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Performance-Based Specifications for Concrete to Advance Sustainable Development

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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 CO_2 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[1] 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[2] 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.

- 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 straight forward as selecting an Energy Star[3]-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[4] and Green Globes[5] 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 CO_2 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.[6] leads to the following observations:

Because a cubic yard of concrete weighs about 2 ton (1.8 metric ton), CO_2 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 CO_2 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 CO_2 emissions.[7] So it is no wonder that there have been a number of articles written about reducing the CO_2 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 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/yd^3 (418 kg/m^3). 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[9] 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[10] 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[11] 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 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[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[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_{cr}' 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, σ 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 σ and improve quality. For f_c' = 4000 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 σ = 350 psi (2.4 MPa) has to attain a target f_{cr}' of 4470 psi (31 MPa) where as a producer with σ = 750 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 (σ) could lower the cementitious materials content and potentially reduce material costs[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 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 view point a $4/yd^3 higher material cost (required for a higher cementitious content for example) is a small cost as compared to the $400/yd^3 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 CO_2 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 CO_2 emissions. But there are two important aspects to this approach.

Sustainability more than CO_2 emissions from cement and concrete production

Focusing on CO_2 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 CO_2 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 CO_2 emissions for a ton of cement produced[19] 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 CO_2 emissions from a cubic yard of concrete produced comes from cement CO_2 emissions it can be calculated that the production of concrete accounts for approximately 1.5% of U.S. CO_2 emissions and approximately 5.2% of global CO_2 emissions.

So whatever way one looks at it focusing on just the production of concrete accounts for a very small percent of over-all CO_2 emissions. This is not to say that progress should not be made in reducing the CO_2 emissions from concrete as produced. However, one should keep in mind that whatever CO_2 emission reductions that are possible will still account for at best a 2% global CO_2 reduction (assuming a challenging 40% reduction in global CO_2 emissions from cement manufacture from now on).

It is important to reduce the CO_2 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 CO_2 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 CO_2 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 CO_2 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 CO_2 emissions

While there is value in reducing CO_2 emissions focusing entirely on CO_2 emissions can result in the following unintended consequences[20]:

- It does not encourage the use of recycled or crushed returned concrete aggregates because use of virgin aggregates constitutes only 1% of all CO_2 emissions from a typical cubic yard of concrete (Table 1). Even replacing all virgin aggregates with recycled aggregates will reduce CO_2 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 CO_2 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 CO_2 emissions from plant operations constitutes only 1% of all CO_2 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 CO_2 emissions from transport constitutes only about 3% of all CO_2 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.
- CO_2 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 CO_2 emissions from a cubic yard of concrete is from cement manufacturing it is important to reduce CO_2 emissions through the greater use of SCM. However, it is important not to focus solely on CO_2 emissions from cement and concrete production. Doing so limits the total global CO_2 reduction possible to at best 2%. Keeping a holistic cradle to cradle perspective and using LCA can help reduce CO_2 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 CO_2 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 CO_2 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 CO_2 Emissions for 1 yd^3 of concrete for different strength classes and mixture proportions[6]

Ready mixed ID	Strength class, psi	Mixture proportions,* lb/yd^3	Total concrete CO_2 emission, lb/yd^3	Breakdown of CO_2 emissions for 1 yd^3, %				
				Cement	SCM	Aggregate	Plant operations	Transport†
1	5000	564/0/0	528	96.8	0.0	0.6	0.6	2.0
2	4000	470/0/0	442	96.3	0.0	0.7	0.7	2.3
3	3000	376/0/0	355	95.7	0.0	0.9	0.8	2.6
4	3000	301/75/0	288	94.6	0.0	1.1	1.0	3.2
5	3000	282/94/0	270	94.3	0.0	1.2	1.1	3.4
6	3000	244/0/132	239	92.4	1.2	1.4	1.2	3.9
7	3000	188/0/188	189	89.8	2.1	1.7	1.6	4.9

*564/0/0 signifies that the mixture contains 564 lb/yd^3 cement, 0 lb/yd^3 fly ash, 0 lb/yd^3 slag cement.
†Transport costs is for material shipped to ready mixed plant.
Note: 1 MPa = 145 psi; 1 lb/yd^3 = 0.5933 kg/m^3; 1 yd^3 = 0.765 m^3.

