CHAPTER 1

Introduction to Concrete

Concrete’s versatility, durability, sustainability, and economy have made it the world’s most widely used construction material. The term concrete refers to a mixture of aggregates, usually sand, and either gravel or crushed stone, held together by a binder of cementitious paste. The paste is typically made up of portland cement and water and may also contain supplementary cementing materials (SCMs), such as fly ash or slag cement, and chemical admixtures (Figure 1-1).

Figure 1-1. Concrete components: cement, water, coarse aggregate, fine aggregate, supplementary cementing materials, and chemical admixtures.

Understanding the basic fundamentals of concrete is necessary to produce quality concrete. This publication covers the materials used in concrete and the essentials required to design and control concrete mixtures for a wide variety of structures.

Industry Trends

The United States uses about 180 million cubic meters (248 million cubic yards) of ready-mixed concrete each year. It is used in highways, streets, parking lots, parking garages, bridges, high-rise buildings, dams, homes, floors, sidewalks, driveways, and numerous other applications (Figure 1-2).

Figure 1-2. Concrete is used as a building material for many applications including high-rise (top) and pavement (bottom) construction.
The cement industry is the building block of the nation’s construction industry (Figure 1-3). Few construction projects are viable without utilizing cement-based products geographically. U.S. cement production is widely dispersed with the operation of 97 cement plants in 36 states. The top five companies collectively operate around 97% of U.S. clinker capacity with the largest company representing around 15% of all domestic clinker capacity. An estimated 80% of U.S. clinker capacity is owned by companies headquartered outside of the U.S. (PCA 2010).

Cement Consumption

In 2009, the United States consumed 68.4 million metric tons (75.2 million tons) of Portland cement (PCA 2010). Cement consumption is dependent on the time of year and prevalent weather conditions. Nearly two-thirds of U.S. cement consumption occurs in the six month period between May and October. The seasonal nature of the industry can result in large swings in cement and clinker (unfinished raw material) inventories at cement plants over the course of a year. Cement producers will typically build up inventories during the winter and then ship them during the summer.

Concrete is used as a building material in the applications listed in Table 1-1. The apparent use of Portland cement by market is provided for 2009 in Figure 1-5. The primary markets (Figure 1-7) are described further in the following sections.

Table 1-1. Markets and Applications for Concrete as a Building Material

<table>
<thead>
<tr>
<th>Market</th>
<th>Applications</th>
<th>Cement Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bridges</td>
<td>Concrete is used for bridges, decks, and</td>
<td>High</td>
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<tr>
<td></td>
<td>piers</td>
<td></td>
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<tr>
<td>Buildings</td>
<td>Residential, commercial, institutional,</td>
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<td></td>
<td>institutional and institutional</td>
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<tr>
<td>Masonry</td>
<td>Masonry for scenic, ornamental, and</td>
<td></td>
</tr>
<tr>
<td></td>
<td>commercial use</td>
<td></td>
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<tr>
<td>Parking Lots</td>
<td>Concrete used for parking lots</td>
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<tr>
<td>Pavements</td>
<td>Pavements used for streets, roads, and</td>
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<tr>
<td></td>
<td>highways</td>
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<tr>
<td>Residential</td>
<td>Concrete used for residential dwellings</td>
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<tr>
<td>Transit and Rail</td>
<td>Concrete used for transit and rail</td>
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</tr>
<tr>
<td>Soil Cement and Roller-Compacted Concrete</td>
<td>Concrete used for roller compacted</td>
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<tr>
<td>Waste Remediation</td>
<td>Waste remediation uses</td>
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<tr>
<td>Water Resources</td>
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</table>

Concrete pavements have been a mainstay of America’s infrastructure for well over 100 years. The country’s first concrete street (built in Bellefontaine, Ohio, in 1891), is still in service today. Concrete can be used for new pavements, reconstruction, resurfacing, restoration, or rehabilitation. Concrete pavements generally provide the longest life, least maintenance, and lowest life-cycle cost of all alternatives. A variety of cement-based products can be used in pavement applications including soil-cement, roller-compact concrete, cast-in-place slabs, pervious concrete, and white-top, and more. They all contain the three basic components of Portland cement, silica, aggregates, and water.

While concrete pavements are best known as the riding surface for interstate highways, concrete is also a durable, economical, and sustainable solution for rural roadways, residential and city streets, intersections, airports, intermodal facilities, military bases, parking lots and much more.

Bridges

More than 70% of the bridges throughout the U.S. are constructed of concrete. These bridges perform year-round in a wide variety of climates and geographic locations. With long life and low maintenance, concrete consistently outperforms other materials as a choice for bridge construction. A popular method to accelerate bridge construction is to use prefabricated systems and elements. These are fabricated off-site or adjacent to the actual bridge site ahead of time, and then moved into place as needed, resulting in a shorter duration for construction. Very frequently, these systems are constructed with concrete – reinforced, pretensioned, or post-tensioned (or a combination thereof).

Engineered to meet specific needs, high-performance concrete (HPC) is often used for bridge applications including: high-durability mixtures, high-strength mixtures, self-consolidating concrete, and ultra-high performance concrete.

Buildings

Reinforced concrete construction for high-rise buildings provides inherent stiffness, mass, and ductility. Occupants of concrete towers are less likely to perceive building motions than occupants of comparable tall buildings with non-structural systems. A major economic consideration in high-rise construction is reducing the floor to floor height. Using a reinforced concrete flat plate system, the floor to floor height can be minimized while still providing high floor to ceiling heights. As a result, concrete has become the material of choice for many tall, slender towers.

The first reinforced concrete high-rise was the 16-story Ingalls Building, completed in Cincinnati in 1903. Greater building height became possible as concrete strength increased. In the 1950s, 34 kPa (5000 psi) was considered high strength; by 1990, two high-rise buildings were constructed in Seattle using concrete with strengths of up to 131 MPa (19,000 psi). Ultra-high-strength concrete is now manufactured with strengths in excess of 150 MPa (21,750 psi).

Slightly more than half of all low-rise buildings in the United States are constructed from concrete. Designers select concrete for one-, two-, and three-story stores, restaurants, schools, hospitals, commercial warehouses, terminals, and industrial buildings because of its durability, excellent acoustic properties, inherent fire resistance, and ease of construction. In addition, concrete is often the most economical choice: load-bearing concrete exterior walls serve not only to enclose the building and keep out the elements, but they also carry roof, wind, and seismic loads, eliminating the need to erect separate systems.

Four concrete construction methods are commonly used to create load-bearing walls for low-rise construction: tilt-up, precast, concrete masonry, and cast-in-place. Traditionally, precast and concrete masonry construction were the standard for low-rise construction. In recent years builders have increasingly used tilt-up construction techniques to erect low-rise commercial buildings quickly and economically.
Examples of early Roman concrete have been found dating back to 300 BC. The very word concrete is derived from the Latin word "concretus" meaning grown together or compounded. The Romans perfected the use of pozzolan as a cementing material. This material was used by builders of the famous Roman walls, aqueducts, and other historic structures including the Theatre at Pompeii, Pantheon, and Colosseum in Rome (Figure 1-8). Building practices were much less refined in the Middle Ages and the quality of cementing materials deteriorated.

