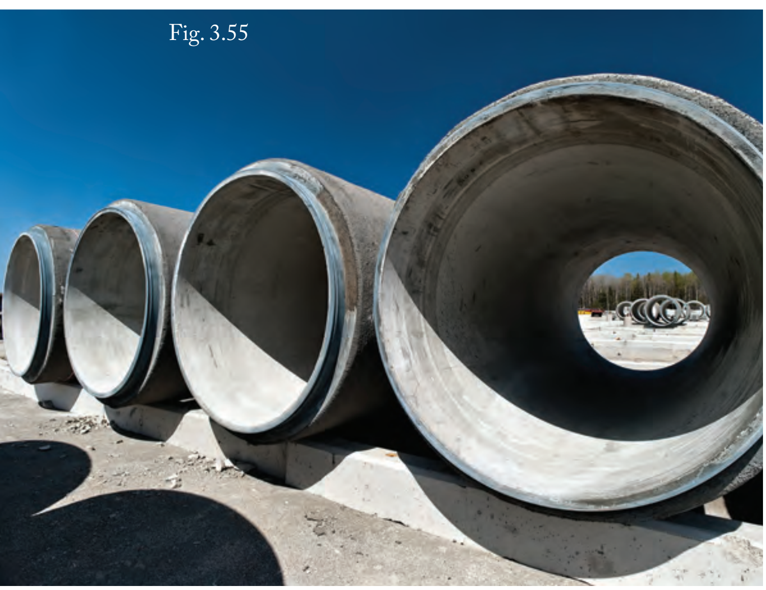


Fig. 3.55

Fig. 3.56

Fig. 3.57

Fig. 3.58

Pipe Top Sustainability Benefits

The American Concrete Pressure Pipe Association and their member company, Hanson Pressure Pipe, contributed content for the top ten via the company's sustainability Web site. All other material in this chapter is contributed by the American Concrete Pipe Association (ACPA).

- Full recycling of all pipe materials (concrete and steel) at the end of the service life (which often exceeds 100 years).
- Inherent strength of the pipe does not require special backfill material (native soil can be used rather than importing material).
- Minimizes surrounding contamination; less likely to leak than other pipe materials.
- Locally manufactured.
- Does not release chemicals into the surroundings.
- Energy conservation through long service life, lower energy footprint.
- Resilient: particularly against terrorist attacks and natural disasters such as fires, hurricanes, tornadoes, and floods.
- Materials efficiency: can use regional and recycled materials.

Resources

ACPA and ACPPA member, Hanson Pressure Pipe, sustainability site:
www.hansonpressurepipe.com

"Evaluation of HDPE Pipelines Structural Performance"
http://www.uta.edu/ce/aareports2.php

The Economic Costs of Culvert Failures
by Joseph Perrin Jr. and Chintan S. Jhaveri
Prepared for the Transportation Research Board, January 2004

Bell (groove)—The portion of the end of a pipe that overlaps a portion of the end of an adjoining pipe to form a connection.

Box culvert—A reinforced concrete pipe with a rectangular cross section. A culvert is a pipeline intended to convey water under a highway, road, slab, railroad, or other similar facility.

Infiltration—The flow that enters a pipeline through its connections, joints, and appurtenances, with the flow coming from sources outside of the sewer system. One of these outside sources is groundwater (typically in reference to sanitary sewer pipe).

Joint—A connection of two pipeline components, usually pipes, manholes, or box section ends, to continue the flow. Joints can be made by several methods and materials.

Storm sewer—A pipeline that is intended to collect and convey storm water.

Chapter 20—Precast

Sustainable attributes

Many of the applications covered in Part 3 use precast concrete. These applications highlight sustainable attributes, such as thermal mass and storm-water management. This chapter focuses on precast specific attributes not summarized elsewhere. Three case studies are included to highlight precast benefits of quick construction, small carbon footprint, energy efficient design, and use of local materials.

Carbon footprint

The carbon footprint issues specific to precast concrete are based primarily on the reduction of materials due to efficiency and quality control at the precasting facility

- Smaller amounts of concrete are needed (and create less waste) because more precise mixture proportions are possible along with tighter tolerances;
- Excess concrete can be used at the plant for improvement projects or for casting other elements for a different project;
- Reusable forms are the standard because precast units ideally are very repetitive to lower costs;
- Time for on-site construction is minimized because there is no delay waiting for concrete strength gain on site; and
- Tighter tolerances result in a better product throughout, making it easier to create thinner precast products that would ultimately use less concrete.

Precast Top Sustainability Benefits

- Precast concrete components can be disassembled and reused, or recycled.
- No staging or on-site formwork is required, thus causing minimal site disruption and waste, and maximizing quality control.
- Precast manufacture provides opportunity for reduced construction waste.
- Prestressed components allow optimization (and often minimization) of section sizes and materials used.
- Solar reflectance can be maximized, thus minimizing solar heat gain.
- Indoor air quality: opportunity for no/low volatile organic compounds (VOCs).
- Plant-controlled production can greatly increase service life to over 100 years.
- Precast concrete panels minimize air and moisture infiltration, and their thermal mass helps control cooling and heating loads.
- Resilient: particularly against terrorist attacks and natural disasters such as fires, hurricanes, tornadoes, and floods.
- Materials efficiency: can use regional and recycled materials.

Longevity and life cycle

The quality control that is achievable at the precast facility helps ensure the best possible service life. Variables that affect the final quality of the concrete, such as temperature, humidity, wind, and consistent materials, are much more controllable at a precast facility.

Storm-water management

Precast products contribute in a variety of ways toward an environmentally friendly storm-water management strategy. These products vary greatly, from precast pipes and box culverts (Chapter 19) to individual hardscape components (Chapter 16).

Human factors and living/working environment

The reduced waste, dust, and disruption on site and near the site are a significant consideration for the local area. Construction with precast elements can be very rapid, particularly with the use of large members.

Reduce, reuse, recycle

A key factor in building reuse is the durability of the original structure. Precast concrete panels provide a long service life due to their durable and low-maintenance concrete surfaces. A precast concrete shell can be left in place when the building interior is renovated. Annual maintenance should include inspection and, if necessary, repair of sealant material. Modular and sandwich panel construction with concrete exterior and interior walls provide long-term durability, both inside and out. As with other concrete, when the product has reached the end of its service life, it can be crushed and reused. The steel can also be recycled.

Compatibility with other innovative strategies

Slab-integrated radiant air conditioning (or heating) systems can utilize standard precast sections such as hollow core plank as part of the cooling/heating system (often called thermo-active slabs). These systems can capture, store, and release heating/cooling energy on demand, thus reducing or eliminating the need for providing heating/cooling from non-renewable sources. The system takes full advantage of the thermal mass of the concrete plank as well as its hollow core geometry. Figure 3.59 shows the basics of the system by Termo-Build. Figure 3.60 shows a schematic of the full system as implemented in a building.

The air passes through loops between the hollow core areas (with concrete plugs on the end of the voids) and then comes out of a diffuser. Additional lines such as power, lighting, and telephone can run through the two exterior voids, leaving the interior voids free for the air system. As air travels through the voids in the concrete slabs, energy is absorbed and transferred to the structure. Prefabricated ceiling panels, pipes, tubes, etc are not needed with this system.

Resilience with respect to climate change

Precast concrete is highly resistant to rain penetration and wind-blown debris, offering excellent protection during extreme weather. Like other concrete components, it will also not catch fire or burn.

Case study

Port of San Diego floating dock

When a wooden floating dock in the Port of San Diego, San Diego, CA, (Fig. 3.61) had deteriorated to the point of having to be torn down, the owners chose to replace it with a floating dock assembled from precast concrete modules, the durability offered by the precast dock was a key consideration, and the modular design allowed a few standard-sized sections to be used in the creation of a variety of configurations.

The new precast dock was designed to withstand a 3 ft (2 m) wave height with a period of 3.1 seconds. The dock uses a system of 50 wave-attenuation panels to calm the water. The system is so stable that the dock was the first wheelchair-accessible dock on the bay.

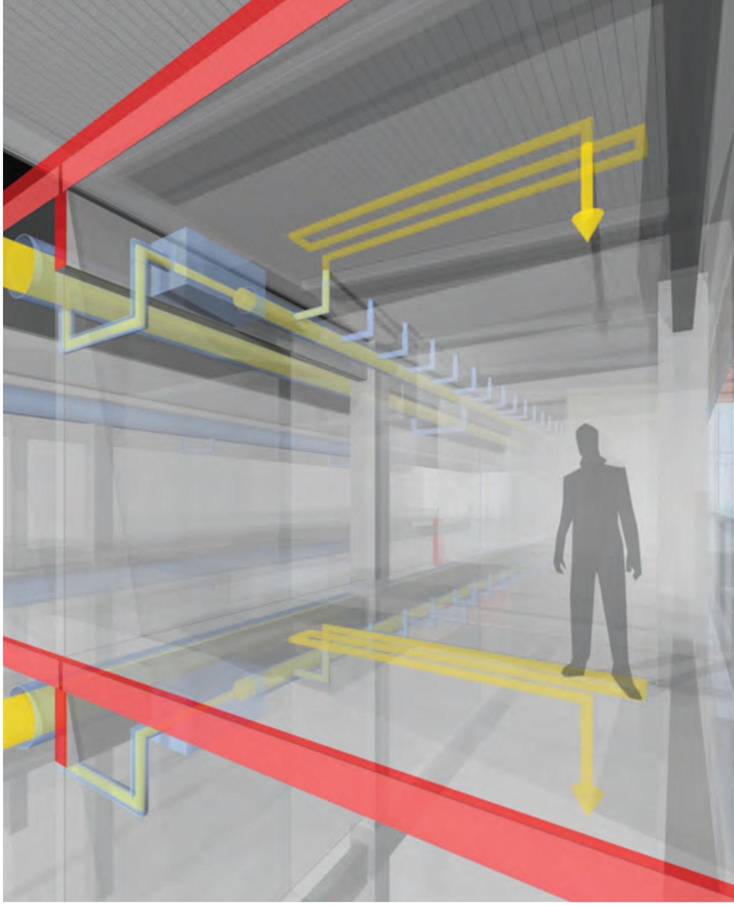


Fig 3.59—Basics of the TermoBuild system. *Photo courtesy of TermoBuild*

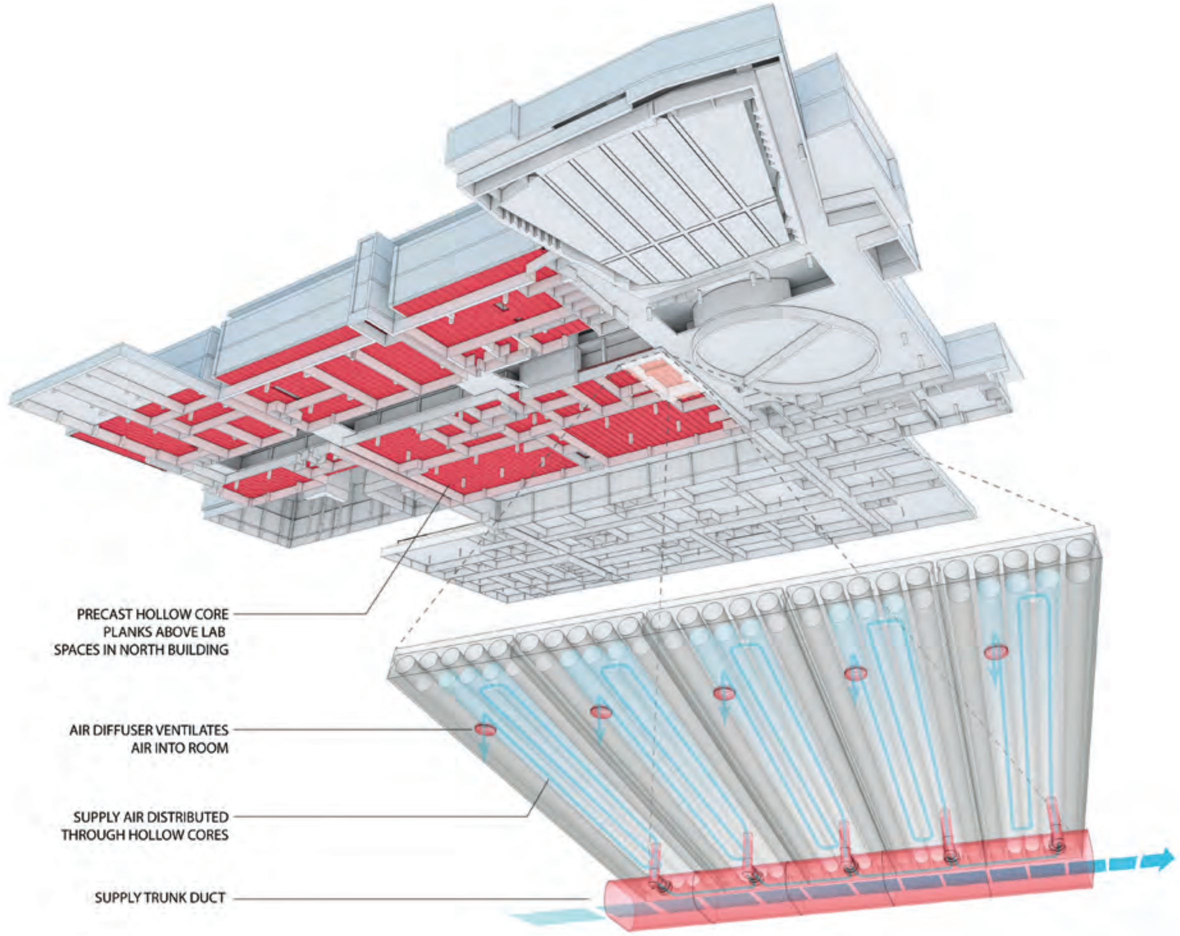


Fig 3.60—Full TermoBuild system implemented in a building. *Photo courtesy of TermoBuild*

The dock system includes nine monolithic precast/prestressed concrete dock sections that are 5 to 12 ft (1.5 to 3.7 m) wide, 3 ft (1 m) tall, and up to 60 ft (18.3 m) long. The sections weigh up to 55,000 lb (25,000 kg) each. The 50 precast wave-attenuator panels are attached by rods to the outboard side of the dock system. The precast sections were constructed of concrete around a foam core. The precast portion of the project was assembled in 2 weeks, and the mechanical portion (including electrical and plumbing) took an additional month.

Precast product examples

Several precast products are highlighted in other chapters in Part 3 of this book—in fact, the majority of the applications have a precast option. This section highlights some of the products that are not specifically covered in other chapters.

Agricultural products

Precast concrete products can withstand the most extreme weather conditions, and will hold up for many decades of constant use. Products include: bunker silos, cattle feed bunks, cattle guards (Fig. 3.62), agricultural fencing and H-bunks, J-bunks (Fig. 3.63), livestock slats, livestock watering troughs, and other agricultural products.

Barriers

Security barriers help protect people in a variety of ways, and enhance the living/working environment. Traffic barriers are used on highways and streets during construction to keep roadways safer for both motorists and construction workers. Precast barrier components, such as oversized flower pots (Fig. 3.64), are being used as natural barriers against terrorist threats. They are an easy addition to keep automobiles from bringing a potential bomb near a building, while still bringing beauty to the site.

Cisterns

Precast cisterns help provide life safety for fire suppression in rural areas where there is no public water system. They can also provide captured rainwater for reuse in irrigation, or water for use in innovative wastewater technologies, such as use in flushing toilets and urinals.

Grease interceptor

Precast concrete grease interceptors (Fig. 3.65) efficiently remove fats, oils, and greases from the waste stream by bringing the water to acceptable effluent standards before discharging it into a sanitary sewer system.

The grease interceptors are easy to maintain, and large enough to hold considerable amounts of grease for sufficient retention.

Hazardous materials containment

The storage of hazardous material, whether short-term or long-term, is an increasingly important

Fig. 3.61—Port of San Diego precast modules. *Photo courtesy of National Precast Concrete Association*

Fig. 3.62—Precast cattle guard.
Photo courtesy of National Precast Concrete Association

Fig. 3.63—Precast J-bunk feed trough.
Photo courtesy of National Precast Concrete Association

Fig. 3.64—Precast planters and barriers. *Photo courtesy of National Precast Concrete Association*

Fig. 3.65—Precast grease interceptor. *Photo courtesy of National Precast Concrete Association*

environmental issue, calling for containers that not only seal in the materials, but are strong enough to stand up to natural disasters or terrorist attacks. Precast concrete products can be designed in all sizes and shapes to meet specifications to protect both the environment and the population. Products include: fuel storage vaults, spill containment products, and a variety of other hazardous material containment elements.

Lift stations

Because precast concrete lift stations are manufactured well in advance of installation, they are ready for transportation to the job site at a moment's notice. Trained technicians are capable of installing and testing pumps and monitoring equipment in a controlled environment before the lift station ever reaches the job site. Once on site, the modular components are quickly set with a crane and a small crew. Backfilling can begin immediately after inlet and outlet pipe connections are made. Also, in contrast to other materials, precast concrete is less susceptible to vibratory damage while the surrounding soil is backfilled and compacted.

Manholes

Precast concrete manholes (Fig. 3.66) can be easily installed on demand and immediately backfilled; there is no need to wait for concrete or mortar to cure at the job site. Contractors are familiar with how to handle precast concrete manholes, and can easily install them. Standard sealants and flexible joints are vital to water-tightness.

Retaining walls

Precast retaining walls can help with surface water management because they help reduce steep slope water runoff, which will also help control soil erosion.

- **Modular block walls:** Modular block (Fig. 3.67), or segmental, retaining walls employ interlocking concrete units that tie back into the earth to efficiently resist loads. These pre-engineered modular systems are an attractive, economical, and durable alternative to stone or poured concrete retaining walls. The inherent design flexibility can accommodate a wide variety of site constraints, project sizes, and aesthetic preferences.
- **Large precast modular block—reinforced wall:** Large precast modular block systems are typically built from individual large concrete blocks, and are generally stacked in a running bond fashion. Large precast modular block (reinforced wall) systems incorporate soil reinforcement with these large precast blocks, given the height of the wall. The soil reinforcement is generally a form of a geo-grid attached to the large blocks either frictionally or mechanically.
- **Mechanically stabilized earth (MSE) systems:** An MSE system is classified as a gravity retaining wall that is designed to withstand lateral earth and water

pressures, and any live and dead load surcharges. MSE walls are built from individual panel sections. They have interlocking panels, and are supported by steel straps that are mechanically attached to the back of the panel and extend back from the panel into the retained soil, resulting in a reinforcing zone behind the wall.

- **Large precast modular block—unreinforced/ gravity wall:** Large reinforced precast modular walls are built from individual large concrete blocks and generally stacked in a running bond fashion. Large precast modular block systems usually have an interlocking feature or shear key mechanism that locks one coarse of block to the next. Large precast modular block systems retain the soil by virtue of their size and weight. There is typically no need for additional soil reinforcement.

Site furnishings

Site furnishings (Fig. 3.68) include all precast site components such as decorative fences, trash receptacles, benches, and planters.

Soundwalls

With growing traffic and expanding communities, road noise has become a problem for communities and

Fig. 3.66—Precast manhole cover. *Photo courtesy of National Precast Concrete Association*

Fig. 3.67—Precast modular block wall. *Photo courtesy of National Precast Concrete Association*

Fig. 3.68—Precast concrete fence. *Photo courtesy of National Precast Concrete Association*

Fig. 3.69—Precast sound wall with decorative features. *Photo courtesy of National Precast Concrete Association*

Fig. 3.70—Precast sound wall during placement. *Photo courtesy of National Precast Concrete Association*

households near major roads. Precast concrete sound walls (Fig. 3.69 and 3.70) can be designed to blend in with a city's architecture and local topography, or even to capture a community's theme or identity. Reflective sound walls can reduce the perceived noise by as much as half, while absorptive treatments have been found to further reduce noise pollution.

Case studies

Melrose Commons, Site 5, Bronx, NY

This five-story, multi-family housing project (Fig. 3.71) highlights the benefits of precast concrete use in a small footprint with energy-efficient construction. The site constraints for this affordable housing project were very tight, but the needs were met with an all-precast concrete structure. The owner chose to have the structure designed with precast concrete to take advantage of many sustainability benefits precast can offer: durability, recycled content, local availability, thermal mass with minimal air infiltration, and no on-site material waste. The precast members also provided a significant reduction in outside noise for the occupants, and worked well with large window openings to allow excellent daylighting of interior spaces. The result is a safe, aesthetically pleasing, quiet environment for the tenants in the building.

The building also includes wind-powered turbine engines that are mounted on the precast roof parapet. The electricity generated is used for the building's common areas, and greatly reduces energy consumption.

Structure specifics and associated sustainability benefits:

- The entire precast structure was erected in just 5 weeks;
- Hollow core units for floors and roof: the ventilation system exhausts air horizontally through the hollow cores, saving floor space and reducing mechanical installation costs;
- Aesthetic exterior wall panels: two types, one has reveals with a light sandblast to emulate stone, the other has embedded thin brick and inset medallions; color additives were also used to complement the brick colors;
- Window and door headers and sills were installed at the precaster's plant;
- The number of exterior joints was minimized (reduced air and moisture infiltration);
- Reduced heating, ventilating, air conditioning (HVAC) loads: thermal mass reduced temperature spikes;
- Reduced curing energy through curing in the enclosed precast plant;
- Reusable steel formwork was used for the precast hollow-core units;
- Long clear spans facilitated potential reuse or remodeling;
- Mold-resistant;
- No exterior paint or coatings were needed; and

Fig. 3.71—Melrose Commons Site 5. *Photo courtesy of Mike Smith, AIA Equus Designs*

- Project numbers for the precast concrete were as follows: 10% recycled content, 85% regionally produced, 30% reduction in construction time.

915 Walnut Parking Structure, Kansas City, MO

This 106,000 ft^2 (9900 m^2), seven-level parking structure (Fig. 3.72) provides 325 parking spaces for the adjacent condominiums. An all-precast solution was used to meet the owner's needs for a highly sustainable design that would attract attention as a green project while also having tight budget and schedule constraints. The focal point of the parking structure is the 16,000 ft^2 (1500 m^2) rooftop garden. The garden provides a beautiful and safe spot for residents to enjoy the outdoors, and has become a popular place in the community for tours, weddings, and other special events.

The site is located in the downtown area between two existing buildings with irregular footprints. The controlled precast environment enabled the elements to be cast with the tolerances required to build within 2 to 3 in. (50 to 75 mm) of the irregularly shaped existing structures. The components were finished at the precast yard and then delivered to the site, reducing site impact and construction time, with a total cost reduction of 25%.

