The Sustainable Concrete Guide

Strategies and Examples

Andrea J. Schokker

U.S. GREEN CONCRETE COUNCIL

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Dedication

The sustainability movement is reality. Architects, engineers, specifiers, and contractors are faced with the challenge of how to produce functional buildings that are expected to be more environmentally friendly, socially acceptable, and economically beneficial.

Designers and builders will continue to use the materials that have served them well for many, many years. But the way in which those materials are manufactured and incorporated into their projects will change as they strive for a more sustainable built environment.

All materials have sustainable benefits and shortcomings, and concrete is no exception. This book is intended to provide the design and construction team with objective information on concrete's characteristics—including its pros and cons related to sustainability—that the design/construction team can consider and use to meet the needs and requirements of building owners.

I applaud Florian Barth for recognizing the need to advance the educational process regarding concrete's strengths and weaknesses. As the 2009-2010 President of the American Concrete Institute (ACI), Florian values the importance of information and information dissemination. I also want to thank Florian for assembling a diverse Editorial Review Panel from both inside and outside the concrete industry to outline the sustainability topics and to provide input and feedback during the writing of this book. My thanks go out to the Editorial Review Panel that included Michael Deane, Vice President and Chief Sustainability Officer at Turner Construction Company and a LEED Accredited Professional; Aris Papadopoulos, CEO, Titan America; Michael J. Paul, Senior Consultant, a LEED Accredited Professional, Duffield Associates, and Chair of ACI Committee 124, Concrete Aesthetics; Richard Stehly, Principal, American Engineering Testing and 2009-2010 ACI Vice President; and Wayne B. Trusty, President, Athena Institute.

Special appreciation is extended to Andrea Schokker who agreed to write the book, even as the Editorial Review Panel was "constantly looking over her shoulder." Andrea is Professor and Head of Civil Engineering at the University of Minnesota Duluth, and Chair of ACI Committee 130, Sustainability of Concrete.

I know that this topic will continue to develop and I welcome the new and innovative manufacturing, design, and construction practices that the concrete industry will inevitably evolve.

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President, Charles Pankow Builders, Ltd.
Past President, American Concrete Institute

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INTRODUCTION

Concrete is the world's most used construction material: over 25 billion tons (23 trillion kg) of concrete are used worldwide each year, and this number continues to increase (World Business Council for Sustainable Development 2009). Because of the sheer volume of concrete used (and the associated resources and energy used to make it), wise use of this material can make a significant contribution to the achievement of sustainable development. This includes looking at the entire life cycle of a concrete structure to focus on areas where changes will make the most impact.

This book is intended as an introduction and reference guide to using concrete in intelligent and innovative ways to achieve sustainable buildings. The target audiences are the building decision makers: owners, architects, construction managers, and engineers. Contractors and students in engineering and architecture can also benefit from this book's content by helping them understand how sustainable structures can be achieved with concrete. This book focuses on providing the reader with an understanding of truly sustainable aspects of concrete rather than simply "receiving rating points" or reviewing trendy applications that make an insignificant impact. The scope of this book focuses on building construction in the U.S., but the sustainable concepts for the use of concrete are globally applicable. While it is written within the context of buildings and their immediate surroundings (site and parking), much of the information applies to other forms of concrete construction.

Many aspects of sustainability were inherent in the concrete industry long before green and sustainable became buzz words. These aspects—including durability/longevity, economy, local impact, and thermal advantages—have long played roles in the selection of concrete as a building material. Architects have welcomed the versatility and aesthetic potential of concrete into their designs, and engineers have appreciated the robustness and economy for many years.

Sustainability and buildings

There are no universally accepted definitions for green building, sustainability, or sustainable development. The most commonly referenced definition is from the Brundtland Commission (Brundtland 1987):

> Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

This tenet encompasses far more than green development or environmental issues, as it is generally accepted to comprise three critical components affecting social, economic, and environmental impacts (sometimes referred

Concrete lends itself to use in conjunction with many other materials, including the innovations in green and sustainable construction arising every day *(photo courtesy of Condell Medical Center).*

McClellan-Palomar Airport, Carlsbad, CA *(photo courtesy of T.B. Penick & Sons).*

to as the "triple bottom line"). Although there is often synergy between the three facets, it is also true that a balance between competing issues must be reached. Thus, it is the intersection of all three overlapping circles where sustainable practices begin to emerge, as shown in Figure A.

The environmental side of sustainability often represents areas of potential harmful impact on the environment. In addition to energy and other resource use, international Life Cycle Assessment (LCA) standards (International Organization for Standardization [ISO] 2006) call for specific measures of environmental impacts such as global warming potential, acidification, smog formation, ozone layer depletion, and eutrophication. The issue of CO_2 emissions from cement production is the most commonly cited reason to criticize concrete as environmentally unfriendly. For this reason, a section in this book is devoted to the issue of CO_2. This is not to imply that it is more important than the other impacts, but rather that criticisms of concrete are generally focused on its CO_2 impact.

The term "cement" is frequently confused with "concrete," and outside of the industry, the two are often incorrectly used as interchangeable words. Cement is a mineral powder of alumina, silica, lime, iron oxide, and magnesium oxide burned together in a kiln and finely pulverized. Usually grey in color, it is used as the binding ingredient of mortar and concrete. Concrete is a mixture of principally aggregate (stone and sand), cement, and water that, when cured, becomes a hardened mass. Using a baking example: if concrete was a cake, then cement would be the flour. Likewise, a sidewalk is not a cement sidewalk, but rather a concrete sidewalk, where cement is one of the components used to make the concrete.

The real question for the owner, designer, and general public is, "What defines a successful building for sustainable development?" There are many perspectives on how to answer this question, but the following five key items are listed as a baseline along with a short discussion of where concrete fits into this picture. Details on each of these items are given in Part II.

- **Improving functionality**—To fulfill its purpose, a building must be functional; that is, it must be fit for its intended use. Concrete, like other traditional structural building materials, has a history of success, particularly because it can be molded into practically any shape. In some applications, such as in footings or slabs, concrete is usually the only cost effective, widely available solution.
- **Ensuring longevity**—An integral part of reducing cost and use of resources is durable, long-lived structures. The longevity of properly designed and constructed structural concrete and its ability to withstand detrimental effects is well established in the building industry.
- **Enhancing occupant factors**—The average person spends 87% of his or her time indoors (Kleipis et al. 2001), so an occupant's comfort is important for ensuring a high quality of life and work. Concrete

can play a role in moderating temperatures, reducing the use of hazardous compounds on interior surfaces (because it can be used as a finish material), resisting the growth of mold, and reducing artificial lighting requirements (because it has high reflectance and readily adapts to unique window shapes, sun filters, and other methods of optimizing natural light).

- **Reducing the use of resources—**Concrete is manufactured using many post-industrial by-products. Even the energy used to produce the key component, cement, is often derived from materials that would otherwise end up in landfills. Innovative design can reduce the total quantity of concrete used and reduce the amount of cement used in each cubic yard of concrete. Concrete components can be crushed for reuse as aggregate in new concrete or as a base for new construction. The durability of concrete reduces the frequency of replacement, and properties such as thermal mass can considerably lower energy use over the life cycle of a building. Concrete is also typically produced locally, reducing the need for extensive transportation.
- **Aesthetics—**Aesthetics is part of the quality of the environment for the public: people using the building and those observing it from the outside. In addition to benefits for the individual, an aesthetic building can be a source of pride for the community. Aesthetic buildings are made from many different types of materials, but concrete has long struck the imaginations of architects and engineers. Concrete's ability to be molded into nearly any form makes it particularly suitable to innovative architecture. This description from Antoine Picon succinctly summarizes concrete's place (Cohen and Moeller 2006):

> Its use is assured by its fundamental, hybrid nature and the capacity for variation and customization that goes with it.

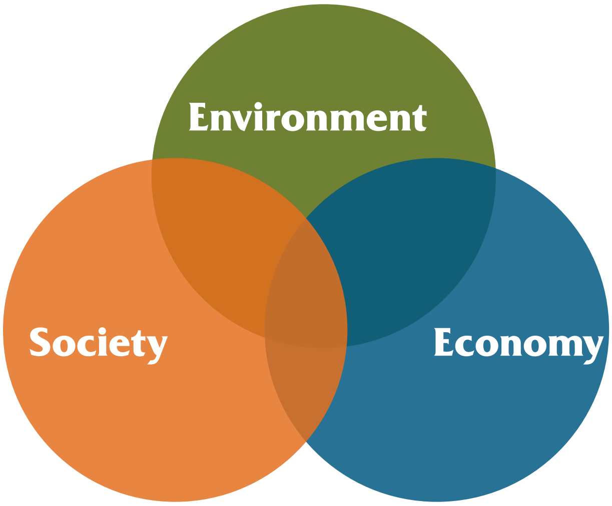


Figure A—The three tenets of sustainability.

CO_2 emissions

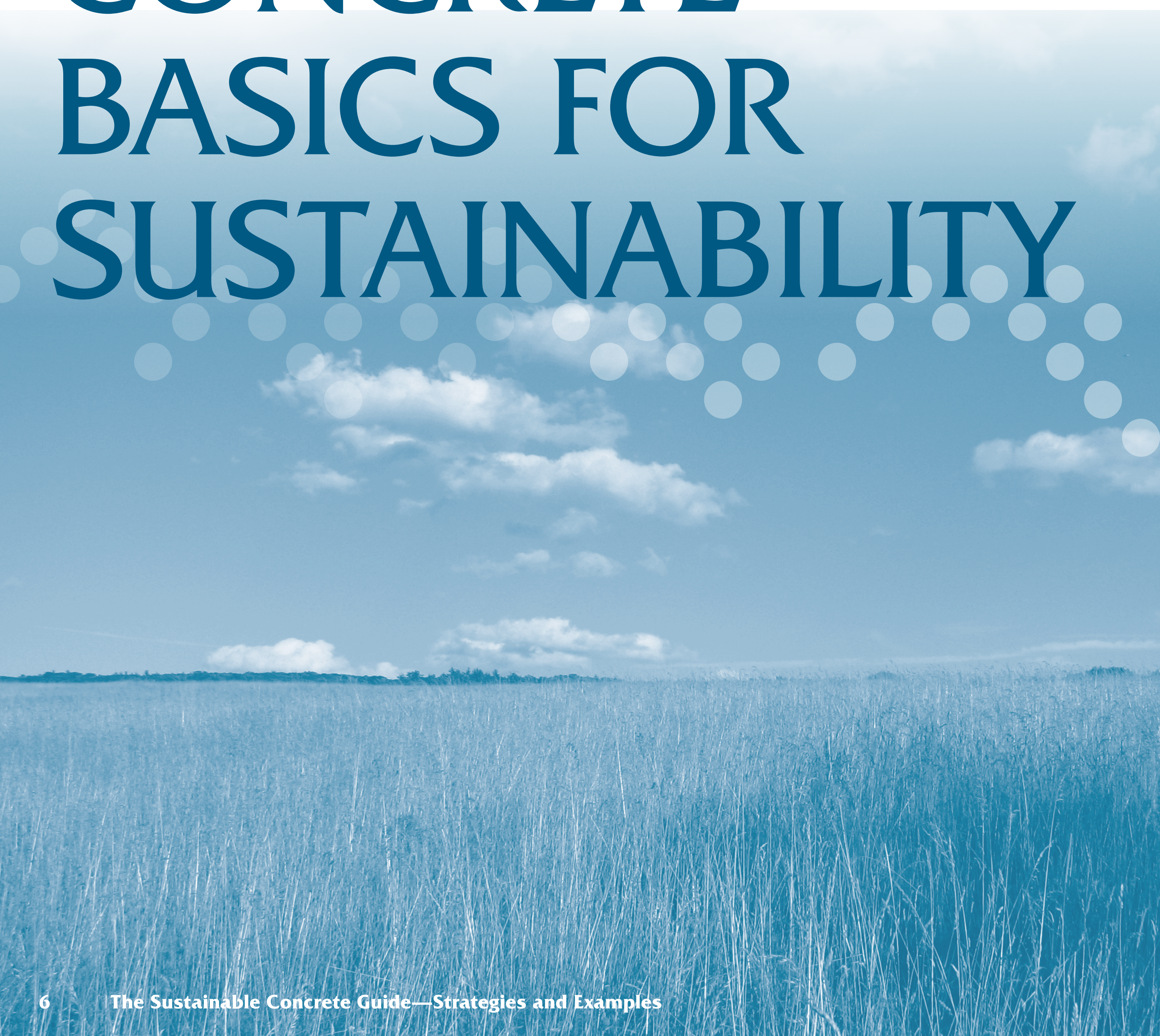
The building sector is a major contributor to CO_2 emissions and, thus, improvements in the manufacturing of materials and good practices in design and construction can have a great impact on the reduction of these emissions. While the public may accept that sustainable practices in the building sector can contribute to reducing CO_2 emissions, reducing energy demands, and overall sustainable development, the full extent of the potential influence is rarely appreciated. The building industry has many players in the process of building design and construction, so isolating factors such as CO_2 contributions by specific industry segments can be difficult. Additionally, a significant percentage of the CO_2 emissions reported for industries such as oil, transportation, and power can be directly attributed to support of the building industry.

The Energy Information Administration compiles the official energy statistics for the U.S. government and reports the 2007 breakdown of energy use in the U.S. as 32% industry/manufacturing, 29% transportation, 21% residential, and 18% commercial. The building industry is not identified as a separate component, but is rather a contributor to each of these components. *The Building Energy Data Book* (U.S. Department of Energy 2009) reports that the residential and commercial building sector in the U. S. had a total primary energy consumption of 38% for 2006, with a forecast of 41% for 2010, and over 50% by 2030. With the building sector representing approximately 40% of energy use in the U.S., it becomes the single biggest sector, making contributions of energy savings in the building area felt directly in total energy consumption.

It is clear that the impact of sustainable development in the building sector is a major component of meeting global and national goals of lowered energy consumption (and thus, reduced CO_2 emissions). The advantages and limitations of concrete in this respect are introduced in Part I. Zero-footprint buildings and communities are being planned in addition to the more aggressive carbon-negative developments across the globe.

Bruntland Commission—Established by the United Nations; developed the report "Our Common Future" that includes the commonly cited definition for sustainable development.
Eutrophication—Nutrient enrichment of water bodies that changes the aquatic ecosystem; accelerates due to runoff with phosphates and nitrates.
Ozone layer—The layer of O_3 (ozone) in the earth's atmosphere that absorbs ultraviolet light from the sun (and thus protects life on earth from potential damage from this light).

PART 1—CONCRETE BASICS FOR SUSTAINABILITY



Concrete as a construction material

As the most widely used construction material in the world, concrete is an integral part of our societies. It is a composite material consisting in its most basic form as a mixture of cement, rock (coarse aggregate), sand (fine aggregate), and water. Concrete may include admixtures to enhance particular properties in its plastic state (such as workability, fluidity, or set time) and its hardened state (such as entrained air or lowered water-cement ratio). Supplemental cementious materials (SCMs) such as fly ash, slag cement, and silica fume may also be used in addition to or in place of a portion of the cement. While rock aggregate is typical, other materials can be used, including industrial by-product materials.

Cement combines with water to form the binder that holds the aggregate in a concrete matrix. The aggregate (rock) serves as a strong, durable "filler" in the matrix. While the general public often uses the words cement and concrete interchangeably, they are distinctly different. Cement is the powder-like binder that chemically reacts and hardens, whereas concrete is the combination of cement, water, sand, and rock that is the final hardened material. The cement used in the majority of concrete applications is known as portland cement (named for portland stone in England where the cement-making process was first patented).

Cement is manufactured from raw materials, typically limestone and clay that combine at high temperatures to form calcium silicates that provide the binding properties of cement. Figure 1.1 shows the basic process of manufacturing cement. Further details can be found in any standard concrete materials textbook (Mindess et al. 2003). The fuel used to heat the kiln can be a number of different materials, industry coal, or waste products (for example, tires). The product that is created within the kiln exists as hard lumps, and is called clinker. The clinker is ground into the fine powder known as cement. During this heating of raw materials in the kiln to form clinker, CO_2 is released from the limestone. In the past, it was generally estimated that just under 1 ton of CO_2 (900 kg) was produced for every ton of cement: approximately 1/2 ton (450 kg) directly from the processing of the limestone in the kiln, 1/3 to 1/2 ton (300 to 450 kg) from the energy used to fire the kiln, and the small remaining amount from electrical use and transportation to the site and during production.

While this has been the rule of thumb for many years, the cement industry has been very active and innovative over the past two decades in reducing the energy input (and therefore the CO_2 emissions) related to production of the clinker, and the rule of thumb does not reflect these efforts.

The majority of the sections in this book focus on the sustainable properties of typical portland cement concrete with rock-based aggregates that are available for any project. New technologies are continuously introduced into the concrete industry to broaden the sustainable aspects, but broadly available concrete materials are the focus of this book.

Reinforcement

Concrete is approximately 10 times stronger in compression than it is in tension. Thus, concrete is very effective with compressive loads, but cracks under much smaller tensile loads. Reinforcement is used to resist tensile loads and to control cracking.

Reinforcement can be unstressed, mild reinforcing steel (typically 60 to 100 ksi [420 to 690 MPa] in yield strength) for use in conventionally reinforced structures, or high-strength steel or strand (typically 150 to 250 ksi [1035 MPa to 1725 MPa] in yield strength) used to prestress or post-tension concrete in an off-site facility or at the job site, respectively. Today, reinforcing steel is an almost entirely recycled material, which reduces the overall CO_2 impact of in-place concrete.

Conventionally reinforced concrete structures use unstressed, mild reinforcement that is placed in formwork on the job site. The reinforcing steel is typically fabricated offsite to its final lengths and shapes for placement. Concrete is then placed in the formwork and around the reinforcing steel. After the concrete has reached an appropriate strength, the formwork is removed.

Prestressed reinforcement provides precompression to the concrete member so that it can withstand high tensile forces (and have minimal cracking). To achieve this, the steel can be pretensioned or post-tensioned.

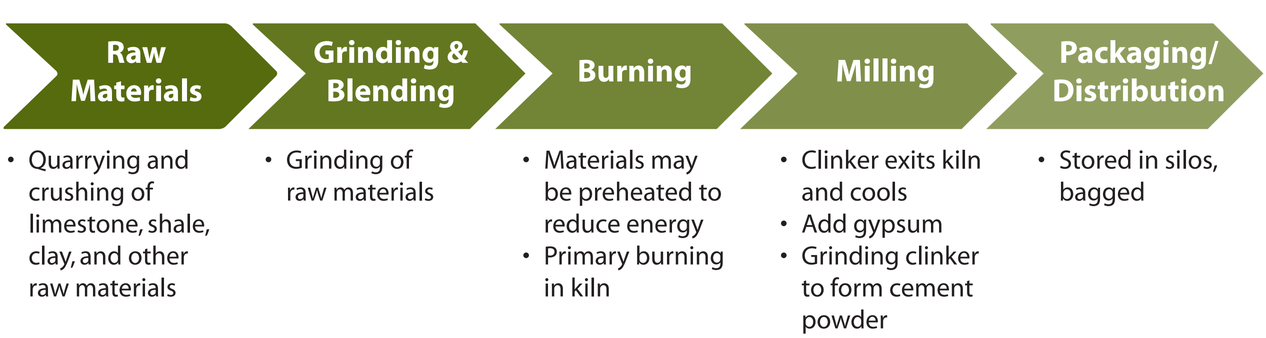


Fig. 1.1—Cement manufacturing process.

Pretensioning generally occurs offsite in a precasting yard where the steel is stretched in a bed and left in tension while the concrete is cast around the steel. After the concrete has reached an appropriate strength, the steel is released from its anchorage, and the force is transferred to the concrete Common pretensioned members in buildings and parking garages include hollow core sections and double-tee sections. More details about pretensioned members can be found in the *PCI Design Handbook* (Precast/Prestressed Concrete Institute 2004).

In post-tensioning, the steel is stressed on the job site after the concrete has been placed and has reached a hardened state. The steel is then permanently anchored at both ends of the member. Post-tensioned steel is typically protected by grout or a corrosion-inhibiting coating (often referred to as "grease"). Post-tensioning can be done with precast concrete sections or cast-in-place sections. Slabs and girder sections are the most common post-tensioned member found in buildings (particularly in residential buildings) and parking structures. More detail about post-tensioned members and structures can be found in the *Post-Tensioning Manual* (Post-Tensioning Institute 2006).

Standard reinforcement in both unstressed and prestressed applications is generally steel. It is sometimes coated with epoxy to resist aggressive environments. Fiber-reinforced polymers (FRPs), however, are also used for applications where nonmetallic reinforcement is desired. A discussion of corrosion of metallic reinforcement is given in Part II. Steel and polypropylene fibers are often used for crack control in slabs-on-ground but are not considered to provide structural strength.

Concrete sustainability and assessment

Each of the three pillars of sustainability (environmental, social, and economic) has a number of embedded variables that make measurement challenging. Up-front price and initial environmental/social benefits typically do not provide the true picture—a product or system should be considered from cradle-to-grave (or more appropriately, cradle-to-cradle) to begin to understand the full ramifications. In the end, it is important to remember that the final building performance is what matters—not just the assessment process. A strong and thorough assessment process, however, will recognize and reward sustainable buildings.

Advantages and limitations

Many of the advantages of concrete are listed in the introduction, and discussed in more detail throughout the book. Concrete is durable; can reduce energy required for heating or cooling through thermal mass; is typically produced locally; uses recycled and waste materials; can be used as a finished surface; is formable; and is light in color, which provides an opportunity for reduced interior lighting and for external reduction in the "heat island effect."

The most discussed limitation for concrete is the contribution of the manufacturing cement to greenhouse gas emission. This contribution is commonly cited as 5% of CO_2 emission from human activity, and 3% of all greenhouse gas emissions (World Business Council for Sustainable Development 2009). There is no doubt that the cement manufacturing process produces a significant amount of CO_2 from three sources: 1) energy provided for the kilns; 2) release from limestone when fired; and 3) from transportation. The cement industry worldwide has responded to Source No. 1 through a number of initiatives that provide modest reductions in CO_2 as discussed in more detail in Part II. The focus for this reduction is on alternative fuels (biomass and waste), energy efficiency (new plants are already very efficient), and carbon capture/storage. Nitrogen oxides (NO_x), sulfur oxides (SO_x), and dust are also emitted during the cement manufacturing process. Most of these other types of emissions (non-CO_2) have been decreased significantly in new cement plants and through modernization of older plants.

Source No. 2 is a the basic physical/chemical reaction that converts limestone, shale, clay, and other raw materials into calcium silicates. Source No. 2 accounts for approximately half of the CO_2 that is produced during cement manufacture. Only limited progress has been made in reducing this contribution directly, although many companies and researchers are working toward a cement production process that can sequester some of the CO_2.

Source No. 3 has a much smaller and limited contribution, because most materials are local and delivery is also local; thus, transportation is not extensive. The ready mixed concrete industry, however, has taken steps to reduce their fuel usage in the final product delivery.

Life cycle assessment

Life cycle assessment (LCA) is a method to evaluate a product (or system) in terms of impact on the environment over the full course of its life. LCA should not be confused with life cycle cost (LCC), which refers to the financial aspects only. While both methods consider effects over time and contribute as factors influencing sustainability, they consider different impacts and different time frames.

A number of life cycle assessment programs are available to aid owners and designers in product selection. Due to the large number of variables and interpretation of importance of the various environmental effects, answers can vary significantly for different programs. Each of the programs works from base data for the environmental impacts in the chosen model. The environmental impacts used follow the focus areas from ISO 14044 (2006), ISO 14045 (under

Photo courtesy of Andrew VanDis/Perfect Polish.

development), and ISO 21930 (2007): global warming potential, acidification, smog formation, ozone layer depletion, and eutrophication. Weights may be incorporated to distinguish the importance level of a given factor. At this time, the models have a uniform treatment of concrete based on initial CO_2 produced from the manufacture of cement (and of the steel reinforcement).

LCA programs in North America are often those of the ATHENA Sustainable Materials Institute (Athena) and the National Institute of Science and Technology. The ATHENA® Impact Estimator for buildings uses LCA methodology to estimate the environmental impact of a building or building system. Manufacturing, transportation, on-site construction, building lifespan, maintenance requirements, operating energy emissions, and demolition are all included in the LCA calculation (Trusty 2004). The estimator does not have the ability to run an energy simulation, but it does allow input from other modeling.

