



Polymer membranes used in slab-on-ground construction are tough enough to resist puncture by embedded hardware and finishing equipment (photo courtesy of Stego Industries, LLC)

Vapor Barriers Used with Capillary Breaks Reduce the Severity of Sulfate Exposure of Concrete

Industry practice and test data provide supporting evidence

by James Klinger, Colin L. Lobo, and Bruce A. Suprenant

A recent Concrete Q&A published in ACI's *Concrete International* dealt with the question "What can be done to protect slabs-on-ground that will be subject to various exposure conditions as defined in ACI 318?"¹ The answer included the recommendation that "...an effective vapor retarder should be used for slabs-on-ground placed in contact with water or exposed to sulfates (Exposure Class W or S per ACI 318, respectively)." This implies that vapor retarders protect concrete slabs-on-ground from sulfates, thus allowing the licensed design professional to consider the concrete not subject to more severe exposure. However, the answer provided no further information. In this article, we support the answer with a summary of industry practice and test data.

ACI 318-19 Exposure Categories, Classes, and Requirements

While ACI 318 (the Code) does not apply to the design and construction of slabs-on-ground that do not transmit vertical loads or lateral forces from other portions of the structure to the soil, designers often defer to the Code to specify requirements for all concrete mixtures on a project. Concrete durability requirements are defined in Section 19.3 of ACI 318-19,² with the requirement that: "The licensed design professional shall assign exposure classes in accordance with the severity of the anticipated exposure of members for each category in Table 19.3.1.1." Concrete in contact with soil or water containing deleterious amounts of water-soluble sulfate ions is deemed to be in Exposure Category S. Based on the amounts of sulfate in the soil or water, four sulfate exposure

classes are defined in Table 19.3.1.1. The Exposure Category S classes are provided in Table 1 herein.

Based on the exposure classes assigned by the licensed design professional, concrete mixture requirements are set forth in Table 19.3.2.1 in the Code. Exposure Category S requirements are provided in Table 2. The requirements include:

- Maximum water-cementitious materials ratio (w/cm);
- Minimum concrete compressive strength f'_c , psi;
- Types of cementitious materials that provide sulfate resistance; and
- Restriction on the use of calcium chloride as an admixture.

The Code permits alternative combinations of cementitious materials when tested for sulfate resistance in accordance with ASTM C1012/C1012M, "Standard Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution," and meeting the expansion limits provided in Table 26.4.2.2(c) (Table 3 herein). Note that the two expansion limits are 0.05 and 0.10% and the test duration can take up to 12 or 18 months for more severe exposure conditions. This test evaluates the sulfate resistance of the cementitious system but not the effect of the w/cm of concrete.

It is generally presumed that the durability requirements in the Code apply if concrete is in contact with the conditions that impact its durability—contact with water, chlorides, sulfates, and cycles of freezing and thawing. While one might surmise that these requirements will not apply to concrete that is adequately isolated from exposure, the Code does not specifically address isolation methods or evaluation of such systems. However, some concrete industry documents do recommend the use of isolation systems.

Industry Standards and Reports

The 2008 edition of PTI DC10.5, “Standard Requirements for Design and Analysis of Shallow Post-Tensioned Concrete Foundations on Expansive and Stable Soils,”³ provided requirements in Section 6.2 for concrete in direct contact with soil containing water-soluble sulfates or chlorides. However, the Commentary stated:

“**R6.2**—When a moisture control barrier such as a polyethylene vapor retarder is placed between the concrete and the soil, the concrete is not considered to be in direct contact with soil within the context of Section 6.2.”

The Commentary to the 2019 edition⁴ of the document has slightly different language, clarifying that the vapor barrier must encapsulate the full interface between the concrete and the soil:

“**C10.4.2**—When a moisture control barrier such as a polyethylene vapor retarder is placed between the concrete (including the sides and bottom of the ribs) and the soil, the concrete is not considered to be in direct contact with soil within the context of Section 10.4.”