Figure 1-8. Colosseum in Rome, completed in 80 AD, was constructed of concrete. Much of it still stands today (Courtesy of J. Caetani).

The practice of burning lime and the use of pozzolan was last until the 1900s. In the 18th century, John Smeaton concentrated his work to determine why some limes possess hydraulic properties while others (those made from essentially pure limestones) did not. He discovered that an impure, soft limestone containing clay minerals made the best hydraulic cement. This hydraulic cement, combined with a pozzolan imported from Italy was used in the reconstruction of the Eddystone Lighthouse in the English Channel, southwest of Plymouth, England (Figure 1-9). The project took three years to complete and began operation in 1759. It was recognized as a turning point in the development of the cement industry.

A number of discoveries followed as efforts within a growing natural cement industry were directed to the production of a consistent quality material. Natural cement was manufactured in Roseendale, New York, in the early 1800s (White 1820). One of the first uses of natural cement was to build the Erie Canal in 1818 (Snell and Snell 2000).

The development of portland cement was the result of persistent investigation by science and industry to produce a superior quality natural cement. The invention of portland cement is generally credited to Joseph Aspdin, an English mason. In 1824, he obtained a patent for a product which he named portland cement. When set, Aspdin’s product resembled the color of the natural limestone quarried on the Isle of Portland in the English Channel (Aspdin 1824). The name has endured and is now used throughout the world, with many manufacturers adding their own trade or brand names.

Aspdin was the first to prescribe a formula for portland cement and the first to have his product patented (Figure 1-10). However, in 1845, J.C. Johnson, of White and Sons, Swanscombe, England, claimed to have “burned the cement raw materials with unusually strong heat until the mass was nearly vitrified,” producing a portland cement as we now know it. This cement became the popular choice during the middle of the 19th century and was exported from England throughout the world. Production also began in Belgium, France, and Germany about the same time and export of these products from Europe to North America began about 1855. The first recorded shipment of portland cement to the United States was in 1868. The first portland cement manufactured in the United States was produced at a plant in Coplay, Pennsylvania, in 1871.
Essentials of Quality Concrete

The performance of concrete is related to workmanship: mix proportions, material characteristics, and adequacy of curing. Each of these will be discussed throughout this publication. The production of quality concrete involves a variety of materials and a number of different processes, including the production and testing of raw materials (Chapters 3-8); determining the desired properties of concrete (Chapters 9-11); proportioning of concrete constituents to meet the design requirements (Chapter 12); batching, mixing, and handling to achieve consistency (Chapter 13); proper placement, finishing, and adequate consolidation to ensure uniformity (Chapter 14); proper maintenance of moisture and temperature conditions to promote strength gain and durability (Chapters 15-17); and finally, testing for quality control and evaluation (Chapter 18).

Many people with different skills come in contact with concrete throughout its production. Ultimately, the quality of the final product depends on their workmanship. It is essential that the work force be adequately trained for this purpose. When these factors are not carefully controlled, they may adversely affect the performance of the fresh and hardened properties.

Suitable Materials

Concrete is basically a mixture of two components: aggregates and paste. The paste, comprised of Portland cement and water, binds the aggregates (usually sand and gravel or crushed stone) into a rocklike mass as the paste hardens from the chemical reaction between cement and water (Figure 1-11). Supplementary cementitious materials and chemical admixtures may also be included in the paste.

Figure 1-10. Japson's patent for portland cement.

Sustainable Development

Concrete is the basis of much of civilization's infrastructure and much of its physical development. Twice as much concrete is used throughout the world than all other building materials combined. It is a fundamental building material to municipal infrastructure, transportation infrastructure, office buildings, and homes. And, while cement manufacturing is resource- and energy-intensive, the characteristics of concrete make it a very low-impact construction material, from an environmental and sustainability perspective. In fact, most applications for concrete directly contribute to achieving sustainable buildings and infrastructure that are discussed in Chapter 2.

Figure 1-11. Concrete constituents include cement, water, and coarse and fine aggregates.

Figure 1-12. Rise in proportions of materials used in concrete, by absolute volume.

The paste may also contain entrained air or purposely entrained air. The paste constitutes about 25% to 40% of the total volume of concrete. Figure 1-12 shows that the absolute volume of cement is usually between 7% and 15% and the water between 14% and 21%. Air content in air-entrained concrete ranges from about 4% to 8% of the volume.

Aggregates are generally divided into two groups: fine and coarse. Fine aggregates consist of natural or manufactured sand with particle sizes ranging up to 9.5 mm (3/8 in.); coarse aggregates are particles retained on the 1.18 mm (No. 16) sieve and ranging up to 150 mm (6 in.) in size. The maximum size of coarse aggregate is typically 19 mm or 25 mm (3/4 in. or 1 in.). An intermediate-sized aggregate, around 9.5 mm (3/8 in.), is sometimes added to improve the overall aggregate gradation.

Since aggregates make up about 60% to 75% of the total volume of concrete, their selection is important. Aggregates should consist of particles with adequate strength and resistance to exposure conditions and should not contain materials that will cause deterioration of the concrete. A continuous aggregategradation of aggregate particle sizes is desirable for efficient use of the paste.

The freshly mixed (plastic) and hardened properties of concrete may be changed by adding chemical admixtures to the concrete, usually in liquid form, during batching. Chemical admixtures are commonly used to (1) adjust setting time or hardening, (2) reduce water demand, (3) increase workability, (4) intentionally entrain air, and (5) adjust other fresh or hardened concrete properties.

The quality of the concrete depends upon the quality of the paste and aggregate and the bond between the two. In properly made concrete, each particle of aggregate is completely coated with paste and all of the spaces between aggregate particles are completely filled with paste, as illustrated in Figure 1-13.
Unnecessarily high water content dilutes the cement paste (the glue of concrete) and increases the volume of the concrete produced (Figure 1-14). Some advantages of reducing water content include:

- Increased compressive and flexural strength
- Lower permeability and increased watertightness
- Increased durability and resistance to weathering
- Better bond between concrete and reinforcement
- Reduced drying shrinkage and cracking
- Less volume change from wetting and drying

The less water used, the better the quality of the concrete provided the mixture can still be consolidated properly. Smaller amounts of mixing water result in stiffer mixtures; with vibration, stiffer mixtures can be more easily placed. Thus, consolidation by vibration permits improvement in the quality of concrete.

![Figure 1-14: Ten cement paste cylinders with water-cement ratios from 0.25 to 0.70. The band indicates that each cylinder contains the same amount of cement. Increased water dilutes the effect of the cement paste, increasing volume, reducing density, and lowering strength.](image)

Reducing the water content of concrete, and thereby reducing the w/c, leads to increased strength and stiffness, and reduced creep. The drying shrinkage and associated risk of cracking will also be reduced. The concrete will have a lower permeability or increased water tightness that will render it more resistant to weathering and the actions of aggressive chemicals. The lower water to cementitious materials ratio also improves the bond between the concrete and embedded steel reinforcement.