The additional loading from the vegetation, soil, and estimates for future mature trees was supported through use of 8 in. (204 mm) double-tee sections. The green roof not only serves the practical purpose of reducing the heat island effect, reducing runoff volume, and covering all of the parking spaces in the garage, but it also has become an icon as the largest elevated garden in the city. The structure includes all locally produced precast components with recycled materials in the concrete and steel.

Intensive Management Unit, Monroe Correctional Complex, Monroe, WA

The 140,000 ft^2 (13,000 m^2) Monroe correctional facility (Fig. 3.73) houses inmates classified as intensive management status (IMS) and segregation management status (SMS) with special needs. Each building has

Fig. 3.72—915 Walnut Parking Structure. *Photo courtesy of Precast/Prestressed Concrete Institute*

100 single-occupancy maximum-security cells along with the necessary facilities that go along with running a complex of this size. Because of extreme security concerns, the structure has exterior walls of precast concrete sandwich panels, and all cells (including bunks, tables, and stools) are also precast concrete.

Specific sustainable benefits include:

- Energy savings were achieved with high R-value precast sandwich panels combined with efficient HVAC control systems. The panels were designed to exceed the baseline model energy code by a minimum of 25%, and use 27% less energy than comparable noncertified buildings;
- Parking stalls were minimized, and employees are encouraged to ride share, bike, or use alternate transportation;
- Storm water is retained in precast tanks and treated on site. The collected rainwater is used for inmate toilets, contributing to a 54% reduction in water consumption and a 58% reduction in potable water consumption as opposed to a comparable facility;
- The facility has natural lighting in over 75% of the occupied space; and
- The precast facility was located only 60 miles (97 km) from the job site, and local and recyclable materials were used in the precast construction.

Fig. 3.73—Monroe Correctional Complex. *Photo courtesy of Precast/Prestressed Concrete Institute*

Precast concrete—Term used for concrete cast in a location other than its final building position. This includes plant-manufactured concrete products (delivered on site as hardened concrete units for placement) and tilt-up concrete (details in Chapter 22).

Chapter 21—Shotcrete

Architects, engineers, developers, and contractors are under ever-growing pressure to use more efficient methods in construction. Shotcrete construction has many unique characteristics that substantially increase the sustainability aspects of both new construction and repair. Shotcrete, as shown in Fig. 3.74, enables key savings in labor, materials, material handling and construction time, as well as providing increased flexibility and efficiency in shapes and thicknesses.

As shotcrete is simply a method for placing concrete, shotcrete enjoys all the sustainability advantages of concrete as a building material including use of recycled materials, SCMs, and the very broad topics related to durability, reparability, etc. The sustainability advantages unique to shotcrete are inherent in the placement process.

The recently published U.S. Green Concrete Council book *The Sustainable Concrete Guide—Strategies and Examples* lists five key aspects that improve sustainability of buildings. Shotcrete can impact each of these key aspects as follows:

Improving functionality—Increased functionality means a more efficient structure to serve its intended purpose. Shotcrete allows great flexibility in structural shapes and efficiency. Shotcrete can easily provide variable section thicknesses to allow various sections of the structure to exactly match the structural requirements without use of excess material. Shotcrete also allows the architect or engineer to easily create non-flat sections to provide smooth transitions in the structure and maximize the use of space.

Ensuring longevity—The longer the usable life of a structure, the less the need for repair or replacement of the structure that would entail using more resources. Concrete as a material, properly designed and constructed is unmatched in its ability to provide durable structures. Shotcrete matches the durability of concrete, and often allows existing concrete structures to be efficiently and economically repaired to provide extended life with much less use of resources when compared to new replacement structures.

Enhancing occupant comfort—A more comfortable environment within a building increases productivity of the users, and thus adds to the efficiency of the structure's overall use. Thermal mass of concrete and shotcrete can help moderate inside temperatures. Naturally light color and the ability to provide a variety

Fig. 3.74—Shotcrete application. *Photos courtesy of American Shotcrete Association*

of finishes to exposed concrete surfaces can help to enhance natural lighting, and reduce use of other finishing materials. Shotcrete finishes can range from a smooth plaster-like finish to a faux-rock surface that looks like natural rock.

Reducing the use of resources—Reduction or elimination of formwork saves the natural resources needed to make the form and supporting structure (wood or steel), as well as the resources to move the formwork to and on the site. Additionally, concrete used in shotcrete is great for reusing many recycled materials, including supplementary cementitious materials such as fly ash or slag, or reused aggregates from crushed concrete. The ability to increase recycling means less material that ends up taking space in landfills and is essentially lost to future use. Also, the long-term durability of concrete means a much longer replacement cycle is needed, and thus resources are not used nearly as often as with other construction materials. The ability to provide variable thickness to exactly match the structural thickness means less material is needed.

Aesthetics—This aspect addresses the social component of sustainability. Visually pleasing structures can give an increased sense of community pride. Shotcrete can produce virtually any shape. It is like clay that an architect or engineer can mold to their creative vision. Combined with the wide variety of finishes available, the aesthetics of shotcrete are extensive and still provide the durability of concrete.

Specific Sustainability Aspects of Shotcrete

Formwork Reduction or Elimination

A detailed listing of the sustainability advantages of shotcrete is included in Table 3.4. Reviewing the table, the first and one of the most significant advantages are realized in formwork material savings. With the shotcrete process, the material is gunned or sprayed in place, so forming becomes unnecessary or is reduced by 50% with the use of one sided forms. This not only reduces or eliminates the amount of wood or other material used in forming, but also reduces or eliminates the milling and transportation environmental impact involved in providing the lumber on thousands upon thousands of construction sites. Where one-sided forms are required, the formwork design is greatly simplified and the materials required are significantly reduced because there is no need to design for internal pressure from fluid concrete within a form.

In overhead work, not only is the formwork eliminated, but the scaffolding and shoring required to support overhead forms is eliminated. This means less on-site labor, as well as on-site equipment to unload, move and load for shipping the forming and shoring materials.

In addition to the formwork materials resource savings, there is a tremendous amount of labor involved in the forming operations. Using shotcrete reduces or totally eliminates time and money expended on the building of forms, whalers, bracing, forming support structures, and the application of release agents. Due to the natural consolidation of concrete when placed via shotcrete, consolidation operations are also eliminated. Post placement formwork labor, including items such as form tie hole patching and cleaning of forms, are also significantly reduced or eliminated.

Construction Efficiency

This leads us to the closely related, but perhaps not as initially obvious, advantage of construction sequencing efficiency. The elimination of half or all formwork and its related operations, paired with the speed and flexibility of the placing of concrete via shotcrete, creates significant opportunities for reducing the construction time of a project. With new construction, the use of shotcrete to place vertical or overhead concrete surfaces often results in a time savings of 33 to 50%. Labor savings alone on repair applications can easily reach 50%.

Repair and Rehabilitation

The last area of note is repair or rehabilitation. Shotcrete is an excellent repair option for existing concrete structures. There are often times, when shotcrete is the only economically or logistically possible option due to limited or restricted access to use normally formed and cast concrete sections. Chapter 25 also includes additional information regarding the use of shotcrete in repair applications.

Creativity and Efficiency of Shotcrete Sections

Most normal formed and placed concrete uses flat surfaced shapes, as these are by far the easiest to form. Curved or even just tapered sections may be used in form and cast work, but the formwork is much more expensive to construct both in labor and materials. Using shotcrete allows total flexibility in shape and surface treatment. Variable thicknesses, curves, or virtually any combination of shapes are readily available to the designer who uses shotcrete construction without any of these additional formwork or labor costs. This is why shotcrete is used for free-form pools, faux-rock surfaces for fountains and zoo enclosures, and tapered walls of liquid storage concrete tanks.

Because the finished shotcrete surface is available immediately when placed, there is no question what the final finish will look like. Also, the finish is limited only by the creativity of the architect or engineer and the talents of the shotcrete contractor.

Summary

Shotcrete offers an exceptional number of placement sustainability advantages, while still enjoying all the sustainability advantages of the concrete material, for both new construction and repair/rehabilitation operations. This 100-year-old process offers the opportunity for

Shotcrete Top Sustainability Benefits

- Crane and other equipment savings or elimination.
- Labor savings of at least 50% in repair applications.
- New construction speed savings of 33 to 50%.
- Better bonding to the substrate enhances durability
- Adaptability to repair surfaces that are not cost-effective with other processes.
- Ability to access restricted space and difficult-to-reach areas, including overhead and underground.
- Complex shapes require very little, if any, formwork.
- Formwork does not have to be designed for internal pressures.
- Material savings through elimination/reduction of formwork.
- Speed of repair reduces or eliminates downtime.

material, labor and speed savings, all of which are critical sustainability advantages. Table 3.4 summarizes benefits/advantages of shotcrete.

Case studies

Atlantic Times Square Project, Monterey Park, CA

This large, mixed-use development project had an extremely tight construction schedule—the contractor had to place walls very quickly. As shown in Fig. 3.75, shotcrete provided the solution: walls used one-sided formwork, shotcrete was applied, and then the free surface was finished by hand. Forms were then moved to the next wall and reused. With a trailer pump on site twice a week, between 80 and 130 yd^3 (61 and 99 m^3) of concrete could be shot in an average 8- to 10-hour day.

The scale of the project was immense, with over 230,000 ft^2 (21,400 m^2) of retail and entertainment space that stretches a full city block adjacent to I-10. It includes three levels below grade, and six levels above grade. Traditionally, the walls would be cast-in-place concrete or masonry, but the contractor chose the speed of shotcrete for all of the concrete walls (interior and exterior) on the project. The reuse of forms and the need for only one formed face per wall also contributed to reducing the environmental impact. With crews working only from one side of the wall, congestion on the job site was also reduced.

Surrey 2010 Olympic Games Preparation Center, Vancouver, BC, Canada

This center played a prominent role in the 2010 Olympic Games in Vancouver as a training venue for Olympians and volunteers, as well as a central location for all recruitment and logistics. The project got off to a late start, so shortening construction time as much as possible was critical. The structure was architecturally intense, with curved top walls up to 40 ft (12 m) high and extensive reveals, recesses, and block-outs. The specified finish was a light sandblast and two coats of clear sealer, so quality finish was essential. The project was planned assuming 24/7 production to increase the chances of completing the project in the 6-week allotted time period (one quarter of the time typically allowed for this type of structure). Shotcrete was an integral part of the success of the project in terms of schedule and quality. The time from the first excavator bucket hitting the ground until structural completion was 3-1/2 weeks, without the need for 24/7 production or even the need for a second shift. The speed of construction was even more remarkable considering the 50-year record-breaking snowfall with up to 3 ft (0.9 m) of snow and subzero weather conditions for the entire duration of the project. All vertical portions of the project were placed with shotcrete, including the structural walls, building envelope, and architectural features. The tall walls were formed on one side to full height (up to 40 ft [12 m]); the use of shotcrete with one-sided forming on such tall walls with multiple block-outs reduced the amount of formwork to one-sixth of what would have been needed on a traditional placement. Figure 3.76 shows the center under construction.

CEMEX Bayano Plant No. 2 Line Expansion, Panama

CEMEX is one of the world's two largest cement companies, with a production capacity of approximately 86 million tons (78 million metric tons) of cement per year. In 2007, CEMEX announced it would construct a new kiln at its Cemento Bayano, S.A. plant in Panama to help meet the anticipated demand for additional cement due to the Panama Canal expansion project (a massive project expected to cost approximately $5.25 billion USD). As shown in Fig. 3.77, the Bayano plant, with the new expansion, has become one of the most modern, efficient, and environmentally friendly cement production facilities in the Americas. The plant expansion included construction of a 77,000 ton (70,000 metric ton) capacity clinker storage facility. Domes provide efficient and economical storage, and have become popular with major cement producers. Advantages include better containment and protection of stored materials, efficient use of land, strength, durability, and rapid construction.

For the Bayano dome, a ring pile cap was constructed that formed the base ring. A fabric form was attached to the base ring and inflated. The fabric was a durable single-ply roofing material that remains in place after completion of the dome to function as the finished roof membrane. After the form was inflated, a 2 in. (50 mm) layer of polyurethane foam was applied against the form's interior surface, and initial reinforcement steel is attached using fasteners embedded in the foam. All work was done in the controlled environment inside the dome. The first layers of shotcrete are sprayed to provide stiffness and strength to support the next

Table 3.4—Summary of shotcrete sustainable attributes

Shotcrete sustainability benefits/advantages	Carbon footprint reduction	Thermal transmission (*R*-values)	Thermal mass and operational energy	Longevity and life cycle	Storm-water management	Human factors and the living/working environment	Security and safety	Reduce, reuse, recycle	Economic impact	Resilience with respect to climate change	Compatibility with other innovative sustainability strategies
Recycled materials: same usage/benefits as cast-in-place concrete		**Same as concrete**	**Same as concrete**							**Same as concrete**	
Silica fume	X	—	—	X	—	—	—	X	—	—	X
Fly ash	X	—	—	X	—	—	—	X	X	—	X
Slag cement	X	—	—	X	—	—	—	X	X	—	X
Recycled aggregate—crushed brick use in refractory applications	X	—	—	X	—	—	—	X	X	—	X
Use of rebound in other applications: for example, soil stabilization, use in other products (for example, form blocks—aggregate)	X	—	—	X	—	—	—	X	X	—	X
Portland cement substitutes											
Limestone cements	X	—	—	—	—	—	—	X	X	—	X
Metakaolin	X	—	—	—	—	—	—	—	—	—	X
Wood/formwork material savings											
At least 50% savings, 100% on some applications. Repair is also 50 to 100%.	X	—	—	X	—	—	—	X	X	—	X
Wood and/or metal material savings	X	—	—	—	—	—	—	X	X	—	X
Transportation/milling cost savings	X	—	—	—	—	—	—	X	X	—	X
Disposal of used form material	X	—	—	—	—	—	—	X	X	—	X
Cleaning of forms	X	—	—	—	—	—	—	X	X	—	X
Reduction/elimination of form release agents' use	X	—	—	—	—	—	—	X	X	—	X
In one-sided forms—reduced thickness of form	X	—	—	—	—	—	—	X	X	—	X
Formwork does not have to be designed for internal pressures	X	—	—	—	—	—	—	X	X	—	X

Table 3.4—Summary of shotcrete sustainable attributes, cont.

Some one-sided forms can stay in place after construction	—	—	—	—	—	—	—	X	X	—	X
Complex shapes require very little if any formwork	X	—	—	—	—	—	—	X	X	—	X
Mining/tunnels—no formwork required	X	—	—	—	—	—	—	X	X	—	X
Crane time savings or elimination	X	—	—	—	—	X	—	X	X	—	X
Bracing savings/elimination	X	—	—	—	—	—	—	X	X	—	X
Speed/labor savings—(calculation or multiplier)											
Labor savings of approximately 50% in repair applications	X	—	—	—	—	—	—	—	X	—	X
New construction—speed savings of 33 to 50% (examples of savings)	X	—	—	—	—	—	—	—	X	—	X
Shortened construction time occupancy/access after repair	X	—	—	X	—	X	—	—	X	—	X
Usability in new construction	—	—	—	—	—	—	—	—	X	—	X
No form ties	X	—	—	—	—	—	—	—	X	—	X
No form tie hole patching	X	—	—	X	—	—	—	—	X	—	X
Walls are in final finish after shooting	X	—	—	X	—	—	—	—	X	—	X
Sequencing time savings/advantages—fill scheduling gaps with shotcrete placement	X	—	—	—	—	—	—	—	X	—	X
Reduced man hours	X	—	—	—	—	X	—	—	X	—	X
Economic impact											
Mixture design advantages resulting from placement compaction—thinner sections	X	—	—	X	—	—	—	X	X	—	X
More efficient and thinner structural sections—repair and new construction	X	—	—	X	—	—	—	X	X	—	X
Overall/bottom line savings due to time savings and reduced direct construction costs	X	—	—	—	—	—	—	X	X	—	X
Repair/strengthening/rehabilitation	—	—	—	—	—	—	—	—	—	—	—
Minimal (if any) formwork	X	—	—	X	—	X	—	X	X	—	X

Table 3.4—Summary of shotcrete sustainable attributes, cont.

Speed of repair reduces or eliminates downtime	X	—	—	X	—	X	—	X	X	—	X
Preservation of structures that could not otherwise be repaired	X	—	—	X	—	X	—	X	X	—	X
Seismic retrofits	X	—	—	X	—	X	X	X	X	—	X
Better bonding to the substrate—will enhance durability	X	—	—	X	—	—	—	—	X	—	X
Adaptability to surfaces that are unrepairable with other processes	X	—	—	X	—	X	—	X	X	—	X
Overhead placement quality and efficiency	X	—	—	X	—	—	—	—	X	—	—
Ability to access restricted space and difficult-to-reach areas	X	—	—	X	—	X	—	X	X	—	—

Table courtesy of American Shotcrete Association

Fig. 3.75—Placing shotcrete at the Atlantic Times Square Project in Monterey Park, CA. *Photo courtesy of American Shotcrete Association*

Fig. 3.76—The Surrey Olympic Games Center during construction. *Photo courtesy of American Shotcrete Association*

Fig. 3.77—CEMEX Bayano Plant No. 2 Line Expansion, Panama. *Photo courtesy of American Shotcrete Association*

mat of heavier structural reinforcing bars. As the shell thickness increased, heavier layers of shotcrete were applied in a single pass. Shotcrete was applied overhead in thinner layers than shotcrete applied to a vertical surface. The project was completed in approximately 4 months (on time and on budget).

Nozzleman—The craftsman that physically directs the placement of the shotcrete. The nozzleman is responsible for the quality of the placed shotcrete, and is an important member of a shotcrete crew. The nozzleman must have an understanding of the equipment's operation, safety procedures, and the material being placed. Critical to all applications of shotcrete is the knowledge and skill level of the nozzleman placing the shotcrete. In assessing nozzleman competency, a two-step qualification process has evolved. The ACI Shotcrete Nozzleman Certification is the industry-recognized credential for identifying individuals who possess the basic knowledge and skill level needed to apply shotcrete. For heavily congested projects, the nozzleman should possess current ACI Certification and be required to shoot test panels that simulate project conditions.

Nozzleman Certification is only one part of a larger process to secure a qualified and experienced shotcrete contractor. The process of qualifying a shotcrete contractor should include a thorough check of the shotcrete contractor's references and project work history, a thorough check of the project work history of the contractor's key personnel, and resumes of nozzlemen that are to participate on the project. Finally, current ACI Certification should be verified for the on-site nozzlemen.

Shotcrete—A process where concrete material is conveyed through a hose and pneumatically projected at high velocity onto a surface to achieve compaction. Shotcrete is used primarily in the construction of vertical and overhead surfaces. This process allows construction of walls and other structures using only a one-sided form. Tanks, swimming pools, tunnels, mines, sculptured rocks, structural walls, erosion control embankments, retaining walls, and shearwalls are all structures commonly built using shotcrete. In addition, a wide variety of repairs are done with shotcrete.

Dry-mix shotcrete—The process illustrated in Fig. 3.78 in which a dry mixture of cementitious materials and aggregates is conveyed pneumatically through a delivery hose at the end of which water is injected at a nozzle. All ingredients, except water, are thoroughly mixed together before being conveyed through the delivery hose. The cementitious materials and aggregate mixture is fed into a special mechanical feeder or gun, called the delivery equipment. The material is then carried by compressed air through the delivery hose to a nozzle body. The nozzle body has an interior water ring, where water is introduced under pressure and thoroughly mixed with the other ingredients. The material is shot from the nozzle at high velocity onto the receiving surface. Mixing occurs in the nozzle and as the material impacts the surface.

Gunite—A term that refers to dry-mix shotcrete. The term was once a proprietary trade name, but became a generic name in 1967.

Wet-mix shotcrete—The process illustrated in Fig. 3.79. It has all the ingredients—including cement, chemical and mineral admixtures, aggregate, and mixing water—thoroughly mixed together before being pumped into a delivery hose or pipeline. Compressed air is added at the nozzle to increase the material velocity. The mortar or concrete is then shot from the nozzle at high velocity onto the receiving surface.

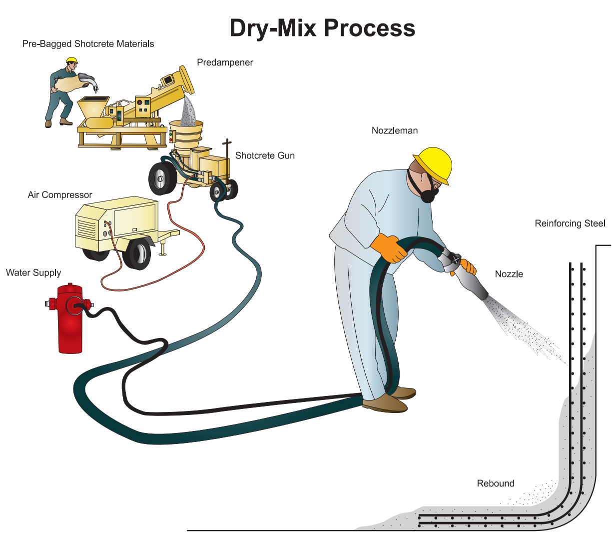


Fig. 3.78—Dry-mix shotcrete process. The dry mixture is conveyed pneumatically through the delivery hose, and water is added at the end nozzle. *Photo courtesy of American Shotcrete Association*

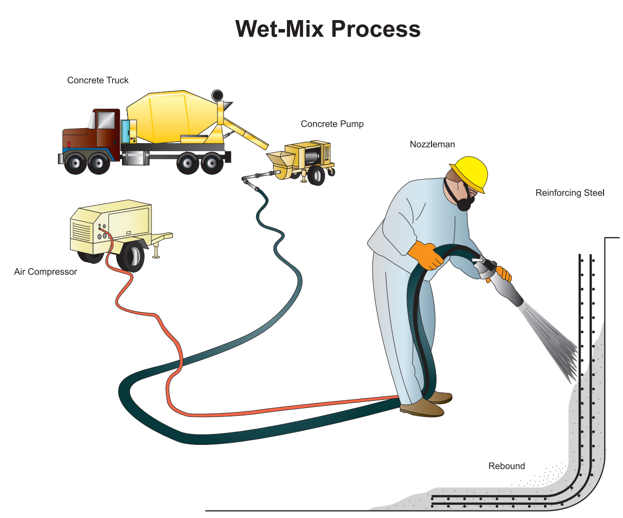


Fig. 3.79—Wet-mix shotcrete process. All ingredients are mixed together before being pumped through the delivery hose. Compressed air is added at the nozzle. *Photo courtesy of American Shotcrete Association*

Chapter 22—Tile roof

Sustainable attributes

Concrete roof tiles have proven to be a durable and sustainable roofing solution. They are available in various shapes, sizes, and colors to provide an aesthetic roof option that is resistant to large hail, wind, fire and other aggressive conditions that a roofing material may encounter during its lifetime—refer to Fig. 3.80 for a variety of concrete roof tile applications. Lighter-colored options are also effective for reducing heat-island effects. Concrete tile is also a very low-maintenance system.

