Sustainable Concrete Design in the Green Revolution: A Producer’s Perspective

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Introduction
More owners and major developers are insisting on sustainable building designs and construction practices. This is a major reason why the sustainable market is one of the fastest growing segments in the construction industry. Fortunately, many technologies exist today to meet this demand; however, the major hindrance in today's construction environment lies in the lack of flexibility in design codes and specifications. Many specifications limit the concrete producer’s ability to achieve a truly sustainable concrete by prescribing mixture proportions rather than setting performance criteria. In the past, there has been a push in the industry to move from prescription to performance (P2P) specifications, however, this concept has floundered due to the lack of proper standards for prescribing performance and a lack of understanding by design professionals of performance outside of strength. This paper outlines the fundamental problems obstructing the concrete construction industry from progressing forward in the green revolution. Methods and solutions for breaking down these barriers are presented along with new innovative concrete design methodologies which can be used to foster growth in a sustainable world.

Environmental Impact of the Industry
The construction industry is not an industry that spurs innovation, mainly because the industry is not organized in a manner that is conducive to innovation\textsuperscript{1}. During the conventional building process, the architects, the engineers, the contractors, and the subcontractors work relatively independent of each other, handing off work products to other disciplines along the way. This separation of disciplines and linear design process significantly limits opportunities for innovation. Design is performed by professional design firms, while construction is scheduled by a general contractor who coordinates between all the subcontractors. This organizational structure yields a very large and diverse group with widely varying interests and financial motivations. This significantly impedes innovation as one group may perceive an innovation as advantageous while another views it as an obstacle. It is often the group that views the innovation as an obstacle that triumphs, as it is this view that does not upset the status quo.

Over the past twenty years however, there has been an impetus to break down these barriers as the growing concern of developing sustainable building practices has affected a majority of the parties involved in the building process. The reason for this growing concern is that buildings account for a large portion of energy and electricity consumption in the United States\textsuperscript{2}. 
Buildings account for roughly 50% of the total energy consumed, as shown in Figure 1a, and over 75% of the total electricity consumed in the U.S. on an annual basis shown in Figure 1b.

![Figure 1 – (a) U.S. Energy consumption by sector, (b) U.S. electricity consumption by sector.](image)

This large consumption of energy has spurred several standards and rating systems to reduce the load buildings have on energy consumption. Programs like Energy Star and the U.S. Green Building Council’s Leadership in Energy and Environmental Design (LEED®) focus more on operational energy consumption and less on the construction-related energy consumption and specifically construction materials selection.

The construction sector accounts for nearly 15% of all greenhouse gas (GHG) emissions when scopes 1, 2, and 3 are from the World Resource Institute standard are included in the carbon calculation. On average the concrete can account for nearly 25%, and as much as 40%, of the GHG emissions of the construction sector, as shown in Figure 2. Concrete can be linked to being responsible for 5% of the global man-made carbon dioxide (CO₂) emissions which are a major contributor to the total GHG emissions. Just a single construction material will contribute more than the entire health care or paper manufacturing industry.

The main reason concrete has such a large contribution to GHG emissions is generally because the large amounts of CO₂ associated the manufacturing of cement. During the calcination of limestone to make cement, CO₂ is driven off according to Equation 1 below. In order for this process to occur, a considerable amount of heat is needed to reach roughly 850°C. This is typically obtained by the burning of fossil fuels, though a considerable amount of progress has been made in using alternative fuels sources such as used tires.

\[ CaCO_3 \rightarrow CaO + CO_2(g) \]  

Equation 1

These result in a rough rule of thumb that for every ton of cement manufactured, one ton of CO₂ is released into the atmosphere.
Supplemental cementitious material’s (SCM) exist that can be used to replace cement, such as fly ash or slag. Unfortunately in current sustainable building rating systems, reducing the carbon footprint of concrete by as much as 30%, gets as much credit as having an accredited professional on the design team. Currently, there is not a universal design standard like ACI 318 for sustainable building design, and often times, building specifications are written that restrict the producer from maximizing the beneficial uses of SCMs. Design codes and specifications have not kept pace with the evolving sustainable construction market, and updates to these are desperately needed.

**P2P, an Attempt to Update Specifications**

The ready mixed concrete industry recognized that owner’s needs for sustainable building designs would be best served through innovative concrete technology, and this would best be accomplished through performance based specifications. Led by the National Ready Mixed Concrete Association (NRMCA), the ready mixed concrete industry has established the Prescriptive-to-Performance (P2P) Initiative to promote a shift from traditional prescriptive specifications to performance specifications. In October 2002, a steering committee was formed charged with the task of developing a strategic roadmap for the P2P Initiative⁸.

