Performance-Based Specifications for Concrete to Advance Sustainable Development

by K. H. Obla

Synopsis: This article makes a strong case that prescriptive specifications are an impediment to sustainability. Some of the least sustainable prescriptive requirements are the use of minimum cementitious contents, restrictions on types and dosages of SCMs, and the overuse of maximum $w/cm$. It is not feasible to adopt an optimized prescriptive specification. On the other hand, performance-based specifications allow for mixture optimization, which requires producers and contractors to be more knowledgeable about their materials. Performance-based specifications reward attaining lower variability, which promotes investment in better quality and improved technology practices. Optimized mixtures with a lower variability will result in mixtures that are more cost-effective and sustainable. The article concludes by making a case that sustainability is more than CO₂ emissions from cement and concrete production only.

Keywords: green; optimization; performance specifications; quality; sustainability; variability.
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INTRODUCTION

A code, such as a building code, establishes minimum requirements for buildings to protect public safety. In the U.S., ACI 318 serves as the building code for structural concrete. It is referenced for the most part by the model building codes, such as the International Building Code, that is then adopted wholly or with amendments, by a local jurisdiction at which point it becomes a law subject to legal review and process. Transportation agencies set the minimum requirements for transportation infrastructure.

A specification such as ACI 301 for concrete construction is a set of requirements to be satisfied by a material, product, system, or service. The specification should incorporate the relevant building code requirements. It is from the owner, typically written by a design professional as his representative, to the concrete contractor. A specification eventually forms the basis of a contract, a legal agreement, between the owner and the contractor and establishes the joint and separate responsibilities of the various stakeholders in the construction team towards achieving the objectives of the owner.

WHAT IS A PRESCRIPTIVE SPECIFICATION?

A prescriptive specification is one that includes clauses for means and methods of concrete mixture proportions and construction techniques rather than defining end product requirements. For example it may include controls on the composition of the concrete such as a minimum cement content, type of cement, limits on the quantity of supplementary cementitious materials, maximum water-cementitious materials ratio ($w/cm$), limits on the grading of aggregates or type used, brand of admixture and required dosage, and the like. In addition there may be requirements on compressive strength or other properties that are implied but not clearly stated in the specification. Many times intended performance requirements are not clearly indicated in project specifications, and the prescriptive requirements may conflict with the intended performance. The ACI 318 building code has some prescriptive requirements in Chapter 4 such as maximum $w/cm$ and cement types, and because the building code is a minimum requirement the design professional typically adds more prescriptive requirements.

WHAT IS A PERFORMANCE SPECIFICATION?

A performance specification is a set of instructions that outlines the characteristics of the fresh concrete for constructibility, functional requirements for hardened concrete depending on the application, and aspects of the construction process that are necessary but do not restrict the innovation of the concrete contractor. For example, the performance criteria for interior columns in a building might be compressive strength only, because durability is not a concern. Aspects such as prevention of thermal cracking (heat of hydration), modulus of elasticity and creep might also be important. Conversely, performance criteria for a bridge deck or parking structure will have strength requirements to resist loads and also might include limits on permeability and cracking because the concrete will be subjected to a harsh environment. Performance specifications should also clearly specify the test methods and the acceptance criteria that will be used to verify and enforce the requirements. The specifications should provide the necessary flexibility to the contractor and producer to provide a mixture that meets the performance criteria and avoid limitations or requirements on the ingredients or proportions of the concrete.

The general concept of how a performance-based specification for concrete would work is as follows:

- There would be a qualification and certification system that establishes the standards for concrete production facilities and possibly the people involved. This establishes the credentials necessary to deliver performance-based concrete.
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- The design professional would define the performance requirements of the hardened concrete.
- Producers and contractors would partner to ensure that the right mixture is designed, delivered, and installed.
- The submittal would not be a detailed list of mixture ingredients, but rather a certification that the mixture will meet the specification requirements including pre-qualification test results.
- After the concrete is placed, a series of field acceptance tests would be conducted to determine if the concrete meets the performance criteria.
- There would be a clear set of instructions outlining what happens when concrete does not conform to the performance criteria.

Advantages of performance-based specifications

Performance-based specifications put the focus where it should be—namely “performance.” For example, a homeowner is interested in how the concrete driveway performs and not on how much cement it contains. Because the producer is free to select the mixture proportions and is responsible for meeting the performance criteria there is an incentive for the producer to acquire more knowledge about its materials. Because a performance specification would allow for mixture optimization and mixture adjustments during the project (to account for source variability of ingredient materials and environmental conditions) there is an incentive for the producer to invest in improved quality, technology, and lab facilities. A knowledgeable quality producer and contractor can help attain improved product quality, reduced construction costs, less conflict, and a reduction in time.

SUSTAINABLE MATERIAL CHOICE

Engineers and architects have choices of the material and products they use to design projects—when it comes to a building frame the choice is typically between concrete, steel, and wood; for paving applications the choice is generally between concrete and asphalt. Material choice depends on several factors including first cost, life-cycle cost, and performance for a specific application. Due to growing interest in sustainable development engineers and architects are motivated more than ever before to choose materials that are more sustainable. However this is not as straightforward as selecting an Energy Star®-rated appliance or a vehicle providing high gas mileage. On what “measurement” basis can engineers and architects compare materials and choose one that is more sustainable or specify a material in such a way as to minimize environmental impact?

Life-Cycle Assessment (LCA) seems to offer a solution. LCA considers materials over the course of their entire life cycle including material extraction, manufacturing, construction, operations, and finally reuse/recycling. LCA takes into account a full range of environmental impact indicators—including embodied energy, air and water pollution (including greenhouse gases), potable water consumption, and solid waste, just to name a few. Building rating systems such as LEED® and Green Globes® are in various stages of incorporating LCA so that they can help engineers and architects select materials based on their environmental performance or specify materials in such a way as to minimize environmental impact.

One potential drawback of LCA however is that the person conducting the analysis often has discretion to set which environmental impact indicator is most important. And often times conducting a full LCA is so complex that only a partial LCA is conducted with a focus on one or two phases of the life cycle. Recent focus on climate change and the impact of greenhouse gas emissions on our environment has caused many to focus on CO2 emissions as the most critical environmental impact indicator and too often the focus is entirely on the material extraction and manufacturing stages of the LCA only which can be detrimental as discussed later. Table 1 has been developed based on data presented by Marceau et al.® leads to the following observations:

Because a cubic yard of concrete weighs about 2 ton (1.8 metric ton), CO2 emissions from 1 ton (0.9 metric ton) of concrete vary between 0.05 to 0.13 ton (0.044 to 0.12 metric ton). Approximately 95% of all CO2 emissions from a cubic yard of concrete is from cement manufacturing. Every 1 ton (0.9 metric ton) of cement produced leads to about 0.9 ton (0.8 metric ton) of CO2 emissions.® So it is no wonder that there have been a number of articles written about reducing the CO2 emissions from concrete primarily through the use of lower amounts of cement and higher amounts of supplementary cementitious materials (SCM) such as fly ash and slag.
PRESCRIPTIVE SPECIFICATIONS—AN IMPEDIMENT TO SUSTAINABILITY

Many common prescriptive specifications from transportation agencies and architects/engineers have minimum cementitious content requirements and restrictions on dosages of SCMs and are not cost effective and sustainable. An example prescriptive high-performance concrete bridge deck specification used by a transportation agency had the following requirements:

- Specified 28-day compressive strength = 4000 psi (28 MPa).
- Maximum \( w/cm \) of 0.39.
- Total cementitious content = 705 lb/yd\(^3\) (418 kg/m\(^3\)), consisting of 15% fly ash and 7% to 8% silica fume.
- Slump = 4 to 6 in. (100 to 150 mm).
- Air entrainment of 4% to 8% required.

An equivalent performance-based specification was proposed with the following criteria:

- Specified 28 day compressive strength, slump, and air were left unchanged.
- SCMs are allowed and quantities will not exceed limits of ACI 318-08 to protect against deicer salt scaling.
- Rapid Indication of Chloride Permeability, RCPT (ASTM C1202) = 1500 coulombs after 45 days of moist curing.
- Length Change (ASTM C157) < 0.04% at 28 days of drying after 7 days of moist curing.

NRMCA Research Laboratory conducted a laboratory based experimental study\(^8\) on the performance of the mixtures designed to meet these specifications. Four concretes were cast. The mixture proportions and test results are provided in Table 2. Mixture BR-1 was the control mixture proportioned according to the prescriptive specification. Mixtures BR-2 to BR-4 were proportioned to satisfy the performance-based criteria and contained similar \( w/cm \), lower cementitious contents, and varying SCM types and dosages as compared to BR-1. The test results show that as compared to the prescriptive mixture the performance mixtures had lower water demands, better workability (less sticky), much lower shrinkage while having similar compressive strength, RCPT, rapid migration test results (AASHTO TP64), and chloride diffusion coefficients (ASTM C1556). Based on data provided in Table 1 the performance mixtures can be estimated to contribute about 25% to 45% less CO\(_2\) emissions as compared to the control prescriptive mixture specified by the transportation agency. In addition the performance mixtures had lower material costs making it even more attractive.

A highway agency specification for a bridge deck had a minimum cementitious content requirement of 650 lb/yd\(^3\) (386 kg/m\(^3\)) maximum \( w/cm \) of 0.40, maximum allowed limit of 15% fly ash, and a 28-day compressive strength requirement of 4000 psi (28 MPa). The project contained aggregates that were susceptible to ASR. When it was pointed out that more than 15% fly ash may be needed to address ASR failure the design professional allowed the greater fly ash content but did not allow more than a 15% cement reduction from 650 lb/yd\(^3\) (386 kg/m\(^3\)). This resulted in total cementitious materials content of 714 lb/yd\(^3\) (424 kg/m\(^3\)) out of which 552 lb/yd\(^3\) (328 kg/m\(^3\)) was portland cement. To attain the required performance a total cementitious content of 600 lb/yd\(^3\) (356 kg/m\(^3\)) that included 25% fly ash was sufficient. Based on the data provided in Table 1, the prescriptive mixture that was ultimately used can be estimated to have contributed about 23% higher CO\(_2\) emissions as compared to a mixture that met all the performance requirements.

Is an optimized prescriptive specification feasible?

It is likely that for a given set of materials a knowledgeable concrete materials engineer can optimize the mixture proportions to meet the performance criteria that he or she seeks. But the design professional cannot specify that optimized mixture proportion in a prescriptive specification. Frequently a project specification is written for a large geographical area—the whole state in the case of a transportation agency or even the whole country, in the case of some large nationwide companies. It is impractical to identify an optimized mixture proportion for the broad range of materials that could be encountered. Even if the same set of materials are used the optimized mixture proportions may not be used in conjunction with lower quality manufacturing, construction, and testing practices. Clearly, the engineer has to develop the prescriptive specification so that the performance criteria are attainable with lower grade materials, manufacturing, construction, and testing practices. This is one of the main reasons why prescriptive specifications are substantially overdesigned, frequently with much higher cementitious contents than necessary to attain the performance requirements. This results in mixtures that are less cost-effective.
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and have a larger environmental impact, and thus are less sustainable. In addition, a very high overdesign does not provide any incentive for improving quality control and this becomes obvious from Fig. 1. The project had a specified strength of 4000 psi (28 MPa) and a minimum cementitious content requirement of 650 lb/yd³ (418 kg/m³). The test results varied between 4330 psi (30 MPa) and 7730 psi (53 MPa) with an average of 6130 psi (42 MPa), and a standard deviation of 1122 psi (7.7 MPa) resulting in a coefficient of variation of 18.3%. According to ACI 214R-02, the data suggests that the standard of concrete control was poor. Yet there were no low strength test results and as a result there was no incentive to improve concrete quality and attain a lower standard deviation.

This inherent deficiency in a prescriptive specification unfortunately provides no incentive to producers, and contractors to be more knowledgeable about their materials (essential to optimize mixture proportions) and invest in better quality and improved technology practices (essential to reduce variability). Table 3 shows the mixture proportions of the newly reconstructed I-35W bridge crossing the Mississippi River in Minneapolis, MN. The project used a performance specification in which the producer had full control over his mixture proportions. Such a set of mixture proportions using ternary cementitious blends and very low amounts of cement contents cannot be possible with a prescriptive specification because of the reasons just discussed.

Prescriptive restrictions on SCM use

One of the most common is a prescriptive restriction on the dosage allowed of an SCM, such as fly ash or slag cement. Chapter 4 of ACI 318-08 restricts SCM dosages only for very severe freeze-thaw Exposure Class F3 (concrete exposed to freezing and thawing cycles that will be in continuous contact with moisture and exposed to deicing chemicals) as follows:

- Fly ash or other C618 pozzolans: maximum 25%.
- Total of fly ash or other pozzolans and silica fume: maximum 35%.
- Combined fly ash, pozzolan, and silica fume: maximum 50% with fly ash or pozzolan not exceeding 25% and silica fume not exceeding 10%.
- Ground granulated blast-furnace slag: maximum 50%.
- Silica fume: maximum 10%.

There is no technical reason to extend these SCM dosage restrictions for concrete that will not be subject to exposure Class F3. Frequently more than 25% of fly ash is required for adequate resistance to alkali-silica reaction (ASR) with some types of aggregate, and for sulfate resistance. While it is true that greater SCM dosage accompanied by lower cement contents can delay setting and early-strength gain, these could be addressed to a large extent through the effective use of chemical admixtures. The concrete producer can evaluate the setting and early strength gain characteristics of such mixtures under varying ambient conditions to assure the contractor that these needs will be achieved.

Another common restriction is a limit on the maximum allowable loss on ignition (LOI) of a fly ash to a level lower (say 2 or 3%) than that required by ASTM C618. LOI is related to the amount of unburnt carbon in fly ash. Certain forms of unburnt carbon can absorb air entraining admixtures and affect air entrainment of concrete. This has led to the perception that by restricting LOI contents the air entrainment problems due to fly ash can be reduced. Figure 2 illustrates that at the same LOI different fly ashes can lead to different performance related to generating the necessary air content. In fact the low LOI fly ash in that study was more sensitive to air entrainment than the higher LOI fly ash. The reason for this is that certain fly ashes have finer carbon and a different surface chemistry which in spite of lower LOI can have a more significant effect on air entrainment. So, restricting LOI of fly ash to 2% or 4% does not reduce the problems with air entrainment in any way. Instead the fly ash marketer and concrete supplier should work together on a quality control test program to ensure that concrete with consistent air entrainment levels can be supplied as required.

Some specifications only permit the use of Class F fly ash. Slag cement may be the preferred supplementary cementitious material in some markets. In many parts of the country ASTM C618 Class C fly ash or Class N pozzolan, such as calcined clay is also available. Concrete producers will generally not stock more than one or two types of supplementary cementitious materials. Project specifications must address local availability and experience to allow fly ash and pozzolans meeting C618, slag meeting C989, and silica fume meeting C1240 in the specification. It is true that Class F fly ash is more effective in increasing concrete’s resistance to ASR and sulfate attack. However, rather than disallowing Class C fly
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ash (thus requiring Class F fly ash to be transported from a great distance), durability can be ensured by requirement of performance data confirming resistance to ASR, and sulfate attack through a performance specification. A Federal Highway Administration report\textsuperscript{12} provides performance criteria to select mixtures that can resist ASR. ACI 318-08 has performance criteria for selecting cementitious material for sulfate resistance.

**Prescriptive requirements on maximum allowable \( w/cm \)**

It is well understood that concrete permeability reduces with decreasing \( w/cm \). ACI 318 requires \( w/cm \) between 0.40 and 0.50 depending upon specific environmental exposure classes such as freeze thaw, sulfates or chlorides. Low \( w/cm \) concrete has become synonymous with better concrete and there has been a tendency for engineers to frequently specify low \( w/cm \) concrete even under benign environmental conditions such as for an indoor column. A project specification for a non-air-entrained topping mixture required the use of ASTM C33 No. 8 aggregate, had a maximum \( w/cm \) requirement of 0.40, a 28-day compressive strength requirement of 4000 psi (28 MPa), and a slump of 4 to 6 in. (100 to 150 mm). In spite of a high dosage of a polycarboxylate Type F admixture and a normal Type A water-reducing admixture the concrete producer needed a mixing water content of 290 lb/yd\(^3\) (172 kg/m\(^3\)) for adequate workability. Due to the maximum \( w/cm \) requirement a cementitious content of 725 lb/yd\(^3\) (430 kg/m\(^3\)) was used in the project. The exposure class for the application did not warrant a maximum \( w/cm \) requirement of 0.40.

If the producer had been allowed to use a more reasonable \( w/cm \) of 0.50 the total cementitious content could have been 580 lb/yd\(^3\) (344 kg/m\(^3\)). As pointed out earlier a maximum \( w/cm \) specification will also generally result in a high overdesign that does not provide any incentive for improving quality control.

Currently ACI 318 uses a low \( w/cm \) of between 0.40 to 0.50 and a minimum specified strength as the primary requirement of controlling the concrete permeability. An NRMCA Research Laboratory study compared the performance of mixtures having the same \( w/cm \) of 0.42 but with different cementitious material types and contents with regards to permeability. Four mixtures were cast. The mixture proportions and test results are provided in Table 4. It is clear that substantial differences in durability and shrinkage can be attained at the same \( w/cm \) and similar strength levels. The study\textsuperscript{8} concluded that code durability provisions should permit performance alternatives to \( w/cm \). This can enable optimized mixtures at lower costs and improved sustainability.

**Mixture submittals**

Almost all concrete project specifications have a specified compressive strength, \( f'_{c} \) requirement. Mixtures submitted for the project need to meet a certain average compressive strength, \( f'_{c} \) to ensure that the strength tests have a low probability of falling below the specified strength. ACI 318 and ACI 301 suggest two ways to calculate \( f'_{cr} \) for \( f'_{c} \) equal to or below 5000 psi (35 MPa):

- If past test records are available the job test standard deviation, \( \sigma \) is calculated and the target average strength, \( f'_{cr} \) should be the maximum of the following two equations:
  \[
  f'_{cr} = f'_{c} + 1.34\sigma \\
  f'_{cr} = f'_{c} + 2.33\sigma - 500 \text{ or } f'_{c} + 2.33\sigma - 3.5 \text{ (MPa)}
  \]
  If no past test records are available \( f'_{cr} \) is calculated as 1000 to 1200 psi (6.9 to 8.3 MPa) greater than \( f'_{c} \).

  Most engineering specifications use the latter option as the default even though past test records may be available. This does not offer any incentive to reduce variability as measured by \( \sigma \) and improve quality. For \( f'_{c} = 4000 \text{ psi (28 MPa)} \) the latter option would require \( f'_{cr} \) of 5200 psi (36 MPa). If the former option (based on past test data) is used a producer with \( \sigma = 350 \text{ psi (2.4 MPa)} \) has to attain a target \( f'_{cr} \) of 4470 psi (31 MPa) where as a producer with \( \sigma = 750 \text{ psi (5.2 MPa)} \) has to attain a target \( f'_{cr} \) of 5250 psi (36 MPa). By proportioning the concrete to target a lower average strength the producer who has a lower variability (\( \sigma \)) could lower the cementitious materials content and potentially reduce material costs\textsuperscript{13} by $3.9/yd\(^3\) and be more sustainable.

**Changes to mixture proportions after submittal**

Once a mixture proportion is submitted for a specific class of concrete in a project the producer is
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held to the same ingredient weights for that class for the duration of the project. The producer is typically allowed to vary only the admixture dosage and attain the concrete performance properties such as compressive strength, air content, slump, etc. Large volume ready-mixed concrete plants receive multiple shipments of cement and aggregate on a daily basis. Even though the material sources are the same it is well known that concrete performance can vary as shipments change. In addition changing temperatures can result in change in concrete performance. A specific performance requirement such as a 28-day compressive strength requirements can be consistently attained with varying material shipments and temperatures by designing the mixture for a higher average strength taking into account the material and temperature variations expected during the project. This is current standard practice.

In a performance mixture submittal the producer would not have to submit mixture proportions with ingredient weights. The producer can make use of semi adiabatic calorimetry, accelerated cured 2-day cylinder testing, standard cured 7-day cylinder testing to predict the strengths of standard cured cylinders at 28 days. If a lower 28-day strength is expected the producer can make minor adjustments to the mixture proportions such a lower \( w/cm \). This will result in two benefits:

- Frequency of lower strength test results and resulting expensive investigations will decrease; and
- Producers can now reduce their average strengths because they can now react on a rapid, continual basis for potential low breaks. The lower average strengths will make the mixture more cost effective and sustainable.

Some other impediments to sustainability

Poor quality testing primarily due to non-standardized initial job site curing has been shown to lead to more than 1000 psi (6.9 MPa) reductions in the 28-day compressive strength test results for a typical 4000 psi (27.6 MPa) concrete.14,15 Because low-strength test results typically lead to expensive investigations, the producer tries to avoid that by increasing the target average strength of the mixture. This results in higher material costs and adversely impacts sustainability.

