

Sustainability of Concrete Construction

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Abstract: Sustainability is important to the well-being of our planet, continued growth of a society, and human development. Concrete is one of the most widely used construction materials in the world. However, the production of portland cement, an essential constituent of concrete, leads to the release of significant amounts of CO₂, a greenhouse gas (GHG); production of one ton of portland cement produces about one ton of CO₂ and other GHGs. The environmental issues associated with GHGs, in addition to natural resources issues, will play a leading role in the sustainable development of the cement and concrete industry during this century. For example, as the supply of good-quality limestone to produce cement decreases, producing adequate amounts of portland cement for construction will become more difficult. There is a possibility that when there is no more good-quality limestone in, say, a geographical region, and thus no portland cement, all the employment associated with the concrete industry, as well as new construction projects, will be terminated. Because of limited natural resources, concern over GHGs, or, both, cement production is being curtailed, or at least cannot be increased to keep up with the population increase, in some regions of the world. It is therefore necessary to look for sustainable solutions for future concrete construction. A sustainable concrete structure is constructed to ensure that the total environmental impact during its life cycle, including its use, will be minimal. Sustainable concrete should have a very low inherent energy requirement, be produced with little waste, be made from some of the most plentiful resources on earth, produce durable structures, have a very high thermal mass, and be made with recycled materials. Sustainable constructions have a small impact on the environment. They use “green” materials, which have low energy costs, high durability, low maintenance requirements, and contain a large proportion of recycled or recyclable materials. Green materials also use less energy and resources and can lead to high-performance cements and concrete. Concrete must keep evolving to satisfy the increasing demands of all its users. Designing for sustainability means accounting for the short-term and long-term environmental consequences in the design.

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Introduction

According to the World Commission on Environment and Development of the United Nations, sustainability means “meeting the needs of the present without compromising the ability of the future generations to meet their own needs” (UNFCCC COP9 Rep. 2004). The sustainability of the cement and concrete industries is imperative to the well-being of our planet and to human development. However, the production of portland cement, an essential constituent of concrete, leads to the release of a significant amount of CO₂ and other greenhouse gases (GHGs) (Malhotra 2004). The environmental issues associated with CO₂ will play a leading role in the sustainable development of the cement and concrete industry during this century. One of the biggest threats to the sustainability of the cement industry is the dwindling amount of limestone in some geographical regions. Limestone is essential

to the production of portland cement. As limestone becomes a limited resource, employment and construction associated with the concrete industry will decline. Therefore, those involved with these industries must develop new techniques for creating concrete with minimal use of limestone. Not only is concrete production a valuable source of societal development, but it is also a significant source of employment. Concrete is the world’s most consumed man-made material. It is no wonder that in the United States alone, concrete construction accounted for 2 million jobs in 2002 (H. R. 394 2004). About 2.7 billion m³ of concrete were produced in 2002 worldwide. This equals more than 0.4 m³ of concrete produced per person annually. Therefore, not only to create sustainable societal development but also to sustain employment—such as batch plant operators, truck drivers, ironworkers, laborers, carpenters, finishers, equipment operators, and testing technicians, as well as professional engineers, architects, surveyors, and inspectors—the concrete industry must continue to evolve with the changing needs and expectations of society worldwide.

What Is Sustainability for the Concrete Industry?

Limestone is used to manufacture portland cement:

limestone → crusher → grinder → raw meal (containing other ingredients) → kiln → clinker + additives → grinder → cement (Worrell and Galtisky 2004).

Limestone is also used as aggregate in concrete:

limestone → crusher → aggregates → concrete.

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Currently, portland cement is the most commonly used material in producing concrete.

Some geographical regions are running out of limestone resources to produce cement. And major metropolitan areas are running out of materials to use as aggregates for making concrete. Sustainability requires those in the construction industry to consider the entire life cycle—including construction, maintenance, demolition, and recycling of buildings (McDonough 1992; Worrell and Galtisky 2004).