This initiative has created a tall order, but the remainder of this paper will cover just one suggestion proposed by this committee. The committee made the suggestion that the concrete mixture submittal would not be a detailed list of mixture ingredients, but rather a certification that the mix will meet the specification requirements including pre-qualification tests results.

**Current Methods for Selection of Concrete Proportions**

In order for P2P to work, a producer needs a method for developing mixture proportions and to be able to reliably and accurately provide performance data. There are two methods outlined in ACI 318 for use as acceptable means of establishing mixture proportions: Proportioning on the basis of field experience; and proportioning on the basis of trial mixtures. The concrete supplier should receive compressive strength results from the testing agency⁹,¹⁰, though in reality, this rarely happens unless there is a low-break. This leaves the three-point curve method as the most
practical way for a producer to establish innovative environmentally friendly mixture proportions, that are desperately needed, and this method is the only way to provide the performance data needed for P2P.

The three-point curve method has been extensively used for determining proportions based on compressive strength requirements. There has been some push-back from engineers that they must have compressive strength history for concrete to be used on their project, but this can often be overcome by pointing out section 5.3.3.2 of ACI 318 allows the three-point curve method to be used. In order to move P2P forward, and ultimately create more sustainable concrete designs, we need to explore the usefulness of this tool.

**Four-Point Curve Performance Submittal for P2P**

The four-point method is based on measuring the performance of four different water-cement ratios (w/c), an example is shown in Table 1, and interpolating other mixture proportions from the curve that results. Most performance that is measured will show a linear relationship, shown as shown in Figure 3, which makes interpolation straightforward.

![Figure 3](image_url) – Relative performance of measures of a four-point curve showing he linear relationship to w/c.

From this method, a countless number of mixture designs and submittals can be created, essentially creating a catalog of mixes with only four actually having to be batched and tested. An example of a catalog with all the performance measures is shown in Figure 4, this catalog can be created at a fraction of the cost and man-hours that would be required to trial batch and test the 36 mixture proportions that were interpolated. This catalog can then be made available so engineers know the capabilities and performance of concrete in their market.
Table 1 – Mixture proportions for a four-point curve. The coarse material remains constant, as fine sand is replaced with increasing amounts of fine cementitious material creating varying w/c.

<table>
<thead>
<tr>
<th>Total Cementitious (lbs/yd³)</th>
<th>w/c</th>
<th>ASTM C #57 Blend Stone (lbs/yd³)</th>
<th>ASTM C 33 Sand (lbs/yd³)</th>
<th>Blend Sand (lbs/yd³)</th>
<th>Water (lbs/yd³)</th>
<th>MRWRA (oz/cwt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>450</td>
<td>0.59</td>
<td>1645</td>
<td>218</td>
<td>952</td>
<td>635</td>
<td>267</td>
</tr>
<tr>
<td>550</td>
<td>0.50</td>
<td>1645</td>
<td>218</td>
<td>890</td>
<td>593</td>
<td>275</td>
</tr>
<tr>
<td>650</td>
<td>0.44</td>
<td>1645</td>
<td>218</td>
<td>827</td>
<td>551</td>
<td>284</td>
</tr>
<tr>
<td>750</td>
<td>0.39</td>
<td>1645</td>
<td>218</td>
<td>764</td>
<td>509</td>
<td>292</td>
</tr>
</tbody>
</table>

Since so many mixtures can be created from so few being tested, more tests can be run in order to yield more performance measurements that were never available before. A typical mixture submittal would likely have compressive strength measurements, and on rare occasion, drying shrinkage measurements. The four-point curve method allows the producer to measure far more parameters, which can be included on a performance submittal, shown in Figure 5, much like the submittal that is necessary for P2P to be successful.

This begs the question of who will do the testing. Does it make sense for a ready mix producer to have an independent laboratory qualify the four-point curves? Or, is it acceptable for the ready mix producer to generate the curves himself? The answer is yes to both. If the 80/20 rule applies to concrete, we can assume that 80% of the specifications could be met with only a few curves for a set of materials. These curves could be created from an independent laboratory at a relative low cost to the producer. However to capture the other 20%, curves would need to be generated even before the concrete for the job is awarded. In this scenario, it does not make as much sense for a producer to spend thousands of dollars for a job he has not been awarded. For these, a prescriptive specification may be necessary; however, it is often these jobs that could take advantage of innovative designs. In these cases, if the ready mix producer has someone qualified, i.e., a licensed engineer, independent results should not be required.