Some state highway agencies have cash incentive/penalty clauses while implementing performance related specifications. For example if the strengths are below specified strengths severe penalties (several times the delivered cost of the lower strength concrete) may be required of the contractor. This forces the contractor to target higher average strengths. From the contractors viewpoint a $4/yd³ higher material cost (required for a higher cementitious content for example) is a small cost as compared to the $400/yd³ penalty for low strength test results. This means that state highway agencies need to reevaluate their performance related specifications so that it encourages the contractor to act sustainably.

SUSTAINABILITY AND CO₂ EMISSIONS

It is understandable that with the recent focus on climate change and the impact of greenhouse gas emissions on our environment there is a lot of interest in reducing CO₂ emissions. But there are two important aspects to this approach.

Sustainability more than CO₂ emissions from cement and concrete production

Focusing on CO₂ emissions from concrete production only misses out on opportunities to significantly increase sustainability in other ways. It is important to keep a holistic cradle to cradle perspective when it comes to the use of a material. Based on Gajda et al.,16 99% of life cycle energy use of a single family home was due to occupant energy-use while less than 1% was due to manufacturing cement and producing concrete.

The annual CO₂ emissions in 2006 for the United States and the world were 5.90 billion metric ton (Bmt) (6.5 billion ton) and 29.20 Bmt (32.1 billion ton), respectively.17 The annual cement consumption in 2006 for the United States and the World were 0.13 and 2.56 Bmt (0.14 and 2.8 billion ton), respectively.18 The average CO₂ emissions for a ton of cement produced19 are 0.75 ton and 0.90 ton for the globe and U.S., respectively. The lower number for the world is because more blended cement is made worldwide as opposed to the U.S. practice where less blended cement is made and supplementary cementitious materials are added at the ready-mixed concrete plant. Because about 75% of the cement produced is consumed in ready-mixed concrete and about 95% of CO₂ emissions from a cubic yard of concrete produced comes from cement CO₂ emissions it can be calculated that the production of concrete accounts for approximately 1.5% of U.S. CO₂ emissions and approximately 5.2% of global CO₂ emissions.
So whatever way one looks at it focusing on just the production of concrete accounts for a very small percent of over-all CO₂ emissions. This is not to say that progress should not be made in reducing the CO₂ emissions from concrete as produced. However, one should keep in mind that whatever CO₂ emission reductions that are possible will still account for at best a 2% global CO₂ reduction (assuming a challenging 40% reduction in global CO₂ emissions from cement manufacture from now on).

It is important to reduce the CO₂ emissions of the material over its entire life cycle through LCA, which considers materials over the course of their entire life cycle—material acquisition, manufacturing, construction, operation, and reuse/recycling. Operationally, concrete is a very sustainable material—it has several advantages such as long term durability, high solar reflectivity, high thermal mass and is almost entirely recyclable. A high solar reflectivity will result in lower heat island, that is, lower urban temperatures and, hence, lower use of air conditioning and energy savings and reduced CO₂ emissions. A high thermal mass will reduce the daily temperature variations inside a building and result in reduced energy consumption for heating and cooling the building. Concrete can absorb CO₂ from the atmosphere during its service life and after it is crushed for recycling. Long-term durability will result in less need for reconstruction and less CO₂ emissions and material use as a result. Concrete can also be used in applications such as pervious concrete that can reduce storm water runoff and recharge groundwater.

**Sustainability more than CO₂ emissions**

While there is value in reducing CO₂ emissions focusing entirely on CO₂ emissions can result in the following unintended consequences:

- It does not encourage the use of recycled or crushed returned concrete aggregates because use of virgin aggregates constitutes only 1% of all CO₂ emissions from a typical cubic yard of concrete (Table 1). Even replacing all virgin aggregates with recycled aggregates will reduce CO₂ emissions by only 1%. But the use of recycled aggregates is important as it can reduce landfills and support sustainable development. So, there is a need to incentivize its use. Several local governments are requiring less land filling and making land filling more expensive. Also prescriptive specification restrictions on the use of recycled aggregates should be removed. Focus on performance will encourage producers to recycle.

- It does not encourage the use of water from ready-mixed concrete operations (water used for cleaning ready-mixed concrete trucks, and precipitation at a plant) because use of mixing water constitutes a negligible amount (<1%) of all CO₂ emissions from a typical cubic yard of concrete. Use of recycled water should be encouraged because fresh water is becomingly increasingly scarce. This can be accomplished by removing specification restrictions that require the use of only potable water and instead specify water according to ASTM C1602 which allows non potable water and water from ready-mixed concrete operations as long as concrete performance data is maintained and met.

- It does not encourage the use of sustainable practices such as energy savings at a ready-mixed concrete plant because CO₂ emissions from plant operations constitutes only 1% of all CO₂ emissions from a cubic yard of concrete.

- It does not encourage the use of sustainable practices such as energy savings during transport of the concrete ingredient materials to the ready-mixed concrete plant because CO₂ emissions from transport constitutes only about 3% of all CO₂ emissions from a cubic yard of concrete.

**SUMMARY**

- Performance-based specifications ensures that the focus is on performance and has numerous advantages over prescriptive specification—Performance specifications provide incentives for producers and contractors to be more knowledgeable about their materials, and invest in improved quality, and adopt new technology, thereby reducing construction costs/time, and lesser conflict.

- It is suggested that in the beginning both prescriptive and performance specifications be allowed in a project. It is certain that over the long term the most cost effective approach with better track record will succeed.

- Performance specifications support sustainable development. Some of the least sustainable prescriptive requirements are the use of minimum cementitious content requirement, restrictions on types and dosages of SCMs and the over use of the maximum w/cm requirement. Minimizing
these prescriptive requirements will be an easy first step for those interested in cautiously moving towards a performance-based specification.

• Allowing changes to mixture proportions after submittal, improving testing quality, and avoiding high penalty clauses for low strength results can also help reduce target average strengths and improve sustainability.

• CO₂ emissions from 1 ton (0.9 metric ton) of concrete varies between 0.05 to 0.13 ton (0.044 to 0.12 metric ton). Because most of the CO₂ emissions from a cubic yard of concrete is from cement manufacturing it is important to reduce CO₂ emissions through the greater use of SCM. However, it is important not to focus solely on CO₂ emissions from cement and concrete production. Doing so limits the total global CO₂ reduction possible to at best 2%. Keeping a holistic cradle to cradle perspective and using LCA can help reduce CO₂ by a much greater amount because there is evidence to show that most of the energy is consumed during the operational phase of the structure (heating and cooling). Concrete is very effective in reducing energy consumption due to its high solar reflectivity, and high thermal mass among other benefits.

• Focusing solely on CO₂ emissions from cement and concrete production does not encourage the use of recycled or crushed returned concrete aggregates; use of water from ready-mixed concrete operations; use of sustainable practices, such as energy savings at a ready-mixed concrete plant and use of sustainable transport practices. This is because only 5% of CO₂ emissions from a cubic yard of concrete is due to use of virgin aggregates, water, plant operations, and material transport to the plant.

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Table 1—Total CO₂ Emissions for 1 yd³ of concrete for different strength classes and mixture proportions

<table>
<thead>
<tr>
<th>Ready mixed ID</th>
<th>Strength class, psi</th>
<th>Mixture proportions,* lb/yd³</th>
<th>Total concrete CO₂ emission, lb/yd³</th>
<th>Breakdown of CO₂ emissions for 1 yd³, %</th>
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<td>6</td>
<td>3000</td>
<td>244/0/132</td>
<td>239</td>
<td>92.4</td>
</tr>
<tr>
<td>7</td>
<td>3000</td>
<td>188/0/188</td>
<td>189</td>
<td>89.8</td>
</tr>
</tbody>
</table>

*564/0/0 signifies that the mixture contains 564 lb/yd³ cement, 0 lb/yd³ fly ash, 0 lb/yd³ slag cement.
†Transport costs is for material shipped to ready mixed plant.

Note: 1 MPa = 145 psi; 1 lb/yd³ = 0.5933 kg/m³; 1 yd³ = 0.765 m³.
## Concrete: The Sustainable Material Choice

### Table 2—Details of the HPC bridge deck mixtures

<table>
<thead>
<tr>
<th>Product</th>
<th>BR-1</th>
<th>BR-2</th>
<th>BR-3</th>
<th>BR-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement, lb/yd³</td>
<td>556</td>
<td>420</td>
<td>307</td>
<td>412</td>
</tr>
<tr>
<td>Fly ash, lb/yd³</td>
<td>106</td>
<td>148</td>
<td>0</td>
<td>145</td>
</tr>
<tr>
<td>Silica fume, lb/yd³</td>
<td>51</td>
<td>24</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Slag, lb/yd³</td>
<td>0</td>
<td>0</td>
<td>307</td>
<td>0</td>
</tr>
<tr>
<td>UFFA, lb/yd³</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>33</td>
</tr>
<tr>
<td>Total cementitious content, lb/yd³</td>
<td>713</td>
<td>591</td>
<td>614</td>
<td>590</td>
</tr>
<tr>
<td>Coarse aggregate (no. 67), lb/yd³</td>
<td>1820</td>
<td>1894</td>
<td>1985</td>
<td>1881</td>
</tr>
<tr>
<td>Fine aggregate, lb/yd³</td>
<td>1133</td>
<td>1182</td>
<td>1237</td>
<td>1174</td>
</tr>
<tr>
<td>Water, lb/yd³</td>
<td>278</td>
<td>231</td>
<td>239</td>
<td>211</td>
</tr>
<tr>
<td>w/cm</td>
<td>0.39</td>
<td>0.39</td>
<td>0.39</td>
<td>0.36</td>
</tr>
<tr>
<td>AEA, oz/100 lb cementitious</td>
<td>0.40</td>
<td>0.45</td>
<td>0.40</td>
<td>0.40</td>
</tr>
<tr>
<td>Type A WR, oz/100 lb cm</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Type F HRWR, oz/100 lb cm</td>
<td>13.0</td>
<td>9.4</td>
<td>18.4</td>
<td>11.1</td>
</tr>
</tbody>
</table>

### Fresh concrete properties

<table>
<thead>
<tr>
<th>ASTM C143, slump, in.</th>
<th>4.00</th>
<th>5.00</th>
<th>5.00</th>
<th>5.75</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTM C231, air, %</td>
<td>4.6</td>
<td>7.2</td>
<td>4.7</td>
<td>7.6</td>
</tr>
<tr>
<td>ASTM C138, density, lb/ft³</td>
<td>145.7</td>
<td>144.1</td>
<td>150.5</td>
<td>142.5</td>
</tr>
<tr>
<td>ASTM C1064, temperature, °F</td>
<td>69</td>
<td>69</td>
<td>65</td>
<td>69</td>
</tr>
</tbody>
</table>

### Hardened concrete properties

<table>
<thead>
<tr>
<th>ASTM C39 compressive strength, psi</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 days</td>
</tr>
<tr>
<td>7 days</td>
</tr>
<tr>
<td>28 days</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ASTM C157 length change (drying shrinkage), %</th>
</tr>
</thead>
<tbody>
<tr>
<td>28 days</td>
</tr>
<tr>
<td>90 days</td>
</tr>
<tr>
<td>180 days</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ASTM C1202 RCPT, coulombs</th>
</tr>
</thead>
<tbody>
<tr>
<td>45 days</td>
</tr>
<tr>
<td>110 days</td>
</tr>
<tr>
<td>180 days</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>AASHTO TP 64, rapid migration test, mm/(V-hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60 days</td>
</tr>
<tr>
<td>120 days</td>
</tr>
<tr>
<td>180 days</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ASTM C1585 69 days rate of water absorption (sorptivity), x 10⁻⁴ mm/s¹/²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
</tr>
<tr>
<td>Secondary</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ASTM C1556 diffusion coefficient, x10⁻¹³ m²/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>140 days</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Surface chloride, % by weight of concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>140 days</td>
</tr>
</tbody>
</table>

Note: 1 lb/yd³ = 0.5933 kg/m³; 1 oz/100 lb = 65.3 mL/100 kg; 1 in. = 25.4 mm; 1 lb/ft³ = 16.02 kg/m³; 1 MPa = 145 psi.
Table 3—Mixture details of new I-35W bridge in Minneapolis, MN

<table>
<thead>
<tr>
<th>Component</th>
<th>$f_c'$, psi</th>
<th>$w/cm$</th>
<th>Total cementitious content, lb/yd$^3$</th>
<th>Portland cement, %</th>
<th>Fly ash, %</th>
<th>Slag, %</th>
<th>Silica fume, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superstructure</td>
<td>6500</td>
<td>0.35</td>
<td>700</td>
<td>71</td>
<td>25</td>
<td>—</td>
<td>4</td>
</tr>
<tr>
<td>Piers</td>
<td>4000</td>
<td>0.45</td>
<td>575</td>
<td>15</td>
<td>18</td>
<td>67</td>
<td>—</td>
</tr>
<tr>
<td>Footings</td>
<td>5500</td>
<td>0.45</td>
<td>&lt;600</td>
<td>40</td>
<td>18</td>
<td>42</td>
<td>—</td>
</tr>
<tr>
<td>Drilled shafts</td>
<td>5000</td>
<td>0.38</td>
<td>&lt;600</td>
<td>40</td>
<td>18</td>
<td>42</td>
<td>—</td>
</tr>
</tbody>
</table>

Note: 1 MPa = 145 psi; 1 lb/yd$^3$ = 0.5933 kg/m$^3$
<table>
<thead>
<tr>
<th>Table 4—Details of ACI 318 mixtures</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Calculated mixture proportions, lb/yd³</strong></td>
</tr>
<tr>
<td>Cement, lb/yd³</td>
</tr>
<tr>
<td>Fly ash, lb/yd³</td>
</tr>
<tr>
<td>Total cementitious content, lb/yd³</td>
</tr>
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<tr>
<td>Water, lb/yd³</td>
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<tr>
<td>w/cm</td>
</tr>
<tr>
<td>AEA, oz/cwt.</td>
</tr>
<tr>
<td>Type A WR, oz/cwt.</td>
</tr>
<tr>
<td>Type F HRWR, oz/cwt.</td>
</tr>
<tr>
<td><strong>Fresh concrete properties</strong></td>
</tr>
<tr>
<td>ASTM C143, slump, in.</td>
</tr>
<tr>
<td>ASTM C231, air, %</td>
</tr>
<tr>
<td>ASTM C138, density, lb/ft³</td>
</tr>
<tr>
<td>ASTM C1064, temperature, °F</td>
</tr>
<tr>
<td><strong>Hardened concrete properties</strong></td>
</tr>
<tr>
<td>ASTM C39, compressive strength, psi</td>
</tr>
<tr>
<td>3 days</td>
</tr>
<tr>
<td>7 days</td>
</tr>
<tr>
<td>28 days</td>
</tr>
<tr>
<td>108 days</td>
</tr>
<tr>
<td>ASTM C157, length change, %</td>
</tr>
<tr>
<td>28 days</td>
</tr>
<tr>
<td>90 days</td>
</tr>
<tr>
<td>180 days</td>
</tr>
<tr>
<td>ASTM C1202, rapid chloride permeability, coulombs</td>
</tr>
<tr>
<td>28 days</td>
</tr>
<tr>
<td>120 days</td>
</tr>
<tr>
<td>180 days</td>
</tr>
<tr>
<td>AASHTO TP 64, rapid migration test, mm/(V-hr)</td>
</tr>
<tr>
<td>50 days</td>
</tr>
<tr>
<td>120 days</td>
</tr>
<tr>
<td>180 days</td>
</tr>
<tr>
<td>ASTM C1585, rate of water absorption (sorptivity) at 56 days, x10⁴ mm/s¹/²</td>
</tr>
<tr>
<td>Initial</td>
</tr>
<tr>
<td>Secondary</td>
</tr>
<tr>
<td>ASTM C1556, diffusion coefficient, x10¹³ m²/s</td>
</tr>
<tr>
<td>210 days</td>
</tr>
<tr>
<td>290 days</td>
</tr>
<tr>
<td>ASTM C1556, surface chloride, % by weight of concrete</td>
</tr>
<tr>
<td>210 days</td>
</tr>
<tr>
<td>290 days</td>
</tr>
</tbody>
</table>

Note: 1 lb/yd³ = 0.5933 kg/m³; 1 oz/100 lb = 65.3 mL/100 kg; 1 in. = 25.4 mm; 1 lb/ft³ = 16.02 kg/m³; 1 MPa = 145 psi.
Fig. 1—Variability of compressive strength test results from a concrete class project demonstrating that minimum cement content requirements do not provide incentive to reduce variability. (Note: 1 MPa = 145 psi.)

Fig. 2—Impact of fly ash LOI (carbon) on air entrainment for a standard air-entraining admixture dose demonstrating that a low LOI specification does not guarantee consistent air content.¹¹
Supplementary Cementitious Materials for Sustainability

by S. Ratchye

Synopsis: Supplementary cementitious materials (SCMs), such as fly ash or blast-furnace slag, can achieve broad sustainable aims, including the mitigation of global warming and easing pressure on landfills. Specifically, SCMs reduce the use of portland cement, increase the recycled content of concrete, and can increase concrete’s durability.

Keywords: cement; fly ash; slag; supplementary cementitious materials (SCMs).
ACI member **Steve Ratchye** is a Senior Associate in the San Francisco office of Thornton Tomasetti, an international multidisciplinary consulting firm. He is a member of ACI Committee 232, Fly Ash and Natural Pozzolans in Concrete. He received his MSE in structures and his MArch from the University of Texas at Austin, Austin, TX.

**INTRODUCTION**

Sustainability is a broad concept that poses the question: What condition will we leave the world in for our children? Many definitions are in circulation, but one of the most cited comes from the United Nation’s Brundtland Report (1987), which defines sustainability as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs.” Sustainability includes many environmental impacts such as climate change, pollution, preservation of natural habitat, and waste disposal, all of which supplementary cementitious materials (SCMs) can affect in a positive manner.

The Intergovernmental Panel on Climate Change, a scientific body with contributors from over 130 countries and more than 2500 expert scientific reviewers, stated in their 2007 Fourth Assessment Report that, “Warming of the earth’s climate system is unequivocal,” and that it is “very likely due to the observed increase in human greenhouse gas concentrations.” Forecast global warming could have severe consequences, including changing precipitation patterns, reducing agricultural output, melting of polar ice and rising sea levels.

Portland cement production contributes a significant portion of mankind’s carbon dioxide emissions: approximately 5% worldwide and 1.5% in the United States. Producing a ton (0.9 metric ton) of portland cement releases approximately 0.9 ton (0.8 metric ton) of carbon dioxide into the atmosphere (Mehta 2009). To put this number in perspective, 7.5 ton (6.8 metric ton) of portland cement is equivalent in CO₂ emissions to that from an average car for a year (Department of Energy). Manufacturing a single ton of portland cement uses 1.1 megawatt-hours (4 GJ) of energy, which is roughly equivalent to a tenth of the electricity used by a typical U.S. household for a year (Department of Energy).

Long-term consumption of concrete is steadily rising, along with populations and standards of living. The human population increased from 1.5 billion to 6 billion over the last century, for example, and the gross domestic product per capita of mainland China, grew five-fold from 1970 to 2000. The increase in portland cement production in the twentieth century from a few million ton to 1.6 billion ton in 2000 is, therefore, not surprising.

**REDUCTION OF PORTLAND CEMENT**

By decreasing use of portland cement, SCMs reduce the greenhouse gas emissions associated with its manufacture, a significant contributor to global warming.

Of all the industrial by-product SCMs, fly ash is the most plentiful, and using it in large proportions to reduce cement is known as high-volume fly-ash concrete (HVFAC). Definitions vary, with some describing HVFAC as concrete with 35% or higher cement replacement and others 50% (Malhotra and Mehta 2008). It has been demonstrated on many projects in North America that 50% replacement fly ash concrete can provide strengths appropriate for commercial construction. Fly ash has many beneficial effects on hardened concrete, and these receive further discussion in the Durability section.

The pozzolanic action of fly ash reduces concrete’s heat of hydration and also slows its rate of strength gain, two effects that make simple substitution of high volumes of cement with fly ash more suited for certain types of concrete elements.

- Foundations and vertical elements such as walls and columns do not need the full specified strength until months after they are placed. In addition, the lower temperature attained by high fly ash replacement mixtures mitigates thermal cracking for massive concrete elements such as mats or pile caps or thick walls.
- Flatwork, such as beams and slabs, usually needs roughly 75% of specified strength in 3 days to keep to schedule depending on the type of formwork, which presents more of a challenge for HVFAC.
- Post-tensioned concrete, likewise, requires high-early-strength, which can be difficult for HVFAC to achieve.
- Thin concrete elements such as slabs or slabs-on-ground present the inverse situation of mass
Concrete: The Sustainable Material Choice

Concrete: thermal blankets or other means may be required to prevent the concrete from losing heat too quickly, which can adversely affect strength.

Fly ash has a natural water-reducing effect on concrete, which signifies a way to lessen the potential impact of slower strength gain. By reducing the water-cementitious materials ratio ($w/cm$), some of the slowed rate of strength gain can be regained. Class F fly ash, as a rule of thumb, reduces water demand by 3% for each additional 10% replacement. For a greater effect, super-plasticizers have been used to reduce $w/cm$ to 0.32 or lower and achieve workability and strengths to maintain project schedule.