A sustainable concrete structure is one that is constructed so that the total societal impact during its entire life cycle is minimal. Designing with sustainability in mind includes accounting for the short-term and long-term consequences of the structure. To decrease the long-term impact of structures, the creation of durable structures is paramount.

Building in a sustainable manner and scheduling appropriate building maintenance are significant in the “new construction ideology” of this new century. In particular, to build in a sustainable manner means to focus attention on the effects on human health, energy conservation, and physical, environmental, and technological resources for new and existing buildings. It is also important to take into account the impact of construction technologies and methods when creating sustainable structures (McDonough 1992). An integrated sustainable design process can reduce project costs and operating costs of the building or the infrastructure construction.

Many challenges are associated with portland cement production. Of these, energy and resource conservation, the cost of producing portland cement, and GHG emissions are the most significant. Therefore, supplementary cementing materials such as fly ash and ground granulated blast-furnace slag should replace larger amounts of portland cement in concrete. However, before any construction occurs, all aspects of the building materials to be used should be evaluated. To build structures and infrastructures that are cost-efficient, environmentally friendly, and durable, the impact of the building materials on local and worldwide air conditions must be examined (McDonough 1992). At the current rate of increase of cement production (USGS 2006, 2007), worldwide cement production is expected to rise from about 2.5 billion t in 2006 to about 5 billion t by 2020. Thus, CO₂ emission caused by portland cement production is expected to rise by 100% from the current level by 2020.

For each metric ton of portland cement clinker, 1.5 to 10 kg of NO_x is released into the atmosphere. In 2000, worldwide cement clinker production was approximately 1.5 billion t. In 2000, between 2.3 and 15 million t of NO_x were produced to make portland cement clinker. Clinker production in the United States was about 85 million t in 2005 (PCA 2006); and therefore, about 125 to 850 thousand t of NO_x were produced in the United States to make portland cement.

If the challenges associated with reducing CO₂, NO_x, and other GHGs are to be met, then the concrete industry must develop other materials to replace portland cement. The use of blended cements and organic chemical admixtures must be significantly increased for sustainability of the cement and concrete industries.

Concrete

For more than 200 years, concrete has been accepted for its long-lasting and dependable nature. In addition to durability and dependability, concrete also has superior energy performance, is

flexible in design, is affordable, and is relatively environmentally friendly (Cement Association of Canada 2004). It can be expected that concrete will be needed to increase industrialization and urbanization while protecting the environment (Milwaukee Journal Sentinel 2006). To do this, the concrete industry should consider recycling industrial by-products such as fly ash safely and economically. When industrial by-products replace cement, even up to 70%, in concrete, the environmental impact improves along with the energy efficiency and durability of concrete (Naik et al. 2003).

Concrete is a building material that is not only strong and durable but can also be produced in ways that are environmentally friendly and architecturally moldable in esthetically pleasing forms (National Building Museum 2004). With sustainable concrete structures and infrastructure, the concrete industry can develop a sustainable future for generations to come. Furthermore, buildings that are constructed to be both durable and environmentally friendly often lead to higher productivity because the buildings generally lead to better air quality and therefore higher productivity. One example of the advantage of sustainable concrete is buildings constructed with concrete that have reduced maintenance and energy costs. Another is concrete highways, which reduce the fuel needed for heavily loaded trucks. A third example of the benefits of sustainable concrete construction is illustrated in insulating concrete homes that have energy reductions of up to 40% (Cement Association of Canada 2004).

The cement and concrete industries can make substantial contributions to sustainable development by creating and adopting technologies that can reduce the emissions of greenhouse gases. The cement and concrete industries could contribute to meeting the goals and objectives of the 1997 Kyoto Protocol (UNFCCC COP9 Rep. 2004). Among other things, the Kyoto Protocol requires meeting a target of reduction in GHGs to the 1990 level. It is estimated that about 28 billion t of CO₂ were emitted worldwide in 2004 (United Nations 2007), with significant portions emitted by the United States (22%), China (18%), E.U. (11%), Russia (6%), India (5%), and Japan (5%). Those involved with the manufacture of portland cement would have a huge impact on the sustainable development of the concrete industry as a whole, because in 2004 cement production contributed about 7% of worldwide GHGs (primarily CO₂); or, about 2 billion t of GHGs. Any future taxes on GHG emission would have noticeable and noteworthy economic impact on the price of cement.

