Review of Sustainable Practices and Approaches in the Concrete Industry

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Introduction

Continuing population growth across the globe is putting pressure on existing infrastructure to meet the demands of an expanding user base. In particular, increasing urbanization requires the construction of new infrastructure to provide for basic living requirements, such as clean water, transportation, energy, and so forth, necessary to sustain life inside the mega-cities. Already, in the past fifty years the number of mega-cities with a population greater than ten million has grown from two to twenty-two\(^1\). However, development can no longer continue at the pace at which it did during the previous century. Environmental concerns, such as climate change and waste production, as well as the depletion of natural resources are driving a shift in philosophy.

Sustainability, or sustainable development, is a term used to describe practices which meet the needs of the present without compromising the ability of future generations to meet their own needs\(^2\). This term was originally defined by the Brundtland Commission in a report to the United Nations in 1987 on sustainable development and its political implications. Even though sustainability was defined over 20 years ago, there is still difficulty in applying sustainable concepts to modern practice due to the broad scope of the original definition.

The American Society of Civil Engineers (ASCE) attempted to clarify the role of sustainability in civil engineering practice by adopting a definition in 1996 which stated that sustainable development should meet human needs while considering the environment and natural resources necessary for the future. Furthermore, the ASCE Code of Ethics was revised to contain language requiring engineers to follow sustainable practices\(^3\).

While the concrete industry itself has not established an overarching guideline for sustainable practice, there still remain two unavoidable challenges. The first is to meet the growing demand for infrastructure necessary to provide an acceptable standard of living. The second is to achieve the first while reducing the environmental impact caused by concrete industry activities. This paper will review the practices and approaches taken in the concrete industry in order to meet these challenges and move towards the ultimate goal of sustainable development.

Concrete and Sustainability

Concrete is an integral part of infrastructure construction, providing the very foundation upon which our society and quality of life are built. However, the concrete industry also plays a major role in environmental deterioration. The production of one ton of Portland cement, the binding agent in concrete, requires 1.5 tons of limestone, consumes large amounts of both fossil fuel and electrical energy, and also releases approximately one ton of carbon dioxide, a greenhouse gas. Production of concrete material also requires large amounts of natural resources such as water, sand, gravel, and crushed rock. By some estimates, the concrete industry is the largest consumer of these resources in the world.

In order to reduce the environmental impact of concrete and cement in the short term, it would be ideal to reduce the total rate of consumption. However, this is not possible, as cement production has been steadily increasing over the last ten years, as shown in Figure 1, and is expected to continue increasing in the foreseeable future to meet demand driven by economic expansion. Additionally, the efficiency of cement production plants has reached a point of diminishing returns, where it is difficult and expensive to further reduce energy consumption. Phasing out

Figure 1 World cement production over the last 10 years\(^4\)
older, inefficient plants and replacing them with modern facilities will provide some relief, but cannot compensate for the forecasted increased demand.

Since concrete consumption cannot be reduced for the time being, and it is difficult to increase efficiency in existing cement manufacturing plants, other means of reducing consumption of cement and other virgin materials must be explored. One option already being utilized to a limited extent is the usage of supplementary cementing materials as a replacement for Portland cement. Other options include replacing natural aggregates with crushed concrete from demolition sites or substituting recycled water from mixing plants for fresh water. These options attempt to conserve the materials necessary for concrete construction. Another approach is to enhance the durability of concrete structures. By increasing durability, service life can be extended, which reduces the need for new infrastructure and thus conserving construction materials.

More so than any one problem, however, the concrete industry should take a holistic approach to concrete construction. The concrete industry must provide more than just a building material, but should take responsibility for other societal needs such as conservation of natural resources and disposal of waste materials.

Mehta proposed that these three elements — conservation of concrete-making materials, durable structures, and a holistic approach — form the foundation upon which sustainable technologies should be developed. In the following sections, these different aspects of concrete and sustainability will be discussed in greater detail.

**Material Conservation**

The concrete industry is a major consumer of raw materials. Utilizing replacement materials such as industrial by-products or recycled waste can help reduce consumption rate as well as utilize waste which would otherwise be thrown away.

**Industrial ecology**

The term industrial ecology refers to the practice of recycling the waste products from one industry as a substitute for virgin materials in another industry. For concrete, there are many opportunities for this practice to be implemented.