**Molding**

To ensure that the components of concrete are combined into a homogeneous mixture requires effort and care. The sequence of changing ingredients into a concrete mixer can play an important part in uniformity of the finished product. The sequence, however, can be varied and still produce a quality concrete. Different sequences require adjustments in the time of water addition, the total number of revolutions of the mixer drum, and the speed of revolution. Other important factors in mixing are the size of the batch in relation to the size of the mixer drum, the elapsed time between batching and mixing, and the design, configuration, and condition of the mixer drum and blades. Approved mixers, correctly operated and maintained, ensure an end-to-end exchange of materials by a rolling, folding, and kneading action of the batch over itself as concrete is mixed.

Concrete must be thoroughly mixed until it is uniform in appearance and all ingredients are evenly distributed through the mixture. If a concrete has been adequately mixed, samples taken from different portions of the batch will have essentially the same density, air content, slump, and coarse aggregate content.

**Transporting**

Concrete must be transported to the site and placed within a reasonable time frame once it leaves the batch plant. ASTM C 94, Standard Specification for Ready-Mixed Concrete (AASTHO M 157)*), requires that the concrete be delivered and placed within 90 minutes after the addition of water to the mixture (when hydration begins) to meet the desired setting and hardening properties, and within 300 revolutions of the mixing drum to prevent segregation and shearing of the aggregate.

**Placement and Consolidation**

Concrete can be placed by a variety of means such as direct chute discharge from a truck mixer or using a power buggy or wheelbarrow for easily accessible, smaller jobs. For more restrictive locations, concrete can be placed by crane and bucket or even helicopter and bucket when necessary. Also, concrete pumps and conveyors allow for placement of concrete over long distances and otherwise inaccessible heights. Specialty applications include placement by a screw spreader for pavement applications, slipforming, and underwater tremie. Selection of the appropriate placement method is dependent on the application, mix design, crew size, service environment, and economy. The contractor should determine the best placement method based on all these considerations.

Once placed, concrete must be adequately consolidated to mold it within the forms and around embedded items and reinforcement. Internal vibrators are commonly used in walls, columns, beams, and slabs. Vibrating screens may be used on the surface of slabs or pavements. Form vibrators may be used on columns and walls where dimensions and congested reinforcement restrict the use of internal vibration.

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*Many ASTM Standards include metric designations for example ASTM 0341(341M). For brevity, these designations are omitted throughout this text. Refer to the Appendix for full ASTM Standard designations.

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Finishing and Jointing

After concrete has been placed, consolidated, and screeded to remove excess concrete, the exposed surfaces require finishing. Finishing involves floating the surface to embed aggregate particles just beneath the surface, to remove slight imperfections in the surface and to compact the mortar at the surface. After floating, interior slabs may be traveled to create a hard dense surface. The surface may require texturing by brooming to produce a slip-resistant surface. Concrete pavements are frequently textured by tiling the surface with stiff wire (this improves traction and reduces hydroplaning).

Slabs or grade may require jointing to provide for movement and to aid in crack prevention due to drying and thermal shrinkage. Joints are cut to induce cracks at predetermined locations. Cuts are formed in the surface by using either hand tools when the concrete is still plastic, or diamond saws after the concrete has hardened sufficiently.

**Hydration and Curing**

Hydration begins as soon as cement comes in contact with water. Each cement particle forms a fibrous growth on its surface that gradually spreads until it links up with the growth from other cement particles or adheres to adjacent substances. This fibrous buildup results in progressive stiffening, hardening, and strength development. The stiffening of concrete can be recognized by a loss of workability that usually occurs within three hours of mixing, but is dependent upon the composition and fineness of the cement, any admixtures used, mixture proportions, and test conditions. Subsequently, the concrete sets and becomes hard.

Hydration continues as long as favorable moisture and temperature conditions exist and space for hydration products is available. As hydration continues, concrete becomes harder and stronger. Most of the hydration and strength development take place within the first month, but then continues slowly for a long time with adequate moisture and temperature. Continuous strength increase exceeding 30 years have been recorded (Yoshia and Wendi 1975 and Wood 1992).

Curing is the maintenance of a satisfactory moisture content and temperature so that the desired properties may develop. When the relative humidity within the concrete drops to about 80%, or the temperature of the concrete drops below freezing, hydration and strength gain virtually stop. If the concrete is allowed to freeze before sufficient strength is obtained it may be irreparably damaged. Concrete should not be exposed to freezing temperatures until it has achieved sufficient strength. Curing should begin immediately following finishing procedures and may also be conducted during placement operations to prevent rapid surface evaporation.

**Design-Workmanship-Environment**

Concrete structural work can withstand a variety of loads and may be exposed to many different environments such as exposure to seawater, dicing salts, sulfate-bearing soils, abrasion and cyclic wetting and drying. The materials and proportions used to produce concrete will depend on the loads it is required to carry and the environment to which it will be exposed. Properly designed and built concrete structures are strong and durable throughout their service life.

After completion of proper proportioning, batching, mixing, placing, consolidating, finishing, and curing, concrete hardens into a strong, noncorrosible, durable, abrasion resistant, and watertight building material that requires little or no maintenance. Furthermore, concrete is an excellent building material because it can be formed into a wide variety of shapes, colors, and textures for use in an unlimited number of applications. Some of the special types of concrete, including high-performance concrete, are covered in Chapters 19 and 20.
CHAPTER 2
Sustainability

Introduction to Sustainability

Contemporary engineering, architecture, and building practices are increasingly moving toward the goal of sustainable development. In alignment with growing public awareness, manufacturers of goods and services are incorporating products and processes that reduce energy use, costs, and pollution while aiming to enhance the social value of the sector. The built environment has a significant impact on energy consumption, water and material use, and waste generation (EPA 2009). Those that create the built environment are in a unique position to take the lead and effect transformative positive changes in all areas of sustainable development.

In the pioneering report of the World Commission on Environment and Development (WCED), Our Common Future (WCED 1987), sustainable development is defined as:

"Meeting the needs of the present generation without compromising the ability of future generations to meet their needs."

Figure 2-1. The concept of sustainability is supported by a balance of social, economic, and environmental principles.
manufacturing processes (see Chapter 5 for information on water conservation in concrete production).

Site Selection and Development
The focus on site selection and site development is intended to minimize the impact of all development by encouraging the reuse of existing sites, optimal occupant density (high-rise versus low-rise construction), preservation of natural habitats, water management, and heat island mitigation. These provisions tend to be equally applicable to both the transportation and building sectors.

Indoor Environments Quality
The intent of indoor environmental quality criteria is to improve occupants' health, comfort and productivity. The focus tends to be on off-gassing from building products and finishes; particulate matter reduction; thermal comfort; lighting; and use of suitable cleaning agents. Although not presently addressed in most national certification programs and standards, consideration is also directed to exterior environmental air quality related to construction practices.

Material Quality and Resources
Material resources criteria tend to focus on landfill avoidance by encouraging pre- and post-consumer content in construction materials where and construction waste minimization. For buildings, this is accomplished by providing adequate facilities to accommodate recycling and reuse of consumer products, appliances, and equipment.

Construction systems intended to be used for sustainable construction should require minimal frequencies for routine maintenance, repair, and replacement. The impacts of maintenance repair and replacement concern more than just the construction materials. Sometimes the larger impact will be the additional energy use to maintain, repair and replace, or the interruption in service and operations.

The provisions in most currently available programs do not adequately address pollution prevention at the points of harvesting, processing, manufacturing, and assembling products. Enforcement considerations are broadened by encouraging the use of locally or regionally available (indigenous) material to minimize fossil fuel consumption necessary to transport materials.