The ATHENA® Ecocalculator provides a more simplified tool to get LCA data for various building assemblies (that were run in more detail with the ATHENA® Impact Estimator). As with the other commercial LCA programs, these tools have a limited number of options relating to concrete mixture designs. And because they do not do energy simulations, they do not consider areas where concrete can provide energy savings (such as thermal mass). The estimator does allow the user to choose from three concrete strengths and to choose from three levels of fly ash content. Other cement replacement materials are not included. These tools use information currently available in the U.S. Life-Cycle Inventory (LCI) Database maintained by National Renewable Energy Laboratory (**www.nrel.gov/lci/**).

BEES® (Building for Environmental and Economic Sustainability) also uses LCA methodology based on a database of economic and sustainability performance of building products. Concrete variables are also limited to three compressive strengths in BEES®. BEES® does include fly ash substitution options, as well as slag cement and limestone cement. This results in a finite matrix of available mixture designs in the database. The *BEES® Technical Manual and User Guide* lists assumptions and values in the database (Lippiatt 2007).

No one material is the best solution for all systems in all areas of sustainability—every material has tradeoffs. While reliability of data input and interpretation of data can be concerns, LCA does provide the most comprehensive mechanism for looking at long-term performance and corresponding environmental impact. It is important to realize that the best use of the data will typically be in a relative sense, such as comparing multiple systems or materials, rather than relying heavily on the numerical output. Additionally, the user should look at the breakdown of results by impact to see how each contributes to the overall environmental score. Details about the concrete's performance in each of the impact areas are covered in Part II and are organized by a natural breakdown of sustainable attributes related to concrete.

Rating systems

With the increased focus on sustainability, rating systems have been developed by a number of organizations to provide an assessment of a structure's success in meeting predefined goals related to sustainability. Several of these organizations provide certification for the building team and owner that a structure meets various goals. The number of available rating systems continues to grow, but the most recognized in the U.S. are Leadership in Energy and Environmental Design (LEED) (**www.usgbc. org**), Green Globes (**www. greenglobes.com**), and the NAHB/ICC (2008). Each of these rating systems provides for third-party certification for buildings with a sustainability focus on energy, water, and CO_2 reduction, as well as indoor air quality and efficient use of resources. Worldwide, BREEAM (BRE Environmental Assessment Method) is the most commonly referenced system. Minnesota's Sustainable Building Guidelines (B3: Buildings, Benchmarks, and Beyond) is an example of a State-mandated rating system. All new buildings funded by the State of Minnesota bond money (fully or partially) after January 15, 2004, must comply with the B3 guidelines. Many states have developed sustainable building initiatives and related guidelines and many more states and municipalities are doing so.

LEED was introduced in 1998 by the U.S. Green Building Council (USGBC). LEED provides certification to buildings (both commercial and residential) that meet specific sustainability-related criteria. Additionally, an individual can become a LEED Accredited Professional (LEED AP) or LEED Green Associate (LEEDGA)—someone who has demonstrated knowledge of green building as well as an understanding of the LEED certification system.

LEED v3 (version 3) was launched on April 29, 2009, and provides the performance standards that must be met for LEED certification based on a point system that has 100 base points, six possible innovation points and four regional priority points. Points are earned in seven areas: sustainable sites, water efficiency, energy and atmosphere, materials and resources, indoor environmental quality, innovation in design, and regional priority. Points are not given for having a specific material, but rather for performance (as with energy performance) or by qualification as a sustainable material (such as recycled or renewable).

Green Globes by the Green Building Initiative (**www. thegbi.org**) is an online tool for evaluating and rating sustainable buildings. Green Globes was introduced in the U.S. in 2004, and its current revision will be issued in 2010 as an American National Standards Institute ANSI standard. The user inputs the sustainability aspects into a detailed online platform and then is given a resulting score along with suggestions for improvement. Both Green Globes and LEED have the same goal of encouraging green building practices and have similar focus areas for assessment. LCA has not had a heavy emphasis in either program in the past, but the newest versions of LEED and Green Globes will have sections incorporating LCA. A comparison of Green Globes and LEED is available in a University of Minnesota study (Smith et al. 2006).

The National Association of Home Builders (NAHB) and the International Code Council (ICC) (2008) developed the "National Green Building Standard (ICC-700-2008)." The document, developed through a consensus process, is approved by (ANSI). The standard covers single- and multi-family homes, site development, and residential remodeling. The standard has mandatory provisions along with threshold point requirements to achieve a performance rating of bronze, silver, gold, or emerald. The categories for achieving points include lot/site development; efficiency of resources, water, and energy; indoor environmental air quality; and operation, maintenance, and building owner education.

Energy Star is not a rating system, but does provide an outline for building techniques to reduce energy use in new construction. The programs through Energy Star (from the Department of Energy and Environmental Protection Agency) have made it a household name, particularly through Energy Star labeling of appliances. Energy Star also has programs for homes and businesses to reduce energy use.

Strategies versus rating systems

Rating systems can be considered checklists of best and desirable sustainability practices. At the same time, rating systems can cause owners, designers, and contractors to be narrow in their focus—merely trying to implement rating system items to achieve a particular score. This is true even when rating systems provide "points" for innovation. Hopefully, those innovative practices that are widely used will eventually be incorporated into the rating system.

The strategies detailed in Part II can be universally applied to most of the aforementioned rating systems. For example, stormwater control is recognized as a desirable outcome by rating systems and Chapter 5 discusses how the use of concrete can contribute to meeting that sustainable goal. By detailing the strategies in which concrete can be best used, it is hoped that the design/construction team will think beyond a rating system and strive for the efficient, effective, and practical applications of concrete that contribute to a sustainable built environment.

Codes and standards

The design and construction of buildings are governed by codes at both the national and local level. The model code that encompasses the full building system for all building materials is the *International Building Code* (International Code Council 2009). States and local municipalities generally adopt such a model code in lieu of creating and maintaining their own independent code. Some cities, however, such as New York and Chicago, maintain their own building codes (but also include portions of other model codes by reference).

The American Concrete Institute's ACI 318, "Building Code Requirements for Structural Concrete and Commentary" (ACI Committee 318 2008) is the primary code document that addresses structural systems in concrete buildings. Because of ACI's ANSI consensus process, ACI 318 is recognized as the definitive source for design of concrete structures, and other codes (most notably the International Buidling Code in the U.S.) often adopt ACI 318 by reference for their concrete systems. By its nature as a building-related code, ACI 318 is focused on minimum requirements for life safety.

Consideration of sustainability has not typically been incorporated into a life-safety-based code, but ACI established a sustainability committee (ACI Committee 130) in 2008 to work with ACI technical committees to incorporate sustainability issues into their documents. It is important, however, that sustainability be considered up front in designing the building system. The information contained in this book can be used as a starting point for major considerations in a concrete system as well as a reference throughout the design process to integrate sustainability considerations into the planning process before design to meet the requirements of ACI 318.

ASTM International publishes technical standards that are often referenced by the codes discussed previously in this section. Concrete materials and testing are included in ASTM's standards. ASTM formed the Sustainability Committee (E60) in 2008 to develop sustainability standards and to work with existing ASTM standards committees.

State building codes and standards are now incorporating sustainability and green building requirements. The *California Green Building Standards Code* (California Building Standards Commission 2008) was first adopted in July 2007 and requires that every new building constructed in California reduce water consumption, divert construction waste from landfills, and install low-pollutant-emitting materials. It also requires separate water meters for indoor and outdoor water use and mandatory inspections of energy systems (for example, heat furnace, air conditioner, and mechanical equipment) for nonresidential buildings over 10,000 ft^2 (930 m^2). Many states have adopted green or sustainable building codes, with some requiring LEED, Green Globes, or another rating system for government buildings, and cities and counties are now following suit.

Acidification (oceans)—Lowered pH due to increased CO_2 dissolved in the oceans.
Cradle-to-cradle—An extension of cradle-to-grave to include recycle/reuse of the materials to bring the cycle back to cradle (birth).
Cradle-to-grave—Life cycle assessment considering manufacture or birth (cradle) through demolition (grave).
Ecocalculator—Tool for life cycle assessment calculations to evaluate potential to contribute to global warming.
Life cycle assessment (LCA)—Quantification of the full environmental impacts of a building (or product or service) over its lifetime.
Life cycle cost (LCC)—Quantification of the full monetary impact of a building (or product or service) over its lifetime.

PART 2—CONSIDERATIONS FOR BEST USE OF CONCRETE FOR SUSTAINABLE STRUCTURES

Chapter 1—Carbon footprint

As discussed in the Introduction, the environmental impact portion of sustainability reaches far beyond CO_2 alone, but CO_2 is given special consideration in this book due to the direct relationship between cement production and CO_2 emissions. A carbon footprint is "the total set of greenhouse gas emissions caused directly and indirectly by an individual, organization, event or product" (Carbon Trust 2007). A carbon footprint essentially measures the potential contribution humans have on climate change as expressed in weight of CO_2 equivalent.

A carbon footprint, therefore, includes both CO_2 emissions directly associated with the manufacture of an item or product (including the extraction of resources, burning of fossil fuels for energy to manufacture, and for transporting materials and the final product) and indirectly through its continued use, operation, and maintenance. For example, the creation of an article of clothing generates CO_2 during the manufacturing and the shipping of the raw and finished materials. Additionally, energy used in laundering the clothing article contributes additional CO_2 emissions. For concrete, the life cycle emissions can be segregated into that generated during the building construction (direct) and the operational energy used by the building (indirect). In the case of buildings, CO_2 emissions generated during the lifetime operational phase are considerably more than those generated during construction.

Cement production

As discussed in Part I, cement production directly produces CO_2. Approximately one-half of the CO_2 emissions from cement production come from combustion (burning of coal or other fossil fuels) with the other half from calcination (the conversion of limestone to lime, liberating CO_2). The Environmental Protection Agency (EPA) published an online version of a working draft in May 2008 on Quantifying Greenhouse Gas Emissions from Key Industrial Sectors in the United States. This working draft provides objective comparisons of the 14 industrial sectors that contribute the majority (over 84%) of greenhouse gas emissions in the U.S. based on 2002 statistics. This report defines a consistent description of boundaries for a sector and consistent year of data collection for all the sectors so that they can justifiably be compared side by side. Electricity purchased for use in production is included in the emissions data. Figures 2.1 and 2.2 are reproduced from data and figures in the EPA working draft (Environmental Protection Agency 2008). Figure 2.1 shows the breakdown of the contributions of greenhouse gases in the production of cement (CO_2 is the only significant contributor in the EPA cement data) from combustion of fossil fuels, purchased electricity, and noncombustion (CO_2 liberated from the limestone to lime conversion). Figure 2.2 shows the contribution of cement production (4%) to greenhouse gas emissions compared with all other industrial sectors. For example, this can be compared with 5% of greenhouse gas emission from mining, 5% from iron and steel, 5% from forest production, and 5% from food and beverage industries.

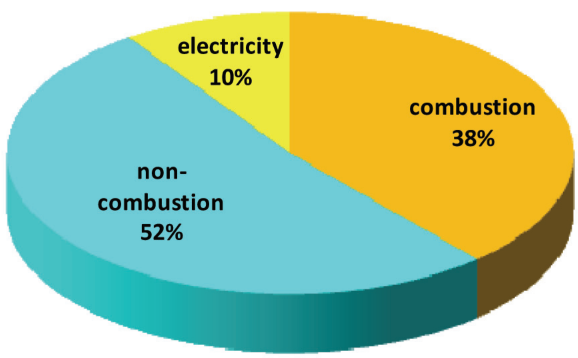


Fig. 2.1—Greenhouse gas (CO_2) emissions by category in cement production.

Major advances in standard practice for the manufacturing of cement can reduce CO_2 emissions, with positive implications for carbon trading or other measures. Measures such as burning waste tires instead of coal and improving plant efficiency have resulted in some significant reductions in CO_2 emissions from the cement manufacturing phase, but the massive growth in quantities of concrete (and thus, cement) used worldwide means that cement will continue to be a major CO_2 contributor even with plants following best practices for reducing emissions. The rate of increase in CO_2 emissions from cement production has decreased in recent years, while the rate of growth in cement production continues to increase (World Business Council for Sustainable Development 2009).

The cement industry worldwide has responded through efforts such as the Cement Sustainability Initiative (CSI) from the World Business Council for Sustainable Development. The Cement Sustainability Initiative charter includes commitments in the following areas: CO_2 and potential climate change effects, responsible use of fuels and raw materials, employee health and safety, emissions reductions, local impacts on land and communities, and reporting and communications. In the area of CO_2, CSI

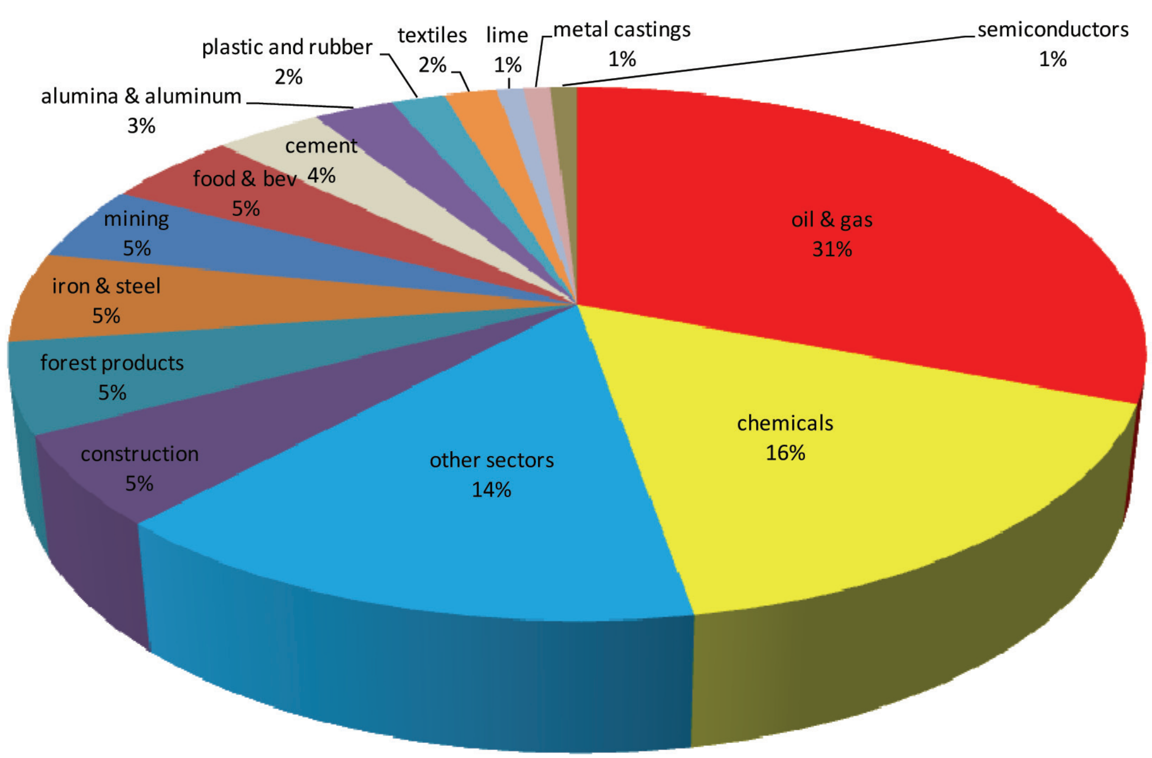


Fig. 2.2—Greenhouse gas emissions by industrial sector.

companies define and make public their baseline CO_2 emissions, develop a climate change strategy with targets and progress markers, and report annually on CO_2 emissions. A key CSI project has been the data collection of CO_2 and energy performance with transparent reporting and publication. The "Getting the Numbers Right" program (World Business Council for Sustainable Development 2009) and the global data are available for online access by any interested parties (**www.wbcsdcement.org**).

In 2007, the U.S. ranked third in quantity of cement produced at approximately 100 million tons [91 billion kg], behind China (1300 million tons [1200 billion kg]) and India (180 million tons [160 billion kg]). (**www.theoildrum.com**)

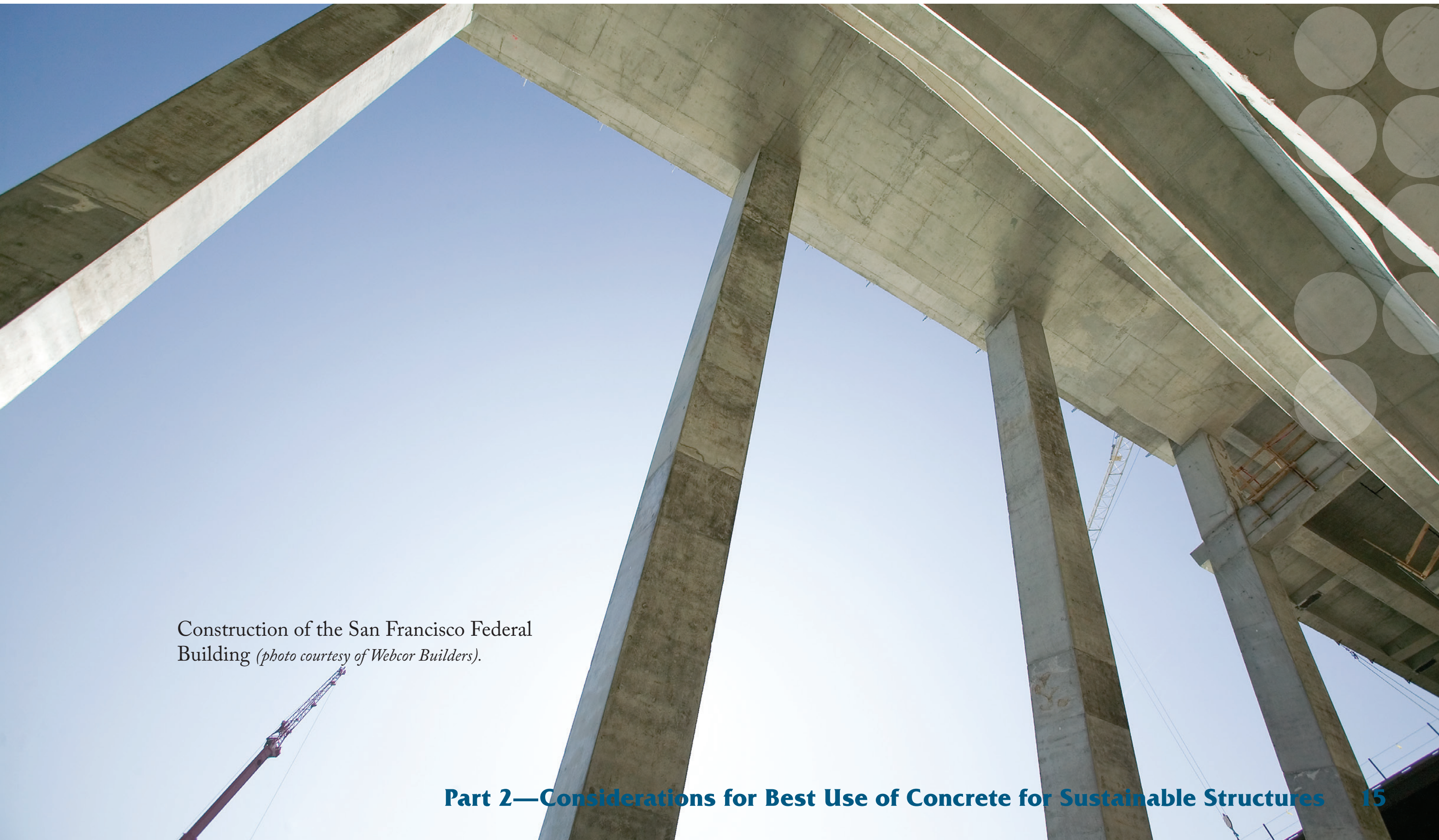
The U.S. cement industry has established a voluntary code of conduct through the Portland Cement Association (PCA) Cement Manufacturing Sustainability Program, and is aggressively working toward achieving four goals. The four goals established for 2020 (from a 1990 established baseline) include: 1) 10% reduction of CO_2; 2) 60% reduction of landfilled cement kiln dust; 3) implementation of an environmental management system in 90% of cement plants; and 4) 20% improvement in energy efficiency (PCA 2004).

Operational contribution to the footprint

Over the life of a building, the carbon footprint due to the initial construction (which includes the portion from all materials, including cement) is small compared with the contribution from the energy used during the

Tires are used as an alternate fuel source in cement manufacturing.

In 2007, the U.S. ranked third in quantity of cement produced at approximately 100 million tons, behind China (1300 million tons) and India (180 million tons).



Construction of the San Francisco Federal Building *(photo courtesy of Webcor Builders).*

remainder of the life of the building. For example, for a residence, the embodied energy may be approximately 10% of the total energy use over the 100-year life of the building (Pullen 2000).

An LCA was conducted on a house modeled with two types of exterior walls: a wood-framed wall and an insulating concrete form (ICF) wall. The LCA was carried out according to the guidelines in International Standard ISO 14044, "Environmental Management–Life Cycle Assessment–Requirements and Guidelines." The house was modeled in five cities, representing a range of U.S. climates: Miami; Phoenix; Seattle; Washington, DC; and Chicago. The system boundary includes the inputs and outputs of energy, materials, and emissions to air, soil, and water from extraction of raw materials though construction, maintenance, and occupancy. The results show that, for a given climate, the life cycle environmental impacts are greater for the wood house than for the ICF house. The most significant environmental impacts are not from construction materials but from the production of electricity and natural gas and the use of electricity and natural gas in the houses by the occupants (Marceau 2008). A large inventory of older buildings exist that have large carbon footprints due to their high operational energy costs. While this book focuses on new construction, it is important to mention the CO_2 reduction that can be achieved in rehabilitating older buildings by making use of some of their existing positive attributes. Taking advantage of thermal mass from concrete or masonry walls and slabs and improving the seal of the building envelope can save operational energy. The conservation of natural resources is considerable through this approach compared with the demolition of a building that will be replaced with new construction.

Reducing the carbon footprint

While improving the manufacturing process of concrete materials (for example, using alternate fuel sources for the manufacturing of cement) offers some opportunity to directly reduce the carbon footprint of a building, another potential opportunity is to design a building using concrete more efficiently. This can start with a reduced square footage in a building that meets the owner's needs, the use of innovative concrete structural systems, and improving the effectiveness of concrete that is used.

A profile of the San Francisco Public Utilities Commission Building is featured in Chapter 22 and is an example of using concrete more efficiently through design. The building incorporates a high-performance, vertically post-tensioned structural design. This type of performance design innovation reduces the overall amount of concrete necessary for vertical structural members and reinforcing bar needed (a 30% reduction over traditional systems), thereby reducing material use and its associated material carbon impact.

While somewhat oversimplified, the following hypothetical example in Table 2.1 demonstrates the concept of using high-strength 9000 psi (62 MPa) concrete columns versus columns made of 4000 psi (28 MPa) concrete. Although the use of high-performance concrete may use more cement per cubic yard of concrete, judicious use of higher cement content and other materials can achieve much higher strengths and ultimately have a lower greenhouse gas footprint due to less materials used overall. It also has the cascading effect of less building weight, which typically results in smaller foundations and reduced seismic design requirements (if applicable).

San Francisco Public Utilities Commission, San Francisco, CA *(rendering courtesy of KMD Architects).*

Table 2.1—Comparison of normal-strength and high-strength concrete columns

	4000 psi (28 MPa) concrete	9000 psi (62 MPa) concrete
Total cementitious materials, lb/yd^3 (kg/m^3)	550 (330)	865 (510)
Supplementary cementitious materials, lb/yd^3 (kg/m^3)	110 (65) fly ash	40 (24) silica fume
Portland cement, lb/yd^3 (kg/m^3)	440 (260)	825 (490)
Column dimensions, in. (mm)	36 x 36 (900 x 900)	24 x 24 (600 x 600)
Concrete per column, yd^3	5.0 (3.8)	2.2 (1.7)
Reduced volume of concrete per column, %	—	55
Portland cement per column, lb/column	2200 (1000)	1800 (820)
Reduced volume of cement per column, %	—	18

Note: column assumed to be 15 ft (4.6 m) high.

Where high-strength concrete is determined as optimal for the design of a specific project, careful review of the strength requirements and load path are essential. Simply lowering the amount of cement per cubic yard of concrete may not always be a suitable solution for a project. The use of high-strength concrete for many design elements may also result in a significant reduction of member cross sections, the elimination of multiple elements, or may provide significantly longer service life.