Figure 4 – Catalog of mixtures made from the four-point curve method, showing all pertinent measured performance for each mixture interpolated from its respective four-point curve.
Figure 5 – Typical mixture submittal showing performance measures that were often not included during the submittal process. These performance measures, including the carbon equivalent, are crucial for turning P2P into reality.
Four-Point Curve for Sustainable Design
The four-point curve method had been quite useful for convincing engineers that they can still get the performance required for their project, while drastically reducing the carbon footprint of their project. One performance measure of the four-point curve could be the carbon footprint, as calculated according to World Resource Institute standards\(^4\). In building construction, LEED is the gold standard for sustainable design, however, in the materials arena, carbon footprint needs to be the major metric for sustainable design. The current difficulty with using carbon footprint as a metric is that there is no standard in the construction industry for calculating a carbon footprint. Each company that calculates their carbon footprint has their own method for doing so, and the resulting carbon footprints cannot be compared. A standard way of measuring the carbon footprint of construction materials is still needed before this metric can be used.

Though there are several reasons why supplemental cementitious materials (SCM’s) are not as widely used as they could be, the most common is that they don’t perform as well as straight cement mixtures. This often is claimed in the winter time when concrete with higher levels of SCM’s tend to have prolonged set time and slow early age strength gain. A mixture design catalog can be used to show the performance differences between different cementitious blends. Figure 6 shows the initial set time of different cementitious blends, a 100% cement mixture, 15% Class F fly ash mixture, and a 50% SCM replacement (EF Technology\(^{®}\) Generation II). With proper mixture proportioning, issues of prolonged set time can be corrected and shown in a performance submittal.

The largest advantage to the four-point curve method of mixture proportioning is easy comparison of similar mix designs. Figure 7a shows the compressive strength of concrete with a w/c of 0.45 and different cementitious blends: 100% cement, 15% Fly Ash, 20% Fly Ash, and 50% SCM (EF Technology\(^{®}\)). In a w/c driven market, the most common w/c specified is 0.45 due to the inherent sulfate resistance or freeze-thaw durability assumed, and it is a rare that the specified strength is over 5,000 psi. For a 100% cement mixture, this would have a carbon footprint of 598 lbs of CO\(_2\) equivalents. By switching to a high SCM replacement mix, the carbon footprint could be reduced 40% to 358 lbs of CO\(_2\) equivalents while maintaining the necessary strength and w/c often specified.
Shrinkage is another performance measure that is often specified, and the specifying engineer will control this by specifying “low-shrink” aggregates from specific quarries. Though quality aggregates are important in determining the ultimate shrinkage of concrete, it is not the most important factor. Revisiting the same 0.45 w/c mixtures, Figure 7b shows the drying shrinkage results which indicate that the higher SCM replacement mixes actually give the best shrinkage performance. In fact, it is the only mixture that meets an often specified value of 0.036% for “low-shrink” concrete.

![Figure 7](image)

The four-point curve method, when utilized, can be useful in producing mixtures that can be easily compared on their performance measures. The four-point curve method still needs to be more widely accepted among design engineers as an acceptable way to proportion concrete.

A major piece that is still needed in the construction industry, as alluded to earlier, is a unified method for measuring the carbon footprint of materials. We cannot control what we cannot manage, and we cannot manage what we don’t measure, and an incorrect measure is worse than no measure at all.

**Conclusions**

Sustainable construction is on the rise in the U.S., and the reduction in the carbon footprint of concrete can play a major role in sustainable construction. This construction industry moves at a snail’s pace when it comes to innovation, but that does not mean we should not continue down the path of innovation. Several fundamental building blocks have been started, but much more is needed in order for truly sustainable construction to materialize. Some of the pieces still needed include, but are not limited to:

- concrete specifications and building codes need to be updated to offer a performance alternative to the prescriptive specifications (P2P);
- the Four-Point curve methods needs to become more widely accepted amongst design professionals as a mixture design method; and
- a standardized method for calculating the carbon footprint of materials is needed.

![Compressive Strength vs Age](image)

![Drying Shrinkage vs Age](image)
Bibliography


10 American Concrete Institute. ACI 301 - Specification for Structural Concrete. Farmington Hills, MI : s.n., 2005.