Achieving Sustainability with Precast Concrete

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Sustainability is often defined as development that meets the needs of the present without compromising the ability of future generations to meet their own needs.[1] While other building materials may have to alter their configurations, properties, or both to be applicable to sustainable structures, precast concrete's inherent properties make it a natural choice for achieving sustainability with today's new buildings. In this paper, sustainability concepts are outlined and different rating systems for evaluating sustainable design are introduced. Finally, ways are provided in which precast concrete meets or exceeds one rating system's requirements to achieve sustainability.

Worldwide, people are currently using 20% more resources than can be regenerated. In particular, the U.S. population consumes more resources on a per capita basis than any other nation. The environmental impact of buildings in the United States is significant. Consider that buildings consume 65% of the electricity generated in the United States and more than 36% of the primary energy (such as natural gas); produce 30% of the national output of greenhouse gas emissions; use 12% of the potable water in the United States; and employ 40% of raw materials (3 billion tons annually) for construction and operation worldwide.[2]

Building materials can have a significant effect on the environmental impact of the construction and operation of a building. Some materials may have to be used in special configurations, or employ different combinations, to achieve sustainability; the inherent properties of precast concrete, however, make it a natural choice for achieving sustainability in buildings. Precast concrete contributes to sustainable practices by incorporating integrated design, using materials efficiently, and reducing construction waste, site disturbance, and noise.

Although most consumers are concerned with the present and future health of the natural environment, few people are willing to pay more for a building, product, process, or innovation that minimizes environmental burdens. The concept of sustainability, however, balances sustainable design with cost-effectiveness.

Using integrated design (also called the holistic or whole-building approach), a building's materials, systems, and design are examined from the perspective of all project team members and tenants. Energy efficiency, cost, durability (or service life), space flexibility, environmental impact, and quality of life are all considered when decisions are made regarding the selection of a building's design.

SUSTAINABILITY CONCEPTS

Triple Bottom Line

The triple bottom line—environment, society, and economy—emphasizes that economic consequences are related to environmental and social consequences. Consequences to society include impacts on employees, communities, and developing countries, as well as ethics, population growth, and security. Reducing materials, energy, and emissions used by buildings has impacts far beyond those of the buildings themselves, such as:

- Fewer new quarries are needed;
- Fewer new power plants need to be constructed, less pollution is emitted into the air, and dependence on foreign sources is reduced;
- The number of respiratory conditions, such as asthma, is reduced; and
- Demands on the infrastructure to find new sources of water decrease.

All of these examples indicate how building energy and utility use affect the local community.

The community can also be considered globally. Carbon dioxide (CO_2) emissions in the United States were reduced in 2002 for the first time; this reduction, however, was due to a decrease in manufacturing and a stagnant economy. That same year, China's production of CO_2 increased by more than the reduction realized in the United States, but this increase was primarily due to production of materials consumed by U.S. citizens. Energy, materials, waste, and emissions to air, land, and water need to be considered from a global perspective in a global market.

Cost of Building Green

A sustainable design can result in reduced project costs and a building that is energy and resource efficient. Buildings that are efficient with energy and water have lower operating costs (in the range of \$0.60 to \$1.50 per square foot versus \$1.80 per square foot) and a higher facility value than conventional buildings.[2]

Lower energy use translates into smaller capacity requirements for mechanical equipment (heating and cooling) and lower first costs for such equipment. Effective use of daylight and passive solar techniques can further reduce heating and cooling costs. Reusing materials, such as demolished concrete for base or fill material, can reduce costs associated with hauling and disposing of materials.

If sustainability is an objective at the outset of the design process, the cost of a sustainable building is competitive. Often, green buildings cost no more than conventional buildings because of the resource-efficient strategies used, such as downsizing of more costly mechanical, electrical, and structural systems.

Reported increases in first costs for green buildings range from 0% to 2%, with costs expected to decrease as project teams become more experienced with green building strategies and design.[3] Generally, a 2% increase in construction costs will result in a savings of 10 times the initial investment in operating costs for utilities (energy, water, and waste) in the first 20 years of the building's life.

Buildings with good daylight and indoor air quality—both common features of sustainable buildings—have increased labor productivity, worker retention, and days worked. These benefits contribute directly to a company's profits because salaries—which are about 10 times higher than rent, utilities, and maintenance combined—are the largest expense for most companies occupying office space. In schools with good daylight and indoor air quality, students have higher test scores and lower absenteeism.

Table 1. Strategies used during sustainable design to incorporate multiple building team disciplines.

Integration Strategy	Sustainability Attribute
Use precast panel as interior surface.	Saves material; no need for additional framing and drywall.
Use hollow-core panels as ducts.	Saves material and energy; eliminates ductwork and charges thermal mass of panel.
Use thermal mass in combination with appropriate insulation levels in walls.	Thermal mass with insulation provides energy benefits that exceed the benefits of mass or insulation alone in most climates.
Design wall panels to be disassembled for building function changes.	Saves material; extends service life of panels.
Use durable materials.	Materials with a long life cycle and low maintenance will require less replacement and maintenance during the life of the building.
Use natural resources such as daylight, trees for shading, and ventilation.	Reduces lighting and cooling energy use. Increases indoor air quality and employee productivity.
Reduce and recycle construction waste.	Reduces transportation and disposal costs of wastes. Less virgin materials are used if construction waste is recycled for another project.
Use building commissioning to ensure that building standards are met.	Energy savings and indoor air quality are most likely attained during the building life if inspections are made to ensure construction was as designed.

Holistic/Integrated Design

A key tenet of sustainable design is the holistic or integrated design approach. This approach requires coordinating the architectural, structural, and mechanical designs early in the schematic design phases to discern possible system interactions and then deciding which beneficial interactions are essential for project success. For example, a well-insulated building with few windows that face east and west will require less heating and air-conditioning.

This added feature could affect the mechanical design by requiring fewer ducts and registers and perhaps would allow for the elimination of registers along the building perimeter. Precast concrete walls act as thermal storage to delay and reduce peak thermal loads, while also affecting the structural design of the building. **Table 1** provides other integrated design strategies.

A holistic approach will also take into account the surrounding site environment. Will shelters be needed for people who take public transportation to work? Will bike paths be incorporated for those who bike to work? Can native landscaping be used to reduce the need for irrigation?

The eight elements of integrated design are:

1. Emphasize the integrated process;
2. Consider the building as a whole—often interactive, often multi-functional;
3. Focus on the life cycle;
4. Have disciplines work together as a team from the start;
5. Conduct relevant assessments to determine requirements and set goals;
6. Develop tailored solutions that yield multiple benefits while meeting requirements and goals;
7. Evaluate solutions; and
8. Ensure that requirements and goals are met.

Contracts and requests for proposals should clearly describe sustainability requirements and project documentation.

Reduce, Reuse, Recycle

Reduce the amount of material used and the toxicity of waste materials. Precast concrete can be designed to optimize (or lessen) the amount of concrete used. Industrial wastes such as fly ash, slag cement, and silica fume can be used, thereby partially reducing the amount of cement used in concrete. Precast concrete generates a low amount of waste with a low toxicity. It is generally assumed that 2% of the concrete at the plant is waste, but because it is generated at the plant, 95% of the waste is used beneficially elsewhere.

Reuse products and containers; repair what can be reused. Precast concrete panels can be reused when buildings are expanded. Concrete pieces from demolished structures can be reused to protect shorelines. Because the precasting process is self-contained, formwork and finishing materials are reused. Wood or fiberglass forms can generally be used 40 to 50 times without major maintenance, while concrete and steel have practically unlimited service lives.

Recycle as much as possible, which includes buying products with recycled content. Concrete in most urban areas is recycled as fill or road base. Wood and steel forms are recycled when they become worn or obsolete. Virtually all reinforcing steel is made from recycled steel. Many cement plants burn waste-derived fuels such as spent solvents, used oils, and tires.

GREEN BUILDING RATING SYSTEMS

Life Cycle Inventory (LCI) and Life Cycle Assessment (LCA) are valid methods of assessing sustainability, but they are a complex accounting of all materials, energy, emissions, waste, and their respective impacts (see "Life Cycle Cost, LCI and LCA" on pp. 56–57). Conversely, green building rating systems have gained popularity because they are comparatively easy to use and straightforward. Focus groups have shown that consumers are interested in furthering sustainability but are unable to define it. Labeling a green building with Leadership in Energy and Environmental Design (LEED™), Green Globes™, or Energy Star certification sends the message the building is green without having to perform a complex LCI or LCA.

Energy Star Certification

Energy Star[4] is a government/industry partnership designed to help businesses and consumers protect the environment and save money through energy efficiency. Energy Star labeling is available for office equipment, such as computers and monitors; appliances, such as refrigerators; and residential and commercial buildings. Buildings that meet certain criteria and achieve a rating of 75 or better are eligible to apply for the Energy Star.

The rating consists of a score on a scale of 1 to 100. The score represents a benchmark energy performance; for example, buildings that score 75 or greater are considered to be among the United States' top 25%. In addition, the building must maintain a healthy and productive indoor environment.

At the present time, five commercial building types are eligible for Energy Star certification: offices, K–12 schools, supermarkets/grocery stores, hotels/motels, and acute care/children's hospitals. These building types are broken down further into a number of specific occupancies. For example, office buildings include general office, bank branch, courthouse, and financial center.