Another widely used tactic to reduce the carbon footprint of a cubic yard of concrete is to not only reduce the cementitious materials used, but also to replace cement using supplemental cementitious materials such as fly ash, slag cement, and silica fume.

Carbon footprint—Total CO_2 and other greenhouse gas emissions produced directly or indirectly from an item or process.
Carbon negative—Having a net negative carbon footprint (overall reduction in CO_2).
Carbon neutral / zero footprint—Having a net zero carbon footprint (no overall CO_2 produced or reduced).
Embodied energy—Energy embodied in the physical building including raw materials, transport, manufacture, and later demolition.
Operational energy—Energy needed for building functions including heating, cooling, and lighting.

Chapter 2—Thermal transmission

Heat transfers through a building envelope by various means: conduction (gradient driven transfer of heat between molecules), convection (transfer of heat through fluid motion in liquids or gases), and thermal radiation (electromagnetic heat emitted from an object at high temperature). Materials used to help insulate a building are chosen on the basis of their resistance to thermal conduction and the system resistance to air infiltration. Thermal conductivity of concrete varies with density, aggregate type, and moisture content. Low-density concrete with lightweight aggregate has a lower thermal conductivity than standard concrete, and thus has better insulating properties when used alone. Like other construction materials, concrete can be used in a layered system with other insulating materials (including air space). In the U.S., the most commonly recognized measure of insulating effect for building materials and systems is thermal resistance (R-value), as described later in this section.

Exterior concrete wall assemblies

There are many types of insulation materials and insulating systems; most combine insulating layers in a sandwich with structural materials to reduce the thermal transmission between the outside environment and the building interior. Several common types of systems and concrete insulating materials are as follows:

- **Concrete masonry units (CMU)—**CMU block is a popular choice for walls in conjunction with additional insulating material, with an exterior finish (such as stucco); or it can also be left bare. The voided cavities in the CMU can include reinforcement and concrete or grout.
- **Cavity walls—**Cavity walls consist of two walls separated by a space (cavity). Masonry walls (often one CMU and one brick, or both CMU) are common in cavity wall systems, and can be used in conjunction with rigid foam insulation. The foams used are derived from fossil fuels, so there is a tradeoff between the use of fossil fuels in a material and the energy savings.

Insulating concrete forms being used in the construction of a walkout ranch home in Omaha, NE. Completed home, bottom photo *(photos courtesy of Fox Blocks).*

- **Precast sandwich panels—**Precast sandwich panels combine two exterior precast concrete layers that sandwich a layer of foam insulation. The panels may be used as cladding, bearing walls, or shear walls. The insulating layer can be continuous through the panel if conductive shear ties are avoided. Similiar to cavity walls, foams are derived from fossil fuels.
- **Insulating concrete forms (ICFs)—**Rather than sandwiching insulation between two layers of concrete or masonry, ICFs use the insulating material as a stay-in-place form for cast-in-place concrete. ICFs are typically preformed blocks or panels (either vertical or horizontal) connected with plastic ties. Both the form type and the cavity space for the concrete vary by manufacturer. Examples of the cavity space include a standard flat wall, waffle, or a tubular grid of concrete (large cylinders running in both directions). The forms are made from expanded polystyrene (EPS), extruded polystyrene (XPS), polyurethane, or a combination of cement with EPS polystyrene beads. As mentioned previously for cavity walls, there is a tradeoff between the use of fossil fuels in a material and the energy savings.
- **Autoclaved aerated concrete (AAC)—**AAC is an ultra-lightweight cellular concrete with weights ranging from 1/5 to 1/3 of that of concrete, or approximately 30 to 50 lb/ft^3 (480 to 800 kg/m^3) with strengths typically in the 500 to 600 psi (3.5 to 4.1 MPa) range. AAC is fabricated at a plant from cement, lime, sand, water, and an expanding agent (aluminum powder). The expanding agent reacts to form small distributed bubbles of hydrogen gas that result in a lightweight cellular material with good insulating properties. The AAC is subjected to high pressure steam curing to achieve its final properties. Large AAC blocks can then be cut into smaller building components. A wire mesh is typically used when reinforcement is needed in AAC panels.
- **Structural lightweight aggregates (SLAs)—**Lightweight aggregates can produce concrete that is lightweight compared with standard concrete. Structural lightweight concretes typically weigh 90 to 115 lb/ft^3 (1400 to 1800 kg/m^3) versus 145 lb/ft^3 (2300 kg/m^3) for standard concrete. Unlike AAC, which is much lighter and has low compressive strengths, structural lightweight concretes have a minimum compressive strength of 2500 psi (17 MPa). SLA is manufactured ceramic aggregate from expanded shale, clays, and slate

Autoclaved aerated concrete was used in the floor slabs, roof slab, and interior/exterior load-bearing walls during construction of this 126-room Holiday Inn hotel in Fort Worth, TX *(photo courtesy of Xella Mexicana, S.A. de C.V.).*

that is produced in a rotary kiln. Naturally occurring lightweight aggregates, such as pumice and scoria from volcanic sources, can also be used. The porous nature of SLA improves the insulating properties of structural lightweight concrete.

Exterior insulation and finish systems (EIFS) can be used in conjunction with cast-in-place concrete walls as an insulated exterior surface. The EIFS is a layer of insulating material (foam board) with an exterior layer of a polymer grout mixture with fiber mesh reinforcement. The EIFS is bonded to the concrete wall and forms a type of synthetic stucco coating over the concrete wall.

Thermal resistance (R-values)

R-values and U-values are tabulated for various materials and systems to aid the engineer in design. The R-value is a measure of resistance of heat transfer under steady-state conditions. The U-value (or U-factor) is the overall heat transfer coefficient. The U-value is

Table 2.2—Thermal properties of common building materials

Material	Density, lb/ft³	R per in. thickness, hr • ft² • °F/Btu	Specific heat, lb • °F
Rigid insulation			
Cellular glass	8.0	3.03	0.18
Glass fiber, organic bonded	4.0 to 9.0	4.00	0.23
Mineral fiber, resin bonded	15	3.45	0.17
XPS (extruded polystyrene), closed cell	1.8 to 3.5	5.00	0.29
Expanded polystyrene (EPS) molded bead	1.0	3.85	—
	1.25	4.00	
	1.5	4.17	
	1.75	4.17	
	2.0	4.35	
Other materials			
Concrete	145	0.063	0.20
	140	0.068	
	130	0.083	
	120	0.10	
	110	0.13	
	100	0.16	
	90	0.21	
	80	0.27	
	70	0.36	
	60	0.44	
	50	0.59	
	40	0.71	
	30	0.91	
	20	1.25	
Gypsum board	50	0.88	0.26
Particle board	50	1.06	0.31
Hardwood	38 to 47	0.94 to 0.80	0.39
Softwood	24 to 41	1.35 to 0.89	0.39
Plywood	34	1.25	0.29

Note: (Adapted from *Designer's Notebook* (PCI 2007); values for a wide range of materials and systems are available in the *ASHRAE Handbook–Fundamentals* (ASHRAE 2009) and ANSI/ASHRAE/IESNA Standard 90.1 (American Society of Heating, Refrigerating and Air Conditioning Engineers 2007).

1 lb/ft³ = 16.0 kg/m³; 1 hr × ft² × °F/Btu = 176 m² × °C/W; and 1 lb × °F = 0.252 kg × °C.

inversely proportional to the R-value, so a material with a high R-value and low U-value represents a good insulation material. Steady state conditions used to determine R-values, however, do not represent the condition of heat loss retardation through a material such as concrete that offers the benefits of thermal mass, as will be described in the next section. Table 2.2 lists R-values for some common building materials, including concrete at varying densities. If there are no penetrations through the insulating layers, the total R-value of a wall system constructed of different layers of materials is equal to the sum of the R-values of each of the layers. Air film surfaces next to the wall (interior and exterior) and air spaces are included in the total R-value.

High R-value insulation is much less effective if there is a direct path between the building exterior and interior through thermal bridges of highly conductive material. Penetrations through the insulating layers often come in the form of exposed slab edges and cantilevered slab balconies, exposed frames, and other thermal bridges. Steel studs can also be thermal bridges if insulation is placed between studs and not continuous over studs. Offsets and exterior insulation to separate potential thermal bridges from the insulating layer are crucial for achieving a building envelope that is energy efficient (Lsitburek 2007).

When a thermal bridge is present, the R-value is reduced, and is not calculated by simply adding each layer's *R*-value. For these types of systems, the series-parallel method should be used instead (American Society of Heating, Refrigerating, and Air Conditioning Engineers [ASHRAE] 2009), as illustrated in Example 2. Metals are not solely responsible for thermal bridging; areas of solid concrete with no insulation layers also allow thermal bridging. Cantilevered balconies, such as those shown in Fig. 2.3, provide a route for conductance through the building envelope unless the balcony is separated from the interior concrete by an insulating layer. Figure 2.4 illustrates a method to prevent thermal bridging between the building's exterior (balcony) and interior.

Heat flow through a CMU wall (either insulated or uninsulated) also requires the series-parallel method of calculation due to the geometry of the CMU units that provide a route for heat transfer between the cells.

Calculating wall R-value

Two simplified calculations are shown in this section to illustrate calculations of thermal resistance in wall sections with and without thermal bridging.

Example 1: No thermal bridging

Take, for example, a sandwich panel cross section with a 6 in. (150 mm) standard concrete wall layer (interior wythe), a 3 in. (75 mm) XPS insulation layer, and a 3 in. (75 mm) outer concrete wythe. The panel is assumed to have non-conductive composite connectors that do not result in thermal bridging.

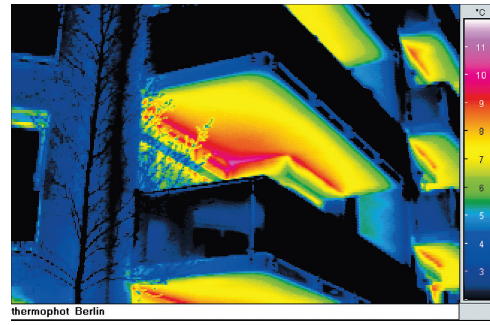


Fig. 2.3—Thermographic image demonstrates heat loss caused by thermal bridge at concrete balcony. Surface temperature drops from approximately 52°F (11°C) near building to less than 41°F (5°C) at balcony edge as concrete conducts heat from building interior to outside environment. Thermal bridges not only waste energy, they can lead to local cold spots on walls and ceilings that can result in condensation and mold.

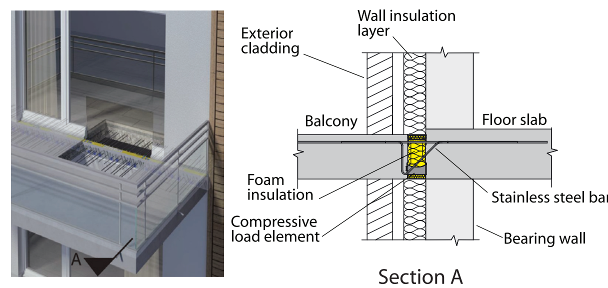


Fig. 2.4—In Europe, connection systems, such as the one shown here, are commonly used to prevent these problems. While bulk of system comprises insulating material, stainless steel bars transfer flexural and shear forces. System can reduce average thermal conductivity by approximately 90% relative to a conventional concrete balcony *(images courtesy of Schöck Bauteile GmbH)*.

Because no thermal bridging is present, the R-value per square foot of panel is found by adding the R-values (found in Table 2.2) of each of the three layers in the series:

Layer	R-value (hr·ft²·°F/Btu)
Interior air film*	0.68
6 in. concrete interior	(0.063/in.)(6 in.) = 0.378
3 in. extruded polystyrene	(5.00/in.)(3 in.) = 15.00
3 in. concrete exterior	(0.063/in.)(3 in.) = 0.189
Exterior air film*	0.17
TOTAL	16.42

Note: *R-values for air films are dependent on surface type, direction of air flow, direction of surface, wind speed (exterior), and other factors. Values shown are for vertical surface, horizontal air flow, and exterior wind velocity of 15 mph (6.7 m/s). Additional values are available in ASHRAE *Handbook–Fundamentals* (ASHRAE 2009).

1 in. = 25.4 mm; 1 hr×ft²×°F/Btu = 176 m²×°C/W.

Example 2: Thermal bridging

If the sandwich panel from Example 1 contains No. 3 steel ties (R-value = 0.013) rather than nonconductive ties, thermal bridging will occur. For this case, the series-parallel method is used to calculate the R-value of the insulating layer:

$$R_{total} = \frac{(R_{insulating\ layer})(R_{ties})}{(A_{insulation})(R_{ties}) + (A_{ties})(R_{insulating\ layer})}$$

The steel ties are spaced at 10 in. (250 mm) on center and penetrate 1 in. (25.4 mm) into each of the concrete layers, so the R-value for the insulating layer includes the XPS layer, plus 2 in. (50 mm) of concrete. The ties make up 0.05% of the insulation area ($A_{insulation}$ = 0.0005).

$$R_{insulating\ layer} = \frac{(15.13)(0.013)}{(0.9995)(0.013) + (0.0005)(15.13)}$$

= 9.57 hr • ft² • °F/Btu (1680 m² • °C/W)

The new R-value for the insulation area is then added in with the other layers in series:

Layer	R-value (hr·ft²·°F/Btu)
Interior air film	0.68
5 in. concrete interior	(0.063/in.)(5 in.) = 0.315
Insulating layer	9.57
2 in. concrete exterior	(0.063/in.)(2 in.) = 0.126
Exterior air film	0.17
TOTAL	10.86

Note: 1 in. = 25.4 mm; 1 hr × ft² × °F/Btu = 176 m² × °C/W.

The presence of the steel ties acting as thermal bridges reduces the R-value for the example wall from 16.42 to 10.86 hr×ft²×°F/Btu (2900 to 1900 m²×°C/W).

Summary

Insulation for reduced thermal transmission is the key consideration for reducing energy costs due to heating and air-conditioning. Concrete can form part of the building envelope that sandwiches outside or between layers of insulating material for energy conservation. Concrete's biggest contribution is from its thermal mass, as will be described in the following chapter.

Autoclaved aerated concrete—Lightweight precast cellular concrete; cured under high temperature and pressure.
Parallel method—A method to calculate R-values in systems without thermal bridges.
Series-parallel method—A method to calculate R-value in systems with thermal bridges.
Thermal transmission—Transfer of heat through a body by convection, conduction, or radiation.

Chapter 3—Thermal mass and storage

The capacity of a body to store heat (heat capacity) can be used to an advantage for energy conservation. Materials with high heat capacities and low thermal diffusivity (slow transfer of heat) have the potential for high thermal mass. Table 2.3 gives a basic comparison of these two properties for various materials. While concrete is not the material with the highest heat capacity or lowest thermal diffusivity, it is a high-mass material. The concrete fireplace shown in Fig. 2.5 illustrates one use of thermal mass. Thermal mass tends to reduce the effects of outside temperature spikes on the building's interior and can contribute to passive heating and cooling in a building. Thermal mass is an area of potential energy reduction using concrete and masonry members, particularly in climates with large diurnal (daily) temperature swings.

Thermal mass effects on the energy requirements of a building tend to be more difficult to envision than the standard practices of increasing energy efficiency through insulation (reduction of thermal transmission). Many architects and engineers are familiar with solar collectors (and photovoltaic systems) (Fig. 2.6), so it is helpful to show a comparison of how this type of active solar system compares with systems using thermal mass. A simplified comparison of solar battery storage versus thermal mass heat storage options is shown in Fig. 2.7 and 2.8. The concrete wall that illustrates thermal mass in these figures does not store energy for on-demand use like the battery. Instead, the wall delays the transfer of the outside heating from the sun into the interior, as shown in Fig. 2.7. A mass wall can also be used inside as indicated in the figure by the case of room heating by a fireplace or radiator in Fig. 2.8. In this situation, the mass wall retains heat from the interior that will be slowly released later as the room cools. This reduces the energy demand for heating the interior.

Thermal mass not only allows for a reduction in energy used due to running the heating, ventilating, and air conditioning (HVAC) equipment less, thermal mass also allows for the use of smaller, more efficient HVAC units to be installed, which adds even more savings, that is, the most savings are realized when the architect, structural engineer, and mechanical engineer incorporate the benefits of thermal mass early on in the design phase.

Incorporating concrete thermal mass in design

Using the benefits of thermal mass is not a new concept. Concrete is a material with a high thermal mass that: 1) stores energy within its mass; 2) moderates the effect of outside temperature extremes; and 3) offsets or delays the peak outside temperatures. In other words, concrete can store or release large amounts of thermal energy (heat) resulting in reduced interior temperature variations by exposing surfaces of concrete floors, ceilings, or walls to the interior environment. During warm weather, exposed concrete surfaces can take advantage of reduced nighttime temperatures to moderate diurnal temperature swings. During cool weather, exposed concrete surfaces can store energy, maintaining interior comfort at night, as shown

Table 2.3—Heat capacity and thermal diffusivity comparison

Material	Heat capacity, Btu/(lb·°F)	Thermal diffusivity, m^2/s
Concrete	0.210	5.38 to 7.53
Iron	0.111	172
Aluminum	0.214	1270
Plaster	0.201	3.77 to 6.46
Wood	0.779	1.18
Water	1.21	1.51
Air	0.288	237

Note: 1 Btu/(lb × °F) = 3467 J/(kg × K); 1 ft^2/s = 0.0929 m^2/s.

Fig. 2.5—Concrete fireplace through interior wall provides heat storage from thermal mass *(photo courtesy of David Duncan Livingston/Buddy Rhodes Studio)*.

in Fig. 2.9. The effects of thermal mass are recognized in publications from the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE).

The effect of temperature lag associated with low and high thermal mass is shown in Fig. 2.10; and Table 2.4 shows some values of time lag and amplitude reduction for various materials. On a hot summer day, thermal energy (heat) absorbed and stored in walls and other elements delays the peak-heat of the day and thus keeps the interior of the building cooler and saves energy. For an office building, this delay alone can have a major influence on tempering the heat generated from lighting and computers. For an occupied residence in warm months, the absorption and delayed release of peak-heat reduces the energy needed to keep a house cool during the day. At night, the process is reversed. Energy absorbed during the daytime is released from the walls into the cool night. Cooling of the interior can be hastened if windows are opened, particularly if the structure has been designed for good air flow and ventilation.

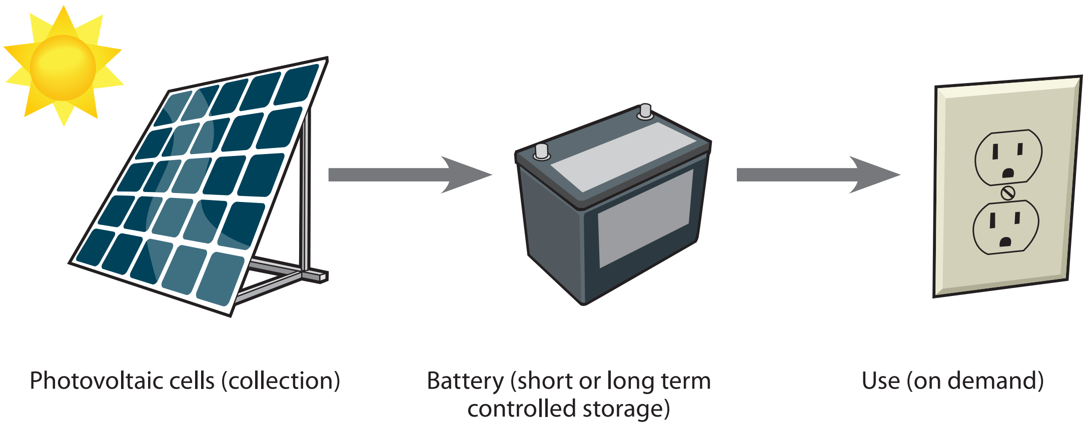


Fig. 2.6—Active solar collection and storage.

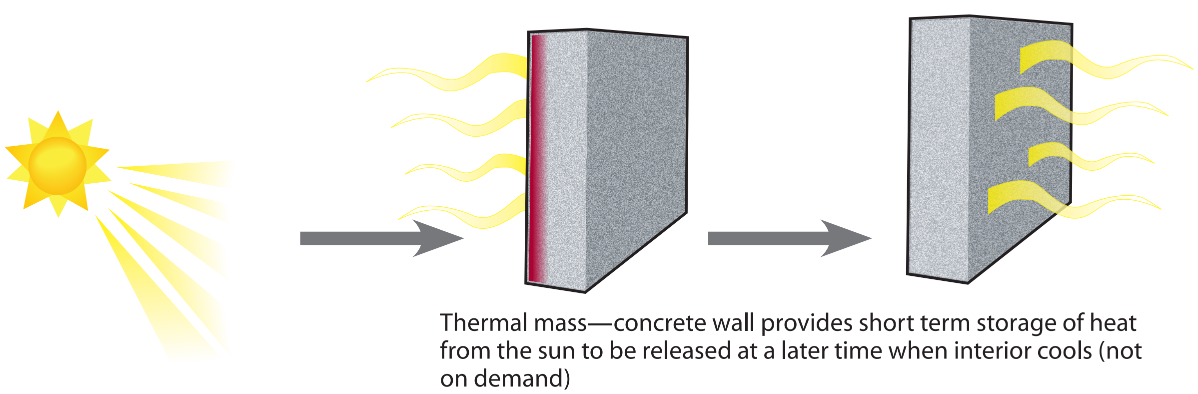


Fig. 2.7—Thermal mass collection and storage: solar/exterior collection

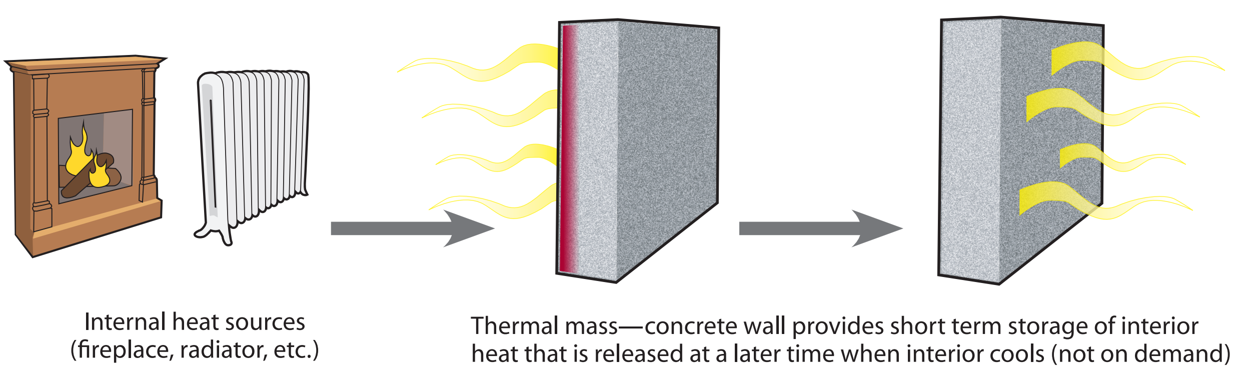
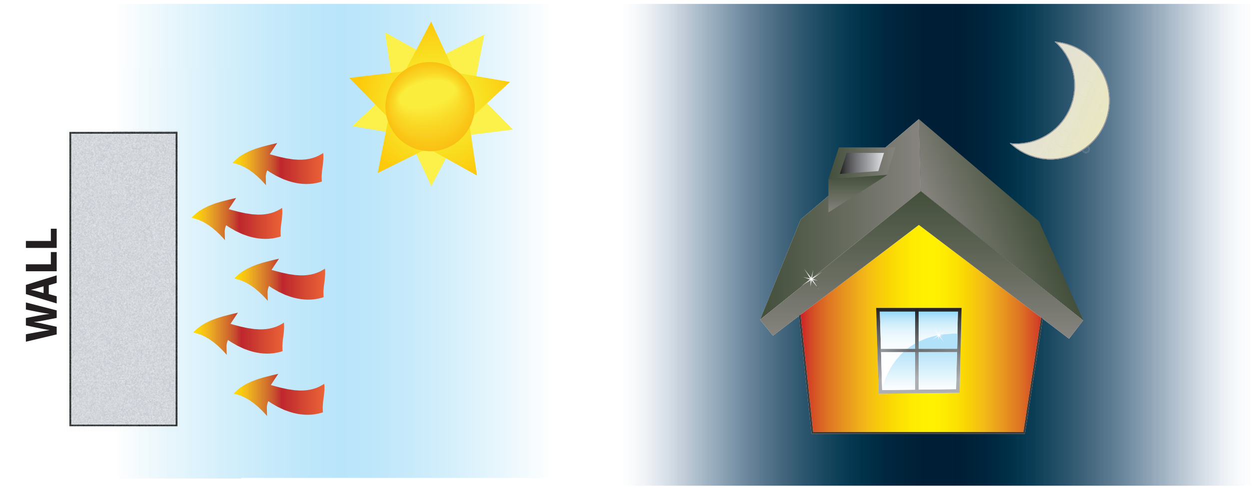
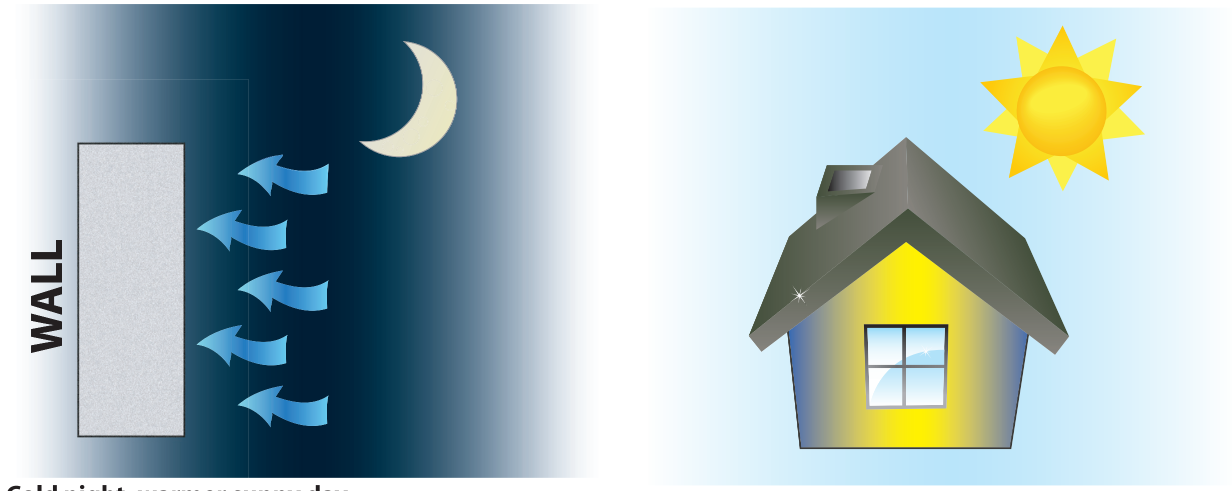


Fig. 2.8—Thermal mass collection and storage: interior heat sources



Cooler night, hot day
Walls cool overnight and delay temperature rise during the day for occupants.
At night, cool outside air can be circulated through building.