One of the most widely-used industrial by-products is fly ash. Fly ash is a pozzolanic material generated by the combustion of coal and can be used as a replacement for Portland cement due to its cementitious properties when mixed with lime. The addition of fly ash to concrete improves strength, durability, and resistance to chemical attack due to its small particle size, which can help fill voids between the cement particles. In addition, the spherical particle shape helps improve workability of fresh concrete and allows for the reduction of mixing water.

While the replacement volume of fly ash is often limited by prescriptive codes, high-volume fly ash concrete has been developed which replaces up to 60% of Portland cement with fly ash. This technology has the potential for utilizing large amounts of fly ash, reducing demand for Portland cement as well as the need for large landfills.

Other supplementary cementing materials include ground granulated blast furnace slag, silica fume, meta kaolin, and rice-husk ash. The availability and application of these materials, however, is limited compared to fly ash, although their use is increasing.

The demand for concrete is particularly high in developing countries such as China and India. These same countries also produce large amounts of fly ash and blast furnace slag, the majority of which is not being utilized in concrete construction. Utilizing these materials instead of cement could meet demand without increasing production capacity, thus demonstrating the importance of utilizing by-products in future development.

In addition to fly ash and blast furnace slag, by-products from other industries also have potential application in the concrete industry. Some examples include: semimetallic waste from metallurgical processes as aggregate for producing high-density concrete; filter cake from calcium carbide production as filler in concrete mixtures; and anhydrite from flocculant production residue as a partial cement replacement material in controlled conditions. Limited practical application of these materials has already been achieved and demonstrates new opportunities for the concrete industry to practice industrial ecology.

**Recycling**

Another source of waste is the demolition of old buildings and infrastructure. This waste concrete can be processed and reused as a replacement for aggregate in new construction, which reduces the need for virgin materials as well as the volume of material disposed of in waste sites and landfills. Recycled aggregates, however, typically have greater porosity and water absorption characteristics due to the cement mortar attached to the old coarse aggregate, which results in lower concrete strength. As a result, the production process of the recycled aggregates plays an important role in assuring final concrete performance.

Some research works have investigated the application of recycled glass as a raw material for concrete. In particular, lightweight aggregate made from foamed glass has potential for future applications. This type of aggregate has an uneven surface which increases bonding capability but requires cement paste with a high filler content to meet workability requirements. However, glass may be considered as reactive in some forms when used in concrete, so cautious mix design is necessary if this material is to be utilized.
Durability

Material conservation can also be achieved by extending the service life of infrastructure. For concrete, durability is typically associated with cracking, which allows the ingress of corrosive agents. Unfortunately, modern concretes tend to crack at early age due to the increased use of high-early-strength cements, which are prone to cracking, and research has found that the emphasis on fast construction schedules and achieving load-carrying capacity as soon as possible is responsible for the large volume of low-durability structures constructed in the 1980s and 90s.

The importance of cracking can be realized by looking at the mechanisms which cause deterioration. In most cases, deterioration is caused by the corrosion of reinforcing steel; however, other causes include alkali-silica reaction, freeze-thaw cycles, or sulfate attack. However, regardless of the cause, deterioration cannot occur without the presence of water. Cracking resistance is therefore extremely important for preventing the intrusion of water.

Cracks are primarily caused by thermal contraction and drying shrinkage in the early stages of construction. These cracks, by themselves, do not reduce the durability of the structure unless they form an interconnected pathway which allows for water transport. These cracks may propagate under structural loading or from exposure to weather until the water tightness of the structural is lost. Deterioration then occurs as a cyclic process whereby deterioration processes cause further cracking, which then allows for water intrusion and thus more deterioration.

For new construction, utilizing fly ash or slag can help reduce early-age cracking, thus improving crack resistance and durability. Other solutions include admixtures for preventing corrosion, epoxy-coated bars, surface coatings, and cathodic protection. For existing structures, maintenance, repair, and retrofitting operations should be considered for extending service.

A Holistic Approach

In his paper on sustainable technology, Mehta proposed that the concrete industry’s reductionist approach is responsible for many unsustainable practices. A holistic approach is necessary to shift the concrete industry toward sustainable practice.

