Structural Sustainability

sustainability and preservation as they pertain to structural engineering

Optimizing Concrete for More Sustainable Bridges

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The built infrastructure is one of the largest contributors to various measures of environmental impacts, e.g., energy consumption and carbon dioxide (CO_2) emissions. There is sustained momentum towards decreasing this impact. This momentum is consistent with the ASCE Code of Ethics which states, in part, that engineers "shall strive to comply with the principles of sustainable development in the performance of their professional duties." Furthermore, several states require analyses of environmental impacts for some transportation projects (FHWA, 2016). For example, in Massachusetts, certain projects must quantify CO_2 emissions and "document the … plans to avoid, minimize or mitigate Damage to the Environment to the maximum extent feasible" (Commonwealth of Massachusetts, 2010). In addition to a similar air quality analysis, New York requires an energy impact analysis for some projects (NYSDOT 2010).

Various sustainability guidelines like Envision, Greenroads, and Leadership in Energy and Environmental Design (LEED) are available for engineers or owners interested in reducing the environmental impact of structures. These guidelines primarily list credits that identify broad goals. To focus on Envision's Resource Allocation Category as one example where structural engineers have a large influence on this rating system, listed goals include: reduce net embodied energy and support sustainable procurement practices. Clearly, prescriptive approaches for achieving these goals are not the intent, which poses a challenge for those with little education on the topic of sustainability. The purpose of this article is to offer specific strategies for achieving the overarching sustainability goals contained in sustainability guidelines, with a focus on concrete.

Significant Environmental Impacts

It is useful to understand which phase of a bridge's life-cycle contributes the most to environmental impacts to identify what strategies are most effective for reducing environmental impacts. Typical bridge life-cycle phases include: manufacture/production, construction, operation/maintenance, and end-of-life.

The impacts of each phase can be quantified using life-cycle assessment (LCA) methodology. In short, the LCA quantifies environmental impacts in categories such as global warming potential using quantities for a well-defined system boundary (a defined portion of the supply chain for a particular project). Numerous LCA studies have analyzed the emissions associated with bridge projects. Some studies report results for each life-cycle phase. Others focus on comparing emissions of different bridge alternatives for a given phase. Many of the studies evaluate various superstructure alternatives, assuming the substructure stays the same. Project-specific LCA studies could be used to quantitatively balance both superstructure and substructure alternatives to minimize environmental impacts. LCA studies can help uncover which project elements have the greatest impacts and which elements have an outsized impact relative to their size or cost. *Figure 1* shows example LCA results for global warming potential on a

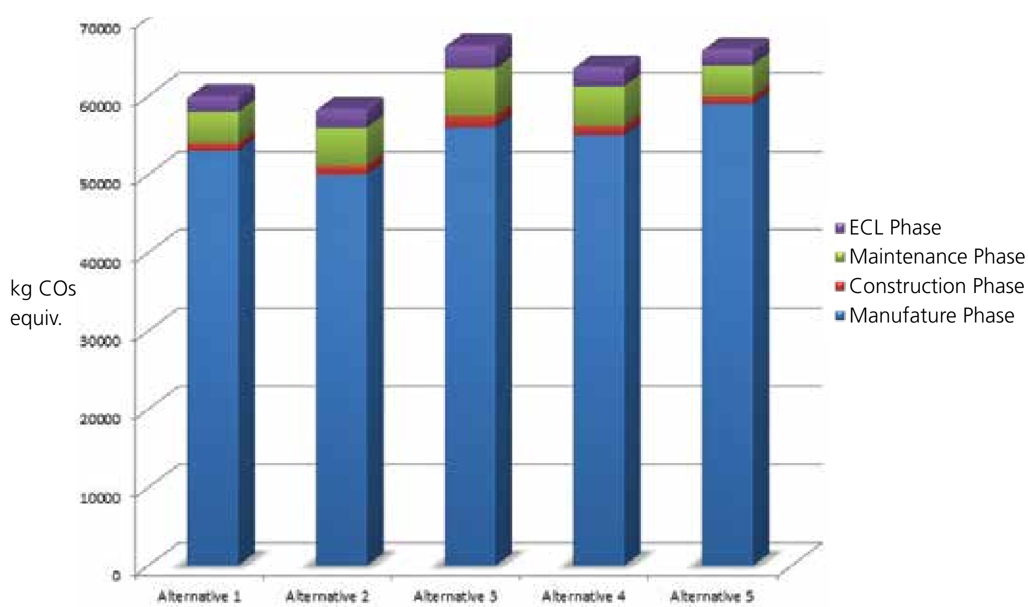

Figure 1. Example LCA results for global warming potential.

Figure 2. Example bridges designed for extended service life: a) Second Gateway Bridge, Brisbane, AU, designed for 300-year service life (© Murarrie, 2016), b) St. Anthony Falls Bridge, MN, USA, designed for 100-year service life (©RJ Watson, Inc., 2016) c) New Tappan Zee Bridge, NY, USA, designed for 100-year service life (© HDR, Inc., 2016)

hypothetical project. Other environmental impact categories can be studied as well.