Cold night, warmer sunny day
During the day, solar warming through windows.
During the night, delayed temperature drop.

Fig. 2.9—Indoor temperature differentials.

On a cold day, thermal mass works particularly well with a passive solar design. Daytime occupants experience light and warming from windows that reduce the energy load for heating. Energy stored in walls and floors from daytime warming (direct gain) carries over into the night to delay cooling of the interior and to temper the effect of temperature drops.

The concept of thermal mass brings to mind very thick concrete walls and elements. Table 2.5 shows values for heat capacity with increasing concrete wall thickness. A rule of thumb is that for walls greater than 8 in. (200 mm) thick, the practical ability to use the full

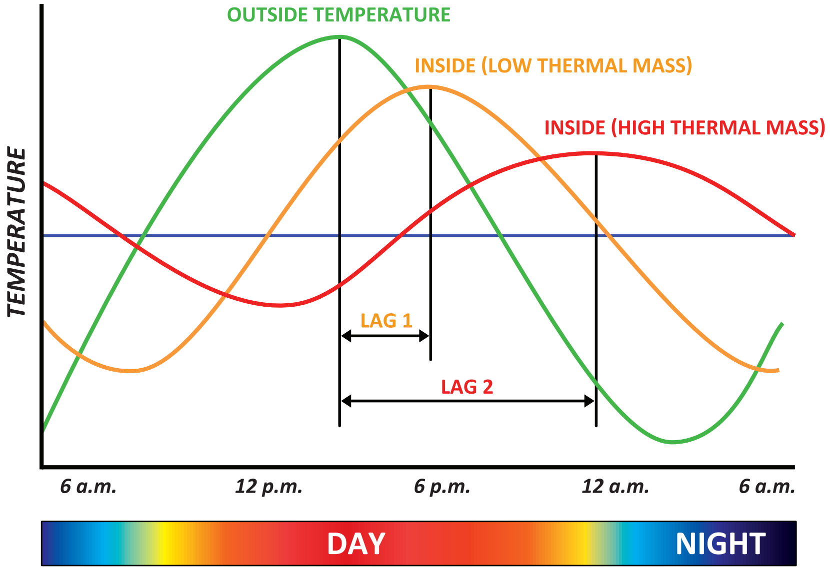


Fig. 2.10—Effect of temperature lag from thermal mass.

Table 2.4—Thermal lag and amplitude reduction measurements from calibrated hot box tests*

Wall no.	Thermal lag, hours	Amplitude reduction, %
1. 8 x 8 x 16 in. (200 x 200 x 400 mm) masonry	3.0	18
2. 8 x 8 x 16 in. (200 x 200 x 400 mm) masonry, with insulated cores.	3.5	28
3. 4-2-4 masonry cavity wall	4.5	40
4. 4-2-4 insulated masonry cavity wall	6.0	38
5. Finished 8 x 8 x 16 in. (200 x 200 x 400 mm) masonry wall	3.0	51
6. Finished 8 x 8 x 16 in. (200 x 200 x 400 mm) masonry wall with interior insulation	4.5	31
7. Finished 6 x 8 x 16 in. (150 x 200 x 400 mm) masonry wall with interior insulation	3.5	10
8. Finished 8 x 4 x 16 in. (200 x 100 x 400 mm) masonry wall with interior insulation	4.5	27
9. Structural concrete wall	4.0	45
10. Structural lightweight concrete wall	5.5	53
11. Low-density concrete wall	8.5	61
12. Finished, insulated 2 x 4 in. (38 x 89 mm) wood frame wall	2.5	–6
13. Finished, insulated 2 x 4 in. (38 x 89 mm) wood frame wall	1.5	7.5
14. Finished, insulated 2 x 4 in. (38 x 89 mm) wood frame wall	1.5	–4
15. Insulated 2 x 4 in. (38 x 89 mm) wood frame wall with a masonry veneer	4.0	–6

*(ACI Committee 122 2002)

Table 2.5—Heat capacity of concrete for varying wall thickness*

Wall thickness, in.	Heat capacity per ft², Btu/(ft² • °F) 145 lb/ft³ (2320 kg/m³)	110 lb/ft³ (1760 kg/m³)
3	7.2	5.5
4	9.6	7.3
5	12.0	9.2
6	14.4	11.0
7	16.8	12.8
8	19.2	14.6
9	21.6	16.5
10	24.0	18.3
11	26.4	20.2
12	28.8	22.0

*Adapted from *Designer's Notebook*, (Precast Prestressed Concrete Institute 2007)
Note: 1 Btu/(ft² × °F) = 20.44 kJ/(m² × K); 1 in. = 25.4 mm.

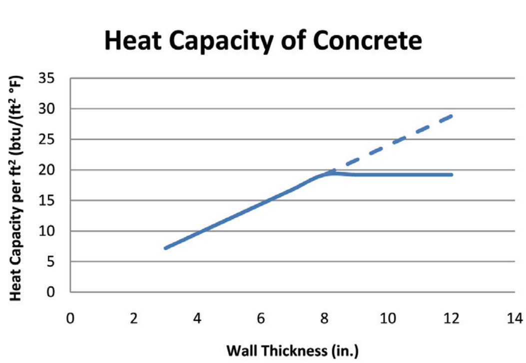


Fig. 2.11—Heat capacity versus concrete wall thickness.

heat capacity of the wall in a 24-hour period tapers off rapidly, as shown in the Fig. 2.11.

These concepts have been elegantly applied in the Maximillian Restaurant in Albuquerque, NM (Fig. 2.12) (Mazria 1979). In the summer, the building's natural cooling system is used to meet its cooling loads. In the winter, much of the restaurant's heating requirements are met by direct solar gain. This system not only reduces the amount of electricity, but it also delays usage to off-peak hours where costs of usage are lower.

Thermal mass can be used to provide energy savings in any climate, but the benefits are more pronounced in the southern and western U.S. where there are significant daily temperature fluctuations year round. This allows a greater amount of energy storage in the concrete elements. When the interior surface of a concrete element (such as the hearth in Fig. 2.5) is directly exposed, energy is more readily absorbed. The thermal mass of interior concrete elements such as walls, columns, stairs, and floors combined with passive solar systems can be very effective. The building shape, orientation, daylighting opportunities (including glazed windows, light shelves, and sun filters), and occupancy type all contribute to energy reduction. Figure 2.13 shows the interior of a building using a combination of these attributes.

Figure 2.14 provides some guidelines for determining the best way to use thermal mass with concrete for different climates. Occupancy is also a consideration because interior heat gains from lights, occupants, computers, and other items can be much higher in an office building during working hours than a residence. With internal heat gains, climates with long heating seasons can benefit significantly from thermal mass.

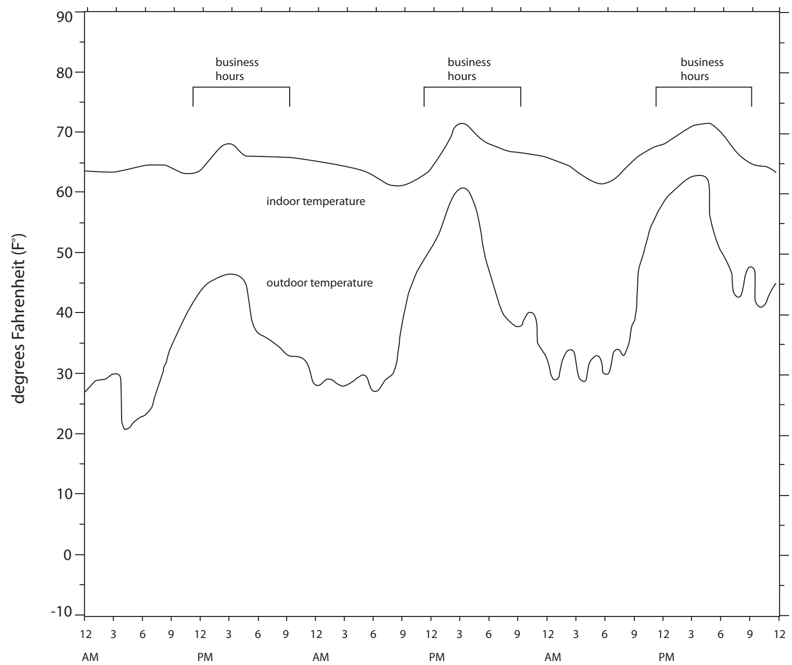
Trombé walls, as shown schematically in Fig. 2.15, can be used to maximize the benefits of thermal mass and solar thermal collection. The radiant energy of the sun passes through glass, striking a dark, high mass wall. A large portion of the energy is absorbed by the wall, while some is transferred to the air within the trombé wall assembly. The glass keeps this warm air from escaping. Strategic venting and fans can be used to circulate air through the air space and direct it inside or outside when temperature adjustments are needed. This passive solar heating concept is called the indirect gain. An example is the 2100 ft^2 (200 m^2) Kelbaugh house, a two-story building in Princeton, NJ, that was built with 600 ft^2 (56 m^2) of thermal storage wall and a south-facing greenhouse (Fig. 2.16). A 15 in. (380 mm) concrete wall, painted black, with two sheets of double-strength window glass placed in front of the wall comprise the solar collection system. The house is heated through radiation and convection from the inside face of the wall. Daytime heating by the natural convection of warmed air from the front face is achieved by vents located at the top and bottom of the wall on each floor.

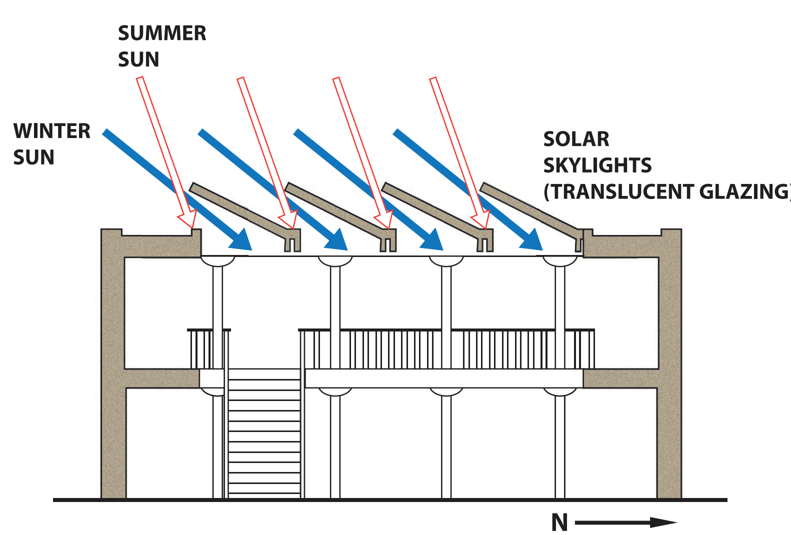
This passive system reduced space heating costs by approximately 76%. The measured temperature fluctuations in the winter of 1977 were small, 3 to 6°F (2 to 3°C) on average. The first story temperatures varied between 68 and 58°F (20 and 14°C), and second story temperatures varied between 72 and 62°F (22 and 17°C). Warm air movement was through the open stairwell connecting the levels. Additional modifications, such as the addition of operable dampers to lessen heat migration to the second floor, improved the system's performance and reduced heating costs by 84% (Mazria 1979).

In a thermal mass situation, the heat flow (hotter to colder) through the wall may change significantly or reverse direction during a night/day cycle. Climate, temperature swings, wind, and other factors affect the actual thermal resistance provided by concrete. ANSI/ASHRAE/IESNA Standard 90.1 (American Society of Heating, Refrigerating, and Air Conditioning Engineers 2007) provides for thermal mass benefits from concrete walls by allowing lower R-values (thermal resistance) than are allowed for wall materials with low thermal mass. More accurate modeling of the effect of thermal mass for a building can be accomplished through performance-based energy modeling software.

Thermal mass modeling example

The thermal mass of an element made from a single material is, in simple terms, the heat capacity multiplied by the amount of material. The thermal mass gives the





SECTION SHOWING SUMMER AND WINTER OPERATIONS

Fig. 2.12—Indoor/outdoor temperatures and schematic of Maximillian Restaurant, Albuquerque, NM. Note: °C = (°F – 32) × 5/9.

Fig. 2.13—Thermal mass with passive solar system. Building is located in Northern Minnesota and takes advantage of daylighting for solar gain and for occupant comfort while using thermal mass benefits from interior elements such as large exposed concrete columns.

Hot /Dry Climate

- High potential for energy savings
- Thermal mass in building envelope retards high flow in during the day and radiates heat back out during the night
- Use with good ventilation to exchange inside air at night with cool outside air

Cold Climate

- Medium potential for energy savings
- Follow passive solar strategies:
  - Good envelope insulation
  - Interior surfaces (walls/framing floors) with thermal mass exposed to direct sunlight

Hot /Humid Climate

- Lower overall potential for energy savings
- Good insulation and thermal mass in the envelope will level out temperature spikes outside and minimize the HVAC load inside

Fig. 2.14—Effect of temperature lag from thermal mass.

designer an indication of the relative contribution, but modeling the system is far more complex. The ability of thermal mass to delay exterior temperature effects and to moderate temperature spikes must be considered to more fully recognize thermal mass benefits. A study by Marceau and VanGeem (2005) for the Portland Cement Association compared several different structural systems that contain concrete walls within differing climates and with different internal loads. While the focus of the report is on modeling for LEED energy-related points, the results of the thermal mass modeling are a good reference for any design that incorporates thermal mass. This study used energy simulation software capable of modeling yearly energy use on an hourly basis as is needed to account for the effects from thermal mass. The software used and further details can be found in the report (Marceau and VanGeem 2005). The study incorporated the effects of varying climate by including six U.S. locations: Miami, Phoenix, Memphis, Salem, Denver, and Chicago. A five-story building (105 x 105 ft [32 x 32 m] in plan) with exterior insulation finish systems and metal stud walls meeting ANSI/ASHRAE/IESNA Standard 90.1 (American Society of Heating, Refrigerating, and Air Conditioning Engineers 2007) with a structural steel frame was used as a baseline. The building has concrete on metal deck for the floors and metal stud interior walls. The baseline building was modified and modeled in a total of 10 variations with the following variables:

- Exterior walls (all meet or exceed ANSI/ASHRAE/IESNA Standard 90.1 [American Society of Heating, Refrigerating, and Air Conditioning Engineers 2007]. Those that exceed are indicated.)
  - EIFS and metal studs
  - Curtain walls
  - Precast concrete
  - Precast concrete exceeding code
- Structural frame
  - Structural steel
  - Reinforced concrete
- Floors
  - Concrete on metal deck
  - 12 in. (300 mm) solid concrete
- Interior walls
  - Metal stud
  - Reinforced concrete

The primary finding related to thermal mass was that the effect of thermal mass lowered both energy use and cost compared with the baseline building for most cases. The difference in mild climates (such as Miami, where temperature fluctuations are less pronounced due to the proximity to the ocean) were small, but in Memphis, Salem, Denver, and Chicago, thermal mass provided at least 5% energy cost savings. The full report contains details about savings due to various structural framing systems, internal loads near the center core of the building, and for the effect of exceeding energy code requirements in the walls.

A detailed example of thermal mass effects with measured data is provided in Appendix A. The data illustrates the magnitude of energy savings that thermal mass can provide in a standard 8 in. (200 mm) concrete wall.

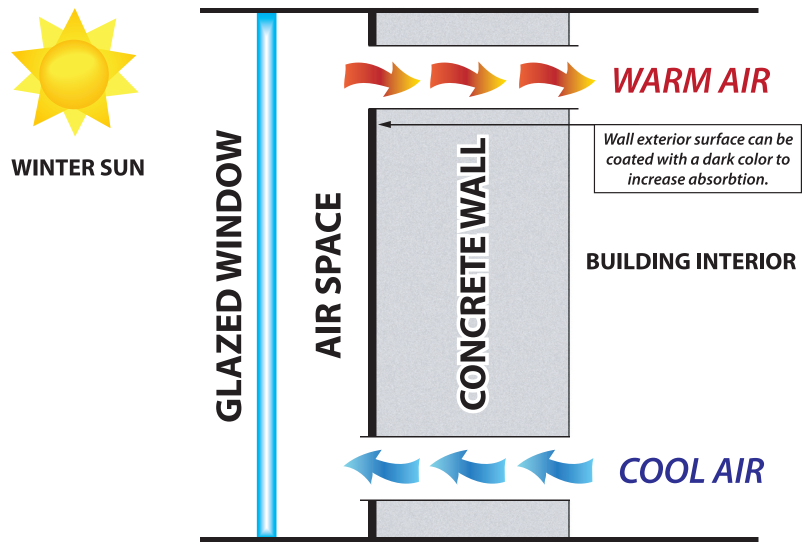
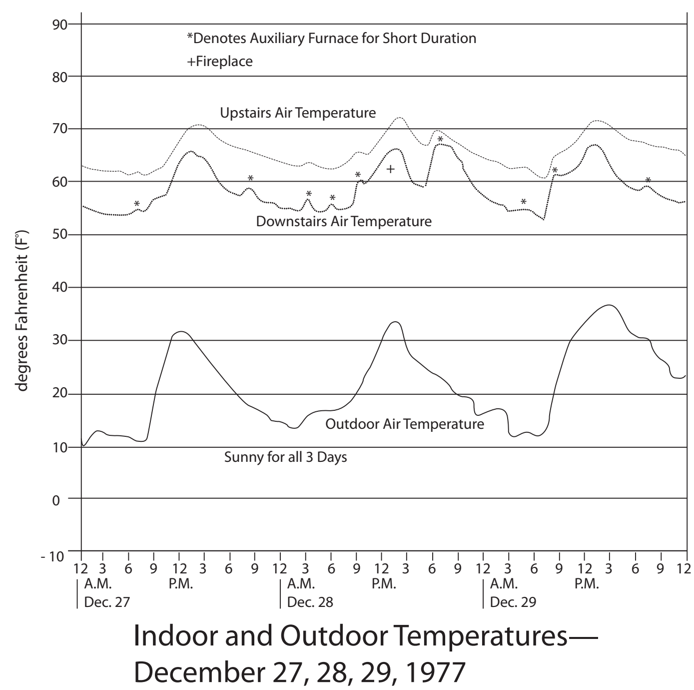


Figure 2.15—Trombé wall.



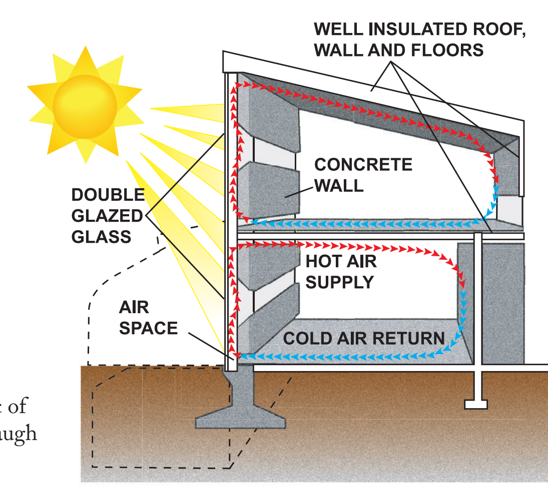


Fig. 2.16—Indoor/outdoor temperatures and schematic of passive solar system—Kelbaugh House, Princeton, NJ.
Note: $^{\circ}C = (^{\circ}F - 32) \times 5/9$.

Summary for thermal mass

Potential advantages/benefits

- Reduction of effects of outside temperature spikes on building occupants
- Time delay in peak temperature effect
  - Cooler inside when warmer outside, and vice versa
  - Shift to off-peak energy use
- Radiant heat benefits from exposed surfaces
- Contributor to using passive solar system
- Energy savings for heating and cooling (level dependent on climate)
- Downsizing (or removal) of HVAC systems

Potential disadvantages/limitations

- Openings (windows and doors) need to be carefully sealed for full benefit
- Difficult to model true energy use incorporating thermal mass
- Storage wall can block view and daylight
- Additional cost is associated with the design of the mass storage wall and its foundation

Diurnal (temperature)—Daily temperature cycles (day to night over a 24-hour cycle).

Passive cooling—Uses ventilation, shading, and materials with slow heat transfer for cooling without mechanical means.

Passive solar—Uses sunlight for energy without mechanical means; includes solar gain for heating air spaces (including use of thermal mass) and solar water heating.

Thermal mass—The capacity of a body to store heat.

Chapter 4—Longevity and service life

Building durability is associated with long service life or, in some contexts, a building with a longer-than-expected service life. In the case of concrete building components, consideration of longevity is important to understand the financial and environmental effects over time. The discussion of service life in this section is not intended to imply that concrete is the only durable construction material, but rather to discuss the ways concrete durability can contribute to sustainable buildings.

The understanding of the balance of upfront price over the life of the structure is well accepted in the building industry, but the broadened concept of LCA (as described in Chapter 1) is not as firmly established. The upfront CO_2 emissions from the manufacture of cement are certainly a critical issue, but this should be taken in context over the service life of the structure. If a significant reduction in CO_2 emissions is realized over the full service life of the structure, this may balance or outperform a structure with a shorter service life and lower upfront CO_2 emission that has to be replaced over the same time frame.

Not all owners have longevity at the forefront of their decision making. A developer that does not intend to own the building for even a small portion of its service life may be far more interested in initial price (monetary or environmental) than any benefits realized after the sale of the structure. Societal pressure for sustainability, however, is likely to override this over time so that a nonsustainable building has reduced market value. Durability should be part of the overall package of sustainability for a building. The design team and owner need to consider the building over its full life. Many buildings change uses and owners over their service life. The longer a sustainably designed building is able to perform its functions without undergoing major renovation or replacement, the more benefit is realized in the overall balance.