Demonstrating conformance is accomplished through a web-based software tool called Portfolio Manager.[5] The program hinges on the unbiased opinions of a professional engineer who must visit the building and verify that data entered about the building are correct.

Through the Portfolio Manager, the engineer inputs the building location and energy consumption and describes its physical and operating characteristics. Operating characteristics include average weekly occupancy hours, number of occupants, and amount of equipment and types such as personal computers, refrigeration cases, cooking facilities, and laundry facilities. Energy consumption is based on all sources of energy used per month. In addition to energy performance, the engineer is responsible for demonstrating compliance with industry standards on thermal comfort, indoor air quality, and illumination.

The professional engineer is expected to give an opinion about the capability of the building to provide acceptable thermal environmental conditions per the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Standard 55[6] and its capability to supply acceptable outdoor air per ASHRAE Standard 62.[7] The engineer is also expected to give an opinion about the capability of the building to provide minimum illumination levels per the Luminance Selection Procedure in the *Illuminating Engineering Society of North America Lighting Handbook*.[8] In addition, Portfolio Manager has the capability to manage energy data, analyze trends in energy performance (to make budget and management decisions regarding investments in energy-related projects), verify building performance, and track the progress of building improvements.

LEED Rating System

The LEED green building rating system is a voluntary, consensus-based national standard for developing high-performance, sustainable buildings. The LEED system is both a standard for certification and a design guide for sustainable construction and operation. As a standard, it is predominantly performance-based, and as a design guide, it takes a whole-building approach that encourages a collaborative, integrated design and construction process.

The system is administered by the U.S. Green Building Council (USGBC). The LEED-NC[9] is a document that applies to new construction and major renovation projects and is intended for use with commercial, institutional, and high-rise residential new construction and major renovation.

Essentially, LEED is a point-based system that provides a framework for assessing building performance and meeting sustainability goals. Points are awarded when a specific intent is met, and a building is LEED certified if it obtains at least 26 points. The points are grouped into five categories: sustainable sites, water efficiency, energy and atmosphere, materials and resources, and indoor environmental quality. The more points that are earned, the "greener" the building is considered. Silver, gold, and platinum ratings are awarded for a minimum of 33, 39, and 52 points, respectively.

Table 2. LEED* project checklist: precast concrete points.

LEED Category	Credit or Prerequisite	Points Available
Sustainable Sites	Credit 5.1: Site Development, Protect or Restore Habitat	1
Sustainable Sites	Credit 5.2: Site Development, Maximize Open Space	1
Sustainable Sites	Credit 7.1: Heat Island Effect, Non-Roof	1
Energy and Atmosphere	Prerequisite 2: Minimum Energy Performance	—
Energy and Atmosphere	Credit 1: Optimize Energy Performance	1–10
Materials and Resources	Credit 1.1: Building Reuse, Maintain 75% of Existing Shell	1
Materials and Resources	Credit 1.2: Building Reuse, Maintain 95% of Existing Shell	1
Materials and Resources	Credit 2.1: Construction Waste Management, divert 50% by weight or volume	1
Materials and Resources	Credit 2.2: Construction Waste Management, divert 75% by weight or volume	1
Materials and Resources	Credit 4.1: Recycled Content, the post-consumer recycled content plus one-half of the pre-consumer content constitutes at least 10% (based on cost) of the total value of the materials in the project	1
Materials and Resources	Credit 4.2: Recycled Content, the post-consumer recycled content plus one-half of the pre-consumer content constitutes at least 20% (based on cost) of the total value of the materials in the project	1
Materials and Resources	Credit 5.1: Local/Regional Materials, Use a minimum of 10% (based on cost) of the total materials value	1
Materials and Resources	Credit 5.2: Local/Regional Materials, Use a minimum of 20% (based on cost) of the total materials value	1
Indoor Environmental Quality	Credit 3.1: Construction Indoor Air Quality Management Plan, During Construction	1
Innovation and Design Process	Credit 1.1: Apply for other credits demonstrating exceptional performance	1†
Innovation and Design Process	Credits 1.2: Apply for other credits demonstrating exceptional performance	1†
Innovation and Design Process	Credits 1.3: Apply for other credits demonstrating exceptional performance	1†
Innovation and Design Process	Credits 1.4: Apply for other credits demonstrating exceptional performance	1†
Innovation and Design Process	Credit 2.1: LEED Accredited Professional	1
Project Totals		23

*LEED: Leadership in Energy and Environmental Design.

†Up to 4 additional points can be earned, must be submitted and approved (not included in total).

Note: Scoring System: Certified, 26–32 points; Silver, 33–38 points; Gold, 39–51 points; and Platinum, 52–69 points.

Fig. 1. The buildings in the corporate campus for CH2M Hill in Englewood, Colo., are framed with a total precast concrete system, including precast shear walls, double tees, inverted tee beams, and load-bearing exterior walls. The buildings are some of the first Leadership in Energy and Environmental Design (LEED)–certified total precast office buildings.

Appropriate use of precast concrete can help a building earn up to 27 points; 26 points are required for LEED certification. Using concrete can help meet minimum energy requirements, optimize energy performance, and increase the life of a building. The constituents of concrete can be recycled materials, and concrete itself can also be recycled. These materials are usually locally available.

These attributes of concrete, recognized in the LEED rating system, can help lessen a building's negative impact on the natural environment. Points applicable to precast concrete are summarized in **Table 2** and are explained throughout this paper. Points must be documented according to LEED procedures to be earned. The USGBC website contains a downloadable "letter template" that greatly simplifies the documentation requirements for LEED.

Green Globes

Green Globes is an online, point-based green building rating system administered by the Green Building Initiative.[10] Many of the points are similar to those in LEED, though the point structure differs; Green Globes has 1000 total points compared with the 69 for LEED-NC. Certification for Green Globes is available at 35% achievement compared with LEED at 38% (26 points). It is easier to obtain certification in Green Globes, however, because points that are not applicable to the building are subtracted from the total number of points so a higher percentage is obtained for those criteria that are met.

DURABILITY

A key factor in building reuse is the durability of the original structure. Precast concrete panels provide a long service life due to their durable and low-maintenance concrete surfaces (**Fig. 1**). A precast concrete shell can be left in place when the building interior is renovated. Annual maintenance should include inspection and, if necessary, repair of joint material.

Modular and sandwich panel construction with concrete exterior and interior walls provides long-term durability, inside and out. Precast concrete construction provides the opportunity to refurbish the building if the building use or function changes, rather than tearing it down and starting anew. These characteristics of precast concrete make it sustainable in two ways: It avoids contributing solid waste to landfills and it reduces the depletion of natural resources and production of air and water pollution caused by new construction.

LEED Materials Credit 1 in Building Reuse

The purpose of this credit is to encourage builders to leave the main portion of the building structure and shell in place when renovating, thereby conserving resources and reducing wastes and the environmental effects of new construction. The building shell includes the exterior skin and framing but excludes window assemblies, interior partition walls, floor coverings, and ceiling systems. This credit should be obtainable when renovating buildings with a concrete skin, since concrete generally has a long life. This is worth 1 point if 75% of the existing building structure/shell is left in place and 2 points if 95% is left in place.

Corrosion Resistance

The most common reason for surface spalling of concrete in buildings is corrosion of reinforcing steel due to inadequate concrete cover. Precast concrete offers increased resistance to this type of spalling because reinforcement and concrete are placed in a plant, with more quality control than cast-in-place construction. This reduces variations in concrete cover over reinforcing steel and reduces the likelihood of inadequate cover.

Inedible

Vermin and insects cannot destroy concrete because it is inedible. Some softer materials are inedible but still provide pathways for insects. Due to its hardness, vermin and insects will not bore through concrete. Gaps in exterior insulation to expose the concrete can provide access for termite inspectors.

RESISTANT TO NATURAL DISASTERS

Concrete is resistant to wind, hurricanes, floods, and fire. Properly designed, reinforced precast concrete is resistant to earthquakes and provides blast protection for occupants.

Fire Resistance

Precast concrete offers noncombustible construction that helps contain a fire within boundaries. As a separation wall, precast concrete helps to prevent a fire from spreading throughout a building or jumping from building to building. During wild fires, precast concrete walls help provide protection to human life and the occupants' possessions. As an exterior wall, concrete that endures a fire can often be reused when the building is rebuilt.

The fire endurance of concrete can be determined by its thickness and type of aggregate. The American Society for Testing and Materials (ASTM) E119 lists procedures for determining fire endurance of building materials. Another good resource is PCI's *Manual on Design for Fire Resistance of Precast, Prestressed Concrete* (MNL 124-89).

Concrete generally fails by heat transmission long before structural failure, whereas other construction materials fail by heat transmission when collapse is imminent. A 2-h fire endurance for a precast concrete wall will most likely mean the wall gets hot (experiences an average temperature rise of 250 °F [140 °C] for all points or 325 °F [180 °C] at any one point). Concrete helps contain a fire even if no water supply is available, whereas sprinklers rely on a water source.