The studies that compare emissions throughout the life-cycle agree that the manufacture/production phase creates the largest emissions. Martin (2011), Hammervold et al. (2013), and Du et al. (2014) report greater than 84% of the total global warming potential is due to the initial phase, and Dequidt reports 64%. Du et al. (2014) also reports that the initial phase accounts for the vast majority of CH_4, SO_2, NO_x, and NH_3 emissions. The magnitude of the emissions is largely sensitive to the cement quantity, steel recycling rate (which is high in the U.S.), and the electricity source used in the steel production. Therefore, the initial manufacture/production phase should be targeted by bridge engineers looking to reduce the most emissions of their projects.

Strategies

Alternative Cementitious Materials

One means of reducing the environmental impact of highway structures, and other structures containing concrete, is to replace all or part of the Portland cement content of concrete with alternative cementitious materials (ACM). These materials are also frequently referred to as supplementary cementitious materials (SCM). While the two terms are essentially synonymous, the term ACM better highlights that some of these materials can be used in place of Portland cement to a significant extent, or even completely in some cases.

Because many of the ACM materials are manufacturing byproducts, the environmental impact of structures can be dramatically improved through their use. Reduced thermal cracking can be another benefit of the use of ACM, which is particularly advantageous for large concrete members. Furthermore, ACM can improve long-term mechanical performance and reduce durability concerns, such as resistance to chloride permeation and resistance to alkali-silica reaction. Thus, there are secondary environmental benefits due to increases in service life, which can be considered in general terms or explicitly considered through a service life design. In fact, through proper mixture design and use of ACM, the expected service life can be significantly extended beyond that conventionally achieved. Example structures designed for extended service life are shown in *Figure 2*.

A wide variety of possible ACM exist. Those with the lowest environmental impact would intuitively be those that are waste products from other sectors (although, to fully assess whether this is true, full consideration of environmental impacts is necessary). Fly ash, blast furnace slag, and silica fume are the manufacturing byproducts most commonly used as ACM at present. Other products that have been used as ACM include other industrial, agricultural, and municipal wastes and natural pozzolans such as clays and volcanic ash.

The proportioning of ACM is critical. Slower strength gains experienced with some ACM dictates that attention is given to ensuring sufficient strengths at early ages. Workability can also be a concern for several potential ACM. Thus, there are few materials available that can be wholly substituted for Portland cement at present. Numerous and varied combinations of ACM have been used to successfully meet strength, serviceability, and constructability requirements while also reducing environmental impacts. In *Table 1*, a synthesis of selected infrastructure owners' specifications (for normal, i.e., not high-performance concrete) gives the typical proportions of the commonly used ACM that are permitted while innovative designs and research projects inform higher proportions of ACM that are possible.

The percentage of fly ash allowed in the standard specifications of owners varies widely but is often up to 30% replacement (expressed as the weight of fly ash relative to the total weight of cementitious material). Some agencies place additional requirements on use, such as specifying the type of fly ash that may be utilized (with Class F regarded as the highest quality and Class C also commonly used).

Other agencies are less restrictive of fly ash use. For example, the Texas Department of Transportation (DOT) allows up to 35% fly ash (assuming other restrictions are met), which is the same proportion at which Bentz et al. (2011) were able to achieve no compromise in early-age properties. An additional example is the Delaware DOT's specific designation for fly ash type concretes, which specifies a minimum of 20% fly ash and no maximum other than a demonstration of acceptable performance. Furthermore, multiple projects have exceeded the upper bounds on fly ash cited previously. These include the Sunshine Skyway Bridge in Florida and Cooper River Bridge in South Carolina utilizing 50% and 43% fly ash, respectively. Even higher percentages of fly ash have been used by Bouzoubaâ and Lachemi (2001), who developed a high-volume blend containing 70% fly ash. Field trials conducted by Cross et al. (2005) used 100% Class C fly ash for foundations and walls where the compromise in early strength gain resulting from the high proportion of fly ash was insignificant. Similar levels of ACM could routinely be used for members that are

Table 1. Comparison of standard and innovative ranges of ACM used.

Material	Representative Range Generally Permitted	Successfully Demonstrated High Volume Ranges
Fly Ash	Up to 30%	Up to 35% w/o strength decrease 100% Class C 70% Class F
Slag	Up to 50%	Up to 75%
Silica Fume	Up to 10%	Up to 10%

Table 2. Example projects using corrosion resistant reinforcement in bridge construction.