A number of characteristics apply to innovative concrete products. First, they are produced with precast or cast-in-place reinforced concrete elements that are made with portland cement and pozzolanic materials that include renewable components, recycled components, or both. Second, innovative concrete products are constructed to enhance the performance of concrete elements, which may also contain recycled concrete as aggregates. High-performance materials are intended to reduce cross sections and the volume of concrete produced. They are also intended to increase the durability of concrete structures to minimize the maintenance needs of the concrete construction and limit the amount of nonrenewable special repair materials that need to be used in maintaining the concrete (Coppola et al. 2004).

Concrete producers are creating sustainable solutions for many market sectors, including agriculture and construction. In agriculture, integrated waste management solutions have been developed that convert manure into biogas, nutrient rich fertilizer, and reusable water. Industrial, commercial, and institutional buildings are being constructed so that they are more energy efficient, have

better air quality, and necessitate less maintenance (McDonough 1992).

Foundries in the United States generate more than 7 million t of by-products. Wisconsin alone produces almost 1.1 million t of foundry by-products, including foundry sand and slag. Most of these by-products are landfilled. Landfilling is not a desirable option because it not only causes a huge financial burden to foundries but also increases liability for future environmental costs, as well as restrictions associated with landfilling. One innovative solution appears to be high-volume uses of foundry by-products in concrete and other construction materials (Naik and Kraus 1999).

According to Construction and Demolition Debris (2003), the United States produced 140 million t of construction and demolition (C & D) debris, about 1.4 kg per person per day, in 2002. About 25 to 40% of landfill space is C & D debris (McKay 2004). If this trend continues, the cost of landfilling will continuously increase, as will the potential health and environmental risks of landfill materials. Furthermore, the cost of landfilling is escalating because of shrinking landfill space and stricter environmental regulations. Such C&D debris (e.g., concrete, as well as gypsum wallboards from C&D debris) can be recycled to make new concrete; in addition, waste glass when finely ground can also be recycled and used as a pozzolanic material (PM) (UWM-CBU 2007).

A study was reported in 1999, the aim of which was to evaluate the environmental impact of controlled low-strength materials (CLSM) incorporating cement and industrial by-products such as coal fly ash and used foundry sand (Naik and Kraus 1999). The results demonstrated that excavatable flowable slurry incorporating fly ash and foundry sand as a replacement for up to 85% of fly ash could be produced. In general, including both clean and used foundry sand caused a reduction in the concentration of certain contaminants. The use of foundry sand in flowable CLSM slurry therefore provided a favorable environmental performance.

Portland Cement

Portland cement is not an environmentally friendly material, because its manufacture creates greenhouse gas emissions; it also reduces the supply of good-quality limestone and clay. As good engineers, we must reduce the use of portland cement in concrete (Malhotra 2004). We must use more blended cements to reduce the need for portland cement clinker per metric ton of blended cement produced by blending with the clinker other PMs, such as coal or wood fly ash, slag, silica fume, and such other PMs as finely ground waste glass. As a cement production feed material, instead of clay, industrial by-products such as used foundry sand or coal combustion products (CCPs) such as fly ash should be used in the optimum possible quantity.

The most energy-intensive stage of portland cement production is during clinker production. It accounts for all but about 10% of the energy use and nearly all of the GHGs produced by cement production. Kiln systems evaporate inherent water from the raw meal and calcine the carbonate constituents during clinker preprocessing (Worrell and Galtisky 2004).

Sources of CO₂ and GHG emissions in the manufacturing of portland cement (Malhotra 2004) are as follows:

- From calcinations of limestone=50–55%.
- From fuel combustion=40–50%.
- From use of electric power=0–10%.