Common goals in early strength for commercial construction include attaining 900 to 1000 psi (6.3 to 7.0 MPa) at one day for stripping of column and wall forms and 3000 psi (21 MPa) at three days for stripping flying forms for beams and slabs. Alternatively, if shores support flatwork forms, slowed strength gain has less impact on project schedule because the shores can simply be left in place longer.

Sharply reducing the water content by using high-range water-reducing admixtures may also reduce bleed water and change the way concrete finishes, so a mockup is recommended in order to familiarize the subcontractors with the material. Curing is crucial with high volumes of fly ash because the reduced bleed water can leave the surface vulnerable to plastic shrinkage cracking.

HVFAC presents several potential concerns in colder climates. Some fly ashes, particularly Class F fly ashes, can interact with air-entraining admixture, which is necessary for concrete to resist cycles of freeze-thaw (ACI 232.2R-03). This hurdle can be overcome in some cases if the fly ash and air-entraining admixture are from consistent sources so the batch plant can learn to adjust the admixture dosage. Another concern is scaling due to deicing salts. Concrete with significant portions of fly ash that is not cured properly may be vulnerable to scaling where exposed to de-icing chemicals. Cold weather placement may also present problems due to the reduced heat of hydration in high volume Class F fly ash mixtures. Concrete’s strength is partially related to the temperature it attains during hardening, and cold weather conditions or thin elements may cause the concrete to lose warmth too quickly, necessitating thermal blankets or other means to maintain temperature.

Blast furnace slag has cementitious properties and is not considered to be high volume until portland cement replacement reaches 60% or higher. The San Francisco Federal Building, completed in 2007, is an example of a large-scale construction project that incorporated significant proportions of slag into the concrete, with 50% replacement on walls, columns and flatwork and 70% replacement in the massive pile caps (Ratchye 2006).

Slag is available in steel-producing areas like the Northeastern United States, Western Europe, and East Asia, but the worldwide supply is more limited than that for fly ash. Coal-fired power plants around the globe produce approximately 500 million ton (450 million metric ton) of fly ash suitable for use in concrete. Blast furnace slag production is roughly 110 million ton (100 million metric ton), and it is worth noting that only a fifth of slag is available for concrete because in many countries only a small portion of the slag is available in suitable granulated form.

Because it has cementitious properties, slag impacts strength gain less than fly ash, but it is still not “high-early” concrete, and form-stripping times should be established with an eye to early strength results. “Greening,” bluish or greenish coloration sometimes visible upon removal of formwork from concrete containing slag, is sometimes raised as an issue for architecturally exposed concrete. This discoloration disappears completely in a month or two, although concrete sealers should not be applied until after the concrete has faded to its final color.

An 85% cement reduction has been achieved in large-scale construction. The new I-35W bridge in Minneapolis, for example, used 15% portland cement in the bridge’s piers (Phipps and MacDonald 2009). The ternary mixture employed 18% fly ash meeting both Class C and Class F and 67% slag. It should be noted that concerns about thermal cracking in the massive piers helped to drive the high level of cement reduction in part because reinforcement of the sculptural piers prevented the placement of cooling pipes.

There is no upper limit on potential replacement of cement by supplementary cementitious materials. Successful field tests have been performed using 100% Class C fly ash for foundations and walls (Cross 2005). Most HVFAC has used Class F ash, but Class C fly ash contains CaO, or lime, which gives it cementitious properties. The Montana field trials used Class C ash with 30% CaO, a percentage on the higher end for Class C, and the mixtures contained 9 to 10 sacks of ash per cubic yard (500 to 560 kg/m$^3$). The $w/cm$ varied from 0.22 to 0.24, and the only admixture used was borax to prevent flash set. The
slumps of 4 to 8-1/2 in. (100 to 220 mm) of these extremely low $w/cm$ mixtures are a striking testament to the water-reducing effect of fly ash. Even more promising is the rate of strength gain: 2800 to 3000 psi (19.4 to 20.7 MPa) at one day, a rate of strength gain contractors can live with for many types of concrete element. The mixtures that were tested at 28 days achieved 4800 psi (31 MPa).

A systematized framework for intentionally reducing cement for sustainable aims is found in LEED, the dominant green building rating system for construction. LEED offers a credit in its Innovation in Design category for reducing cement. This category of credit aims to reward sustainable design practices that surpass the goals set out in other LEED categories of Sustainable Site, Water Efficiency, Energy and Atmosphere, Materials and Resources, and Indoor Environmental Quality. To codify a new type of Innovation in Design point, LEED makes a Credit Interpretation Ruling, which sets out criteria so other projects may follow suit.

The Credit Interpretation Ruling for reducing cement establishes the following three requirements for attaining for an Innovation in Design point.

- Portland cement is reduced on average by 40% for all cast-in-place concrete on the project compared to typical 28-day strength mixtures in the region.
- Use of any SCM is allowed, as well as lengthening the time to attain the specified strength beyond 28 days.
- Concrete is a significant portion of the project. In other words, a project with concrete only in the foundations will not earn the point.

Reducing cement can be implemented in many ways on a project, though it should be done by construction teams with knowledge of the potential difficulties in using high volumes of pozzolans listed above. The Owner may direct the contractor to find a ready-mix plant with experience in high volumes of SCMs, the design team may lay out the goals in the specifications and drawings, or the contractor may submit low-cement mixtures as a substitution (Obla et al. 2003). If the design team sets the goals, lengthening strength times according to type of concrete element and specifying maximum cement content leaves the ready-mix plant flexibility to achieve the targets.

**RECYCLED CONTENT**

SCMs, such as fly ash, slag and silica fume, are industrial by-products that add recycled content to concrete because otherwise they would likely be landfilled. Fly ash is captured from the waste stream exiting flues at coal-fired power plants, slag is collected and ground from the early stages of steel production, and silica fume is a by-product from silicon production. Redirecting these wastes into the construction reduces environmental impact from materials processing as discussed above, and also from extraction of virgin resources, which includes disruption of natural habitats, fugitive dust, and runoff.

Adding fly ash to concrete has a benefit over landfill disposal. Fly ashes contain small amounts of potentially toxic materials that can be leached out if they are placed in landfills. The hardened cement matrix, on the other hand, permanently locks up the toxic materials from fly ash and solves the problem, as has been confirmed by studies at CANMET (Canadian Centre for Mineral and Energy Technology) and the University of Aachen. In short, concrete is an ideal place to dispose of fly ash.

LEED offers a real world incentive for recycling materials for construction in its Materials and Resources category credit Recycled Content. Two points are available for this credit.

- If 5% of a project’s materials by cost is recycled, one point is achieved.
- If 10% of a project’s materials by cost is recycled, another point is awarded.

The total percentage of recycled content is calculated as the sum of the full percentage of post-consumer recycled content, and half of the percentage of pre-consumer recycled content. Aluminum from cans is an example of post-consumer, whereas fly ash, slag, and silica fume constitutes pre-consumer recycled content.

LEED considers composite materials to be “assemblies” and measures their recycled content by weight. However, in recognition that the environmental impact of cement is disproportionate to those of the other ingredients of concrete, LEED Version 2.2 and later allow as an option that the percentage of SCMs of the total cementitious materials to count as the recycled content percentage of the concrete. For example, a mixture with fly ash as 40% of the total cementitious material by weight would be considered to have a recycled content of 40%.

Once the percentage of recycled material in the concrete is established either by weight or by
percentage of SCM, then it is tallied with the rest of the products and materials for the building to establish
the total recycled percentage by cost.

LEED’s two methods for calculating the recycled content of concrete reduce the incentive for a holistic
approach to recycled materials in concrete. Establishing the recycled content by weight of the materials
undercounts the outsized environmental impact of portland cement. A mixture that is 35% SCMs, for
example, may be 6% recycled by weight, and because it is pre-consumer, the percentage shrinks to an
insignificant 3%. Please note that this mixture, if used in an entire project, would not qualify for the
Innovation in Design credit. LEED’s alternative, to consider the recycled content exclusively as
proportion of SCMs to total cementitious, disregards potential for re-use of water or aggregates. Recycling
water from reclaimed concrete is a sustainable practice, particularly in dry regions such as the south-
west region of the U.S. Using recycled aggregate from demolished concrete likewise presents great
potential for sustainability as regionally available sources of aggregate in some areas are depleted. A
better yardstick for sustainable construction would simultaneously provide incentive for all of these
green concrete practices.

**DURABILITY**

SCMs can improve the durability of concrete and add to its service life, another contribution to
sustainability. Compare the total environmental impact of a concrete structure that lasts 1000 years
to that from rebuilding the same project twenty times for the typical design life of 50 years. A durable
structure can have a small fraction of the environmental impact provided it retains its usefulness.

Some Roman concrete structures such as harbor walls, bridges and buildings, have lasted two
millennia. Volcanic ash, a pozzolan, was rarely absent from concrete construction during the height
of the Roman Empire (MacDonald 1982). It is interesting to note that the volcanic ash used in their
concrete has been shown to meet ASTM C618. In addition, where the ash was not available, they also
used broken pottery, another pozzolan. Roman structures underline the importance of social utility for
durability as a sustainable strategy. Whereas some of the structures listed above are still in use, many
others serve only historical and architectural interest now.

It must be acknowledged that the Romans cheated with these structures: there was no reinforcing to
corrode! Reasons for the lack of tension resisting elements in Roman construction include construction
methods such as ramming together mortar and aggregate and unawareness of the benefits of reinforce-
ment (Harries 1995).

Fly ash, particularly Class F, improves the durability of concrete by making the concrete matrix less
permeable. The particles are smaller than those of portland cement, and they reduce the permeability
of the concrete by filling up capillaries and continuing to react with by-products of the cement hydration
reaction. This continued reactivity also improves the long-term strength gain of the concrete.

Fly ash can increase the Life-365 Service Life Prediction model of chloride corrosion in concrete by
an order of magnitude. The Life-365 model assumes that ionic diffusion is the mechanism that conveys
the chloride to the rebar and employs Fick’s second law of diffusion to calculate the time for active
corrosion to start (Violetta 2002). Class F fly ash in particular improves durability by improving
resistance to sulfate attack as stipulated in ACI 318 and also alkali-silica reaction from aggregates.

Slag similarly makes the concrete matrix less permeable, thereby improving resistance to sulfates
and alkali-silica reaction. Silica fume used as an admixture improves resistance to chloride penetration.

**OTHER CONTRIBUTIONS TO SUSTAINABILITY**

Slag in medium or high volumes gives concrete a whiter shade, which has been employed on projects
to increase reflectivity for lighting. The floor slabs on the San Francisco Federal Building, for example,
were exposed as the ceiling, and all electric lighting was reflected off the soffit. A 50% replacement slag
concrete was chosen by the architects Morphosis to lighten the shade of the concrete and improve both
day-lighting and electrical lighting (Ratchye 2006).

If SCMs are available near a building project, such as from a local coal-fired power plant, their use can
reduce impact from transport. LEED’s Regional Materials credit awards points if 10% or 20% of a project’s
materials by cost are extracted, harvested or recovered, and manufactured within a radius of 500 miles
of the project site.
REFERENCES

ACI Committee 232, 2003, “Use of Fly Ash in Concrete (ACI 232.2R-03),” American Concrete Institute, Farmington Hills, MI, 41 pp.


Cementitious Blends and Their Impact on Sustainable Construction

by B. Blair

Synopsis: Today, the demand for high-performance building materials continues to grow along with the demand for “green” product manufacturing and sustainable building practices. Supplementary cementitious materials (SCMs) and blended cements offer sustainable and performance advantages for those who build and occupy structures of all kinds. The growing use of these environmentally friendly materials is due to several performance factors, including low permeability, resistance to chlorides and sulfates, mitigation of alkali silica reaction, greater strength, lower temperatures for mass concrete, and improved workability.

The use of cementitious blends not only results in stronger, more durable, high-performance concretes but also helps reduce global climate impact by lowering energy consumption and greenhouse gas emissions. In fact, each ton of portland cement that is replaced by SCMs reduces CO$_2$ emissions by approximately 0.8 ton (0.7 metric ton). Using cementitious blends also reduces solid waste disposal because SCMs are by-products from other industries. These environmental benefits are increasingly important to project developers and owners.

Keywords: alkali-silica reaction (ASR); cementitious blends; clinker; fly ash; permeability; portland limestone cement; silica fume; slag; supplementary cementitious materials (SCMs); sustainability.
Bruce Blair has over 25 years of experience in the concrete construction industry in manufacturing, quality management, and marketing. Blair is actively involved in key standards organizations and chairs various subcommittees within these groups.

INTRODUCTION

Strong evidence presented by the scientific community suggests that we need to reduce emissions of gases linked to global change approximately 76% by 2050 to stabilize the climate. The discussion now is not about whether the world needs to respond to climate change but what the response should be—a path of emissions cuts that stabilizes concentrations of atmospheric carbon dioxide (CO₂) and other greenhouse gases in a way that minimizes damage from rising temperatures.

According to a recent McKinsey report, the general consensus is that any successful program of action must support the dual objectives of stabilizing atmospheric greenhouse gases and maintaining economic growth. “However, while the extent of economic transformation implied is similar to the Industrial Revolution, the ‘carbon revolution’ must be achieved in one-third of the time if we are to maintain current growth levels while keeping CO₂e [carbon dioxide equivalent] levels below a level that many experts believe is the maximum that can be allowed without significant risks to the climate.”

In the end, addressing climate change is neither a scientific nor even an economic challenge—it is a human challenge. A recent BBC GlobeScan survey of 22,000 people in 21 countries found that 65% of respondents felt it was necessary to take major steps to address climate change very soon, while only 6% believed action was not necessary. This widespread agreement that global action needs to be taken to address global warming issues has spurred the rapidly growing green movement in the construction industry.

GREEN BUILDING MOVEMENT

Green building is an immediate, measurable, and cost-effective solution to the complex challenges of climate change. The building sector accounts for 38% of CO₂ emissions (lighting, heating, cooling, and the like) in the U.S. per year and represents a significant portion of the greenhouse gas emissions that affect climate change. With the built environment having such a profound impact on our natural environment and economy, it is hard to imagine that just 10 years ago no common definition existed for a high-performance green building, and only a sprinkling of buildings exhibited such features. The U.S. Green Building Council released the green building standard, Leadership in Energy & Environmental Design (LEED) in 2000. Since then, market acceptance and growth have been significant; LEED buildings now approximate 5% of the new construction market and have been growing at a 50 to 75% annual rate for the last four years.

Clearly, rapid changes and tremendous progress have been made in sustainable construction practices over the last 10 years. Today, green building is everywhere—impacting the way buildings and communities are built, influencing the product selection process, and changing the relationship between suppliers and specifiers. As the biggest movement in the design community, this trend will continue to gain momentum as the green building market (both non-residential and residential) is projected to more than double from today’s $36 to $49 billion to $96 to $140 billion by 2013.

SUSTAINABLE CONSTRUCTION CHALLENGES

As the demand for housing and infrastructure grows, the response to sustainability challenges by all industry players is to continue to build, but to do so in a different way. Sustainable construction aims to identify building materials and methods that are cleaner and more environmentally friendly while guaranteeing the highest quality in terms of esthetics, durability, and strength. Because of today’s environmentally conscious marketplace, concrete is standing out as a responsible choice for sustainable development due to its durability, recycled content, and energy efficiency.

In response to the challenges to reduce greenhouse gases and promote sustainable construction, cement manufacturers were among the first groups to tackle the issue of climate change by optimizing production processes to improve energy efficiency and minimize emissions. The calcination of limestone (CaCO₃ → CaO + CO₂) is an inevitable process in the production of portland cement clinker. As shown in Fig. 1, the calcination of raw materials (primarily limestone) is the primary source of CO₂
emissions during cement manufacturing. This reaction (calcination) accounts for approximately 60% of CO_2 emissions per ton of cement produced. The combustion of fuels (coal, coke, and the like) to heat the cement kiln accounts for the remaining 40% of CO_2 emissions per ton of cement. Heating limestone and clay in high-temperature kilns (1500°C [2700°F]) causes chemical and physical changes that transform the raw materials, such as limestone, into clinker, an intermediate product that is then ground with other additives to produce portland cement.

Process improvements have enabled cement manufacturers to reduce energy requirements and related CO_2 emissions by 33% since 1972. According to the Energy-Related Carbon Dioxide Emissions in the U.S. Manufacturing, the cement industry accounts for 2.3% of the industrial sources of CO_2 emissions and the industrial sources account for 29.5% of the total CO_2 emissions, thus the cement industry accounts for less than 1% of U.S. CO_2 emissions. According to the U.S. Department of Energy, U.S. cement production now accounts for only 0.33% of energy consumption compared to petroleum refining at 6.5%, steel production at 1.8%, and wood production at 0.5%.

Cement manufacturers have worked to make the process more energy efficient. Further significant reductions in the CO_2 footprint of portland cement can only be achieved by reducing the clinker content of the cement. Mehta recently pointed to cements with reduced clinker contents as one of the three tools for reducing the cement industry's CO_2 emissions. In his paper he proposed that this could be achieved by producing blended cements with high levels of supplementary cementitious materials (SCMs), such as fly ash, slag, or natural pozzolans.

**OPPORTUNITIES TO REDUCE CO_2 EMISSIONS**

In support of the U.S. Environmental Protection Agency’s Climate Vision initiative, the cement industry adopted a voluntary goal to reduce CO_2 emissions from cement manufacturing by 10% per ton produced below the 1990 baseline level by 2020. Methods that provide opportunities to achieve this goal include:

- Improving energy efficiency with new state-of-the-art manufacturing equipment;
- Increasing the use of blended cements (increase additives/cement ratio);
- Using biomass and industrial by-products to replace non-renewable fossil fuels;
- Adding alternative raw materials to partially replace clinker (for example, steel slag);
- Reducing clinker production by incorporating cement admixtures; and
- Improving clinker reactivity to allow more SCMs (fly ashes, slag, and the like).

This multi-faceted approach has made a significant contribution to reducing the industry’s CO_2 emissions. Opportunities to reduce CO_2 attributed to manufacturing portland cement clinker involve the use of alternate raw materials as a substitute for limestone or the use of SCMs as a direct substitute for portland cement in blended cements and/or concrete. For every ton (0.9 metric ton) of CaCO_3 replaced in the raw mixture, CO_2 is reduced by approximately 0.5 ton (0.45 metric ton) per ton (0.9 metric ton) of clinker. For every ton (0.9 metric ton) of clinker replaced, CO_2 is reduced by approximately 0.8 ton (0.7 metric ton).

Because SCMs are used as a substitute for cement, they reduce the amount of clinker used to produce cement and also the fuel required to produce the clinker.

**BUILDING “GREEN” WITH BLENDED CEMENTS**

The Pantheon in Rome was built in around 125 A.D., and although it is centuries old it remains one of the best preserved ancient buildings. The modern formulation of concrete is very different from that used in the construction of this monument, but the materials used at that time already contained lime and pozzolan. Today, pozzolan is still used as a cement additive, or cementitious product, but other materials, including by-products from other industries, can also be used.

The most common SCMs are slag cement (a by-product of the iron-manufacturing process), fly ash (a coal combustion by-product from power plants), and silica fume (a by-product of manufacturing silicon metals and ferro-silicon alloys). SCMs can be used in concrete either as a separate component or as a constituent of a blended cement. Binary blends contain portland cement and one SCM; ternary blends contain portland cement and two SCMs; and quaternary blends contain portland cement and three SCMs. Cementitious blends have many properties that contribute to sustainable design—their proper use results in stronger, longer-lasting concretes, reduces the consumption of nonrenewable raw materials and the emission of greenhouse gases, and turns by-products from other industries into resources that would otherwise be disposed of in landfills (Fig. 2).
Blair

Considering the fact that concrete is the most widely used construction material in the world, the use of cementitious blends can have a major impact on the environment. The global potential for $\text{CO}_2$ emission reduction through producing blended cement is estimated to be at least 5% of total $\text{CO}_2$ emissions from cement making, but may be as high as 20%\textsuperscript{9}. The potential savings will vary by country, and even by region. In European markets with a long tradition of making blended cements, the average clinker content of the cement is around 60%. The rest is slag, pozzolanic material, fly ash, and/or ground limestone. North America lags far behind other world regions in the use of blended cements, due to the historical trend of adding these materials directly at the batch plant.

Today, building green is a way of life that not only helps protect our environment in the near-term, but also represents a more holistic view of how to maintain more of our natural resources in a long-term, sustainable manner. The use of blended cements can help architects and engineers meet sustainable building objectives, such as those prescribed by the U.S. Green Building Council’s LEED program. Concretes containing SCMs can contribute to LEED credits in the following categories: Sustainable Sites, Energy and Atmosphere, Materials and Resources, Indoor Environmental Quality, and Innovation in Design.