Functional Resilience
Functional resilience extends beyond material quality and resources. The key sustainability concept of functional resilience is to provide new construction that has adequate longevity for continued use and is readily adaptable to future use. Concepts of functional resilience include robustness, durability, enhanced disaster resistance, and longevity of which some components have been referred to as passive survivability. These criteria are often satisfied by exceeding the minimum requirements through design and construction that is more resistant to damage from floods, high wind events, earthquakes, fires, hail, frost, and other catastrophic events.

Rating Systems
Several organizations have developed rating systems that attempt to quantify improvements in green performance. For example, the United States Green Building Council (USGBC) developed and launched a simplified rating system titled Leadership in Energy and Environmental Design (LEED) in 1998. LEED encourages designers to select from a menu of green strategies with the intent of reducing environmental impacts of a project. LEED provides for four increasingly stringent levels of building certifications: silver, gold, and platinum. Following successful third party verification, the building becomes certified as constructed to one of these four levels of performance (www.leadnet.org). In 2004, the Green Building Initiative (GIB) distributed Green Globes® in the United States. Green Globes is a building guidance and assessment program that offers a way to advance the overall environmental performance and sustainability of commercial buildings (www.hpgib.org/green-globes). Today, work progresses to formalize sustainable construction strategies in building codes and standards.

Concrete and LEED
Concrete use can contribute credits in fifteen categories in the LEED for New Construction and Major Renovations (NC) 2009 system as summarized in Table 2-1. Although LEED-NC is the most commonly cited LEED product covering commercial structures, schools and core and shell construction of speculative buildings, LEED has similar rating systems for Neighborhood Development (ND), homes (HI), retail, healthcare, and existing buildings.

It is now common for some states and municipalities to require LEED silver certification for government owned buildings. Some jurisdictions have adopted LEED or other certification programs as part of their building code. The dilemma with such regulations is that LEED is not written in, and was never intended to serve as, mandatory code language. Further, many of the provisions in LEED and other certification programs, such as using slabs near mass transit facilities or redeveloped or brown fields, are outside the purview of the general building code.

Concrete Sustainability
Concrete structures are the basis for much of civilization's infrastructure. Each year, approximately four metric tons of concrete are used for every one of the nearly seven billion people on our planet (USGS 2009). Concrete is a fundamental building material for municipal and transportation infrastructure, office buildings, and homes. Buildings use concrete for their foundations, walls, columns and floors. Highways and bridges are built with concrete. Airports and rail systems use concrete. Our drinking water is delivered through concrete pipes from treatment plants made with concrete.

Ready-mix concrete and concrete-product manufacturers also strive to improve production processes and enhance transportation efficiency and delivery methods to reduce the environmental impact of the concrete production process, including the use of alternate energy sources. For example, the National Ready Mixed Concrete Association (NRMCA) is committed to promoting environmental stewardship within concrete plants through the NRMCA Green StartTM Certification Program. This program provides guidelines through the use of the environmental management systems that would ensure an environmentally friendly concrete plant (NRMCA 2010). The Massachusetts Institute of Technology (MIT) Concrete Sustainability Hub (CSH) was formed in 2009. The mission of CSH is to advance the technology transfer from concrete science into the engineering practice, by translating the synergy of three fields of study (engineering, architecture and planning, and management) into a powerful hub for concrete sustainability studies relevant to industry and decision makers (MIT 2010). As knowledge of sustainable development principles and practices advances, so do the techniques and strategies employed to achieve even greater efficiency and environmental impact reductions with concrete.

<table>
<thead>
<tr>
<th>Credit</th>
<th>Description</th>
<th>Points</th>
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<tbody>
<tr>
<td>Credit 3</td>
<td>Brownfield redevelopment</td>
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</tr>
<tr>
<td>Credit 5.1</td>
<td>Site development, protect or restore habitat</td>
<td>1</td>
</tr>
<tr>
<td>Credit 5.2</td>
<td>Site development, maximize open space</td>
<td>1</td>
</tr>
<tr>
<td>Credit 6.1</td>
<td>Stormwater design, quantity control</td>
<td>1</td>
</tr>
<tr>
<td>Credit 6.2</td>
<td>Stormwater design, quality control</td>
<td>1</td>
</tr>
<tr>
<td>Credit 7.1</td>
<td>Cool building materials, non-metal</td>
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<tr>
<td>Credit 7.2</td>
<td>Heat island effect, roof</td>
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<td>Energy and atmosphere (30 possible points in this credit category)</td>
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<tr>
<td>Credit 1</td>
<td>Optimize energy performance</td>
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<td>Materials and resources (14 possible points in this credit category)</td>
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<tr>
<td>Credit 11.1</td>
<td>Building reuse, maintain existing walls, floors, and roof</td>
<td>1–2</td>
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<tr>
<td>Credit 1.2</td>
<td>Building reuse, maintain existing interior non-structural elements</td>
<td>1–2</td>
</tr>
<tr>
<td>Credit 2</td>
<td>Construction waste management</td>
<td>1–2</td>
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<tr>
<td>Credit 4</td>
<td>Recycled content</td>
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<td>Credit 5</td>
<td>Regional materials</td>
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<td>Indoor environmental quality (15 possible points in this credit category)</td>
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<td>Credit 4.3</td>
<td>Low emitting materials – flooring systems</td>
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<td>LEED Certification levels: certified 40–49 points, silver 50–79 points, gold 80–110 points.</td>
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The following sections elaborate on the characteristics of concrete structures that contribute to its sustainability. The use of reinforced concrete is described in Chapter 11 of "Sustainable Design and Construction of Concrete Structures" (ACI 318-08). Durability Durability is the ability to resist weathering action, chemical attack, and abrasion while maintaining desired engineering properties. Concrete structures require different types of durability depending on the exposure environment and desired engineering properties, as discussed in Chapter 11. A durable material benefits the environment by conserving resources, reducing waste and environmental impacts related to repair and replacement.

The longevity of concrete structures is readily apparent. As the most widely used building material in the world, concrete structures have withstood the test of time for many years. For example, the Hoover Dam was completed in 1936, the Glenfinnan Viaduct in Scotland was completed in 1901, and the Pantheon in Rome was completed around 125 AD. All are still in use today. Depending on the application, the design service life of building interiors is often 30 years. However, the actual average life span for a building in the U.S. is 75 years, with 65% of buildings at 50 years. The concrete portion of structures often lasts 100 years longer. When properly designed, concrete structures can be reused or repurposed several times in the future. Reusing concrete buildings conserves future materials and resources and reduces the need for new structures may require.

The oldest concrete street in America was built in 1891 in Bellefontaine, Ohio and is still in use today. Long-life concrete pavements provide 30 years more of low maintenance service life. These pavements require less frequent repair and rehabilitation than competing materials and contribute to highway safety and congestion mitigation (Hall and others 2007). Reductions in traffic congestion reduce fuel consumption and related pollution from vehicles. Safety Safety is a significant social value when utilizing engineered concrete structures. Under proper conditions, safety can be achieved. The ACI 318 Building Code addresses the structural implications of sustainable development by supplying minimum design and construction requirements necessary to provide for public health and safety. ACI 318 also permits the use of environmentally responsible materials and provides durability requirements to enhance lifecycle considerations in sustainable design (ACI 318-08).