Concrete tile roofing systems do not contain petroleum products that are used in traditional asphalt-based shingles. The waste from concrete tile production can be immediately recycled back into the manufacturing process and used tiles can also be recycled. Concrete tiles are Class A fire rated, and both concrete and clay tiles are resistant to hailstones as large as 2 in. (50 mm) in diameter.

Like other concrete products, concrete tile has thermal mass that can temper the effect of temperature extremes and offset the timing of temperature peaks in the building interior. Airspace around the tiles also creates natural ventilation to reduce heat transfer to the roof deck.

Tile Roof Top Sustainability Benefits

- Tile roofs have been tested according to FM4473 for hail resistance ratings. Concrete and clay tiles can resist damage from hailstones as large as 2 in. (50 mm).
- Durability: tile roofs are Class A fire resistant as a product and a system, and are designed and tested to meet Florida's 150 MPH wind speeds.
- Durability and longevity: centuries old tile roofs are still enduring today, meaning that tile roofs' long life reduces the need for reroofing that adds to landfills.
- Natural air ventilation under the tile creates a heat transfer barrier that can provide the benefit of a cooler house in the summer and a warmer house in the winter.
- Materials efficiency: can use regional and recycled materials.

Fig. 3.80—Concrete roof tiles are available in various shapes, sizes, and colors and provide protection against large hail, wind, fire, and other aggressive conditions. *Photo courtesy of Tile Roof Institute*

Chapter 23—Tilt-up

Sustainable attributes

Site-cast tilt-up concrete construction has had sustainable attributes since the inception of the tilt-up construction method. Improvements in the manufacturing of cement, the materials used in creating the panels, and the methods of handling and erecting panels have improved the standing of tilt-up construction as a sustainable construction method. A constant stream of new products continues to enhance the sustainable nature of tilt-up.

Carbon footprint

As with other concrete applications, the local acquisition of raw materials reduces transportation costs. Tilt-up panels are manufactured on site, so there is no additional cost to transport the final product. The sizes of tilt-up elements are typically much larger than those cast off-site because of transportation size and weight limitations. The larger element size results in fewer lifting operations, reducing transportation and fuel usage. Repetitive, large elements also contribute greatly to the speed of construction. Figure 3.81 shows a construction site with both casting and erection of the tilt-up panels.

Thermal transmission (*R*-values)

Insulation systems are available for tilt-up walls that significantly reduce thermal transmission of the concrete assembly. They include interior applied systems and sandwich walls. The most popular of the sandwich systems use nonconductive fiber composite ties and edge-to-edge extruded polystyrene insulation in thicknesses of 1.5 to 6 in. (38 to 150 mm) or thicker, which eliminate thermal bridging and deliver an extremely thermally efficient wall system. Figure 3.82 shows a tilt-up sandwich panel under construction.

Thermal mass and operational energy

Tilt-up construction offers the benefit of thermal mass to reduce energy consumption, with or without insulation. In temperate climates, energy use can be reduced by 25% or more compared with an uninsulated wall. In all climates, thermal mass combined with insulation can greatly reduce energy use. Thermal mass exposed to the interior of the structure provides a stabilizing effect on interior temperatures, improving comfort in the structure and reducing temperature swings. The net result is that heating and cooling

Fig. 3.81—Construction site with tilt-up panels during casting and erection. *Photo courtesy of Tilt-Up Concrete Association*

systems can often be down-sized when compared with systems with nonmassive walls. *The Sustainable Concrete Guide—Strategies and Examples* (Schokker 2010) provides a detailed discussion of thermal mass and thermal transmission.

The low permeability of solid concrete minimizes air infiltration and moisture penetration when compared with multi-layered and multi-jointed wall systems. The size of the wall elements (as large as 2950 ft^2 [7 m^2] without a joint) greatly reduces infiltration between adjacent wall elements. This helps decrease heat loss in cold climates, and heat gain (or loss of conditioned air) in hot, tropical climates.

High emissivity wall coating systems can further enhance the performance of a tilt-up structure in southern climates. The engineered coating reflects more of the sun's energy instead of absorbing it. This will help keep the tilt-up panels cooler, providing lower daily diurnal temperature swings. Likewise, the coatings also help minimize a tilt-up building's heat island effect.

Longevity and life cycle

Tilt-up concrete buildings have similar benefits to other types of concrete buildings with respect to longevity and low maintenance. Tilt-up offers an additional benefit that can extend the usable life of the structure by allowing wall panels to be relocated to other positions in the building if modifications are needed later. Openings can be cut in most locations in the panel with little, if any, structural modifications. Panels can also be designed with "knock-outs" to facilitate future or phased expansion. These "knock-outs" can be designed to be easily cut away and thus reduce the amount of materials to be recycled or discarded. Figure 3.83 shows the AOL (America Online) Creative Center that was adapted from the previous 90,000 ft^2 (8400 m^2) warehouse building that was previously a British Aerospace maintenance and parts storage facility in Loudoun County, VA.

Human factors and living/working environment

The concrete in tilt-up structures can be covered, painted, sandblasted, or simply left in a raw state, depending on the application. Raw concrete is often used by architects to express the nature of the material. Unfinished concrete greatly reduces volatile organic compounds (VOCs) and maintenance costs. Exposed concrete also reduces the risk of mold, as discussed in

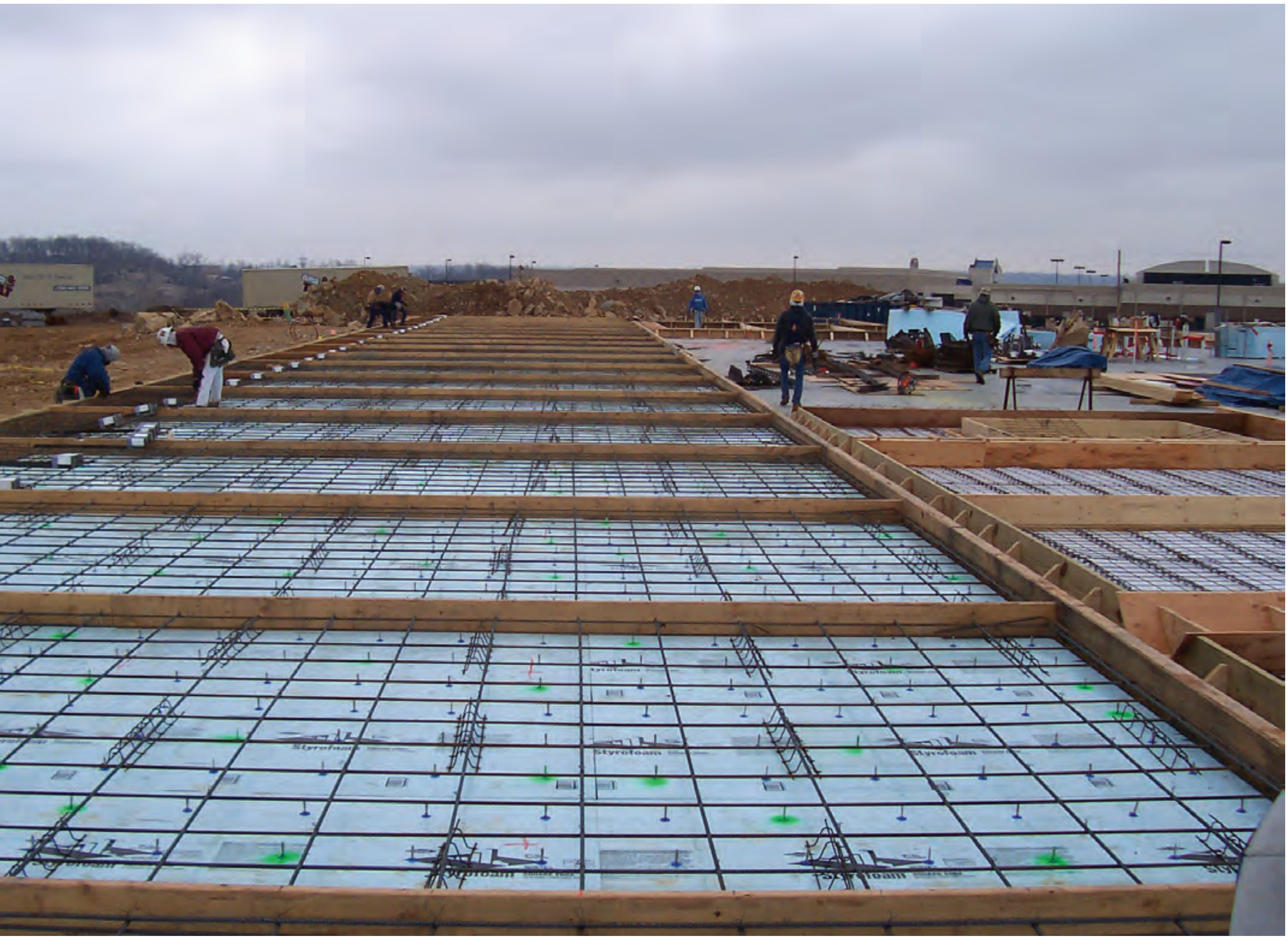


Fig. 3.82—Construction of a sandwich panel system. *Photo courtesy of Tilt-Up Concrete Association*

other chapters. The formation of mold requires spores (present everywhere), moisture, and a food source (wood or other organic material). Concrete is not a food source, thereby eliminating the concrete wall as a source of mold.

Natural daylighting can be provided and controlled by compatible window systems in combination with the structural efficiency of tilt-up panels. Large openings allow increased amounts of natural light, reducing the demand load on the mechanical and electrical systems, while maximizing views. Taken even further, tilt-up panels can be designed, engineered, and crafted in an amazing number of ways—horizontally, vertically, diagonally, or curved—to help reflect natural light into the depths of a space. In contrast, the strategic placement of tilt-up panels along the façade or around the perimeter can provide critical, yet economical, sun shading. Refer also to the shadow panels shown in Fig. 3.84.

Fig. 3.83—AOL Creative Center after being adapted from a large maintenance and storage facility. *Photo courtesy of Tilt-Up Concrete Association*

Security and safety

Tilt-up structures offer significant protection from storms and blast effects. Not only can the structures resist hurricane and tornado force winds, but they offer excellent protection against wind-borne debris, which is one of the greatest hazards in storms.

Fig. 3.84—Shadow panels on the Dade Paper building in Miami, FL. *Photo courtesy of Tilt-Up Concrete Association*

The largest market for tilt-up is in California, which has significant seismic activity. Proper detailing and wall design contribute to the excellent performance of tilt-up concrete in seismic events.

Tilt-up structures also perform well in fire, both from within and from the outside. Interior tilt-up walls provide fire separation between building segments, with 2-hour or greater rated assemblies. The inherent fire resistance of concrete also provides excellent performance in areas of wild fires. Shafts of all types, such as stairwells, elevator shafts, electrical shafts, trash chutes, and others, require various ratings and can easily exceed code minimum requirements by being constructed of tilt-up panels.

Reduce, reuse, recycle

Tilt-up construction applies the concepts of recycling and reuse through many of the same ways that are described for other concrete applications, including recycled reinforcing material, SCMs, and reusable forms. Tilt-up wall panels can be crushed and used as the subbase for sidewalks, parking lots, casting slabs, or roads.

Under the reuse category, existing tilt-up structures offer an ease of expansion and retrofit that is not readily available with many other construction methods. Panels can be designed to be movable, and engineered to allow for modification and/or creation of openings. "Knock-out" openings can be designed into panels to allow for new doorways or windows based on the future phasing or change in use of a structure.

Economic impact

Tilt-up concrete offers a low-cost, energy-efficient, and durable wall system with minimal maintenance through the ways described in this chapter.

Tilt-Up Top Sustainability Benefits

- Adaptive reuse—Tilt-up concrete facilities offer considerable options for expansion, reuse, and building program adaptation to extend the service life of the structural resources well beyond the designed program life.
- Recycled materials—On site, extra concrete material and casting surfaces can be reused or recycled with no waste for hauling saving fuel, money, and impact to the environment.
- When using non-painted systems, the durability is further extended with limited-to-no maintenance through the facility's life.
- Reduced energy consumption—Tilt-up concrete can incorporate the most effective continuous insulation designs to meet and substantially exceed minimum code requirements and greatly lower energy use.
- Lighting and heat island reduction—Concrete is light in color and therefore reflects light. This reduces the cost of lighting energy, which consumes 20% of America's energy usage and significantly reduces the intensity of stored solar radiation.
- Longest use life—Tilt-up concrete walls provide a life-span endurance of more than 100 years.
- Durability: provides economic benefit over building life cycle.
- Thermal mass: energy efficiency.
- Resilient: particularly against terrorist attacks and natural disasters such as fires, hurricanes, tornadoes, and floods.
- Materials efficiency: can use regional and recycled materials.

Tilt-up concrete—The process of casting concrete building elements on site and lifting them from their casting location to their position in the structure. The concept is applied primarily to structural walls, but beams, columns, light shelves, and other building elements also fit the application.

PART 4—CONCRETE IN SUSTAINABLE STRUCTURES

Introduction

The first three parts of this book focused on materials used in concrete structures, construction, and specific applications. Part 4 looks at two areas not covered in the previous sections: 1) integration of concrete in sustainable structures; and 2) repair of existing structures. Even in structures that don't use concrete members as their primary structural framing system, concrete is often still a major component of a structure (such as steel buildings with concrete slabs or cladding) and is the foundation of virtually every building in the industrialized world. Concrete's durability and versatility also makes it an easy choice to support many of the sustainable attributes for other materials and systems such as green roofs.

The first two chapters of Part 4 summarize the sustainable concepts and attributes described throughout this book. The last two chapters of Part 4 focus on the repair of concrete structures, repair of other existing structures with concrete (such as the repair of stone structures with concrete), and the adaptive reuse of concrete structures. With the large inventory of existing buildings and the associated embodied energy and carbon footprint, repair and reuse will naturally take an ever-increasing role in sustainability.

Chapter 24—Integration of concrete structural elements

The applications discussed in Part 3 included many concrete structural elements. In addition to these elements that form part of a structural framing system in a concrete building, concrete is often the choice for structural components as part of a steel or wood framing system. Table 4.1 lists structural elements that can be used as components of buildings of any material to provide sustainability benefits.

When reviewing Table 4.1, one finds a recurring attribute for applications within the Advantages column. Durability is arguably the most sustainable of all attributes in that it affects all three aspects of the Triple Bottom Line, as well as influences the outcomes of many sustainable strategies. Yet, current provisions of green rating systems and green codes typically address site development, energy and water consumption, materials and resources and indoor air quality while not acknowledging durability.

As an example, U.S. Green Building Council's LEED program does not offer credit for durable systems. Some say this is a due in part to the difficulty of proving longevity, while others consider that economic pressure for a low initial cost drives us to build only to minimum code requirements and nothing more. A report from the Brookings Institution in Washington, DC, projects that by 2030 we will have demolished and replaced 82 billion square feet of our current building stock, or nearly 1/3 of our existing buildings, largely because the vast majority of them weren't designed and built to last any longer

Table 4.1—Integration options by element type

Concrete element	Typical applications	Advantages
Foundations and slabs-on-ground Cast-in-place (CIP) Post-tensioned slabs CIP or masonry walls Shotcrete	Nearly all building foundations are concrete or masonry	Efficient load transfer Durability Thermal mass Ability to incorporate in-floor radiant heat Ability to use as finished surface Ability to dampen sound and vibration
Supported floor slabs Post-tensioned CIP Pretensioned precast (hollowcore) CIP on metal decking	Multistory buildings	Reduced depth of floor structure Durability Incorporation of in-floor radiant heat systems Thermal mass Ability to use as finished surface Fire resistance
Shear walls CIP Precast Post-tensioned CIP Reinforced masonry Shotcrete Tilt-up construction	As lateral resisting system	Durability Thermal mass Ability to use as finished surface Can focus lateral system at cores Shelter from extreme loads Fire resistance
Bearing walls CIP Precast Post-tensioned CIP Reinforced masonry Shotcrete Tilt-up construction	As vertical load resisting system (in lieu of steel or wood frame)	Reduced building volume possible Incorporate building skin as part of walls Incorporate architectural features Durability Thermal mass Ability to use as finished surface Shelter from extreme events Resistance to extreme loading
Retaining walls CIP Precast Block/masonry Shotcrete	For earth retention	Durability Aesthetics with stamping, texture, or color Minimal construction disruption
Columns CIP Precast Post-tensioned Block/masonry	In conjunction with concrete beams or flat slab	Reduced building volume possible (slab tying directly into column) Durability Thermal mass

(Moe 2008). Interestingly, the Canadian version of LEED does offer a credit for durability.

Durability comes in many flavors—extended service life, low maintenance, fire and storm resistance, blast resistance, and others. A recent way to consider these attributes is functional resilience—the ability to minimize repair, maintenance and replacement due to normal operations or catastrophic events. Regardless of the material, durability reduces the annual environmental "expense" of creating and installing the materials.

Durability

In considering durability, the first thing that comes to mind is typically service life—the expected length of time an assembly (wall, roof, roadway) is designed to provide functional use. While some durable assemblies can have a higher initial cost, the longer service life often represents the best economic value. It reduces the amount of time and effort required to accommodate the disruption during repairs or replacement. An unexpectedly short service life can have additional negative impacts. Repair or replacement of interior finishes, remediation of mold, and disruption to the building users is often a result of a roof leak. Many times, it is the associated damage that is the indicator that the roof has reached the end of its service life.

A prime example of extended service life is found in a concrete pavement. I-10 west of Los Angeles was constructed in 1946 as part of US Route 66. The surface was ground 19 years later to improve joint alignment and surface deterioration. It was ground two more times; once in 1984 and again in 1997. At 64 years old, this pavement still provides daily service to 240,000 Los Angeles commuters.

Disaster Resistance

The effects of functional resilience go beyond the physical properties of the building. It addresses the building's ability to allow the users to continue operations. For a home, this may mean the difference between keeping or losing a job, as we saw in the New Orleans area following Hurricane Katrina. Many citizens were required to relocate on a permanent basis. For a business, an extended disruption often results in business failure. And for a municipality, this means a struggle to provide essential services for the health and safety of the citizens (hospitals, fire and police, social services) as well as on-going economic viability of the community.

As a society, people don't think that they will be affected by a natural disaster. However, the National Oceanic and Atmospheric Administration (NOAA) data (2010) indicates the average direct property loss due to weather related natural disasters in the Unites States exceeds $35 billion annually. This figure does not include earthquakes and fires, nor does it include indirect costs associated with the loss of the homes or business closures, and the resources expended for emergency services.

- Approximately 40 percent of the U.S. population resides in counties that face medium to high seismic risk.
- Data from the U.S. Census Bureau indicates that, in 2006, 34.9 million people were seriously threatened by Atlantic hurricanes, compared with 10.2 million people in 1950.
- In 2008 alone, there were 16 named tropical storms (eight of which were hurricanes), 1700 tornadoes, widespread flooding due to winter storms, spring melts, tropical storms and other severe weather events in the U.S.
- One-quarter of U.S. residents live in a county that has been ravaged by wildfire during the last 25 years.

Disasters don't just come from natural sources. Technical failure (power outages, broken water lines, electrical fires, and gas leaks) can be just as damaging to an individual home or business.

In 2005, as a result of Hurricane Katrina, more than one million residents were driven from their homes on the Gulf Coast. Tens of thousands of homes in New Orleans were flooded, many requiring either demolition

TRIPLE BOTTOM LINE IMPACTS

Environmental—

- Durability's impact is widespread in a world of finite resources.
- Materials—fewer resources are extracted or harvested when replacement is not required.
- Energy—The additional energy required to demolish, acquire, make, transport and construct replacement materials or a building is eliminated.
- Emissions—water and air emissions, resulting manufacturing, shipping, and construction are reduced.
- Solid Waste—less material is landfilled. U.S. Federal Emergency Management Agency reported 44 million cubic yards of construction debris was generated from the Katrina Hurricane disaster.

Economic—

- The cost to remove and replace materials is reduced, as well as the associated damage from system failure.
- The disruption of operations from a building failure can often result in business collapse.

Social—

- Business disruptions can result in job loss for the employees of the business and unemployment benefits paid out by the community.
- Key employees can be forced to relocate.

or gutting before reconstruction. Three years later, the New Orleans area still faced significant debris management issues and challenges. For example, the Louisiana Department of Environmental Quality (LDEQ) stated that while the Department of Homeland Security's Federal Emergency Management Agency (FEMA) estimated in July 2008 that it had funded about 16,900 home demolitions, and an estimated 6100 homes remained to be demolished around the New Orleans area (U.S. Government Accountability Office 2008).

Foundations and slabs-on-ground

Concrete foundations or masonry/block foundation walls are the standard solution for nearly all types of buildings. No other material provides the durability and efficient load transfer to the earth that these types of foundations provide. In slab-on-ground foundations, the slab can also incorporate the necessary conduit for in-floor, radiant heat. In both the slabs and basement walls, the thermal mass of concrete is very effective for reducing temperature spikes and to lag temperature effects. Any exposed surface can also double as the direct finished surface so that drywall, carpet, paint, and other finishing materials are not needed.

Fig. 4.1—Shear wall under construction at Taylor Place, on the campus of Arizona State University. *Photo courtesy of American Concrete Institute*

Supported floor slabs

As with slabs-on-ground, all floor slabs can have the benefits of in-floor heating, thermal mass, durability, and use as a finished surface. Concrete floor slabs, either as a composite system of cast-in-place concrete on metal decking or as a stand-alone structural concrete slab, are by far the most widely used type of supported floor slab. In buildings over three to four stories, they are the industry standard, providing not only structural support, but also required fire separation and rating, and reduced noise transmission and vibration.