**PERFORMANCE BENEFITS OF BLENDS**

A whole range of exceptional properties, which are particularly sought after by construction professionals, essentially explains the growing use of cementitious blends. Portland cement, slag, and fly ash all contain similar oxides, though the proportions are different (Table 1). When portland cement hydrates, calcium silicate hydrate (CSH) is formed, which is the glue that holds the concrete together. When SCMs are added, particles pack more tightly within the concrete and additional CSH forms from the SCM hydration process. With fewer voids, the concrete is less permeable and stronger. These chemical and physical properties improve the performance of concrete in both its plastic and hardened states.

**Improved Plastic Properties**

*Workability*—In general, the addition of SCMs will enhance concrete’s workability. The spherical shape of fly ash particles and the glassy nature of slag cement particles can reduce the amount of water needed to produce workable concrete, depending on the materials selected. The use of silica fume, depending on the replacement rate, can have an adverse impact on workability, and special attention should be given to concrete placing and finishing.

*Set time*—Slag cement and fly ash tend to delay concrete’s setting time, which can provide additional time for placement, consolidation, and finishing in warmer temperatures. In cooler temperatures, the use of heated water and aggregates or the addition of an accelerating admixture may be necessary to reduce setting time. Silica fume has little effect on concrete setting times.

*Bleeding*—The development of bleed water on the concrete surface can impact finishing and durability. Slag cements, which are generally ground finer than the portland cement, affect the migration of water and reduce bleeding, while slag cement ground coarser than the portland cement particles tend to increase bleeding. Fly ash generally reduces the water demand necessary to achieve a given workability of the mixture, which reduces the amount of bleeding. Silica fume can virtually eliminate bleeding, which requires special attention to be paid to concrete placing, finishing, and curing to achieve the best possible results.

**Improved Hardened Properties**

*Enhanced strength*—SCMs contribute to the strength gain of concrete. Typically, the use of slag cement and fly ash will lower early strengths (1 to 14 days) but can significantly improve long-term strength development (28 day and beyond), but this strength gain curve is very dependent on the proportions and materials used (refer to Fig. 3 and Table 2). For example, Class F fly ashes tend to have a slow strength gain curve contributing mainly to the strength beyond 28 days, whereas silica fume contributes primarily to the 3- to 28-day strengths. Both compressive and flexural strengths can increase markedly at 28 days and beyond with the addition of SCMs.

*Reduced permeability*—SCMs can significantly extend the life of concrete by reducing the permeability of concrete to the ingress of chlorides and other aggressive agents, especially at later ages. Silica fume has a very profound effect on permeability, exhibiting as much as a five-fold reduction in permeability. The Rapid Chloride Permeability Test, as described in ASTM C1202-09\textsuperscript{10}, has proven to be a reliable
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indicator of permeability. ASTM C1202-09 determines the electrical conductance of concrete, providing a rapid (approximately 20 hours after curing) indication of the resistance to the penetration of chloride ions. Figure 4 shows typical data, which demonstrates the benefits of SCMs and synergistic effects of using more than one SCM in the mixture.

Mitigating Distress Mechanisms

Alkali-silica reaction (ASR)—When used in the correct proportions, SCMs can effectively prevent excessive expansion due to ASR in three ways:

- SCMs can reduce the alkali loading in the concrete, as generally SCMs contain fewer alkalis than portland cement.
- The fly ash and slag in blends also react with the alkalis in portland cement, making them unavailable for the reaction.
- Lower permeability reduces the ingress of water.

The efficiency of slag cement in controlling damaging expansion due to ASR depends on the nature of the slag cement, the reactivity of the aggregate, and the alkali loading of the concrete. In most cases, 50% slag cement is sufficient for controlling damaging expansion in concrete with highly reactive aggregates and high alkali content. The amount of fly ash required to mitigate excessive expansion typically is in the range of 15 to 55%, depending on the chemical composition of the ash, reactivity of the aggregate, and the alkali loading of the concrete. Generally, Class F ashes are much more effective in controlling expansion due to ASR than Class C ashes. Silica fume can be used to control ASR; however, the amount required generally results in poor constructibility.

Blends of SCMs have also been shown to be effective in controlling expansion due to ASR. Blends of slag cement and silica fume, as well as blends of fly ash and silica fume, seem to have a synergistic effect in mitigating expansion due to ASR, while producing a very workable concrete.

Sulfate attack—Protection against sulfate attack can be obtained by utilizing materials not susceptible to deterioration when exposed to sulfate ions in addition to producing concrete that retards the ingress and movement of water. Concrete containing SCMs generally offers superior resistance to sulfate attack as they lower the permeability, thus restricting the ingress of sulfate-bearing ions. In a number of cases they additionally reduce the compounds that can react with sulfates. Typically, slag cement, silica fume, and Class F fly ashes are very effective in improving sulfate resistance. The effectiveness of Class C fly ashes is very dependent on the ash chemistry and the replacement level.

Thermal stress—If the temperature differential between the concrete’s surface and interior is too high, cracking and loss of structural integrity can result. Utilizing high replacement levels of slag cement and/or fly ash in properly proportioned mixes can reduce the peak temperatures as well as the rate of heat generation. Reducing the heat of hydration of the mixture can moderate the development of thermal stresses within the concrete and prevent cracking.

NEXT GENERATION CEMENTS

The trend is clear—the sustainability movement in general, and the LEED program in particular, will continue to provide a strong incentive for developing and specifying even more innovative, sustainable building solutions. The cement industry is making strides in reducing its energy use and emissions but must continue to respond to the challenges of sustainable building both through the material itself and its manufacture, but also in the context of construction systems.

The U.S. cement industry has a number of environment-related goals that it is striving to meet to minimize its environmental footprint. One proven method to reduce greenhouse gases per ton of cement is the use of interground limestone. Portland limestone cement can be produced by intergrinding portland cement clinker, limestone in quantities greater than 5%, and calcium sulfate. Such cements have been in use in Europe for decades and in 2004 more than one third of the cement produced in the European community was CEM II portland limestone cement containing between 6 to 35% limestone. In Canada, the incorporation of up to 5% limestone has been permitted in portland cements since 1983. After 20 years, ASTM finally allowed the use of the same amount of limestone in ASTM C150-09 and AASHTO M85 in 2004, with AASHTO M85 following suit in 2007. These recent changes (ASTM C150-09 and AASHTO M85) have the potential to reduce energy consumption by 11.8 trillion BTUs and CO₂ emissions by more than 2.5 million tons (2.3 million metric tons) per year.
In response to growing pressures to reduce the clinker content in cement, the Canadian Standards Association (CSA) introduced a new classification of cement in 2008, this being portland limestone cement (PLC) containing up to 15% limestone. Limestone can be used up to this level in all types of cement, except for sulfate-resisting cements.

Considerable laboratory and field testing has been conducted in Canada in recent years to demonstrate that PLC with up to 15% limestone can be manufactured to produce equivalent performance to a portland cement in terms of concrete strength and other properties, including durability. The equivalent performance is achieved by optimizing the PLC with regards to composition and particle-size distribution and requires intergrinding rather than blending of the portland cement and limestone.

There is generally no measurable consistent difference between the results obtained for concrete produced with PLC compared with portland cement, either in plain concrete or at a given level of SCM. It should be noted that the PLC was ground to a significantly higher fineness than the portland cement in most of these studies, as laboratory studies have shown this is required to achieve equivalent performance. Although limestone is often considered an inert filler when added to portland cement, it is not completely chemically inert and it contributes to the development of the microstructure in a number of ways. Firstly, because limestone is softer than portland cement clinker, it will achieve a finer particle size when interground with the clinker, producing an improved particle size distribution and improving particle packing. The fine limestone particles may also act as nucleation sites, thereby increasing the rate of hydration of the calcium silicates at early ages and, possibly, improving the distribution of the hydrates. Finally, CaCO₃ will react chemically with the aluminates to form carboaluminate phases. The extent of this reaction increases as the fineness of the limestone increases and, when used together with fly ash or slag, due to additional reaction with the additional aluminates.

The results of field trials to date demonstrate that the properties of fresh concrete made with PLC are similar to those of a concrete containing general use (GU) portland cement. At the same water-cement ratio, concrete made using PLC has equivalent 3-day and 28-day compressive strengths as concrete made using GU cement (Table 3 and 4). PLC also demonstrates a generally better initial reactivity (set time, 3-day strength) and a similar performance in respect to durability (freezing and thawing resistance, salt-scaling resistance). Results of the salt scaling testing are shown in Table 5.

Such an increase in limestone content results in a reduction in the clinker content of the cement of more than 8%. When combined with 40% to 50% SCM, the effective reduction in clinker content is in the range of 50%. Of course, the level of SCM that can be used will depend on the properties of the SCM and the type of application.

Finding new ways to further reduce energy needs and CO₂ emissions is a top priority for cement companies, and solutions are continually being developed that minimize the amount of clinker while maximizing the use of alternative materials. With this next-generation class of cement, customers can use similar amounts/percentages of SCMs (slag, fly ash, and silica fume) in their mixture while also replacing 15% of the portland cement in the mixture with limestone, compared to 5% now (that is, PLC is a direct replacement of portland cement).

Many standards writing organizations, such as ASTM and CSA, develop consensus standards where minimum specifications are set for materials, and standard test methods are used to determine compliance with the specification limits. In the development of these consensus standards, volunteer members provide a balanced representation of a range of different interests, typically including both producers and users of a standard as well as general and governmental agency interests. Manufacturers often provide technical assistance to help develop these specifications, and most can offer detailed test results, quality control records, and additional support to specifiers. In support of data collection for the code process and to support the product development process, Lafarge has been conducting plant, lab, and field trials at a number of sites.

Materials specifications for cements and other concrete ingredients are referenced in concrete specifications, which are in turn referenced in building codes. This can result in a lengthy process before these “new” cements can be introduced to the market. However, standards do evolve over time as needs evolve. With increasing demand for continuous improvement in green building practices, it should be expected that the performance data from PLC applications in Canada and corresponding CSA standards would influence the development of future proposals for ASTM standard specifications that meet the collective needs of all interested parties.
CONCLUSION

In an effort to reduce their overall environmental footprint, all industries, including cement, are embracing the concept of sustainable development—the ability to build structures we need today without depleting resources for the future. Sustainable construction aims to identify building materials, such as blended cements, that are more environmentally friendly while guaranteeing the highest quality in terms of esthetics, durability, and strength.

While the performance benefits of cementitious materials to plastic and hardened concrete are quite numerous, their effect on the worldwide trend toward ever more “green” construction practices will continue to increase—and cannot be overstated. Blends represent a class of cement that can help designers and builders achieve stronger, more durable, longer-lasting structures, and they reuse by-products from other industries normally destined for landfills. These high-performance cementitious blends help maintain our environment in a sustainable manner for the long-term by reducing the use of nonrenewable natural resources, energy consumption, and greenhouse gas emissions.

Many existing specifications—especially those developed in less environmentally sensitive areas—routinely specify portland cement. In most cases, blends can be substituted to obtain equal or superior results. Various organizations, including ACI (American Concrete Institute) and the SCA (Slag Cement Association), offer detailed recommendations that specifiers can consult to determine whether and how to specify such substitutions.

In addition, manufacturers can provide technical assistance to help develop or modify specifications, and manufacturers can provide detailed test results, quality control records and additional support to specifiers. Often, the best approach is to move from materials-based specifications for concrete to performance-based specifications, allowing contractors greater control over choosing the specific blend.

REFERENCES

11. ACI Committee 233, “Slag Cement in Concrete and Mortar (ACI 233R-03),” American Concrete Institute, Farmington Hills, MI, 2003.
Table 1—Typical chemical oxides for various cementitious materials

<table>
<thead>
<tr>
<th></th>
<th>Portland cement</th>
<th>Slag cement</th>
<th>Fly ash, Class C</th>
<th>Fly ash, Class F</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaO</td>
<td>65</td>
<td>45</td>
<td>25</td>
<td>3</td>
</tr>
<tr>
<td>SiO₂</td>
<td>20</td>
<td>33</td>
<td>37</td>
<td>58</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>4</td>
<td>10</td>
<td>16</td>
<td>20</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>3</td>
<td>1</td>
<td>7</td>
<td>10</td>
</tr>
<tr>
<td>MgO</td>
<td>3</td>
<td>6</td>
<td>7</td>
<td>1</td>
</tr>
</tbody>
</table>

*Courtesy of Slag Cement Association.

Table 2—Test results comparing lower early strengths and higher later strengths of concrete with use of supplementary cementitious materials

<table>
<thead>
<tr>
<th>Mixture</th>
<th>psi</th>
<th>MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-day 28-day</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OPC</td>
<td>2218</td>
<td>15.3</td>
</tr>
<tr>
<td>OPC + 10% ash</td>
<td>1960</td>
<td>13.5</td>
</tr>
<tr>
<td>OPC + 20% slag</td>
<td>1507</td>
<td>10.4</td>
</tr>
<tr>
<td>OPC + 10% ash + 20% slag</td>
<td>1250</td>
<td>8.6</td>
</tr>
</tbody>
</table>

Note: OPC is ordinary portland cement.

Table 3—Compressive strength development at 3 days of site-cast, standard-cured cylinders.

<table>
<thead>
<tr>
<th>Mixture</th>
<th>3 day (MPa)</th>
<th>3 day (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GU</td>
<td>GU</td>
<td>GU</td>
</tr>
<tr>
<td>50% blend</td>
<td>15.3</td>
<td>15.6</td>
</tr>
<tr>
<td>40% blend</td>
<td>18.9</td>
<td>19.2</td>
</tr>
<tr>
<td>25% blend</td>
<td>21.7</td>
<td>20.7</td>
</tr>
<tr>
<td>0% blend</td>
<td>24.2</td>
<td>25.2</td>
</tr>
</tbody>
</table>

Note: GU is general use; GUL is general use limestone (13%).
Concrete: The Sustainable Material Choice

Table 4—Compressive strength development at 28 days of site-cast, standard-cured cylinders.
Blend is optimized blend of slag and Class C fly ash

<table>
<thead>
<tr>
<th>Mixture</th>
<th>28-day (MPa)</th>
<th>28-day (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GU</td>
<td>GU</td>
<td>GU</td>
</tr>
<tr>
<td>50% blend</td>
<td>43</td>
<td>42.5</td>
</tr>
<tr>
<td>40% blend</td>
<td>43.5</td>
<td>43.5</td>
</tr>
<tr>
<td>25% blend</td>
<td>41.3</td>
<td>39.8</td>
</tr>
<tr>
<td>0% blend</td>
<td>37.7</td>
<td>38.2</td>
</tr>
</tbody>
</table>

Note: GU is general use; GUL is general use limestone (13%).

Table 5—All mixtures pass salt scaling test (ASTM C 672).
Blend is optimized blend of slag and Class C fly ash

<table>
<thead>
<tr>
<th>Mixture</th>
<th>kg/m²</th>
<th>lb/ft²</th>
</tr>
</thead>
<tbody>
<tr>
<td>GU</td>
<td>GUL</td>
<td>GU</td>
</tr>
<tr>
<td>50% blend</td>
<td>0.399</td>
<td>0.317</td>
</tr>
<tr>
<td>40% blend</td>
<td>0.079</td>
<td>0.23</td>
</tr>
<tr>
<td>25% blend</td>
<td>0.031</td>
<td>0.05</td>
</tr>
<tr>
<td>0% blend</td>
<td>0.036</td>
<td>0.12</td>
</tr>
</tbody>
</table>

Note: GU is general use; GUL is general use limestone (13%).

Fig. 1—Firing of raw materials is primary source of carbon dioxide (CO₂) emissions during cement manufacturing.
Fig. 2—Designed to last for 100 years, the Confederation Bridge connecting Prince Edward Island to New Brunswick used various supplementary cementitious materials in seven different high-performance concretes to achieve both durability and strength.

Fig. 3—Test results comparing lower early strengths and higher later strengths of concrete with use of supplementary cementitious materials. (Note: OPC is ordinary portland cement; 1 MPa = 145 psi.)

Rapid Chloride Permeability Test

Fig. 4—Typical data for various mixture proportions containing supplementary cementitious materials using rapid chloride permeability test. Ranking per ASTM 1202: 4K = high; 2-4K = moderate; 1-2 K = very low; 0.01 = negligible.
Performance-Based Specifications and Sustainable Development Using Slag Cement

by C.-M. Aldea, B. Shenton, and B. Cornelius

Synopsis: In recent years, human sustainability has been increasingly associated with the integration of economic, social, and environmental spheres. The concrete industry is committed to minimizing any negative impact it may contribute to the natural environment. When performance-based specifications are used, performance requirements are stated in measurable terms. They promote a better use of materials, including supplementary cementitious materials, provided that the finished product meets performance requirements. Slag is an industrial by-product, which when used in concrete has engineering, economical, and ecological benefits; therefore it makes concrete a more sustainable product. In this paper, performance-based specifications and sustainable development are defined in the context of the concrete industry, and examples of two projects, where performance-based specifications, sustainable development and high volumes of slag were successfully used: 50% slag replacement was used to mitigate the alkali-silica reaction of local fine aggregate for use in making concrete for the construction of DeBeers diamond mine facilities in Northern Ontario, Canada; 50% slag replacement was used to limit the heat-generation capacity of high-density concrete during the initial period of curing and subsequent cooling to avoid thermal cracking for high level used nuclear fuel waste storage containers.

Keywords: alkali-silica reaction (ASR); heat of hydration; high-density concrete; performance specifications; semi-adiabatic curing; slag cement; sustainability.
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**INTRODUCTION: CONCRETE SPECIFICATIONS AND SUSTAINABILITY**

In recent years, the trend has been for the construction industry to move away from a prescriptive approach for concrete specification to a performance approach. The Canadian Standards Association (CSA) defines prescriptive concrete specification as “a method of specifying a construction product in which all the processes, activities, materials, proportions and methods used to achieve the intended final outcome are specified in mandatory language contained in the project specification” (CSA 23.1-04, Annex J). Therefore, contractors, subcontractors, materials suppliers, and manufacturers must follow a prescribed process and use prescribed materials and proportions to deliver the product. When prescriptive specifications are used concrete is treated as a commodity, assuming a prescribed mixture of ingredients produces identical performance, while in fact concrete, like most products, varies widely (Braselton and Blair 2004). It is common knowledge that two batches of concrete with assumed identical mixture proportions may exhibit very different properties, depending on variations in the ingredients.

CSA defines performance concrete specification as “a method specifying a construction product in which the final outcome is given in mandatory language, in a manner that the performance requirements can be measured by accepted industry standards and methods” (CSA 23.1-04, Annex J). Therefore, processes, materials, and activities used are left to the discretion of the contractors, subcontractors, manufacturers, and materials suppliers. However, in a performance specification, the concrete supplier still must use materials that meet the standard specifications for the individual components: aggregate, cement, admixtures, and supplementary cementitious materials (SCM). In a performance specification, the performance requirements are stated in measurable terms, and the ability of the finished product to meet those requirements can be verified during or following construction. Performance-based specifications focus on properties such as consistency, strength, durability, and aesthetics, rewarding quality, innovation, and technical knowledge, in addition to promoting better use of materials (Braselton and Blair 2004). They allow a producer to use different portland cements in varying proportions, or SCMs, to deliver concrete meeting the specified strength while improving workability and potentially reducing overall costs.

While the concrete industry is theoretically moving away from prescriptive- toward performance-based specifications, in reality few performance-based specifications are actually written for concrete; most of them are hybrids, combining elements of both performance and prescriptive specifications (Braselton and Blair 2004).

Sustainability in general is defined in dictionaries as the ability to maintain a certain process or state. Sustainability has become a complex term that can be applied to almost every facet of life on Earth and is most frequently used in connection with biological and human systems. Among others it is part of organization concepts, such as: sustainable cities, eco-municipalities, and activities and disciplines, such as: sustainable architecture and renewable energy. Since the 1980s, human sustainability has been increasingly associated with the integration of economic, social, and environmental spheres. In 1987, the World Commission on Environmental and Development (Brundland Commission 1987) articulated
what has now become a widely accepted definition of sustainability: “[to meet] the need of the present without compromising the ability of future generations to meet their own needs.”

In the sustainability context, the concrete industry is committed to minimizing any negative impact it may contribute to the natural environment. Concrete has a life cycle, including phases such as: material acquisition, production, construction, use (operation and maintenance), and recycling. Therefore, to reduce concrete’s environmental footprint, the concrete industry has approached sustainable development through the concrete life-cycle perspective by evaluating all phases of concrete life cycle and by minimizing energy use, reducing emissions, conserving water, minimizing waste, and increasing recycled content. Although increasing recycled materials content is one of the means to reduce the environmental impact of concrete, one needs to be cautious regarding recycled materials to avoid any detrimental effect on the finished concrete. Performance indicators per unit of concrete produced used to quantify sustainability goals, which are measured and reported by the concrete industry, include: embodied energy, carbon footprint, potable water used, waste, and recycled content.

Mehta presents the U.S. experience with high-volume fly ash concrete for sustainable high-performance concrete structures (Mehta and Manmohan 2006) and tools for moving forward to cut carbon emissions to support global concrete industry sustainability (Mehta 2009). Among the primary concrete-making materials, cement production is largely responsible for carbon dioxide (CO₂) emission. Methods to meet the targets for drastic cuts in the global CO₂ emission rate include minimizing concrete consumption through innovative architecture and structural design, and mixture proportioning optimization by use of blended cements containing high volumes of supplementary cementitious materials (SCMs) (Mehta 2009). Mixture proportions, properties, and applications for concrete using SCMs are reported in the literature. These mixtures are more durable and sustainable.

