

Specification in Practice

What, why & how?



SIP 1 – Limits on Quantity of Supplementary Cementitious Materials

by the NRMCA Research Engineering and Standards Committee

WHAT is the typical specification requirement?

The typical clause incorporated in specifications from the AIA MasterSpec (2014) is:

Cementitious Materials: [Limit percentage, by weight, of cementitious materials other than portland cement in concrete as follows:]

1. Fly Ash: 25 percent.
2. Combined Fly Ash and Pozzolan: 25 percent.
3. Slag Cement: 50 percent.
4. Silica Fume: 10 percent...

The MasterSpec (2014) notes inform the designer that this clause is used for concrete exposed to freezing and thawing cycles and the application of deicing salts. However, this advice seems to be ignored by specification writers. In an NRMCA review of more than 100 specifications for private work, these limits were noted in 85% of the specifications, without consideration of the anticipated exposure condition for concrete members. Some specifications specifically prohibit the use of supplementary cementitious materials (SCMs).

Do industry standards require limits on SCM quantities?

Table 1 replicates Table 26.4.2.2(b) in ACI 318-14, which establishes limits on the quantity of SCMs for concrete members in Exposure Class F3 – defined as “Concrete exposed to freezing-and-thawing cycles with frequent exposure to water and exposure to deicing chemicals”. The concern is that surface scaling will reduce cover and result in reinforcement corrosion. Additionally, ACI 318-14 requires air entrainment, a maximum water-cementitious materials ratio (w/cm) of

0.40, and a minimum specified strength of 5000 psi (35 MPa) and for structural concrete. The limits on w/cm and specified strength are 0.45 and 4500 psi (31 MPa), respectively, for plain concrete.

ACI 301-10 includes the above limits and additionally limits fly ash in concrete for floors to 15 minimum and 25% maximum by weight of cementitious materials unless otherwise specified.

The committee is not aware of other industry standards that place limits on the quantity of SCMs in concrete mixtures.

WHAT is the basis for this specification requirement?

Research conducted by Malhotra and Mehta (2012) has indicated that concrete mixtures containing higher quantities of SCMs than those shown in Table 1 have not performed well in tests conducted in accordance with ASTM C672/C672M. However, it is generally understood that the ASTM C672/C672M test is unduly harsh for mixtures containing fly ash and slag cement (Thomas 1997) and results from a more realistic test could allow the use of greater amounts of SCMs (Bouzoubaa et al. 2008). A significant factor in concrete surface defects such as scaling is related to improper concrete finishing and curing (CIP 2). Scaling is observed for higher slump concrete finished by manual methods and is rarely seen in machine finished concrete, as in slipform construction (Thomas 2007).

The use of SCMs generally increases the setting time and decreases the early age strength of concrete. This is beneficial in warm weather but can be a concern for construction in cooler weather. Restricting the quantity of SCMs can be an implicit attempt to attain shorter setting times and increased early age strengths. A research study using 11 fly ash sources illustrated that setting time and early-age strength of 20% fly ash mixtures can vary widely – they can be similar to or considerably delayed when compared to control mixtures without fly ash (Malhotra and Ramezaniapour 1994). Concrete temperature also has an effect on these properties of concrete. So, restricting the SCMs quantity does not assure control of setting time and early-age strength.

Table 1: Limits on cementitious materials for concrete assigned to Exposure Class F3 (Table 26.4.2.2(b) in ACI 318-14)

Cementitious materials	Maximum percent of total cementitious materials by mass
Fly ash or other pozzolans conforming to ASTM C618	25
Slag cement conforming to ASTM C989	50
Silica fume conforming to ASTM C1240	10
Total of fly ash or other pozzolans and silica fume	35
Total of fly ash or other pozzolans, slag cement and silica fume	50

How can these limits be restrictive?

- Workability/pumpability can be adversely impacted;
- With some materials, and under some conditions, the quantity of SCMs allowed can be inadequate to prevent later-age durability problems, such as alkali silica reaction (ASR) or sulfate attack;
- Temperature control in mass concrete members can be difficult to achieve;
- Reduced permeability of concrete can be difficult to achieve, and this could impact durability, specifically by reducing the time to onset of corrosion of reinforcing steel; and
- Later-age development of strength and other mechanical properties of concrete can be curtailed.

What is the alternative to this specification requirement?