Shear walls

Shear walls (as shown in Fig. 4.1) for resisting lateral forces have traditionally been cast-in-place reinforced concrete or reinforced masonry. The development of connection details and research on precast walls and tilt-up concrete under seismic forces has led to more widespread use of these systems as well. Shear walls of other materials (such as steel) are possible, but not commonly used. The shear walls are often located at elevator cores, stair wells, or on a portion of the exterior walls of a building. Shear walls (such as those at a stair well) are extremely durable, and can double as a shelter for people in the building when high winds may damage other components of the building. By nature, shear walls are often very substantial, and can thus have significant thermal mass and sound/vibration dampening qualities. As with other types of exposed concrete, they can be used as a finished surface.

Bearing walls

Bearing walls can be used in place of a steel framing system. As described in Part 3, architectural precast, tilt-up, or cast-in-place walls can be used as structural bearing walls. Insulation can be integral to a precast sandwich wall system, thus reducing the building's skin thickness because a skin does not have to be added over a steel frame along with the insulation and interior finished wall (framing and drywall) surfaces. Bearing walls are durable and also share the same benefits as other types of exposed concrete.

Columns

Concrete columns have the benefits of durability and thermal mass, as with other types of exposed concrete.

Chapter 25—Solutions by integration of concrete elements

The applications discussed in Part 3 touched on many of the nonstructural benefits of concrete. Table 4.2 provides a summary of different beneficial aspects of integrating concrete within any type of building. The companion book, *The Sustainable Concrete Guide—Strategies and Examples* (Schokker 2010) provides a more in-depth discussion on the background of the sustainable strategy involved with many of these items.

Table 4.2—Integration solutions with concrete for sustainability

Need	Typically accomplished	Alternative sustainable solutions
Interior finish	Wood or metal framing with drywall and paint Carpet (with adhesive), ceramic tile, wood, or laminate flooring	**Use concrete as finished surface and incorporate insulation in sandwich panels as needed** Decorative concrete wall and slab finishes Precast concrete sandwich panels Polished/exposed concrete floors
Cladding/building envelope	Metal, vinyl, wood, quarried stone, or other cladding materials attached to the structural members	**Concrete walls that serve as both the external surface and the structural member and that reduce thermal bridging** Precast sandwich panels Precast cladding with nonmetallic studs Precast, shotcrete, or cast-in-place (CIP) walls Durable thin outer layers Cement board, stucco, tile roof
Historic preservation	Repair with original material, such as quarried stone	**Reduction in labor, dust, noise, waste material, transportation, cost, and natural resource use** Cast stone Post-tensioning Shotcrete
Energy efficiency	Energy efficient electrical items Well-sealed building Additional insulation	**Thermal mass (and passive solar heating) combined with well-sealed building** Concrete members of most types
Fire resistance	Fireproofing layer (or spray on fire coating)	**Fire-resistant material that does not need additional fireproofing layer** Concrete members of most types
Improved indoor air quality	Coatings to reduce mold/rot potential Low volatile organic compounds (VOC) paints and carpets	**Naturally mold/rot-proof material with no paint or carpet** Concrete members of most types
Appropriate acoustics	Use of multiple layers of materials to reduce transmission Use of absorptive materials to reduce reflection	**Reduction of transmission through structure** Concrete members and well-sealed envelope (Reduction of reflected sound must be achieved with sound absorptive materials—can be used in combination with concrete for reduced transmission and increased absorption)
Storm-water management	Detention ponds	**Concrete systems filter water directly back to aquifer** Pervious concrete Permeable interlocking concrete pavers Concrete cisterns (above ground, below ground) to store gray water for reuse Green roof

Table 4.2—Integration solutions with concrete for sustainability, cont.

Shelter from extreme events	Basements or storm shelters	**Entire building shell robust in tornados, hurricanes, extreme climate changes (thermal mass to regulate temperate extremes), loss of electricity, blast, impact** Concrete walls, roofs, floors of most types Concrete/masonry basements and storm shelters when main structure is not storm-resistant Shotcrete domes
Reduction of heat-island effect	Light-colored coatings, layers, or paint Trees or other vegetation	**Inherently light-colored material** Naturally colored concrete and even higher solar reflective index (SRI) from concrete with slag or white cement Green roof (with concrete structural members to support the weight and durability requirements)
Lighting with reduced energy demand	Natural light; artificial lighting with low-energy bulbs	**Use of natural lighting in conjunction with light-colored materials on interior and shading as needed by ledges/fins on exterior** Exposed concrete surfaces Concrete ledges/overhangs
Flatwork/hardscape	Concrete, asphalt, or pavers	**Use of decorative, durable concrete material with high SRI (can save on number of light poles and luminaires for roads and parking lots compared with asphalt)** Decorative concrete Pervious concrete Permeable interlocking concrete pavers Standard CIP concrete
Decorative/aesthetic	Paint, carving/sculpture, ornamentation	**Use of decorative, durable material with high SRI** Decorative concrete (colored, stamped, textured, unique forming) Cast stone Exposed aggregate concrete Polished concrete Concrete countertops Shotcrete

Caveats

The concrete solutions listed in Table 4.2 have distinct advantages for incorporation into a sustainable building system. As with all materials, designers should consider the full process of getting the material in place, including transportation and construction. For instance, a bare concrete surface can avoid volatile organic compounds, (VOCs) by eliminating the need for paint or carpet, but a sealer may still be needed. To complete the sustainable application of the concrete wall surface, a sealer that emits zero or low VOCs should be used. These types of items are readily available, but must be specified to ensure that environmental gains from reducing finishing are not then partially lost by a poor choice of sealer.

Chapter 26—Maintenance and repair

With broadening awareness and understanding, sustainable thinking demands consideration of preserving through maintenance first, and repair of existing structures, when feasible, second. This approach is far more sustainable than demolishing and rebuilding simply because of perceived need or simply the desire to build new because it's possible. Some of the most useful, responsible, and durable building projects begin with existing structures. Blair Kamin, the Pulitzer Prize-winning architecture critic of the *Chicago Tribune*, puts the idea of a new, broader reality squarely in perspective in his discussion about preservation versus conservation (building green) when he suggests that these endeavors are really about the same ends. The argument is "not technical, but cultural. It's about how we live and how we ought to navigate between perilous extremes: not with overzealous ideology but with an enlightened pragmatism that reshapes and reinvigorates old ideals in response to new realities" (Kamin 2010). The thoughtful extension of the life of existing structures through a commitment to long-term maintenance and careful repair is a responsible answer to the reality of living sustainably.

This chapter is about concrete protection, maintenance, and repair that offer the ultimate inherent sustainable advantages in terms of cost, longevity, energy, and even social responsibility. Current repair technology has been developed to particularly address infrastructure, but the same considerations and techniques can apply to buildings as well. Infrastructure will be referred to in this section because it provides numerous examples and technologies for repair. The following chapter is related in considering how structures can be saved, modified, and used for other functions.

The longer concrete can stay in service through regular preventive maintenance, the more the environmental impact is diminished over its full life cycle. As the next alternative, concrete can be repaired, although such repair may contribute significantly to the environmental impact of a structure because the embodied energy and carbon footprint impacts are further compounded by the removal-disposal of deteriorated concrete, the use of repair materials (more exotic materials are often transported long distances), and service disruptions. Preventing the need to repair concrete is much more beneficial and cost effective through proactive maintenance than the short-sighted solution of: 1) placement; 2) wait for deterioration; 3) remove and patch; and 4) repeat.

The case for preventive maintenance

Because concrete is highly durable, it is frequently ignored once it is in place until signs of deterioration are evident. When concrete begins to lose its ability to function as designed, root causes can be classified as design and construction errors, improper maintenance, damage, and deterioration. These factors combine to shorten the potential life cycle of concrete structures, including buildings. In terms of design and construction errors alone, visible defects in new construction often require repair, whereas those that go unnoticed and remain out of view, such as inadequate concrete cover for the reinforcement, improper consolidation, lack of attention to jointing details, and improper curing, can eventually lead to deterioration. A 1979 survey (Fraczek 1979) estimated that 52% of serious concrete problems are discovered during construction. The lowest cost technique to improve concrete durability in new construction is to merely follow good industry practices such as the use of proper mixture proportions, providing sufficient cover over reinforcement, and thoroughly curing the concrete. With adherence to these best practices, concrete stands above many other construction materials in its ability to resist insect damage, fire, impact, abrasion, moisture exposure, and other factors when the structure is systematically maintained.

The most effective sustainability strategy for concrete structures is to avoid the need for repairs altogether. The BRE, formerly known as the Building Research Establishment, a well-known entity in the United Kingdom, agrees that prevention through monitoring, inspection, and maintenance can result in great savings over the life cycle of a concrete structure (De Sitter and Tuutti 2003). Investment in preventative maintenance results in shorter, less disruptive interventions that are highly cost effective over the life cycle of the structure compared with waiting until deterioration—such as from reinforcement corrosion—has initiated. Addressing repairs after the deterioration has caused damage, evident as rust weeping, spalling, cracks, and other processes, greatly increases the cost of mitigation. For example, keeping concrete dry minimizes freezing-and-thawing damage, alkali-aggregate reaction, most types of sulfate attack, and deicer salt scaling. For new, good-quality concrete construction, addressing cracks; providing treatment with penetrating sealers, coatings, or membranes; and other proactive maintenance over the life of a structure can postpone repair needs almost indefinitely.

When repair is needed

The need for repair is never more evident than when considering the large scale of existing infrastructure. The ASCE "2009 Infrastructure Report Card" (American Society of Civil Engineers 2009) captures a snapshot every few years of the estimated status and cost of infrastructure in the U.S. based on an acceptable condition in 1988 of a C grade. The 2009 report card gave America's Infrastructure a grade of D averaged over 15 categories. This rating estimates that a 5-year investment need of $2.2 trillion (or greater than $7000 per person in the U.S.) is required to return to a C grade. Figures 4.2 and 4.3 highlight some related infrastructure statistics.

The only categories showing a grade C or better are bridges and solid waste, yet even these relatively bright spots contain alarming details. The ASCE report card states: "Usually built to last 50 years, the average bridge in our country is now 43 years old. According to the U.S. Department of Transportation, of the 600,905 bridges across the country as of December 2008, 72,868 (12%) were categorized as structurally deficient and 89,024 (15%) were categorized as functionally obsolete."

Although the repair of existing structures is typically a responsible solution to the need for usable buildings and infrastructure, the reality of repair and associated demolition does generate the need for new replacement materials, and creates waste destined for landfills. Non-hazardous solid waste is classified into municipal solid waste (MSW), which we tend to think of as household garbage, and non-MSW, including coal ash, foundry waste, flue gas desulfurization waste, and construction and demolition waste (C&D waste). Much of the effort in recycling programs focuses on MSW, and ignores the significant volumes of the other waste streams.

A survey of 11 states (Staley and Barlaz 2009) estimates that 4.2 lbs (1.9 kg) of MSW is generated per person per day. Figure 4.4 shows the average breakdown of solid waste from data in the survey. C&D waste was estimated at 20% of the total solid waste, with some states indicating C&D as nearly 30% of their solid waste. In 2003, renovation was estimated at 42% of the C&D waste (U.S. Environmental Protection Agency 2003). Making concrete last longer—as well as having more durable repairs—can help reduce this waste stream.

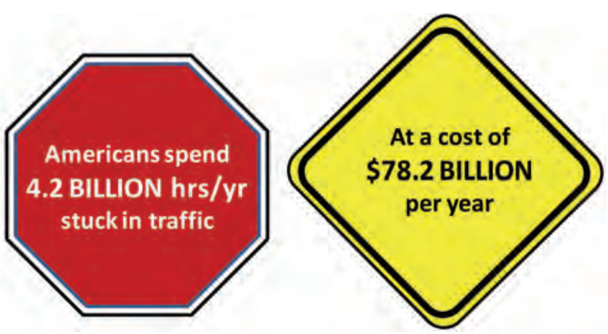


Fig. 4.2—The cost of deteriorating infrastructure: roads.

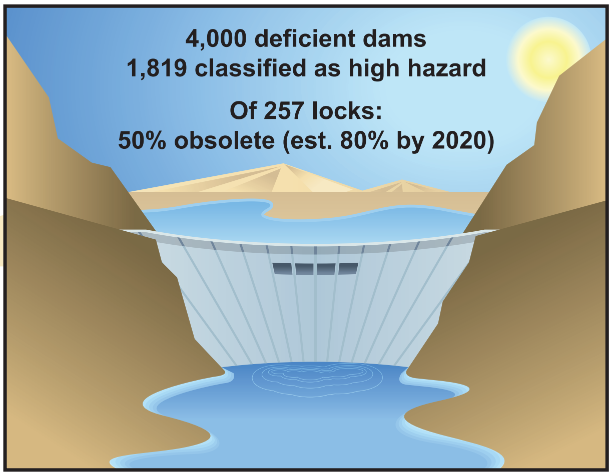


Fig. 4.3—The cost of deteriorating infrastructure: locks and dams.

Repair process to minimize environmental impact

Proactive (preventative) maintenance and structural repairs are inherently more sustainable than complete removal and replacement. There are key steps, however, to the repair process that should be considered to minimize the environmental impact.

Condition evaluation

The first important step is to have a licensed professional engineer conduct a comprehensive condition evaluation to identify the cause(s) and degree of deterioration or damage. To design a durable repair, it is important to understand specific deterioration mechanisms that affect a structure. For example, it is important to know whether the concrete that is being left in place is contaminated with chlorides, is carbonated, or both. Without considering such key factors and countering them with appropriate corrosion control measures, repairs could actually accelerate deterioration in the parent concrete. For additional information, refer to ACI 364.1R-07, "Guide for Evaluation of Concrete Structures before Rehabilitation," (ACI Committee 364 2007).

Life-cycle cost analysis

By considering anticipated maintenance and repair requirements over an extended period of time, an optimal maintenance and repair plan can be devised following the condition evaluation. For example, cutting initial costs by deleting corrosion control measures could greatly increase repair costs over the long term. Repairs should not be planned or carried out with a narrow focus. Life-cycle implications of various options should be considered to highlight their strengths and weaknesses over the long term.

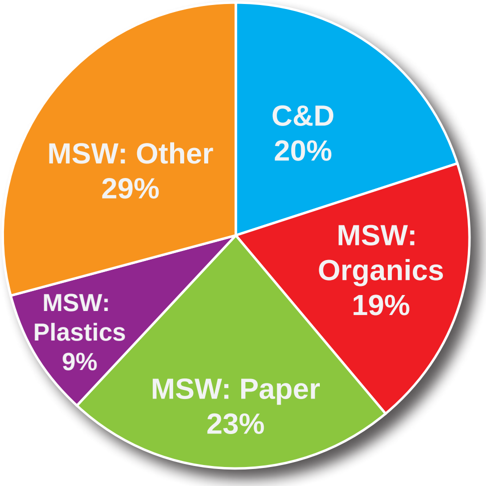


Fig. 4.4—Distribution of solid waste.

Repair design

To minimize the environmental impact, a repair approach should salvage as much concrete as possible while achieving durability. For this to happen, the repairs should include appropriate measures to control reinforcing steel corrosion in both the parent concrete and in the repairs themselves. The repairs should also include measures that will address the potential for future concrete contamination, such as from chlorides and carbonation. This can normally be achieved by protecting the concrete on the surface to prevent contamination, through intrinsic corrosion control measures, or a combination of both.

Waste management

A plan should be devised and implemented to deal with waste from the portions of the structure that must be removed, and packaging for new materials. Where possible, removed materials should be recycled, or preferably reused, to avoid being sent to landfills. Similarly, new materials should be shipped with minimal, reusable and/or recyclable packaging.

Use green repair materials: once a repair approach has been selected, it is important to implement it using repair materials that will minimize the environmental impact. Factors that should be considered include:

- Recycled content;
- Regional content;
- Volatile organic compound (VOC) content;
- Durability;
- Packaging;
- Recyclability;
- Ease of use (lowering probability of premature failure);
- Embodied energy;
- Greenhouse gas emissions from manufacturing and transport; and
- Impact on heat island effect (solar reflectance and emissivity).

With more awareness for considerations of environmental impact, many manufacturers have documentation readily available that support green aspects of their product line.

Successful repair implementation

Even with an optimal design and green material selection, a repair project should be implemented properly to minimize its environmental impact. To maximize the likelihood of success, repairs should be carried out by a contractor in combination with a comprehensive quality control plan. The quality control should include the designer's site review to check for compliance with the design specifications, site visits by manufacturers' representatives to check compliance with their product requirements, and field/laboratory testing to verify that measurable requirements (such as strength, adhesion, temperature, and environmental conditions) are met.

Future monitoring

Once repairs are completed, it is important to monitor the condition of the structure to determine when preventative maintenance or subsequent repairs will be required. This is typically achieved by periodic condition evaluations. Embedded sensors and data acquisition systems can also be used to continuously monitor certain performance parameters (such as corrosion activity, chloride contamination, water leakage, temperature, structural deformations, and cracking).

Specific repair techniques

Nearly all of the techniques listed in Part 3 can be used in various repair scenarios. The two applications discussed in this section have some specific applications within the repair industry that tend to differ from their use in new construction.

Post-tensioning

Post-tensioning, as discussed in Chapter 5 of Part 1, provides an efficient use of materials to achieve sustainable new construction. An additional area where post-tensioning has a strong presence is in repair and retrofit. Most retrofit systems only involve passive strengthening through the addition of material to strengthen the section to increase ultimate capacity. Due to the active prestressing force applied by post-tensioning, it not only strengthens a section, but can also alleviate excessive deflections and close cracks, which are a concern for durability (and aesthetics).

Post-tensioning for new construction is typically within a duct cast into the concrete section. Some tendons external to the concrete, but inside a box-type

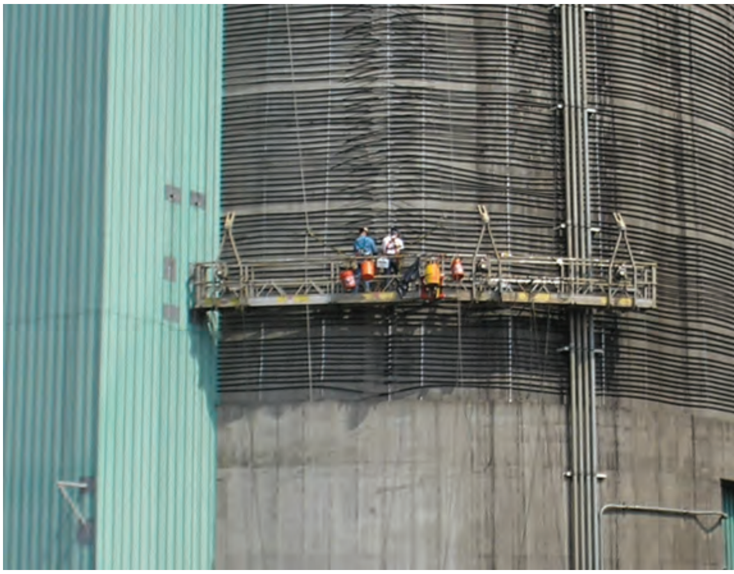


Fig. 4.5—Tank retrofit with external post-tensioning. *Photo courtesy of VStructural, LLC (VSL)*

Fig. 4.6—External post-tensioning for strengthening concrete beams. *Photo courtesy of VStructural, LLC (VSL)*

Fig. 4.7—Shotcrete being applied directly to the newly exposed surface without forming. *Photo courtesy of American Shotcrete Association*

section are also used (such as with segmental post-tensioned bridges). In repair, the post-tensioning is typically applied externally, so the repair is relatively quick and straightforward.

The advantages of external post-tensioning as a repair or retrofit option include versatility in applications, weight reduction, easy installation, and easy monitoring. The anchorage can also remain accessible for future adjustments, such as retensioning to counteract long-term creep in concrete. Reasons for the use of external post-tensioning for strengthening include design or construction deficiencies, loss of strength from deterioration, extension of service life, change in building use, or change in code requirements (Vejvoda 1992). The post-tensioned repair of Frank Lloyd Wright's Fallingwater House is discussed in the case studies section at the end of this chapter. Figures 4.5 and 4.6 show examples of different types of post-tensioning retrofit applications.

Shotcrete

Shotcrete is discussed in more detail in Chapter 21 in Part 3 on applications, but shotcrete has substantial benefits for enhanced sustainability in the repair industry as well. Shotcrete is an efficient repair method that offers significant material, labor and speed advantages in many repair applications; all of which are critical sustainability advantages.

Using shotcrete allows the repair contractor to economically and efficiently address a wide range of concrete repairs with these sustainability benefits:

- Use minimal if any formwork;
- Excellent bonding, eliminating the need for bonding agents;
- Allow unique overhead placement quality and efficiency;
- Increased speed of placement;
- Ability to provide custom finishes to the exposed shotcrete surface;
- Ability to provide the precise shape and thickness required for the structural or aesthetic functionality of the repaired concrete members;
- Gives the ability to access restricted or difficult to reach areas that may not be able to be repaired by normal form and pour methods;
- May eliminate or at least reduce shoring and scaffolding that would be needed for form-and-pour repair methods.
- May eliminate the need for heavy lifting equipment or forklifts on the site that would be needed for form-and-pour methods to build, set, and strip formwork.

As an example of shotcrete's inherent ability to facilitate a concrete repair, consider a concrete structure that has concrete cover that has spalled or deteriorated. The damaged concrete is removed, leaving an exposed surface of good-quality concrete and reinforcement. The shotcrete can then be shot directly onto the newly exposed surface without requiring forming or bonding agents. In addition to significant sustainability benefits from material resource savings by eliminating formwork, the use of shotcrete can result in a labor savings of up to 50% on a repair project. The shotcrete process offers all the sustainability advantages of concrete as a repair material, plus a significant number of sustainability advantages inherent in the placement process.

The seismic retrofit of the University of Memphis' Cecil C. Humphreys School of Law is included in the case studies section at the end of this chapter as an example application.

Concrete sawing and drilling

Concrete sawing and drilling is applicable for both new construction and repair or renovation. Because a large portion of its use is in renovation, the topic is included in this chapter.

The concrete sawing and drilling industry began in North America in the late 1940s when a flat saw was used experimentally to saw highway joints. Since those early beginnings, many changes have occurred in diamond-tipped tools that saw and drill concrete. The early homemade machines have been replaced by modern, efficient machines capable of a far wider range of applications than the original machines. Today, the specialty contractors who perform the concrete sawing and drilling services are experts in their field, and architects, engineers, general contractors, and government officials can take advantage of these advances in technology by employing a specialized sawing and drilling contractor who uses these diamond-cutting techniques in the construction and renovation industry.