Slag is an industrial by-product that originates during the production of iron in a blast furnace. American Concrete Institute (ACI) Committee 233 defines slag as a “nonmetallic product consisting essentially of silicates and aluminosilicates of calcium and other bases, that is developed in a molten condition simultaneously with iron in a blast furnace” (ACI Committee 233 2003), then water chilled rapidly to form glassy granular particles, and then ground to cement fineness or finer (ACI Committee 233 2003). When used in conjunction with portland cement, slag contributes to the properties of the hardened concrete through hydraulic or pozzolanic activity, or both. Through granulation and grinding, slag cement captures and makes available the materials and energy that would otherwise be waste if slag were disposed. The benefits of the use of slag in the cement and concrete industries can be divided into three categories: engineering, economic, and ecological (Bouzoubaâ and Fournier 2003). Although slag grinding releases around 0.07 tonne (0.08 ton) of CO₂ for every tonne (1.1 ton) of slag produced, for every tonne of portland replaced by slag there is a saving of almost a tonne CO₂, which reduces greenhouse gas emissions. As part of ACI’s mandate to all the technical committees to include sustainability on their agendas, ACI Committee 233 has incorporated into the Guide to Use of Slag Cement in Concrete and Mortar (ACI 233R-03), currently under review, a chapter relating slag cement and sustainability. According to the current version of the document use of slag cement in concrete makes concrete a more sustainable product by:

- Reducing disposal and increased use of a recovered industrial material;
- Reducing embodied energy;
- Reducing embodied greenhouse gas emissions;
- Reducing virgin material used in the manufacture of concrete;
- Reducing the quantity of cement required to achieve a specified strength;
- Improving service life through greater concrete durability; and
- Increasing concrete reflectance, lowering the urban heat island effect.

This paper presents two examples of projects where performance-based specifications, sustainable development, and high volumes of slag were used:

- To mitigate the alkali-silica reaction (ASR) of the local fine aggregate for the use in making concrete for the construction of mine facilities; and
- To limit the heat generation capacity of high-density concrete (HDC) during the initial period of curing and subsequent cooling for high level used nuclear fuel waste storage containers.
USE OF SLAG TO MITIGATE ASR IN REACTIVE AGGREGATES IN CONCRETE

Background

DeBeers Canada Incorporated Victor Mine, the first diamond mine in Ontario, Canada, is located in the James Bay district of Northern Ontario, approximately 90 km (56 mi) west of Attawapiskat. The mine site is in a remote location, with limited air and winter road access. Potential sources of aggregate, particularly suitable sand, were limited due to terrain and local geology. Project requirements included the use of local aggregates for concrete in construction of the mine facilities. Additionally, the construction schedule was accelerated by six months resulting in the need to utilize volumetric mixing trucks to produce structural concrete until conventional batching and systems arrived via winter ice road.

Experimental program

Petrographic evaluation of local aggregates was conducted following CSA A23.2-15A (CSA Committee A23.2 2004) to evaluate the local aggregate proposed for use in concrete in the construction of mine facilities. Preliminary gradation analysis of sand samples from site showed that the sand was very fine. To resolve this issue the sand was blended with crusher fines from the production of coarse concrete aggregate to produce a composite sand blend. Ultimately, once the sand source was properly developed and a more representative sample analyzed, it was determined that it would not be necessary to use the composite blend for concrete production. Figure 1 presents the results of the sieve analysis of the final local concrete sand used on site. The aggregate gradation shows that the sand is marginally not within the specification limits.

As part of the local aggregate evaluation the potential for deleterious expansion of concrete aggregates due to the ASR was conducted following CSA A23.2-25A (CSA Committee A23.2 2004). This test method allows detection within 16 days of ASR aggregate by means of mortar bars subjected to accelerated test conditions. Three types of aggregates were used for the accelerated expansion of mortar bar tests: local sand concrete sand, composite sand, and a sand of known reactivity Spratt control. Spratt is a quarried limestone from Eastern Ontario frequently used as a reference for mortar bar tests. Figure 2 presents the results of the mortar bar testing. The accelerated expansion mortar bar test results show that the local sand is susceptible to ASR.

According to CSA A23.2-27A (CSA Committee A23.2 2004) both the concrete sand and the composite sand exceed the 0.15% maximum expansion limit, and they are classified as highly reactive. In normal circumstances a different sand source would be sought and this source would not be used in concrete production. Due to the remote location of the Victor Mine site this was not an option and the issue had to be resolved by other means. The solution proposed to suppress the ASR of the local aggregate was to use various SCMs, as recommended by CSA A23.2-28A (CSA Committee A23.2 2004).

Evaluation of the effectiveness of various SCMs combinations in suppressing the ASR of the available local fine aggregates was conducted using a modified version of the accelerated mortar bar test CSA A23.2-25A extended to 56 days (CSA Committee A23.2 2004). Table 1 presents the mixtures tested. Variables included the type of SCM: Type GU cement, low-alkali cement, 10SF cement, and slag; the SCM dosage rate, in percent by weight, 0, 50, and 100; the SCM manufacturer: 1, 2, and 3; and the type of fine aggregate used: composite sand and Spratt. Type GU cement and 10SF cement are Canadian nomenclatures as defined by CSA A3000 for general use (GU) cement similar to Type I cement, as per ASTM C150-09, and blended 7 to 8% silica fume (SF) and GU cement, respectively.

Results and discussion

Figure 3 presents average expansion measurements for the mixtures tested. According to CSA A23.2-28A an expansion below 0.10% at 14 days for mortar bars tested following CSA A23.2-25A shows that the cementitious material proposed is effective in suppressing ASR. Mix 2 with 100% low alkali cement was least successful in the suppression of expansion due to ASR. Its 14-day expansion was above the CSA limit and it continued to increase over time. Mixes 3 and 8, which included 100% 10SF cement, were both below the 0.10% CSA limit at 14 days; however they differ by manufacturer. Both mixtures showed a similar performance at 56 days and they were effective in suppressing expansion. Mixes 4 and 9 containing 50% low alkali cement and 50% slag, and 50% GU cement and 50% slag, respectively had similar performance. They were both below the 0.10% expansion limit at 14 days and even after 56 days they continued to be effective in suppressing ASR.
Concrete: The Sustainable Material Choice

Low alkali cement did not provide any noticeable support in suppressing the deleterious reaction. The results suggested that slag used both in Mixes 4 and 9 was responsible for the suppression of ASR. Mixes 5 and 10, which included 50% 10SF and 50% slag from different manufacturers, showed identical results over the 56 days period. They were below the expansion limit at 14 days and they were the most effective for extended periods. Mixes 6 and 11 were similar with Mixes 5 and 10, except for Spratt aggregate. However, Mixes 6 and 11 showed trends similar to Mixes 5 and 10. These results confirmed the effectiveness of the combination 50% 10SF cement and 50% slag in suppressing ASR, as well as that there was no difference between the materials produced by different manufacturers.

Based on the results in Fig. 3, the most effective cementitious materials combination at suppressing ASR of the composite sand tested was 50% 10SF cement and 50% slag. However, the mixtures containing 50% low alkali cement and 50% slag, and 50% GU cement and 50% slag, respectively, were also effective in significantly reducing the expansion of the composite sand, although to a lesser extent. The recommendation and selection of the cementitious material combination to be used at site was made based on performance, cost, and availability; 50% GU cement and 50% slag was selected and used for concrete in the mine facilities.

The concrete volume placed on site with 50% type GU cement and 50% slag was in excess of 12,000 m³ (15,700 yd³). A concrete volume of approximately 5000 m³ (6600 yd³) was produced by volumetric mixing trucks prior to the arrival and commissioning of the conventional concrete batch plant. Concretes containing high percentages of slag often require longer curing times due to the retarding effect of the cement replacement. This situation did not arise for this project due to the strict adherence to the curing requirements set forth in the project specifications and CSA construction codes. No accelerators were used and there were no delays in construction time.

Concrete was mixed in a volumetric batch trunk at temperatures as low as –35°C (–31°F). This was accomplished by pre-heating the aggregate and mixing water, hoarding and heating the formwork, and careful temperature monitoring of the structure to ensure proper curing. Slag also helped, due to its low heat of hydration, to eliminate the need for supplemental cooling for mass concrete placements. Several placements in excess of 400 m³ (500 yd³) were executed on site during the summer months when ambient air temperature exceeded 35°C (95°F) and cooling was never required. This was possible due to strict adherence to proper curing requirements for hot and cold concreting in CSA A23.1.

USE OF SLAG TO LIMIT HEAT GENERATION CAPACITY OF HIGH DENSITY CONCRETE

Background

Materials specifications of mass HDC, which may be subjected to elevated temperatures, require the use of special-use portland cements, either low heat of hydration (LH) portland cement, moderate heat of hydration (MH) portland cement, or high sulphate resistant (HS) portland cement. The cement industry in Canada has moved away from manufacturing special-use portland cements, which were approved for some applications of mass HDC, and for which temperature rise in the concrete is of importance. Special-use cements have been replaced by blending SCM with GU portland cement to provide blended cements with the performance properties of the special-use cements.

The total heat released during hydration depends on factors including the composition of cementitious materials, amount of cementitious materials and the water-cementitious materials ratio (w/cm) of the mixture. For practical purposes, the rate of heat evolution is more important than the total heat of hydration. The rate of heat development is typically measured in an adiabatic calorimeter where the evolution of temperature over time is monitored.

The objective of the project presented in this paper was to conduct a technical evaluation of SCMs as an alternative to Type LH, Type MH, and Type HS cement, and development of HDC mixture proportions to meet specific target properties. Type LH, Type MH, and Type HS cements are Canadian nomenclatures, as defined by CSA A3000, for low heat of hydration, moderate heat of hydration, and high-sulphate-resistant portland cements similar to Type IV, Type II, and Type V cements, respectively, as per ASTM C150-09. Essential factors identified for the cementitious material to be used for the application discussed were: heat of hydration, as related to potential concrete cracking, and protection of embedded steel components from corrosion. The selection of a candidate SCM was based on a combination of technical and market factors, with slag providing the best combination of engineering performance, extensive performance
history in the concrete industry, and long term consistency and availability. Aldea et al. presented more
details about the project work conducted and the results obtained (Aldea et al. 2007, Aldea et al. 2009).
This paper presents the study of the effect of the addition of high-volume-slag blended cement for HDC on
the heat generating capacity of concrete during the initial period of curing and subsequent cooling evaluated
by measuring the 7-day heat of hydration and by using semi-adiabatic curing.

Experimental program

The experimental program described here was conducted to investigate the potential for thermal
 cracking of the concrete during the curing period. The reference HDC mixture proportions used 375 kg/m³
(630 lb/yd³) of Type HS (high-sulphate resistance) cement. Therefore, Type HS cement was used
throughout the experimental program as a reference.

The 7-day heat of hydration of the cementitious powders was determined following the test method
described in ASTM C186 (Aldea et al. 2009). According to this test method the heat of hydration is deter-
mined by measuring the heats of solution of unhydrated cement and partially hydrated cement for 7 and
28 days in a mixture of nitric and hydrofluoric acids. The difference between the two values represents
the heat of hydration for the respective hydrating period, which can be used for calculating temperature
rise in mass concrete. Test candidates included special use portland cements Type HS and Type MH;
general use portland cement Type GU; and blended cements using Type GU cement and slag, at cement
replacement ratios of 25%, 35%, and 50%.

Semi-adiabatic curing was used to simulate the heat generating capacity for the mass concrete during
the initial period of curing and subsequent cooling (Aldea et al. 2009). The temperature rise of the high
density concrete was tested in plywood boxes containing approximately 0.22 m³ (0.78 ft³) of concrete
surrounded on all sides by 0.3 m (0.98 ft) of expanded polystyrene foam insulation, which provided a
good simulation of the heat evolution in a large concrete mass using a relatively small sample size. The
concrete in the curing boxes was instrumented with vibrating wire strain gauges (VWSG) embedded in
the center of the concrete to monitor strain and temperature rise as the concrete set and cured. The
concrete compositions tested used cementitious materials at two contents: higher cementitious materials
content 375 kg/m³ (632 lb/yd³), which was similar to the reference concrete mixture proportions, and
lower cementitious materials content 325 kg/m³ (548 lb/yd³). The higher cementitious content mixtures
used: Type HS cement at \( w/cm = 0.31 \); Type MH cement at \( w/cm = 0.31 \); and slag blended cements using
Type GU cement and slag at a slag replacement ratio of 50% at \( w/cm = 0.37 \). The lower cementitious
content mixtures were all blended cements using Type GU cement and slag replacement ratios of 25%,
35%, and 50%, at \( w/cm = 0.42 \). All the mixtures used natural iron-ore based aggregates, air-entraining
admixture, as required to provide freeze-thaw resistance, and superplasticizer, as required for suitable
workability and placeability. Several trial batches were prepared for each mixture formulation in order
to optimize the mixture proportions.

Results and discussion

Table 2 presents the 7-day heat of hydration results (Aldea et al 2009). CSA A3000-03 (CSA A3000 2003)
allows a maximum value for 7-day heat of hydration of 300 kJ/kg (129 BTU/lb) for Type MH cement,
and of 275 kJ/kg (118 BTU/lb) for Type LH cement. There is no CSA specification limiting 7-day heat of
hydration for Type HS cement. However, the low \( \text{C}_A \) requirement for Type HS cement results in a heat
of hydration similar to that of Type MH cements. The results for the heat of hydration obtained in this
project are within the range expected for the respective cement types. Cement replacement with slag
reduced the heat of hydration and the reduction increased with the replacement percentage. Additionally,
slag blended cements generate their heat of hydration over a more extended time frame, resulting in
lower overall temperature rise values for a given amount of total heat generated.

Figure 4 presents a summary of the test results obtained for various concrete mixture proportions
(Aldea et al. 2009). The total temperature rise of the mixtures was corrected to a common starting
temperature to facilitate the comparison (see also Table 2). For the mixtures with 375 kg/m³ (632 lb/yd³)
of cementitious material the maximum temperature rise ranged between 20.4°C (68.7°F) and 22.5°C
(72.5°F). The mixture containing 50% slag had the lowest rise. Type HS and MH cementitious mixtures
had comparable temperature rises and the highest temperature rise was that of Type HS cement. The
50% slag blended cemented mixture with higher cementitious content (375 kg/m³ (632 lb/yd³)) had a
higher temperature rise compared to that with a lower cementitious content (325 kg/m\(^3\) [548 lb/yd\(^3\)]). This result confirms the effect of the amount of cementitious materials in the mixture on the heat of hydration and is due to the higher amount of Type GU cement in the higher cementitious material mixture. The mixture with 325 kg/m\(^3\) (548 lb/yd\(^3\)) of cementitious material containing 50% slag had a temperature rise of 18.1°C (64.6°F), which was the lowest among the mixtures tested.

Table 3 presents the semi-adiabatic temperature rise and the heat generated for the concretes tested (Aldea et al. 2009). The heat generated per unit mass of cementitious material by the hydration of concrete in the semi-adiabatic curing boxes was approximated using the temperature profiles, the mass of the concrete, the total cementitious materials, the aggregate and water contents and the maximum temperature rise. These semi-adiabatic concrete curing results are in agreement with the ASTM C186 cement heat of hydration results. The 7-day heat of hydration results for Type HS cement, Type MH cement and blended Type GU cement and with 50% slag (see Table 3) showed the same trends as those for temperature rise and the heat generated in corresponding concretes. The results are presented per unit mass of cementitious material for the concretes with the same cementitious content [375 kg/m\(^3\) (632 lb/yd\(^3\))] and cementitious materials type in Table 2. The concretes using blended cement type GU and 50% slag showed the lowest heat generated within the set of concretes with the same cementitious material content.

The concrete with 325 kg/m\(^3\) (548 lb/yd\(^3\)) of cementitious material content using blended Type GU cement and 50% slag significantly reduced the temperature of the concrete during curing. It is generally accepted that thermal cracking of concrete occurs for temperature differentials above 20°C (68°F) (Chini and Acquaye 2005). Therefore, based on the results in Table 3 this mixture is the best performing mixture. It is also the only mixture which is not likely susceptible to thermal cracking among the concretes tested.

The concrete with 325 kg/m\(^3\) (548 lb/yd\(^3\)) of cementitious material content using blended Type GU cement and 50% slag was selected and proposed for use for the project application. The mixture met or exceeded design specifications for the reference mixture with 375 kg/m\(^3\) (632 lb/yd\(^3\)) Type HS cement. It also significantly improved the temperature rise of the concrete during curing compared to the reference Type HS cement mixture.

### CONCLUSIONS

The objective of this paper was to define performance-based specifications, sustainable development and to use as examples two projects where performance-based specifications, sustainable development and high volumes of slag were used: 50% slag replacement was used to mitigate the ASR of local fine aggregate for the use in making the concrete for the construction of remote mine facilities; 50% slag replacement was used to limit the heat-generation capacity of HDC during the initial period of curing and subsequent cooling.

- Performance specifications facilitate incorporation of high volumes of SCM in concrete provided that the materials are within specifications.
- Examples of projects where presented where high volumes of slag cement were successfully used to meet project requirements related to sustainability of concrete performance indicators.
- Successful placement of mass high volume slag cement concrete was possible due to strict adherence to proper application of the curing requirements for hot and cold concreting.

### ACKNOWLEDGMENTS

The project work has been conducted at AMEC Earth & Environmental, Hamilton office. Financial support provided by DeBeers Canada Inc., Ontario Power Generation and AMEC Earth & Environmental is greatly appreciated.

### REFERENCES

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American Concrete Institute, Farmington Hills, MI, pp. 95-110.


Table 1—Testing matrix showing mixture variables

<table>
<thead>
<tr>
<th>ID</th>
<th>Details</th>
<th>Supplementary cementitious material (% by mass)</th>
<th>Aggregate</th>
</tr>
</thead>
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<tr>
<td></td>
<td></td>
<td>Low alkali 1 10SF 1 Slag 1 GU cement 2 2 3 1</td>
<td>Composite sand Spratt</td>
</tr>
<tr>
<td>Mix 1</td>
<td>No SCMs</td>
<td>- - - - - - - - 100 - - - - - - x -</td>
<td></td>
</tr>
<tr>
<td>Mix 2</td>
<td>Low alkali 100</td>
<td>- - - - - - - - - - - - - - - - - - - - x -</td>
<td></td>
</tr>
<tr>
<td>Mix 3</td>
<td>10SF 100</td>
<td>- - 100 - - - - - - - - - - - - - - - - - x -</td>
<td></td>
</tr>
<tr>
<td>Mix 4</td>
<td>Low alkali &amp; slag 50</td>
<td>- - 50 - - - - - - - - - - - - - - - - - - x</td>
<td></td>
</tr>
<tr>
<td>Mix 5</td>
<td>10SF &amp; slag 100</td>
<td>- 100 - 50 - - - - - - - - - - - - - - - - x</td>
<td></td>
</tr>
<tr>
<td>Mix 6</td>
<td>Spratt, 10SF &amp; slag 50</td>
<td>- - 50 - - - - - - - - - - - - - - - - - - x</td>
<td></td>
</tr>
<tr>
<td>Mix 7</td>
<td>Spratt, no SCMs 100</td>
<td>- - - - - - - - - - - - - - - - - - - - - - x</td>
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</tr>
<tr>
<td>Mix 8</td>
<td>10SF GU cement &amp; slag 100</td>
<td>- - - 100 - - - - - - - - - - - - - - - - x</td>
<td></td>
</tr>
<tr>
<td>Mix 9</td>
<td>GU cement &amp; slag 100</td>
<td>- - - 50 - - - - - - - - - - - - - - - - - - x</td>
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<tr>
<td>Mix 10</td>
<td>10SF &amp; slag 100</td>
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<tr>
<td>Mix 11</td>
<td>Spratt, 10SF &amp; slag</td>
<td>- - - 50 - - - - - - - - - - - - - - - - - - x</td>
<td></td>
</tr>
</tbody>
</table>

Note: GU is general use portland cement, SCM is supplementary cementitious material, and SF is silica fume.
Concrete: The Sustainable Material Choice

Table 2—7-day heat of hydration results for cementitious materials tested (Aldea et al. 2009)

<table>
<thead>
<tr>
<th>Cement type</th>
<th>Heat of hydration</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>kJ/kg</td>
</tr>
<tr>
<td>Type GU 335</td>
<td>144</td>
</tr>
<tr>
<td>Type HS 297</td>
<td>128</td>
</tr>
<tr>
<td>Type MH 287</td>
<td>123</td>
</tr>
<tr>
<td>Type GU + 25% slag</td>
<td>127</td>
</tr>
<tr>
<td>Type GU + 35% slag</td>
<td>121</td>
</tr>
<tr>
<td>Type GU + 50% slag</td>
<td>115</td>
</tr>
</tbody>
</table>

Note: GU is general use portland cement, HS is high-sulphate-resistant portland cement, and MH is moderate heat of hydration portland cement.