This is the only industry reference we have found that

explicitly advocates using a vapor retarder to impact the class selection within ACI 318 Exposure Category S.

ACI 201.2R-16, Section 8.5,⁵ recommends, in case of the risk of physical salt attack, separating concrete from contact using a capillary break or protective coating. The capillary break prevents water-soluble sulfate ions from being in contact with the concrete and the vapor retarder minimizes moisture vapor transmission. Data and information with respect to using a capillary break and a vapor retarder to improve durability of concrete exposed to sulfate environments is provided.

ACI 515.2R-13⁶ provides recommendations for protective systems. Although resin sheets are not referred to in the guide for selecting protective treatments, the document notes in Section 4.18 that resin sheets may be used wherever comparable resin coatings are recommended. The guide also notes that sheet types include acrylic, polyethylene, and polypropylene. These materials are widely recognized as being resistant to sulfates (see, for example, www.tdiinternational.com/technical-source-product-info/chemical-compatibility-charts/acrylic, www.hmcpolymers.com/uploads/files/resources/hmc-pp-chemical-resistance.PDF, and

Table 1:

Exposure classes for Exposure Category S per ACI 318-19, Table 19.3.1.1

Sulfate (S)	Class	Water-soluble sulfate (SO ₄ ²⁻) in soil, percent by mass (per ASTM C1580)	Dissolved sulfate (SO ₄ ²⁻) in water, ppm (per ASTM D516 [†] or D4130 [‡])
	S0	SO ₄ ²⁻ < 0.10	SO ₄ ²⁻ < 150
S1	0.10 ≤ SO ₄ ²⁻ < 0.20	150 ≤ SO ₄ ²⁻ < 1500 or seawater	
S2	0.20 ≤ SO ₄ ²⁻ ≤ 2.00	1500 ≤ SO ₄ ²⁻ ≤ 10,000	
S3	SO ₄ ²⁻ > 2.00	SO ₄ ²⁻ > 10,000	

*ASTM C1580, “Standard Test Method for Water-Soluble Sulfate in Soil.”

†ASTM D516, “Standard Test Method for Sulfate Ion in Water.”

‡ASTM D4130, “Standard Test Method for Sulfate Ion in Brackish Water, Seawater, and Brines.”

Table 2:

Requirements for concrete by exposure class per ACI 318-19, Table 19.3.2.1

Class	Max w/cm	Min f' _c , psi	Cementitious materials			Calcium chloride admixture
			ASTM C150/C150M [*]	ASTM C595/C595M [†]	ASTM C1157/C1157M [‡]	
S0	N/A	2500	No type restriction	No type restriction	No type restriction	No restriction
S1	0.50	4000	II	Types with (MS) designation	MS	No restriction
S2	0.45	4500	V	Types with (HS) designation	HS	Not permitted
S3	Option 1	4500	V plus pozzolan or slag cement	Types with (HS) designation plus pozzolan or slag cement	HS plus pozzolan or slag cement	Not permitted
	Option 2	5000	V	Types with (HS) designation	HS	Not permitted

*ASTM C150/C150M, “Standard Specification for Portland Cement.”

†ASTM C595/C595M, “Standard Specification for Blended Hydraulic Cements.”

‡ASTM C1157/C1157M, “Standard Performance Specification for Hydraulic Cement.”

www.braskem.com.br/Portal/Principal/Arquivos/html/boletm_tecnico/PP%20Chemical%20Resistance.pdf and at least polyethylene is commonly used in vapor retarder sheets for building construction.