Table 2—Details of the HPC bridge deck mixtures

Product	BR-1	BR-2	BR-3	BR-4
Cement, lb/yd^3	556	420	307	412
Fly ash, lb/yd^3	106	148	0	145
Silica fume, lb/yd^3	51	24	0	0
Slag, lb/yd^3	0	0	307	0
UFFA, lb/yd^3	0	0	0	33
Total cementitious content, lb/yd^3	713	591	614	590
Coarse aggregate (no. 67) , lb/yd^3	1820	1894	1985	1881
Fine aggregate, lb/yd^3	1133	1182	1237	1174
Water, lb/yd^3	278	231	239	211
w/cm	0.39	0.39	0.39	0.36
AEA, oz/100 lb cementitious	0.40	0.45	0.40	0.40
Type A WR, oz/100 lb cm	4	4	4	4
Type F HRWR, oz/100 lb cm	13.0	9.4	18.4	11.1
Fresh concrete properties				
ASTM C143, slump, in.	4.00	5.00	5.00	5.75
ASTM C231, air, %	4.6	7.2	4.7	7.6
ASTM C138, density, lb/ft^3	145.7	144.1	150.5	142.5
ASTM C1064, temperature, °F	69	69	65	69
Hardened concrete properties				
ASTM C39 compressive strength, psi				
3 days	4150	3650	2600	3710
7 days	5420	4880	5560	5160
28 days	7480	6800	8970	7180
ASTM C157 length change (drying shrinkage), %				
28 days	-0.037%	-0.017%	-0.021%	-0.018%
90 days	-0.045%	-0.027%	-0.029%	-0.027%
180 days	-0.043%	-0.024%	-0.025%	-0.024%
ASTM C1202 RCPT, coulombs				
45 days	1563	1257	1126	1244
110 days	541	434	541	479
180 days	327	275	375	242
AASHTO TP 64, rapid migration test, mm/(V-hr)				
60 days	0.0190	0.0180	n/a	0.0230
120 days	0.0090	0.0070	0.0060	0.0110
180 days	0.0058	0.0045	0.0054	0.0047
ASTM C1585 69 days rate of water absorption (sorptivity), x 10^{-4} mm/s$^{1/2}$				
Initial	6.19	7.37	8.89	15.20
Secondary	3.47	4.59	4.52	6.37
ASTM C1556 diffusion coefficient, x10^{-13} m^2/s				
140 days	21.9	17.9	15.4	34.2
Surface chloride, % by weight of concrete				
140 days	0.90	0.95	0.58	0.67

Note: 1 lb/yd^3 = 0.5933 kg/m^3; 1 oz/100 lb = 65.3 mL/100 kg; 1 in. = 25.4 mm; 1lb/ft^3 = 16.02 kg/m^3; 1 MPa = 145 psi.

Table 3—Mixture details of new I-35W bridge in Minneapolis, MN[8]

