New Technologies for Sustainable Concrete

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ABSTRACT: The focus of this paper is to look at some innovative ideas that show promise of improving the sustainability of concrete systems in the near term. The discussion includes a definition of sustainability in the context of providing societal needs for infrastructure and examples of innovative technologies that show promise of improving sustainability of concrete structures and pavements. The technologies addressed include materials, mixtures and construction approaches.

WHAT IS SUSTAINABILITY?

Fundamentally, being sustainable in the context of the built environment is simply good engineering – the art of balancing limited resources to provide the best possible infrastructure to meet growing demands.

In the past, economic factors were the only ones considered, while sustainability considerations require that environmental and social factors be considered as well (Figure 1).

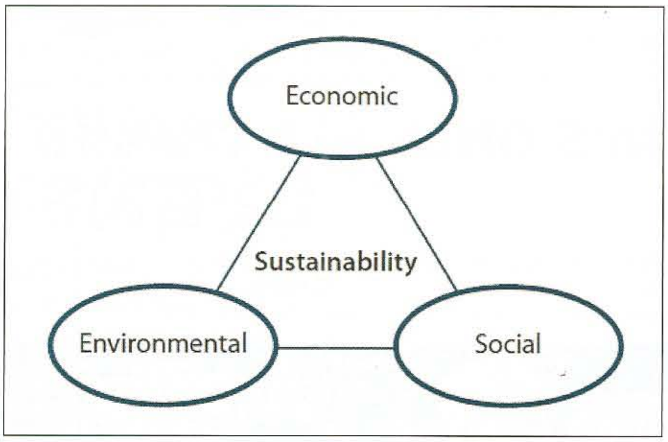

Figure 1. Representation of the critical aspects of sustainability

In addition, the analysis should include the entire life cycle of the project and address all impacts from the point of inception until the structure is removed and disposed of or recycled (Figures 2 and 3). This makes the process considerably more complex and demands wisdom in balancing and weighting the relative importance of the various parameters that have to be considered. It should be noted that over-emphasising any of economic, environmental and societal needs will lead to an imbalance which is, by definition, unsustainable [1]

At heart we are trying to provide for the needs of the present population without compromising the resources available to their children. Another way to express it would be: The use of practices and materials in concrete construction that provides a durable structure, while minimising the use of energy and non-renewable resources, and generating a minimum of pollutants in the most cost effective manner possible, while maximising the benefits to society.

As construction involves use of significant quantities of energy and materials, there will almost always be some environmental impact until significant changes in the way we obtain materials and build things with them are developed and adopted. In the meantime, we need to be diligent about reducing, as best we can, environmental impacts without sacrificing engineering quality.

A fundamental premise behind improving sustainability is to make our structures last as long as needed with a minimum of repair or rehabilitation.

Barriers to innovation are often institutional, such as standards or specifications that do not permit new ideas, and conservatism and fear of litigation forces engineers to choose to do things the way they have in the past. Any new idea, therefore, has to be rigorously demonstrated to be reliable and cost effective.

This is a very broad topic and any discussion about sustainability is inevitably skewed by the experiences and interests of those involved in the discussion. The focus of this paper is to look at some innovative ideas that show promise of improving the sustainability of concrete systems in the near term.

WHAT ARE WE TRYING TO CHANGE?

As stated above, we are trying to provide for the needs of the present population without compromising the resources available. It can be debated what the critical parameters are, but