Tests of Isolation Systems

There have been several evaluations of systems for isolating concrete from sulfates, chlorides, or other aggressive chemicals; for example:

- Redner et al.^{7,8} evaluated the performance of more than 20 different coating systems in a 10% solution of sulfuric acid;
- Vipulanandan and Liu⁹ evaluated the performance of a glass-fiber-reinforced epoxy coating in a 3% solution of sulfuric acid;
- Aguiar et al.¹⁰ evaluated the protection provided by water-based acrylic coatings in a sulfate environment;
- Suleiman et al.¹¹ evaluated the effectiveness of surface treatments in protecting concrete from physical sulfate attack;
- Pan et al.¹² summarized the effectiveness of surface treatments against chemical sulfate attack; and
- Sakr and Bassuoni¹³ evaluated the effectiveness of three surface coatings in protecting concrete from physical sulfate attack.

These studies generally indicate that isolating concrete from sulfate exposure minimizes the risk of chemical and physical sulfate attack.

We know of two additional studies, one conducted for a concrete contractor and one for a manufacturer of vapor retarders, in which sheet materials were evaluated for protection of concrete against sulfate attack. The first one was conducted using a modified ASTM C1012/C1012M test and the second in accordance with ASTM F739, “Standard Test Method for Permeation of Liquids and Gases Through Protective Clothing Materials Under Conditions of Continuous Contact.” In addition, the second study included

Table 3:
Requirements for establishing suitability of combinations of cementitious materials exposed to water-soluble sulfate per ACI 318-19, Table 26.4.2.2(c)

Class		Maximum length change for tests in accordance with ASTM C1012/C1012M, %		
		At 6 months	At 12 months	At 18 months
S1		0.10	No requirement	No requirement
S2		0.05	0.10*	No requirement
S3	Option 1	No requirement	No requirement	0.10
	Option 2	0.05	0.10	No requirement

*The 12-month expansion limit applies only if the measured expansion exceeds the 6-month maximum expansion limit.

testing of the effect of a sulfate solution on the properties of a vapor retarder/barrier material. These evaluations were for project-specific needs and not published. They are described in this article.

Contractor-sponsored study

In 2002, Baker Concrete Construction, Inc., was engaged to place a 1 million ft² industrial slab-on-ground. Based on the soil sulfate content stated in the project’s geotechnical report, the project specification called for a concrete mixture with a maximum *w/cm* of 0.45 and Type V cement plus a pozzolan. Type V cement was not locally available, and a mixture with a *w/cm* below 0.47 is generally considered to be too harsh to consistently produce a high-quality, hard-troweled finish. The contractor engaged CTLGroup, Skokie, IL, USA, to perform tests to determine whether a vapor barrier placed on a capillary break would provide adequate protection of the concrete slab so that a concrete mixture applicable to the construction needs could be used.

Four tests were carried out to evaluate the performance of mortar bars exposed to a 5% concentrated sodium sulfate (Na₂SO₄) solution. Based on previous experience, CTLGroup produced mortar specimens using a cement that was known to fail the length change criterion in ASTM C1012/C1012M. Mortar bars that did not expand would indicate that a vapor retarder/barrier provided effective protection from sulfate attack.

The four test exposures were:

- Continuous immersion in a 5% Na₂SO₄ solution in accordance with ASTM C1012/C1012M (Exposure 1)—this is considerably more concentrated than that measured in the soil;
- Storage of mortar bars on a 12 in. granular base that was compacted on a coarse crushed rock layer inundated with the Na₂SO₄ test solution contained within a polymer storage container; and
 - The container was left uncovered during the test (Exposure 2);
 - The container was covered with a polymer lid during the test (Exposure 3); or
 - A 10 mil (0.25 mm) vapor retarder was placed beneath the mortar bar specimens and the container was left uncovered during the test (Exposure 4).

The polymer container for Exposure 1 was 7 x 11 in. in cross section and 4 in. deep. The containers for the other three exposure conditions were 16 x 20 in. in cross section and 15 in. deep. For Exposures 1 and 3, the covers on the containers were sealed to prevent evaporation and to maintain a high relative humidity (RH).

