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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 CO_2 emissions from cement and concrete production only.

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

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Karthik H. Obla, FACI, is Vice-President, Technical Services at the National Ready Mixed Concrete Association (NRMCA). He received the ACI Young Professional Achievement Award. He is Chair of ACI Committee 232, Fly Ash and Natural Pozzolans in Concrete. He has published over 50 technical articles and has presented in several international conferences. He received his PhD in civil engineering from the University of Michigan, Ann Arbor, MI, and is a licensed professional engineer in the states of Michigan and Maryland. He has over 18 years of experience in concrete materials technology and research and his research interests include mixture proportioning, durability, quality control, specifications, and the use of recycled materials.

INTRODUCTION

A code, such as a building code, establishes minimum requirements for buildings to protect public safety. In the U.S., ACI 318¹ 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 301² 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 Star³-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 LEED⁴ and Green Globes⁵ 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.

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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/yd³ (418 kg/m³), 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 study⁸ 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 CO₂ 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/yd³ (386 kg/m³) 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/yd³ (386 kg/m³). This resulted in total cementitious materials content of 714 lb/yd³ (424 kg/m³) out of which 552 lb/yd³ (328 kg/m³) was portland cement. To attain the required performance a total cementitious content of 600 lb/yd³ (356 kg/m³) 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 CO₂ 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-02⁹ 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 proportions¹⁰ 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 2¹¹ 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 report¹² 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/yd³ (172 kg/m³) for adequate workability. Due to the maximum w/cm requirement a cementitious content of 725 lb/yd³ (430 kg/m³) 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/yd³ (344 kg/m³). 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 study⁸ 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 $\sigma = 350$ psi (2.4 MPa) has to attain a target $f_{cr'}$ of 5250 psi (31 MPa) where as a producer with $\sigma = 750$ 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 costs¹³ by \$3.9/yd³ 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 view point 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 CO_2 emissions. But there are two important aspects to this approach.

Sustainability more than CO, 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), respectively¹⁷. 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), respectively¹⁸. The average CO_2 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 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.