- Delete limits on quantities of SCMs in concrete mixtures, except those limits for concrete used in members that would be assigned to Exposure Class F3 as defined above;
- Include performance-based requirements, such as early age strength, when required for the project; and
- Allow construction-related requirements for time of setting, finishability, and formwork removal to be set through separate contracts, purchase orders, and at pre-construction meetings between producers and contractors.

How can these alternative requirements benefit the project?

It is well researched and established that concrete with SCMs has enhanced workability as well as improved mechanical and durability properties (ACI 232.1R-12, 232.2R-03, 232.3R-14, 233R-03, 234R-06, CIP 30). Some of these beneficial properties may not be achieved with mixtures containing only portland cement or if there are restrictions on the quantity of SCMs, specifically:

- Improved resistance to ASR and sulfate attack;
- Enhanced durability of concrete related to chloride-induced corrosion;
- Continued improvement in later-age properties that can increase the service life of structures; and
- Achievement of more sustainable construction.

Concrete producers can optimize concrete mixtures to achieve required setting times, early age strengths, or concrete temperature requirements for mass concrete by using SCM quantities in excess of those in Table 1, through the use of chemical admixtures, and other parameters (Jeknavorian 2014; Obla et al. 2003). These requirements need to be clearly stated. Placing restrictions on quantities of SCMs may not allow mixtures to achieve the desired performance. In contrast to this, concrete mixtures with up to 85% SCMs by weight of cementitious materials have been used in structural members to achieve the performance requirements mandatory on some projects (Concrete International 2009; Kite 2005).

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SIP 2 – Limits on water-cementitious materials ratio (w/cm)

by the NRMCA Research Engineering and Standards Committee

WHAT is the typical specification requirement?

The typical clauses incorporated in specifications on the water-cementitious materials ratio (w/cm) are:

The maximum w/cm for all concrete on this project shall be 0.XX

Compressive strength for different members in the structure shall be as indicated on the drawings.

The limit on w/cm is often accompanied by a specified compressive strength and sometimes a limit on minimum cementitious materials content.

In an NRMCA review of more than 100 specifications for private work, maximum w/cm was stated in 73% of the specifications for concrete that was not expected to be subjected to exposure conditions that would require the specification of maximum w/cm .

Do industry standards require limits on w/cm ?

ACI 318-14 specifically states maximum w/cm in its durability provisions for concrete members. The design professional assigns the member to durability exposure classes based on the anticipated exposure of the member in service. ACI 318-14 requires maximum w/cm and minimum specified strength for these conditions:

- Exposure Classes F1, F2 and F3 – members exposed to cycles of freezing and thawing;
- Exposure Classes S1, S2 and S3 – members exposed to water soluble sulfates in soil and water;
- Exposure Class W1 – members in contact with water and requiring low permeability; and
- Exposure Class C2 – members that will be wet in service and exposed to an external source of chlorides.

The Code recognizes that w/cm cannot be verified during the project and states the specified strength level should be reasonably consistent with what can be achieved with the required w/cm . The strength acceptance criteria are used to enforce these requirements. The paired w/cm - strength requirements for different exposure classes listed in ACI 318-14 are: 0.40 - 5000 psi (35 MPa); 0.45 - 4500 psi (31 MPa); 0.50 - 4000 psi (28 MPa); and 0.55 - 3500 psi (24 MPa).

ACI 350-06 states similar requirements for durability. ACI 301-10 incorporates the ACI 318-08 requirements in the reference specification. Exterior work, such as

parking areas, which are not covered by ACI 318, have similar requirements for w/cm and strength.

WHAT is the basis for this specification requirement?

The primary intent of specifying w/cm limits is to reduce the penetration of water and dissolved chemicals into concrete. This is necessary when the concrete will be in a moist condition in service and is exposed to freezing and thawing, harmful chemicals, or both. Besides w/cm , supplementary cementitious materials (SCMs) content, aggregate characteristics, and curing of the concrete structure also impact the permeability of concrete.

The w/cm should not be specified if the exposure condition does not warrant it. While w/cm is an important parameter for a concrete mixture, there is a perception that low w/cm translates to good concrete performance such as low shrinkage and high durability. An important point is that the specification should ensure that concrete meets the performance requirements of the application and achieves the design service life.