As discussed in Part I, service life and life cycle are not design constants across the building industry. The actual life of the structure can be significantly longer than the design service life. While design for a 50-year service life is common, one can argue that today's concrete technology with high-performance concrete (including production and installation) can confidently be used to produce a 200+ year service life. High-performance concrete is defined by ACI as a "concrete that meets special performance and uniformity requirements that cannot always be achieved routinely by using only conventional materials and normal mixing, placing, and curing practices." The definition encompasses the fact that the required performance must be defined before the appropriate high-performance concrete mixture can be developed. High strength requirements are only one aspect of high-performance concrete; durability requirements can also determine a high-performance concrete.

A history of longevity

Concrete has a long history of providing robust structures. The Pantheon in Rome (Fig. 2.17) (commissioned by Hadrian and finished in 126 A.D.) is an impressive concrete domed structure with a height of 140 ft (43 m) over a 140 ft (43 m) rotunda. The Pantheon still stands today, nearly 1900 years later,

Fig. 2.17—The Pantheon *(photo courtesy of Jennie Miller).*

as one of the best preserved of all Roman buildings. The concrete in Roman times used pozzolan cement that was tamped into the forms rather than cast, as is done today. Upon seeing the Pantheon in the early 1500s, Michelangelo was so impressed that he proclaimed that it must be the work of angels and not man—at that point the structure was already nearly 1400 years old.

Fig. 2.18—Ward's Castle.

In the U.S., the first reinforced concrete house was completed in 1873. The structure, known as Ward's Castle (Fig. 2.18) was commissioned by William Ward as a residence for himself and his wife (who had a phobia of fire). Ward was a mechanical engineer, and performed extensive testing of iron in concrete before the construction of the house. The entire house is constructed of concrete, with the only exception being the wood used for window and door frames. All of the ornamentation (both exterior and interior) is cast concrete, including the ceiling cornices (Collins et al. 2004). The building is still in excellent shape today after more than 135 years of service.

Historic county courthouses and other government buildings across the U.S. are good examples of the longevity of concrete. Figure 2.19 shows the St. Louis county courthouse (Duluth, MN) on the year of its 100th anniversary. The structure was completed in 1909, and was designed by the architect Daniel Brunham (known for his roles in city planning for Chicago and Washington, DC, and as the architect of the Flatiron building in

Fig. 2.19—St. Louis county courthouse (Duluth, MN).

New York City). The building is in excellent condition, and still in use as the St. Louis county courthouse.

Concrete durability

Properly designed and constructed concrete can last for decades—or even centuries—with little or no maintenance. Concrete is often subjected to severe environments: chemicals, repeated freezing-and-thawing cycles, coastal chloride and moisture, deicing salts, sulfates, abrasion, overload, and extreme events. The concrete itself must resist these attacks while also protecting the reinforcement. As with any commonly used material, there are examples of failures of concrete structures under these harsh environments due to improper design or construction. Methods to address concrete durability in a range of environments have been the subject of a large battery of research and case studies over many years. The "Guide to Durable Concrete" (ACI Committee 201 2008) provides a comprehensive user reference in this area. In each severe environment, there are recommendations about mixture design and construction practice that can be used to provide a durable concrete structure.

Corrosion

In considering the longevity of a structure, it is necessary to understand potential mechanisms of degradation of the materials used. Codes and standards are followed for life safety, but premature end-of-service life from loss of functionality must also be considered. Numerous innovative materials and coatings have come into the market to address the corrosion issue, particularly in aggressive environments (such as coastal areas or structures exposed to deicing salts).

In the case of reinforced concrete, the steel reinforcement is embedded in the concrete and the high pH of concrete produces a protective environment where a passive film forms on the surface of the steel. With the film intact, the steel will not corrode. If the pH, however, is lowered by carbonation or chlorides at the level of the steel, the passive film is breached, and pitting corrosion can begin.

In low permeable concrete without cracking close to the level of the steel, the reinforcement is well protected and will remain in a passive state, particularly in a typical building environment. In a parking garage, deicing salts brought in by cars can contribute to a very aggressive corrosion environment, so care should be taken to use a low-permeable concrete with design details to avoid chloride access to the reinforcement. Prestressed concrete is typically designed to minimize concrete cracking. In a post-tensioned system, the prestressing steel is protected from corrosion by a fully encapsulated system, which makes it a popular choice for parking garages.

Supplemental cementitious materials

Supplemental cementitious materials (SCMs) are often used to replace a portion of the cement in a concrete mixture. Many of these materials are waste materials from other industries, but they also have beneficial effects on concrete, such as lowering permeability. Certain SCMs can also increase workability or sulfate resistance. The most common cementitious mineral admixtures are silica fume, fly ash, and slag cement. These materials are discussed in more detail in Chapter 8.

Keeping concrete low maintenance

Painted materials typically require repainting on a periodic basis to retain their aesthetic appeal and to protect the underlying material. Concrete does not need paint for protection, so the addition of paint turns a maintenance-free material into one requiring repainting. Color, texture, and finish can be integrated directly into the concrete mixture. Concrete floors can be polished to provide a surface that requires limited maintenance to retain shine. Colors can be added into the mixture, and special forms can provide a molded texture or replicate stone. Because the color and texture are integrated into the final concrete form, they do not need to be refinished. It is important that the design take advantage of these aspects of concrete, rather than try to impose a finish that adds maintenance. Color and texture are discussed in more detail Chapter 6.

Summary

Advantages/benefits

- Durable, robust
- Low maintenance

Disadvantages/limitations

- Potential for degradation if not designed properly for the environment or length of service

Service life (buildings)—The expected useful life of a building (design life); service life is not the predicted or actual life of a building.

Chapter 5—Stormwater management

Development (the construction of buildings, pavement, and hardscape) replaces natural vegetation with roofs and hard surfaces. Because these features are often impermeable, precipitation is prevented from percolating into the soil. The volume and rate of surface runoff are increased, and the time lag between the peak rainfall and peak runoff is decreased, leading to larger volumes of discharge into sewer systems, streams, and lakes. This can lead to increased risk of flooding, and in cities with combined sanitary and stormwater sewage systems, storm surges can force the release of raw sewage into streams and lakes. Even when flooding and emergency discharges can be avoided, surface runoff can carry pollutants into streams and lakes, including soil, debris, pesticides, and fertilizers from lawns; oil from parking lots; and deicing chemicals from parking lots and sidewalks.

Infiltration of water into the soil allows soil microbes to break down organic pollutants, and it can help recharge aquifers. Breaking down pollutants reduces the biochemical oxygen demand, nitrates, and phosphates in surface waters (reducing the risk of fish kills and algae blooms), and recharging aquifers helps to level stream flows (reducing risks of flooding and dry stream beds). The traditional civil engineering approach to stormwater remediation has focused on the use of retention ponds or structures to store the large volume of runoff from impervious surfaces during a rain event. The water is then released (typically through a pipe system) to nearby water bodies at a reduced rate. Filtration media, such as sand in the retention ponds, can help break down some of the pollutants and solids. This bypass of water, however, does not give the aquifer in the built-up region a chance to recharge, and the large volume of water can cause scour problems and habitat disruption at the location where it enters a lake or stream. Additionally, the filtration media in the retention pond may not be effective in removing all the pollutants introduced from site development. Retention, detention, and filtration structures consume additional land and resources, leading to opportunity costs and additional capital outlays.

Sustainable stormwater remediation focuses on keeping the quantity and quality of runoff from the developed site as close as possible to those of the original undeveloped site. Some ways to address this balancing act include:

- Minimizing the physical footprint of a development (Fig. 2.20);
- Providing vegetated swales (shallow channels with dense vegetation for filtration) (Fig. 2.21);
- Creating rain gardens (low-lying areas with native plants) (Fig. 2.22);
- Providing concrete tanks or cisterns for water storage and reuse;
- Providing pervious paving and hardscape materials (Fig. 2.23); and
- Providing green roofs (Fig. 2.24).

Typically, a combination of methods will be appropriate for a given site. If infiltration is not desirable because the site is contaminated or otherwise unsuitable for infiltration (for example, the site has bedrock at or near the surface or the water table is near the surface), detention structures may be necessary. Concrete cisterns

Fig. 2.20—View of first Carmel City Center building and plaza structure, in which parking will be available below the plaza and all Carmel City Center buildings *(photo courtesy of Jenell Fairman, McComas Engineering).*

Fig. 2.21—Vegetated swale *(photo courtesy of Schokker).*

can be used to hold water for future use in watering vegetation or other nonpotable water needs.

The role of concrete in stormwater management

Concrete is often used in detention systems, for pipes to carry stormwater, for curbs and swales, or as riprap for erosion protection. The most sustainable stormwater management system, however, is one that allows infiltration. Pervious surfaces also reduce the calculated impervious area for the site. Many municipalities limit the percentage of impervious area on a developed property, so use of pervious paving can reduce the overall development footprint. This, in turn, reduces the disturbance to the area, reduces the amount of water runoff that reaches the sewer system, and reduces the quantity of water that needs to be treated. Pervious concrete and permeable interlocking concrete pavement systems are common options that allow infiltration while providing a hard surface for parking or walking.

Pervious concrete

The finished appearance of pervious concrete is often likened to a concrete "Rice Krispie Treat®" in nontechnical discussions. The surface can provide a significant amount of water infiltration to the subgrade while providing a flat surface.

As with more typical concrete, pervious concrete mixtures include cementitious material, water, admixtures, and coarse aggregate. The mixtures generally do not, however, contain fine aggregate (sand). Pervious concrete is designed so that the course aggregate is coated with the cementitious paste, but leaves an interconnected system of voids. The resulting hardened concrete is very permeable.

The coarse aggrerate in pervious concrete is uniform, or nearly uniform, in size (ranging between 3/4 and 3/8 in. [19 and 9.5 mm] [ACI Committee 522 2006]). This uniformity contributes to the interconnected void system that gives pervious concrete the ability to filter water at a high rate. Details about proportioning pervious concrete and developing mixture designs are available in ACI 522-06, "Pervious Concrete" (ACI Committee 522 2006).

The strength and unit weight of pervious concrete decreases as the percentage of voids (air void content) increases. The greater the void content, the higher the percolation rate of water through the concrete matrix. The challenge for the designer is to strike a balance between required strength and required percolation for a given situation. A 15% minimum air void content is needed for a reasonable level of percolation (Meininger 1988), and much higher percentages are preferable in most situations. Figures 2.25 and 2.26 show the relationships between strength, air void content, and percolation from laboratory tests of pervious concrete. The percolation rates of the pervious concrete alone can be extremely high (as shown in Fig. 2.26 varying from 10 to 90 in.

Fig. 2.22—Construction of six rain gardens at Mollie Dodd Anderson Library in Newtown, PA, makes collection of all site and building runoff possible, allowing water to infiltrate and recharge groundwater supplies as well as help to restore larger ecosystem of Neshaminy Valley *(photo courtesy of Viridian Landscape Studio).*

Fig. 2.23— (Top) Pervious concrete parking lot in Leawood, KS *(photo courtesy of Concrete Promotional Group).* (Bottom) Use of colored pervious concrete at entrance to Loma Real Housing Development in Reynosa, México, reduces maintenance and allows infiltration of rainwater *(photo courtesy of Concrete and Cement Technology Center, CEMEX México).*

Fig. 2.24—View of green roof from lobby of Birthing Center at Henry Ford West Bloomfield Hospital in West Bloomfield, MI *(photo courtesy of Ray Manning, Henry Ford Health System).*

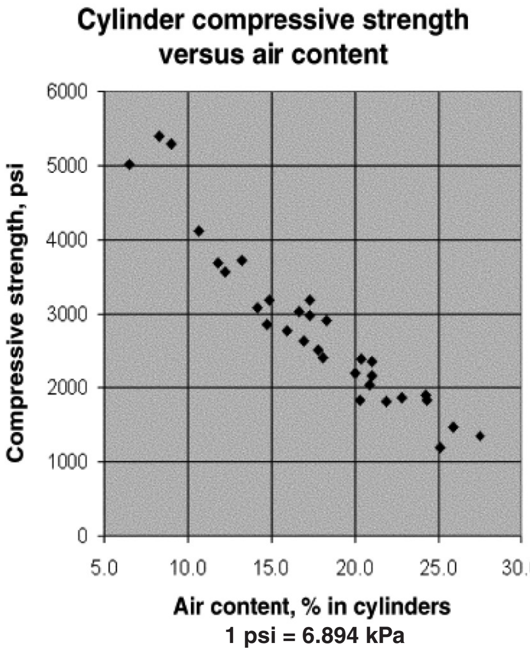


Fig. 2.25—Relationship between air content and compressive strength *(Meininger 1988)*.

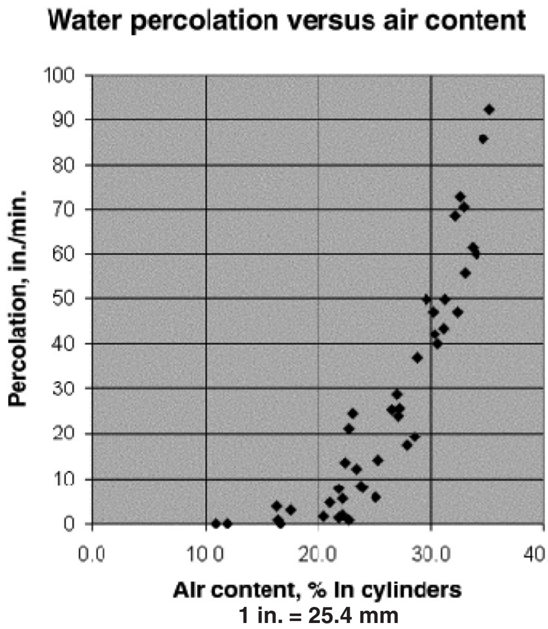


Fig. 2.26—Relationship between water percolation and air content *(Meininger 1988)*.

[250 to 2300 mm] per minute), so the actual hydraulic performance of the system is typically controlled by the subbase materials and subgrade.

Initial use of pervious concrete in the U.S. was more widespread in states with warm climates, so freezing-and-thawing issues were not often a major concern. Pervious concrete is now used throughout the U.S., and must have adequate freezing-and-thawing resistance to meet durability needs. Freezing-and-thawing problems occur when the concrete becomes saturated (the voids/pores are full of water) and then freezes. The expansion can cause cracking and spalling of the concrete. In the case of pervious concrete, the void area is large, and saturation should not occur unless there are drainage problems through the voids (through improper design or maintenance). In very cold climates where the frost line is deep for several months, the pervious concrete will experience very few freezing-and-thawing cycles because the temperatures do not warm sufficiently during this time to achieve thawing. The ability of the underlying layer to move the water away from the pervious concrete layer is also a critical factor in avoiding saturation.

Typical uses of pervious concrete are low-traffic pavements, parking lots, sidewalks, alleys between city buildings, as a base-layer for standard high-traffic pavement, and recreation areas such as tennis courts. The first water that runs off during a rain event carries the highest load of pollutants. Pervious concrete allows this pollutant load to infiltrate to the ground where it can be filtered rather than go directly to a retention pond or water body. Base layers of filtration media, such as crushed rock, can add to both the filtration and the storage capacity of the system while the water filters more slowly down into the aquifer. Additionally, trees can suffer from lack of water if they are isolated on a small soil island surrounded by impervious pavement. The ability of pervious concrete to allow water directly into the soil provides more access to water for the trees in the area.

As would be expected, placement methods for pervious concrete vary from those used for traditional concrete. Details on placement (including base preparation) are available in ACI 522-06 (ACI Committee 522 2006).

The primary maintenance required for pervious concrete to be effective over its intended design life is to prevent clogging of the voids. During construction, sand, soil, and any other materials that can potentially clog the voids should also be kept away from the immediate area. Landscaped areas or other areas that may carry debris should not be designed to drain onto the pervious concrete. If possible, the pervious concrete should be at a higher elevation than neighboring landscaping. Debris, including vegetation, may also blow onto the concrete. In areas where this is pervasive, the pervious concrete may need periodic cleaning. Well-placed and well-designed pervious concrete can maintain consistent flow rates year to year (Wanielista and Chopra 2007).

The design of pervious concrete for stormwater management includes structural design for the loads as well as hydraulic design. The thickness and percentage voids (directly related to compressive strength) may be governed by either case. A simple sample calculation is presented herein for consideration of runoff quantity. Additional examples with other variables, including water quality requirements, are available in ACI 522R-06 (ACI Committee 522 2006).

Containment of runoff calculation

As described previously, the pervious concrete layer can filter extremely high amounts of water quickly, so the hydraulic portion of the design is related to the storage capacity of the pervious system rather than the filtration rate of the pervious concrete.

Consider a basic pervious system as shown in Fig. 2.27 with a 5 in. (125 mm) layer of pervious concrete over a 6 in. crushed gravel subbase (as determined by structural considerations). For this case, the pervious concrete is 22% voids, and the crushed gravel layer is 35% voids. The subgrade is a fine sandy loam with an infiltration rate of 3/4 in. (18 mm) per hour. The depth of water (d) that the pervious concrete and subbase can store are as follows

$d_{pervious}$ = 5 in. (125 mm) x 0.22 = 1.1 in. (28 mm)

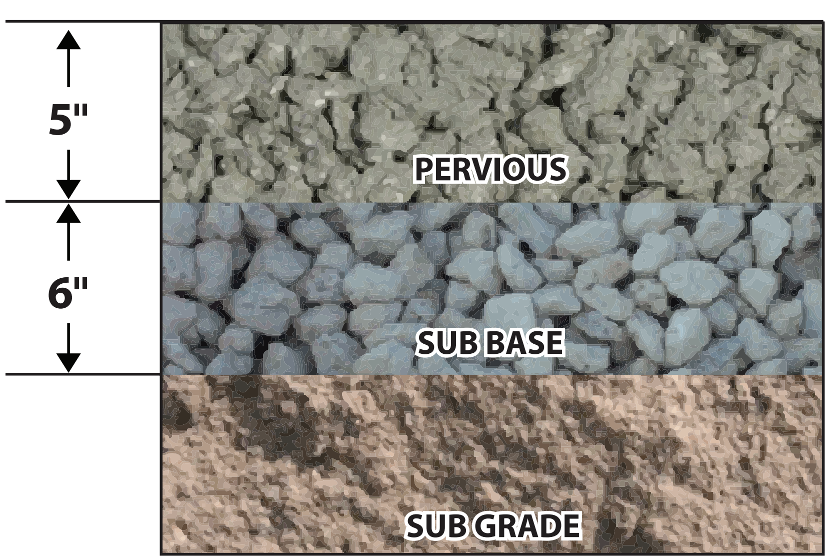


Fig. 2.27—Pervious concrete. (Note: 1 in. = 25.4 mm.)

$d_{subbase}$ = 6 in. (150 mm) x 0.35 = 2.1 in. (53 mm)

total storage = 1.1 in. (28 mm) + 2.1 in. (53 mm) = 3.2 in. (81 mm)

This calculation indicates that the pervious system can store a total of 3.2 in. (81 mm) of rain before additional rain goes directly to runoff. The design storm should be compared with the calculated 3.2 in. (81 mm) to determine if storage is adequate for a given situation. A rain event that causes more than 3.2 in. (81 mm) of rain before the water drains from the system would result in standing water. The accommodation of a given rainfall event is directly related to not only the amount of rain that can be held, but also the length of the event. If this system is bordered by a curb of standard concrete or other barrier, additional water can be retained above the permeable layer during an extreme event, and held for the time period needed for the system to drain. If standing surface water is not desirable, the thickness of the pervious concrete layer or subbase layer can be increased.

Standing water should move through the pervious concrete and subbase in a timely matter (less than 24 hours is a good basic rule of thumb, but requirements will be different for each situation). The time required for the layers to drain by infiltration through the subgrade for the example case is as follows

$$T_{pervious} = \frac{1.1 \text{ in. (28 mm)}}{0.75 \text{ in. (18 mm)/hour}} = 1.5 \text{ hours}$$

$$T_{subbase} = \frac{2.1 \text{ in. (53 mm)}}{0.75 \text{ in. (18 mm)/hour}} = 2.8 \text{ hours}$$

$$T_{total} = 1.5 \text{ hours} + 2.8 \text{ hours} = 4.2 \text{ hours}$$

In this case, the full pervious system can infiltrate within a relatively short amount of time (4.2 hours). After 1.5 hours, the pervious concrete layer will have drained. Clearly, this amount of time is directly dependent on the infiltration rate of the subgrade, so subgrades with very low infiltration rates (such as clay) can significantly increase this number, while soils and sands with high infiltration rates can allow even the toughest rainfall conditions (such as hurricanes) to be stored within the pervious system. In the previous example, the system can accommodate a storm with 3.2 in. (81 mm) of rain every 4.2 hours (or a rate of a 2 in. [51 mm] per hour) without leaving standing water above the paved area.

Grid pavers

Concrete grids allow the use of standard concrete or masonry in a way that allows the underlying grass, soil, or gravel to be directly exposed to runoff while still providing a surface that can support vehicles or pedestrian traffic. Grid paving units fall into two basic categories: lattice or castellated. They have a maximum surface dimension of 2 x 2 ft (610 x 610 mm), and a minimum nominal thickness of 3-1/8 in. (80 mm) (ASTM C1319-01 [ASTM International 2006]).

The lattice-style pavers, as shown in Fig. 2.28, are essentially a grid of concrete that allows the grass (or aggregate base) to show through the openings in the grid. Castellated pavers are also a grid system, but they have widely spaced, taller concrete knobs that are visible at the surface. The rest of the grid is at a lower elevation that makes the grass appear more continuous after installation.

Grid pavers can be used in many different areas such as parking lots, driveways, picnic areas, or other pedestrian areas. Open grid pavers can also be used for stabilizing embankments or for reducing scour. In areas of high pedestrian usage, solid pavement will be more comfortable for walking, but grid pavers can be used along the edge of sidewalks or in adjacent open areas. Parking areas with handicap access should be solid pavers or pavement for safety and comfort. Preparation of the base for grid pavers and their placement should be done properly to avoid uneven paver settlement. Aggregate in the openings may be a desirable alternative to grass if the area will be subjected to intensive use that may make it difficult for grass to survive.

Permeable interlocking concrete pavers and general grid systems

Any paving system that includes enough joints or spaces to allow water infiltration reduces rainfall runoff, particularly when combined with a permeable gravel subbase. Both pavers and larger precast elements can provide this type of permeable system, as well as cast-in-place concrete with joints or strips of gravel or vegetation that are adequate to allow infiltration. Interlocking concrete pavers, such as those shown in Fig. 2.29, use gravel in the spaces between pavers to provide access for stormwater to reach the gravel subbase below and infiltrate through the soil.

Summary

It is important to note that minimizing impervious surfaces and providing pervious ground cover where possible will not only help resupply the aquifer, but minimize stormwater sent to water treatment plants. The numbers for single projects are staggering. For example, a new 2-acre parking lot for an office building in Chicago, IL (annual average rainfall of approximately 34 in. [780 mm]) could resupply the groundwater with over 1.8 million gal. (6800 m^3) and unload water treatment plants by the same amount. For this and the other reasons outlined in this chapter, the designer should carefully consider the advantages and limitations of open grid or pervious surfaces.

Fig. 2.28—(Top) Example of concrete grid pavement *(photo courtesy of Interlocking Concrete Pavement Institute)*. (Bottom) Concrete grid pavements cover pull-over area near main terminal and concrete parking garage at Washington Dulles International Airport in Virginia *(photo courtesy of Interlocking Concrete Pavement Institute)*.

Fig. 2.29—(Left) Permeable interlocking concrete pavement manages roof and parking lot runoff at Marine Market Way in Burnaby, British Columbia *(photo courtesy of Interlocking Concrete Pavement Institute).* (Right) Residential development called Autumn Trails in Moline, IL, used permeable interlocking concrete pavement because it eliminated the need for a storm drainage system, thereby making permeable pavement cost-competitive with conventional asphalt *(photo courtesy of Interlocking Concrete Pavement Institute).*

Advantages/benefits

- Direct infiltration of stormwater to ground with opportunities for filtration of runoff before it reaches the aquifer
- Aquifer recharge
- Lower quantity of runoff
- Reduces land use by minimizing or eliminating retention/detention basins
- Reduces liability and mainteance for retention/detention basins

Disadvantages/limitations

- Pervious
  - Maintenance may be needed to keep pores clear depending on the location and design of the pervious concrete
- Pavers and grid systems
  - More difficult to clear snow and ice
  - Not as comfortable for walking as standard pavement or solid pavers (should not be used for handicapped access areas)

Cistern—Tank or container for rainwater collection and storage.
Green roof—Roof with vegetation planted in soil to absorb rainwater and combat heat island effect.
Rain garden—A vegetated area with hardy plantings in a flat, depressed area that allows rainwater runoff from nearby impervious areas to be absorbed directly back into the ground.
Recharge—The movement of surface water (such as rainwater runoff) through the ground down to the depth of the water table (the top of the groundwater).
Vegetated swale—A long, narrow vegetated depression (also called bioswale) used to slow rainwater runoff and increase direct infiltration to the groundwater.