Table 3—Semi-adiabatic temperature rise and heat generated for concrete tested (Aldea et al. 2009)

<table>
<thead>
<tr>
<th>Cement type</th>
<th>Cementitious material content</th>
<th>Temperature rise</th>
<th>Heat generated</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kg/m³</td>
<td>lb/yd³</td>
<td>°C</td>
</tr>
<tr>
<td>Type HS</td>
<td>375</td>
<td>632</td>
<td>22.5</td>
</tr>
<tr>
<td>Type MH</td>
<td>375</td>
<td>632</td>
<td>22.0</td>
</tr>
<tr>
<td>Slag blended Type GU+50% slag</td>
<td>375</td>
<td>632</td>
<td>20.4</td>
</tr>
<tr>
<td>Slag blended Type GU+25% slag</td>
<td>325</td>
<td>548</td>
<td>23.0</td>
</tr>
<tr>
<td>Slag blended Type GU+35% slag</td>
<td>325</td>
<td>548</td>
<td>21.9</td>
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<tr>
<td>Slag blended Type GU+50% slag</td>
<td>325</td>
<td>548</td>
<td>18.1</td>
</tr>
</tbody>
</table>

Note: GU is general use portland cement, HS is high-sulphate-resistant portland cement, and MH is moderate heat of hydration portland cement.

Fig. 1—Sieve analysis. (Note: 1 mm = 0.039 in.)
Fig. 2—Accelerated expansion of mortar bars.

Fig. 3—Average expansion measurements for mixtures tested.
(Note: GU is general use portland cement, SCM is supplementary cementitious material, and SF is silica fume.)
Fig. 4—Temperature profiles for various concrete mixture proportions (Aldea et al. 2009).
(Note: $1°C = \frac{9}{5} °F$, $1 \text{ kg/m}^3 = 1.69 \text{ lb/yd}^3$.)
Use of Slag Cement for Improved Durability in Virginia Department of Transportation Structures

by C. Ozyildirim

Synopsis: Slag cement was introduced to the Virginia Department of Transportation (VDOT) in the early 1980s. Early laboratory studies indicated that slag cement provides resistance to alkali-silica reaction and reduces the permeability of concrete.

Since the mid-1980s, slag cement has been successfully used by VDOT in bridge structures and pavements to reduce permeability and improve the durability of concrete. The bridge structures with concrete containing slag cement (slag concrete) included normalweight concrete in beams and decks, and lightweight concrete or self-consolidating concrete in beams. In large footings, slag cement has been used at a high replacement rate of 75% to control thermal cracking from temperature rise and reduce permeability. Testing of slag concrete obtained during the construction of field projects has indicated the low permeability of these concretes. Evaluations and tests on cores from bridge decks with some field exposure have confirmed the benefit of slag concrete in reducing permeability, thus increasing the durability of these concretes.

Keywords: bridge; durability; mass concrete; pavement; permeability; slag; slag cement; strength; temperature control.
INTRODUCTION

The durability of concrete is related to loads causing abrasion and wear and reducing surface properties; overloads leading to cracking; and environmental effects resulting in cracks and disintegration. Four major types of environmental distress occur in reinforced concretes: corrosion of the reinforcement, alkali-silica reaction (ASR), freezing and thawing deterioration, and attack by sulfates (Ozyildirim 1993). Corrosion of the reinforcing steel is the major distress. In each type of environmental distress, water or aggressive solutions containing deleterious ions such as chloride and sulfate penetrating the concrete initiate or accelerate the distress, making costly repairs necessary. Thus, durability depends largely on the concrete’s ability to resist the penetration of water and aggressive solutions. Workable, air-entrained concretes with satisfactory strength and low permeability (that can resist the penetration of solutions) are needed when they will be exposed to a severe environment. High-performance concretes (HPC) including those with slag cement have been introduced to improve the durability of concrete structures (Ozyildirim 1998, Ozyildirim 1999, and Zia et al. 1999). Concrete containing slag cement has been successfully used in transportation facilities in Virginia since the mid-1980s and has become an important component of the Virginia Department of Transportation’s (VDOT’s) HPC program.

In Virginia, ASR observations in the 1980s led to the adoption of a special provision that restricted the alkali content of portland cement to 0.40 (later increased to 0.45) if precautions are not taken. If the cement alkalis exceeded this limit, a pozzolan or slag cement was required in the mixture. The amount of these supplementary cementitious materials (SCM) was related to the alkali content of the cement. A table was prepared, and if the material used was not in the table, testing was required to show that expansion attributable to ASR was not an issue.

The use of pozzolans and slag, either alone or in combination, is very effective in reducing the permeability of concrete (Lane and Ozyildirim 2000). These SCMs are readily available in Virginia, widely used, and extremely helpful in improving the durability of concrete. In addition to reducing the permeability, concrete with SCMs resist chemical degradation caused by ASR and sulfate attack (ACI 233R 2003).

Concrete that become critically saturated can be damaged by cycles of freezing and thawing unless necessary precautions are taken. Concrete must be properly air entrained, have sound aggregates, and have the maturity to develop sufficient strength (exceeding 4000 psi [28 MPa]) for long-lasting service (Mather 1990). A minimum compressive strength of 4000 psi (28 MPa) is often specified for bridge decks. Air-entraining admixtures provide small, closely spaced, and uniformly distributed air voids, with a diameter less than 1 mm (0.04 in.). The size of the air voids is indicated by the specific surface, which is equal to the average surface area divided by the volume of the voids. The average distance water must travel to reach a protective air void in concrete undergoing freezing is indicated by the spacing factor. It is generally accepted that a specific surface greater than 24 mm²/mm³ (600 in.²/in.³) and a spacing factor less than 0.2 mm (0.008 in.) are needed for adequate protection during freezing and thawing (Whiting and Nagi 1998).

PURPOSE AND SCOPE

This paper summarizes the use of slag cement to improve the durability of concretes. ASR, permeability, and thermal control are included. VDOT has used a binary cementitious system of portland and slag cements and ternary systems of portland and slag cements with silica fume or fly ash to mitigate ASR, reduce the permeability of concrete, and control thermal rise. Concrete samples were prepared from fresh field concretes during the construction of bridge beams and decks, pavements, and mass elements. These specimens were tested for various properties, including permeability. In addition, core samples were taken from older bridge decks constructed with binary cementitious systems and compared to cores taken from plain concrete decks of similar age.

ALKALI-SILICA REACTION

VDOT has used the standard method described in ASTM C441 (Test Method for Effectiveness of
Pozzolans or Ground Blast-Furnace Slag in Preventing Excessive Expansion of Concrete Due to the Alkali-Silica Reaction) for evaluating the ability of pozzolans or slag cement to prevent ASR. Results of a laboratory study (Lane and Ozyildirim 1995) lead to the adoption of minimum amounts of Class F fly ash, slag cement, or silica fume to inhibit ASR for cement alkali contents up to 1%. In ASTM C441, crushed pyrex glass is the reactive aggregate. VDOT uses 56-day results, where a strong linear relationship between increasing expansion and increasing alkali content was observed (Lane and Ozyildirim 1995). The expansion of the samples is limited to a maximum of 0.10% (later increased to 0.15%) at 56 days. VDOT accepted slag cement conforming to the requirements for ASTM C989 Grade 100 or Grade 120 with a minimum of 25% replacement when the portland cement alkali content is below 0.60%; a minimum replacement of 35% when the alkali content is below 0.90%; and a minimum replacement of 50% for an alkali content of 0.90% to 1.00%. Recently, the table was modified to require 40% slag cement for a cement alkali content of 0.75% or less and 50% for an alkali content greater than 0.75% up to 1%. The test procedure is specified as ASTM C227 (Potential Aggregate Reactivity of Cement-Aggregate Combinations) using borosilicate glass as aggregate. Approval of a lower slag cement content or another material may be obtained by submitting test results to VDOT for assessment. The assessment should be based on testing performed at a minimum of three alkali levels: each level would include control cement and cement with the proportion of the proposed material requested. For cement alkali contents below 0.45%, a pozzolan or slag cement is not required for ASR; however, other requirements such as reduced permeability; thermal control, and corrosion or sulfate resistance may require use of pozzolans or slag cement. The minimum amounts of slag cement required for ASR may not be sufficient for other durability issues.

REDUCED PERMEABILITY

Bridge beams and decks

In the 1990s, the Federal Highway Administration initiated the HPC program. Under this program, VDOT built its first HPC bridge, which carries Route 40 over Falling River (Ozyildirim 2002). The bridge was completed in 1995. It is performing well without any repairs. The use of slag concretes in the deck and the substructure reduced permeability and is expected to enhance durability. The substructure concrete had a minimum 28-day design compressive strength, \( f'_{c} \), of 3000 psi (21 MPa), and the bridge deck concrete had a minimum of 4000 psi (28 MPa). The permeability was measured using the electrical conductance test: ASTM C1202 (Electrical Indication of Concrete’s Ability to Resist Chloride Ion Penetration). In this test, coulomb values less than 1000 indicate very low penetrability and those between 1000 and 2000 low penetrability. The maximum permeability requirement was 3500 coulombs for the substructure and 2500 for the bridge deck at 28 days using accelerated curing. In accelerated curing, specimens are moist cured for 1 week at 73°F (23°C) and then for 3 weeks at 100°F (38°C). This accelerated curing indicates the long-term permeability of the concretes (Ozyildirim 1998). Table 1 gives the mixture proportions, which also summarizes the strength and permeability data. The permeability values were very low for the deck concrete and close to very low for the substructure concrete. Portland cement concretes used in bridge decks usually have high coulomb values initially, which are reduced to a moderate range (2000 to 4000 coulombs) with age (Ozyildirim 1998).

In the bridge on Route 33 over the Pamunkey River at West Point in Virginia, regular and self-consolidating concrete (SCC) bulb-T beams containing slag cement were used (Ozyildirim 2008). Table 2 summarizes the mixture proportions, strength, and permeability values for the beams. The permeability values were very low.

The first lightweight HPC structure in Virginia was the Route 106 bridge over the Chickahominy River built in 2001 (Ozyildirim and Gomez 2005). This bridge has beams made with lightweight concrete containing slag cement with a minimum 28-day compressive strength of 8000 psi (55 MPa) and a maximum permeability of 1500 coulombs. Table 3 summarizes the mixture proportions, strength, and permeability of the concrete used in the beams. The permeability of the lightweight concrete beams with slag cement was very low.

A ternary system of portland and slag cements with silica fume was used in an overlay on Route 60 (Sprinkel and Ozyildirim 2000). A core tested at 6 months had a permeability of 422 coulombs; the average permeability of two cores tested at 3.5 years was 497 coulombs, indicating very low permeability. A ternary system of portland and slag cements with fly ash was successfully used in a bridge deck on Route 11 over the New River and Norfolk Southern Railroad tracks in Virginia. The mix proportions are
The test results from 31 sublots (summarized in Table 4) indicate very low permeability and small variability.

Pavements

Slag cement was used in an experimental jointed plain concrete pavement on I-64 in Newport News, Virginia (Ozyildirim 2004a). In this project, large-sized aggregate and combined grading were tried. Most of the project used 1 in. (25 mm) nominal maximum size aggregate (NMS) and Class F fly ash. However, in two experimental sections, the producer used concrete with slag cement. One section with concrete containing slag cement used 1 in. (25 mm) NMS, and another 2 in. (50 mm) NMS for comparison. Table 5 shows the mixture proportions and the permeability and strength of these concretes. The results show that both sections with concrete containing slag cement with different aggregate size had satisfactory strengths and low permeability.

In another application, a two-lane continuously reinforced concrete pavement was built in Blacksburg, Virginia, as part of the Virginia Smart Road (Ozyildirim 2004b). A total of 2247 ft (685 m) of pavement was placed. The mixture contained 35% slag cement as shown in Table 6. Number 57 coarse aggregate with 1 in. (25 mm) maximum size was used. The maximum water-cementitious materials ratio (w/cm) was low, 0.40, to achieve a high early strength since the contractor wanted trucks on the pavement in 7 days to allow construction of the adjacent lane. The strengths given in Table 6 indicate high flexural and compressive strengths. The permeability values were very low.

THERMAL CONTROL IN MASS CONCRETE

Temperature control in mass concrete is important to minimize initial thermal cracks and to avoid delayed ettringite formation (ACI 207.1R 2005). Specifications generally set a maximum temperature and a maximum differential between the core and the surface temperature. Generally, limits are 160°F (71°C) for the maximum temperature and 35°F (20°C) for the temperature differential. Based on a thermal analysis considering the reinforcement in the bridge footings on I-895, VDOT approved a maximum temperature of 170°F (77°C). The footings averaged 730 yd³ (560 m³), but the two footings in the river crossing were much larger, with each having about 4000 yd³ (3000 m³) of concrete. The minimum cementitious material was 565 lb/yd³ (335 kg/m³) and the maximum w/cm was 0.49. The minimum 28-day compressive strength was 4350 psi (30.7 MPa). To control temperature and comply with the specifications, 75% of the portland cement was replaced with slag cement. Permeability values for two cylinders were 561 and 840 coulombs, indicating very low permeability. The temperature requirements were met, and there were no objectionable, visible, wide cracks in the elements.

VDOT’s successful use of high slag cement replacement in mass concrete indicates that thermal rise can be controlled to acceptable levels, thus avoiding cracking and damage to the structure. At the same time, concretes with very low permeability, which is essential for durability, can be achieved.

FIELD EVALUATION OF DECKS

The information provided in the previous sections was primarily obtained from specimens prepared during construction and subjected to accelerated curing to estimate the potential permeability and durability. In this section, information on cores obtained from structures exposed to the environment for more than a decade is presented. Cores were obtained from 36 bridge decks throughout Virginia (Lane 2006). There were two sets of bridge decks:

- Those constructed from 1968 through 1971; and

The older group consisted of 10 decks constructed with only portland cement as a cementitious material, a maximum w/cm of 0.47, and uncoated reinforcement. The younger group consisted of 26 decks, some constructed with only portland cement and others with binary cementitious blends of fly ash or slag cement with portland cement, had a maximum w/cm of 0.45; and had epoxy-coated steel reinforcement. The absorption values were evaluated by testing the top 2 in. (50 mm) of two cores in accordance with ASTM C1585 (Measurement of Rate of Absorption of Water by Hydraulic Cement Concretes). The decks were also visually inspected, and cores were examined petrographically (Lane 2006).

Two rates of absorption values were obtained: an initial rate \((C_i)\) that reflects the absorption rate over the first few hours controlled by capillary suction and a usually slower secondary rate \((C_s)\) reflecting
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the longer term absorption (Bentz et al. 2001, Lane 2006, and Martys and Ferraris 1997). This absorption test measures fluid transport into unsaturated concrete, which is typical of bridge decks. In the Virginia study, the field performance and rate of absorption results (an example displayed in Fig. 1), showed considerable variability; however, concretes containing binary cementitious material, that is, portland cement containing fly ash or slag cement, were, in general, providing lower absorption values (Lane 2006). It was concluded that based on the results of the rate of absorption test, concretes containing fly ash and slag are affective in lowering the transport properties of concrete. Also, the field performance led to the conclusion that fly ash and slag concretes are not inherently prone to scaling problems. In summary, the Virginia study demonstrated the beneficial contributions that fly ash and slag cement provide to concrete durability (Lane 2006).

CONCLUSIONS

Concretes containing slag cement have been successfully used in bridge structures and pavements in Virginia since the mid-1980s to enhance the durability of concretes. Slag concrete provides the following:

- Low permeability;
- High resistance to ASR at appropriate replacement rates (depending on the alkali contents); and
- Temperature control in mass concrete minimizing thermal cracking, especially when used in high replacement rates.

Such improvements in transport properties, resistance to chemical attack, and thermal control are expected to minimize common distresses and cracking, leading to extended service life. The field structures containing slag cement are performing satisfactorily and display attributes of durable concrete.

ACKNOWLEDGMENTS

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Table 1—First high-performance concrete structure on Route 40

<table>
<thead>
<tr>
<th>Material (lb/yd³)</th>
<th>Substructure</th>
<th>Deck</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>352</td>
<td>329</td>
</tr>
<tr>
<td>Slag cement</td>
<td>235</td>
<td>329</td>
</tr>
<tr>
<td>Coarse aggregate</td>
<td>1773</td>
<td>1773</td>
</tr>
<tr>
<td>Fine aggregate</td>
<td>1254</td>
<td>1173</td>
</tr>
<tr>
<td>Water</td>
<td>259</td>
<td>263</td>
</tr>
</tbody>
</table>

Test (28 days)

| Compressive strength (psi) | 5930 | 8710 |
| Permeability (coulombs)    | 1094 | 778  |

Note: The permeability specimens were moist cured 1 week at 73°F (23°C) and 3 weeks at 100°F (38°C). 1 lb/yd³ = 0.59 kg/m³; 1 psi = 6.89 kPa.

Table 2—Mixture proportions of concretes for Route 33 beams

<table>
<thead>
<tr>
<th>Material (lb/yd³)</th>
<th>SCC</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Portland cement</td>
<td>480</td>
<td>510</td>
</tr>
<tr>
<td>Slag cement</td>
<td>320</td>
<td>340</td>
</tr>
<tr>
<td>Coarse aggregate size</td>
<td>No. 78</td>
<td>No. 68</td>
</tr>
<tr>
<td>Coarse aggregate</td>
<td>1451</td>
<td>1731</td>
</tr>
<tr>
<td>Fine aggregate</td>
<td>1411</td>
<td>1029</td>
</tr>
<tr>
<td>Water</td>
<td>272</td>
<td>336</td>
</tr>
</tbody>
</table>

Test (28 days)

| Compressive strength (psi) | 10,405| 7785 |
| Compressive strength (psi) 1 yr | 11,085| 9240 |
| Permeability (coulombs)    | 932  | 998   |

Note: SCC = self-consolidating concrete; VMA = viscosity-modifying admixture was added to SCC; Retarding admixture and high-range water-reducing admixture in all beams; also 2 gal./yd³ (10 L/m³) was added to all beams. 1 lb/yd³ = 0.59 kg/m³; 1 psi = 6.89 kPa.
### Table 3—Lightweight concrete for Route 106 bridge beams

<table>
<thead>
<tr>
<th>Material (lb/yd³)</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>451</td>
</tr>
<tr>
<td>Slag cement</td>
<td>301</td>
</tr>
<tr>
<td>Coarse aggregate LW</td>
<td>696</td>
</tr>
<tr>
<td>Coarse aggregate NW</td>
<td>605</td>
</tr>
<tr>
<td>Fine aggregate LW</td>
<td>390</td>
</tr>
<tr>
<td>Fine aggregate NW</td>
<td>541</td>
</tr>
<tr>
<td>Water</td>
<td>255</td>
</tr>
</tbody>
</table>

**Test**
- 28-day compressive strength (psi): 8100
- 1-year permeability (coulombs): 916

Note: LW = lightweight, NW = normalweight. 1 lb/yd³ = 0.59 kg/m³; 1 psi = 6.89 kPa.

### Table 4—Ternary system of portland cement, fly ash, and slag cement

<table>
<thead>
<tr>
<th>Material (lb/yd³)</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>318</td>
</tr>
<tr>
<td>Class F fly ash</td>
<td>159</td>
</tr>
<tr>
<td>Slag cement</td>
<td>159</td>
</tr>
<tr>
<td>Coarse aggregate</td>
<td>1755</td>
</tr>
<tr>
<td>Fine aggregate</td>
<td>1101</td>
</tr>
<tr>
<td>Water</td>
<td>286</td>
</tr>
</tbody>
</table>

**Test (28 days)**
- Compressive strength (psi): 5016 (305)
- Permeability (coulombs): 391 (72)

Note: Test data are an average of 31 sublots. The standard deviation is in parenthesis. 1 lb/yd³ = 0.59 kg/m³; 1 psi = 6.89 kPa.

### Table 5—I-64 Pavement

<table>
<thead>
<tr>
<th>Material (lb/yd³)</th>
<th>NMS (2 in.)</th>
<th>NMS (1 in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>375</td>
<td>395</td>
</tr>
<tr>
<td>Slag cement</td>
<td>160</td>
<td>169</td>
</tr>
<tr>
<td>Coarse aggregate</td>
<td>1935</td>
<td>1840</td>
</tr>
<tr>
<td>Fine aggregate</td>
<td>1171</td>
<td>1217</td>
</tr>
<tr>
<td>Water</td>
<td>242</td>
<td>250</td>
</tr>
</tbody>
</table>

**Test (28 days)**
- Compressive strength (psi): 4530 | 4620
- Flexural strength (psi): 670 | 685
- Permeability (coulombs): 1774 | 1672

Note: NMS is nominal maximum size aggregate. 1 in. = 25.4 mm; 1 lb/yd³ = 0.59 kg/m³; 1 psi = 6.89 kPa.
Table 6—Smart road pavement

<table>
<thead>
<tr>
<th>Material (lb/yd³)</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>384</td>
</tr>
<tr>
<td>Slag cement</td>
<td>206</td>
</tr>
<tr>
<td>Coarse aggregate</td>
<td>1795</td>
</tr>
<tr>
<td>Fine aggregate</td>
<td>1267</td>
</tr>
<tr>
<td>Water</td>
<td>236</td>
</tr>
</tbody>
</table>

| Test (28 days)          |        |
| Compressive strength (psi) | 7260   |
| Flexural strength (psi)  | 1055   |
| Permeability (coulombs)  | 611    |

Note: 1 lb/yd³ = 0.59 kg/m³; 1 psi = 6.89 kPa.