For example, if the specified compressive strength for concrete in an interior column is 3000 psi (21 MPa), a concrete mixture can be furnished with about 450 lb/yd³ (270 kg/m³) of cementitious materials. Adding a 0.40 w/cm requirement to this concrete will result in a mixture with about 700 lb/yd³ (420 kg/m³) of cementitious materials and the strength of the concrete could exceed 6000 psi (41 MPa). Since this member will not be exposed to the environment, the specified w/cm is not necessary and the concrete is significantly over-designed for the application. The 50% higher paste volume will increase the potential for cracking due to shrinkage and heat of hydration and result in increased deflection due to creep. The mixture is not cost effective for the designed member. The specified strength of 3000 psi (21 MPa) is not consistent with the specified maximum w/cm . Since w/cm cannot be reliably verified, acceptance will be based on the specified compressive strength (Lobo 2006). In this example, since the strengths will be much higher than the specified strength when the maximum w/cm requirement of 0.40 is imposed, there is less incentive for the producer to achieve concrete with low strength variability (see SIP 3).

For every set of materials and type of mixture, a unique relationship exists between w/cm and strength.

It is possible for two mixtures with the same w/cm to have considerably different paste volumes and different properties in terms of strength, durability, and resistance to cracking.

In an attempt to achieve higher strength or improved durability, a w/cm considerably lower than 0.40 is sometimes specified. This can make it difficult to provide concrete with the required workability and can increase the potential for cracking due to chemical or autogenous shrinkage (Bentz and Jensen 2004). For these high-performance concrete projects, it is better to rely on performance-based requirements instead of specifying exceedingly restrictive w/cm .

How can these requirements be restrictive?

- The ability to place and finish concrete can be adversely impacted;
- Concrete may not be optimized for the performance required by the application;
- When the specified w/cm is not consistent with specified strength, strength acceptance criteria will not reliably ensure that the specification is being complied with; and
- Specifying a w/cm considerably lower than 0.40 can adversely impact workability and increase the potential for cracking.

WHAT is the alternative to this specification requirement?

- Conform to the durability provisions of ACI 318-14 – specify a maximum w/cm and a companion strength level that is consistent with the assigned exposure class;
- Do not specify w/cm for concrete members not subject to exposures that require reduced permeability; and

- For concrete members that require high-performance concrete, consider using performance-based tests such as ASTM C1202 (NRMCA 2012, 2015). Criteria for other test methods, such as sorptivity, conductivity, and resistivity, are being developed. Specifying a maximum w/cm should be avoided when performance-based tests are used. These test methods can be used to pre-qualify concrete mixtures and the results can be documented in a pre-construction submittal.

How can these alternative requirements benefit the project?

Specifying w/cm requirements for concrete only when necessary for improved durability ensures that concrete mixtures can be optimized and developed for the performance required by the specific application. This ensures that the specification evolves to performance-based requirements, the concrete mixtures are cost effective, and sustainable construction is supported.

Specifying w/cm and strength requirements that are consistent, as in the durability provisions of ACI 318-14, ensures that the specification requirements can be enforced using the strength acceptance criteria.

Avoiding very restrictive requirements on w/cm allows the concrete mixtures to be developed for required workability and prevents potential problems such as increased cracking.

Using performance-based test methods to prequalify concrete mixtures as an alternative to specifying w/cm lower than 0.40 for more critical projects that require an enhanced level of durability, provides better assurance that concrete mixtures are developed to satisfy the requirements for the anticipated concrete exposure.

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Specification in Practice

What, why & how?



SIP 3 – Minimum Cementitious Materials Content

by the NRMCA Research Engineering and Standards Committee

WHAT is the typical specification requirement?

The typical clause in specifications for concrete states:

Concrete for XXX members shall comply with the following:

Minimum cement content xxx lb/yd³

Note: The limit on minimum cement content is sometimes stated as minimum content of cementitious materials.

In an NRMCA review of more than 100 specifications for private work, these limits were noted in 46% of the specifications. Specifications that stated these limits for interior slabs-on-ground were not counted.

Do industry standards include a minimum cement content?

There is no requirement for minimum cement or cementitious materials content in ACI 318-14.

ACI 301-10 has minimum cementitious materials content requirements only for interior floor slabs (see Table 1). These limits are considerably lower than that seen in some specifications. The intent is to ensure adequate paste to facilitate finishability. A test slab placement is permitted as an alternative to the minimum cementitious content requirement.