Innovative Cement Products

Although the embodied energy linked to concrete production is low, PMs, especially coal fly ash, have been used by the concrete industry for more than 70 years. Their use can contribute to a further reduction of concrete's embodied energy. When used wisely and judiciously, PMs can improve the long-term properties of concrete. Fly ash can and does regularly replace portland cement in concrete (Mehta 2002; Naik et al. 2003; Malhotra 2004).

One process that is even more environmentally friendly and productive is the use of blended cements. Blended cements have been used for many decades. Blended cements are made when various amounts of clinker are blended or interground with one or more additives, including fly ash, natural pozzolans, slag, silica fume, and other PMs. Blended cements allow for a reduction in the energy used and reduce GHG emissions (Malhotra 2004; Mehta 2002).

Most innovative concrete mixtures make use of PMs to partially replace cement. The advantages of blended cements include increased production capacity, reduced GHG emissions, reduced fuel consumption in the final cement production, and recycling of PMs (Worrell and Galtisky 2004; Cement Association of Canada 2004).

The manufacture of portland cement is the third most energy-intensive process, after aluminum and steel manufacture. In fact, for each metric ton of portland cement, about 5-1/2 million BTU of energy are needed (Naik and Kraus 1999).

Although cement production is energy-inefficient, major initiatives have reduced energy consumption (Worrell and Galtisky 2004). Of these, the most significant has been the replacement of wet production facilities with dry processing plants. In addition, the cement industry has also moved away from petroleum-based fuel use.

Despite these advances, some shortcomings still exist when energy use is evaluated for the concrete industry. Dry process cement plants use preheaters, which increase the alkali content of cement (Worrell and Galtisky 2004). Thus, cement producers need to continue to develop ways to control the alkali content without increasing the energy consumption levels of the cement (Coppola et al. 2004). Furthermore, current innovations and energy savings are linked to the amount of energy consumption by converting wet-process to dry-process cement production and the number of preheaters needed to complete the process (Worrell and Galtisky 2004).

For each million metric ton of capacity, a new portland cement plant costs more than \$225 million. The cost associated with producing portland cement, along with the CO₂ emissions and energy issues, makes it unlikely that developing countries will be able to employ modern technology to reduce GHGs. Also, government regulations of GHGs will likely force the cement industry to create blended cements and use supplementary materials for blended cements to meet societal development needs (Malhotra 2004; Worrell and Galitsky 2004).

To produce 1 t of portland cement, 1.6 t of raw materials are needed (Wu 2000). These materials include good-quality limestone and clay. Therefore, to manufacture the current worldwide production of 2.5 billion t of cement annually (USGS 2007), at least 4 billion t of raw materials are needed.

As good engineers, we must employ environmentally friendly materials to reduce the use of portland cement by replacing a major part of portland cement with PMs for use in concrete. In the United States, such materials—primarily fly ash, slag, silica fume, natural pozzolans, rice-husk ash, wood ash, and agricultural-

products ash—are available for up to 70% replacement (Naik et al. 2003). All these materials can be used to supplement the use of cement in concrete mixtures while improving the concrete product durability.

One of the important benefits of the increased use of other types of cementitious materials (such as PMs) is the reduction of GHG emissions. With replacement of cement with other recyclable resources, worldwide CO₂ emissions would be reduced. A replacement of 50% of cement worldwide by other cementitious materials would reduce CO₂ emissions by more than 1 billion t. This is equivalent to removing approximately one-quarter of all automobiles in the world (Malhotra 2004).

Fly ash production in the United States in 2005 was estimated at 64 million t by the American Coal Ash Association (ACAA 2006); by 2010 it is estimated to be 70 million t. Portland cement use in the United States in 2005 was estimated at more than 125 million t; by 2010 it is estimated to be 140 million t (PCA 2006). The fly ash disposal challenge and the limited availability of portland cement have the same solution: replace large amounts of portland cement with fly ash to create durable and sustainable concrete.