Tornado, Hurricane, and Wind Resistance

Precast concrete is resistant to tornadoes, hurricanes, and wind. In 1967, a series of deadly tornadoes hit northern Illinois, killing 57 people and destroying 484 homes. Damages at the time were estimated at $50 million. Two precast, prestressed concrete structures, a grocery store and a high school, were in the direct path of two tornadoes that struck almost simultaneously. Repairs to the structural system of the grocery store (limited to a single crack in the flanges and stem of a beam subjected to uplift) were less than $200. In the high school, structural damage was limited to the flange of one double-tee member (24 ft [7 m] of which was broken off by flying debris) and blown out concrete diaphragm end closures from between the webs near the damaged tee.

Photo courtesy of A. C. Martin Partners.

Fig. 2. The Joe Serna Jr. California EPA Headquarters—a 27-story LEED Platinum–certified office building in downtown Sacramento—has precast concrete panels with punched openings. The panels were pre-mounted, glazed, and caulked at the precast plant after casting.

Photo courtesy of Johnston Design Group, LLC.

Fig. 3. A U.S. Green Building Council (USGBC) LEED-registered, mixed-use development, the "Bookends" in Greenville, S.C., features street-level retail and residential condominiums. The precast concrete walls have a combination of sandblasted and cast-in thin brick finishes. The facade of this building has four distinct architectural styles to appear as four separate and unique buildings.

Flood Resistance

Concrete is not damaged by water; concrete that does not dry out continues to gain strength in the presence of moisture. Concrete submerged in water absorbs very small amounts of water over long periods of time, so the concrete is not damaged. In flood-damaged areas, concrete buildings are often salvageable.

Concrete will only contribute to moisture problems in buildings if it is enclosed in a system that does not let it breathe or dry out, trapping moisture between the concrete and other building materials. For instance, a vinyl wall coverings in hot and humid climates will act as a vapor retarder and moisture can get trapped between the concrete and the wall covering. For this reason, impermeable wall coverings (such as vinyl wallpaper) should not be used.

Earthquake Resistance

Precast concrete is resistant to earthquakes. Earthquakes in Guam, the United States (Richter scale 8.1); Manila, the Philippines (Richter scale 7.2); and Kobe, Japan (Richter scale 6.9) have subjected precast concrete buildings to some of nature's deadliest forces. Precast concrete framing systems have a proven capacity to withstand these major earthquakes. Precast panels are a material of choice in seismic areas because they can span long distances between attachments to the main structure (**Fig. 2**).

Another pertinent example is the 1994 Northridge, Calif., earthquake (Richter scale 6.8). It was one of the costliest natural disasters in U.S. history, with total damages estimated at $20 billion. Most engineered structures within the affected region performed well, including structures with precast concrete components.

In particular, no damage was observed in precast concrete cladding due to either inadequacies of those components, or inadequacies of their connections to the building's structural systems, and no damage was observed in the precast components used for the first floor or first-floor support of residential housing. It should be noted that parking structures with large plan areas—regardless of structural system—did not perform as well as other types of buildings.

WEATHER RESISTANCE

High Humidity and Wind-Driven Rain

Precast concrete is resistant to wind-driven rain and moist outdoor air in hot and humid climates. Concrete is impermeable to air infiltration and wind-driven rain. Moisture that enters a precast building must come through joints between precast concrete elements. Annual inspection and repair of joints will minimize this potential. More importantly, if moisture does enter through joints, it will not damage the concrete.

Good practice for all types of wall construction is to have permeable materials that breathe (are allowed to dry) on at least one surface and not encapsulate concrete between two impermeable surfaces. Concrete breathes and will dry out. Therefore, as long as a precast concrete wall is allowed to breathe on at least one side and is not covered by an impermeable material, the potential for moisture problems within the wall system is minimal.

Ultraviolet Resistance

The ultraviolet portion of solar radiation does not harm concrete. Using colored pigments in concrete retains the color in concrete long after paints have faded due to the sun's effects. Precast concrete is ideal for using pigments because the controlled production allows for replication of color for all panels for a project (**Fig. 3**).

MITIGATING THE URBAN HEAT ISLAND EFFECT

Precast concrete provides reflective surfaces that minimize the urban heat island effect. Cities and urban areas are 3 °F to 8 °F (2 °C to 4 °C) warmer than surrounding areas due to the urban heat island effect. This difference is attributed to buildings and pavements that have taken the place of vegetation. Trees provide shade that reduces temperatures at the surface. Trees and plants provide transpiration and evaporation that cool the surfaces and air surrounding them. Research has shown that the average temperature of Los Angeles has risen steadily over the past half century and is now 6 °F to 7°F (3 °C to 4 °C) warmer than it was 50 years ago.[11]

Warmer Surface Temperatures

Urban heat islands are primarily attributed to horizontal surfaces, such as roofs and pavements, that absorb solar radiation. In this context, pavements include roads, streets, parking lots, driveways, and walkways. Vertical surfaces, such as the sides of buildings, also contribute to this effect. Using materials with higher albedos, such as concrete, will reduce the heat island effect, save energy by reducing the demand for air-conditioning, and improve air quality (**Fig. 4**).

Studies indicate people will avoid using air conditioners at night if temperatures are less than 75 °F (24 °C). Mitigating the

Fig. 4. In cities such as Cape Coral, Fla., mitigating the heat island effect is especially important. Note the white color of the architectural precast concrete—built for the city of Cape Coral City Hall.

urban heat island effect to keep summer temperatures in cities less than that temperature at night has the potential to save large amounts of energy by avoiding air conditioner use.

Smog Effects

Smog levels have also been correlated to temperature rise. Thus, as the temperature of urban areas increases, so does the probability of smog and pollution. In Los Angeles, the probability of smog increases by 3% with every degree Fahrenheit of temperature rise.

Studies for Los Angeles and 13 cities in Texas have found that there are almost never any smog episodes when the temperature is below 70 °F (21 °C). The probability of episodes begins at about 73 °F (23 °C) and, for Los Angeles, exceeds 50% by 90 °F (32 °C). Reducing the daily high in Los Angeles by 7 °F (4 °C) is estimated to eliminate two-thirds of the smog episodes.[11]

Smog and air pollution are the main reasons the Environmental Protection Agency (EPA) mandates expensive, clean fuels for vehicles and reduced particulate emissions from industrial facilities such as cement plants and asphalt production plants. The EPA now recognizes that air temperature is as much a contributor to smog as nitrogen oxide and volatile organic compounds (VOCs) are. The effort to reduce particulates in the industrial sector alone costs billions of dollars per year, whereas reduction in smog may be directly related to the reflectance and colors of the infrastructure that surround us. Installing low albedo roofs, walls, and pavements is a cost-effective way to reduce smog.

Albedo

Albedo, which in this case is synonymous with solar reflectance, is the ratio of the amount of solar radiation reflected from a material surface to the amount shining on the surface. Solar radiation includes the infrared and ultraviolet as well as the visible spectrum. Albedo is measured on a scale of not reflective (0.0) to 100% reflective (1.0). Generally, materials that appear to be light-colored in the visible spectrum have high albedo and those that appear dark-colored have low albedo. Because reflectivity in the solar radiation spectrum determines albedo, color in the visible spectrum is not always a true indicator of albedo.

Surfaces with lower albedos absorb more solar radiation. The ability to reflect infrared light is of great importance because infrared light is most responsible for heating. On a sunny day when the air temperature is 55 °F (13 °C), surfaces with dark acrylic paint will heat up to 90 °F (50 °C) more than air temperatures, to 145 °F (63 °C). Light surfaces, such as white acrylic, will heat up 20 °F (11 °C) more to a temperature of 75 °F (24 °C). The color and composition of the materials greatly affect the surface temperature and the amount of absorbed solar radiation. The effect of albedo and solar radiation on surface temperatures is referred to as the sol-air temperature and can be calculated.

Traditional portland cement concrete generally has an albedo or solar reflectance of approximately 0.4, though values can vary; measured values are reported in the range of 0.4 to 0.5. The solar reflectance of new concrete is greater when the surface reflectance of the sand and cementitious materials in the concrete are greater.

Surface finishing techniques also have an effect, with smoother surfaces generally having a higher albedo. For "white" portland cement, values are reported in the range of 0.7 to 0.8. Albedo is most commonly measured using a solar-spectrum reflectometer (ASTM C 1549)[12] or a pyranometer (ASTM E 1918).[13]

Emittance

In addition to albedo, the material's surface emittance affects a surface temperature. While albedo is a measure of the solar radiation reflected away from the surface, surface emittance is the ability of the material to emit, or "let go of," heat. A white surface exposed to the sun is relatively cool because it has a high reflectivity and a high emittance. A shiny metal surface is relatively warm because it has a low emittance, even though it has a high albedo.

The emittance of most non-reflecting (non-metal) building surfaces such as concrete is in the range of 0.85 to 0.95. The emittance of aluminum foil, aluminum sheet, and galvanized steel, all dry and bright, are 0.05, 0.12, and 0.25, respectively.

Moisture

Moisture in concrete helps cool the surface by evaporation. Concrete, when placed, has a moisture content of 100% relative humidity. The concrete surface gradually dries over a period of one to two years to reach equilibrium with its surroundings. Concrete surfaces exposed to rain and snow will continue to be wetted and dry.