Disaster Resistance Properly designed reinforced concrete is resistant to storms, floods, fire, and earthquakes. These structures can also provide blast protection for occupants. The Federal Emergency Management Agency (FEMA) recognizes these attributes by promoting concrete safe rooms for providing occupants protection from natural disasters (FEMA 2008). Concrete structures provide greater functional resilience helping essential service providers housed in more robust fire and police stations, hospitals, and community shelters to continue operation after a disaster strikes. The long-term viability of private business operators can also benefit from functional resilience as well.

Tornado, Hurricane and Wind Resistance. Concrete is resistant to forces from high winds, hurricanes, and tornados (Figure 2-3). Compliance with the SSTO 30, Standard for Hurricane Resistant Construction can reduce the amount of damage observed in structures. Impact resistance of structures to tornado and hurricane debris missiles is tested using a 50 mm x 100 mm (2 in x 4 in.) piece of wood travelling at 45 m/s (100 mph) and weighing 6.8 kg (15 pounds) (FEMA 2008). When tested against 21 MPa (3000 psi) concrete walls as thin as 50 mm (2 in.), debris missiles shattered on impact without damaging the concrete (Kiesling and Carter 2005).

Fire Resistance. Noncombustible concrete buildings offer excellent fire resistance. As a separation wall, concrete helps to prevent a fire from spreading within a structure. As an exterior wall or roof, concrete helps to prevent a fire from involving other buildings. The fire endurance of concrete can be determined by its thickness and type of aggregate used by applying ACI Committee 216 procedures (ACI 216 2007).

Earthquake Resistance. In reinforced concrete construction, the combination of concrete and reinforcing steel provides the three most important properties for earthquake resistance: stiffness, strength, and ductility. Reinforced concrete walls work well because of the composite capabilities of materials within the structural system. Concrete resists compression forces, and reinforcing steel resists tensile forces produced by an earthquake. See Fanella (2007) or Cleland and Glash (2007) for a detailed summary of seismic design and detailing requirements.

Blast Resistance. Concrete can be designed to have improved blast-resistant properties (Smith, McCann, and Kansara 2009). Blast-resistant concrete often have a compressive strength exceeding 100 MPa (15,000 psi) and typically contain steel fibers. These structures are often used in bank vaults, military applications, and buildings requiring enhanced security.

Energy. Concrete can enhance overall energy performance in several applications. Structures made of exterior concrete envelope can use less energy to heat and cool than similarly insulated buildings with lighter weight wood- or steel-frame enclosures. Lower fuel consumption of vehicles traveling over rigid concrete pavement results in reductions in greenhouse gas emissions over the service life of a pavement. Moreover, use of concrete for pavements can help mitigate the urban heat-island effect, lowering ambient air temperatures. This can indirectly reduce the operational energy usage of urban buildings. In addition, indoor and outdoor lighting efficiency can be improved reducing energy costs through the use of more reflective concrete floors and rooftops. This efficiency also leads to increased safety in buildings and on pavements.

Thermal Mass. Thermal mass is a property that enables building materials to absorb, store, and later release significant amounts of heat. Buildings constructed of cast-in-place, tilt-up, precast, autoclaved aerated concrete, insulating concrete forms (ICFs) (Figure 2-3), or masonry possess thermal mass that helps moderate indoor temperature extremes and reduces peak heating and cooling loads. These materials absorb energy slowly and hold it for much longer periods than do less thermally massive materials. This slow absorption and release of energy delays and reduces heat transfer through the material contributing to three important results:

1. There are fewer spikes in the heating and cooling requirements, because the thermal mass slows the response time and moderates indoor air temperature fluctuations.

2. Thermal mass can shift energy demand off-peak time periods when utility rates are lower (Figure 2-4).

3. Incorporating thermal mass can lead to a reduction in HVAC equipment capacity, resulting in upfront cost savings.

The most energy is saved when significant reversals in heat flow occur within a wall during the day, in climates with large daily temperature swings and longer. Below the balance point of the building (13°C to 18°C [55°F to 65°F]), in many climates, these buildings have lower energy consumption than non-insulated buildings with walls of similar thermal resistance (Gaia 2001, Marcuse and VanGeen 2005).

Figure 2-3. Insulating concrete forms (ICFs) provide thermal mass and high levels of insulation, key components for net-zero energy use buildings.

Figure 2-4. Damping and peak effects of thermal mass (CIAG 2009).

ASHRAE Standard 90.1 (ASHRAE 2007), the International Energy Conservation Code (IECC 2009), and most other energy codes recognize the benefits of thermal mass and require less insulation for mass walls. Computer programs such as DOE-2 and EnergyPlus take into account the heat transfer on an annual basis, which allows for more accurate determination of energy loss in buildings with mass walls and roofs. For more detailed description of thermal mass performance and benefits, see Thermal Mass...
Explained (The Concrete Centre 2009). For more information on thermal mass modeling, see Marcenau and VanGeem (2003).

Fuel Consumption. Studies demonstrate the lower fuel consumption for vehicles traveling on concrete pavement. The improvement in fuel consumption for heavy trucks ranges from 1% to 11% (Zaniawski 1998 and Taylor and Patten 2006). Further study into the effect on smaller vehicles found that fuel consumption in city driving is reduced from 3% to 17% (Ardakani and Suminiasian 2010). Reducing fuel consumption results in lower greenhouse gas emissions than asphalt pavements.

Heat-Island Reduction. Heat islands are areas that have higher ambient air temperatures as compared to their surrounding areas. Studies have shown that urban environments are 2°C to 4°C (3°F to 7°F) warmer than adjacent areas and this temperature difference is attributed to the replacement of natural vegetation with buildings and pavements. The additional heat causes air-conditioning systems to work harder, which uses more energy, and promotes the formation of smog. For example, in Los Angeles, the probability of smog increases 5% with each degree Celsius temperature increase (3% with each degree Fahrenheit) for temperatures that rise above 24°C (75°F) (Gadja and VanGeem 2001). Maintaining temperatures below the 24°C (75°F) threshold improves outdoor air quality, minimizes health effects such as asthma, and helps reduce the use of air-conditioning systems (Figure 2-5).

Strategies to reduce the amount of dark horizontal surfaces include white-colored roofing, shade trees in parking lots, and lighter-colored surfaces for paving, parking lots, and sidewalks. Light-colored concrete materials have higher solar reflectance (also known as albedo) further reducing the heat-island effect.

Solar reflectance is the ratio of the amount of solar radiation reflected from a surface in comparison to the total amount of solar radiation reaching that surface. Ordinary portland cement concrete generally has a solar reflectance of approximately 0.35 to 0.45 (Table 2-2) although values can vary (Marcenau and VanGeem 2007). These values are predominantly a result of the light color of the cement paste. This value can decrease over time as the pavement collects dirt and the cement paste at the surface is abraded. Pressure washing of the surface can reduce much of the original reflectance. Surface finishing techniques and drying time also affect solar reflectance. Solar reflectance is most commonly measured using a solar reflectometer (ASTM C1549, Standard Test Method for Determination of Solar Reflectance Near Ambient Temperature Using a Portable Solar Reflectometer) or a pyranometer (ASTM E1918, Standard Test Method for Measuring Solar Reflectance of Horizontal and Low-Sloped Surfaces in the Field).