Table 1: Minimum cementitious materials content requirements for floors (Table 4.2.2.1 in ACI 301-10)

Nominal maximum size of aggregate, in.	Minimum cementitious materials content, lb/yd ³
1-1/2	470
1	520
3/4	540
3/8	610

Note: When fly ash is used as a supplementary cementitious material, quantity shall not be less than 15% nor more than 25% by weight of total cementitious material, unless otherwise specified.

Note: 1 in. = 25 mm; 1 lb/yd³ = 0.6 kg/m³

WHAT is the basis for this specification requirement?

Historically, when concrete was proportioned with only portland cement, a minimum cement content was commonly specified to ensure that the strength and durability requirements were met. The perception still remains that some minimum cement content is required to ensure durability, even though there is now an adequate understanding that using supplementary cementitious materials (SCMs) is an essential method for improving most prop-

erties of concrete related to durability. Sometimes, the specified cement content is an implicit control on the quantity of SCMs.

Wasserman et al. (2009) identified three possible reasons for specifying a minimum cementitious content:

1. It provides assurance that a low water-cementitious materials ratio (w/cm) is attained, even if good control of the mixing water content is not exercised.
2. It ensures there is enough paste to fill the voids between the aggregates and provide adequate workability, and
3. It offers corrosion protection by chemically binding the chlorides and CO_2 that penetrate the concrete.

Wasserman et al. (2009) and Dhir et al. (2003) reported that at any given w/cm , increasing cement contents lead to similar compressive strengths and carbonation rates, but higher absorption and chloride penetration. A mixture with higher cement content had increased chloride thresholds to initiate corrosion but this benefit was offset by higher chloride penetration. Dhir et al. (2003) reported that for mixtures with similar w/cm values, increasing cement contents led to similar flexural strengths, moduli of elasticity, and levels of deicer salt scaling. However, increasing cement contents led to reduced sulfate resistance, increased chloride diffusion, greater air permeability, and higher length change due to shrinkage. These studies concluded that the minimum cementitious materials content should not be specified for concrete durability. Obla (2012) and Yurdakul (2010) looked at a broader range of cementitious materials contents and found that increasing cement content at a given w/cm did not result in higher strength. With increasing cement contents, concrete resistance to chloride penetration was reduced and shrinkage increased. Mixtures with very low paste contents resulted in poor workability and reduced compressive strengths. It should be noted that ACI 211.1-91 mixture proportioning approaches typically yield adequate paste volume for workability.

How can these limits be restrictive?

The specified cement content:

- May be much higher than the amount needed to meet the performance requirements;
- Can impact the ability to place and finish the mixture in some applications;
- Can increase the paste volume in the mixture, increasing potential for cracking due to plastic or drying shrinkage and temperature effects;
- Can increase the alkali content in the mixture and

cause an alkali aggregate reaction problem;

- May result in a mixture that fails to achieve expected and unstated durability objectives;
- Is not supportive of sustainable construction; and
- Places competitive bids that support quality and performance at a disadvantage.

WHAT is the alternative to this specification requirement?

- Delete limits on content of cement or cementitious materials for concrete mixtures;
- Specify the performance requirements for the project (NRMCA 2012, NRMCA 2015) (there is no technical basis for specifying cement content if the performance requirements are defined);
- Invoke the durability requirements of ACI 318-14, by specifying w/cm and appropriate compressive strength, and other requirements when applicable (NRMCA 2012).
- Consider requiring a test floor slab placement or documentation of successful past field history as an alternative to specifying the cement content;
- Specify an appropriate compressive strength rather than a minimum cementitious materials content if a low w/cm is required, as compressive strength is a better indicator of w/cm; and
- If the implicit purpose is to ensure improved quality, require and review the quality plan of the producer and contractor (NRMCA administers a quality certification program for concrete producers (NRMCA 2013)).

How can these alternative requirements benefit the project?

Specifying compressive strength that is consistent with the required w/cm for durability provides better assurance for durable concrete than specifying cement content. In contrast, specifying a minimum cementitious

materials content does not ensure a low w/cm or improved durability. In fact, such a specification benefits entities that have not made investments in quality and provides no incentive to optimize mixtures for performance.

Figure 1 illustrates a poor level of quality on a project. The specified strength was 4000 psi (28 MPa), with a minimum cementitious content of 650 lb/yd³ (390 kg/m³). The coefficient of variation of strength results was 18.3%, which is categorized as poor control, according to ACI 214R-11. There were no low strength test results and, as a result, there was no incentive to reduce variability. This does not benefit the owner.