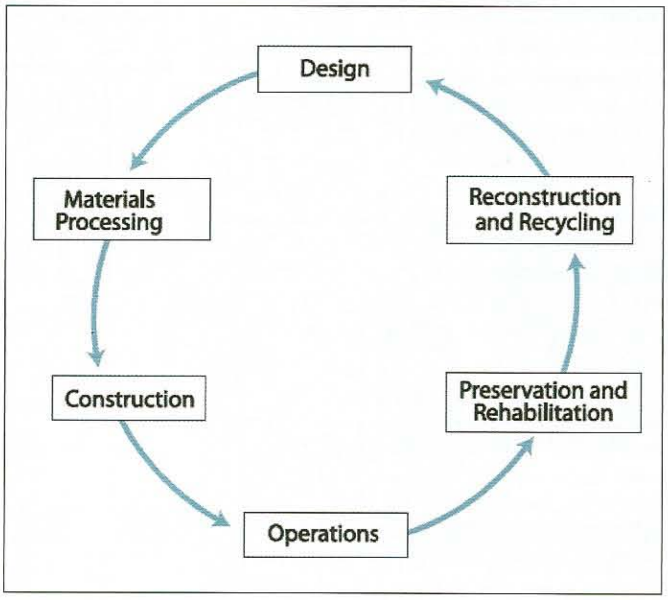

Figure 2. Sustainable engineering must expand to a complete life-cycle analysis

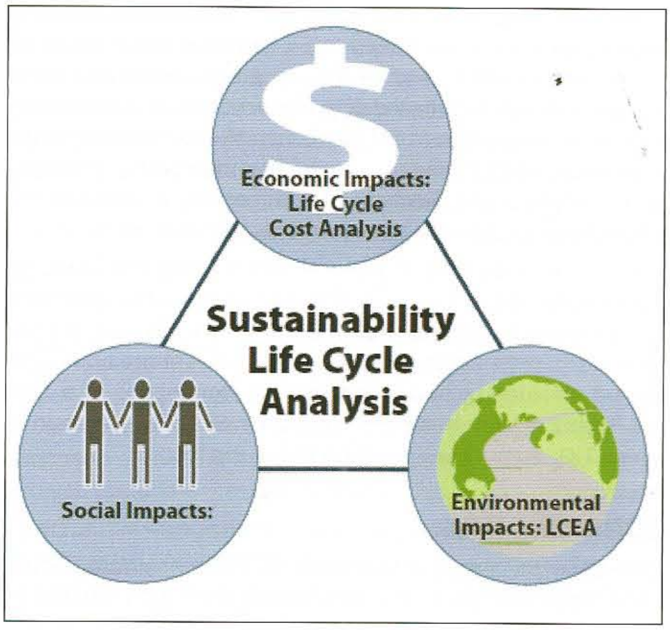

Figure 3. Economic, environmental, and social factors must be identified, measured, and balanced

there seems to some agreement that the most critical points to consider in the context of concrete construction include:

- Economic measures
    - Cost
- Environmental measures
    - Global warming potential (carbon footprint)
    - Human toxicity
    - Energy requirement
    - Hazardous waste generated
    - Materials
- Societal measures are not often discussed but may include
    - Infrastructure sufficiency and reliability
    - 'Liveability'
    - Impacts such as noise, traffic delays and safety

It should also be noted that each phase of the life of a structure will have a different impact. For instance, manufacture of cement does generate carbon dioxide. This is due to the nature of the chemical reactions, but during the use of operations or recycling phases, a concrete system is largely inert or may indeed capture CO_2. On the other hand fuel consumption during construction of a pavement is significantly less than that used by the traffic on it.

All of these issues are complex and interrelated. The remainder of this paper, however, will focus on materials and construction technologies that are currently available or nearing implementation, which have the potential to significantly benefit one or more of the measures listed above.

HOW DO WE MAKE CONCRETE MORE SUSTAINABLE?

Materials

A number of innovative materials and approaches are available or under development that contribute in some way to reducing the impacts discussed above.

Cements

While Portland cement carries with it a significant carbon footprint and energy requirement to manufacture, it is used in relatively small quantities in concrete mixtures. However, reducing the amount of Portland cement in a given element is an effective way reducing the construction phase impact of a structure. This can be achieved by reducing the amount of clinker in cement, or reducing the amount of cement in a mixture and using concrete efficiently in the design. The alternative is to consider non-Portland based cementitious materials.