For Exposures 2, 3, and 4, the 4 in. deep granular base comprised 52 lb of crushed dolomite rock (Fig. 1(a)). After the base layer was rodded and tamped, 16 lb of Na₂SO₄ solution was added to bring the solution to a 1/2 in. head above the compacted crushed stone (Fig. 1(b)). This was followed by the addition of 65 lb of a blended mixture of dolomite and siliceous sand that was compacted by rodding, resulting in an



Fig. 1: Preparation of the base layer in a 16 x 29 x 15 in. test container: (a) compacting the 4 in. base layer; and (b) adding 16 lb of an Na_2SO_4 solution to the base layer

8 in. layer of “soil” above the 4 in. granular base. Shortly after placement of the soil layer, a thin film of the Na_2SO_4 solution appeared at the top.

Twenty companion mortar bars were made for this program, with five specimens randomly selected and placed in each test exposure container (Fig. 2). As required in ASTM C1012/C1012M, 2 in. mortar cubes were tested for compressive strength to establish when the mortar bars would be exposed to sulfate solution in accordance with ASTM C1012/C1012M.

Length and weight change measurements were determined up to an age of 15 weeks (105 days). RH measurements were made three times during the test period. These readings were taken electronically, immediately after containers were opened to take a measurement. At the conclusion of the test period of 105 days, the RHs measured for Exposures 1, 2, 3, and 4 were 99%, 53%, 92%, and 47%, respectively.

The length change results are illustrated in Fig. 3.

For the ASTM C1012/C1012M evaluation (Exposure 1), the mortar bar specimens failed the ACI 318 expansion criteria for sulfate resistance. The use of this cement in concrete is not suitable for Exposure Category S. The average expansion of these mortar bars exceeded the 0.05% criteria at about 2 months. Expansion exceeded 0.10% in about 3 months, and it was about 0.30% at the conclusion of testing at 105 days of exposure.

The negative length change of specimens placed directly on the sulfate-contaminated soil layer and in an open container (Exposure 2) is consistent with drying shrinkage. Samples in Exposure 3, where the container was closed and sealed with a lid, exhibited negligible expansion. The length changes for Exposures 2 and 3 are consistent with the measured RH in each (53% and 92%, respectively).

The specimens placed on the vapor retarder, separated from the sulfate soil layer, exhibited the largest negative length change (drying shrinkage), illustrating that the vapor retarder

provided protection from sulfate attack. This supports the premise that the use of a vapor retarder/barrier with a capillary break protects concrete from the potential of damage from sulfate attack.

Supplier-sponsored study

In 2010, Stego Industries, LLC, contracted with a lab to conduct sulfate permeation and exposure tests on a sample of Stego® Wrap Vapor Barrier (15 mil [0.38 mm]). The sulfate permeation test quantifies sulfate penetration, and the sulfate exposure test evaluates the effect of sulfate exposure on the vapor barrier properties.

Sulfate permeation: Permeability of sulfate ions through a vapor barrier sample was tested in accordance with ASTM F739, modified for discrete sampling time points over a 5-week period. In this test, the vapor retarder served as a barrier between two chambers, with one filled with a 10,000 ppm solution of SO_4^{2-} and the other filled with distilled water (Fig. 4). In this modified version of the test, the concentration of the SO_4^{2-} in the distilled water chamber was measured after 1, 3, 7, 14, 28, and 35 days of exposure.

For each of the seven measurements, sulfate permeation was not detectable (the limit of detection was 0.5 ppm).