Fig. 1—Graphical example of rate of absorption (ASTM C1585) data. Materials group:
1 = PCC 0.47; 2 = PCC 0.45; 3 = fly ash; 4 = slag cement (Lane 2006). (Note: 1 mm = 0.0394 in.)
Achieving Sustainable Goals with Architectural Concrete

by L. Rowland

**Synopsis:** Concrete is the most widely used building material in the world. Fortunately, concrete, especially architectural and decorative concrete, is a very sustainable material. The constituent materials that make up concrete are readily available throughout most of the world and can be collected, processed, and manufactured in an environmentally sound manner.

Concrete has low embodied energy and great thermal mass that can enhance buildings’ energy efficiency. All human activities have some greenhouse gas associated with them. The electrical power generation and transportation sectors of our economy generate over 60% of the greenhouse gas emissions in the United States. The greenhouse gas emissions associated with concrete and cement’s manufacture is only approximately 1% of the U.S. total.

Durability and superior life cycle are solid benefits commonly associated with decorative and architectural concrete. When using Life-Cycle Assessments conforming to international standards, concrete outperforms other building products because it conserves resources by preventing premature replacement and excessive maintenance while delivering superior service life and smaller environmental impacts than other commonly used building products.

Architectural concrete is sustainable because it combines form and function in a single material. Designers and industry professionals can improve the long-term viability of architectural finishes and decorative elements by anticipating maintenance needs and designing with the future in mind.

**Keywords:** architectural; decorative; emissions; energy; life-cycle; sustainability.
Larry Rowland is the Manager of Marketing and Technical Services for Lehigh White Cement and has been a LEED Accredited Professional since 2004. He has over 20 years of experience in construction and material sales. He has presented papers on material best practices and the topic of sustainability at American Institute of Architects conventions and ACI conventions.

WHY SHOULD CONCRETE BE SUSTAINABLE?

Concrete is the world’s most used building material; fortunately members of the design, construction, and materials industries are committed to reducing the ecological impacts associated with using this dynamic product. Understanding the environmental impact of building with concrete and ways to optimize its role in sustainable design ensures that concrete and concrete products will be used wisely to achieve performance and sustainability objectives.

Sustainable design seeks to reduce the environmental impact of a given project’s construction and operation by promoting sound choices and implementing proven strategies to meet environmental goals. It selects materials, methods, and systems to be used in the pursuit of performance objectives for efficient land use, energy efficiency, indoor air quality, and material and water conservation.

Occupants of sustainably designed buildings are generally more satisfied with their work spaces because they have more natural lighting, better indoor air quality, and feature more individual environmental controls. Operating expenses go down because green buildings use roughly a third less energy and water than their counterparts constructed without sustainable design strategies.

For concrete to maintain its position as the world’s premier building product the material, construction, and design communities must understand its impacts and sustainable benefits. In this way concrete’s inherent sustainability can be maximized while minimizing impact to the environment.

CONSTITUENT MATERIALS DETERMINE SUSTAINABILITY

Sustainable components contribute to a sustainable finished product. Typical concrete is a combination of coarse and fine aggregate, portland cement, supplementary cementitious materials (SCMs), water, and chemical and/or mineral admixtures. By evaluating the environmental impact of each of these constituent materials, one can determine the environmental impact of the mixture as a whole. The ingredients of architectural and decorative concretes are very often exposed; you can literally see what you are getting.

Aggregates

Aggregate is extracted from naturally occurring deposits of sand, gravel, and stone and is the greatest part of most mixtures, making up roughly 67% of the total volume. Concrete aggregates are selected for their durability and abundance in fixed locations that can be collected and processed very efficiently. Based on the Portland Cement Association’s publication, Life Cycle Inventory of Portland Cement Concrete, aggregates’ embodied energy (energy expended to make it ready for use in concrete) is approximately 0.05 GJ/m³ (10.6 kW-hr/yd³) of concrete. Naturally occurring gravel deposits that require minimal processing supply 74% of the aggregate used in the U.S., while hard stone quarries where material must be crushed to the appropriate size to be used account for the other 26%. Based on these national averages, aggregate accounts for roughly 4% of concrete’s embodied energy.¹

Because the aggregate is the product being sought in the extraction processes, aggregate quarries produce very little waste compared to mining endeavors that must extract then refine an ore to get at a desired mineral. The final product of other common manufactured building materials such as steel and aluminum represent a very small fraction of the total material that must be processed to get the finished good. In contrast, non-durable materials such as clay and topsoil encountered in the aggregate mining process can be used as fill or set aside for use in future quarry-reclamation efforts.

The USGBC’s LEED Green Building Rating System² recognizes the value of utilizing regional materials; that is building materials or products that have been extracted, harvested, or recovered, as well as manufactured, within 800 km (500 miles) of the project site. Aggregate is bulky and heavy so it is relatively costly to haul long distances from extraction site to consumer. As a result, most concrete aggregate is produced close to the concrete plant. In fact, many concrete operations are located on the source quarry property. Utilizing local aggregate sources is good for the environment and good for a project’s
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point count towards LEED certification. Some architectural mixtures may require special aggregates from outside the region. Designers should work closely with concrete producers to weigh the sustainable benefits of selecting a given aggregate source.

Aggregate used in concrete is selected for its durability and resistance to degradation during the mixing process. Because it is so tough, it is easily reclaimed and recycled. Unused concrete returned to the concrete plant can be reclaimed by a process of washing and screening that separates the aggregate and makes it available to be reused in new concrete. Hardened concrete can be broken up and crushed into new aggregate; this recycled aggregate can account for 85% of a mixture’s volume. Some of the most visually striking decorative concrete contains high volumes of recycled glass as its coarse and fine aggregate. Because it is such a big part of a mixture, using recycled aggregate in concrete can be a big contributor towards earning recycled content points under the LEED Green Building Rating System.

Portland Cement

Like aggregate, portland cement has its beginnings in the quarry. Unlike aggregate, portland cement cannot be extracted directly from a quarry, it must instead go through an intensive manufacturing process which makes it the most energy and emission intensive part of a typical concrete.

Raw material deposits that contain calcium, silica, alumina, and iron are collected to supply the right mineral mixture needed to make clinker, which is the main ingredient in portland cement. Fortunately, these minerals are amongst the top five most commonly found on our planet. Along with oxygen, over 90% of the mass of the earth’s crust is made up of these elements. When making white portland cement; which is widely used in architectural and decorative concretes, raw material sources rich in calcium, silica and alumina are selected that contain little or no iron. Iron is the primary ingredient that gives portland cement its gray color.

Once collected the raw materials are carefully blended and pulverized to a coarse powder, which is then pyroprocessed in a kiln at temperatures above 1400°C (2550°F). This extreme heat drives the physical and chemical changes that convert the raw materials into portland cement clinker. Cement clinker is then ground, along with a small amount of gypsum and limestone, into a very fine powder, which is the finished product: portland cement. It takes a lot of fuel to generate all that heat and a lot of energy to process the raw materials and then grind the clinker to powder. For this reason cement is the most energy intensive component in a typical concrete.

Products reclaimed from other industries that would otherwise end up in landfills can be used in place of newly extracted raw materials. Cement companies use millions of tons of fly ash, bottom ash, and other reclaimed materials to produce the raw feed needed to make clinker, thereby reducing their environmental impact or footprint.

Cement companies also reduce their environmental footprint by burning reclaimed fuels or byproducts of other industrial or agricultural processes. Petroleum coke, used motor oil, waste plastics, and bio fuels, such as waste wood products, make good fuel stock for cement plants. Because they are highly refined and contain lots of embodied energy waste, automobile and truck tires can be used as high energy fuel, which keeps them out of the rivers, streams, and vacant lots in our communities. In fact, cement manufacturers are the greatest consumers of tire-derived fuel in the U.S. Cement kilns are expertly controlled and operate at extremely high temperatures so tire-derived fuels are clean-burning and environmentally friendly.

Whether burning alternative fuels or traditional fossil fuels the energy intensity of a given concrete will strongly correlate to the amount of cement used. If no SCMs are in the mixture, portland cement will account for about 85% of the 1.12 GJ/m³ (238 kW-hr/yd³) of energy associated with producing a typical 20 MPa (3000 psi) mixture with 279 kg of cement per m³ (470 lb/yd³) and about 90% of the 1.63 GJ/m³ (346 kW-hr/yd³) of the energy associated with a typical 35 MPa (5000 psi) mixture with 335 kg of cement per m³ (564 lb/yd³). Generally speaking every 1% of SCMs such as fly ash or slag cement used in replacement of portland cement will result in a 1% reduction in a mixtures energy profile.

In addition to taking the most energy to produce, portland cement accounts for up to 96% of the total CO₂ emissions associated with concrete production. Generally speaking, for every kg of portland cement produced, 0.9 kg of CO₂ is emitted. CO₂ is both a manmade and naturally occurring a greenhouse gas. Of the human-made emissions tracked by the U.S. Environmental Protection Agency (EPA), carbon dioxide (CO₂) is by far the most common, accounting for over 85% of all the greenhouse gas emitted in the United States in 2007.
The CO₂ emissions associated with portland cement come primarily from two sources: fuel combustion and calcination. The proportions vary from one cement plant to the next but generally speaking, the emissions associated with the burning of fuel to generate process heat is between 40% and 50% of the total. Almost all the rest of the CO₂ emissions come from calcination.

Calcium (Ca) typically from limestone occurs naturally in the form of calcium carbonate (CaCO₃). Calcination yields CO₂ as Ca based compounds are formed in the kiln. The process is expressed in the following formula: CaCO₃ + heat = CaO + CO₂. Unfortunately, there is no way to reduce this type of CO₂ release. In its April 15, 2009 Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2007, the U.S. EPA calculated “an emission factor of 0.51 tonnes of CO₂ per tonne of clinker produced”. Assuming there are no SCMs in the mixture limestone calcination can account for approximately 60% of the CO₂ emissions embodied in a given concrete.

The EPA tracks emissions by the sector of the economy that they come from. Electric power generation is the sector with the highest emissions at 34%. Transportation is next largest at 28%, industry accounts for 19%, agriculture 7%, commercial buildings were 6%, and residential 5% (Fig. 1).

Cement production falls within the industry sector. The EPA considers greenhouse gases released in calcination “as the by-products of various non-energy-related industrial activities” which fall under the heading “Industrial Processes.” Industrial process greenhouse gas emissions from cement production in 2007 are 0.6% of the U.S. total. To put this into context, industrial process emissions for iron and steel & metallurgical coke production were 1.1% of the total, coal mining were 0.8%, and petroleum systems were 0.4%.

When the electrical power emissions are apportioned to its end users, the percentages change. Because we use very little electricity for transportation in the U.S., the transportation sector stays at 28% of the total. Industry goes up by half to 29% and agriculture stays at 7%. However, the commercial and residential building sectors both more than triple their consumption to 17.5% and 17.2%, respectively. This is one reason why it is so important we build energy-efficient buildings.

Fuel-related emissions for cement production is lumped into the industry total for fossil fuel combustion. Based on national averages, burning fossil fuel for cement production accounts for 0.4% to 0.5%, bringing the total greenhouse gas emissions for cement production to approximately 1.1% or less of the U.S. total. In other words, 98.9% of greenhouse gas emissions in the U.S. come from sectors of the economy other than cement production.

The CO₂ emissions associated with 0.76 m³ (1 yd³) of typical concrete will be approximately 180 kg (400 lb). To put this into perspective, this is roughly equivalent to the amount of CO₂ emissions released when you burn 61 L (16 gal.) of gasoline in your car or use electrical power to run home appliances such as a microwave oven or home computer for a year. Applying EPA published average annual driving distances and fuel efficiencies, a typical family with two cars generates more CO₂ in auto emissions each year than is embodied in their home’s concrete foundation.

Concrete producers can reduce the embodied energy and CO₂ emissions associated with their mixtures by replacing a portion of their portland cement with SCMs. Many SCMs such as fly ash and ground-granulated blast-furnace slag have the added environmental advantage of being byproducts of other industrial processes. Using SCMs is a proven sustainable strategy that can enhance concrete’s physical properties while shrinking its environmental footprint. Because SCMs become part of the paste component of a mixture they can have a big effect on color. SCM’s affect on concrete performance and appearance is an important consideration when specifying these products.

Besides shaping the energy and greenhouse gas profile of a product, the constituent materials that go into that product help determine how it will affect indoor air quality (IAQ). Concrete typically does not contain anything that will off-gas harmful volatile organic compounds (VOCs). Admixtures, form release agents, curing agents, and surface-applied materials must all be evaluated to ensure they do not introduce harmful volatile materials into the indoor environment. Testing on concrete placed using water-based form releases has been found to have VOC emission rates of 0.003 mg/m²/hr (8.9 × 10⁻⁶ oz/yd²/hr), compared to common building materials such as linoleum and plywood paneling that have VOC emission rates of 0.220 and 1.000 mg/m²/h (6.52 × 10⁻⁶ and 2.97 × 10⁻⁵ oz/yd²/hr), respectively.

EMBODIED AND OPERATING ENERGY

There are two types of energy to consider in a building project: embodied and operating. A building’s...
embodied energy is the energy expended during raw material acquisition, manufacturing and transporting the building materials that go into the project, construction, and finally maintenance and repair of the building elements. Generally speaking, the embodied energy that goes into constructing a given building is 5% to 10% of the energy consumed in the building’s life-cycle. Canadian researchers studied a generic 4620 m² (50,000 ft²) three-story office building with underground parking, using wood, steel, and concrete. When the buildings were designed to the same energy efficiency performance, researchers found the average embodied energy for each option was approximately 4.82 GJ/m² (937 kW-hr/yd³). Concrete structures have the added advantage of being quieter and more secure, while offering protection from termites, fire, and tornadoes. Operating energy, which includes the energy to heat, cool, illuminate, and operate the equipment inside a building, is 90% to 95% of the total energy used during the building’s life. This is why the commercial and residential building sectors show such a significant jump in greenhouse gas emissions when the emissions for electrical power generation are distributed to their end users. The average U.S. resident uses a tremendous amount of energy to make his or her living and work spaces comfortable. In recognition of this reality, the USGBC has made energy efficiency the most point intensive category in the LEED Green Building Rating System.

Concrete saves energy by reducing heating and cooling loads because it has a great deal of thermal mass. Thermal mass, especially when combined with conventional rigid insulation, reduces the daily temperature swings. Buildings stay cooler in the summer and warmer in the winter. The moderating benefit from the thermal mass associated with concrete is most pronounced in cool climates. Well insulated concrete frame buildings with concrete walls and building envelopes can yield 21% energy cost savings compared to baseline buildings. The size and power of heating and cooling equipment can actually be downsized due to the benefits of thermal mass.

Energy modeling software is used to predict energy savings as part of efforts to earn LEED Energy and Atmosphere points. Unfortunately, some energy modeling programs do not adequately account for the thermal mass effect. Energy modeling software should calculate yearly energy use on an hourly basis in order to account for all the energy savings to be gained from using concrete building systems. The Portland Cement Association issued SN 2880a, “Modeling Energy Performance of Concrete Buildings for LEED-NC Version 2.2: Energy and Atmosphere Credit 1,” to demonstrate how to get all the LEED points deserved for concrete’s thermal mass.

In addition to having thermal mass, building systems such as insulating concrete forms (ICFs) and precast sandwich panels have the added benefit of being effective air barriers. The National Institute of Standards and Technology reports that air barriers can reduce a building’s natural gas use by more than 40% and cut electricity consumption in excess of 25%. It is important to note that air barriers must be permeable to water vapor to avoid issues of condensation. Another important consideration in maximizing the benefits of concrete wall systems is to use non-conductive ties that do not act as a thermal bridge to transmit heat or cold through exterior walls.

Concrete’s energy saving benefits do not stop at the walls. Polished and decorative concrete floors are low maintenance and have superior durability with much less embodied energy than other flooring systems. Designing these floors to be reflective makes them energy savers. Reflectivity is most dependent on color but can also be enhanced by polishing the concrete. Reflective concrete floors save energy by reducing the number of lighting fixtures needed to brighten a space. Less lighting means less heat is given off by the lighting system, which in turn reduces the need for air-conditioning. An energy modeling study sponsored by PROSOCO Consolideck High Performance Concrete Products found that light gray to white concrete floors will reduce whole-building energy consumption by 8% to 21% when compared to the ASHRAE 90.1 standard commercial building with flooring that has the default reflectivity values. Reflectivity can save energy outside your building as well. Building owners that choose concrete parking lots over asphalt can reduce the number of lighting fixtures by 35% for a typical parking lot. Assuming parking lot lighting is on only five hours a day, it will take 57% more electrical energy to illuminate a 50 x 100 m (160 x 330 ft) parking lot that is paved with asphalt than it would to illuminate the same parking lot that utilized concrete paving.

Reflective surfaces are also beneficial because they reduce the urban heat-island effect. Urban heat islands are the result of dark surfaces, predominantly roofs and paving, that absorb heat throughout the day and then release it in the afternoon and evening, increasing the temperature of urban areas over the
surrounding undeveloped areas.

The USGBC’s LEED Green Building Rating System awards points to projects that have reflective concrete paving and hardscapes. Concrete paving is much more reflective than asphalt. Solar reflectance indexes (SRIs) are an established way of comparing material reflectivity. SRIs range from zero to 100 with 100 being the most reflective. The LEED Reference Guide for Green Building Design and Construction, 2009 edition, gives default SRI values for new gray and new white concrete of 35 and 86, respectively, compared to asphalt, which starts at 0 and only goes up to 6 after weathering has exposed the aggregate within.²

**DURABILITY AND LIFE CYCLE**

Durability means different things to different people. Terms such as service life, strength, longevity, permanent, and tough are often used to describe durable building products. In green-building terminology, durable products conserve resources by requiring less maintenance and having long service lives. ACI 201.2R-08 Guide to Durable Concrete says, “Durability represents one of the key characteristics of concrete that has led to its widespread use. Durability of hydraulic-cement concrete is determined by its ability to resist weathering action, chemical attack, abrasion, or any other process of deterioration.” The concrete industry invests a great deal of talent and treasure ensuring the products we produce will last. These efforts have made concrete the material of choice for long life and low maintenance.

Decorative treatments to exterior flatwork and interior flooring are one of many places the durability of concrete can really shine. Grinding and polishing concrete floors brings out the natural beauty of this dynamic material. New generation densifiers enhance durability and are more user friendly than older versions of these products. They generate less waste and require less clean-up and are being used on a wide range of applications, including industrial, residential, commercial, and institutional projects. The rule of thumb for concrete floors should be to finish them as a decorative feature in your building. Covering concrete with less durable products that must be replaced every few years is not a sustainable practice.

The LEED Canada-NC Green Building Rating System awards points for durable buildings that utilize longer-service-life materials in the building structure and envelope. Material and Resources, Credit 8: Durable Building, list the credit’s intent as “Minimize materials use and construction waste over a building’s life resulting from premature failure of the building and its constituent components and assemblies.”¹² This credit was driven by a major class action lawsuit in British Columbia over what is sometimes referred to as the “BC Leaky Condo Crisis”. The credit calls for extended design service life for buildings earning the credit and the implementation of a building durability plan. Key plan components are to direct water away from the building, provide proper drainage, and use durable building envelope materials.

Concrete is ideally suited to the requirements for earning the durable building credit.¹³ Designers, producers and contractors alike can enhance concrete’s durability by keeping water cement ratios low, carefully selecting materials and applying American Concrete Institute (ACI) placement guidelines to produce concrete with low absorption rates of not more than 6%.

Life-cycle assessments (LCAs) are a reliable way to evaluate materials and determine the “environmental aspects associated with a product over its life cycle - from raw material acquisition through production, use, and disposal.”¹⁴ The goal of LCAs is to take a comprehensive look at materials, so properly completed LCAs tend to be quite complex and detailed. Fortunately, the International Organization for Standardization (ISO) has guidelines in place that ensure that LCAs are done in a transparent manner where all assumptions are listed and methods explained. A number of high-quality LCAs on concrete building performance have been published by the Portland Cement Association; concrete consistently outperforms other building products in durability with lower environmental impacts. Material ratings that do not follow ISO guidelines and are based on undefined or poorly detailed inputs and assumptions are suspect and should not be used.