Reducing the clinker content can be achieved by using blended systems, either blended at the cement plant or at the batch plant. Specifications have generally limited the dosages of limestone or Supplementary Cementitious Materials (SCM) because of concerns about setting times, early strengths, or frost resistance. This trend is beginning to change as users become more familiar with the materials and are prepared to modify their practices in order to accommodate the side effects of increasing SCM dosages. Work is ongoing on investigating how much SCM can be used in a given situation without compromising strength or durability of the final system [2]. One example of this change is the adoption of a performance based specification (ASTM C 1157) for cement that has no chemical requirements. Some of the other cements discussed in this paper are being marketed as 1157 compliant cements despite their containing no Portland cement.

A number of cementitious systems are being investigated that are either more efficient, or carry lower carbon and energy burdens than Portland cement:

- CeraTech Inc. is marketing non-portland cements that are claimed to comply with the performance requirements of ASTM C 1157. They are manufactured using activated pozzolanic materials. Performance of the system is claimed to be equivalent or superior to Portland cement [3,4].
- CCS Materials are conducting work under a Department of Energy grant to produce a substitute for Portland cement that reportedly requires less energy and is CO_2 negative. Strengths are described as similar while strength gain is very rapid [5].
- Ecocement is marketed as non-structural cement based on a mixture of Portland cement and magnesia that has the potential to sequester CO_2 as part of the hardening process [6].
- Novacem is a product developed at Imperial College and is being marketed as a carbon negative material based on magnesium silicates [7].
- Geopolymers are a broad class of materials characterised by chains or networks of inorganic molecules. The greatest potential seems to be in those comprised of aluminosilicate materials. These rely on thermally activated materials such as kaolinite, fly ash or slag) to provide a source of silicon (Si) and aluminum (Al), which is dissolved in an alkaline activating solution and subsequently polymerises to create the hardened binder. These are also referred to as alkali-activated cements. Many systems have been patented, but they are generally difficult to produce and work with. There are also safety risks associated with the high alkalinity of the activating solution. The systems require more processing, resulting in increased energy consumption and greenhouse gas generation [8].

Other ideas are regularly announced in the media but little technical information is available about them at present.

Significant barriers include: Portland cement is very cheap and industry is familiar with its application and resistant to change. This topic has captured the interests of inventors and scientists and a number of significant changes are likely to occur in the near future.

In the meantime, work on Portland cement is likely to include finding alternative sources of raw materials that will not involve the decomposition of carbonate but rather use calcium rich industrial by-products.

Aggregates

Synthetic aggregates have been produced by pressing or sintering fly ash and other industrial by-products for many years [9, 10]. These have the advantage of reducing the need for non-renewable resources and at the same time, reducing waste associated with leaching and contamination. The processing of materials and transportation required offsets some of these advantages. There use has often been limited by economic factors rather than any technical concerns.

Lightweight aggregates have proved successful and are used to reduce the weight of concrete elements. Sustainability benefits include the reduction in structural mass, which leads to lower support systems required and reduced transport costs. This balances the increase of energy required to manufacture them. In some applications, concrete made with these materials offers better insulation properties, through reduced heating and cooling demands, which may be significant.

A relatively new application for lightweight fine aggregate is to ensure that the aggregate is fully saturated before being placed in the mixture, with the purpose of allowing the absorbed water to assist with internal curing. This is particularly beneficial to very low water cement ratio mixtures where internal desiccation is probable. The benefits are a marked reduction in cracking risk and improved hydration of the element interior where exterior water will not reach [11]. Reduced cracking will most likely make a significant contribution to increasing the longevity of structures such as bridge decks.

An increasing trend that will have a significant effect of reducing energy required for construction is the use of recycled concrete as aggregate, particularly in the case of pavements where equipment is available to crush the existing pavement in situ [12]. Work is ongoing on how to develop quality assurance tools to ensure that the existing concrete is not going to cause later deleterious effects in a mixture.

An innovative approach to manufacturing aggregate is being developed by Calera Corporation, which uses carbon dioxide and brine. Work is also ongoing to produce pozzolanic materials using the same approach. The key benefit of the methodology is that it is reportedly able to capture significant quantities of gaseous carbon dioxide [13, 14].