A composite index called the solar reflectance index (SRI) is used to estimate expected surface temperatures during exposure to full sun. The temperature of a surface depends on the surface's reflectance and emittance, as well as solar radiation. Emittance, also known as emissivity of a surface, is a measure of how efficiently a surface emits or releases heat. It is a value ranging from 0 to 1. Most opaque non-metallic materials encountered in the built environment (such as concrete and masonry) exhibit an emissivity of 0.85 to 0.95. A value of 0.90 is commonly assumed. The SRI is calculated using ASTM E1980, Standard Practice for Calculating Solar Reflectance Index of Horizontal and Low-Sloped Opaque Surfaces. The SRI is used to determine the effect of the reflectance and emittance on the surface temperature, and SRI values vary from 100 for a standard white surface to zero for a standard black surface. Materials with the highest SRI are the coolest and the most appropriate choice for mitigating the heat-island effect.

New concrete without added pigments has an SRI value greater than 29, the threshold value required for hard- scape in most green building standards and rating systems (Marcenau and VanGeem 2007).

Lighting Efficiency. Ordinary concrete and other reflective surfaces reduce energy costs associated with indoor and outdoor lighting compared to darker and less reflective materials. The more reflective surfaces have a higher brightness, which allows for a reduction in lighting power consumption or, alternatively, a reduction in the number of lighting fixtures (Adrian and Jobanputra 2005). For example, due to the differences in the light reflectance of paving materials, asphalt pavement requires 57% more energy to illuminate in comparison to portland cement concrete pavement (Novak and Bilow 2009). Even as it ages, concrete continues to reflect a significant amount of light.

The use of white cement or slag cement results in higher reflectance values (up to about 0.75). Using white cement, white fine aggregate, and white coarse aggregate for concrete provides the brightest white surface and consistent color throughout the entire depth of the concrete. Since natural white cement is not generally available in all regions, a manufactured sand, crushed from white stone provides a good alternative. In this case, both fine and coarse aggregate can be derived from a single source, resulting in uniform concrete color.

There are several options available for the construction of light reflective concrete. When white concrete is placed throughout the entire slab thickness, it is referred to as full-depth construction. Alternately, a layer of white concrete can be placed over new or existing floors. In new construction, this is known as a two-course floor, while in retrofit applications, this is referred to as a topping (generally bonded to the base slab). New floor surfaces can also be made light reflective by applying proprietary on materials to the fresh concrete. Each of these options: full-depth, two-course, topping, and shake-on; result in permanent color, as opposed to painted or coatings that will eventually wear off. See Fanny (2001) and Tarr and Fanny (2008) for information on white concrete and floor construction.

Indoor Air Quality. The need to control indoor air quality has dramatically risen as a result of more efficiently sealed or "tighter" building envelopes to accommodate increased energy performance. Air quality concerns have also increased as a result of greater sensitivity by the general public to material off-gassing from construction products and materials (similar to the odor new car purchasers experience). Concrete assemblies can provide several benefits to achieve better indoor air quality performance within these parameters.

Concrete contains low to negligible levels of volatile organic compounds (VOCs) (Budac 1998). Decorative concrete floor (Figure 2-6), wall, and ceiling assemblies can replace carpeting, wood flooring, and painted finishes which can be a source of VOCs and other air emissions. In addition, carpeting is linked to higher levels of allergens because it captures dust and can harbor mites and mildew. Decorative concrete finishes can be integral to the interior or exterior surface of concrete walls or to the top surface of concrete slabs. Interior decorative finishes eliminate the need for siding materials while also providing a hard, durable exterior surface. These finishes minimize materials for construction and reduce jobsite waste (VanGeem 2008).

Uncontrolled air infiltration through a building envelope is problematic. It can allow dust, pollen, airborne pollutants, and unconditioned air into the living space or allow filtered and conditioned air to escape. Water vapor from warm, humid air can condense within wall cavities as it leaks through the wall in cold weather climates, creating moisture and mold issues. The monolithic nature of site cast and precast concrete wall systems with fewer joints and seams, reduces uncontrolled through-wall infiltration more commonly seen in frame construction.

Acoustics. Concrete can provide excellent acoustic control. Excessive noise has an adverse effect on hearing loss, personal health and well-being, the ability to perform quiet tasks, personal comfort, and general productivity. The sound transmission class (STC) and Inside-Outside Transmission Class (OTC) are values used to rate walls, partitions, doors, and windows for their effectiveness in blocking
Pervious Concrete. Pervious concrete technology creates more efficient land use by eliminating the need for retention ponds, swales, and other stormwater management devices. Pervious concrete is a porous or no-fines concrete that has interconnected voids. Water percolates through these voids into the soil beneath the concrete system. If the absorbent capacity of the soil is inadequate to effectively handle the anticipated runoff the pervious concrete is placed over engineered granular base material. The depth of the base is sized to provide adequate capacity to provide temporary detention of anticipated storm water to allow the surrounding soil to gradually absorb the runoff.

In pervious concrete applications, carefully controlled amounts of water and cementsitious materials are used to create a paste that forms a thick coating around similarly sized aggregate particles. A pervious concrete mixture contains little or no sand, creating a substantial void content (typically between 15% and 25%). Using sufficient paste to coat and bind the aggregate particles together creates a system of highly permeable, interconnected voids that drain quickly (Figure 2-7). Water flow rates through pervious concrete are commonly measured at 0.34 cm/s (480 in./hr), which is 800 L/m²/min (5 gal/ft²/min), although they can be much higher. For more information on pervious concrete, see Chapter 20 and Tennis, Lening, and Akers (2004).

Permeable-Grid Paver Systems. Permeable interlocking concrete pavers and grid paver systems are constructed with special interlocking pavers (Figure 2-8) that provide spaces between adjacent units. These spaces are typically filled with crushed granular material to allow water to infiltrate into the base and sub-base of the pavement. These base courses are designed to collect water so that it can be quickly diverted from the surface and provide a storage are that allows water to slowly percolate into the ground or to be controlled by other stormwater management techniques.

Concrete pavers are made with dense concrete mixtures and can be colored or textured. As a result of their physical characteristics, pavers are durable in all climates and appropriate for a range of loading and traffic. If utility or other subsurface access is necessary, the pavers can be easily removed and then replaced without damaging the surface of the pavement.

In addition, there are proprietary cast-in-place and precast concrete grid systems that allow grass or other vegetation to grow (sometimes called cellular grassed paving systems). These systems allow a green-scape or lawn appearance for water percolation while providing a structure for vehicles to drive on (parking lots, access roads, shoulders, and driveways). They can also provide ground stabilization for embankments and level surfaces. Approximately 50% of the surface is concrete and the remaining surface contains voids for vegetation or granular fill.
Recycled materials. Building products that contain con- cernant materials originating from recycled products reduce the need for virgin materials in new construction and reduce the environmental impacts from extracting and processing virgin materials.

Post-consumer recycled material is defined as waste generated by households or by commercial, industrial, and institutional facilities as the end-users of a product. These are products that are sold and used for a specific purpose and that require disposal. Post-consumer recycled materials include crushed concrete (Figure 2-12) and masonry from demolished buildings that are reused as aggregate for concrete in new buildings or pavements.