Diamond-cutting systems can provide significant advantages over conventional concrete removal methods. These advantages vary depending on the project, but include reduced downtime, precision cutting, maintenance of structural integrity, reduced noise, reduced dust and debris, limited-access cutting, and the ability to cut heavily reinforced concrete. Advantages of a diamond-cutting system over conventional removal systems include:

- Ability to cut through reinforcement and other materials and around existing pipes, existing electrical fixtures, and equipment;
- Ability to remove large amounts of concrete quickly while maintaining structural integrity;
- Cutting with precision to limit patchwork;
- Vibration-free and relatively quiet;
- Cuts can be made in close spaces, minimizing structural impact when making or enlarging openings and doorways;
- Minimizing airborne contaminants when wet-cutting and drilling;
- Recycling and reusing water, dust, or both from diamond tool operations;
- Producing a "final finish" that does not require further work or products to maintain; and
- Possible underwater operations.

Concrete cutting techniques

Diamond-cutting techniques used by cutting contractors vary depending on the application and job-site requirements. The main concrete cutting tools that are used include the wall (or track) saw, the flat (or slab) saw, the core drill, and the wire saw. Each of these cutting tools is described as follows, along with an example of a typical application.

Wall sawing

Wall sawing employs a circular blade on a track-mounted machine. The track is attached to vertical walls or steep inclines or floors that will not permit the use of flat saws. Wall or track sawing is typically specified to cut precise dimensional door, vent, and window openings. Straight and bevel cuts are possible with the wall saw. The wall saw is also an excellent choice for creating precise openings in any concrete structure.

The diamond wall saw blade consists of a circular steel core, with diamond segments attached to the periphery. The blade is mounted on the spindle of the wall saw. The spindle runs along the wall saw track that is typically bolted to the cutting surface. The power source for a wall saw system is either hydraulic, air, or electric. Wall saw blades can range from 18 to 72 in. (457 mm to 1800 mm) in diameter, and can cut up to 33 in. (838 mm) in depth.

Example application: The use of a wall saw allowed a general contractor to safely remove a silo in the middle of existing buildings to perform a renovation of a fire brick manufacturing plant in Manistee, MI. The contractor was hired to remove the silo in the middle of the winter with temperatures below freezing. The 57 ft (17 m) tall reinforced concrete silo was cut with the wall saw and removed in three 19 ft (5.8 m) sections. In total, 1025 ft (312 m) of 9 in. (229 mm) thick and 341 ft (104 m) of 12 in. (305 mm) thick reinforced concrete, weighing over 350 tons (318 metric tons), was removed in only 6 weeks.

Flat sawing

Flat sawing is the most commonly used diamond cutting method. It is typically used to cut horizontal flat surfaces such as floors, bridge decks, and pavement. Also called slab saws, flat saws feature a diamond blade that is mounted on a walk-behind machine that requires only one operator. Flat saws are typically used to provide expansion joints, remove damaged pavement sections, clean and repair random cracks for repair, and remove concrete sections for demolition purposes.

As with the diamond wall saw blade, a flat saw blade consists of a circular steel core, with diamond segments attached to the periphery. The blade is mounted vertically on the spindle of the flat saw. The flat saw is pushed or propelled along a flat surface, while the diamond blade makes the vertical cut to the required depth. Flat saws are typically powered by gasoline or diesel engines, or electric or hydraulic sources. Flat saw blades can range from 12 to 54 in. (305 mm to 1400 m) in diameter, and can cut up to 24 in. (610 mm) in depth.

Example application: While flat sawing has many highway and airport applications, a typical building application is the removal of floor structures. A contractor removed three levels of a Syracuse, NY, parking building. The parking deck had to be removed after a section collapsed and made the building unsafe. The concrete structure was primarily made of 10-1/2 in. (267 mm) thick CIP concrete with 5/8 in. (16 mm) reinforcing bar on 12 in. (305 mm) centers. Over 3048 ft (929 m) of 15 in. (381 mm) slab, 3048 ft (929 m) of 8 in. (203 mm) slab, 24,476 ft (7460 m) of 10-1/2 in. (267 mm) slab, 3058 ft (932 m) of 15 in. (381 mm) slab, and 933 ft (284 m) of 18 to 24 in. (457 to 610 mm) slab was cut with flat saws and removed by cranes. Slab sawing, as well as wall sawing, was the best demolition choice due to its speed, control of the process, low noise in a downtown setting, and safety in a confined area.

Core drilling

Core drilling techniques are used when precise, circular cuts are needed. Holes of almost any diameter are easily drilled to make openings for plumbing, electrical, and heating, ventilating, air conditioning (HVAC) installations. Core drilling is also commonly used to create holes for routing cables or placing anchoring bolts, installing load-carrying devices or dowel bars, or for concrete sample analysis.

A core drill bit consists of a steel tube with diamond segments brazed or laser welded on the drilling end. The core bits are mounted on the rotating shaft of various types of drilling machines. Core drills can be operated in any orientation—vertical or horizontal. Core drill machines can be powered by electric, hydraulic, or air power sources. Core drill bits can range in diameter from 0.5 to 60 in. (13 to 1524 mm), and drilling depths are virtually unlimited with the use of barrel extensions.

Example application: Core drilling played a major part in a hospital renovation in Halifax, FL. A contractor was hired to remove a 20 x 20 x 4 ft (6.1 x 6.1 x 1.2 m) tower crane footing that had been left behind when the hospital was originally built. Three electric drills were used to line drill 355 six in. (152 mm) diameter holes to a depth of 4.5 ft (1.4 m). Line drilling is a process where the holes are drilled side by side in a line. This process was used to partition the footer into 4 x 4 x 4 ft (1.2 x 1.2 x 1.2 m) sections weighing approximately 11,000 lb (4990 kg) each. A total of 355 holes were drilled in 10 days. This project, using core drilling, allowed the renovation to be completed within budget, allowed undisturbed use of the existing facilities, and demonstrated the advantages of today's diamond tool-cutting techniques as used by a professional cutting contractor.

Wire sawing

Wire sawing is a technique that originated in quarries to extract stone. It has proven to be an ideal choice for removal of thick sections of concrete. A wire saw consists of a multistrand cable with diamond segments that are threaded through a series of pulleys attached to a drive wheel that is powered by a hydraulic power unit. The combination of the spinning wire and constant pulling force cuts a path through the concrete and steel reinforcement. A typical wire diameter is 3/8 in. (10 mm). Wire saws can cut in any orientation—vertical or horizontal. Because the length of wire can be made to virtually any length, the cutting depth is unlimited.

Because virtually no concrete structure or cross section is too large to cut, wire saws are used whenever other cutting methods are impractical. The only restrictions are the lifting and removal specifications of the job. Wire sawing is ideal for removing large sections of heavily reinforced concrete, such as piers, towers, and bridge sections, and cutting concrete in areas where work space is restricted.

Example application: A nuclear power plant renovation in South Haven, MI, was performed with the use of a wire saw. Four large blocks of concrete with a steel liner were cut to change steam generators. The blocks of concrete were 3.5 ft (1.1 m) thick with 2 in. (51 mm) diameter reinforcing bar and lined with a 1/4 in. (6 mm) thick steel plate. The largest block measured 28 x 27 ft (8.5 x 8.2 m). The sawing was accomplished in 9 days using two four-man crews. The capability of the wire saw, in combination with the expertise of the professional cutting contractor, allowed this project to be completed in time and under budget.

Hand sawing

Hand sawing refers to the lighter-duty use of diamond blades in handheld power saws and chain-type saws. Hand sawing provides portability, speed, and accessibility at construction and demolition sites. Typical applications include sawing concrete pipe to length; creating openings for electrical, plumbing, or other needs in concrete walls, floors, and ceilings; eliminating overcuts associated with other types of sawing; and precision trimming.

Case studies

Restoration and corrosion protection of reinforced concrete airport terminal building

In 2005, the Washington Airports Authority decided to rehabilitate and maintain the exterior façade of the architecturally unique and historic Terminal A at Ronald Reagan Washington National Airport (Fig. 4.9).

Instead of demolishing the over-60-year-old structure, repairs were made to the damaged concrete areas, and electrochemical realkalization (Fig. 4.10) was used to increase the pH of the severely carbonated concrete façade to mitigate further corrosion and to extend the service life of the structure (Fig. 4.11).

Completing this work allowed the building to remain in service. As a result, 6755 yd^3 (5165 m^3) of concrete was maintained in service, and a comparable quantity of new concrete was not needed to rebuild a similar structure. Keeping the concrete in service and not replacing it with a similar quantity of new concrete prevented the release of 1688 tons (1531 metric tons) of CO_2 (equivalent to the average annual emissions of 335 people) and 67 tons of acid rain constituents (SO_2 and NOx). In terms of thermal pollution, maintaining the existing structure prevented the release of 18,000 GJ (17 million Btu) of heat into the environment. These quantities do not include the impact or contribution of demolition and disposal activities.

Restoration and service life extension of the Rainbow Bridge

Through the use of concrete repair procedures recommended by the International Concrete Repair Institute (ICRI) (chloride extraction and galvanic protection), a 50-year service life extension to this 75-year-old structure was designed and implemented. Designed and built in the 1930s as a Depression-era work project, the Rainbow Bridge (Fig. 4.12) is a critical transportation link in the Cascade Mountains north of Boise, ID. Completion of this project kept 1809 yd^3 (1383 m^3) of concrete in service. The CO_2 equivalent of this quantity of concrete is 450 tons (408 metric tons) of CO_2—equal to 90 person-years of CO_2 emissions. The embedded energy in this quantity of concrete is

Fig. 4.8—Hand sawing provides portability, speed, and accessibility at construction and demolition sites. *Photo courtesy of Concrete Sawing and Drilling Association*

approximately 4800 GJ (4.5 million Btu)—enough heat to boil three Olympic-sized swimming pools.

Parking deck repairs, Towson, MD

This 5200 ft^2 (483 m^2) parking deck (Fig. 4.13) was nearing the end of its service life, and was characterized by widespread concrete deterioration and severe corrosion of reinforcing and prestressing steel. As an alternative to demolition and reconstruction, the owner was able to repair the structure, reducing environmental impact while providing significant initial cost savings, life-cycle cost savings, and schedule savings.

Fig. 4.9—Deteriorated concrete condition before completion of the work (Terminal A at Ronald Reagan Washington National Airport). *Photo courtesy of International Concrete Repair Institute*

Fig. 4.10—Installation of realkalinization system. *Photo courtesy of International Concrete Repair Institute*

Fig. 4.11—Restored structure. *Photo courtesy of International Concrete Repair Institute*

The repair solution included selective concrete demolition and removal, concrete patching, shotcreting, carbon fiber wrapping, and additional post-tensioning. This fully integrated solution removed the poorly performing parts of the structure while maintaining the intact parts of the structure (Fig. 4.14). Completing this work allowed the building to remain in service. As a result, 1400 yd^3 (1070 m^3) of concrete was maintained in service, and a comparable quantity of new concrete was not needed to rebuild a similar structure. Keeping 6755 yd^3 (143 m^3) of concrete in service and not replacing it with a similar quantity of new concrete prevented the release of 350 tons (318 metric tons) of CO_2, (equivalent to the average annual emissions of 70 people) and 14 tons (13 metric tons) of acid rain constituents (SO_2 and NOx). In terms of thermal pollution, maintaining the existing structure prevented the release of 3700 GJ (3.5 million Btu) of heat into the environment. These quantities do not include the impact or contribution of demolition and disposal activities.

Frank Lloyd Wright's Fallingwater, Mill Run, PA

Fallingwater (Fig. 4.15) is a mainstay of American architecture, and is considered Frank Lloyd Wright's greatest work. While the beauty of the house and its blend with the local terrain is impressive, the structural design was not adequate for the loads. The major components of the architectural appeal of the house are the dramatic cantilevered concrete terraces that hang over a waterfall. Insufficient tensile reinforcement resulted in excessive deflections of the cantilevers from the day the house was constructed. Had the contractor not added additional reinforcement, the house terraces would not likely have remained standing under their own dead load to make it through the construction of the house in the 1930s. The cantilevers continued to deflect, and the lower terrace was finally propped to avoid potential failure, as shown in Fig. 4.16. The house is owned by the Western Pennsylvania Conservancy, and generates income for repairs and maintenance through tours. The repair method chosen needed to meet the following conditions:

- Maintain the architectural features of the original design (that is, maintain the cantilevered configuration of the terrace without adding additional supports and without changing the overall appearance of the structure);
- Be completed by a small crew (work was focused inside the space of a living room);
- Be accomplished quickly with minimal disruption so that tours could continue; and
- Provide a lasting solution that would not require continual patching and maintenance.

Fig. 4.12—Rainbow Bridge during rehabilitation (Cascade Mountains, ID). *Photo courtesy of International Concrete Repair Institute*

Fig. 4.13—Before and after rehabilitation (parking structure in Towson, MD). *Photo courtesy of International Concrete Repair Institute*

Fig. 4.14—Exposing structural members for repair. *Photo courtesy of International Concrete Repair Institute*

Post-tensioning was the optimal choice for the repair of the lower terrace because it had the ability to meet all of the constraints while providing a reliable, lasting solution. The lower terrace (that contains the living room) was an inverted T-beam system. The structural slab was on the bottom, and the floor for the living room consisted of large pieces of slate. The slate floor was temporarily removed so that the beams could be post-tensioned. Once the post-tensioning was complete, the slate floor was replaced, and the post-tensioning tendons were no longer visible to the public. The Conservancy decided to replace one slate piece with a clear "window" so that visitors could look at how the repair system was achieved. The dead-end anchorage for the post-tensioning was under the floor slab, and the live end (stressing end) was in recesses on the exterior of the terrace (Fig. 4.17). The recesses were filled after post-tensioning so that the anchorage was hidden from view.

The use of post-tensioning also provided the critical control necessary in adjusting the force so that the cantilevers were raised the correct amount to provide the needed strength and crack closure, but not to move them beyond their original deflection. The windows and interior components had been installed with a

Fig. 4.15—Frank Lloyd Wright's Fallingwater before retrofit. *Photo courtesy of James Loper and Jason Hughes*

Fig. 4.16—Shoring of main terrace and additional shoring of cave below. *Photo courtesy of Justin Brennan*

deflection in the cantilevers, so raising the cantilevers too high could cause destruction of the nonstructural elements that are an important part of the house. A very small crew was able to work inside the house during the retrofit, and special tours were given during weekends to Conservancy donors. The retrofit was a success, and the steel frame used to prop the cantilevered terrace was removed, restoring Fallingwater to its intended form.

Cecil C. Humphreys School of Law, University of Memphis, Memphis, TN

The Cecil C. Humphreys School of Law is housed in the historic structure that once housed Memphis Customs, the Federal Court House, and the Post Office (Fig. 4.18). The 140,000 ft^2 (13,006 m^2) building was originally built in the early 1880s, and had several additions during the early 1900s. The granite, marble, and limestone used in the building had held up well, but the building needed to be retrofit to meet earthquake building codes. The building sits near the New Madrid Fault Line, known for a series of major earthquakes in the early 1800s.

The original 1880 building core required the most serious retrofit. Shotcrete was chosen for the massive shear walls and other additions needed. No. 8 (25M) steel reinforcing bars were constructed on a new footing in the basement floor, and then covered with 12 in. (304.8 mm) of shotcrete to create the reinforced concrete shear walls. The 4 ft (1.22 m) wide footer was built with a depth of 4 or 6 ft (1.22 or 1.83 m) to meet the design specifications. During the construction of the steel-reinforced shear walls, mounting plates and dowels were carefully placed for the location of the new floors. Within the building's rectangular core, a 3 ft (1 m) area was demolished around the perimeter of the existing floors to provide access to the walls of the steel reinforcing bar that connected the separate levels of the building. The completed internal shell of reinforcement steel and shotcrete provided the structure with enough strength to allow for the removal of the pre-existing flooring and support beams. The roof above the building's rectangular core was demolished to provide access to the interior levels. Large cranes used wrecking balls to demolish the old horizontal floor of arched brick and concrete around the steel support beams. The old beams were connected to the crane, and then cut to be lifted away just before the new steel I-beams were installed at each level. The new floor plans included auditorium seating in the large classrooms, so they required slanted support beams at varying heights. The accurate placement of the end plates during the shotcrete process was critical to the I-beam installation. The application of shotcrete allowed for minimal forming for the 12 to 20 ft (3.66 to 6.1 m) tall shear walls and ease of access for multiple contractors working on the project (Fig. 4.19).

Shotcrete's minimal forming allowed large areas to be prepared with reinforcing bars in advance of the shotcrete placement. The large historical building with multiple levels and an existing floor plan created many challenges during this project, but the use of shotcrete allowed the seismic retrofit to have minimal impact to the building's appearance. The Cecil C. Humphreys School of Law is a modern learning environment in a historical building, and the use of shotcrete helped to ensure a safe environment for many years to come.

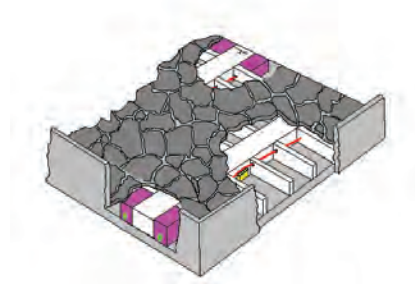


Fig. 4.17—Post-tensioning layout on main terrace below slate flooring (post-tensioning anchor blocks in pink, post-tensioning tendons in red, deviator in yellow).

Fig. 4.18—University of Memphis' Cecil C. Humphreys School of Law following the renovation project. *Photo courtesy of Lindsey Lissau*

Fig. 4.19—Interior wall in preparation for shotcrete application. *Photo courtesy of American Shotcrete Association*

Chapter 27—Preservation and adaptive reuse

The previous chapter makes a case for the benefits of maintenance and repair. To merely claim a place for repair in the relatively recent environmental dialog is to diminish the fact that it is truly part of the foundation of a repair and preservation philosophy that has a long and distinguished history that began long before the green building movement began.

Preservation

It is enlightening to consider concrete repair as we know it today from the perspective of the early development of the historic preservation movement in the United States that was codified in the National Historic Preservation Act (NHPA) of 1966. At the time NHPA was enacted, there was a growing acceptance that reusing existing structures was desirable on many levels. In its infancy, the application of NHPA tended to focus on nationally important historic landmarks, but it quickly grew to encompass a wide range of structure types and sites as well as professionals and trades-people from many design and construction-related fields. The individuals and organizations involved recognized long ago that the preservation of the existing built environment is beneficial for preserving cultural heritage for social reasons, but also for limiting urban sprawl, assisting with economic growth and development, and many other reasons now at the focus of sustainable practices.

Many of the arguments commonly heard in current mainstream dialogs about the need to create sustainable communities have been, for decades, the very tenets by which the repair and preservation communities have purposefully extended the life of those communities as they already exist.

In 1966, the U.S. Congress stated in the text of the NHPA that "the preservation of this irreplaceable heritage is in the public interest so that its vital legacy of cultural, educational, aesthetic, inspirational, economic, and energy benefits will be maintained and enriched for future generations of Americans" (National Trust for Historic Preservation 2010). This statement, issued 44 years ago, is clearly echoed in the widely accepted definition of sustainability offered by the U.N. Bruntland Commission's 1987 report (Bruntland 1987), which defines sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs," and the context of the three separate—but interrelated—principles of sustainability that are currently recognized, including environmental, economic, and social aspects. In other words, the principles of preservation formed long ago, which have underscored the motivation for repair projects for ages, are an intrinsic component of current efforts toward environmental sustainability.

Giving economic teeth to programs that encourage sustainable building practices, the Federal Historic Preservation Tax Incentives program (2009), an outgrowth of NHPA, allows for 10 to 20% tax credits for the substantial rehabilitation of qualified existing structures. This program has become one of the nation's most successful and cost-effective community revitalization programs ever enacted. In fiscal year 2006, 1253 projects that represented a record-breaking $4.08 billion U.S. dollars in private investment were approved. This program generates jobs while investing in the infrastructure of neighborhoods and historic city cores. Additionally, more than one-half of the states in the U.S. have also enacted tax credit laws for building preservation that offer tax relief for owners of existing buildings.

Beyond green

A unique public-private partnership grew from the successes of NHPA, namely the supportive working relationship between the federal government and the National Trust for Historic Preservation (NTHP). NTHP is the only public-private partnership of its kind at the federal level. The NTHP's focus goes beyond historic buildings to include all existing buildings, and has a strong position on the need for historic preservation as a key component of sustainability. Extending the life of existing structures is the ultimate act of sustainability. It reduces the depletion of additional natural resources, and reduces energy consumption. Through the conservation of materials and overall structures, we benefit from the energy that was consumed during the original material manufacturing and construction of existing structures. Models have been developed that can calculate the energy consumption for many types of structures. Figure 4.20 illustrates a comparison from NTHP data on energy use in an average office building.

Another model for assessing energy cost is life-cycle analysis (LCA). More details about LCA modeling are available in *The Sustainable Concrete Guide—Strategies and Examples* (Schokker 2010), but the key point is that, similar to the embodied energy discussion in the previous paragraph, numbers point toward repair and reuse.

To this end, consider the concrete repair industry in terms of the National Trust for Historic Preservation's Sustainability Initiative designed "to develop a national policy for the integration of sustainability and preservation" (**http://www.preservationnation.org/issues/sustainability/**). The organizations currently involved are the American Institute of Architects (AIA), the Association for Preservation Technology International (APT), the National Park Service (NPS), the National Trust for Historic Preservation (NTHP), the General Services Administration (GSA), and the National Conference of State Historic Preservation Officers (NCSHPO). This effort toward integrating the practices and principles of preservation into the green building movement are directly supportive of the evidence that shows how repair is environmentally and economically desirable.

In "Making the Case: Historic Preservation as Sustainable Development," a white paper (Frey 2007) written in advance of a research retreat for the Trust's Sustainability Initiative, conservation of energy and natural resources through building reuse are addressed in support of the idea that preservation promotes environmentally, economically, and socially sustainable development. The Trust's Initiative addresses several perceived environmental weaknesses of historic buildings, including that old buildings are often considered to be energy hogs. In reality, many historic buildings are more energy efficient than more recent buildings—particularly concrete and masonry buildings that inherently possess significant thermal mass—which reduces mechanical heating-and-cooling needs. Frey (2007) reports that 2003 data from the U.S. Energy Information Agency suggests that buildings constructed before 1920 are actually more energy efficient than buildings built any time afterwards up until 2000. The General Services Administration found in a 1999 study that the utility costs for the historic buildings in the GSA inventory were 27% less than for more modern building (National Trust for Historic Preservation [2010]). It is important to realize, however, that many inefficient older buildings certainly do exist, and that misguided alterations to others have actually reduced their energy efficiency.

adaptive reuse and restoration of historic buildings that kept the building shell intact.