A survey of the ready mixed concrete industry (Obla 2014) revealed that the average cementitious material content used in a cubic yard of concrete is about 100 lb/yd³ (59 kg/m³) more than that required to meet the strength requirement. This represents a waste of resources and is not supportive of sustainable construction. Mixtures with lower cementitious materials content can be proportioned and this can lead to improved workability and durability as well as reduced potential for cracking.

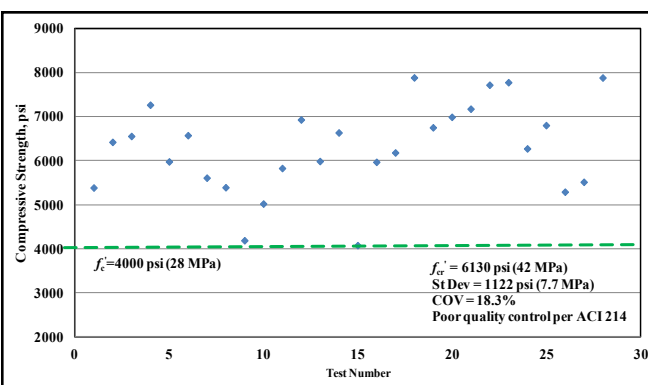


Figure 1: Variability of compressive strength test results from a project with a specified minimum cementitious materials content requirement

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What, why & how?



SIP 4 – Restrictions on Type and Characteristics of Fly Ash

by the NRMCA Research Engineering and Standards Committee

WHAT restrictions to fly ash are seen in specifications?

Typical restrictions to fly ash seen in specifications for concrete include:

Class C fly ash is not permitted

The calcium oxide (CaO) content of fly ash shall not exceed XX%

The Loss on Ignition (LOI) of fly ash shall not exceed X.X% (more restrictive than ASTM C618)

Fly ash fineness—The percent retained on the 45 μ m (No. 325) sieve shall not exceed XX% (more restrictive than ASTM C618)

The [available] alkali content of fly ash shall not exceed X.X%

In an NRMCA review of more than 100 specifications for private work, these types of restrictions were noted in 25% of the specifications, 80% of which did not allow the use of Class C fly ash or had restrictions on the CaO content of the fly ash.

Do industry standards have restrictions on fly ash?

ACI 318-14 permits the use of fly ash that complies with ASTM C618. It imposes no additional restrictions on the characteristics of fly ash.

ASTM C618 classifies fly ash as Class F or Class C based on composition and has the following requirements:

Requirement	Class F	Class C
(SiO ₂ + Al ₂ O ₃ + Fe ₂ O ₃), min %	70.0	50.0
Loss on Ignition (LOI), max %	6.0*	6.0
Fineness, retained on 45 μ m (No. 325) sieve, max %	34	34

*ASTM C618 permits up to 12% LOI with documented service records or laboratory evaluation.

Additionally, there are limits on sulfur trioxide (SO₃), moisture content, soundness, strength activity index, water requirement, and uniformity requirements for material from a single source. Optional requirements, when specifically requested, are also covered in the specification. There are no limits on alkali content of fly ash, but the supplier may report this, expressed as equivalent sodium oxide (Na₂O).

WHAT is the basis for these restrictions?

In general, Class F fly ashes are more effective in mitigating deleterious expansion due to alkali-silica reaction (ASR) and improving the sulfate resistance of concrete. Fly ashes with higher CaO content are less ef-

fective when these durability conditions exist (Thomas 2007). A limit on available alkalis was removed from ASTM C618 in the 1990s based on work that indicated that the available alkalis in fly ash were not a good indicator when considering the use of fly ash in concrete containing potentially reactive aggregate (Smith 1987). However, specifying Class F fly ash does not ensure that the concrete will be resistant to ASR and sulfate attack. A methodical approach to addressing ASR is covered in ASTM C1778. Sulfate resistance of concrete is addressed in ACI 318-14 and the effect of fly ash in improving sulfate resistance is covered in the optional requirements of ASTM C618.