Chapter 6—Human factors and the living/working environment

Human factors include all aspects of how people relate to their environment, typically with a focus on improving health, safety, comfort, ease of use, and performance/productivity. Ergonomics (design to fit the worker) is also integral to a discussion of human factors. Human factors—or the "softer" sides of sustainability—have been shown to positively influence worker and student productivity.

As an example of this impact, a national study of the costs and benefits of sustainable design in 30 schools in the U.S. (Kats 2006) highlights the financial, health, and productivity benefits obtained from designing for sustainability. The financial benefit provided an average direct savings (including teacher retention) to a green school of approximately \$12 per ft^2 (\$130 per m^2) (in 2006) versus an average cost of \$3 per ft^2 (\$32 per m^2) in additional initial cost of the green building. In an average school in the study, the savings were enough to pay for an additional full-time teacher. Some of the schools had no additional cost for building a sustainable school. Good lighting alone was shown to improve test scores and student attention in a review of 17 studies from the mid-1930s to 1997, and a review of over 50 more recent studies showed an increase in overall student achievement.

Indoor air quality is a major factor in health, safety, and productivity for building occupants. Increasing outside air, moisture control, and control of pollutant sources all contribute to higher indoor air quality. The same study discussed previously (Kats 2006) also found a reduction of over 80% for flu and cold symptoms, and over 60% for asthma and allergies that resulted from improved indoor air quality in sustainable schools. Other human factor issues include temperature, acoustics, and support of a healthy lifestyle that includes exercise. Each of these comfort factors is incorporated into sustainable rating systems for buildings because they are an important part in completing the picture of sustainability on the social and economic side.

Several items that relate to human factors in the living and working environment are discussed in more detail in this chapter; specifics related to concrete design and construction are highlighted. The discussion is not intended to imply that concrete is the only material that can achieve these results, but it does emphasize the ways that concrete can be used to support efforts in these areas.

Indoor air quality

Increased outdoor air ventilation and natural ventilation are key components in the improvement of indoor air quality in most buildings. Well-planned ventilation systems, which include operable windows for natural ventilation, can be included in almost any building so that occupants can moderate their own local ventilation. When the thermal properties of a concrete system are combined effectively with a good ventilation design, occupant comfort levels increase. Concrete does not mold or rot, so it provides a good base material for improved indoor air quality.

Another major consideration to maintain good indoor air quality is the use of low-emitting materials. Paints, stains, adhesives, carpets, and other materials should have low volatile organic compound (VOC) levels. Some use of these materials can be avoided through use of concrete as the finished surface for ceilings, walls, and floors. Aesthetically pleasing features can be incorporated through textured and colored concrete without the use of paints or carpet. In a bare concrete system, care should be taken to choose a sealer that has low VOC levels. The bare concrete surfaces are also advantageous from a passive solar standpoint, as discussed in Chapter 3. The designer should encourage the architect to review all concrete surfaces, both vertical and horizontal, within and outside the structure for potential as finished surfaces.

Lighting

Natural lighting through skylights and large windows can improve concentration and performance in workers and students. Light shelves and sun filters (as shown in Fig. 2.30 and 2.31) help distribute light through the room while reducing glare. The light shelves are typically mounted horizontally at a high enough level so that light is reflected up to ceilings rather than into occupant's eyes. Blinds can then be used to control brightness during the day.

The use of natural lighting significantly reduces the need for electrical lighting, but when used, the electric demand can be reduced through the installation of occupancy sensors and dimming devices (user controlled, sensor controlled, or scheduled). Figures 2.32 and 2.33 show examples of concrete elements used together with daylighting. In these figures, a combination of the natural concrete color and a white painted concrete are used to achieve the architect's intended effect. Based on the mixture design, the concrete itself can vary in color from white (when white cement or slag cement use used) to various shades of gray and tan/gray without coloring additives or paints.

Exterior concrete pavements can also reduce the electricity needed for night safety lighting of parking and walking areas around the building. The reflectivity of concrete pavements has been shown to increase luminance (a measure of the amount of light that is reflected to the user [in candela per square foot or cd/ft^2]) over other paving materials (Adrian and Jobanputra 2005). This increased luminance allows a reduction in the number of light sources needed, saving energy for exterior lighting and reducing light trespass. For parking

Fig. 2.30—Example of light shelves *(photo courtesy of Jerry Foreman, Northern Arizona University).*

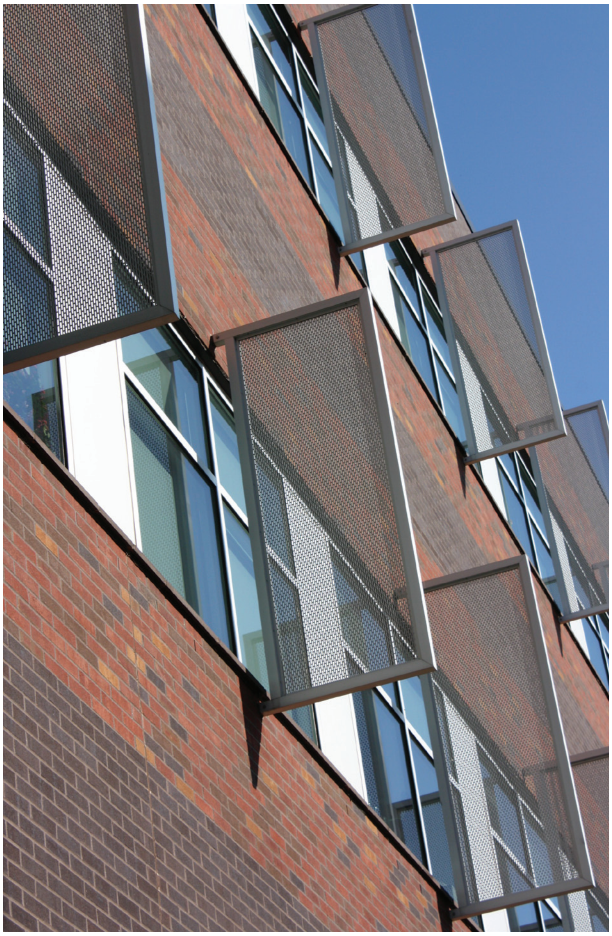


Fig. 2.31—Example of sun filters *(photo courtesy of Schokker).*

Fig. 2.32—*Photo courtesy of Schokker.*

Fig. 2.33—*Photo courtesy of Vince Harker, Duracon Canada.*

lots and roadways, the selection of paving materials is an important consideration for sustainable development. Using concrete pavement instead of asphalt for a parking lot leads to a sustainable solution. Due to the differences in the light reflectance of paving materials, asphalt pavement requires 57% more energy to light than portland cement concrete pavement (Novak 2009). The higher reflectance of the concrete pavement results in less electricity required and in a reduced number of installed lamp poles and luminaries to provide the same level of illumination. The Adrian and Jobanputra (2005) study included modeling of a parking lot lighting system with a lighting software package (Lumen Micro 7.5©). The parking lot used in the case study was approximately 150 x 300 ft (45 x 90 m) and had two central lightpoles with quad luminaries, and 14 poles with single luminaires along the perimeter, for a total of 22 luminaires on 16 lightpoles. Using a standard dark-colored asphalt parking surface, the software calculated an average luminance. To reach the same luminance on a standard concrete surface required only 14 luminaires on 11 lightpoles. Considering annualized initial cost along with electricity and maintenance, the yearly cost for the concrete parking lot scenario with reduced light fixture demand was 34% less than the standard case with a dark surfacing material.

Acoustics

Acoustics can have a major effect on the comfort and productivity of occupants. Work places can be more productive, and residences more quiet. There are two main goals in noise reduction: 1) reducing transmission of noise to neighboring rooms; and 2) reducing reflected noise within a room. Each of these issues requires a different solution. When transmission is an issue, high mass materials are effective in keeping the sound from penetrating into an adjacent area. Concrete, brick, and masonry are known for excellence in reducing the transmission of noise through walls (or floors or ceilings) as long as the noise cannot go around the barrier (or through openings).

If the intent is to reduce the noise within a room, however, a sound-absorbing material is needed to keep the sound waves from reflecting. Concrete tends to be a highly sound-reflective material. Surface finish or texture on the formed concrete surface may alter the direction of reflection, but not the intensity of the reflection. In large rooms, particularly with high ceilings, the reflected noise can be very disruptive. The bare finished concrete mentioned previously may not be desirable for all surfaces in a room, or for rooms that must minimize reflective sound. The designer and architect will be required to determine the trade-off between sound absorption and minimizing material use to cover the concrete.

Fibrous or porous materials are commonly used to absorb sound. Felt, wool, or glass fiber fabric; drapes; carpets; aerated plaster; and open-cell foam are just a few of the many sound-absorbing materials. A layer of absorptive material must be thick enough to absorb the majority of the reflected sound. In many situations, a combination of reduction of transmission and reduction of reflection is needed, so the two types of materials are used in combination to provide this effect. Table 2.6 shows absorption coefficients for some common building materials and finishes over a range of frequencies. A value of 1 indicates complete absorption (or transmission as would be similar through an open window), and a value of 0 indicates complete reflection. For the frequency ranges given in the table, a bare concrete surface would absorb 1 to 2% of sound, and reflect 98 to 99%. A 1 in. (25.4 mm) layer of polyurea foam would absorb between 13 and 97% of sound, with higher absorption at higher frequencies. Furniture, carpet, drapes, and people are also good at absorbing sound, so even a solid concrete room can have reasonable absorption combined with lack of transmission to neighboring rooms.

Table 2.6—Absorption coefficients of common materials*

Material	Frequency		
	125 Hz	500 Hz	4000 Hz
Concrete	0.01	0.15	0.02
Linoleum/vinyl on concrete	0.02	0.03	0.02
Carpet on concrete	0.02	0.14	0.65
Carpet on foam	0.08	0.57	0.73
Wood flooring on joists	0.15	0.10	0.07
Unglazed brick	0.03	0.03	0.07
Painted brick	0.01	0.02	0.03
Coarse concrete block	0.36	0.31	0.25
Painted concrete block	0.10	0.06	0.08
Fiberglass (1 in. spray)	0.16	0.70	0.85
Polyurea foam (1 in.)	0.13	0.68	0.97
Glass window	0.35	0.18	0.04
Sheetrock (1/2 in.)	0.29	0.05	0.09
Plywood (3/8 in.)	0.28	0.17	0.11
Smooth plaster (on brick)	0.01	0.02	0.05
Acoustic ceiling tiles	0.70	0.72	0.75

*Compiled from http://www.sengpielaudio.com/calculator-RT60Coeff.htm

Note: 1 in. = 25.4 mm.

Decorative concrete

As a free-flowing formable material, concrete is easily able to blend into the surrounding landscape or architecture style through use of shape, color, and texture. These properties can be used as an integral part of concrete without painting, coating, or working the hardened surface. Appearances can range from basic free-flowing forms with natural concrete coloring to intricate designs and textures. Concrete produced with texture and color for aesthetic purposes is often called architectural concrete. More recently, texture and color in concrete used on slabs-on-grade or other flat surfaces has been termed decorative concrete. A popular use of color and texture is to give concrete the look of pure stone for floors or countertops. Durability and ease of maintenance are positives with unpainted concrete surfaces. Figures 2.34 through 2.37 show several examples of decorative concrete in and around buildings.

Color and texture can also be functional beyond their aesthetic value. Various textures can produce different acoustics, traction, or light reflection. Light colors will reflect light, while dark colors will absorb light and heat; both of these options have benefits depending on whether the consideration is using thermal mass for

Fig. 2.34—Decorative concrete driveway *(photo courtesy of Rowland Concrete).*

Fig. 2.35—Concrete inside McClellan-Palomar Airport, Carlsbad, CA *(photo courtesy of T.B. Penick & Sons).*

Fig. 2.36—Cathedral of Our Lady of Angels Catholic Church in Los Angeles, CA, is built with architectural concrete in a color reminiscent of sun-baked adobe walls of California Missions *(photo courtesy of Lehigh White Cement).*

Fig. 2.37—Example of colored concrete floor *(photo courtesy of CSolutions, Atlanta, GA).*

passive solar or reflecting light for more daylighting. White cement can produce very light-colored concrete or be used in conjunction with specific colors to attain the specific tint needed.

The role of concrete for artistic expression has long been known in the architectural field. Numerous books are available that showcase the potential of concrete in this area. *Liquid Stone: New Architecture in Concrete* (Cohen and Moeller 2006) gives a good perspective from architects, engineers, and researchers on some significant projects in concrete with a focus on structure, texture, and sculpture. A sample of some of the many concrete colors and textures is shown in Fig. 2.36 and 2.37.

Heat island effect

Urban areas can reach temperatures up to 10°F (5.5°C) higher than surrounding nondeveloped areas. The difference of surface temperature between grass and paving materials can reach 40°F (4.4°C). In summer, 99% of this temperature increase is due to dark surfaces such as roofs and pavement (Rosenfeld et al. 1997). Figure 2.38 illustrates the local temperature extremes between light and dark hardscape and vegetated areas. The heat island effect has multiple consequences that affect sustainability. Higher temperatures mean that more energy is used for cooling in buildings, which in turn results in more CO_2 release and pollution. The speed of ozone formation and evaporation of VOCs increases at higher temperatures.

"Cool" roofs and pavements, along with vegetation, have the biggest influence on reducing the heat island effect. Light-colored materials and porous materials, such as pervious concrete, tend to provide the most relief. Light-colored materials reflect heat instead of absorbing it, while porous materials have lower storage capacity for heat due to their large void percentage, and they 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 generally has a high SRI value, particularly the lighter shades of concrete.

Rating systems often require an SRI of 29 or greater, and almost all concrete will meet or exceed this requirement. A PCA study by Marceau and VanGeem (2007) measured the SRI values of different constituents of concrete in addition to SRI values of various mixtures to analyze the effect of the constituents on the final SRI value for the in-place concrete. Forty-five concrete mixtures (135 specimens) were tested, and all were above an SRI value of 29. The SRI value of the concrete

Fig. 2.38—Grass, concrete pavement, and asphalt pavement surface temperatures measured using an infrared thermometer. These readings, taken within meters of each other on same spring afternoon, demonstrate effects of transpiration and solar reflectance on surface temperatures. Grass remains cool because it reflects some solar energy and sheds heat by evaporative cooling. Concrete pavement remains cool because it reflects solar energy very well, but asphalt pavement reaches high temperatures because it absorbs almost all incident solar energy.

was influenced most by the SRI value of the cement, followed by the supplementary cementitious materials. Aggregates had a minimal effect. Table 2.7 shows the reflectance, emittance, and SRI of some common building materials. Table 2.8 shows a sample of the measured SRI values of cement, fly ash, and slag cement used in the study.

Table 2.7—Solar reflectance (albedo), emittance, and solar reflective index (SRI) of select material surfaces

Material surface	Solar reflectance	Emittance	SRI
Black acrylic paint	0.05	0.9	0
New asphalt	0.05	0.9	0
Aged asphalt	0.1	0.9	6
"White" asphalt shingle	0.21	0.91	21
Aged concrete	0.2 to 0.3	0.9	19 to 32
New concrete (ordinary)	0.35 to 0.45	0.9	38 to 52
New white portland cement concrete	0.7 to 0.8	0.9	86 to 100
White acrylic paint	0.7 to 0.8	0.9	100

Table 2.8—Solar reflectance for various types of concrete

Material	Description	Solar reflectance
Cement	Dark gray	0.38
	White	0.87
Cement + fly ash	Dark gray	0.28
	Medium gray	0.40
	Very light gray	0.55
	Pale buff	0.44
	Yellow buff	0.46
Cement + slag cement	Dark	0.71
	Medium	0.75
	Light	0.75

Summary

Advantages/benefits

- Healthier occupants
- More productive workers/students
- More comfortable workers/students
- Easier recruitment
- Aesthetics

Disadvantages/limitations

- Up-front cost for some items may be higher, but benefits for occupants (and increased productivity) will typically offset any initial cost increases in a well-planned design

Absorption coefficient—Numerically represents a material's tendency to reflect (0) or absorb (1) sound.
Albedo—Measure of an object's reflectivity of sunlight.
"Cool" roof—Roofs that reflect light (typically white or very light colored) and have high emissivity (ability to release absorbed heat).
Decorative concrete—Concrete that is designed for aesthetic value; texture, stamping, dyes, staining, and other processes are used to achieve the desired effects.
Emittance—Portion of energy radiated from the material surface.
Heat island effect—Increase in metropolitan area temperatures compared to surrounding areas due to buildings (particularly dark colored roofs) constructed with materials that have high retention of heat.
Human factors—Study of how humans behave in relation to their environment including ergonomics (designing the workplace for the worker); commonly used to evaluate productivity in the work environment.
Light trespass—Light spilling across boundaries where it is unwanted (into a neighboring window, into an animal habitat, etc.).
Noise absorption—Materials with good noise absorption transform sound waves to reduce reflection and echoes.
Noise reflection—Materials with good noise reflection can block sound from transmitting to neighboring rooms, but do not reduce noise inside the room itself.
Solar reflective index (SRI)—An index to quantify how hot a surface would be relative to a standard black (low SRI) or standard white (high SRI) surface; the SRI combines both solar reflectance and emittance.

Chapter 7—Safety and security

The safety and security of building occupants are critical components of the social and economic aspects of sustainability. Both natural and man-made hazards can compromise the safety and security of the occupants as well as damage the building structure and material contents. The most common hazards or extreme events for a building are storms (hurricanes, tornados, and floods), earthquakes, fire, blast and impact, organic decay, and insect damage. Owners are increasingly aware of the need to make structures more robust to resist hazards, and concrete has significant advantages in this area. The use of concrete structures as shelter in emergencies has long been established due to its strength, longevity, and durability.

Storms (hurricanes, tornados, and floods)

A high-mass material, such as concrete, provides resistance against high winds present in tornados and hurricanes. Exterior surfaces of concrete in these weather conditions are preferable to siding or facade materials that can be dislodged and become flying debris, thereby risking loss of life and exposing the building to the elements. Concrete has proven to be effective in extreme high winds, as illustrated in Fig. 2.39.

A major concern during hurricanes and other major rain events is flooding. Flooding (and the risk flash-flooding) can be exacerbated in low-lying regions and where the amount of impervious surface has been increased with development, resulting in much more danger to individuals and damage to property than the storm event itself.

Concrete and earth dams and levees have been constructed to manage water use and allow farming in areas that would have been part of a flood plain, and levees now protect populated, low-lying areas such as New Orleans. In too many cases, these dams and levees are in increasingly poor repair (as shown with dramatic results during Hurricane Katrina) and will be under greater stress due to increasing storm-water runoff. Properly maintained concrete can be very effective in resisting normal rain events and the potentially more damaging storm surge created by a flash flood—maintaining its structural integrity over periods of submersion.

After a flood, many building materials are no longer useable due to rot or mold that can cause serious health issues for the occupants and those assisting in cleanup. Concrete does not rot or mold, so it can be cleaned and generally returned to service in short order after a flood.

Fig. 2.39—Concrete home stands alone in Pass Christian, MS, after Hurricane Katrina in 2005. High water mark is 28 ft (8.5 m) up the structure *(photo courtesy of John Fleck, FEMA).*

Earthquakes

Many materials and systems, including concrete, can be effective for preventing loss of life and minimizing structural damage when properly designed for earthquake resistance. Design for seismic forces is a specialized part of building design, and is covered in ACI 318 (ACI Committee 318 2008) as well as in numerous textbooks. Each earthquake provides additional data on potentially weak areas in any structural system, so seismic design and construction knowledge is continually improving. As an example, today's codes and specifications include considerations and provisions for ductile performance during an earthquake. Other provisions now require separation of participating and nonparticipating structural elements for all common building materials that provide for a safer shelter.

Fire

Fire can cause severe damage to the building structure and contents in a very short amount of time. Concrete does not burn and is not only resistant to fire but can also be used as fireproofing to protect other materials.

Because concrete members do not typically need additional fireproofing, construction costs are reduced, and the introduction into the building of materials and chemicals associated with applied fire-proofing systems can be avoided.

At extreme temperatures (beginning above 500°F [260°C]), concrete will begin to degrade and visibly becomes a pinkish, chalky material. Design for high temperatures and long fire durations should include additional concrete cover to protect internal steel reinforcement. Code requirements for determining fire resistance for concrete members are available in ACI 216.1-07/TMS-0216-07 (Joint ACI/TMS Committee 216 2007).

In addition to burning building materials, the surviving portions of the building will typically be affected by smoke damage, and particularly from water damage resulting from sprinkler systems and fire-fighting efforts to extinguish the fire.

Concrete is a completely termite-resistant material.

Blast and impact

Terrorist attacks, including vehicular or ballistic impact, comprise threats that many owners are taking seriously, particularly for high-profile buildings. Concrete has excellent resistance to the extreme loads produced in a bomb blast, vehicular impact, or ballistic impact. Concrete can also be used in combination with innovative materials, such as fibers in the concrete matrix or blast-resistant coatings, to further improve resistance to impact and spalling. Details on the design of concrete members for blast loading can be found in the "United Facilities Criteria: Structures to Resist the Effects of Accidental Explosions" (U.S. Department of Defense 2008). Secondary fires that result from blasts are also well resisted by concrete.

Termites

Termites feast on cellulose and thrive in locations that have the right combination of warmth and humidity (warmer states and coastal states). They can cause heavy damage that may go undetected under surface cladding, allowing the structure to become totally infested. Termites and other pests do not eat or destroy concrete, so concrete is a completely termite-resistant material.

Summary

Advantages/benefits

- Protection of public as a safe shelter from flooding, wind, earthquakes, blast, and impact
- Stormwater control through dams, levees, and cisterns
- Robust and durable solution for natural and manmade disasters and resistant to rot and pests
- Easily cleaned and restored for further use

Disadvantages/limitations

- As with other materials and systems, seismic design is one area that continues to improve based on additional research and data from earthquakes.

Chapter 8—Reduce, reuse, recycle

A designer can use concrete to integrate all of the 3-Rs (reduce, reuse, recycle) from development to demolition. On the surface, the 3-Rs appear to be intertwined, but there are important differences in their definitions:

- **Reduce—**minimizing waste through reduction of resource use (virgin, reused, and recycled) and energy during construction.
- **Reuse—**using again in basically the same form for the same purpose or for a new purpose.
- **Recycle—**breaking down the material into components to form a new component or use.

As illustrated in Fig. 2.40, the 3-Rs are hierarchical, starting with the most desirable in terms of the least energy required (reduce). All three are preferable to disposal.

Reduce

An efficient and innovative design can reduce the total amount of structure needed through reduced building square footage and volume. For example, a significant reduction in the depth of the floor-ceiling assembly can be achieved with concrete structures, thus dramatically reducing the overall building volume and area of exterior finishes. Reduce can also mean smaller houses, or in a cultural change, more urbanization leading to higher density housing, as in high-rise construction. Additionally, structural optimization of building components can also reduce the volume of materials used.

The use of blended cement or the replacement of portland cement with industrial by-products reduces the amount of clinker required per cubic yard of concrete, and thus reduces the amount of energy needed and resultant CO_2 emissions.

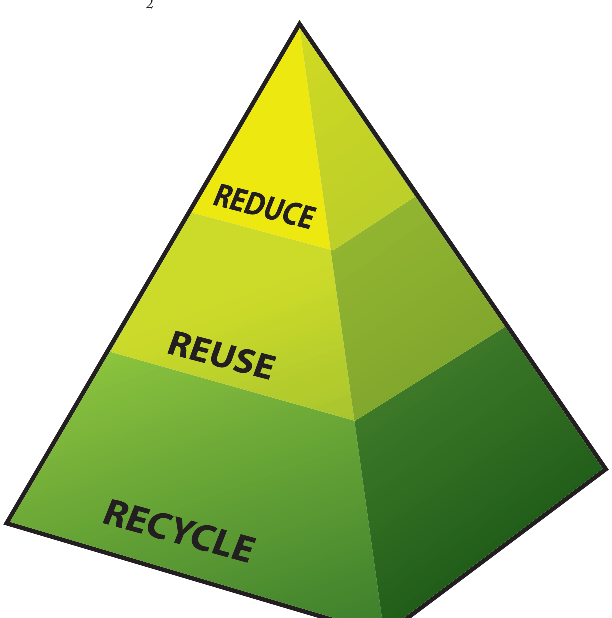


Fig. 2.40—Hierarchy of reduce, reuse, recycle.