This moisture in the concrete surface will help cool the concrete by evaporation whenever the vapor pressure of the moisture in the surface is greater than that of the air. In simpler terms, when the temperature and relative humidity of the air are less than that just beneath the concrete surface, the concrete will dry and cool somewhat by evaporation.

The albedo of concrete decreases when the surface is wet. Consequently, albedo is lower when concrete is relatively new and the surface has not yet dried or when the concrete becomes wet. The albedo of new concrete generally stabilizes within two to three months.

LEED Sustainable Sites Credit 7.1 on Heat Island Effect, Non-Roof

The intent of this credit is to reduce heat islands. The requirements are met by placing a minimum of 50% of parking places underground or in a covered by parking structure. Precast concrete parking structures can be used to help obtain this point. Any roof used to shade or cover parking must meet specified criteria. This credit is worth 1 point.

Mitigating the Heat Island Effect

One method to reduce the urban heat island effect is to change the albedo of the urban area. This is accomplished by replacing low albedo surfaces with materials of higher albedo. This change is most cost-effective when done in the initial design or during renovation or replacement due to other needs.

Planting trees for shade near buildings also helps mitigate the urban heat island effect. Shade also directly reduces the air-conditioning load on buildings. Using deciduous trees shades the buildings in the summer and allows the sun to reach the buildings in the winter.

Thermal Mass and Nocturnal Effects

The thermal mass of concrete delays the time it takes for a surface to heat up but also delays the time to cool off. For example, a white roof will get warm faster than concrete during the day but will also cool off faster at night. Concrete surfaces are often warmer than air temperatures in the evening hours.

Concrete's albedo and thermal mass will help mitigate heat island effects during the day but contribute to the nocturnal heat island effect. The moisture absorbed by concrete helps reduce the daytime and nocturnal heat island effect when it evaporates. The challenge is to use concrete to mitigate heat islands while keeping evening temperatures as cool as possible.

ENVIRONMENTAL PROTECTION

Radiation and Toxicity

The goal of sustainability is to reduce radiation and toxic materials; concrete provides an effective barrier against radiation and can be used to isolate toxic chemicals and waste materials. Concrete protects against the harmful effects of x-rays, gamma rays, and neutron radiation.

Concrete is resistant to most natural environments, but it is sometimes exposed to substances that can attack and cause deterioration. Concrete in chemical manufacturing and storage facilities is especially prone to chemical attack. The resistance of concrete to chlorides is good, and using less permeable concrete can increase it even more. This is achieved by using a low water-cementitious materials ratio (approximately 0.40), adequate curing, and supplementary cementitious materials, such as slag cement and silica fume. The best defense against sulfate attack is the measures suggested previously, in addition to using cement specially formulated for sulfate environments.

Resistance to Noise

Precast concrete walls provide a buffer between outdoor noise and the indoor environment. Because land is becoming scarcer, buildings are being constructed closer together and near noise sources such as highways, railways, and airports. The greater mass of concrete walls can reduce sound penetrating through a wall by over 80% compared with wood or steel frame construction. Although some sound will penetrate the windows, a concrete building is often two-thirds quieter than a wood or steel frame building. Precast concrete panels also provide effective sound barriers separating buildings from highways or industrial areas from residential areas (**Fig. 5**).

PRECAST CONCRETE PRODUCTION

The production of precast concrete has many environmental benefits. Fewer materials are required because precise mixture proportions and tighter tolerances are achievable.

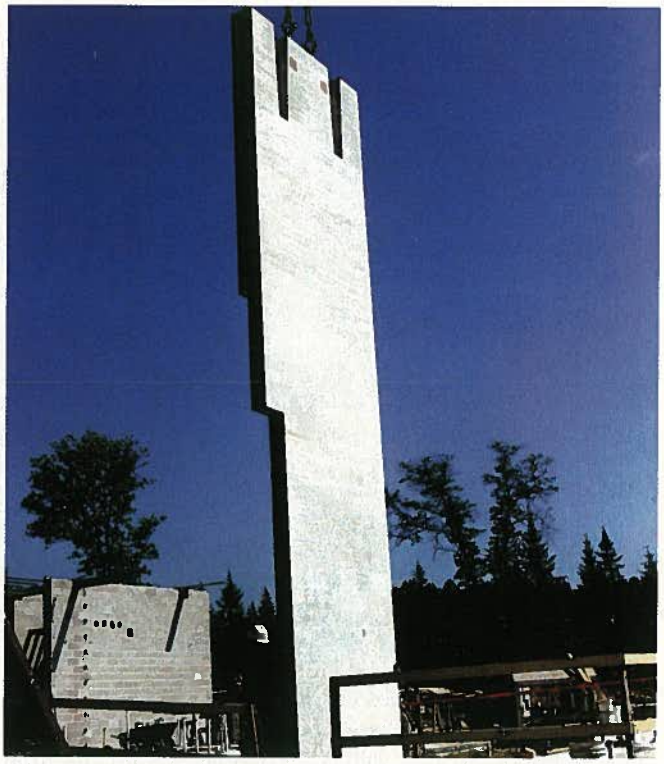
Photo courtesy of Portland Cement Association.

Fig. 5. Precast concrete panels provide effective sound barriers separating buildings from highways or industrial areas from residential areas.

Optimal insulation levels can be incorporated into precast concrete sandwich panel walls. Less concrete waste is created because of tight control of quantities of constituent materials. Waste materials are more likely to be recycled because concrete production is in one location. For example, gray water is often recycled into future mixtures; hardened concrete is recycled (about 5% to 20% of aggregate in precast concrete can be recycled concrete); sand and acids for finishing surfaces are reused; and steel forms and other materials are reused. Less dust and waste is created at the construction site because only precast concrete elements that are needed are delivered; there is no debris from formwork and associated fasteners. Fewer trucks and less time are required for construction because concrete is made off site, which is particularly beneficial in urban areas where minimal traffic disruption is critical. Precast concrete units are normally large components, so greater portions of the building are completed with each activity. And finally, there is less noise at the construction site because the concrete is made off site.

Less concrete is generally used in precast buildings than in other concrete buildings because of the optimization of materials. A properly designed precast concrete system will result in smaller structural members, longer spans, and less material used on site; this translates directly into economic savings, which can also result in environmental savings. Using fewer materials means using fewer natural resources and less manufacturing and transportation energy—not to mention the avoided emissions from mining, processing, and transporting raw and finished material.

Concrete products can provide both the building structure, and the interior and exterior finishes. Structurally efficient

LEED Sustainable Sites Credit 5.1 on Site Development, Protect or Restore Habitat

The intent of this credit is to encourage the conservation of natural areas on the site and the restoration of damaged ones. The requirements are met by limiting site disturbance to prescribed distances. Tuck-under parking, such as precast concrete parking structures, can be used to help obtain this point. This credit is worth 1 point.

LEED Sustainable Sites Credit 5.2 on Site Development, Maximize Open Space

The intent of this credit is to provide a high ratio of open space to development footprint. The requirements are met by limiting the size of the development footprint, specifically by exceeding the local zoning's open space requirement for the site by 25%. Tuck-under parking, such as precast concrete parking structures, can be used to help obtain this point. This credit is worth 1 point.

columns, beams, and slabs can be left exposed with natural finishes. Interior and exterior concrete walls offer a wide range of profile, texture, and color options that require little or no additional treatment to achieve aesthetically pleasing results.

Exposed ceiling slabs and architectural precast panels are some examples of this environmentally efficient approach. This structure/finish combination reduces the need for the production, installation, maintenance, repair, and replacement of additional finish materials. It also eliminates products that could otherwise degrade indoor air quality.

CONSTITUENT MATERIALS

Portland Cement

Portland cement (hereafter called cement) is made by heating common minerals, primarily crushed limestone, clay, iron ore, and sand, to a white-hot mixture to form clinker. This intermediate product is ground with a small amount of gypsum to form a fine gray powder called cement. To trigger the necessary chemical reactions in the kiln, these raw materials must reach a temperature of about 2700 °F (1500 °C), the temperature of molten iron. Although the portland cement industry is energy intensive, the U.S. cement industry has reduced energy usage per ton of cement by 35% since 1972.[14]

Carbon dioxide emissions from a cement plant are divided into two source categories: combustion and calcination. Combustion accounts for approximately 35% and calcination 65% of the total CO_2 emissions from a cement manufacturing facility. The combustion-generated CO_2 emissions are related to fuel use. The calcination CO_2 emissions are formed when the raw material is heated and CO_2 is liberated from the calcium carbonate.

When concrete is exposed to the air and carbonates, it reabsorbs some of the CO_2 released during calcination. Calcination is a necessary key to cement production; the focus of reductions in CO_2 emissions during cement manufacturing is on reducing fuel and energy use.

White portland cement is a true portland cement that differs from gray cement chiefly in color. The manufacturing process is controlled so that the finished product will be white. White portland cement is made of selected raw materials containing negligible amounts of iron and magnesium oxides—the substances that give cement its gray color. White cement is used primarily for architectural purposes in structural walls, precast and glass fiber–reinforced concrete facing panels, terrazzo surfaces, stucco, cement paint, tile grout, and decorative concrete. White cement is also used to manufacture white masonry cement meeting ASTM C 91 (the standard specification for masonry cement).