Pre-consumer material is defined as material collected from the waste stream of a manufacturing process. Supplemental cementitious materials (SCMs) such as fly ash, slag cement, and silica fume are examples of pre-consumer materials used in concrete.

Concrete incorporates three major types of recycled materials:
- industrial by-products, used in blended cement or as SCMs in conjunction with portland cement;
- recycled material, used as aggregates in concrete; and
- industrial by-products used as fuel, as raw materials for manufacturing portland or blended cement.

If not used in concrete, many of these materials would be treated as debris and landfilled. When used properly, SCMs may reduce the carbon and energy footprint of cement and concrete and contribute beneficially to the fresh and hardened properties of concrete (see Chapter 4).

The environmental impact of concrete can be further reduced by using aggregates derived from industrial waste or by using recycled concrete as aggregates. Blast furnace slag is a lightweight aggregate with a long history of use in the concrete industry. The FHWA reports that eleven states use recycled concrete aggregate in new concrete (FHWA 2008). These states report that concrete containing recycled aggregate performs equal to concrete containing natural aggregates. See Chapter 6 for more information on recycled-concrete aggregate.

The durability of products with recycled content materials should be carefully evaluated during the design process to ensure comparable life-cycle performance.

Locally Produced

The primary raw materials used to make cement and concrete are abundant throughout the world. The cement, aggregates, and reinforcing steel used to make concrete and the raw materials used to manufacture cement are usually manufactured and extracted from sources within 500 km (300 miles) of the project site. Most ready-mixed concrete plants are within 150 km (100 miles) of the project site. Most precast concrete plants are within 300 km (200 miles) of the project site.

Reduced shipping distances associated with local building materials minimize fuel requirements and the associated energy and emissions from transportation and handling. Locally produced materials contributes to the local economy and reduces imports of materials that may have been produced in countries with much less stringent environmental regulations than in the U.S.

CO₂ Sink

During the life of a concrete structure, the concrete carbonates and absorbs much of the carbon dioxide (CO₂) initially released by calcination during the cement manufacturing process. This may be viewed simply as a loop of the carbon cycle. Concrete does not even necessarily have to be directly exposed to the atmosphere for this process to occur. Underground concrete piping and foundations can absorb CO₂ from air in the soil, and underground and underwater applications might absorb dissolved carbon dioxide present in groundwater, freshwaters, and saltwaters (Hassellback 2009).

A recent study indicates that in countries with the most favorable recycling practices, it is appropriate to estimate that approximately 86% of the concrete is carbonated after 100 years. During this time, the concrete will absorb approximately 57% of the CO₂ emitted during the original calcination. Approximately 35% of the CO₂ is absorbed shortly after the concrete is crushed and exposed to air during recycling operations (Kjellsen and others 2005).

Concrete Ingredients and Sustainability

A key benefit of concrete is the ability to modify the concrete constituents and proportions to best meet the sustainability goals of a particular application. Concrete is composed of cementitious materials, water, aggregate, admixtures, and reinforcement. Each ingredient has sustainable attributes that contribute to the overall sustainability of concrete.

Cement, representing only 7% to 15% of the volume of concrete, provides the primary engineering and durability properties of concrete. Portland and blended cements commonly use waste fuels and by-product materials in their production to reduce energy demand, conserve natural resources, reduce emissions, and reduce the amount of material sent to landfills. The role of cement in sustainability is addressed in Chapter 3.

The use of supplementary cementitious materials (fly ash, slag, and silica fume) in the production of cement or concrete reduces the use of natural resources and energy, reduces emissions, reduces landfilled materials, and can increase the durability of concrete. The role of supplementary cementing materials on sustainability is addressed in Chapter 4.
Water is essential to the hydration of cement in concrete. Municipal drinking water for use in concrete is partially replaced with water reclaimed from concrete production or municipal water treatment facilities, industrial waste water, and water sources not fit for human consumption. This conserves limited sources of potable water. See Chapter 5 for more information.

Aggregates, constituting 60% to 75% of concrete by volume, are traditionally sand, gravel or crushed stone. Reclaimed aggregate from concrete production and recycled hardened concrete from demolished buildings and pavements, can be used to replace a portion of new aggregate in the mix. Aggregate can also be made from industrial by-products, such as blast furnace slag aggregate. These alternative aggregate sources reduce the use of natural resources and reduce the amount of landfilled waste materials.

To conserve natural resources, the use of marginal aggregate in concrete is becoming more common. For example, a two-lift concrete pour could effectively address the limitation of an aggregate with poor wear resistance (the marginal aggregate can still be used, just not at the surface). Similarly, reactive aggregate can be used through careful selection of cementitious materials. For more information on aggregate’s contribution to sustainability, see Chapter 6.

Chemical admixtures, often made by by-products of other industries, enhance the engineering and durability properties of concrete. They also can reduce the amount of water and cementing materials in a concrete mixture resulting in a conservation of natural resources. For more information on chemical admixtures, see Chapter 7. Reinforcement provides tensile and flexural strength to concrete elements. Reinforcing bars are primarily made from recycled steel, which conserves natural resources. Reinforcement is covered in Chapter 8.

**Life-Cycle Analysis**

A life-cycle analysis is a tool used to select building materials and influence design choices.

**Life-Cycle Cost Analysis**

A life-cycle-cost analysis (LCCA) is the practice of accounting for all expenditures incurred over the service life of a particular structure. An LCCA is performed in units of dollars and is equal to the construction (initial or first) costs plus the present value of future utility, maintenance, insurance, and replacement costs over the service life of the building. Quite often, designs with the lowest first costs for new construction require higher maintenance costs and generate higher energy costs during the service life. Thus these structures will have a higher life-cycle cost. Conversely, durable designs using concrete, often have life-cycle costs that are less than those using other construction materials.

The service life must be accurately reflected in an LCCA study for the impact of concrete use to be correctly measured. The service life of building interiors and equipment is often considered to be 30 years, but the average life of the building shell ranges from 50 to 100 years. Studies that use too short a service life, for example a twenty year service life, produce skewed and incorrect LCCA results. Such studies overstate the cost of construction materials and underestimate the cost of maintaining and operating the structure.

**Life-Cycle Assessment and Inventory**

A life-cycle assessment (LCA) is an environmental assessment of the life cycle of a product or process. Moving towards sustainable engineering solutions requires a better understanding of construction activities that affect the natural environment. The products and services that we consume impact the environment throughout their service life, beginning with raw materials extraction and product manufacturing, continuing on through use and ad operation, and finally ending with a waste management strategy (Figure 2-14). Alternatively, the ultimate use may include evaluation of the building or products use phase or even the building’s end-of-life constituents. The LCA of a structure is a requisite measure necessary to evaluate the environmental impact of a product or structure over its useful life. Conventional assessments often overlook one or more of these phases, leading to incomplete results and indefensible conclusions.