Concrete reduces waste during construction because the desired amount of concrete is mixed to fill the volume of forms being used. Concrete left over after casting can often be used elsewhere on the project site.

Concrete, used as the final finish, reduces the need for paint, carpeting, and other finishes (including partition studs/walls, tile, and other floor finishes).

Reuse

Components such as precast concrete panels, pavers, and masonry blocks have the potential for direct reuse.

The manufacturing process for cement also includes reuse of waste materials such as paints, coatings, solvents, chemical manufacturing waste, and old tires to fire the kiln. These materials are often classified as hazardous waste, requiring special treatment and land disposal. The temperatures reached in a kiln are far higher (over 1800°F [1000°C]) than in a typical incinerator; thus, the waste materials undergo extremely rapid and complete combustion. Using these materials for fuel instead of fossil fuels saves nonrenewable resources while safely disposing of waste materials.

The wash water from cleanup after mixing concrete is regulated by the EPA, and is required to be disposed of properly. The volume of wash water produced at a ready mixed concrete facility is considerable. This water is now increasingly being reused to make new concrete.

Industrial by-products are used as supplemental cementitious materials (SCMs) or cement replacement and not only provide a sustainable option through reuse, but also improves concrete properties while reducing cost. The most commonly used by-products are fly ash, silica fume, and slag cement. Table 2.9 indicates quantities produced and usage of slag cement, silica fume, and fly ash.

- **Fly ash—**Fly ash is a by-product from the combustion of pulverized coal. It can be used as a separate ingredient in the batching process, or blended with cement. ASTM C618 (ASTM International 2008) defines two classes of fly ash: Class C and Class F. Fly ash is a pozzolan (defined as having little cementitious value, but that forms compounds with some cementitious properties). Some fly ash also has cementitious value. The majority of fly ash is made

Table 2.9—Supplemental cementitious materials usage in concrete, 2004*

Material	Material produced	Material beneficially used in concrete
Silica fume	100 to 200	80
Slag cement	4100 (estimated)	3600
Fly ash	64,000	12,800

*All quantities listed in thousands of metric tons.
(Environmental Protection Agency 2007).

Fly ash concrete is available in a wide palette of desirable colors, including a very light, almost white color *(photo courtesy of American Coal Ash Association).*

Portland cement, left, and slag cement, right *(photo courtesy of Slag Cement Association).*

Silica fume *(photo courtesy of Silica Fume Association).*

up of solid and hollow glassy spheres. The main constituents are SiO_2, Al_2O_3, Fe_2O_3, and CaO. Fly ash is classified based on the sum of the first three components (greater than 70% for Class F, and greater than 50% for Class C). Class C ashes contain a higher amount of CaO.

Fresh properties that are influenced by fly ash include increased workability, increased set time, and reduced bleed. Hardened properties that are influenced by fly ash include a reduced rate of strength gain and reduced heat of hydration (Class F), lowered permeability, and improved sulfate resistance (Class F) (ACI Committee 232 2004). The reduced permeability of fly ash is important to provide a more durable concrete.

- **Silica fume—**Silica fume is a by-product of the ferrosilicon industry, and can be added directly as an ingredient in the concrete or in a blend with cement. While the term "silica fume" is the most appropriate, other terms, such as microsilica and condensed silica fume, are sometimes used. Silica fume is primarily SiO_2 (generally more than 90%), and it is a highly reactive pozzolan, as defined in ASTM C1240 (ASTM International 2005). It consists of fine spherical particles (surface area of 83,000 to 150,000 ft^2/lb [17,000 to 30,000 m^2/kg] as compared with 1500 to 2400 ft^2/lb [300 to 500 m^2/kg] for cement, and 2000 to 3400 ft^2/lb [400 to 700 m^2/kg] for fly ash), and generally increases the water demand of the concrete mixture. High-range water reducers (HRWRs) are typically needed to maintain workability when silica fume is used in concrete. Silica fume is used at practical quantities of up to 10% by mass of cementitious material, but lower percentages of 3 to 7% are more common. Silica fume can be transported and used in several different forms: 1) as-produced in bulk or in bags; 2) as a water-based slurry; 3) densified; or 4) pelletized. As-produced silica fume causes handling difficulties due to the very fine particle size, so water-based slurries or densified silica fume are used to overcome this difficulty. Pelletized silica fume can be inter-ground with clinker to form an inter-ground silica fume cement.

  Silica fume is gray in color, and typically has the following effects on fresh concrete properties: increased water demand, need for increased slump to maintain workability, reduced bleed, and increased plastic shrinkage cracking if not properly cured (to retain surface moisture). Hardened property effects include higher strength (developed at an early age) for the same water-cementitious material ratio (*w/cm*) and improved durability properties, namely, improved chemical attack resistance, abrasion resistance, sulfate resistance, increased electrical resistivity, and lower permeability (ACI Committee 234 2006).

- **Slag cement—**Slag, also referred to as ground granulated blast furnace slag (GGBFS), is a by-product of smelting iron ore, and is primarily comprised of silica, calcium, aluminum, magnesium, and oxygen. It is used as a partial cement replacement in concrete either by blending with cement or batching as a separate ingredient. Slag has been used in proportions of 25 to 70% (by mass of cementitious material), with ranges of 40 to 50% typically optimum for strength (ACI Committee 233 2003). Slag cement does have cementitious properties that are accentuated when the slag is quenched immediately as it leaves the furnace. Slag is classified by Grade 80, 100, or 120 based on its activity-index, as given in ASTM C989 (ASTM International 2009). Slag cement can increase workability and delay set time (depending on slag and cement amounts). Hardened property changes include a reduced rate of strength gain with equal or higher compressive strengths at later ages, a higher modulus of rupture at later ages, a reduction in temperature rise during hydration in mass concrete, lower permeability, and improved sulfate resistance (ACI Committee 233 2003). The lower permeability of concrete that contains slag cement improves durability against reinforcement corrosion from chloride and moisture ingress, similar to concrete that contains fly ash or silica fume.

- **Ternary blends—**Ternary mixtures combine portland cement, silica fume, and either slag cement or fly ash. These blends can take advantage of the positive aspects of the constituents while offsetting some of the effects on strength gain or other targeted properties. A summary of the previous work in this area is included in ACI 233R-03 (ACI Committee 233 2003). Recent revisions to ASTM C595 and ASTM C1157 provide provisions for ternary blended cements (ASTM International 2009).

Recycle

All concrete used in a building can be recycled in some manner during demolition. The hardened concrete is broken apart and turned into rubble on site. The reinforcement is removed and can be recycled. The demolished concrete can be used directly on the site for some applications, but for use in recycled concrete, it is typically sent to a plant for additional processing. At the recycling plant, the concrete is crushed to 2-1/2 to 3 in. (65 to 75 mm) pieces. At that point, any remaining steel pieces can be removed with a magnet. The final round of crushing produces a maximum aggregate size of 3/4 to 1 in. (20 to 25 mm) (ACI Committee 555 2001). Any additional contaminants are then removed if possible.

Contaminants such as oil, plastic, and wood must be sufficiently removed for the concrete to be used as concrete aggregate so that properties of the recycled concrete are not adversely affected. If the concrete has been contaminated by deicing salts, it is inappropriate for reuse in an environment with moisture present because of the high risk of embedded reinforcing steel corrosion.

Richmond Olympic Skating Oval, built for 2010 Winter Olympics in Vancouver, BC, uses fly ash as cement replacement for parking slab, buttresses, shear wall, suspended slab, and activity slab *(photo courtesy of Lihe [John] Zhang).*

Crushed concrete can be stockpiled for future reuse (*photo courtesy of Recycled Materials Company, Inc.).*

Recycled aggregates will have higher water absorption than virgin aggregates and should be presoaked before batching. Concrete made with recycled aggregates tends to have lower strength, which is related to the strength of the original concrete that was recycled to make the aggregate. Creep, shrinkage, and permeability also tend to be higher in the recycled concrete (Hansen 1986).

Some of the components that go into new concrete construction also come from recycled materials:

- Demolished concrete can be used on site as a base material for pavement.
- Demolished concrete can also be or mixed into new concrete as recycled aggregate.
- Steel reinforcement starts as recycled steel before use in concrete, and can be recycled again after demolition of a reinforced concrete component.
- Waste rubber (often tires) can be chopped into small pieces and be used as a filler material that provides an energy-absorbing surface such as a playground or running track.
- Waste fiber material (such as polypropylene carpet fiber, carbon fiber, and nylon) can be used in the concrete matrix to reduce plastic shrinkage cracking.

Chapter 9—Economic impact

Economic impact is one of the three tenets of sustainability (along with environmental impact and social impact). When a company discusses the "triple bottom line," it is important to realize that the economic component should relate to more than internal company profit. The economic component of sustainability extends to the local community (or beyond to the global community), and is integrated with both the environmental and social impacts. The economic impact should itself be sustainable to significantly contribute to the community. The complex interaction that results in economic benefit to the community through sustainable building is difficult to quantify. A disaster-resistant concrete structure will reduce economic disruption due to natural disasters by enabling businesses, employment, and commerce housed within these structures to begin to function more quickly.

Local impact

In both the social and economic tenets of sustainability, local impact is a key factor. A sustainable building should be a "good neighbor" for the community in terms of providing employment, stimulating the local economy, providing a positive focal point, and not disrupting the surrounding area.

Cast-in-place and precast concrete are typically locally produced, thus using local materials and labor (including local transport). The materials often come from within 100 mi (160 km) of the building site, and ready mixed concrete comes from within a 30 mi (50 km) radius (typically much less). The supporting trades and businesses for construction with concrete also tend to be local. Aggregate quarries cause disruption to the environment, but the site can be restored when it is no longer used as a quarry. Delineation of quarry restoration programs are now part of initial quarry permitting in most locales. The mined product (rock) is an abundant natural resource, and its sale and use feeds directly into the local economy. Additionally, the environmental impact caused by material shipping is minimized when using local resources.

Placing pervious concrete with local labor.

Material savings

A reduction in cost of materials and the reuse of materials in making concrete can have a very direct and positive economic impact. The practices that support reduction in up-front material costs have been in place in the construction industry for decades (due to the original "bottom line" of providing an economic structure).

Savings in the amount of material used not only reduces the up-front cost, but also reduces the amount of natural resources used (materials for the building components and the energy used to produce and transport them). Concrete (both ready mixed and precast) tends to be locally produced, so this also reduces transportation costs while stimulating the local economy.

The structural engineer strives for efficient sections to carry the building loads. Prestressed (pretensioned or post-tensioned) concrete can aid in that efficiency with smaller cross sections for a given span and load. These sections can also increase durability and service life because they are typically designed not to crack at service loads. Sections such as precast, prestressed hollow core slabs provide efficiency with lowered weight and also provide the opportunity to use the hollow spaces as ducts.

Precast concrete reduces on-site waste from forming, reinforcing cage tying, and excess concrete in the concrete truck. The precast units can be brought to the site and erected quickly, which results in less time and labor needed on site. The use of concrete as a finished surface rather than carpet, paint, drywall, and other materials is discussed in Chapter 6. Precast concrete is a popular choice for providing concrete with architectural finishes because of the quality control possible in a precasting facility.

Reuse

While this book focuses on new construction, the economic impact associated with new construction versus building reuse is an important topic. It is commonly perceived that a new energy-efficient building will quickly make up the difference in up-front cost through energy savings during operation. This approach does not always consider the economic impact on the additional use of natural resources, the long-term cost associated with landfill of the demolished building materials, and additional economic drivers for the community (such as the tourism value associated with historic buildings and more affordable building rent). Frey (2007) provides an extensive literature review of the work done in this area related to historic structures. Renovation of existing structures will increasingly be a bigger contribution to sustainability for local communities.

Chapter 10—Resilience with climate change

As one of the oldest and most popular building materials, concrete has been resilient to the changing environment, service requirements, and construction practices since Roman times. A primary environmental consideration for the future is global climate change. Materials that can adapt to a dramatically changing environment (and thus, different construction practices and service requirements) will be the biggest contributors to true sustainability in the future.

The Intergovernmental Panel on Climate Change's (IPCC) *Synthesis Report* (2007) details findings in five key areas: 1) observed changes in climate and their effects; 2) causes of change; 3) projected climate change and its impacts; 4) adaptation and mitigation options; and 5) the long-term perspective on climate change. The projected temperature rise for the 21st century from this report varies with the modeled scenarios, ranging up to 11.5°F (6.4°C), with a corresponding projected sea level rise of 0.59 to 1.9 ft (0.18 to 0.59 m). Even the more conservative projections will have an overall negative impact on water and food availability, the ecosystem (with high rates of species extinction), coastal flooding, and human health. Extreme weather events (heat waves, droughts, and floods) are projected to become more recurrent.

Frequent extreme weather will further the need for even more robust structures that can provide shelter. This need will be the basis for new construction design and will dominate retrofitting of existing structures, as design loads for environmental exposure are likely to increase with time. Concrete's history and potential in this area are discussed in detail in Chapters 4 and 7. Heating and cooling of buildings by passive means will be critical for comfort when energy and resources are limited. Increased insulation and increased daylighting will also be more critical. The IPCC report (2007) outlines additional examples of adaptation strategies, many of which relate to the potential use of concrete:

- Rainwater harvesting and water reuse (cisterns and concrete storage tanks);
- Settlement/infrastructure relocation;
- More seawalls, storm surge barriers, and protection of existing natural barriers; and
- Retrofit of existing infrastructure for warming climate, drainage, and storms.

The Netherlands has many formidable examples of concrete under extreme design requirements: one-third of the county is below sea level. The Delta Works (considered one of the Seven Wonders of the Modern World by the American Society of Civil Engineers [1994]) protects a large area of land from the sea through a system of locks, dams, storm surge barriers, and bridges. In 1953, a heavy storm caused the dikes to give way, resulting in over 1800 fatalities in the Netherlands, primarily in the Zeeland region. The Delta Works was constructed to prevent this type of catastrophe in the future, and was completed in 1997 after over 40 years of construction. The largest of the 13 dams in the system is the Oosterscheldekering, completed in 1987, as shown in Fig. 2.41. The Oosterschelde Bridge (alongside the dam) is shown in Fig. 2.42. The project was designed for a 200-year service life in the harsh environment of the North Sea. Concrete is used extensively throughout the structure, with the exception of the steel sluice gates. Concrete was chosen due to its excellent performance in massive flood walls and dams. Plans are already in the works for extending the height and width of the dikes in some portions of the Delta Works due to sea-level rise from climate change.

Fig. 2.41—Oosterschedekering (*photo courtesy of Raimond Spekking/ Wikimedia Commons / CC-BY-SA-3.0 & GDFL).*

Fig. 2.42—Oosterschelde Bridge (*photo courtesy of Raimond Spekking/ Wikimedia Commons / CC-BY-SA-3.0 & GDFL).*

Chapter 11—Compatibility with other innovative sustainable strategies

This book focuses on the use of concrete within multiple areas relating to sustainable structures, but no material can stand alone as the solution for every situation. Some of the qualities that make concrete an easy choice as a compatible material include:

- The ability to mold to any shape;
- The flexibility to cast on- or off-site;
- The low cost per unit volume;
- Resistance to aggressive environments;
- High stiffness;
- High thermal mass; and
- Light color.

Table 2.10 summarizes some of the ways concrete plays a role in sustainability. By using every building material in a way that can best contribute to sustainability, major advances can be made in the building sector.

Photo courtesy of Steve Linder, Photographer/Twin City Photography

Compatibility (concrete)—Ability to work with other materials without modification or to exist in harmony with other materials.

Table 2.10—Concrete's role in sustainability by topic

Topic	Concrete's potential role
Carbon footprint	• Reduces over life cycle (recognizing the upfront CO_2 from cement manufacturing)
Thermal resistance	• Robust exterior and interior layer for sandwiching insulating materials
Thermal mass	• Walls, floors, and mass elements to reduce temperature spikes and to lag temperature effects
Longevity	• Provide durability and long life to structural and nonstructural elements
Stormwater management	• Provide pervious area for parking and sidewalks • Concrete cisterns and pipes • Support frame for green roof systems
Security and safety	• Provide shelter for extreme loads (weather, earthquakes, and blast and impact)
Human factors	• Aesthetics (form, color, durability, and longevity) • Works with daylighting (light color) • Acoustics (combined with a sound absorptive material) • Indoor air quality (won't mold, doesn't need paint or carpet)
Reduce, reuse, recycle	• Recycled aggregates, washwater, concrete, fuel (tires to fuel cement manufacture), and waste material in admixtures
Economic impact	• Local material • Low cost
Resilience with climate change	• Adaptable to many systems • Robust in face of climate extremes (storms and temperature swings)

PART 3—BEYOND SUSTAINABLE RATING SYSTEMS: PROJECT PROFILES

The strategies detailed in Part II provide insight and direction for using concrete in the design and construction of sustainable buildings. Part III profiles 12 projects that help identify specific examples of concrete's contribution to sustainable buildings, while also serving as inspiration for new ideas.

Project profiles included here are either completed or under construction, and provide real-life examples of the strategies and techniques that enhance the social, environmental, and economic benefits of sustainable development. Projects were selected to represent the diversity of concrete applications, and include parking structures and surface parking lots; single and multi-family residential; office, civic, and institutional; as well as retail/industrial warehouse.

Members of the design/construction teams that offered these profiles and photographs/renderings are hereby thanked for allowing inclusion in this book, and commended for their sustainable use of concrete.

Photo courtesy of Schokker.

Chapter 12—Blue Cross Blue Shield of Michigan Parking Structure

Location: Detroit, MI

Type: Parking structure

Awards and certifications

- LEED Certified
- International Parking Institute Award of Excellence
- Precast/Prestressed Concrete Institute Best Parking Structure

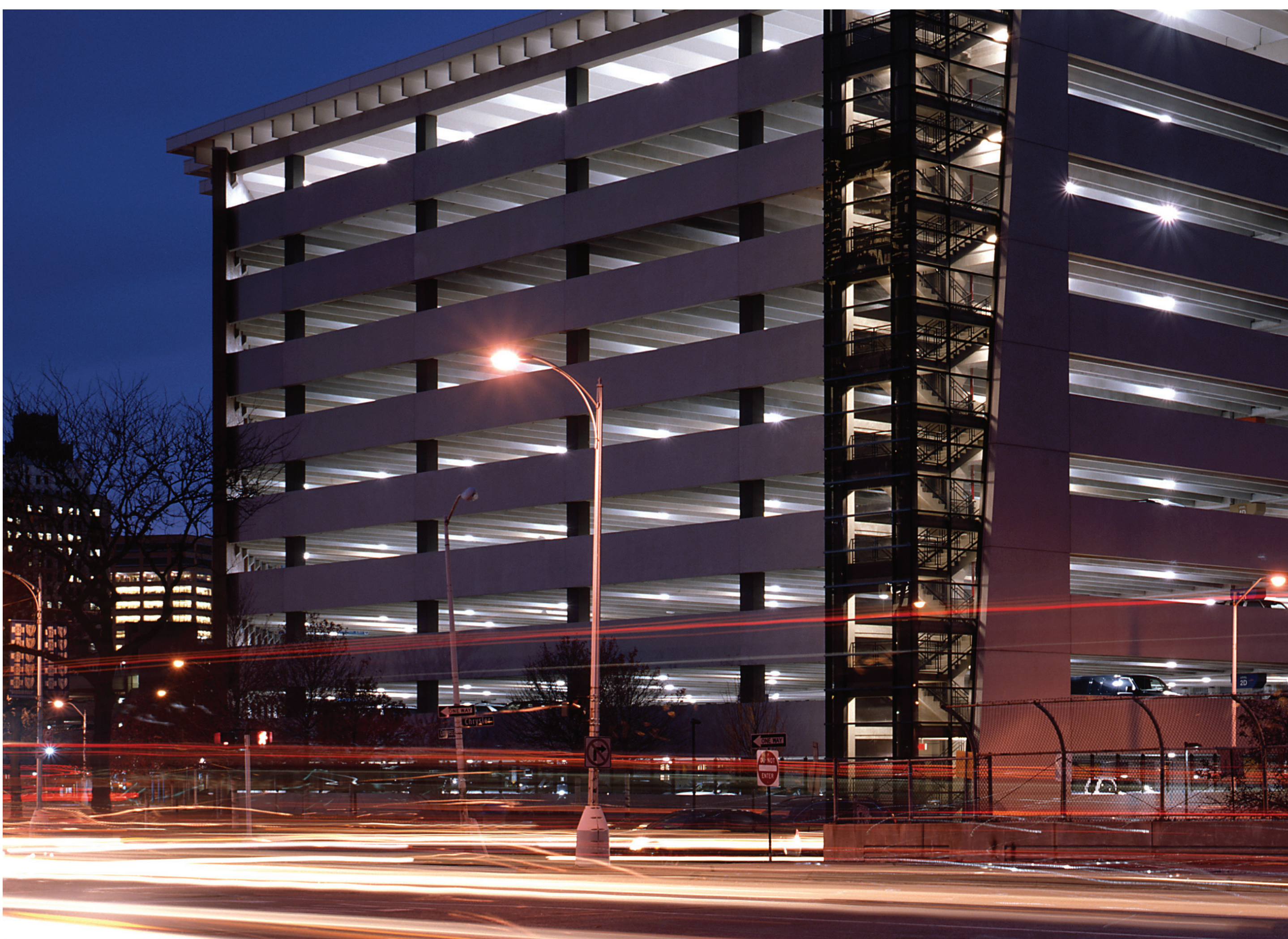
Structure specifics

This precast concrete parking structure was built on the site of a surface parking lot that previously held 125 cars in downtown Detroit. The new structure is nine stories and holds 1808 cars.

Sustainable concrete features

The Blue Cross Blue Shield parking structure has a number of sustainable features related to concrete. Slag cement was used in the concrete as a partial replacement for cement, resulting in lower CO_2 emissions while also providing a more durable structure. Locally produced precast panels and double-tees were also used in the structure, reducing on-site waste and labor and decreasing transportation distance.

A major sustainable feature of the Blue Cross Blue Shield parking structure is a concrete cistern capable of collecting 90,000 gal. (340 m^3) of rainwater runoff. The cistern collects filtered water from a green roof in addition to collecting runoff from adjacent buildings. The water is then reused for irrigation on the campus. The green roof reduces the heat island effect, reduces runoff, and shields the underlying parking levels from rain and snow. The roof also incorporates a 1/10 mile (160 m) walking track with recycled pavers.



Photos courtesy of Neumann/Smith Architecture & Maconochie Photography.

Chapter 13—I'Lan Park Parking Lot

Location: Leawood, KS

Type: Parking lot

Awards and certifications

- PCA Sustainable Leadership Award (to the city of Leawood, KS, for the I'Lan Parking Lot)

Structure specifics

This 6300 ft^2 (585 m^2) parking area was constructed in 2007 as a test case for pervious pavement in a region with significant freezing-and-thawing cycles.

Sustainable concrete features

The I'Lan pervious parking lot has served as an example project for other cities in Kansas. It was originally planned as a traditional asphalt lot that typically requires the city of Leawood to perform maintenance at intervals of 4 to 6 years. The pervious lot was designed to be maintenance-free for 20 years. Due to the proximity of the area to a creek, the function of pervious concrete to filter deposits of contaminants, including oil and grease, becomes even more important.

In this demonstration, the pervious concrete parking lot infiltrated 9000 gal. (34,000 l) of water in 4 minutes *(photos courtesy of Concrete Promotional Group).*

Chapter 14—Indianapolis Midfield Terminal Parking Garage

Location: Indianapolis, IN

Type: Parking structure

Awards and certifications

- Project is applying for LEED certification
- *Midwest Construction Magazine's* Best of Transportation Award

Structure specifics

The Midfield Terminal Parking Garage is located adjacent to the terminals, reducing transportation needs for passengers between parking lots and the airport terminal. The garage provides 5900 parking spaces.

Sustainable concrete features

The parking garage uses silica fume in the concrete to reduce the required cement content while providing considerably lowered permeability and durability. Day-lighting and reflectivity are key aspects of the project, providing a reduced need to use energy for lighting.