Abundant Materials

Concrete is used in almost every country of the world as a basic building material. Aggregates, which comprises about 85% of concrete, are generally low-energy, local, naturally occurring sand and stone. The limestone and clay needed to manufacture cement are prevalent in most countries. Concrete contributes to a sustainable environment because it does not use scarce resources.

Limestone and aggregate quarries are easily reused. While quarrying is intense, it is closely contained and temporary. When closed, aggregate quarries are generally converted to their natural state or into recreational areas or used for agriculture. In contrast, other material mining operations can be extensive and involve deep pits that are rarely restored, and deforestation can have negative environmental effects.

Fly Ash, Slag Cement, and Silica Fume

Fly ash, slag cement, and silica fume are industrial by-products; their use as a replacement for portland cement does not contribute to the energy and CO_2 effects of cement in concrete. If not used in concrete, these pozzolans would use valuable landfill space. Fly ash (**Fig. 6**) is a by-product of the combustion of pulverized coal in electric power generating plants. Slag cement (**Fig. 7**) is made from iron blast-furnace slag. Silica fume (**Fig. 8**) is a by-product from the electric arc furnace used in the production of silicon or ferrosilicon alloy.

These types of industrial by-products are considered post-industrial or pre-consumer recycled materials. Fly ash is commonly used at cement replacement levels up to 25%; slag cement up to 60%; and silica fume up to 5% to 7%. When

Photo courtesy of Portland Cement Association.

Fig. 6. Fly ash, a by-product of the electric industry, can be used as a partial replacement for portland cement.

slag cement replaces 50% of the portland cement in 7500 psi (50 MPa) concrete, greenhouse gas emissions per cubic yard of concrete are reduced by 45%. Because the cementitious content of concrete is about 15%, these pozzolans typically account for only 2% to 5% of the overall concrete material in buildings.

Testing determines the optimum amounts of supplementary cementing materials used with portland or blended cement, the relative cost and availability of the materials, and the specified properties of the concrete. When supplementary cementitious materials are used, the proportioned mixture (using the project materials) should be tested to demonstrate that it meets the required concrete properties for the project. Some pozzolans increase curing times, but this is not as great a concern for precast concrete manufacturing as it is in cast-in-place applications where the construction schedule has a greater impact.

The durability of products with recycled content materials should be carefully researched during the design process to ensure comparable life cycle performance. There would obviously be a net negative impact if a product offering a 20% to 30% recycled content had only half the expected service life of a product with a lower or no recycled content.

Recycled Aggregates

The environmental attributes of concrete can be improved by using aggregates derived from industrial waste or using recycled concrete as aggregates. Blast furnace slag is a lightweight aggregate with a long history of use in the concrete industry.

LEED Materials Credit 4 on Recycled Content

The requirements of this credit state: "Use materials with recycled content such that the sum of post-consumer recycled content plus one-half of the pre-consumer content constitutes at least 10% (based on cost) of the total value of the materials in the project." The percentage is determined by multiplying the price of an item by the percent of recycled materials—on a mass basis—that make up that item.

To earn this credit, the project must meet the threshold percentages based on the total of all permanently installed building materials used on the project. Supplementary cementitious materials, such as fly ash, silica fume, and slag cement, are considered pre-consumer. Because the cementitious content of concrete is about 15%, these pozzolans typically account for only 2% to 5% of the overall concrete material in buildings. For this reason, LEED-NC v2.2 allows the recycled content of concrete to be based on the recycled content of the cementitious materials.

Using recycled concrete or slag as aggregate instead of extracted aggregates qualifies as post-consumer. Although most reinforcing bars are manufactured from recycled steel, in LEED, reinforcement is not considered part of concrete. Reinforcing materials should be considered as a separate item. This credit is worth 1 point for the quantities quoted previously and 2 points for double the amount.

Recycled concrete can be used as aggregate in new concrete, particularly the coarse portion. When using the recycled concrete as aggregate, the following should be taken into consideration:

Photo courtesy of Portland Cement Association.

Fig. 7. Slag cement is a cementitious material and also a by-product of the iron industry.

- Recycled concrete as aggregate will typically have a higher absorption rate and lower specific gravity than natural aggregate and will produce concrete with slightly higher drying shrinkage and creep. These differences become greater when recycled fine aggregate amounts are increased;
- Too many recycled fines can produce a harsh and unworkable mixture. Many transportation departments have found that using 100% coarse recycled aggregate, but only about 10% to 20% recycled fines, works well.[15] The remaining percentage of fines is natural sand;
- When crushing the concrete (**Fig. 9**), it is difficult to control particle size distribution, meaning that the "aggregate" may fail to meet grading requirements of ASTM C 33[16]; and
- The chloride content of recycled aggregates is of concern if the material will be used in reinforced concrete.

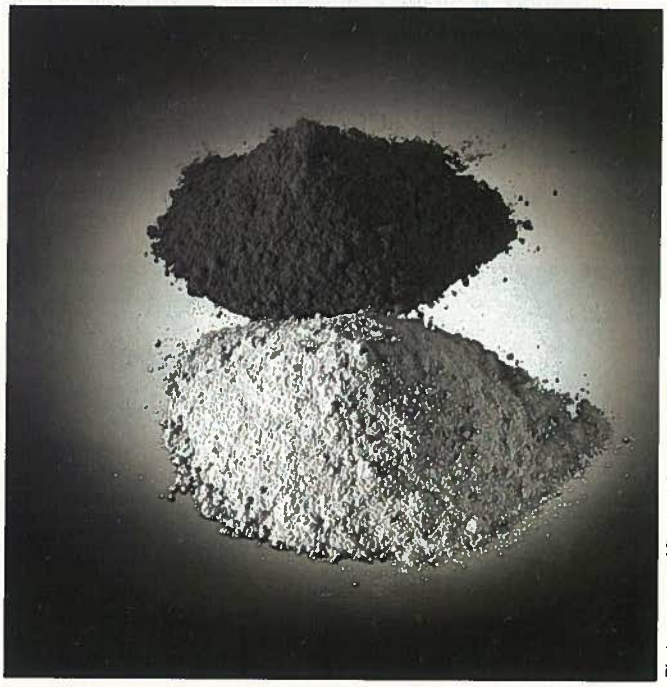

Photo courtesy of Portland Cement Association.

Fig. 8. Silica fume, an industrial by-product, is commonly used to replace cement in quantities from 5% to 7%.

Photo courtesy of CTLGroup.

Fig. 9. Crushed concrete from other sources can serve as recycled aggregate.

This is particularly an issue if the recycled concrete is from pavements in northern climates where road salt is freely spread in the winter. The alkali content and type of aggregate in the system is probably unknown, and therefore, if mixed with unsuitable materials, a risk of alkali-silica reaction is possible.

Admixtures

Adding chemical admixtures, usually in liquid form, to the concrete during batching may change the fresh and hardened properties of concrete. Chemical admixtures are commonly used to adjust setting time or hardening, reduce water demand, increase workability, intentionally entrain air, and adjust other fresh or hardened concrete properties. Admixtures provide enhancing qualities in concrete but are used in such small quantities that they do not adversely affect the environment. Their dosages are usually in the range of 0.005% to 0.2% of the concrete mass.

Photo courtesy of Portland Cement Association.

Fig. 10. The color pigments that provide the decorative colors in precast concrete are generally insoluble and non-toxic.

Color Pigments

Color pigments are used to provide the decorative colors in precast concrete. They are generally insoluble and non-toxic, though they may contain a heavy metal component like many other materials (**Fig. 10**).

Local Materials

Using local materials reduces the transportation required to ship heavy building materials and the associated energy and emissions. Most precast concrete plants are within 200 miles (300 km) of a building site. The cement, aggregates, and reinforcing steel used to make the concrete and the raw materials used to manufacture cement are usually obtained or extracted from sources within 200 miles of the precast concrete plant. The primary raw materials used to make cement and concrete are abundant in all areas of the world.

Precast concrete elements are usually shipped efficiently because of their large, often repetitive sizes and the ability to plan their shipment during the normal course of the project.

> **LEED Materials Credit 5 on Regional Materials**
>
> *The requirements of this credit state: "Use building materials or products that have been extracted, harvested or recovered, as well as manufactured, within 500 miles (800 km) of the project site for a minimum of 10% (based on cost) of the total materials value." This means that a precast plant within 500 miles of the building would qualify if the materials to make the concrete were extracted within 500 miles. Calculations can also include concrete either manufactured or extracted locally.*
>
> *Precast concrete will usually qualify because precast plants are generally within 200 miles to 500 miles (300 km to 800 km) of a project. Precast plants generally use aggregates that are extracted within 50 miles (80 km) of the plant and within 200 to 500 miles of the project. Cement and supplementary cementitious materials used for buildings are also primarily manufactured within 500 miles of a project. Reinforcing steel is also usually manufactured within 500 miles of a project and is typically made from recycled materials from the same region.*
>
> *Using materials that are extracted or manufactured locally supports the regional economy. In addition, reducing shipping distances for material and products to the project minimizes fuel requirements for transportation and handling. This credit is worth 1 point for the quantities quoted above and 2 points for double the amount, or 20% of the materials.*

ENERGY USE IN BUILDINGS

Energy conservation is a key tenet of sustainability. About 90% of the energy used during a building's life is attributed to heating, cooling, and other utilities. The remaining 10% is attributed to manufacturing materials, construction, maintenance, replacement of components, and demolition.