A life cycle inventory (LCI), the first portion of an LCA, includes all of the materials and energy inputs as well as any emissions to air, water, and land (solid waste) from the stages listed in Figure 2-14. Marcoux, Nisbet, and VanCeeem (2007) provide a detailed life cycle inventory of Portland cement concrete using a variety of mixture proportions with and without supplementary cementitious materials. Marcoux, Nisbet, and VanCeeem (2006) also provide a life cycle inventory of Portland cement manufacture. The National Renewable Energy Laboratory (NREL). U. S. Life Cycle Inventory Database provides an accounting of energy and material flows for materials, components, and assemblies in the United States (www.nrel.gov/ki).

In LCA provides a consistent methodology applied across all products and at all stages of their production, transport, use, and recycling at end of life or disposal. A full LCA includes the effects of operational energy such as heating and cooling (and associated emissions) and raw material use over the life of the product or structure. A full LCA categorizes these effects into impact categories such as land use, resource use, climate change, health effects, acidification, and toxicity. ISO Standard 14044 provides guidance on conducting a full LCA (ISO 2006).

These guidelines offer a standard method for conducting an LCA, but do not discuss the specifics relevant to a particular product. Mapping the life cycle, developing functional units, drawing systems boundaries, and mining data are left to the discretion and challenge of individual practitioners. As more information regarding the product and its application are known, the specifics can be better described and assessed. Tables 2-3 and 2-4 demonstrate the life cycle phases and components for concrete pavements and buildings. Even though the basic material (concrete) and phases (materials, construction, use, and end of life) are the same, many of the components in the life cycle are different, especially in the use phase. Understanding and modeling the application of the product are key steps in accurately quantifying its impact.

Data for LCA come from a wide variety of sources, including government databases, industry reports, system models, and first-hand collection. Since the entire life cycle is being analyzed, the volume of necessary data is often large and overwhelming. There are a number of other LCA tools that have been developed for general building professionals. LCA software packages, such as GaBi, SinaPre, and EoD/LCA, can assist in the data collection process, and can provide modeling framework. The NREL U. S. LCI Database provides data for cement and concrete as well as other materials. The NIST LCA model, Building for Environmental and Economic Sustainability (BEES), addresses a variety of concrete elements and structures with numerous mixture proportions (https://nrl.nist.gov/softw/ software.html). These types of packages are generally proficient at quantifying upstream impacts for commodities, but third-party information is often necessary to evaluate detailed processes and niche products. External models, such as those describing building energy consumption, vehicle dynamics, or electricity generation, are commonly used to complement the core LCA and provide spatial, temporal, and system-specific data. Such models are particularly useful when characterizing the operation phase of the life cycle.

It is important to use tools that consider all aspects of a comprehensive LCA, including all of the impact categories.

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**Table 2-3. LCA Phases and Components for Concrete Pavements**

<table>
<thead>
<tr>
<th>Materials</th>
<th>Construction</th>
<th>Use</th>
<th>End of life</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aggregate quarrying</td>
<td>Equipment</td>
<td>Rolling resistance</td>
<td>Demolition</td>
</tr>
<tr>
<td>Cement production</td>
<td>Closures, traffic delay</td>
<td>Carbonation</td>
<td>Landfilling</td>
</tr>
<tr>
<td>Base, Other materials</td>
<td>Transportation</td>
<td>Abedo</td>
<td>Recycling/reuse</td>
</tr>
<tr>
<td>Mixing</td>
<td>Transportation</td>
<td>Maintenance</td>
<td>Carbonation</td>
</tr>
<tr>
<td>Transportation</td>
<td>Rehabilitation</td>
<td>Transportation</td>
<td></td>
</tr>
</tbody>
</table>

**Table 2-4. LCA Phases and Components for Concrete Buildings**

<table>
<thead>
<tr>
<th>Materials</th>
<th>Construction</th>
<th>Use</th>
<th>End of life</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aggregate quarrying</td>
<td>Equipment</td>
<td>Plug loads</td>
<td>Demolition</td>
</tr>
<tr>
<td>Cement production</td>
<td>Temporary structures</td>
<td>Lighting</td>
<td>Landfilling</td>
</tr>
<tr>
<td>Installation, Other materials</td>
<td>Transportation</td>
<td>HVAC systems</td>
<td>Recycling/reuse</td>
</tr>
<tr>
<td>Mixing</td>
<td>Transportation</td>
<td>Thermal mass properties</td>
<td>Carbonation</td>
</tr>
<tr>
<td>Transportation</td>
<td></td>
<td>Routine maintenance</td>
<td>Transportation</td>
</tr>
</tbody>
</table>
LCAs can be used for any number of purposes. The flexible analysis framework and systematic approach make LCA particularly useful for comparing alternative systems. Validating and marketing green claims, establishing environmental footprints, and identifying opportunities for improvement within the life cycle. However, among the strongest applications is their function in creating sound environmental policies. As a policy instrument, LCA provides comprehensive and scientifically defensible strategies to reducing environmental impact. The life-cycle approach ensures that policies are not implemented that benefit from near-term improvements at the expense of long-term deficits. Adapting such insightful principles is the key to establishing a sustainable path towards environmental goals.

LCA at the MIT Concrete Sustainability Hub
At the Massachusetts Institute of Technology Concrete Sustainability Hub, a team of professors, researchers, and students are using LCA to evaluate and improve the environmental performance of buildings and their materials. Each year, building operation and transportation activities release nearly five billion tons of carbon dioxide into the atmosphere, accounting for over two-thirds of carbon emissions in the United States. To reduce these emissions, the materials, designs, and performance of the supporting infrastructure need to be optimized. LCA provides the ideal platform for MIT to construct the life cycles of buildings and pavements in order to identify opportunities to reduce emissions.

Preliminary analyses from MIT indicate that the operation components of the infrastructure—primarily heating and cooling systems for buildings and rolling resistance for pavements—hold the most potential for large-scale improvement. While embedded emissions in the materials manufacturing and construction are important, the emissions associated with the decades of operation tend to dominate the carbon footprint (Figure 2-15). However, best-practice decisions are also context-sensitive, meaning that a one-size-fits-all sustainability solution is not practical given the range of operating conditions for buildings and pavements. Determination of optimal materials, maintenance, and performance properties depend on the local climate, intended function, and performance criteria.

The case studies that MIT are evaluating for buildings and pavements are a critical step towards creating context-specific sustainability solutions. For buildings, this includes residential, multi-family residential, and commercial structures are being evaluated in several locations in the United States. The differing climates and building codes affect how the buildings are designed and operated over the year, which plays a significant role in the life-cycle emission footprint. Likewise, pavement design and performance is affected by the local climate and traffic demand on a given segment, leading to different optimal materials, service life, and maintenance schedules. Analyzing how external variables affect best-practice approaches will allow decision-makers to react with solutions that are more specific to their individual goals.

As we better understand these infrastructure systems and how they affect the environment, we achieve more insightful and effective approaches to reducing environmental impact and life cycle economic costs. Given the ubiquity of buildings and pavements, LCA conclusions have relevance in both policy discussions and design discussions, and the results are of interest to a range of audiences. MIT's LCA project strives to deliver a new level of clarity on carbon accounting, which will help the cement and concrete industry to lead the market in developing more quantitative approaches to green construction.

The MIT CS Hub Concrete Science Program is also using nano technology to explore the fundamentals of cement. Through advanced modeling of cement hydration, MIT will improve the performance of cement and enhance its sustainable properties.

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