**ARCHITECTURAL ADVANTAGES**

Concrete is the world’s most versatile building material. It can be finished in a way that combines aggregate, texture, color, and technique in a limitless variation to achieve architectural and decorative effects. Best of all, concrete’s beauty is more than skin deep. Form and function meet when properly designed concrete is used as a structural element with architectural and decorative features. By applying lessons learned, industry professionals can improve the long term viability of architectural finishes and decorative elements.
Concrete: The Sustainable Material Choice

Finishes and texture variations are typically achieved by exposing different levels of the concrete matrix. Dramatic effect can be achieved or avoided if you understand that textures and porosity affect how well a surface will resist moisture and discoloration. Generally speaking, the rougher and more porous a concrete surface is, the more it will trap and hold moisture and airborne dust or grit. Some surfaces benefit from being polished and or sealed to improve their resistance to staining. This is certainly true for floors, countertops, and decorative treatments exposed to wear.

The ability to color concrete has improved in recent years, resulting in more dramatic colors and exciting new applications. The composition and finish of colored concrete should be designed and detailed in anticipation of the service environment. Colors and sealers that are ideal for an interior commercial sales floor may not be appropriate for a garden walkway. Exterior color treatments need to be evaluated in relation to their ability to withstand ultraviolet (UV) exposure from sunlight. Designers of large structures where repeating patterns yield a unified appearance should consider requiring strict mixture controls. Careful selection and control of aggregate sources and specifying white cement can dramatically improve color consistency and yield brighter colors.

Sustainable design requires we not only evaluate materials on how they look and perform today, we must plan ahead to anticipate long term performance and maintenance needs. The goal is to achieve a desired look throughout the service life of a given structure or decorative element to prevent short cleaning or maintenance cycles.

Managing how water will come into contact with an external building element is a primary consideration in architectural design. Airborne soot and dust common to urban areas settles on roofs and horizontal surfaces during dry weather. Rainwater picks up this grime and carries it to vertical surfaces where it can stain the finish. In this way, dirty rainwater runoff can discolor exposed surfaces, accelerating cleaning cycles. Water should be removed or distributed away from areas where color uniformity is important via drip notches, concealed drainage, or shelter for the area. Another method for dealing with roof or eve drainage is to use it to accentuate transition zones and enhance the contrast between finishes. Careful direction of rainwater runoff can lend a patina to a structural or architectural element that becomes an intended feature of the design.

Architectural and decorative concrete can be a bold or dominant feature of a building or the finest of detailed elements. Too often designers fail to consider the sustainable benefits of concrete. This can lead to the selection of less durable, less energy efficient building materials. Once the facts about concrete are known, designers, energy professionals, and sustainability experts are very likely to embrace the limitless design applications of this most versatile architectural and structural product.

CONCLUSION

Throughout the world concrete is synonymous with the built environment. Building materials all have some environmental impact associated with their use. The environmental impact of a product is closely linked to how highly processed it must be so it is project ready. Concrete’s environmental impact is lower than most other building materials because its primarily ingredient is aggregate. In fact aggregate (sand and stone) make up 2/3 of a typical concrete. These resources are very common and can be extracted essentially ready to use.

Portland cement which is about 11% of the total concrete volume can account for about 85% of the energy and up to 96% of the total CO₂ emissions associated with concrete production.¹ According to the U.S. EPA, cement production generated about 1% of the greenhouse gas emissions in the U.S. in 2007. About half of these emissions come from heating limestone, which releases CO₂. Cement producers reduce their emissions and environmental impact by utilizing alternative fuels and raw materials.

Concrete producers reduce their impact by designing their mixtures to allow the use of recycled aggregate and/or water and by using SCMs in replacement of a portion of the portland cement. Most SCMs are reclaimed from other industrial operations so they help concrete producers make mixtures with less embodied energy and emissions. Specifiers should work with producers to determine how to optimize mixtures and conserve resources while achieving their aesthetic and structural goals.

Concrete delivers excellent durability and service life and can be combined with traditional insulation to impart superior energy efficiently, security and comfort for building occupants. It has the advantage of having dual roles of being a structural element with architectural potential. Leveraging this potential by specifying decorative or architectural finishes is a very sustainable design strategy. Designers improve
the sustainability of architectural finishes and decorative elements by anticipating maintenance needs and designing with the environment in mind. Anticipating how water will be handled, distributed, or channeled is the mark of intelligent design.

By understanding the environmental impacts of using concrete and proven strategies for reducing that impact designers can take advantage of the many benefits concrete delivers to structural and architectural applications.

REFERENCES


Fig. 1—U.S. Greenhouse Gas Emissions by Sector. Source: EPA 430-R-004, Table 2-12: US GHG Emissions Allocated to Economic Sectors.
Sustainable Bridges—Otay River Bridge Case Study

by E. Lorenz

Synopsis: The transportation industry is viewed by some as less sustainable due to its lack of a green rating system similar to the U.S. Green Building Council’s Leadership in Energy and Environmental Design (LEED) system. However, many long-standing design considerations of the transportation market segment have embraced sustainable design criteria. This paper relates current bridge design and construction terminology to sustainable design concepts and the sustainable benefits of precast concrete. A case study of the Otay River Bridge illustrates some of these concepts in practice. Sustainable concepts discussed in the case study include material choices, minimizing site disturbance, community involvement, and wildlife preservation.

Keywords: bridge; green; sustainability; transportation.
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INTRODUCTION

The construction industry has been changing over the last decade with the proliferation of the adoption of the Leadership in Energy and Environmental Design (LEED) rating system by architects in the building sector. In addition, the public’s increased awareness has created a greater demand for green and sustainable practices in products. Lacking a green rating system of its own, one large construction market segment—transportation—is viewed as less responsive to the green building movement. This paper will highlight sustainable building practices that are inherent in the transportation-market segment. A case study of the Otay River Bridge will also highlight sustainable design and construction practices of one bridge in southern California.

Due to length limitations of this paper, other transportation-related components—such as pavements, sound walls, and the like—will not be discussed explicitly. However, many of the sustainable properties of bridges relate to these other sub-sets of the transportation market as well.

Green versus sustainable

There are many definitions of green, and there is a general confusion about the difference between the terms green and sustainable. This confusion has caused the terms to be used interchangeably in public dialog. For this paper, the term green defines those qualities in a product, technique, or decision that are meant to lessen the impact to the environment.

For the definition of sustainable qualities, or those qualities that promote sustainable development, the definition provided by the World Commission on Environment and Development is used. In its 1987 report, “Report on Our Common Future,” the commission defines sustainable development as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs.”

In practice, owners, architects, engineers, and other decision makers use the concept of the triple bottom line to guide choices on the sustainability of a product or technique. The triple bottom line is a concept used to evaluate a product, technique, or decision based on its environmental, economic, and societal impact.

Bridge-design and construction terminology

The public and design-community misconception that the transportation sector is less in-tune with sustainable-design practices stems from the sector’s lack of rating system. However, many of the bridge-design community’s existing terminology and design practices share sustainability concepts. Past bridge-design practices that embrace sustainability include:

- Reducing or eliminating negative site impacts;
- Improving quality of life; and
- Substituting less harmful products and processes for conventional ones.

Other transportation-sector design concepts such as Right Sizing; Get in, Get out, and Don’t Come Back; and Highways for LIFE also improve the sustainability of a bridge project.

Right sizing

The concept of right sizing has to do with optimizing section sizes to reduce material use. This has an obvious impact in reducing the cost of materials, but it also minimizing the environmental impact of the project by reducing the use of virgin materials in the fabrication and construction of the components.

Get in, get out

Get in, get out, and don’t come back is a design concept with the primary goal of reducing public inconvenience by lessening construction delays, and minimizing maintenance and repair requirements.
Concrete: The Sustainable Material Choice

This strategy's primary goal related to the public reduces the societal impact of the project, but it also lessens the environmental impact of the project by improving the project’s durability and reducing the emissions related to idling vehicles in traffic- or construction-related delays.

For LIFE

Highways for LIFE are long lasting, innovative, fast to construct, and economical. This design solution also focuses on durable materials and design and construction techniques to lengthen the design life of the structure. According to the Federal Highway Administration (FHWA), the mission of the Highways for LIFE program is “to advance long lasting highways using innovative technologies and practices to accomplish fast construction of efficient and safe pavements and bridges, with the overall goal of improving the driving experience for America.”

Sustainable benefits of precast concrete bridges

Expanding the Get in, Get out and Highways for LIFE design programs, an American Association of State Highway and Transportation Officials (AASHTO) Technology Implementation Group (TIG) collaborated with the FHWA beginning in 2001 to “champion the use and facilitate the implementation of innovative prefabrication in bridges.”

What AASHTO and FHWA might not have recognized was that this program was placing sustainability into the forefront for the bridge-design community. Through this AASTHO TIG, prefabricated bridges were investigated as a technology to minimize traffic disruption and congestion through faster bridge construction. These strategies have residual positive societal and economic impacts such as improved user satisfaction (the traveling public) with reduced commute times, and reduced environmental impacts through reduced emissions from idling vehicles.

The key for the transportation sector is agreement on a common set of metrics or indicators to distinguish the sustainability of a transportation project. Litman proposed a set of economic, societal, and environmental indicators for use in transportation projects. These indicator categories are presented in Tables 1 through 3.

In the next section, project features of the Otay River Bridge are presented as they relate to the indicator categories in Tables 1 through 3.

Otay River Bridge

Opened to traffic in November 2007, the Otay River Bridge is located in rapidly growing San Diego County, CA. The 1012-m-long (0.6 mi) bridge is 23.1 m wide (75 ft), with a total deck area of 23,375 m² (250,000 ft²). Twelve spans, with a typical span length of 90.5 m (300 ft) and two end spans of 53.5 m (176 ft), carry four lanes of traffic 50 m (160 ft) above grade on a radius of 1600 m (5200 ft) and a typical grade of 2.7%.

The owner, the California Department of Transportation (Caltrans), had strict seismic design criteria for the structure, and additional project goals related to blending the bridge with the aesthetics of the site and minimizing the environmental impact to the environmentally sensitive river valley. The project team (Table 4) chose precast concrete segmental technology to meet the various project requirements.

Erection of the 640 precast concrete segments that comprise the Otay River Bridge was performed in a balanced cantilever method with an overhead gantry. Each segment weighs between 66 tonnes and 77 tonnes (60 tons and 70 tons). The tallest column is 58 m (190 ft) from foundation to deck, with foundations extend an additional 26 m (85 ft) into the ground. Each pair of columns rests on a 23-m-wide by 16-m-long by 3-m-thick (75 ft by 50 ft by 10 ft) rectangular pile cap.

Precast concrete

Precast concrete was chosen for the structure to help meet the owner’s goal of minimizing impact of construction on the site. By precasting the superstructure, the volume of concrete placed on site was reduced by 50% (Habitat protection, Table 3). This strategy also improved the safety of workers on the site, by reducing the amount of work they had to perform 50 m (160 ft) over the river valley.

The superstructure concrete included recycled materials with a 15% fly ash substitution for portland cement. Using recycled materials, instead of virgin materials, reduces the environmental impact of the structure.

It is easier and more efficient to ensure quality of precast concrete components, which are manufactured
in a controlled casting yard. In addition, the maintenance requirements for precast concrete segmental bridges are minimal.

**Erection**

Erection took place with a self-launching gantry via the balanced-cantilever method, by which all components were erected from overhead. The absence of falsework lessened the impact into the river valley below.

**Community**

One pillar of sustainability is the social impact a project has on society. Because most transportation-related projects are funded by the government on behalf of the public, there are inherent societal benefits. The Otay River Bridge brought benefits such as improved regional mobility and safety and reduced congestion to local residents.

Progress in terms of engineering decisions made and milestones reached were reported to the local community. The project team also kept the community involved through meetings (Inclusive planning, Table 2) and the use of time-lapsed webcams.

**Other local residents**

Sustainable projects attempt to minimize, if not entirely prevent, disturbance to the local ecosystem. For the Otay River Bridge, the valley where the structure was located was home to bats. Bat boxes, or bat roosts, were installed on some of the bridge columns.

"The bats fly into the bridge and hang upside down on the bat roof," says Lorenzo Garrido, director of project development for Southbay Expressway. 'It's a small refuge for a species that is native to the valley, and we thought it was a nice way to accommodate them.'

**Drainage**

As with most construction projects that create impermeable surfaces where there were once permeable surfaces, the water that runs off the impermeable surface must be collected in a retention basin. The design of the segments for this bridge did not allow for conventional drain pipes due to the dense reinforcement. In this case, water from the bridge had to be collected in a drainable system that would prevent runoff into the river.

According to Ben Soule, the engineer of record for the project, "the challenge was to take all of the runoff from the entire bridge – a total of 250,000 square feet – to a single point." Once drawn into the retention basin, the runoff would be deposited into a conventional drainage system. 'Dealing with that volume of water was very cumbersome, so the team devised an external system that avoided conflicts between the large pipes required and the structural members.'

**Unique project solutions**

Concrete bridges can offer many sustainable attributes. It is important to remember, however, that each project is unique, and so too will be the sustainable solutions to the challenges of the project. Rating systems and checklists may serve as good guideposts for those new to sustainability concepts, true sustainable design comes from the project team’s understanding of trade-offs and synergies related to all design decisions on a project.

**References**

Table 1—Economic indicators of sustainable transportation

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Description</th>
<th>Direction</th>
<th>Data Availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>User satisfaction</td>
<td>Overall transport system user satisfaction ratings.</td>
<td>More is better</td>
<td>3</td>
</tr>
<tr>
<td>Commute time</td>
<td>Average door-to-door commute travel time.</td>
<td>Less is better</td>
<td>1</td>
</tr>
<tr>
<td>Employment accessibility</td>
<td>Number of job opportunities and commercial services within 30-minute travel distance of residents.</td>
<td>More is better</td>
<td>3</td>
</tr>
<tr>
<td>Land use mix</td>
<td>Average number of basic services (schools, shops and government offices) within walking distance of homes.</td>
<td>More is better</td>
<td>3</td>
</tr>
<tr>
<td>Electronic communication</td>
<td>Portion of population with internet service.</td>
<td>More is better</td>
<td>2</td>
</tr>
<tr>
<td>Vehicle travel</td>
<td>Per capita motor vehicle-mileage, particularly in urban-peak conditions.</td>
<td>Less is better</td>
<td>1</td>
</tr>
<tr>
<td>Transport diversity</td>
<td>Variety and quality of transport options available in a community.</td>
<td>More is better</td>
<td>3</td>
</tr>
<tr>
<td>Mode split</td>
<td>Portion of travel made by non-automobile modes: walking, cycling, rideshare, public transit and telework.</td>
<td>More is better</td>
<td>2</td>
</tr>
<tr>
<td>Congestion delay</td>
<td>Per capita traffic congestion delay.</td>
<td>Less is better</td>
<td>2</td>
</tr>
<tr>
<td>Travel costs</td>
<td>Portion of household expenditures devoted to transport.</td>
<td>Less is better</td>
<td>2</td>
</tr>
<tr>
<td>Transport cost efficiency</td>
<td>Transportation costs as a portion of total economic activity, and per unit of GDP.</td>
<td>Less is better</td>
<td>2</td>
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<tr>
<td>Facility costs</td>
<td>Per capita expenditures on roads, parking and traffic services.</td>
<td>Less is better</td>
<td>1</td>
</tr>
<tr>
<td>Cost efficiency</td>
<td>Portion of road and parking costs borne directly by users.</td>
<td>More is better</td>
<td>2</td>
</tr>
<tr>
<td>Freight efficiency</td>
<td>Speed and affordability of freight and commercial transport.</td>
<td>More is better</td>
<td>3</td>
</tr>
<tr>
<td>Delivery services</td>
<td>Quantity and quality of delivery services (international/intercity courier, and stores that offer delivery).</td>
<td>More is better</td>
<td>2</td>
</tr>
<tr>
<td>Commercial transport</td>
<td>Quality of transport services for commercial users (businesses, public agencies, tourists, convention attendees).</td>
<td>Higher is better</td>
<td>3</td>
</tr>
<tr>
<td>Crash costs</td>
<td>Per capita crash costs</td>
<td>Less is better</td>
<td>2</td>
</tr>
<tr>
<td>Planning quality</td>
<td>Comprehensiveness of the planning process: whether it considers all significant impacts and uses best current evaluation practices.</td>
<td>More is better</td>
<td>2</td>
</tr>
<tr>
<td>Mobility management</td>
<td>Implementation of mobility management programs to address problems and increase transport system efficiency.</td>
<td>More is better</td>
<td>2</td>
</tr>
<tr>
<td>Pricing reforms</td>
<td>Implementation of pricing reforms such as congestion pricing, parking cash out, tax reforms, etc.</td>
<td>More is better</td>
<td>2</td>
</tr>
<tr>
<td>Land-use planning</td>
<td>Applies smart growth land use planning practices, resulting in more accessible, multi-modal communities.</td>
<td>More is better</td>
<td>2</td>
</tr>
</tbody>
</table>

Data availability: 1 = usually available in standardized form; 2 = often available but not standardized; 3 = limited, may require special data collection.
### Table 2—Social indicators of sustainable transportation

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Description</th>
<th>Direction</th>
<th>Data Availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>User rating</td>
<td>Overall satisfaction of transport system by disadvantaged users.</td>
<td>More is better</td>
<td>3</td>
</tr>
<tr>
<td>Safety</td>
<td>Per capita crash disabilities and fatalities.</td>
<td>Less is better</td>
<td>1</td>
</tr>
<tr>
<td>Fitness</td>
<td>Portion of population that walks and cycles sufficient for fitness and health (15 minutes or more daily).</td>
<td>More is better</td>
<td>3</td>
</tr>
<tr>
<td>Community livability</td>
<td>Degree to which transport activities support community livability objectives (local environmental quality).</td>
<td>More is better</td>
<td>3</td>
</tr>
<tr>
<td>Cultural preservation</td>
<td>Degree to which cultural and historic values are reflected and preserved in transport planning decisions.</td>
<td>More is better</td>
<td>3</td>
</tr>
<tr>
<td>Non-drivers</td>
<td>Quality of transport services and access for non-drivers.</td>
<td>More is better</td>
<td>3</td>
</tr>
<tr>
<td>Affordability</td>
<td>Portion of budgets spent on transport by lower income households.</td>
<td>Less is better</td>
<td>2</td>
</tr>
<tr>
<td>Disabilities</td>
<td>Quality of transport facilities and services for disabled people.</td>
<td>More is better</td>
<td>2</td>
</tr>
<tr>
<td>NMT transport</td>
<td>Quality of walking and cycling conditions.</td>
<td>More is better</td>
<td>3</td>
</tr>
<tr>
<td>Children’s travel</td>
<td>Portion of travel to school and other local destinations by walking and cycling.</td>
<td>More is better</td>
<td>2</td>
</tr>
<tr>
<td>Inclusive planning</td>
<td>Substantial involvement of affected people, with special efforts to insure that disadvantaged and vulnerable groups are involved</td>
<td>More is better</td>
<td>2</td>
</tr>
</tbody>
</table>

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### Table 3—Environmental indicators of sustainable transportation

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Description</th>
<th>Direction</th>
<th>Data Availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climate change emissions</td>
<td>Per capita fossil fuel consumption, and emissions of CO₂ and other climate change emissions.</td>
<td>Less is better</td>
<td>1</td>
</tr>
<tr>
<td>Other air pollution</td>
<td>Per capita emissions of “conventional” air pollutants (CO, VOC, NOₓ, particulates, and the like.)</td>
<td>Less is better</td>
<td>2</td>
</tr>
<tr>
<td>Air pollution</td>
<td>Frequency of air pollution standard violations.</td>
<td>Less is better</td>
<td>1</td>
</tr>
<tr>
<td>Noise pollution</td>
<td>Portion of population exposed to high levels of traffic noise.</td>
<td>Less is better</td>
<td>2</td>
</tr>
<tr>
<td>Water pollution</td>
<td>Per capita vehicle fluid losses.</td>
<td>Less is better</td>
<td>3</td>
</tr>
<tr>
<td>Land use impacts</td>
<td>Per capita land devoted to transportation facilities.</td>
<td>Less is better</td>
<td>3</td>
</tr>
<tr>
<td>Habitat protection</td>
<td>Preservation of high-quality wildlife habitat (wetlands, old-growth forests, and the like.)</td>
<td>More is better</td>
<td>3</td>
</tr>
<tr>
<td>Habitat fragmentation</td>
<td>Average size of roadless wildlife preserves.</td>
<td>More is better</td>
<td>3</td>
</tr>
<tr>
<td>Resource efficiency</td>
<td>Non-renewable resource consumption in the production and use of vehicles and transport facilities.</td>
<td>Less is better</td>
<td>2</td>
</tr>
</tbody>
</table>

Data availability: 1 = usually available in standardized form; 2 = often available but not standardized; 3 = limited, may require special data collection.
Table 4—Otay River Bridge Team Members

<table>
<thead>
<tr>
<th>Team member</th>
<th>Name</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Owner</td>
<td>California Department of Transportation</td>
<td>Sacramento, CA</td>
</tr>
<tr>
<td>Engineer of record</td>
<td>International Bridge Technologies</td>
<td>San Diego, CA</td>
</tr>
<tr>
<td>Contractor</td>
<td>Otay River Constructors</td>
<td>San Diego, CA</td>
</tr>
<tr>
<td>Precaster</td>
<td>Pomeroy Corp.</td>
<td>Perris, CA</td>
</tr>
</tbody>
</table>