Approximately 5% of the world's population resides in the United States, yet 25% of the world's energy is consumed in the United States. The United States' dependence on foreign energy sources is greater than ever, which has an effect on U.S political and defense policies. Meanwhile, many developing nations, like China and India, have increased energy demands due to increased manufacturing and urbanization.

Energy Codes

Energy codes provide cost-effective, minimum building requirements that save energy. The energy saved is a cost savings through lower monthly utility bills, and smaller, and thus less expensive, mechanical equipment. More than two-thirds of the electricity and one-third of the total energy in the United States are used to heat, cool, and operate buildings.[17]

This means that implementing and enforcing energy codes will result in fewer power plants and natural resources being used to provide electricity and natural gas. It also means fewer emissions will be released into the atmosphere. In the United

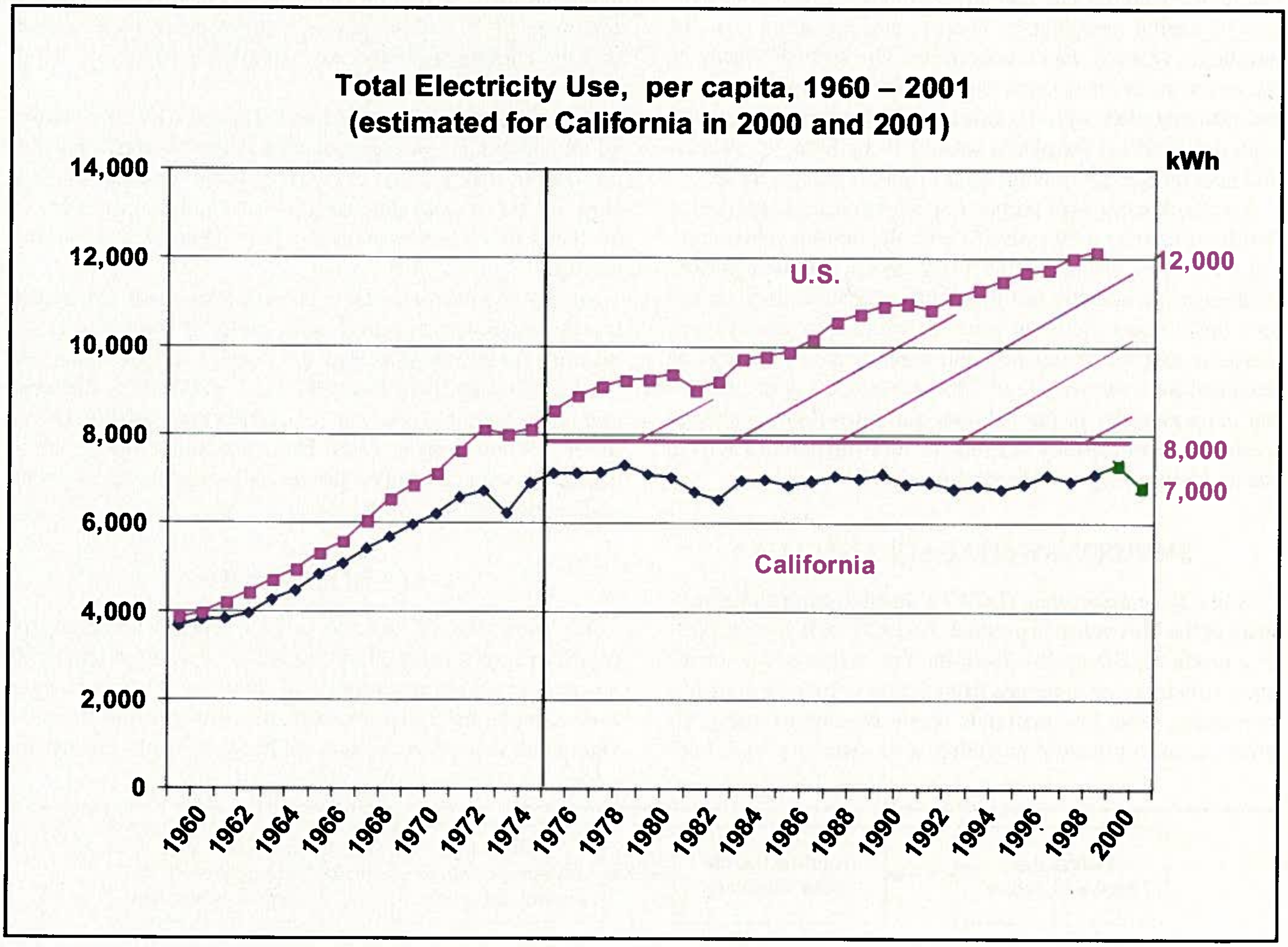

Fig. 11. Energy savings due to implementation of energy codes in 1976 in California.

Life Cycle Cost, LCI, and LCA

A life cycle cost analysis is a powerful tool used to make economic decisions for selection of building materials. This analysis is the practice of accounting for all expenditures incurred over the lifetime of a particular structure. Costs at any given time are discounted back to a fixed date, based on assumed rates of inflation and the time-value of money. A life cycle cost is in dollars and is equal to the construction cost plus the present value of future utility, maintenance, and replacement costs over the life of the building.

Using this widely accepted method, it is possible to compare the economics of different building alternatives that may have different cash flow factors but that provide a similar standard of service.

Quite often, building designs with the lowest first costs for new construction will require higher costs during the building's life. So, even with their low first cost, these buildings will have a higher life cycle cost. Conversely, durable materials such as precast concrete often have a lower life cycle cost. In the world of selecting the lowest bid, owners need to be made aware of the benefits of a lower life cycle cost so that specifications require durable building materials such as precast concrete.

The building life cycle cost software[1] from the National Institute of Standards and Technology provides economic analysis of capital investments, energy, and operating costs of buildings, systems, and components. The software includes the means to evaluate costs and benefits of energy conservation and complies with the American Society of Testing and Material (ASTM) standards related to building economics and Federal Energy Management Program requirements.

Accepted methods of performing life cycle cost analyses of buildings assume a 20-year life with the buildings maintaining 80% of its residual value at the end of this time period. Buildings can actually last hundreds of years if they are not torn down due to obsolescence. Sustainability practitioners advocate that the foundation and shell of new buildings be designed for a service life of 200 years to 300 years. Allowing extra capacity in the columns for extra floors and floor loads and extra capacity in roofs for roof-top gardens adds to the building's long-term flexibility.

ENVIRONMENTAL LCI AND LCA

A life cycle assessment (LCA) is an environmental assessment of the life cycle of a product. An LCA looks at all aspects of a product's life cycle—from the first stages of harvesting and extracting raw materials from nature to transforming and processing these raw materials into a product to, using the product, and ultimately recycling it or disposing of it back into nature. **Figure 1** shows the four phases of an LCA.

The LCA of a building is necessary to evaluate the environmental impact of a building over its life. Green buildings rating systems, models such as Building for Environmental and Economic Sustainability (BEES)[1], and programs that focus only on recycled content or renewable resources provide only a partial snapshot of the environmental impact a building can have. An LCA of a building includes environmental effects due to:

- Extraction of materials and fuel used for energy;
- Manufacture of building components;
- Transportation of materials and components;
- Assembly and construction;
- Operation, including energy consumption, maintenance, repair, and renovations; and
- Demolition, disposal, recycling, and reuse of the building at the end of its functional or useful life.

A full set of effects includes land use, resource use, climate change, health effects, acidification, and toxicity.

An LCA involves a time-consuming manipulation of large quantities of data. A model such as SimaPro[2] provides data for common building materials and options for selecting LCA impacts. The Portland Cement Association[3] publishes reports with life cycle inventory (LCI) data on cement and concrete. All models require a separate analysis of annual heating, cooling, and other occupant loads using a program such as DOE2.1e.[4]

An LCI is the first stage of an LCA. An LCI accounts for all the individual environmental flows to and from a product throughout its life cycle. It consists of the materials and energy needed to make and use a product and the emissions to air, land, and water associated with making and using that product.

Several organizations have proposed how an LCA should be conducted. Organizations such as the International Organization for Standardization[5], the Society of Environmental Toxicology and Chemistry (SETAC)[6], and the U.S. Environmental Protection Agency[7] have documented standard procedures for conducting an LCA. These procedures are generally consistent with each other; they are all scientific, transparent, and repeatable.

LCI BOUNDARY

The usefulness of an LCA or LCI depends on where the boundaries of a product are drawn. A common approach is to consider all the environmental flows from cradle to gate. For example, the system boundary in **Fig. 2** shows the most significant processes for precast concrete operations. It in-

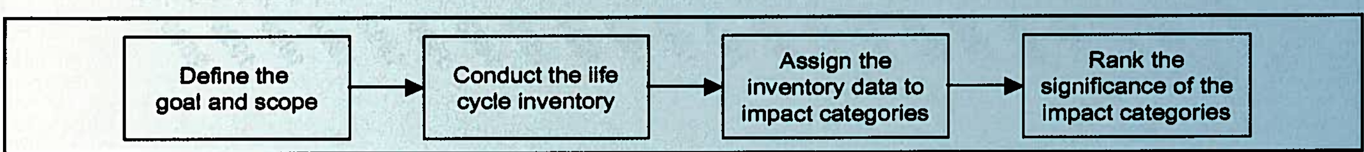

Fig. 1. The four phases in the process of developing an LCA.