Photos courtesy of Silica Fume Association.

Chapter 15—Melrose Commons Site 5

Location: Bronx, NY

Type: Residential (multi-family)

Awards and certifications

- LEED Platinum (LEED for Homes/Affordable Housing)
- Precast/Prestressed Concrete Institute's (PCI) Sustainable Design Award

Structure specifics

This precast multi-family residential structure is five stories, over 70,000 ft^2 (6500 m^2), and provides apartments for 63 low-income families. The site also includes 6300 ft^2 (585 m^2) of green recreational space for residents and a community garden. The project is a demonstration site for a gas-fired micro-combined heat and power system, and also includes wind turbines on the roof.

Sustainable concrete features

The entire structure is precast concrete: precast hollow-core planks for the floors, precast units for stairs and interior bearing walls, and a precast panel exterior with an inlaid brick façade. The exterior venting is run through the hollow core planks, which saves on duct work and energy use. The exterior precast panels provide a well-sealed building envelope for energy-efficient heating and cooling while also allowing a significant amount of glass for daylighting. The precast structure also provides for excellent material efficiency, fire resistance, and reduced noise transmission between units and the outside of the structure. An estimated 30% reduction in construction time was gained by having an entirely precast structure (compared with the original design).

Photos courtesy of Mike Smith, AIA Equus Designs.

Chapter 16—Paterson Model Home

Location: Paterson, NJ

Type: Residential (single family)

Awards and certifications

- LEED for Homes Gold rating as a pilot project

Structure specifics

The Paterson model home was designed and built by a partnership of over 50 organizations through BASF Corporation's "Better Home, Better Planet" initiative. The house serves as an example for designers and builders in an area where nearly 3000 affordable new homes are planned. The near zero-energy home is 2900 ft^2 (270 m^2), and is 80% more energy efficient than a conventional home. It includes solar thermal and photovoltaic panels to work in conjunction with the well-sealed building envelope.

Photos courtesy of BASF.

Sustainable concrete features

Concrete was used throughout the building envelope to provide an extremely airtight system with excellent insulation. Insulating concrete forms (ICFs) were used for the basement and first floor of the house (structural insulated panels were used on the upper floor and roof). Polymer-enhanced shotcrete was sprayed directly over the ICFs in a 0.5 in. (13 mm) layer, forming a strong weather- and fire-resistant exterior shell. The ICF walls are also mold- and insect-resistant.

Concrete floors on both the first and second levels in the home provide radiant heat that is energy efficient and comfortable for occupants. Other uses of concrete in the home include terraced concrete masonry unit (CMU) walls incorporated into the landscaping and concrete pavers.

Chapter 17—North Central College Residence Hall and Recreation Center

Location: Naperville, IL

Type: Residential and athletic

Awards and certifications

- LEED Silver

Structure specifics

This 201,440 ft^2 (18,710 m^2) structure is a unique combination of residential, recreational, and sustainable concepts in a single structure. A 265-bed student dormitory wraps around the central 58,780 ft^2 (5460 m^2) athletic arena. The arena includes a 660 ft (200 m) running track, numerous multipurpose courts, an elevated walking track, offices, fitness facilities, and training facilities.

Sustainable concrete features

The building has over 1300 precast concrete panels for the arena walls and the dorm walls, floors, and stairs. The locally-produced precast panels reduced material waste on site while facilitating rapid on-site construction. The wall panels include cast-in aesthetic detailing to give the building a brick and block façade to match the existing campus architecture. The building uses concrete thermal mass to great advantage. The precast floor panels include radiant heating supplied from a geothermal system. Concrete pavers and retaining wall units are also used outside the building.

Photos courtesy of Dukane Precast, Inc.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Chapter 18—Northern Arizona University Applied Research and Development Building

Location: Flagstaff, AZ

Type: Institutional

Awards and certifications

- LEED Platinum
- 2007 Architectural Merit Award, Arizona Chapter of American Concrete Institute

Structure specifics

This three-story, 60,000 ft^2 (5600 m^2) building houses the facilities for research and application of sustainable technology on the Northern Arizona University campus.

Sustainable concrete features

Fly ash was used as partial cement replacement for the concrete in the building, contributing to a lower CO_2 footprint through the use of waste material and a reduction in cement use. The structural concrete in the building provides thermal mass that regulates temperature in the building. The concrete structural system works well with the extensive amount of exterior glass for passive solar and daylighting.

In addition to the sustainable features of the building itself, the parking lot was constructed with pervious concrete. This enables water to be filtered of particulate matter and surface contaminants before being absorbed back into the ground, reducing runoff quantity and improving runoff water quality.

Photos courtesy of Jerry Foreman, Northern Arizona University.


USGS

Chapter 19—San Francisco Federal Building

Location: San Francisco, CA

Type: Commercial (government)

Awards and certifications

- AIA San Francisco Design Award
- GSA Design Honor Award for Architecture
- GSA Design Award Citation in Sustainability

Structure specifics

This 600,000 ft^2 (56,000 m^2) building complex owned by the General Service Adminstration houses government agencies. The central feature of the building campus is an 18-story concrete tower.

Sustainable concrete features

The tower uses exposed concrete walls and ceilings for thermal mass benefits. The building layout was designed to promote natural ventilation that works in conjunction with the thermal mass. During the day, the exposed concrete absorbs occupational heat (from computers and lighting); at night, computer-controlled windows are opened to cool the concrete. This efficient combination of thermal mass and ventilation enables the upper floor perimeter areas to be cooled without the use of air conditioning. The exposed concrete was chosen by the architect for its aesthetic value as well as its thermal mass function. While lightweight concrete would typically be considered for a building of this type in a seismic region, normalweight concrete was used to receive the full benefit of thermal mass. Concrete also worked very well to attain the security and seismic requirements for the design.

Slag cement was used to replace 50% of the cement in the concrete (and 70% replacement of the cement in the concrete for the massive pile caps to reduce heat of hydration). This use of waste material provided a lower CO_2 emission for the building materials and contributed to a light concrete color favored by the architect. The light color also worked well to reduce lighting needs.

Photo courtesy of Andrew VanDis/Perfect Polish.

Rendering courtesy of Morphosis.

Mock-ups helped assure the contractor that 50% slag mixture and unconventional slab profile could be achieved to specifications and architects desired aesthetic. Because design loads for walls were controlled by seismic effects, strengths were specified at 56 days, thereby allowing cement savings without affecting the project schedule (*photo courtesy of Arup).*

Photo courtesy of Webcor Builders.

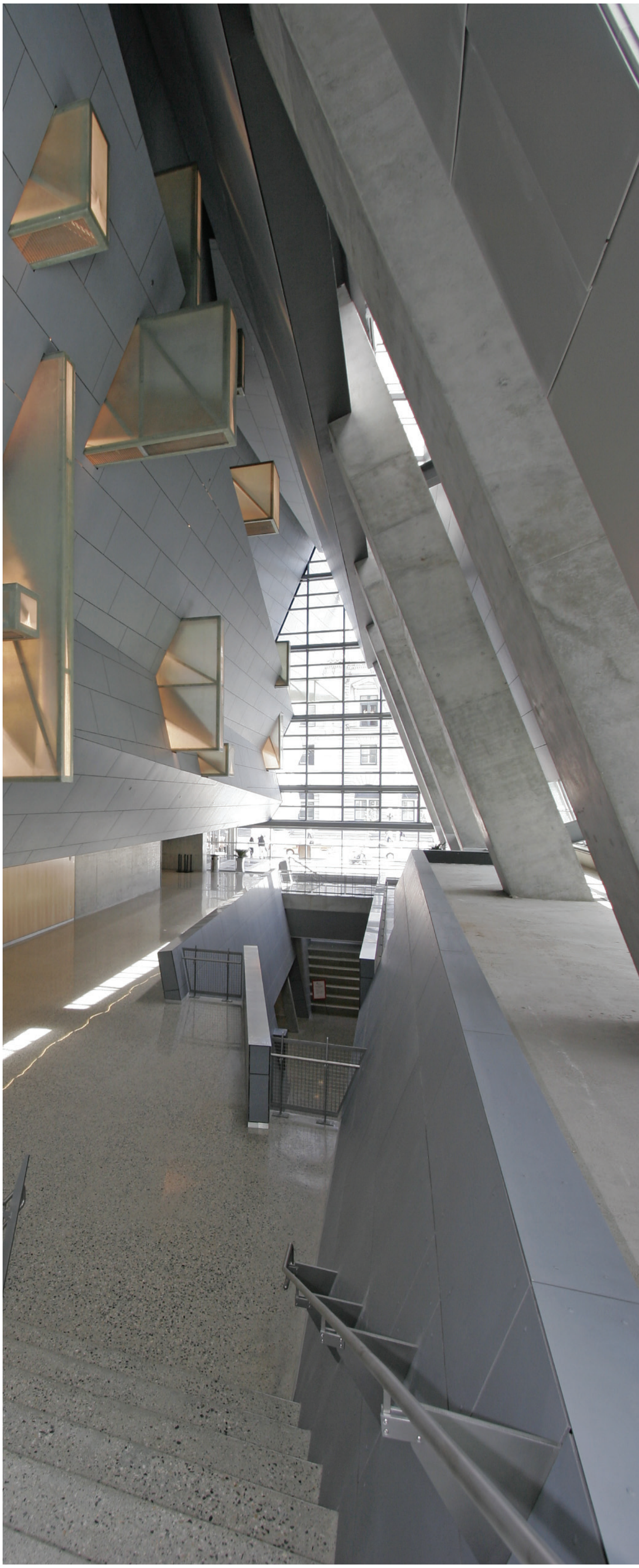


Photo courtesy of Andrew VanDis/Perfect Polish.

Chapter 20—Southface Energy Institute

Location: Atlanta, GA

Type: Commercial

Awards and certifications

- LEED Platinum
- Conserve Georgia Water Conservation Award

Structure specifics

This 8300 ft^2 (770 m^2) office building houses the Southface Energy Institute, which promotes sustainable development. As the Southface headquarters, the structure is intended to be a prominent showcase building to teach about environmentally friendly materials and design.

Sustainable concrete features

As part of the energy conservation strategy for the Eco Office, insulating concrete forms (ICFs) were used for the building walls. The ICF system helps reduce heating and cooling costs in the building through excellent insulation and a well-sealed building envelope. To reduce the heat island effect, a green roof supported on a concrete slab and light-colored pervious concrete hardscape are used. Both the green roof and pervious hardscape reduce stormwater runoff and help filter contaminants from water before it returns to the aquifer.

Both fly ash and slag cement were used for partial cement replacement in the concrete. These recycled by-product materials (from the coal and steel industries, respectively) not only reduce the CO_2 footprint of the building, but also improve the durability of the concrete.

The extensive use of concrete in the Southface Energy Institute is an example of the ways that concrete can contribute to sustainable design and construction and be a showcase of its versatility.

Green roof (*photo courtesy of Lord, Aeck & Sargent Architecture*).

Photo courtesy of Jonathan Hillyer Photography Inc.

Above renderings courtesy of Lord, Aeck & Sargent Architecture.

Placing the pervious concrete sidewalk
(photo courtesy of American Concrete Institute).

Chapter 21—University of Minnesota Duluth Labovitz School of Business and Economics

Location: Duluth, MN

Type: Institutional

Awards and certifications

- LEED Gold

Structure specifics

This 65,000 ft^2 (6000 m^2) building houses the Labovitz School of Business and Economics at the University of Minnesota Duluth (UMD). It includes classrooms, laboratories, offices, a large auditorium, and public gathering spaces. It connects directly to neighboring buildings on campus to minimize loss of heat (and to increase the comfort of students and others moving between buildings in the cold climate). The building was the first new public higher education building in Minnesota to be LEED certified.

Sustainable concrete features

Concrete is used both for the structural members and for aesthetic consideration throughout the building. Classrooms and offices are organized around a large three-story common area that is lit by large skylights. The use of glass for daylighting is extensive throughout the building, providing excellent harvesting of diffused sunlight without excess heat or glare (and the benefit of Lake Superior views). The exposed concrete throughout the building provides the thermal mass to work in conjunction with the large areas of glass to regulate building temperatures. Large, three-story concrete columns in the atrium are both visually stunning and excellent collectors of solar heat.

The exterior offices and classrooms are shielded from unwanted sunlight through concrete overhangs (coated with weathering steel to blend with the architectural theme of the campus and iron mining roots of the region).

All photos courtesy of Schokker.

Chapter 22—San Francisco Public Utilities Commission Building

Location: San Francisco, CA

Type: Civic office building

Awards and certifications

- Seeking LEED Platinum

Structure specifics

This concrete office building has 14 stories above grade and one additional story below grade for a total of 277,000 ft^2 (26,000 m^2). The building was designed to be one of the most energy efficient buildings of its type in the U.S.

General sustainable features include a raised floor system with under-floor air distribution, greywater recycling, photovoltaic panels, and wind turbines mounted within a wind-accelerating airfoil structure. Building information modeling (BIM) and virtual building (VB) tools were used to analyze design options, consider material changes, and measure system performance to help select materials that reduce the carbon footprint.

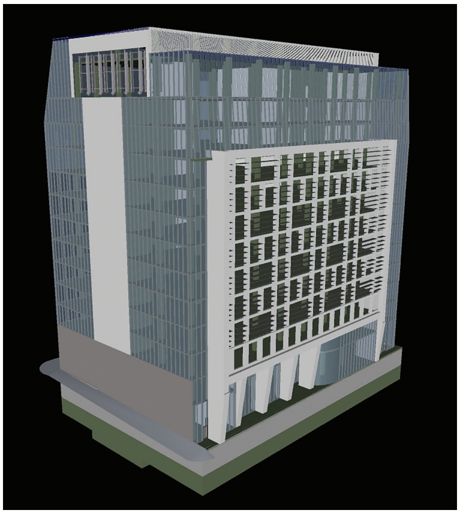
Sustainable concrete features

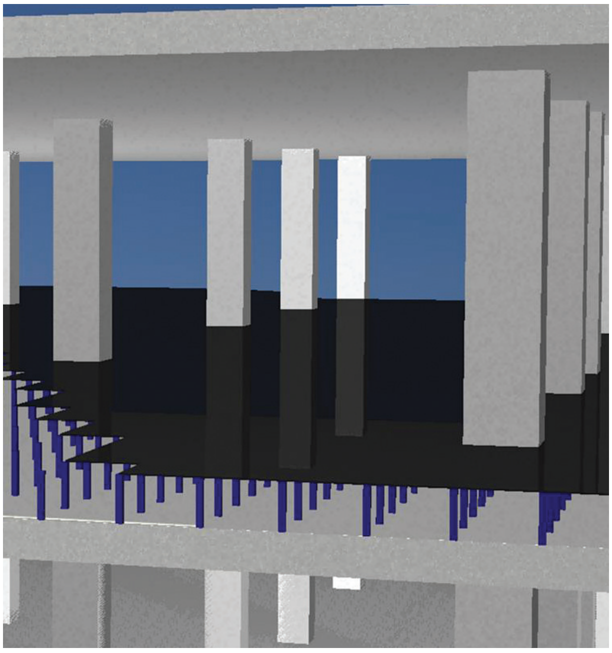
The San Francisco Public Utilities Commission (SFPUC) building has a significantly reduced carbon footprint through efficient and sustainable use of concrete. Vertical post-tensioning throughout the building core provides a 30% reduction in concrete and reinforcement over a traditional concrete system. The concrete mixture design includes both fly ash and slag cement to achieve the required material performance with reduced carbon impact. Exposed concrete finishes are used in the building, eliminating the need for additional finishing materials.

Concrete throughout the building provides the benefits of thermal mass to reduce energy demand for heating and cooling. Additionally, the concrete structural decking and the under-floor air distribution also reduce operational energy needs. The building's façade and long-span concrete decks allow daylight to penetrate deep into the interior of the building, providing natural light for workers in the building.

While both concrete and steel structures can be designed to effectively resist seismic forces, the SFPUC building's concrete post-tensioned building system was designed to withstand a seismic event with only minor system repairs rather than significant system replacement. The vertical post-tensioning provides a "self-healing" scenario in which energy is dissipated during the seismic event, but then the active compressive force in the concrete provided by the post-tensioning helps return the system to its original configuration after the seismic event.

Rendering courtesy of KMD Architects.





Renderings above courtesy of Webcor Builders.

Chapter 23—Premier Beverage Distribution Warehouse and Office Building

Location: Tampa, FL

Type: Industrial and office building

Awards and certifications

- Seeking LEED Silver
- NAIOP (Commercial Real Estate Development Association)
  - Outstanding Industrial Building, Hillsborough County, FL
  - Broker Deal of the Year—Industrial

Structure specifics

The building consists of a 520,000 ft^2 (48,000 m^2) warehouse (800 x 650 ft [74 x 60 m^2]) and a two-story, 50,000 ft^2 (4600 m^2) office building (86 x 300 ft [8 x 28 m]). The facility houses sophisticated material-handling systems for beverage distribution, including a 60,000 ft^2 (5600 m^2) climate-controlled area for fine wines. More than 9000 cases of spirits are processed, checked, and shipped per hour from this facility.

The structure includes tilt-up concrete exterior walls, structural steel roof framing, reflective white thermoplastic polyolefin (TPO) roof, an early suppression fast response (ESFR) fire suppression system, redundant power systems, air rotation units for warehouse conditioning in the wine area, a chilled water system central plant, and a dock with a 37 ft (11 m) clear height.

The initial LEED goal was a Certified designation, but the project is currently scheduled to receive a Silver designation that will make it the largest LEED Silver industrial building in the Southeast. The status upgrade from Certified to Silver was achieved with minimum financial outlay, even with the challenges of an industrial project site that is nearly 100 acres (400,000 m^2).

Sustainable concrete features

The exterior walls consist of 30 ft (9 m) wide concrete tilt-up wall panels that minimize the number of joints needed, thus reducing joint sealant usage and increasing air tightness. The concrete walls provide the load-bearing support for the interior steel structure, eliminating the need for perimeter columns. The walls were produced locally, and no additional finish was needed, including the area where the walls are adjacent to the office space (and no additional materials were needed for fire rating). Traditional tilt-up wall panels without an insulating layer are sufficient to meet the energy needs of the unconditioned Florida warehouse space.

Durability was a significant factor in choosing concrete for an extra-wide (800 x 80 ft [74 x 24 m]) truck apron. The office building's main plaza entry was specified as decorative concrete for durability, ease of maintenance, and aesthetic appeal. Concrete mixtures chosen for the project included fly ash as partial cement replacement, which further reduced the carbon footprint.

Photo courtesy of R. R. Simmons.

A construction waste management plan was implemented at the start of construction of the Premier Beverage project, which resulted in 1000 tons (909 mt) of concrete being redirected back to the manufacturing process (an overall 76% diversion rate). The recycling program was closely monitored by a team of on-site project superintendents, and included education of the trade subcontractors and weekly reinforcement of goals. Additionally, all concrete trucks were required to dispose of washout concrete in bins.

Photos courtesy of R. R. Simmons.

APPENDIX A—
THERMAL MASS EXAMPLE

Thermal mass by the numbers

It is informative to take a look at thermal mass data collected from concrete wall specimens as an aid in understanding the effect of thermal mass in magnitude and in principle. Table A.1 summarizes data that compares measured energy and calculated energy (heat transfer) from a study by VanGeem et al. (1983). The data is from a normal concrete wall that is 8 ft 6 in. x 8 ft 6 in. (2.6 x 2.6 m) in surface area and 8 in. (200 mm) thick (actual measured thickness of 8.31 in. [211 mm]). The wall was tested in a calibrated hot box with temperatures cycling over a 24-hour period in one-half of the box (the simulated outside air temperature), and temperatures held on the other side of the box (the simulated inside) at 71 to 73°F (22 to 23°C). The simulated outside temperatures (t_o) ranged from a high of 99°F (37°C) at 4 hours, to a low of 43°F (6°C) at 19 hours of the 24-hour cycle. Figure A.1 shows a plot of the measured data compared with a direct calculation of heat transfer that ignores thermal mass effects; in other words, the actual heat transferred versus what the designer counted on having transferred. The green shaded area represents the total heat flow calculated, ignoring thermal mass, and the red shaded area represents the measured heat flow, including thermal mass. The total thermal energy calculated for the 24-hour period shown is 2522 Btu (2660 kJ) versus 1071 Btu(1130 kJ) actual (measured). This difference of 1451 Btu (1530 kJ) (42% difference) would have a substantial effect on the energy needed to heat the interior of the structure. Additional savings can also result in the time lag that places the peak temperature during an off-peak time when energy costs are lower.

Notation and equations used:

$$Q_{ss} = \frac{C \cdot A \cdot (t_2 - t_1)}{3.413} \text{ in units of watt hours per hour}$$

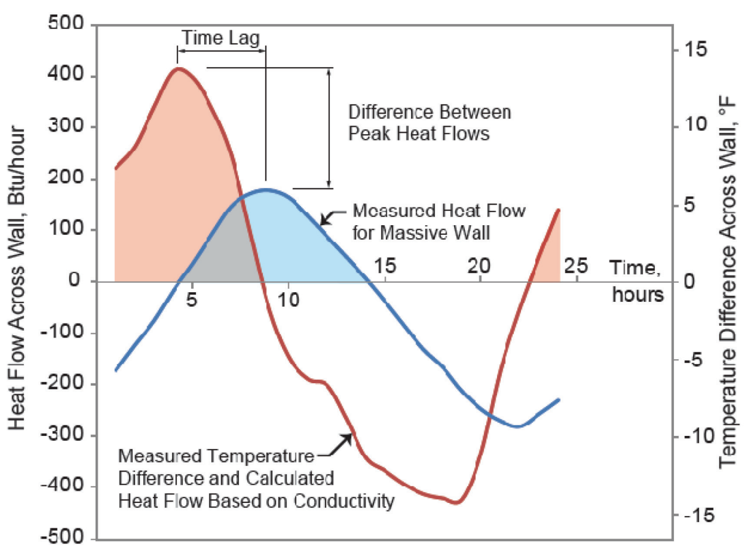
where

Q_{ss} is the net energy based on steady-state predictions, W • hr/hr or Btu/hr; A is the area of wall surface normal to heat flow, ft^2; C is the average thermal conductance, Btu/(hr • ft^2 • °F); t_2 is the average temperature of outside wall surface, °F; t_1 is the average temperature of inside wall surface, °F; and 3.413 is the conversion factor from W • hr/hr to Btu/hr.

Table A.1—Thermal mass data

Time, hours	t_0, °F*	t_2, °F	t_1, °F	ΔT, °F†	Q_{ss}, Btu/hour	Q_w, Btu/hour‡
1	87.2	77.61	70.26	7.35	223	-171
2	89.81	79.85	71.09	8.76	266	-121
3	95.21	83.21	71.91	11.3	343	-74
4	99.21	86.38	72.76	13.62	414	-15
5	97.26	86.84	73.63	13.21	401	37
6	92.82	85.64	74.45	11.19	340	94
7	86.62	83.25	75.07	8.18	249	148
8	75.64	78.56	75.43	3.13	95	173
9	66.29	73.68	75.49	-1.81	-55	179
10	61.14	70.31	75.16	-4.85	-147	165
11	59.21	68.37	74.63	-6.26	-190	129
12	58.78	67.33	73.99	-6.66	-202	89
13	53.18	64.53	73.37	-8.84	-269	49
14	48.26	61.41	72.73	-11.32	-344	8
15	46.96	59.82	72	-12.18	-370	-37
16	45.05	58.22	71.27	-13.05	-397	-84
17	43.96	56.9	70.59	-13.69	-416	-130
18	43.49	56	69.96	-13.96	-424	-165
19	43.45	55.34	69.38	-14.04	-427	-211
20	51.67	57.84	68.87	-11.03	-335	-246
21	63.12	62.86	68.56	-5.7	-173	-269
22	70.48	66.83	68.58	-1.75	-53	-280
23	76.7	70.49	68.91	1.58	48	-256
24	82.57	74.1	69.43	4.67	142	-229

*t_0 = outdoor air temperature; †$\Delta T = t_2 - t_1$, °F; ‡Q_w = measured net energy, W × hr/hr or Btu/hr; temperature in °C = (Temperature in °F – 32) × (5/9)
Note: 1 Btu = 1.055 kJ.



1 Btu = 1.055 kJ
°C = °F x (5/9)

Fig. A.1—Measured versus calculated heat transfer data for an 8 in. (200 mm) concrete wall.

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