The Hannover Principles—Design for Sustainability

In 1991, as the planning of the World's Fair was under way, the city of Hannover, Germany asked William McDonough and Michael Braungart to create sustainability principles to guide the large-scale development of EXPO 2000 in Hannover. "The Hannover Principles—Design for Sustainability" also include directives concerning the use of water. Although these guidelines were created for the World's Fair, they are still a good tool to guide current and future development around the world (McDonough 1992).

Designers, planners, government officials, and all those who participate in the construction of new buildings and infrastructures should use the Hannover Principles. The new design philosophy that has developed from these principles should be included in sustainable systems and construction in the future. A number of societies have created sustainable and environmentally friendly communities. There is hope that the Hannover Principles will inspire development and improvements that are committed to sustainable growth with practical limits to create a sustainable and supportive future for communities and the world.

The Hannover Principles by William McDonough (McDonough 1992) are as follows: Insist on rights of humanity and nature to coexist; recognize interdependence; respect relationships between spirit and matter; accept responsibility for consequences of design; create safe objects of long-term value; eliminate the concept of waste; rely on natural energy flows; understand the limitations of design; and seek constant improvement by sharing knowledge.

The Hannover Principles are not "cast in concrete." They were devised to provide a tangible document that could evolve and be adapted as our understanding of our interdependence with nature becomes more important over time.

For sustainability, consider your actions on the following (McDonough 1992):

- Materials—use indigenous materials.
- Land use—protect and create rich soil.
- Urban context—preserve open spaces.
- Water—use rainwater and graywater (shower, sink, bath, and laundry excess).

- Wastes—recycle.
- Air—create clean air.
- Energy—use solar and wind energy, recycle waste energy.
- Responsibility to nature—create silence.
- Maintenance—minimize or eliminate for future generations.

Materials are critical for creating sustainable and responsible concrete designs. To ensure that the most effective and environmentally friendly materials are being used, the entire life cycle of the structure should be considered. Material choice should include anticipation of the extraction, processing, transport, construction, operation, disposal, reuse, recycling, and off-gassing and volatile organic compounds (VOCs) associated with the material (McDonough 1992). According to McDonough, constructions should be flexible to serve a variety of different needs (e.g., today's storage building can be tomorrow's school). Adapt materials that are sustainable in their process of extraction, manufacture, transformation, and degradation, as well as recyclability. Consider toxicity, off-gassing, finish, and maintenance. Recycling is essential. Make allowance for disassembly and reuse. Plan for reuse of the entire structure in the future. Minimize use of hazardous chemicals. Eliminate waste that cannot be part of a naturally sustainable cycle. Any solid wastes remaining must be dealt with in a non-toxic manner. Life-cycle costs must be studied, analyzed, and incorporated in planning and constructing a building or infrastructure. The life-cycle cost analysis process must evaluate energy use and environmental impact during the life of the product, process, or activity. This process must include extracting and processing raw materials, manufacturing, transporting, maintaining, recycling, and returning to the environment. Costs and benefits must be evaluated and understood in both the short term and the long term. Demolished concrete must be recycled. It can be readily used in new concrete for aggregates.

For the sustainability of the cement and concrete industries, use less water and portland cement in concrete production, and use more blended cements and tailor-made organic chemical admixtures. The devastation of air is a global problem, regardless of the locality in which the pollution is created (McDonough 1992). The overall design of concrete structures must not contribute to atmospheric degradation. Those involved in the cement and concrete industries must evaluate ozone depletion and global warming throughout the construction and planning process. A major contribution to this effort is the use of more blended portland cement to minimize global climate change.

Water resources are being depleted by various uses (Bourg 2004). Therefore, potable water should be conserved to serve life-sustaining needs rather than infrastructure needs. Rainwater and surface runoff water can be used as a water conservation method by recycling these water resources in construction instead of using potable water. Graywater should be recycled and used for grass, shrubs, plants, trees, and gardens, as well as for concrete production (McDonough 1992). Furthermore, mixtures with less water should be developed with new technologies to create mortar and concrete containing a minimal amount of water.