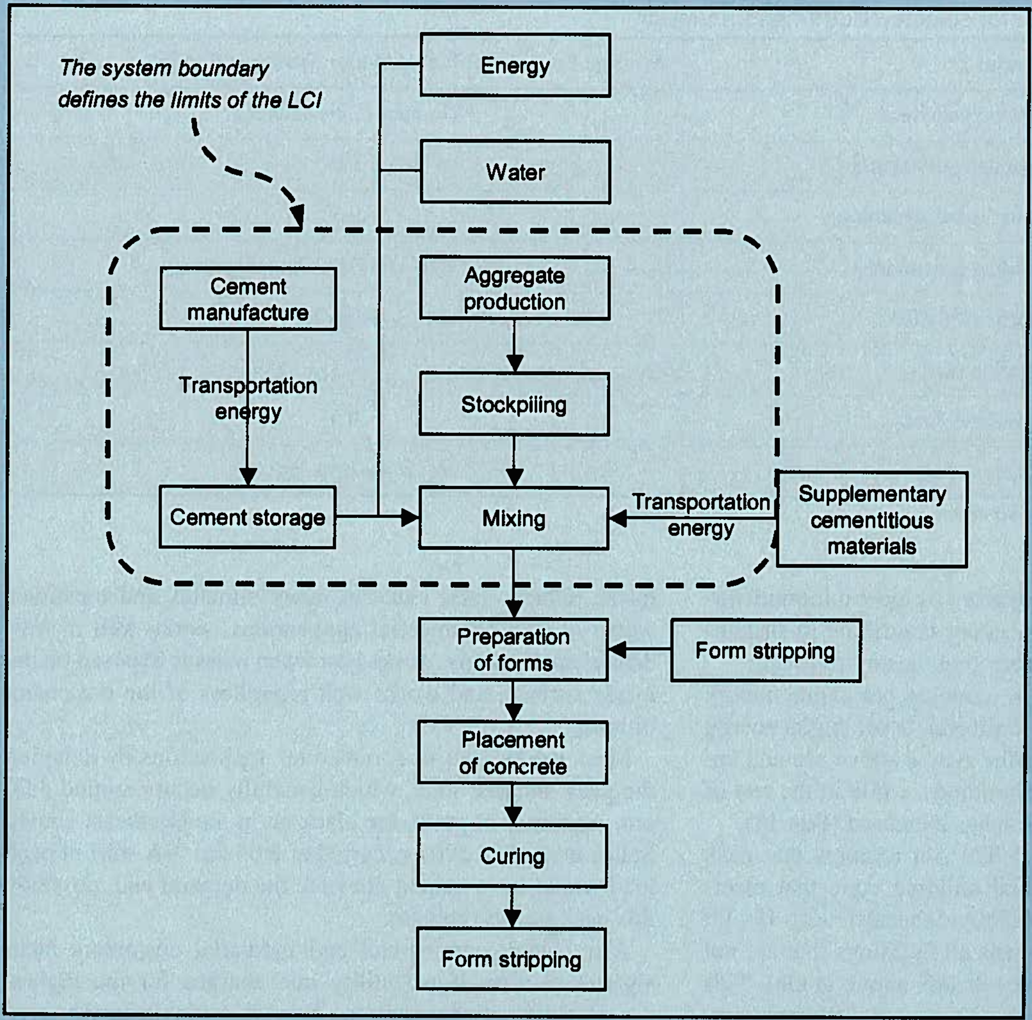

Fig. 2. Precast concrete system boundary

cludes most of the inputs and outputs associated with producing concrete—from extracting raw materials to producing concrete ready for placement in forms. The system boundary also includes the upstream profile of manufacturing cement, as well as quarrying and processing aggregates, and transporting cement, fly ash, and aggregates to the concrete plant. Energy and emissions associated with transporting the primary materials from their source to the concrete plant are also included in the boundary. It does not include, however, upstream profiles of fuel, electricity, water, or supplementary cementitious materials. This LCI also does not include form preparation, placing the concrete in the formwork, curing, and stripping. A complete precast concrete LCI would include all these steps.

An upstream profile can be thought of as a separate LCI that is itself an ingredient to a product. For example, the upstream profile of cement is essentially an LCI of cement, which can be imported into an LCI of concrete. The LCI of concrete itself can then be imported into an LCI of a product, such as an office building.

To get the most useful information out of an LCI, precast concrete should be considered in the context of its end use. For example, in a building, the environmental impact of the building materials is usually dwarfed by the environmental effects associated with building operations such as heating, ventilating, cooling, and lighting.

The LCI of materials generally do not consider embodied energy and emissions associated with construction of manufacturing plant equipment and buildings, nor the heating and cooling of such buildings. This is generally acceptable if their materials, embodied energy, and associated emissions account for less than 1% of those in the process being studied. For example, SETAC guidelines indicate that inputs to a process do not need to be included in an LCI if they are less than 1% of the total mass of the processed materials or product; they do not contribute significantly to a toxic emission; and they do not have a significant associated energy consumption.[6]

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4. Architectural Energy Corporation, *Visual DOE 4.0*, Boulder, CO, www.archenergy.com.
5. International Organization for Standardization, Geneva, Switzerland, www.iso.org.
6. The Society of Environmental Toxicology and Chemistry, Pensacola, FL, www.setac.org.
7. The United States Environmental Protection Agency, Washington, DC, www.EPA.gov.

Table 3. Measured air leakage for selected building materials.[21]

Material	Average Leakage at 0.3 in. Water Surface (cfm/ft^2)
6 mil (0.15 mm) polyethylene	No measurable leakage
1 in. (25 mm) expanded polystyrene	1.0
12 mm (0.47 in.) fiberboard sheathing	0.3
Breather type building membranes	0.002–0.7
Closed cell foam insulation	0.0002
Uncoated brick wall	0.3
Uncoated concrete block	0.4
Precast concrete wall	No measurable leakage

Note: 1 in. = 25.4 mm; 1 cfm/ft^2 = 0.3048 m^3 per min/m^2

States, most buildings are constructed to meet minimum energy code requirements; energy codes contribute to sustainability by saving energy and protecting the environment.

Energy codes are effective in reducing per capita energy usage (energy use per person). California's per capita energy use has remained steady due to the state's active use and enforcement of energy codes for buildings, while in the rest of the United States, that energy use has increased (**Fig. 11**).

The U.S. National Energy Policy Act requires that each state certify it has a commercial building code that meets or exceeds ANSI/ASHRAE/IESNA Standard 90.1-1999.[18] In this sense, "commercial" means all buildings that are not low-rise residential (three stories or less above grade). This includes office, industrial, warehouse, school, religious, dormitories, and high-rise residential buildings. The ASHRAE standard and most codes recognize the benefits of thermal mass and require less insulation for mass walls.

Thermal mass in exterior walls delays and reduces peak loads, reduces total loads in many climates and locations, works best in commercial applications, works well in residential applications, works best when mass is exposed on the inside surface, and works well regardless of the placement of mass.

Mass works well in commercial applications by delaying the peak summer load, which generally occurs around 3:00 pm. As a case in point, the blackout in the Northeast United States in August 2003 occurred at 3:05 pm.[19] A shift in peak load would have helped alleviate the demand and, possibly, this peak power problem.

Also, many commercial and industrial customers incur significant time-of-use utility rate charges for the highest use of electricity for any one hour in a month in the summer. Thermal mass may help shift the peak hour of electric demand for air-conditioning to a later hour and help reduce these time-of-use charges. Nighttime ventilation can be used to cool thermal mass that has been warmed during the day. Local outdoor humidity levels influence the effectiveness of nighttime ventilation strategies.

As occupant and equipment heat is generated, it is absorbed not only by the indoor ventilated air but also by the massive elements of the building. Interior mass from interior walls, floors, and ceilings will help moderate room temperatures and reduce peak energy use.

Thermal mass is most effective in locations and seasons where the daily outdoor temperature rises above and falls below the balance point temperature of the building. The balance point temperature is the outdoor temperature below which heating will be required. It is less than room temperature, generally between 50 °F and 60 °F (10 °C and 15°C), at the point where internal heat gains are about equal to the heat losses through the building envelope. In many climates, buildings with thermal mass have lower energy consumption than non-massive buildings with walls of similar thermal resistance. In addition, heating and cooling needs can be met with smaller equipment sizes.

LEED Energy and Atmosphere Prerequisite 2 on Minimum Energy Performance

All buildings must comply with certain sections on building energy efficiency and performance as required by the ANSI/ASHRAE/IESNA 90.1-2004, Energy Standard for Buildings Except Low-Rise Residential Buildings. *In certain cases, local energy codes can be used for compliance if they have been shown to be equivalent or exceed the ASHRAE standard. This prerequisite is a requirement and is not worth any points. The requirements of the ASHRAE standard are cost-effective and not particularly stringent for concrete. Insulating to meet or exceed the requirements of the standard is generally a wise business choice. Determining compliance for the envelope components is relatively straightforward using the tables in Chapter 5 of the ASHRAE standard. Minimum requirements are provided for mass and non-mass components, such as walls and floors.*

Lighting

Light-colored precast concrete and other surfaces will reduce energy costs associated with indoor and outdoor light-

Table 4. LEED* NC v2.2 points awarded for energy costs saved beyond minimum code.