LOI is a measure of the amount of unburnt carbon in fly ash. Certain forms of unburnt carbon absorb air-entraining admixtures and affect the air content of air-entrained concrete. Research has indicated that at the same LOI, fly ash from different sources can exhibit varying impacts on air entrainment (Hill and Folliard 2006). It was also observed that fly ashes with lower LOI were more sensitive to air entrainment. Possible reasons for the varying impacts are total carbon surface area, available surface area, and surface reactivity of the carbon (ACI 232.2R-03). Imposing a lower LOI limit on fly ash does not ensure better control of the air content in air-entrained concrete. The concrete producer is responsible for achieving the specified air content in concrete.

Specifying more restrictive fineness requirements on fly ash could be an attempt to ensure that a more reactive material is used. Research on this aspect indicates that when fineness of fly ash from the same source varied substantially (between 15% and 30%) over a period of time, there was no significant difference in strength of mortar cubes (Obla 2014). Besides fineness, fly ash reactivity is impacted by factors such as chemical and physical composition, morphology, and the portland cement with which it is used (ACI 232.2R-03). The concrete producer is responsible for supplying concrete mixtures that meet the specified strength requirements.

WHAT problems do these restrictions cause?

- Fly ash may need to be obtained from distant sources and the concrete producer will need to gain experience on optimized use;
- Locally available materials that have history of acceptable mixture performance and service record

are restricted from use; and

- There is a false sense of security that imposing restrictions ensures achievement of the intended performance.

WHAT is the alternative to this specification requirement?

- As an alternative to prohibiting Class C fly ash or imposing a limit on the CaO content of fly ash, consider performance-based tests:
 - ◊ For ASR, ASTM C1778 provides a reasonable and rather detailed approach; ASTM C1567 expansion test results equal to or less than 0.1% at 14 days when the fly ash is used with the producer's aggregates and cementitious materials;
 - ◊ For sulfate resistance, consider the performance requirements of ACI 318-14 or the optional requirements of ASTM C618 that evaluate the ability of fly ash to improve sulfate resistance of concrete based on ASTM C1012/C1012M testing;
- Do not include more restrictive requirements on LOI or fineness than those in ASTM C618. The market will determine the acceptability of fly ash. The fly ash supplier and concrete producer are responsible for monitoring the quality and uniformity of fly ash to ensure that the specified air content and strength are achieved (Obla 2014).

Additional guidance and rationale for eliminating prescriptive requirements in specifications are provided elsewhere (NRMCA 2012; NRMCA 2015).

WHAT is the benefit of the alternative requirements?

Alternative performance requirements ensure that concrete attains improved durability such as resistance to ASR and sulfate attack. Limiting the use to only Class F fly ash does not ensure improved concrete durability.

Mitigation of ASR has been attained by increasing the percentage of Class C fly ash, or by using Class C fly ash with other supplementary cementitious materials (SCMs) and lithium based admixtures (Shehata and Thomas 2000). Sulfate resistance has been attained with ternary blends of Class C fly ash and silica fume (Shashiprakash and Thomas 2001). The alternative performance requirements can make it feasible to use locally available Class C fly ash sources that results in cost-effective concrete mixtures, and supports sustainability initiatives.

Eliminating restrictive limits on the LOI and fineness of fly ash will permit the use of fly ash sources available in some markets that might otherwise be restricted. These restrictions do not ensure concrete performance.

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Specification in Practice

What, why & how?



SIP 5 – Restrictions on Aggregate Grading

by the NRMCA Research Engineering and Standards Committee

WHAT is the typical specification requirement?

The typical alternative clauses controlling the grading of aggregates in specifications are:

The grading of the combined aggregate shall conform to the percent retained on individual sieves between 8 and 18% (or 6 and 22%), with the exception of the smaller and higher sieves.

The Coarseness Factor and the Workability Factor determined from the combined aggregate grading shall be within the [required] Zone on the Aggregate Constructability Chart.

The combined aggregate grading when plotted on a 0.45 power chart of the sieve size shall not deviate from a line drawn from the origin to the largest aggregate size within a tolerance of 2%.

These types of requirements are typically included in specifications for some conventional and industrial floor slabs, specifications of some state highway agencies for road pavements, and a specification for airport pavements (FAA 2014). In some cases, these are stated as general requirements for all concrete on a project. An NRMCA review of more than 100 project specifications found that about 25% of reviewed project specifications included requirements for combined aggregate grading.

Do industry standards have these requirements?

ACI 318-14 and ACI 301-10 require aggregate used in concrete to conform to ASTM C33/C33M. There are no requirements on the grading of the combined aggregate.

ASTM C33/C33M establishes grading bands for coarse aggregate based on size number and for fine aggregate.