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

Note: 1 MPa = 145 psi; 1 lb/yd^3 = 0.5933 kg/m^3

Table 4—Details of ACI 318 mixtures

	318-1	318-2	318-3	318-4
Calculated mixture proportions, lb/yd^3				
Cement, lb/yd^3	727	540	419	416
Fly ash, lb/yd^3	0	180	140	139
Total cementitious content, lb/yd^3	727	720	558	555
Coarse aggregate (no. 67) , lb/yd^3	1746	1852	1781	1989
Fine aggregate, lb/yd^3	975	1086	1314	1111
Water, lb/yd^3	303	299	233	231
w/cm	0.42	0.42	0.42	0.42
AEA, oz/cwt.	0.35	0.39	0.49	0.39
Type A WR, oz/cwt.	4	4	4	4
Type F HRWR, oz/cwt.	0	0	7.4	9
Fresh concrete properties				
ASTM C143, slump, in.	4.75	6.5	3.75	5.25
ASTM C231, air, %	7	4.1	7.2	7.4
ASTM C138, density, lb/ft^3	138.8	146.5	143.7	143.7
ASTM C1064, temperature, °F	70	69	67	65
Hardened concrete properties				
ASTM C39, compressive strength, psi				
3 days	3800	3610	3220	3110
7 days	4270	4330	4060	4020
28 days	5440	5950	5670	5600
108 days	6400	7920	6740	7420
ASTM C157, length change, %				
28 days	-0.048	-0.034	-0.029	-0.024
90 days	-0.064	-0.048	-0.039	-0.033
180 days	-0.064	-0.048	-0.037	-0.032
ASTM C1202, rapid chloride permeability, coulombs				
28 days	8356	5610	4462	4036
120 days	3421	1181	996	835
180 days	2772	608	533	457
AASHTO TP 64, rapid migration test, mm/(V-hr)				
50 days	0.069	0.042	0.049	0.037
120 days	0.037	0.016	0.017	0.016
180 days	0.030	0.0077	0.015	0.0082
ASTM C1585, rate of water absorption (sorptivity) at 56 days, x10^{-4} mm/s$^{1/2}$				
Initial	11.6	16.4	7.51	11.4
Secondary	6.43	9.46	4.72	4.70
ASTM C1556, diffusion coefficient, x10^{-13} m^2/s				
210 days	49.6	28.7	26.1	25.8
290 days	53.6	13.7	30.6	18.9
ASTM C1556, surface chloride, % by weight of concrete				
210 days	0.98	1.19	0.72	0.74
290 days	0.87	1.35	0.79	0.85

Note: 1 lb/yd^3 = 0.5933 kg/m^3; 1 oz/100 lb = 65.3 mL/100 kg; 1 in. = 25.4 mm; 1 lb/ft^3 = 16.02 kg/m^3; 1 MPa = 145 psi.