Bridge and/or Owner	Sustainable Component
Woodrow Wilson Bridge, MD SHA/Virginia DOT	1100 tons of stainless steel on the bascule spans of the bridge to prevent corrosion.
US 2 Bridge over Winooski River, Vermont DOT	Bridge deck with high-performance concrete and stainless steel reinforcement.
Wenzlick, 2007. Missouri DOT	Constructed its first cast-in-place bridge deck using stainless steel reinforcing bars in 2006.
New York State DOT	Stainless steel reinforcing in the decks of several bridges. Offset some cost of solid stainless steel by design efficiencies (CITRE 2006).
Rollins Road Bridge, New Hampshire DOT	Concrete deck steel-free and reinforced with carbon fiber reinforced polymer (CFRP) grid. Long-term performance modeling.
Haynes Inlet Slough Bridge, Oregon DOT	Select stainless steel reinforcement in highly corrosive locations of the bridge.
Virginia DOT	Commonly uses corrosion-resistant reinforcing (such as stainless steel) in bridges.

not schedule-critical when these components do not need to achieve their full design strength until later in the construction process.

Higher proportions of slag are permitted compared to fly ash. For example, Wisconsin DOT is one of the several agencies allowing up to 50% slag. Up to this threshold, the final structural and environmental benefits are advantageous. Elahi et. al (2010) showed increased strengths at 28 days and later and significantly decreased chloride permeability, although reduced strength at 3 and 7 days is the tradeoff in performance as compared to the 100% Portland cement alternative. Considering the advantages of combining structural performance demands and environmental goals, there are innovative examples where the use of slag as an ACM has been maximized, including 75% slag employed in the James River Bridge in Virginia and 69% slag used in combination with 16% fly ash in the I-35W St. Anthony Falls Bridge in Minnesota (*Figure 2b*).

Silica fume is used less extensively than fly ash and slag and is limited in proportion. Thus, the benefits of using it are presently more restricted than other ACM. While the majority of the case studies and research performed to date focus on the utilization of a single ACM, combinations of various ACM are also possible. An ASTM standard specification for blended ACM exists for this purpose (ASTM C1697, 2010).

In addition to minimizing environmental impacts, two critical challenges continue to spur research and development of ACM. One is the compromised early-age strength mentioned previously. Various strategies have been used and are under consideration to mitigate these effects. For example, one technique is the "filler effect," which can be achieved through the addition of materials such as fine limestone. Another concern is that the local demand for ACM can exceed the available supply. Availability of high-quality fly ash is a problem at times and could be a bigger problem in the future due to changes in regulations and the phasing-out of coal power plants.

This issue provides strong motivation to pursue research into fly ash alternatives which are currently available and to evaluate emerging technologies. Texas DOT (Seraj et al., 2014) sponsored a study to look at possible alternatives for Class F fly ash. Six ACM were identified. However, the material costs at the time of the study were typically more than double the fly ash cost and greater than the cement cost. Increased use of slag from steel making processes, which are sustained in part by "Buy America" requirements, may help to fill the gap.

Cement Production Efficiency

Sourcing cement from energy-efficient plants is a sustainable strategy. A 2008 report conducted by the Lawrence Berkeley National Laboratory investigated over 40 improvements plants can implement to increase energy efficiency and to reduce CO_2 emissions. Ideally, cement plants would be able to provide an environmental product declaration to detail their product's environmental impacts. However, in the absence of a detailed report, specifications could be written to favor cement suppliers who have made investments in energy-efficient and environmental impact reduction technologies.

Other Emerging Technologies

Emerging technologies have been developed to improve reinforced concrete's sustainability performance. For example, replacement of steel reinforcement with corrosion-resistant materials can significantly improve the lifespan of concrete bridges. Corrosion-resistant reinforcement materials include stainless steel (SS), fiber reinforced polymer composites (FRP), galvanized reinforcing steel (GRS), and low carbon chromium reinforcing steel (LCC). Proper use of these materials alone may extend maintenance-free service life when compared to conventional steel rebar (CS).

Another strategy is using waste CO_2 as an admixture in producing PCC. In this application, the upcycled waste CO_2 is mineralized within the concrete thereby significantly reducing the material's carbon footprint (**http://carboncure.com**). Alkali Activated Fly Ash Concrete (AAFAC) is another option, which uses fly ash as a 100 % replacement for Portland cement. AAFAC relies on industrial byproducts to significantly reduce its carbon footprint, while also being very resistant to many of the durability issues that can plague PCC. Other emerging technologies related to improving concrete's sustainability rating include completely recyclable concrete (CRC), calcium sulfoaluminate (CSA) cement, and incorporating recycled concrete aggregates into concrete. This latter strategy has been successfully applied for concrete pavements at present, and some recent research provides favorable results in structural applications involving recycled aggregates.

Case Studies

Presented in *Table 2* are examples of corrosion resistant reinforcements that have been used in components of bridges to extend the service life of the structure.

Conclusion

As the sustainability knowledge-base continues to grow, engineers can expect new alternatives and increasing application of existing methods for reducing the environmental impact of highway infrastructure. Methods such as LCA and service life design offer many benefits presently, and it is expected that the ease and preciseness of quantifying outcomes through these methods will only increase. The available data suggest that ACM, other improvements in cement production processes, and more corrosion-resistant reinforcements are among the present best practices for reducing the environmental impact of concrete used in highway bridges, and thus the overall environmental impact of these structures.▪

The online version of this article contains detailed references. Please visit **www.STRUCTUREmag.org**.

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