A holistic approach values the whole as greater than a sum of its individual parts. For the concrete industry, this approach would suggest that society is the greater whole, with the concrete industry as just one part. One way to implement a holistic approach would be to place more emphasis on durable, crack-free construction rather than faster construction speed. Such an approach would place responsibility on the concrete industry to provide not only a cheap construction material, but also carry other societal needs.

Considering other societal needs could open up new markets for the concrete industry. Jahren suggests that the concrete industry should look at the production of artificial reefs and sea life breeding-ground restoration as two areas where the concrete industry could create a product which would contribute to the well-being of society by helping to meet the growing demand for seafood necessary to feed a growing world population.

The difficulty in shifting from reductionist to holistic practice lies with problems in how engineering and science are taught at the university level. There is a lack of courses on concrete technology and few students pursue graduate-level study of concrete material. In addition, the problems faced in the real world often cannot be solved by application of scientific or engineering knowledge alone, but requires an integration of knowledge from many fields such as the social sciences or humanities. A holistic approach is necessary to bring together these different areas of knowledge and apply concrete material technology for sustainable practice.

Institutional Barriers

While there is a growing awareness of the importance of sustainable practices, and many green technologies have been proven to be both cost-effective and practical, many barriers to implementing these practices still remain.

One problem is the importance of fast construction and low initial cost over durability and life cycle cost. As discussed before, speedy construction often comes at the cost of early-age cracks, which severely reduce durability and service life. Another issue is out-dated building codes which restrict the use of recycled or by-product supplementary cementing materials such as fly ash. Many of these codes are prescriptive in nature, which places limits on the proportions of cement replacement or specifies a material or mix proportion rather than a level of performance. Shifting from prescriptive to performance-based specifications would provide freedom for the usage of new innovative technologies with proven performance capabilities, such as high-volume fly ash concrete. Finally, as proposed by Mehta, the concrete industry’s reductionist approach results in practice which places the profit of the concrete industry before the benefit of society.

Recent Progress

In order to meet the challenges of sustainability, the American Concrete Institute (ACI) established a Board Advisory Committee on Sustainable Development (BACSD) to develop recommendations for ACI on how to promote sustainable practice. In 2005, the BACSD proposed that the concrete industry adopt a definition of sustainability containing the following elements:
- Specification, design, and proportioning of concrete must be...
performed considering durability, conservation, and minimal environmental impact
- Production of ingredients, concrete, and construction practice must be environmentally responsible
- Concrete must be sustainable and viewed as sustainable by the public
- Concrete industry must remain competitive

In addition to this definition, the BACSD also made several recommendations to ACI, ranging from policy statements to documentation and guidelines for sustainable practice to education for both concrete engineers and non-engineers alike. However, it is not clear how much progress has been made towards achieving these goals.

In 2007, ACI and the Portland Cement Association (PCA) organized the Concrete Summit on Sustainable Development to discuss the challenge of sustainability to the concrete industry. At this summit, opportunities for improvement were identified as energy consumption, generation of greenhouse gases, land use, resource consumption, dust and diesel emissions, and reduce/reuse/recycle applications. The committee understood that, while there are many areas for improvement, there are aspects of concrete which should be enhanced to increase the competitiveness of concrete as a building material: fire and force protection, thermal mass, and durability. A sustainable framework was also proposed to encompass and illustrate the variety of discussions which were held (Fig. 2).

Conclusion

Just as the concrete industry serves as a leader in infrastructure construction, so too should it become a leader in promoting sustainable development as a design philosophy to enhance the longevity and quality of our construction works while minimizing their impact on society and the environment. As reviewed in this paper, many new concrete mixtures utilizing industrial by-products or recycled materials have been applied and practically proven, but there exist institutional barriers such as prescriptive codes which restrict the adoption of these new technologies. Performance-based codes would allow for the application of innovative, sustainable technologies with proven performance. Durability is also an important factor for sustainable practice, but the current business philosophy emphasizes construction speed over life cycle performance, which results in early-age cracks which decrease structural durability and shorten the service life.

A shift away from reductionist practice to a holistic view would promote durable structural design and lower life cycle cost.

There is an awareness of the sustainable issues facing the concrete industry. However, professional groups need to take the lead by turning sustainable concepts into practical policy and guidelines which can be understood and used by practicing engineers.

(Manuscript received. November 10, 2008)

References

8) Jahren, P., "Do not forget the other chapters!," ACI Concrete International, July 2002, pp. 41–44.