Equipped for the future

As a nation, we are much too inclined to think of our buildings as disposable rather than a renewable resource. A 2004 report from the Brookings Institution projects that by 2030, we will have demolished and replaced 82 billion ft^2 (7.6 billion m^2)of our current building stock. It is estimated that there are approximately 300 billion ft^2 (27.9 billion m^2) of space in the U.S. today, which means that we anticipate demolishing nearly one-third of our building stock in the next 20 to 25 years. If we were to rehabilitate and/or adapt even 10% of the 82 billion ft^2 (7.6 billion m^2), we would save enough energy to power the state of New York for well over a year.

As the design and construction industries become increasingly more complex, we must be personally and collectively equipped to sit at the table and present the environmental, economic, and social arguments supporting the idea that just because we can build new, tall, and large, it does not follow that we should if viable repair and modification alternatives exist. Conversely, just because the technology exists for almost any level of repair, we should not do it at all costs, or in every situation.

Concrete that is properly designed, constructed, and maintained requires fewer repairs over its service life. Preventative maintenance and periodic repair tends to

Adaptive reuse

Adaptive reuse targets buildings that may or may not need to be repaired—buildings that have lived out their intended need by the original occupants. A building itself can continue to operate efficiently, but the primary function for which it was designed is no longer appropriate. A building can be reused (or readapted) for a small portion of the cost (both monetary and to the environment) that would be needed to demolish it and build again. Chapter 22 on tilt-up concrete applications provides a good example of going from one extreme (an aerospace warehouse and maintenance facility) to another (the AOL Creative Center) in adapting a 90,000 ft^2 (8400 m^2) building very effectively (Fig. 3.29). Other more common types of adaptive reuse include modifications among hotel, office building, and condominium facilities. Two case studies are given that highlight the

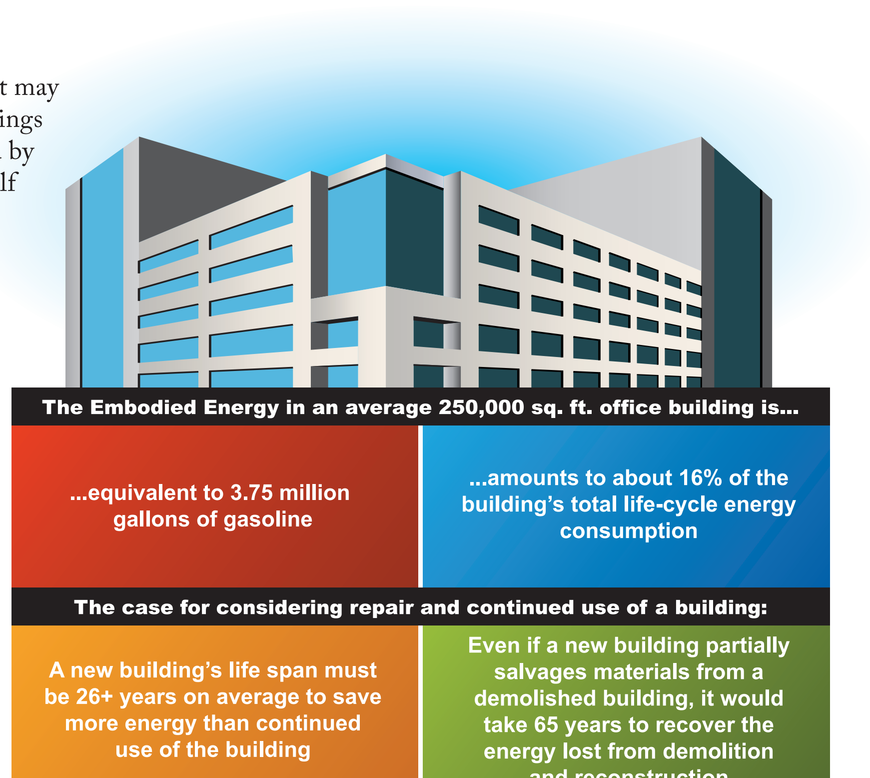


Fig. 4.20—The case for repair.

be more effective in extending the service cycle of concrete structures than allowing deterioration to propagate with occasional, poor-quality repairs.

Due to the continued deterioration of our existing building inventory and infrastructure, a large volume of concrete repair will be needed for the foreseeable future. Each cycle of repair contributes to the waste stream, consumes resources, and may be less durable than desired. The debris from the repair, as well as the replacement material composition and packaging, should have a management plan developed for recycling, reuse, or disposal to minimize the environmental impact.

When repairs are required, proper condition evaluation is needed to understand the causes and extent of deterioration. A life-cycle cost analysis can demonstrate the financial implications of deferred repairs, proactive maintenance, and cost effectiveness of remedial measures.

To minimize environmental impact, repairs that are implemented should be as durable as the remaining structure, address the root cause of the deterioration, and prevent future deterioration, such as that which results from reinforcement corrosion. The quality of the installed repairs should be verified during installation, and the structure should be monitored and inspected as appropriate based on the criticality of the structure.

Current sustainability initiatives tend to focus on new construction. It is more difficult to capture the value of structures based on their longevity, social impact, historical contribution, and embodied energy. The decision regarding the fate of a structure is biased to favor replacement instead of realizing that the time to offset the energy consumption of new construction is often many years compared with modernizing the operating efficiency of existing structures.

The facts and issues addressed herein argue for the intrinsic value of our existing built environment. Acknowledging their validity, these facts and issues further point to the need for extending the life of existing structures, which entails understanding the essential repair tools and approaches used in that pursuit. Full participation in the commitment to living and building sustainably should include an acceptance of these primary truths.

PART 5— CODES

Introduction

Building design and construction are governed by codes to safeguard public health, safety and general welfare through structural strength, means of egress facilities, stability, sanitation, adequate light and ventilation, energy conservation, and safety to life and property from fire and other hazards attributed to the built environment and to provide safety to fire fighters and emergency responders during emergency operation. These codes exist at all levels: national, state, and local. Part 5 focuses on what can be done in the area of sustainability while remaining within the building code framework. Several entities are developing new documents in an attempt to "standardize" and "codify" sustainable concepts and practices that enhance the provisions of codes and referenced standards that address criteria related to green or sustainable buildings. Such recent green codes are also discussed.

It is important to realize the difference between green rating systems (certification systems) and green building codes. Rating systems such as U.S. Green Building Council LEED (Leadership in Energy and Environmental Design) and Green Building Initiative Green Globes generally provide prescriptive solutions to incorporating select sustainable concepts into buildings across areas such as site use, water, energy, materials, emissions, and air quality. Third-party verification is then required to acknowledge that a building has incorporated a certain level of these sustainable building strategies. These rating systems are not codes or standards. They are not written in mandatory language, and are not properly suited for adoption by regulatory jurisdictions, although several jurisdictions have or are considering adoption of these programs as mandatory building code requirements. These rating systems have, however, had a crucial role in establishing a heightened awareness of the types of improvements that can make a measurable difference toward sustainable building. Indeed, they are moving to transform the design and construction of buildings.

As the building industry has matured in the area of sustainable building through the green rating systems, the development, acceptance, and use of a green building code is more likely at a national level. A building code has a fundamental objective to address life safety along with performance during service. Code items are written in mandatory language (such as "shall be…"), and are intended to be followed rigorously. Reports and commentaries written in nonmandatory language can be used to explain background or intent of code language, but they are technically not codes or parts of codes. Codes are intended to be included by reference without a change in wording of the code language. The green building codes currently being developed are discussed in this section, and are a major move forward in integrating green rating system categories into appropriate mandatory code language to achieve sustainable buildings. However, such efforts like the ratings systems are remiss in that these national initiatives do not adequately consider the need for appropriate enhancements to assure functional resilience.

Fortunately, as green codes continue to evolve, there is developing discussion on the importance of a structure's ability to withstand natural disasters such as wind, fire, and flood. Terms such as "functional resilience" express a structure's durability, competence to maintain its integrity, and ability to have its function restored following environmental change or disaster. Ensuring that our building stock does not have to be replaced (thus consuming additional resources) may well become an extension of the current definition of sustainability developed specifically for certification programs.

A sustainable building should be built above the minimum requirements of a building code, and green codes often enhance and set more stringent requirements than building codes. However, these provisions do not adequately provide the necessary level of functional resilience for high-performance buildings.

In addition to the benefits of enhanced functional resilience during normal operations, when disasters occur, building components are often contaminated or irreparable. High-efficiency appliances and heating, ventilating, air conditioning (HVAC) components, low-flow plumbing fixtures, and building materials with high recycled content contribute very little to sustainability when they end up in landfills or must be incinerated. The result is not only an inefficient use of materials and repetitive installation due to repair, reconstruction, demolition, and replacement, but it is also disruption to business continuity and is an added drain on local, state and federal resources and often increase the exposure to risk for emergency responders than in more functionally resilient buildings.

Figure 5.1 illustrates the relationship typically discussed between rating systems and existing building codes. The lines connecting the green issues (covered by the rating systems) and the individual codes indicate where codes are referenced from the rating systems. This relationship does not provide the full picture, as true sustainable design is more systematic through the building. For instance, concrete would seem to fall under the "materials" category (governed by the appropriate sections of the building code and ACI 318-08 [ACI Committee 318 2008]), but this only tells a portion of the story. A choice of material, such as concrete, can also influence green issues such as energy (through thermal mass), air quality (elimination of coatings), site use (storm-water control via pervious concrete, and others. Figure 5.2 shows an expanded representation that indicates how a green building code can incorporate green issues along with code requirements in a comprehensive green code such as the *International Green Construction Code (IGCC)* (International Code Council 2010) that is discussed in the following chapter.

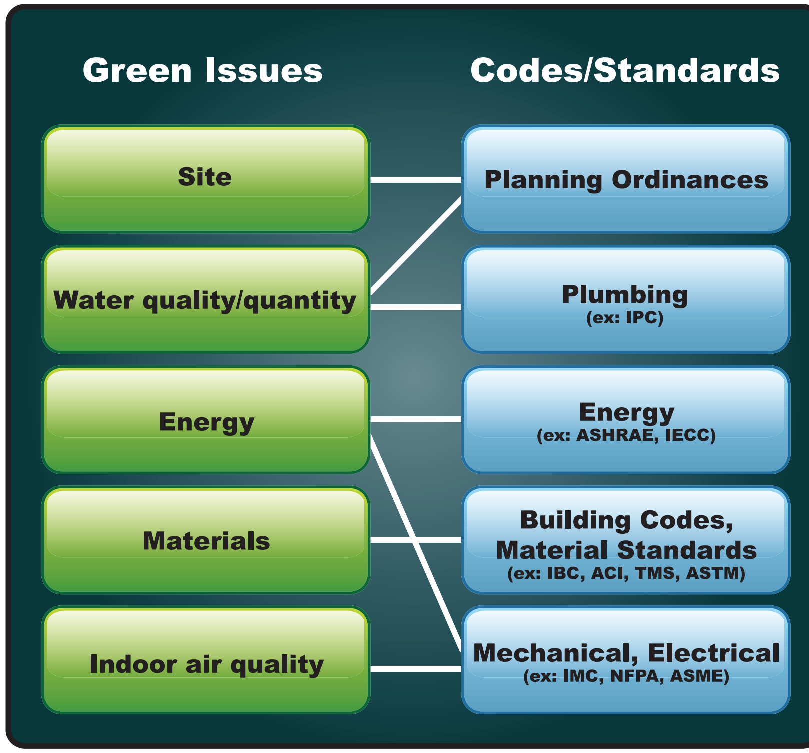


Fig. 5.1—Green issues and their relation to existing codes and standards.

Fig. 5.2—Comprehensive incorporation of green issues and codes/standards by the IGCC.

Chapter 28—National, state, and local codes

The *International Building Code* (IBC) (International Code Council 2009) is the model building code addressing the design and construction of buildings other than low-rise residential buildings. This code is often adopted by state and local jurisdictions in full or in part, although some jurisdictions do maintain their own building code. This chapter briefly discusses traditional codes related to concrete and masonry, national model codes developed as part of an initiative toward sustainable building, and model codes specific to energy performance in buildings Voluntary rating systems, such as LEED and Green Globes, are not included in this discussion.

The U.S. Environmental Protection Agency (EPA) and the U.S. Department of Energy (DOE) do not have a green building code or rating system certification, but rather have developed the ENERGY STAR® program to qualify buildings as energy efficient (both for new construction and renovations), the Environmentally Preferable Purchasing program, and other programs.

National Green Building Standard (ICC-700-2008)

The *National Green Building Standard* (NGBS) was developed jointly by the National Association of Home Builders (NAHB) and the International Code Council (ICC) (2008). The document is approved by the American National Standards Institute (ANSI), and covers residential construction: single- and multi-family homes, residential remodeling, and site development. The standard includes both mandatory provisions and a performance rating system. In the performance rating system, a threshold point value is given for achieving one of four different levels: emerald, gold, silver, or bronze. The categories for achieving point values include lot/site development; efficiency of resources, water, and energy; indoor environmental air quality; and operation, maintenance, and education of building owners.

International Green Construction Code (IGCC)

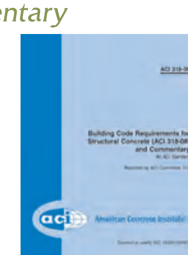
The *International Green Construction Code* (International Code Council 2010) is currently under development to be published in 2012 (release of public review version 1.0 was in March of 2010). The IGCC is intended to be distinct from the voluntary rating systems in that it is written in mandatory language and is intended to be administered by code officials and adopted by state and local governments (International Code Council 2010). The IGCC provides requirements that are intended to reduce negative impacts of a building on the environment. The initial draft was developed by the ICC in cooperation with the American Institute of Architects (AIA) and ASTM International (ASTM). The cooperative effort has since been expanded to include the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), U.S. Green Building Council (USGBC), and Illuminating Engineering Society of North America (IES).

The current draft of the IGCC is applicable to design and construction; additions, alterations, and demolition; change of use or occupancy; equipment; location; and maintenance. The IGCC is also applicable to all occupancies, except residential structures that fall under the *National Green Building Standard* (National Association of Home Builders and the International Code Council 2008). The IGCC is not a stand-alone document, and is intended as an overlay code, enhancing the criteria of the IBC. Indeed, the IBC must still be invoked along with the IGCC. ASHRAE 189.1, *Standard for the Design of High-Performance Green Buildings*, *Except Low Rise Residential Buildings* (The American Society of Heating, Refrigerating and Air-Conditioning Engineers 2009) is also included by reference as a compliance path option in IGCC. ASHRAE codes are described later in this section.

Unlike rating systems, the IGCC, where adopted, provides the owner with a document they must use to specify requirements in their specific area of concern (such as water, energy, conservation of natural resources, etc). The IGCC is primarily mandatory requirements rather than options that give the owner or designer choices on which requirements they would like to follow to achieve sustainability. State and local governments can specify any level of criteria that meets their needs and will be supplied with mandatory language that can be enforced to meet those needs.

Codes specific to concrete and masonry

ACI 318-08: Building Code Requirements for Structural Concrete and Commentary



ACI 318-08 (ACI Committee 318 2008) is developed by the American Concrete Institute (ACI) through an ANSI-approved consensus process, and has a focus on life safety. Related to life safety is the long-term durability consideration outlined in ACI 318-08, protecting a concrete's ability to survive and function during its lifetime. ACI 318-08 is recognized as the definitive source for the design of concrete buildings, and is adopted by reference in the IBC. The applications discussed in Part 3 are currently in use, and are being designed to meet the requirements of ACI 318-08. Life safety design codes perform a very important function. Their development via a rigorous

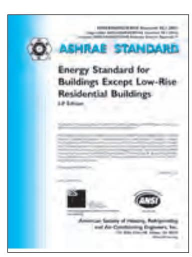
and necessary consensus process may occasionally slow the direct implementation of highly innovative new systems, but a majority of innovative structural members can often fit within the current life safety requirements. Those that don't can be introduced through the consensus process to be properly vetted before their use as a structural component.

Building Code Requirements for Masonry Structures (ACI 530-02/ASCE 5-02/TMS 402-02), Specifications for Masonry Structures (ACI 530.1-02/ASCE 6-02/TMS 602-02) and Commentaries

ACI 530-02/ASCE 6-02/TMS 602-02 (Joint ACI/ASCE/TMS Committee 530 2002) covers design of masonry structures, and is referenced by the IBC and the National Fire Protection Association (NFPA) Code. The masonry building products discussed in Part 3 would be designed by this code.

Codes Specific to Energy and Thermal Performance

Thermal comfort is one of the main reasons we have buildings. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) produces standards that affect the design and construction of building enclosures and mechanical equipment needed to ensure thermal comfort. These standards include:



- ASHRAE Standard 90.1, Energy Standard for Buildings Except Low-Rise Residential Buildings;
- ASHRAE Standard 90.2, Energy Efficient Design of Low-Rise Residential Buildings;
- ASHRAE Standard 62.2, Ventilation for Acceptable Indoor Air Quality; and
- ASHRAE Standard 55, Thermal Environmental Conditions for Human Occupancy.

ASHRAE also publishes the Advanced Energy Design Guide series. These documents allow designers to detail and specify buildings with high energy efficiencies—without needing to resort to detailed analyses. The initial guides were developed to provide an energy savings target of 30% relative to Standard 90.1-1999. Several new guides are in work and will provide the tools needed to achieve 50% energy savings compared to buildings that meet the minimum requirements of Standard 90.1-2004.

Some states and local municipalities have incorporated sustainable building requirements into their codes, either by reference of the model codes or referenced standards covered in Chapter 27, by establishing their own specific requirements, or implementing certification programs as code requirements. The IGCC is envisioned to be a code that can be easily incorporated by state and local jurisdictions; or where not mandatory, used by owners to achieve the level of sustainable requirements appropriate for a particular region and situation. Certain states, such as California, have established their own substantial green building codes. "CalGreen," the California Green Building Standards Code (California Building Standards Commission 2010) was the first state code of its kind, and played a key role as a reference for the new IGCC. In New York City, a Green Codes Task Force reviewed all of New York City's existing codes to provide recommendations for changes to make the codes green. These recommendations included removing language that was an impediment to green building practices.

Most states and municipalities do not have the resources to develop their own green building codes. To aid them in customizing (above a minimum life safety standard) the IBC requirements to meet their needs in the sustainability area, the Portland Cement Association (PCA) has developed an extensive resource document of "Proposed Amendments to the International Building Code, 2009 Edition, Relating to High Performance Building Requirements for Sustainability" (Portland Cement Association 2009). The intention of the proposed amendments is to provide requirements for sustainability, including energy efficiency, increased disaster resistance, and improved durability in a format that is easily adopted. This publication effectively and efficiently aids a state or municipality in having a sustainability-enhanced building code even if they do not have extensive resources to develop their own. Additional details can be found at **www.cement.org**.

APPENDIXES

Appendix A—ACI Manual of Concrete Practice

Developed to be comprehensive, the American Concrete Institute's Manual of Concrete Practice contains the Institute's documents needed to answer questions about code requirements, specifications, tolerances, concrete proportions, construction methods, evaluations of test results, and many more topics. In fact, the Manual of Concrete Practice includes 200 of ACI's most-used documents on concrete technology. Available from **www.concrete.org** as a six-volume set, CD-ROM, or online subscription.