More than 200 years ago, Benjamin Franklin said in *Poor Richard's Almanac*, "When the well's dry, we know the worth of water." Many facilities may have requirements that can be completed with nonpotable water. By using nonpotable water, a significant amount of money can be saved by avoiding or reducing potable water purchases and sewerage costs. To be as cost-effective as possible, nonpotable water for construction and building uses should be identified early in the planning and designing process. Four ways to use and recycle water are to reuse water on-site for repeated cycles of the same task, treat and reuse water

on-site for multiple purposes, use graywater after solids have been eliminated, and collect nonpotable water from such sources as rainwater, lakes, rivers, and ponds for use in construction (Bourg 2004).

Energy efficiency, providing the same (or more) services for less energy, helps to protect the environment. When less energy is used, less energy needs to be generated by power plants, thus reducing energy consumption and production. This in turn reduces GHGs and improves the quality of the air. Energy efficiency also helps the economy by saving costs for consumers and businesses. According to McDonough (1992): (a) use the thermal inertia of buildings (e.g., concrete mass of a building allows it to retain heat); (b) use day lighting and natural ventilation; (c) use wind power and solar power; (d) recycle waste energy; (e) judiciously use colored materials on surfaces; (f) reduce heat islands in buildings; and (g) manage and moderate microclimates of buildings.

Waste Materials

Engineers, architects, planners, and builders should reuse industrial by-products and postconsumer wastes in concrete and other cement-based construction materials. Postconsumer wastes that should be considered for use in concrete include glass, plastics, tires, demolished concrete, and clay bricks. To do this successfully, designers must watch for harmful hydration reactions of portland cement and changes in the volume of concrete. The recycling of industrial by-products has been well established in the cement and concrete industries over the past several decades (UWM-CBU 2007). The use of coal fly ash in concrete began in the 1930s, but volcanic ash has been used in mortar and primitive concrete for several millennia in Egypt, Italy, Mexico, and India. The use of by-products such as rice-husk ash, wood ash, silica fume, and other pozzolanic materials, in addition to coal fly ash, can help reduce the need for portland cement in addition to creating more durable concrete and reducing greenhouse gas emissions (Malhotra 2004; Mehta 2002; ACI 2004). This will also contribute to the improvement of air quality, reduction of solid wastes, and sustainability of the cement and concrete industry (Mehta 2002).

In summary, for sustainability of the cement and concrete industries, use less portland cement; use less water; use application-specific high-quality, durable aggregates; and use organic chemical admixtures.

Fundamental laws of nature state that we cannot create or destroy matter; we can only affect how it is organized, transformed, and used. To manage natural resources, humanity must obey the rules of nature: use only what you need and never use a resource faster than nature can replenish it.

Resources are extracted from the earth at a rate of 20% more than the earth produces. Therefore, what is consumed in 12 months will take 14.4 months to be replenished. The use of sustainable development procedures will reduce that rate (*Time Magazine* 2002). "The issue is not environment vs. development or ecology vs. economy; the two can be (and must be) integrated" (Ricoh Company 2004).

Conclusions

As Kofi Annan, U.N. Secretary General, said in 2002, "We have the human and material resources needed to achieve sustainable

developments, not as an abstract concept but as concrete reality" (*Time Magazine* 2002). Professionals involved in the cement and concrete industries have the responsibility to generate lasting innovations to protect the industries' future viability, as well as the health of our environment. Large volumes of by-product materials are generally disposed in landfills. Because of stricter environmental regulations, the disposal costs for by-products are rapidly escalating. Recycling and creating sustainable construction designs not only contribute to reduced disposal costs but also aid in conserving natural resources. This conservation provides technical and economic benefits. It is necessary for those involved in the cement and concrete industries to eliminate waste and take responsibility for the life cycle of their creations. To be responsible engineers, it is necessary to think about the ecology, equity, and economy of our design (McDonough 1992).

Engineers must apply forethought into direct and meaningful action throughout our development practices. Sustainable designs must be used as alternatives and as better approaches to traditional designs. The impacts of every design choice on the natural and cultural resources of the local, regional, and global environments must be recognized in the new design approaches developed and used by the cement and concrete industries.

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