New Buildings, Energy Saved	Existing Buildings, Energy Saved	Points
10.5%	3.5%	1
14%	7%	2
17.5%	10.5%	3
21%	14%	4
24.5%	17.5%	5
28%	21%	6
31.5%	24.5%	7
35%	28%	8
38.5%	31.5%	9
42%	35%	10

* LEED: Leadership in Energy and Environmental Design.

ing. Reflective surfaces will reduce the amount of fixtures and lighting required.

Air Infiltration

Precast concrete panels have negligible air infiltration. Minimizing air infiltration between panels and at floors and ceilings will provide a building with low-air infiltration. These effects will lower energy costs and help prevent moisture problems from infiltration of humid air. In hot and humid climates in the southeastern United States, infiltration of moist air is a source of unsightly and unhealthy moisture problems in buildings. Some building codes[20] now limit air leakage of building materials to 0.004 cfm/ft^2 (0.0012 [m^3/min]/m^2) under a pressure differential of 0.3 in. (7.6 mm) water (1.6 psf [0.75 kPa]); precast concrete meets this requirement. **Table 3** lists the measured air leakage values for select building materials.

Advanced Energy Guidelines

Sustainability or green building programs (such as LEED or Energy Star) encourage energy savings beyond minimum code requirements. The energy saved is a cost savings to the building owner through lower monthly utility bills and smaller, less expensive mechanical equipment. Some government programs offer tax incentives for energy-saving features. Other programs offer reduced mortgage rates. The Energy Star program offers simple computer programs to determine the utility savings and lease upgrades associated with energy-saving upgrades.

Many energy-saving measures are cost-effective even though they exceed minimum codes. Insulation and other energy-saving measures in building codes generally have a return investment cycle of about 5 years, even though the building life may be anywhere from 30 years to 100 years. The New Buildings Institute has developed the *E-Benchmark* guidelines to save energy beyond codes.[21] The ASHRAE *Advanced Energy Design Guide For Small Office Buildings*[22] has a similar purpose. Many utilities are interested in these advanced guidelines to delay the need for new power plants.

The panelized construction of precast concrete lends itself to good practice and optimization of insulation levels. To maximize the effectiveness of the insulation, thermal bridges should be minimized or avoided. Metal thermal bridges may occur as fasteners that penetrate insulation to connect concrete layers. Concrete thermal bridges may occur at the tops and bottoms of concrete panels. Using fiberglass composite fasteners or thermal breaks may minimize thermal bridges.

LEED Energy Credit 1 on Optimizing Energy Performance

This credit is allowed if energy cost savings can be shown compared to a base building that meets the requirements of ANSI/ASHRAE/IESNA 90.1-2004, Energy Standard for Buildings Except Low-Rise Residential Buildings. *The method of determining energy cost savings must meet the requirements of Appendix G, "Performance Rating Method," of the standard.*

Many engineering consulting firms have the capability to model a building to determine energy savings as required using a computer-based program, such as DOE2.[23] *When concrete is considered, it is important to use a program, such as DOE2, that calculates annual energy use on an hourly basis. Such programs are needed to capture the beneficial thermal mass effects of concrete. Insulated concrete systems used in conjunction with other energy-saving measures will most likely be eligible for points. The number of points awarded will depend on the building, climate, fuel costs, and minimum requirements of the standard. From 1 to 10 points are awarded for energy cost savings of 10.5% to 42% for new buildings and 3.5% to 35% for existing buildings (***Table 4***). A small office building less than 20,000 sq ft (1900 m*^{2}*) complying with ASHRAE* Advanced Energy Design Guide For Small Office Buildings 2004 *can achieve 4 points, and a building complying with* E-Benchmark v1.1 *can achieve 1 point.*

Table 5. Concentrations and emission rates of VOCs* for common materials.

Building Material	VOC Concentration, mg/m³	VOC Emission Rate, mg/m²h
Concrete with water-based form-release agent	0.018	0.003
Acryl latex paint	2.00	0.43
Epoxy, clear floor varnish	5.45	1.3
Felt carpet	1.95	0.080
Gypsum board	N/A	0.026
Linoleum	5.19	0.22
Particle board	N/A	2.0
Plastic silicone sealer	77.9	26.0
Plywood paneling	N/A	1.0
Putty strips	1.38	0.34
PVA† glue cement	57.8	10.2
Sheet vinyl flooring	54.8	2.3
Silicone caulk	N/A	< 2.0
Water-based EVA‡ wall and floor glue	1410.0	271.0

*VOCs: volatile organic compounds.

†PVA: polyvinyl acetate.

‡EVA = ethylene vinyl acetate.

Note: 1 mg/m³ = 0.000009 oz/yd³; 1 mg/m²h = 0.00001 oz/yd²h.

LEED Indoor Environmental Quality Credit 3.1 on Construction IAQ Management Plan, During Construction

This credit prevents indoor air quality problems resulting from the construction process. The intent is to reduce and contain dust and particulates during construction and to reduce moisture absorbed by materials that are damaged by moisture. During construction, the project must meet or exceed the recommended Control Measures of the Sheet Metal and Air Conditioning National Contractors Association IAQ Guidelines for Occupied Buildings under Construction, *1995, Chapter 3 on Control Measures.*

Using precast concrete can help meet the requirements because it is delivered to the site in pieces that do not require fabrication, processing, or cutting, thereby reducing dust and airborne contaminants on the construction site. Concrete is not damaged by moisture and does not provide nutrients for mold growth. This credit is worth 1 point.

INDOOR ENVIRONMENTAL QUALITY

Concrete contains low to negligible VOCs. These compounds degrade indoor air quality when they off gas from new products, such as interior finishings, carpet, and furniture. Manufactured wood products such as laminate, particleboard, hardboard siding, and treated wood can also lead to off gassing. In addition, VOCs combine with other chemicals in the air to form ground-level ozone.

Table 5 presents the VOC concentration and emission rates for common materials. Complaints due to poor indoor air quality routinely include dryness of the mucous membranes and skin, nose bleeds, skin rash, mental fatigue, headache, cough, hoarseness, wheezing, nausea, dizziness, increased incidence of asthma, and eye, nose, and throat irritation.

Polished concrete floors do not require carpeting. Exposed concrete walls do not require finishing materials. The VOCs in concrete construction can be further reduced by using low-VOC materials for form release agents, curing compounds, dampproofing materials, wall and floor coatings and primers, membranes, sealers, and water repellants.

DEMOLITION

Precast concrete panels can be reused when buildings are expanded, and precast concrete can be recycled as road base or fill at the end of its useful life. Concrete pieces from demolished structures can be reused to protect shorelines. Most concrete from demolition in urban areas is recycled and not placed in landfills.

CONCLUSION

Sustainable practices contribute to saving materials and energy and reducing the negative effects of pollutants. The

LEED Materials Credit 2 on Construction Waste Management

This credit is extended for diverting construction and demolition debris from landfill disposal. It is awarded based on diverting at least 50% by weight or volume of the previously listed materials. Since precast concrete is a relatively heavy construction material and is frequently crushed and recycled into aggregate for road bases or construction fill, this credit should be obtainable when concrete buildings are demolished. This credit is worth 1 point if 50% of the construction and demolition debris is recycled or salvaged and 2 points for 75%.

LEED Innovation and Design Process Credit 1

This credit is available for projects that demonstrate exceptional performance above the requirements in LEED or not specifically addressed in LEED. For example, close collaboration with structural engineers on a given project to develop innovative systems that are more resource efficient or use less energy may earn a project an additional point. To earn credits (up to 4), the user must submit the intent of the proposed credit, the proposed requirement for compliance, submittals to demonstrate that compliance, and the design approach used to meet the requirement.

Innovation and Design Process Credit 2

One point is also given if a principal participant of the project team is a LEED Accredited Professional. The concrete industry has LEED-experienced professionals available to assist teams with concrete applications and help maximize points for concrete.

use of precast concrete contributes to these practices by incorporating integrated design, using materials efficiently, and reducing construction waste, site disturbance, and noise. Concrete is durable, resistant to corrosion and impact, and inedible.

Precast concrete structures are resistant to fires, wind, hurricanes, floods, earthquakes, wind-driven rain, and moisture damage. Light- or natural-colored concrete reduces heat islands, thereby reducing outdoor temperatures, saving energy, and reducing smog. Recycled materials such as fly ash, slag cement, silica fume, and recycled aggregates can be incorporated into concrete, thereby reducing the amount of materials that are taken to landfills and reducing the use of virgin materials.

Concrete structures in urban areas are recycled into fill and road base material at the end of their useful lives. Cement and concrete are generally made of abundant local materials. The thermal mass of concrete helps save heating and cooling energy in buildings. Concrete acts as an air barrier, reducing air infiltration and saving more energy. Concrete has low VOC emittance and does not degrade indoor air quality.

Sustainability attributes can be evaluated by performing a life cycle assessment. Because these procedures are time consuming, green building rating systems such as LEED have become popular. Precast concrete can help a project earn up to 23 points toward LEED certification for new buildings (a total of 26 points are required).

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