Specifications for Tolerances for Concrete Construction and Materials (ACI 117-10) and Commentary—117-10

Specifications for Tolerances for Concrete Construction and Materials (ACI 117M-10) and Commentary—117M-10

Guide for Concrete Construction Quality Systems in Conformance with ISO 9001—121R-08

Guide to Thermal Properties of Concrete and Masonry Systems—122R-02

Guide to Recommended Format for Concrete in a Materials Property Database—126.3R-99(08)

Guide for Conducting a Visual Inspection of Concrete in Service—201.1R-08

Guide to Durable Concrete—201.2R-08

Guide to Mass Concrete—207.1R-05

Report on Thermal and Volume Change Effects on Cracking of Mass Concrete—207.2R-07

Practices for Evaluation of Concrete in Existing Massive Structures for Service Conditions—207.3R-94 (Reapproved 2008)

Cooling and Insulating Systems for Mass Concrete—207.4R-05

Roller-Compacted Mass Concrete—207.5R-99

Prediction of Creep, Shrinkage, and Temperature Effects in Concrete Structures—209R-92 (Reapproved 2008)

Report on Factors Affecting Shrinkage and Creep of Hardened Concrete—209.1R-05

Guide for Modeling and Calculating Shrinkage and Creep in Hardened Concrete—209.2R-08

Erosion of Concrete in Hydraulic Structures—210R-93 (Reapproved 2008)

Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete—211.1-91 (Reapproved 2009)

Standard Practice for Selecting Proportions for Structural Lightweight Concrete—211.2-98 (Reapproved 2004)

Guide for Selecting Proportions for No-Slump Concrete—211.3R-02 (Reapproved 2009)

Guide for Selecting Proportions for High-Strength Concrete Using Portland Cement and Other Cementitious Materials—211.4R-08

Guide for Submittal of Concrete Proportions—211.5R-01 (Reapproved 2009)

Chemical Admixtures for Concrete—212.3R-04

Guide for the Use of High-Range Water-Reducing Admixtures (Superplasticizers) in Concrete—212.4R-04

Guide for Structural Lightweight-Aggregate Concrete—213R-03

Evaluation of Strength Test Results of Concrete—214R-02

Guide for Obtaining Cores and Interpreting Compressive Strength Results—214.4R-10

Code Requirements for Determining Fire Resistance of Concrete and Masonry Construction Assemblies—216.1-07

Code Requirements for Determining Fire Resistance of Concrete and Masonry Construction Assemblies—216.1M-07

Guide for Use of Normal Weight and Heavyweight Aggregates in Concrete—221R-96 (Reapproved 2001)

Report on Alkali-Aggregate Reactivity—221.1R-98 (Reapproved 2008)

Protection of Metals in Concrete Against Corrosion—222R-01 (Reapproved 2010)

Corrosion of Prestressing Steels—222.2R-01 (Reaproved 2010)

Design and Construction Practices to Mitigate Corrosion of Reinforcement in Concrete Structures—222.3R-03

Standard Practice for the Use of Shrinkage-Compensating Concrete—223-98

Control of Cracking in Concrete Structures—224R-01 (Reapproved 2008)

Causes, Evaluation, and Repair of Cracks in Concrete Structures—224.1R-07

Cracking of Concrete Members in Direct Tension—224.2R-92 (Reapproved 2004)

Joints in Concrete Construction—224.3R-95 (Reapproved 2008)

Guide to the Selection and Use of Hydraulic Cements—225R-99 (Reapproved 2009)

In-Place Methods to Estimate Concrete Strength—228.1R-03

Nondestructive Test Methods for Evaluation of Concrete in Structures—228.2R-98 (Reapproved 2004)

Controlled Low-Strength Materials—229R-99 (Reapproved 2005)

Report on Soil Cement—230.1R-09

Report on Early-Age Cracking: Causes, Measurement, and Mitigation—231R-10

Use of Raw or Processed Natural Pozzolans in Concrete—232.1R-00 (Reapproved 2006)

Use of Fly Ash in Concrete—232.2R-03

Slag Cement in Concrete and Mortar—233R-03

Guide for the Use of Silica Fume in Concrete—234R-06

Self-Consolidating Concrete—237R-07

Report on Measurements of Workability and Rheology of Fresh Concrete—238.1R-08

Specifications for Structural Concrete—301-10

Specifications for Structural Concrete—301M-10

Field Reference Manual—SP-15(05)

Guide for Concrete Floor and Slab Construction—302.1R-04

Guide for Concrete Slabs that Receive Moisture-Sensitive Flooring Materials—302.2R-06

Guide to Cast-in-Place Architectural Concrete Practice—303R-04

Standard Specification for Cast-in-Place Architectural Concrete—303.1-97

Guide for Measuring, Mixing, Transporting, and Placing Concrete—304R-00(09)

Guide for the Use of Preplaced Aggregate Concrete for Structural and Mass Concrete Applications—304.1R-92 (Reapproved 2005)

Placing Concrete by Pumping Methods—304.2R-96 (Reapproved 2008)

Heavyweight Concrete: Measuring, Mixing, Transporting, and Placing—304.3R-96 (Reapproved 2004)

Placing Concrete with Belt Conveyors—304.4R-95(08)

Guide for Use of Volumetric-Measuring and Continuous-Mixing Concrete Equipment—304.6R-09

Guide to Hot Weather Concreting—305R-10

Specification for Hot Weather Concreting—305.1-06

Cold Weather Concreting—306R-88 (Reapproved 2002)

Standard Specification for Cold Weather Concreting—306.1-90 (Reapproved 2002)

Code Requirements for Reinforced Concrete Chimneys (ACI 307-08) and Commentary—307-08

Guide to Curing Concrete—308R-01 (Reapproved 2008)

Standard Specification for Curing Concrete—308.1-98

Guide for Consolidation of Concrete—309R-05

Behavior of Fresh Concrete During Vibration—309.1R-08

Identification and Control of Visible Effects of Consolidation on Formed Concrete Surfaces—309.2R-98 (Reapproved 2005)

Compaction of Roller-Compacted Concrete—309.5R-00 (Reapproved 2006)

ACI Manual of Concrete Inspection—311.1R-07 [SP-2-07]

Guide for Concrete Inspection—311.4R-05

Guide for Concrete Plant Inspection and Testing of Ready-Mixed Concrete—311.5-04

Specification for Ready-Mixed Concrete Testing Services—311.6-09

Specification for Ready-Mixed Concrete Testing Services—311.6M-09

Standard Practice for Design and Construction of Concrete Silos and Stacking Tubes for Storing Granular Materials—313-97

Commentary on Standard Practice for Design and Construction of Concrete Silos and Stacking Tubes for Storing Granular Materials—313R-97

ACI Detailing Manual—SP-66(04)

Building Code Requirements for Structural Concrete and Commentary—318

Building Code Requirements for Structural Concrete and Commentary—318M

ASTM Standards in ACI 318-08—SP-71(08)

Report on Roller-Compacted Concrete Pavements—325.10R-95 (Reapproved 2001)

Accelerated Techniques for Concrete Paving—325.11R-01

Guide for Design of Jointed Concrete Pavements for Streets and Local Roads—325.12R-02

Concrete Overlays for Pavement Rehabilitation—325.13R-06

Guide for the Design and Construction of Concrete Parking Lots—330R-08

Specification for Unreinforced Concrete Parking Lots—330.1-03

Residential Code Requirements for Structural Concrete (ACI 332-10) and Commentary—332-10

Residential Code Requirements for Structural Concrete (ACI 332M-10) and Commentary—332M-10

Guide to Residential Concrete Construction—332.1R-06

Concrete Shell Structures—Practice and Commentary—334.1R-92(02)

Construction of Concrete Shells Using Inflated Forms—334.3R-05

Specification for the Construction of Drilled Piers—336.1-01

Suggested Analysis and Design Procedures for Combined Footings and Mats—336.2R-88 (Reapproved 2002)

Design and Construction of Drilled Piers—336.3R-93 (Reapproved 2006)

Seismic Analysis and Design of Concrete Bridge Systems—341.2R-97 (Reapproved 2003)

Seismic Evaluation and Retrofit Techniques for Concrete Bridges—341.3R-07

Analysis and Design of Reinforced Concrete Bridge Structures—343R-95 (Reapproved 2004)

Guide for Concrete Highway Bridge Deck Construction—345R-91 (Reapproved 2005)

Guide for Maintenance of Concrete Bridge Members—345.1R-06

Guide for Widening Highway Bridges—345.2R-98 (Reapproved 2005)

Specification for Cast-in-Place Concrete Pipe—346-09

Specification for Cast-in-Place Concrete Pipe—346M-09

Guide to Formwork for Concrete—347-04

Guide for Shoring/Reshoring of Concrete Multistory Buildings—347.2R-05

Formwork for Concrete—SP-4(05)

Code Requirements for Nuclear Safety-Related Concrete Structures (ACI 349-06) and Commentary—349-06

Code Requirements for Nuclear Safety-Related Concrete Structures (ACI 349M-06) and Commentary—349M-06

Reinforced Concrete Design for Thermal Effects on Nuclear Power Plant Structures—349.1R-07

Guide to the Concrete Capacity Design (CCD) Method—Embedment Design Examples—349.2R-07

Evaluation of Existing Nuclear Safety-Related Concrete Structures—349.3R-02 (Reapproved 2010)

Code Requirements for Environmental Engineering Concrete Structures and Commentary—350-06

Code Requirements for Environmental Engineering Concrete Structures and Commentary—350M-06

Tightness Testing of Environmental Engineering Concrete Structures and Commentary—350.1-01

Concrete Structures for Containment of Hazardous Materials—350.2R-04

Seismic Design of Liquid-Containing Concrete Structures and Commentary—350.3-06

Design Considerations for Environmental Engineering Concrete Structures—350.4R-04

Grouting between Foundations and Bases for Support of Equipment and Machinery—351.1R-99 (Reapproved 2008)

Report on Foundations for Static Equipment—351.2R-10

Foundations for Dynamic Equipment—351.3R-04

Recommendations for Design of Beam-Column Connections in Monolithic Reinforced Concrete Structures—352R-02 (Reapproved 2010)

Recommendations for Design of Slab-Column Connections in Monolithic Reinforced Concrete Structures—352.1R-89 (Reapproved 2004)

Qualification of Post-Installed Mechanical Anchors in Concrete and Commentary—355.2-07

Guide for the Design and Construction of Fixed Offshore Concrete Structures—357R-84 (Reapproved 1997)

Report on Floating and Float-In Concrete Structures —357.2R-10

Analysis and Design of Reinforced and Prestressed-Concrete Guideway Structures—358.1R-92

Code for Concrete Containments—359-07

Guide to Design of Slabs-on-Ground—360R-10

Guide for the Design of Durable Parking Structures—362.1R-97 (Reapproved 2002)

Guide for Structural Maintenance of Parking Structures—362.2R-00 (Reapproved 2005)

Report on High-Strength Concrete—363R-10

Guide to Quality Control and Testing of High-Strength Concrete—363.2R-98

Guide for Evaluation of Concrete Structures before Rehabilitation—364.1R-07

Increasing Shear Capacity Within Existing Reinforced Concrete Structures—364.2T-08

Treatment of Exposed Epoxy-Coated Reinforcement in Repair—364.3T-10

Determining the Load Capacity of a Structure When As-Built Drawings are Unavailable—364.4T-10

Guide for Cementitious Repair Material Data Sheet—364.3R-09

Importance of Modulus of Elasticity of Repair Materials—364.5T-10

Service-Life Prediction—365.1R-00

Guide for the Analysis, Design, and Construction of Elevated Concrete and Composite Steel-Concrete Water Storage Tanks—371R-08

Design and Construction of Circular Wire- and Strand-Wrapped Prestressed Concrete Structures—372R-03

Design and Construction of Circular Prestressed Concrete Structures with Circumferential Tendons—373R-97 (Reapproved 2010)

Acceptance Criteria for Moment Frames Based on Structural Testing and Commentary—374.1-05

Code Requirements for Design and Construction of Concrete Structures for the Containment of Refrigerated Liquefied Gases (ACI 376-10) and Commentary—376-10 (Provisional)

Bond and Development of Straight Reinforcing Bars in Tension—408R-03

Bond Under Cyclic Loads—408.2R-92 (Reapproved 2005)

Guide for Lap Splice and Development Length of High Relative Rib Area Reinforcing Bars in Tension and Commentary—408.3R-09

Shear Reinforcement for Slabs—421.1R-08 (Reapproved 2006)

Guide to Seismic Design of Punching Shear Reinforcement in Flat Plates—421.2R-10

Recommendations for Concrete Members Prestressed with Unbonded Tendons—423.3R-05

Corrosion and Repair of Unbonded Single Strand Tendons—423.4R-98

Specification for Unbonded Single-Strand Tendon Materials and Commentary—423.7-07

Test Method for Bleed Stability of Cementitious Post-Tensioning Tendon Grout—423.9M-10

Control of Deflection in Concrete Structures—435R-95 (Reapproved 2000)

Observed Deflections of Reinforced Concrete Slab Systems, and Causes of Large Deflections—435.8R-85 (Reapproved 1997)

Strength Evaluation of Existing Concrete Buildings—437R-03

Load Tests of Concrete Structures: Methods, Magnitude, Protocols, and Acceptance Criteria—437.1R-07

Types of Mechanical Splices for Reinforcing Bars—439.3R-07

Report on Steel Reinforcement—Material Properties and U.S. Availability—439.4R-09

Report on Fiber-Reinforced Polymer (FRP) Reinforcement for Concrete Structures—440R-07

Guide for the Design and Construction of Structural Concrete Reinforced with FRP Bars—440.1R-06
Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures—440.2R-08
Guide Test Methods for Fiber-Reinforced Polymers (FRP) for Reinforcing or Strengthening Concrete Structures—440.3R-04
Prestressing Concrete Structures with FRP Tendons—440.4R-04
Specification for Construction with Fiber-Reinforced Polymer Reinforcing Bars—440.5-08
Specification for Construction with Fiber-Reinforced Polymer Reinforcing Bars—440.5M-08
Specification for Carbon and Glass Fiber-Reinforced Polymer Bar Materials for Concrete Reinforcement—440.6-08
Specification for Carbon and Glass Fiber-Reinforced Polymer Bar Materials for Concrete Reinforcement—440.6M-08
Guide for the Design and Construction of Externally Bonded Fiber-Reinforced Polymer Systems for Strengthening Unreinforced Masonry Structures—440.7R-10
Report on High-Strength Concrete Columns—441R-96
Recent Approaches to Shear Design of Structural Concrete—445R-99 (Reapproved 2009)
Fracture Mechanics of Concrete: Concepts, Models, and Determination of Material Properties—446.1R-91 (Reapproved 1999)
Finite Element Analysis of Fracture in Concrete Structures—446.3R-97
Report on Dynamic Fracture of Concrete—446.4R-04
Use of Epoxy Compounds with Concrete—503R-93 (Reapproved 2008)
Standard Specification for Bonding Hardened Concrete, Steel, Wood, Brick, and Other Materials to Hardened Concrete with a Multi-Component Epoxy Adhesive—503.1-92 (Reapproved 2003)
Standard Specification for Bonding Plastic Concrete to Hardened Concrete with a Multi-Component Epoxy Adhesive—503.2-92 (Reapproved 2003)
Standard Specification for Producing a Skid-Resistant Surface on Concrete by the Use of a Multi-Component Epoxy System—503.3-92 (Reapproved 2003)
Standard Specification for Repairing Concrete with Epoxy Mortars—503.4-92 (Reapproved 2003)
Guide for the Selection of Polymer Adhesives with Concrete—503.5R-92 (Reapproved 2003)
Guide for the Application of Epoxy and Latex Adhesives for Bonding Freshly Mixed and Hardened Concretes—503.6R-97 (Reapproved 2003)
Specification for Crack Repair by Epoxy Injection—503.7-07
Guide to Shotcrete—506R-05
Guide to Fiber-Reinforced Shotcrete—506.1R-08
Specification for Shotcrete—506.2-95
Guide for the Evaluation of Shotcrete—506.4R-94 (Reapproved 2004)
Guide for Specifying Underground Shotcrete—506.5R-09
Report on Pervious Concrete—522R-10
Specification for Pervious Concrete Pavement—522.1-08
Guide for Cast-in-Place Low-Density Cellular Concrete—523.1R-06
Guide for Precast Cellular Concrete Floor, Roof, and Wall Units—523.2R-96
Guide for Design and Construction with Autoclaved Aerated Concrete Panels—523.4R-09
Guide to Portland Cement-Based Plaster—524R-08
Building Code Requirements for Masonry Structures—530-08/ASCE 5-02/TMS 402-02
Specification for Masonry Structures—530.1-08/ASCE 6-02/TMS 602-02
Commentary on Building Code Requirements for Masonry Structures—530R-08/ASCE 5-02/TMS 402-02
Commentary on Specification for Masonry Structures—530.1R-08/ASCE 6-05/TMS 602-05
Guide for Precast Concrete Wall Panels—533R-93 (Reapproved 2004)
Design Responsibility for Architectural Precast-Concrete Projects—533.1R-02
Design, Manufacture, and Installation of Concrete Piles—543R-00 (Reapproved 2005)
Report on Fiber Reinforced Concrete—544.1R-96 (Reapproved 2009)
Measurement of Properties of Fiber Reinforced Concrete—544.2R-89 (Reapproved 2009)
Guide for Specifying, Proportioning, and Production of Fiber-Reinforced Concrete—544.3R-08
Design Considerations for Steel Fiber Reinforced Concrete—544.4R-88 (Reapproved 2009)
Report on the Physical Properties and Durability of Fiber-Reinforced Concrete—544.5R-10
Concrete Repair Guide—546R-04
Guide to Underwater Repair of Concrete—546.2R-10
Guide for the Selection of Materials for Repair of Concrete—546.3R-06
Guide for the Use of Polymers in Concrete—548.1R-09
Report on Polymer-Modified Concrete—548.3R-09
Standard Specification for Latex-Modified Concrete (LMC) Overlays—548.4-93 (Reapproved 1998)
Guide for Polymer Concrete Overlays—548.5R-94 (Reapproved 1998)
Test Method for Load Capacity of Polymer Concrete Underground Utility Structures—548.7-04
Specification for Type EM (Epoxy Multi-Layer) Polymer Overlay for Bridge and Parking Garage Decks—548.8-07

Specification for Type EM (Epoxy Multi-Layer) Polymer Overlay for Bridge and Parking Garage Decks—548.8M-07

Specification for Type ES (Epoxy Slurry) Polymer Overlay for Bridge and Parking Garage Decks—548.9-08

Specification for Type ES (Epoxy Slurry) Polymer Overlay for Bridge and Parking Garage Decks—548.9M-08

Specification for Type MMS (Methyl Methacrylate Slurry) Polymer Overlays for Bridge and Parking Garage Decks—548.10-10

Specification for Type MMS (Methyl Methacrylate Slurry) Polymer Overlays for Bridge and Parking Garage Decks—548.10M-10

Report on Ferrocement—549R-97 (Reapproved 2009)

Guide for the Design, Construction, and Repair of Ferrocement—549.1R-93 (Reapproved 2009)

Report on Thin Reinforced Cementitious Products—549.2R-04

Report on Glass Fiber-Reinforced Concrete Premix—549.3R-09

Emulating Cast-in-Place Detailing for Seismic Design of Precast Concrete Structures—550.1R-09

Tilt-Up Concrete Construction Guide—551.1R-05

Design Guide for Tilt-Up Concrete Panels—551.2R-10

Removal and Reuse of Hardened Concrete—555R-01

Specification for High-Strength Concrete in Moderate to High Seismic Applications—ITG-4.1-07

Materials and Quality Considerations for High-Strength Concrete in Moderate to High Seismic Applications—ITG-4.2R-06

Report on Structural Design and Detailing for High Strength Concrete in Moderate to High Seismic Applications—ITG-4.3R-07

Acceptance Criteria for Special Unbonded Post-Tensioned Precast Structural Walls Based on Validation Testing and Commentary—ITG-5.1-07

Acceptance Criteria for Special Unbonded Post-Tensioned Precast Structural Walls Based on Validation Testing and Commentary—ITG-5.1M-07

Requirements for Design of a Special Unbonded Post-Tensioned Precast Shear Wall Satisfying ACI ITG-5.1 (ACI ITG-5.2-09) and Commentary—ITG-5.2-09

Design Guide for the Use of ASTM A1035/A1035M Grade 100 (690) Steel Bars for Structural Concrete—ITG-6R-10

Specification for Tolerances for Precast Concrete—ITG-7-09

Specification for Tolerances for Precast Concrete—ITG-7M-09

ACI Design Handbook—SP-17(09)

ACI Design Handbook—SP-17M(09)

Appendix B—Technical contacts

Information used in compiling this guide was obtained by several of the concrete industry's leading technical institutes and associations. For additional information on any of the materials, technologies, or applications included in the preceding pages, please contact the organizations listed herein. Each of these organizations has significantly more information on the use of concrete in sustainable development than was able to be included in this guide.

American Coal Ash Association
15200 E Girard Ave., Suite 3050
Aurora, CO 80014-3955
720-870-7897
www.acaa-usa.org

American Concrete Institute
38800 Country Club Drive
Farmington Hills, MI 48331
248-848-3700
www.concrete.org

American Concrete Pavement Association
5420 Old Orchard Road
Suite A-100
Skokie, IL 60077-1059
847-966-2272
www.pavement.com

American Concrete Pipe Association
1303 West Walnut Hill Lane, Suite 305
Irving, TX 75038-3008
972-506-7216
www.concrete-pipe.org

American Concrete Pressure Pipe Association
3900 University Drive, Suite 110
Fairfax, VA 22030-2513
703-273-7227
www.acppa.org

American Concrete Pumping Association
606 Enterprise Dr.
Lewis Center, OH 43035
614-431-5618
www.concretepumpers.com

American Shotcrete Association
38800 Country Club Drive
Farmington Hills, MI 48331
248-848-3780
www.shotcrete.org

American Society of Concrete Contractors
2025 S Brentwood Blvd.
St. Louis, MO 63144
314-962-0210
www.ascconline.org

Architectural Precast Association
6710 Winkler Rd, Suite 8
Fort Myers, FL 33919
239-454-6989
www.archprecast.org

Associated General Contractors of America
2300 Wilson Blvd., Suite 400
Arlington, VA 22201
703-548-3118
www.agc.org

Brick Industry Association
1850 Centennial Park Drive, Suite 301
Reston, VA 20191
703-620-0010
www.gobrick.com

Canadian Precast Prestressed Concrete Institute
100-196 Bronson Avenue
Ottawa, ON, Canada K1R 6H4
613-232-2619
www.cpci.ca

Cast Stone Institute
PO Box 68
813 Chestnut Street
Lebanon, PA 17042
717-272-3744
www.caststone.org

Concrete Foundations Association
PO Box 204
113 W First Street
Mt. Vernon, IA 52314
319-895-6940
www.cfawalls.org

Concrete Reinforcing Steel Institute
933 North Plum Grove Road
Schaumburg, IL 60173-4758
847-517-1200
www.crsi.org

Concrete Sawing & Drilling Association
13577 Feather Sound Drive
Suite 560
Clearwater, FL 33762
727-577-5004
www.csda.org

Design-Build Institute of America
1100 H Street, NW, Suite 500
Washington, DC 20005-5476
866-692-0110
www.dbia.org

Expanded Shale, Clay and Slate Institute
230 East Ohio St., Suite 400
Chicago, IL 60611
801-272-7070
www.escsi.org

Insulating Concrete Form Association
PO Box 3470
Crofton, MD 21114
888-864-4232
www.forms.org

Interlocking Concrete Pavement Institute
13921 Park Center Road
Suite 270
Herndon, VA 20171
703-657-6900
www.icpi.org

International Concrete Repair Institute
10600 West Higgins Road, Suite 607
Rosemont, IL 60018
847-827-0830
www.icri.org

Mason Contractors Association of America
1481 Merchant Drive
Algonquin, IL 60102
800-536-2225
www.masoncontractors.org

National Concrete Masonry Association
13750 Sunrise Valley Drive
Herndon, VA 20171
703-713-1900
www.ncma.org

National Precast Concrete Association
1320 City Center Dr. Suite 200
Carmel, IN 46032
800-366-7731
www.precast.org

National Ready Mixed Concrete Association
900 Spring Street
Silver Spring, MD 20910
301-587-1400
www.nrmca.org

National Sand, Stone & Gravel Association
1605 King Street
Alexandria, VA 22314
703-525-8788
www.nssga.org

National Slag Association
PO Box 1197
Pleasant Grove, UT 84062
801-785-4535
www.nationalslag.org

Portland Cement Association
5420 Old Orchard Road
Skokie, IL, 60077-1083
847-966-6200
www.cement.org

Post-Tensioning Institute
38800 Country Club Drive
Farmington Hills, MI 48331
248-848-3180
www.post-tensioning.org

Precast/Prestressed Concrete Institute
200 W Adams Str. #2100
Chicago, IL 60606
312-786-0300
www.pci.org

Silica Fume Association
38860 Sierra Lane
Lovettsville, VA 20180
412-551-7873
www.silicafume.org

Slag Cement Association
Suite 349
2516 Waukegan Road
Glenview, IL 60025
847-977-6920
www.slagcement.org

The Masonry Society
3970 Broadway, Suite 201-D
Boulder, CO 80304-1135
303-939-9700
www.masonrysociety.org

Tile Roofing Institute
230 East Ohio St., Suite 400
Chicago, IL 60611
312-670-4177
www.tileroofing.org

Tilt-Up Concrete Association
PO Box 204
Mount Vernon, IA 52314
319-895-6911
www.tilt-up.org

Wire Reinforcement Institute
942 Main Street, Suite 300
Hartford, CT 06103
800-522-4974
www.wirereinforcementinstitute.org

REFERENCES

ACI Committee 201, 2008, "Guide to Durable Concrete (ACI 201.2R-08)," American Concrete Institute, Farmington Hills, MI, 49 pp.