Other materials

Sinak Corporation is marketing a surface treatment compound based on lithium silicate [15]. It is marketed as both a finishing aid and as a curing compound. The silicate in the material combines with the hydration product of the cement thus sealing the surface and reducing permeability. The benefit of this approach is that unlike traditional curing compounds it is not easily polished off the surface. It has also been reported that it reduces the risk of cracking and improves the surface durability.

Soybean oil is commercially available as an emulsion and has shown promise in concrete curing. It has been tested for moisture retention when used as a surface application and when integrally mixed. Results indicate that soybean oil substantially reduces moisture loss from fresh concrete and provides greatly improved de-icer scaling resistance. This material has potential to be beneficial in projects in environmentally sensitive areas where traditional curing compounds are not allowed [16].

Titanium dioxide modified cements are being marketed by Italcementi and reported to reduce pollution and provide a self-cleaning surface to the concrete [17]. Work is underway to assess the extent of the benefit to the atmosphere and water run-off afforded by this technology. A test section of a Two-Lift Paving system has been planned in St Louis, Missouri in which TiO_2 cement will be used in the top lift.

CONSTRUCTION

Innovative construction practices may be considered when used appropriately and can improve the sustainability of concrete systems.

Pervious concrete is a mixture with little or no fine material resulting in a system that is very permeable. Parking lots and local streets made with this material capture storm water and allow it to seep into the ground thus recharging groundwater and reducing the amount of that has the accommodated in water treatment plants. This is a significant benefit in locations where the amount of hard surface on a given property is limited because of concerns about water storage and treatment. Work has been conducted to develop mix proportioning methods and to ensure that such mixtures are resistant to the effects of cold weather. The surface noise is reported to be extremely quiet with respect to traffic [18, 19].

Ultra high performance concrete is a mixture containing significant amounts of fibre and high cementitious contents. Lafarge is marketing a proprietary system known as Ductal that achieves strengths up to 400MPa. It has been used in structural elements and in bridge decks. While the high binder content and energy required for steam curing carries a relatively high carbon footprint, the extreme efficiency of materials use and potential longevity mean that the system may still be considered sustainable [20, 21].

Two-Lift construction of pavements involves running two slipform paving machines, one close behind another to form a double layer system. While this approach is relatively commonplace in Europe, it is still in demonstration phase in the US. Advantages include using local materials that are normally an unacceptable wearing surface, such as aggregates can be used in the thicker lower lift, while a harder imported material can be used in limited quantities on the top layer. The economic effects of this approach are still being investigated in the US [22]. Another advantage of using a Two-Lift system is small, single-sized aggregate can be used in the top lift that is later exposed by acid washing. This surface has been demonstrated to be durable and quiet [23].

CONCLUSION

There is a significant need for a standardised approach to be developed that will allow engineers to quantify and demonstrate the relative benefits of any given approach, or innovate system, and this is the focus of a significant amount of work at present.

Life cycle cost analyses are relatively familiar and a number of models are available. Life cycle environmental analysis has been outlined in broad terms in ISO 14000 documents, but considerable work is required to prepare detailed methodologies and collect valid databases of materials' environmental factors. Such work is currently underway by the Massachusetts Institute of Technology (MIT) Arizona State, University of Cape Town and the Federal Highway Administration who are looking at the societal impacts.

The other needs include methods to produce affordable cementitious systems with lower environmental impacts. These may include methods to capture and take advantage of CO_2 and mercury by-products. As aggregate sources become more limited, there is likely to be considerably more effort focused on finding alternative aggregate sources or on how to use materials that are currently considered unacceptable.

Part of this work is likely to be looking at developing specifications with a greater emphasis on performance requirements, rather than on recipe based approaches. This means that risk is passed onto the contractor, who is looking for a greater potential reward. Associated with this trend is the need for good test methods that measure the properties accurately. Training and education is required to provide specifiers and builders with knowledge and skill to take advantage of some of the innovative approaches described above.

The topic of sustainability is complex, the research needs are daunting and the consequences are global. This means that there is a huge opportunity for all to provide the infrastructure required to meet the needs of the planet.

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