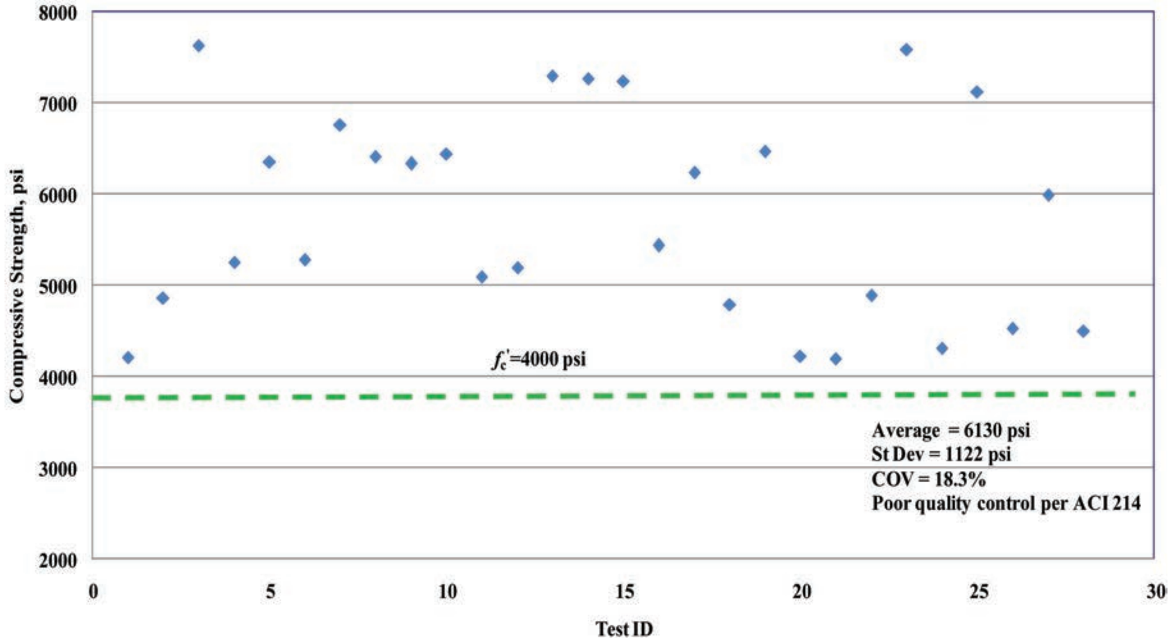

Fig. 1—Variability of compressive strength test results from a concrete class project demonstrating that minimum cement content requirements do not provide incentive to reduce variability. (Note: 1 MPa = 145 psi.)

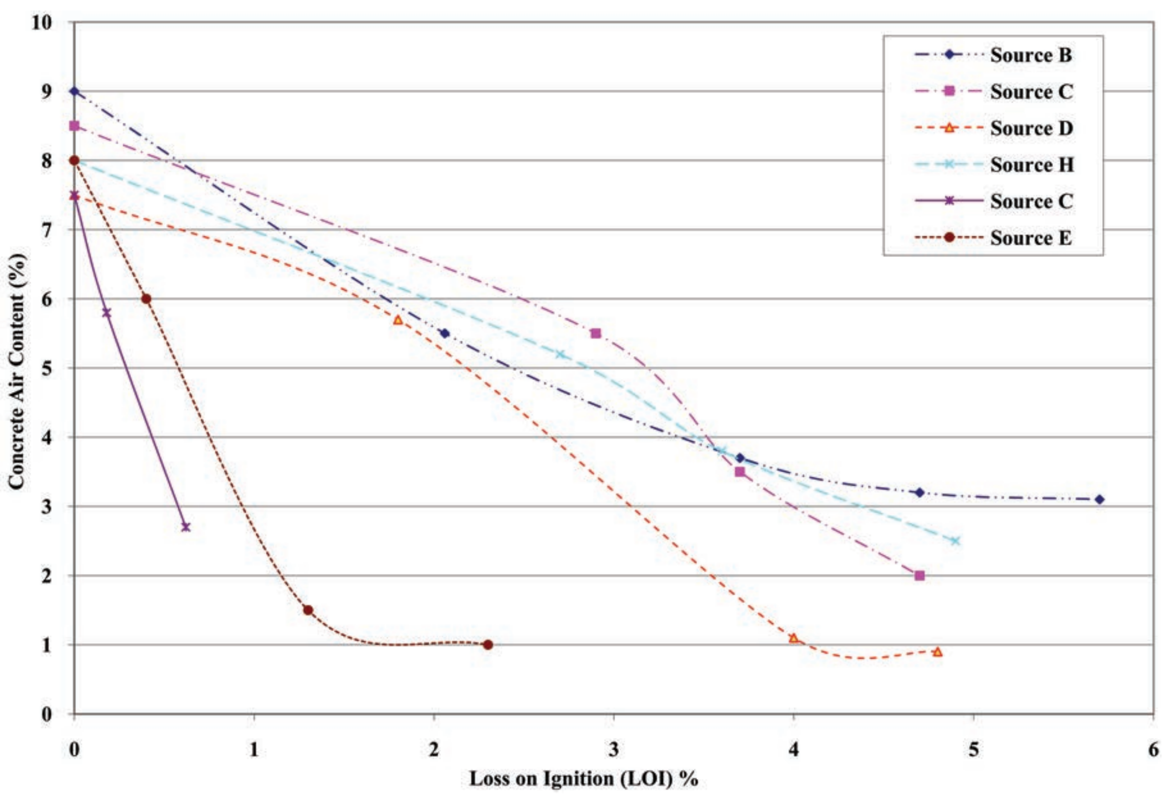

Fig. 2—Impact of fly ash LOI (carbon) on air entrainment for a standard air-entraining admixture dose demonstrating that a low LOI specification does not guarantee consistent air content.[11]