ACI Committee 211, 2001, "Guide for Submittal of Concrete Proportions (ACI 211.5R-01) (Reapproved 2009)," American Concrete Institute, Farmington Hills, MI, 6 pp.

ACI Committee 213, 2003, "Guide for Structural Lightweight-Aggregate Concrete (ACI 213R-03)," American Concrete Institute, Farmington Hills, MI, 38 pp.

ACI Committee 216, 2007, "Code Requirements for Determining Fire Resistance of Concrete and Masonry Construction Assemblies (ACI 216.1-07/TMS-0216-07," American Concrete Institute, Farmington Hills, MI, 32 pp.

ACI Committee 221, 1996, "Guide for Use of Normal Weight and Heavyweight Aggregates in Concrete (ACI 221R-96) (Reapproved 2001)," American Concrete Institute, Farmington Hills, MI, 28 pp.

ACI Committee 221, 2008, "Report on Alkali-Aggregate Reactivity (ACI 221.1R-98 [Reapproved 2008])," American Concrete Institute, Farmington Hills, MI, 31 pp.

ACI Committee 301, 2005, "Specifications for Structural Concrete (ACI 301-05)," American Concrete Institute, Farmington Hills, MI, 49 pp.

ACI Committee 318, 2008, "Building Code Requirements for Structural Concrete (ACI 318-08) and Commentary," American Concrete Institute, Farmington Hills, MI, 473 pp.

ACI Committee 347, 2004, "Guide to Formwork for Concrete (ACI 347-04)," American Concrete Institute, Farmington Hills, MI, 32 pp.

ACI Committee 364, 2007, "Guide for Evaluation of Concrete Structures before Rehabilitation (ACI 364.1R-07)," American Concrete Institute, Farmington Hills, MI, 18 pp.

ACI Committee 440, 2007, "Report on Fiber-Reinforced Polymer (FRP) Reinforcement for Concrete Structures (ACI 440R-07)," American Concrete Institute, Farmington Hills, MI, 100 pp.

ACI Committee 555, 2001, "Removal and Reuse of Hardened Concrete (ACI 555R-01)," American Concrete Institute, Farmington Hills, MI, 26 pp.

ACI Committee E-701, 2007, "Aggregates for Concrete (ACI Education Bulletin E1-07)," American Concrete Institute, Farmington Hills, MI, 26 pp.

ACI Committee E-703, 2003, "Chemical Admixtures for Concrete (ACI Education Bulletin E4-03)," American Concrete Institute, Farmington Hills, MI, 16 pp.

American Society of Civil Engineers, 2009, "2009 Infrastructure Report Card," http://www.infrastructurereportcard.org/. (accessed June 1, 2010)

ANSI/ASHRAE Standard 90.1-2007, 2007, "Energy Standard for Buildings Except Low-Rise Residential Buildings," American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA, 186 pp.

ANSI/ASHRAE Standard 90.2-2007, 2007, "Energy Efficient Design of Low-Rise Residential Buildings," American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA, 48 pp.

ANSI/ASHRAE Standard 189.1-2009, 2009, "Standard for the Design of High-Performance Green Buildings," American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA, 122 pp.

ASTM A615/A615M-09b, 2009, "Standard Specification for Deformed and Plain Carbon-Steel Bars for Concrete Reinforcement," ASTM International, West Conshohocken, PA, 6 pp.

ASTM A706/A706M-09b, 2009, "Standard Specification for Low-Alloy Steel Deformed and Plain Bars for Concrete Reinforcement," ASTM International, West Conshohocken, PA, 6 pp.

ASTM A767/A767M-09, 2009, "Standard Specification for Zinc-Coated (Galvanized) Steel Bars for Concrete Reinforcement," ASTM International, West Conshohocken, PA, 5 pp.

ASTM A775/A775M-07b, 2007, "Standard Specification for Epoxy-Coated Steel Reinforcing Bars," ASTM International, West Conshohocken, PA, 11 pp.

ASTM A884/A884M-06, 2006, "Standard Specification for Epoxy-Coated Steel Wire and Welded Wire Reinforcement," ASTM International, West Conshohocken, PA, 6 pp.

ASTM A934/A934M-07, 2007, "Standard Specification for Epoxy-Coated Prefabricated Steel Reinforcing Bars," ASTM International, West Conshohocken, PA, 16 pp.

ASTM A955/A955M-10, 2010, "Standard Specification for Deformed and Plain Stainless-Steel Bars for Concrete Reinforcement," ASTM International, West Conshohocken, PA, 11 pp.

ASTM A1055/A1055M-08ae1, 2008, "Standard Specification for Zinc and Epoxy Dual-Coated Steel Reinforcing Bars," ASTM International, West Conshohocken, PA, 9 pp.

ASTM A1064/A1064M-09, 2009, "Standard Specification for Steel Wire and Welded Wire Reinforcement, Plain and Deformed, for Concrete," ASTM International, West Conshohocken, PA, 10 pp.

ASTM C33/C33M-08, 2008, "Standard Specification for Concrete Aggregates," ASTM International, West Conshohocken, PA, 11 pp.

ASTM C76-10a, 2010, "Standard Specification for Reinforced Concrete Culvert, Storm Drain, and Sewer Pipe," ASTM International, West Conshohocken, PA, 11 pp.

ASTM C94/C94M-09a, 2009, "Standard Specification for Ready-Mixed Concrete," ASTM International, West Conshohocken, PA, 12 pp.

ASTM C150/C150M-09, 2009, "Standard Specification for Portland Cement," ASTM International, West Conshohocken, PA, 10 pp.

ASTM C330/C330M-09, 2009, "Standard Specification for Lightweight Aggregates for Structural Concrete," ASTM International, West Conshohocken, PA, 4 pp.

ASTM C331-05, 2005, "Standard Specification for Lightweight Aggregates for Concrete Masonry Units," ASTM International, West Conshohocken, PA, 4 pp.

ASTM C332-09, 2009, "Standard Specification for Lightweight Aggregates for Insulating Concrete," ASTM International, West Conshohocken, PA, 3 pp.

ASTM C361-08, 2008, “Standard Specification for Reinforced Concrete Low-Head Pressure Pipe,” ASTM International, West Conshohocken, PA, 17 pp.

ASTM C443-05ae1, 2005, “Standard Specification for Joints for Concrete Pipe and Manholes, Using Rubber Gaskets,” ASTM International, West Conshohocken, PA, 3 pp.

ASTM C494/C494M-10, “Standard Specification for Chemical Admixtures for Concrete,” ASTM International, West Conshohocken, PA, 10 pp.

ASTM C595/C595M-10, 2010, “Standard Specification for Blended Hydraulic Cements,” ASTM International, West Conshohocken, PA, 8 pp.

ASTM C618-08a, 2008, “Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete,” ASTM International, West Conshohocken, PA, 3 pp.

ASTM C877-08, 2008, “Standard Specification for External Sealing Bands for Concrete Pipe, Manholes, and Precast Box Sections,” ASTM International, West Conshohocken, PA, 6 pp.

ASTM C979-05, 2005, “Standard Specification for Pigments for Integrally Colored Concrete,” ASTM International, West Conshohocken, PA, 5 pp.

ASTM C989-09a, 2009, “Standard Specification for Slag Cement for Use in Concrete and Mortars,” ASTM International, West Conshohocken, PA, 6 pp.

ASTM C990-09, 2009, “Standard Specification for Joints for Concrete Pipe, Manholes, and Precast Box Sections Using Preformed Flexible Joint Sealants,” ASTM International, West Conshohocken, PA, 4 pp.

ASTM C1131-95(2007), 2007, “Standard Specification for Least Cost (Life Cycle) Analysis of Concrete Culvert, Storm Sewer, and Sanitary Sewer Systems,” ASTM International, West Conshohocken, PA, 4 pp.

ASTM C1157/C1157M-10, 2010, “Standard Performance Specification for Hydraulic Cement,” ASTM International, West Conshohocken, PA, 5 pp.

ASTM C1202-10, 2010, “Standard Test Method for Electrical Indication of Concrete’s Ability to Resist Chloride Ion Penetration,” ASTM International, West Conshohocken, PA, 7 pp.

ASTM C1240-05, 2005, “Standard Specification for Silica Fume Used in Cementitious Mixtures,” ASTM International, West Conshohocken, PA, 7 pp.

ASTM C1364-10, 2010, “Standard Specification for Architectural Cast Stone,” ASTM International, West Conshohocken, PA, 3 pp.

ASTM C1602/C1602M-06, 2006, “Standard Specification for Mixing Water Used in the Production of Hydraulic Cement Concrete,” ASTM International, West Conshohocken, PA, 4 pp.

ASTM C1603-05a, 2005, “Standard Test Method for Measurement of Solids in Water,” ASTM International, West Conshohocken, PA, 4 pp.

ASTM C1628-06, 2006, “Standard Specification for Joints for Concrete Gravity Flow Sewer Pipe, Using Rubber Gaskets,” ASTM International, West Conshohocken, PA, 7 pp.

ASTM F2322-03, 2003, “Standard Test Methods for Physical Assault on Vertical Fixed Barriers for Detention and Correctional Facilities,” ASTM International, West Conshohocken, PA, 8 pp.

Bhatty, J. I., and Tennis, P. D., 2004, “U.S. and Canadian Cement Characteristics: 2004,” SN2879, Portland Cement Association, Skokie, IL, 67 pp.

Bouzoubaa, N.; Bilodeau, A.; Sivasundaram, B. F.; and Golden, D., 2004, “Development of Ternary Blends for High-Performance Concrete,” *ACI Materials Journal*, V. 101, No. 1, Jan.-Feb., 11 pp.

Bruntland, G., 1987, *Our Common Future: The World Commission on Environment and Development*, Oxford University Press, Oxford, UK, 374 pp. http://worldinbalance.net/intagreements/1987-brundtland.php. (accessed Jan. 2, 2010)

California Building Standards Commission, 2008, “California Green Building Standards Code,” California Code of Regulations, Title 24, Part 9, 80 pp. http://www.documents.dgs.ca.gov/bsc/2009/part11_2008_calgreen_code.pdf. (accessed January 2, 2010)

Construction Materials Recycling Association, 2010, “Case Histories,” http://www.concreterecycling.org/histories.html. (accessed August 20, 2010)

De Sitter, W. R., and Tuutti, K., 2003, *Residual Life Models for Concrete Repair—Assessment of the Concrete Repair Process*, Building Research Establishment Ltd, 63 pp.

EN 15051, 2006, “Workplace Atmospheres: Measurement of the Dustiness of Bulk Materials, Requirements and Test Methods,” British Standards Institution, London, UK, 28 pp.

Engelsen, C. J.; Sæther, D. H.; Mehus, J.; and Pade, C., 2005, *CO_2 Uptake during the Concrete Life Cycle: Carbon Dioxide Uptake in Demolished and Crushed Concrete*, Nordic Innovation Center, Oslo, Norway, 40 pp.

European Parliament, 2006, “Registration, Evaluation, Authorization and Restriction of Chemicals (REACH),” EC No. 1907/2006, 849 pp. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2006:396:0001:0849:EN:PDF. (accessed August 23, 2010)

Expanded Shale, Clay and Slate Institute, 1971, *Lightweight Concrete, History, Applications, and Economics*, Salt Lake City, UT, 44 pp.

Federal Historic Preservation Tax Incentives program, 2009. http://www.nps.gov/history/hps/tps/tax/. (accessed August 1, 2010)

Fraczek, J., 1979, “ACI Survey of Concrete Structure Errors,” *Concrete International*, V. 1, No. 12, Dec., 7 pp.

Frey, P., 2007, “Making the Case: Historic Preservation as Sustainable Development,” National Trust for Historic Preservation, Washington, DC, 26 pp. http://www.preservationnation.org/issues/sustainability/additional-resources/DiscussionDraft_10_15.pdf. (accessed January 2, 2010)

Hansen, T. C., 1986, “The Second RILEM State of the Art Report on Recycled Aggregates and Recycled Aggregate Concrete,” *Materials and Structures*, V. 1, No. 111, May-June, 246 pp.

Hawkins, P.; Tennis, P. D.; and Detwiler, R. J., 2005, "The Use of Limestone in Portland Cement: A State-of-the-Art Review," EB227, Portland Cement Association, Skokie, IL, 44 pp.

Headwaters Resources, 2006, "Brayton Point CBO Fly Ash," South Jordan, UT, 6 pp., http://www.flyash.com/data/upimages/press/Brayton%20Point.pdf. (accessed August 10, 2010)

International Code Council, 2009, "International Building Code," Washington, DC, 645 pp.

International Code Council, 2010, "Synopsis: International Green Construction Code," Public Version 1.0, Mar., Washington, DC, 33 pp.

ISO/TS 27687, 2008, "Nanotrechnologies—Terminology and Definitions for Nano-Objects—Nanoparticle, Nanofibre and Nanoplate," American National Standards Institute, Washington, DC, 25 pp.

Joint ACI/ASCE/TMS Committee 530, 2002, "Building Code Requirements for Masonry Structures (ACI 530-02/ASCE 5-02/TMS 402-02), Specifications for Masonry Structures (ACI 530.1/ASCE 6/TMS 602) and Commentaries," American Concrete Institute and The Masonry Society, 166 pp.

Joint ACI-TMS Committee 216, 2007, "Code Requirements for Determining Fire Resistance of Concrete and Masonry Construction Assemblies (ACI 216.1-07/TMS-216-07)," American Concrete Institute, Farmington Hills, MI, 32 pp.

Kamin, B., adapted from a speech for the Michigan Historic Preservation Network that will appear in *Terror and Wonder: Architecture in a Tumultuous Age*, a collection of his columns to be published this fall by the University of Chicago Press. http://www.preservationnation.org/magazine/2010/march-april/green-architecture.html.

Maingot, M., 2008, "The First Green Building in the United States: Mosler Lofts, Seattle, Washington," *PTI JOURNAL*, V. 6, No. 2, Aug., 2 pp.

Maingot, M., 2009, "Sustainability and Post-Tensioned Concrete: Gray is the New Green," *PTI JOURNAL*, V. 7, No. 1, Aug., 4 pp.

Marceau, M. L.; Nisbet, M. A.; and VanGeem, M. G., 2006, "Life Cycle Inventory of Portland Cement Manufacture," SN2095b, Portland Cement Association, Skokie, IL, 69 pp.

Marceau, M. L.; Nisbet, M. A.; and VanGeem, M. G., 2007, "Life Cycle Inventory of Portland Cement Concrete," SN3011, Portland Cement Association, Skokie, IL, 120 pp.

Marceau, M. L., and VanGeem, M. G., 2007, "Solar Reflectance of Concretes for LEED, Sustainable Sites Credit: Heat Island Effect," PCA R&D Serial No. 2982, Portland Cement Association, Skokie, IL, 94 pp.

Moe, R., 2008, "Sustainable Stewardship—Historic Preservation Plays and Essential Role in Fighting Climate Change," *Traditional Buildings*, V. 21, No. 3, June. http://www.traditional-building.com/Previous-Issues-08/JuneFeature08Sustainable.html. (accessed September 6, 2010)

National Association of Home Builders (NAHB) and the International Code Council (ICC), 2008, National Green Building Standard (ICC-700-2008), Builderbooks.com, Washington, DC, 116 pp.

National Concrete Masonry Association, 2003, "Impact Resistance of Concrete Masonry for Correctional Facilities," TEK 14-10B, National Concrete Masonry Association, 20 pp.

National Cooperative Highway Research Program, 1998, "Service Life of Drainage Pipe," *NCHRP Synthesis 254*, 39 pp.

National Ready Mixed Concrete Association, 2010, "Sustainable Concrete Plant Guidelines," http://www.nrmca.org/sustainability/guidelines/. (accessed August 1, 2010)

National Oceanic and Atmospheric Administration, National Weather Service Office of Climate, Water, and Weather Services, National Hazard Statistics, www.weather.gov/os/hazstats.shtml. (accessed September 6, 2010)

National Trust for Historic Preservation, 2010, http://www.preservationnation.org/issues/sustainability/. (accessed August 1, 2010)

Nisbet, M. A., 1996, "Reduction of Resource Input and Emission Achieved by Addition of Limestone to Portland Cement," SN2086, Portland Cement Association, Skokie, IL, 11 pp., http://www.cement.org/pdf_files/SN2086.pdf. (accessed on July 1, 2010)

Occupational Safety and Health Administration, "Preventing Skin Problems from Working with Portland Cement," http://www.osha.gov/dsg/guidance/cement-guidance.html. (accessed August 10, 2010)

Panarese, W. C.; Litvin, A.; and Farny, J. A., 2005, "Performance of Architectural Concrete Panels in the PCA Outdoor Display," PCA RD133, Skokie, IL, 109 pp.

Portland Cement Association, 2006a, "Third Quarter 2006 Survey of Portland Cement by User Group," Portland Cement Association, Skokie, IL, Nov., 21 pp.

Portland Cement Association, 2006b, "U.S. and Canadian Portland Cement Industry: Plant Information Summary," ER373, Portland Cement Association, Skokie, IL, 211 pp.

Portland Cement Association, 2007, "Guide Specification for Concrete Subject to Alkali-Silica Reactions," Portland Cement Association, Skokie, IL, 8 pp.

Portland Cement Association, 2008, "North American Cement Industry Annual Yearbook," ER385, Portland Cement Association, Skokie, IL, 70 pp.

Portland Cement Association, 2009a, "Photocatalytic (Self-Cleaning) Concrete: Bibliography of Selected Publications," LB032, Portland Cement Association, Skokie, IL, 14 pp.

Portland Cement Association, 2009b, "Proposed Amendments to the International Building Code, 2009 edition, Relating to the High Performance Building Requirements for Sustainability," Version 1.5, Skokie, IL, Oct., 132 pp., http://www.cement.org/codes/pdf/HPBRS_v1-5.pdf. (accessed July 1, 2010)

Precast/Prestressed Concrete Institute, 2007, *Architectural Precast Concrete*, third edition, Chicago, IL, 588 pp.

Ries, J. P.; Speck, J.; and Harmon, K. S., 2010, "Lightweight Aggregate Optimizes the Sustainability of Concrete through Weight Reduction, Internal Curing, Extended Service Life, and Lower Carbon Footprint," *Proceedings of the Concrete Sustainability Conference*, 15 pp., http://www.concretetechnologyforum.org/2010CSCProceedings/documents/Ries%20Paper%204-14-10.pdf. (accessed July 1, 2010)

Rosenfeld, A. H.; Romm, J. J.; Akbari, H.; and Lloyd, A. C., 1997, "Painting the Town White—And Green, MIT Technology Review," http://eetd.lbl.gov/HeatIsland/PUBS/PAINTING/. (accessed January 2, 2010)

RSMeans, 2008, *Concrete and Masonry Cost Data*, 26th edition, Reed Construction Data, Kingston, MA, 549 pp.

Schokker, A., 2010, *The Sustainable Concrete Guide—Strategies and Examples*, U.S. Green Concrete Council, Farmington Hills, MI, 86 pp.

Silica Fume Association, 2005, Silica Fume User Manual, FHWA-IF-05-016, Lovettsville, VA, 194 pp.

Smith, K. M.; Schokker, A. J.; and Tikalsky, P. J., 2004, "Performance of Supplemental Cementitious Materials in Concrete Resistivity and Corrosion Monitoring Evaluations," *ACI Materials Journal*, V. 101, No. 5, Sept.-Oct., 6 pp.

Staley, B. F., and Barlaz, M. A., 2009, "Composition of Municipal Solid Waste in the United States and Implications for Carbon Sequestration and Methane Yield," *Journal of Environmental Engineering*, Oct., 9 pp.

Thomas, M.; Shehata, M. H.; Shashiprakash, S. G.; Hopkins, D. S.; and Cail, K., 1999, "Use of Ternary Cementitious Systems Containing Silica Fume and Fly Ash in Concrete," *Cement and Concrete Research*, V. 29, No. 8, Aug., 8 pp.

U.S. Environmental Protection Agency, 2003, "Estimating 2003 Building-Related Construction and Demolition Materials Amounts," Washington, DC, 60 pp.

U.S. Environmental Protection Agency, 2006, "Sector Strategies Performance Report 2006," Washington, DC, 112 pp.

U.S. Environmental Protection Agency, 2008a, "Quantifying Greenhouse Gas Emissions from Key Industrial Sectors in the United States—Working Draft," 132 pp., http://www.epa.gov/ispd/pdf/greenhouse-report.pdf. (accessed on January 2, 2010)

U.S. Environmental Protection Agency, 2008b, "Study on Increasing the Usage of Recovered Mineral Components in Federally Funded Projects Involving Procurement of Cement or Concrete," Report to Congress: EPA530-R-08-007, Washington, DC, 225 pp.

U.S. Environmental Protection Agency, 2009, *Compilation of Air Pollutant Emissions Factors, Volume 1: Stationary Point and Area Sources*, fifth edition, http://www.epa.gov/ttn/chief/ap42/index.html. (accessed March 26, 2010)

U.S. Government Accountability Office, 2008, "Hurricane Katrina: Continuing Debris Removal and Disposal Issues," Report GAO-08-985R, August 25, 2008, http://www.gao.gov/htext/d08985r.html. (accessed September 6, 2010)

VanderWerf, P., 1997, *Energy Consumption Comparisons of Concrete Homes versus Wood Frame Homes*, Portland Cement Association, Skokie, IL, 25 pp.

Van Hampton, T., 2007, "Smog-Eating Concrete May Soon Cover U.S. Buildings," *Engineering News-Record*, V. 258, No. 9, 49 pp.

Vejvoda, M. F., 1992, "Strengthening of Existing Structures with Post-Tensioning," *Concrete International*, V. 14, No. 9, Sept., 6 pp.

World Business Council for Sustainable Development, 2009, Cement Industry Energy and CO_2 Performance: Getting the Numbers Right, 43 pp., http://www.wbcsd.org/DocRoot/02fH0Bj3tZNV1RvmG2mb/CSIGNRReportfinal.pdf. (accessed January 18, 2010)

INDEX

NOTES

NOTES

NOTES