ACI 302.1R-04 has suggested requirements on combined aggregate grading when proportioning concrete mixtures for floors. This is a non-mandatory guide and is not a specification.

WHAT is the basis for this specification requirement?

The coarseness factor chart was developed by Shilstone (1990). Coarseness factor (x-axis) is the percent of the combined aggregate retained on the No. 8 (2.36 mm) sieve that is also retained on the 3/8 in. (9.5 mm) sieve. Workability factor (y-axis) is the percent of the combined aggregate that passes the No. 8 (2.36 mm) sieve. In the 0.45 power chart, the y-axis represents the percent of the combined aggregate passing each sieve and the x-axis represents the sieve opening in

micrometers raised to the 0.45 power.

ACI 302.1R-04 states that compliance with the combined aggregate grading specifications will increase aggregate packing, reduce the water demand, and lower the cement paste volume required to coat the aggregate. Some state highway agencies, such as Iowa and Minnesota, invoke aggregate grading requirements with the intent of reducing cement content, shrinkage, and cracking.

Research at NRMCA (Obla et al. 2007a, b; Obla and Kim 2008) found that combined aggregate gradings meeting the 8-18 and the coarseness factor chart requirements did not result in reduced aggregate void content and did not improve concrete performance through lower water demand, shrinkage, or higher strength. Based on experimental studies on Florida aggregates, McCall et al. (2005) concluded that concrete with combined aggregate grading meeting the 8-18 requirements did not yield lower water demand, drying shrinkage, or cracking. A study conducted for the Mississippi highway department (Varner 2010) concluded that optimized combined aggregate grading did not lead to concrete with lower shrinkage, chloride ion penetrability, or higher strength. Recently, Cook et al. (2013) and Varner (2012) have shown that the typical 8-18 and coarseness factor chart requirements did not lead to improved concrete performance, but did recommend modified limits on the individual percent retained for combined aggregate. Varner (2012) suggests that contractors be allowed to submit shrinkage data in lieu of combined aggregate grading requirements. The void content of combined aggregate determined in accordance with ASTM C29/C29M has been suggested as a tool for concrete mixture proportioning (ACI 211.6T-14; Yurdakul 2013; Obla 2012).

How can these requirements be restrictive?

- While conformance can be verified in a submittal, aggregate grading requirements cannot be verified and enforced during concrete production for a project. Grading of aggregate changes with transport and intra-plant handling;
- Factors other than aggregate grading impact workability and shrinkage. The intended performance may not be achieved and instills a false sense of security;
- Most concrete producers use two or three aggre-

gates to produce concrete and their ability meet the grading requirements may be constrained by the additional bin storage needed; and

- The grading of available aggregates in some markets makes it difficult to achieve the requirements without importing aggregates from distant sources.

WHAT is the alternative to this specification requirement?

- Use a performance-based option to determine the shrinkage potential of the concrete mixture: length change of concrete, determined by ASTM C157/C157M, with 7 days of moist curing followed by 21 days of drying shall not exceed 0.05%;
- Avoid specifying w/cm less than 0.40 for floor and pavement applications, because autogenous/chemical shrinkage, which can be a significant component of total shrinkage that occurs in the first 24 hours, will not be measured by ASTM C157/C157M;
- Specify demonstration of workability and handling characteristics of concrete through either past field history or through a trial slab as suggested in ACI 301-10; and
- Request aggregate grading and void content of the combined aggregate in the submittal.

Other fresh and hardened concrete properties can be ensured by specifying the applicable performance

WHAT is the benefit of this alternative requirement?

The performance-based alternative to determine the shrinkage potential of the mixture provides more assurance of reduced drying shrinkage than specifying aggregate grading. The concrete producer can use aggregate grading and other methods, such as the use of shrinkage reducing admixtures, to proportion concrete mixtures and achieve the specified shrinkage requirement.

Similarly, the finishability is ensured by a trial slab placement rather than specifying aggregate grading.

It is recognized that wide variations in the combined aggregate grading can affect concrete workability and hardened concrete properties. It is the responsibility of the concrete producer to monitor and control the grading of aggregates within reasonable target limits as part of their quality management system (Obla 2014).

The alternative permits the concrete producer to use locally available aggregates and avoid excessive investment in increasing storage capacity and bins for additional aggregates. This helps optimize costs and supports sustainability.

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