Sulfate exposure: To simulate severe exposure, samples of 15 mil vapor barrier material were soaked in a 10,000 ppm solution of SO_4^{2-} for 28 days at ambient temperature and with constant liquid stirring as described in ASTM D5322, “Standard Practice for Laboratory Immersion Procedures for Evaluating the Chemical Resistance of Geosynthetics to Liquids.” In addition, control samples were soaked in distilled water under the same test conditions. Test coupons were evaluated for mass and volume for each exposure. Mass was measured with an analytical balance. Density was determined by the displacement method, as described in ASTM D792, “Standard Test Methods for Density and Specific Gravity (Relative Density) of Plastics by



Fig. 2: Specimens and containers for sulfate exposure tests: (a) Exposure 1, per ASTM C1012/C1012M; (b) Exposure 2, with specimens bearing directly on an 8 in. thick soil layer containing an Na_2SO_4 solution and with container left open during the test; (c) Exposure 3, with specimens bearing directly on an 8 in. thick soil layer containing an Na_2SO_4 solution and with container sealed during the test; and (d) Exposure 4, with specimens placed on a 10 mil vapor barrier/retarder over an 8 in. thick soil layer containing an Na_2SO_4 solution and with the container left open during the test

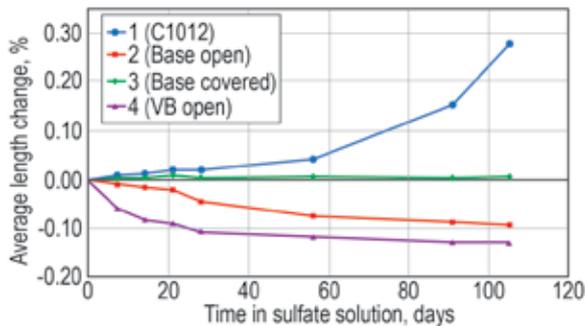


Fig. 3: Length change of mortar bars subjected to various sulfate exposures

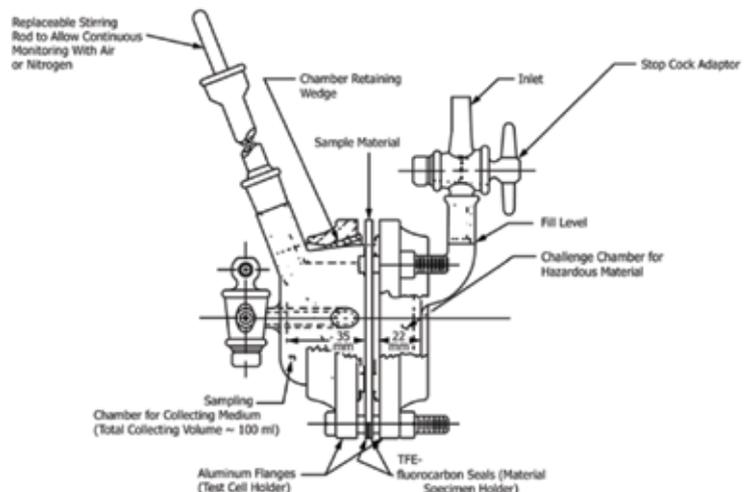


Fig. 4: Test apparatus used for evaluation of a vapor barrier as protection against a sulfate solution

Displacement.” Volume was calculated based on dry mass and density. Percent change in mass and volume were calculated from these data.

Specimens cut from a larger vapor barrier sample that had been immersed in the severe sulfate solution were evaluated for tensile properties per ASTM D882, “Standard Test Method for Tensile Properties of Thin Plastic Sheeting.” The results were compared to a set of control specimens immersed in distilled water for 28 days. The yield strength, ultimate strength, and elongation were reported for each principal direction (lengthwise and crosswise). Two specimens exposed to the sulfate solution were further tested for water vapor permeance per ASTM F1249, “Standard Test Method for Water Vapor Transmission Rate Through Plastic Film and Sheeting Using a Modulated Infrared Sensor.”

The five test coupons exposed to the sulfate solution exhibited slight changes in mass and volume during exposure. The average mass change was -0.03% , and the average volume change was -0.73% . The average mass change for the five test coupons exposed to the distilled water solution was $+0.06\%$, and the average volume change was -0.02% . The average ultimate tensile strengths of the five specimens exposed to the sulfate solution were 74.2 lbf/in. lengthwise and 69.2 lbf/in. crosswise. The average ultimate tensile strengths of the five specimens exposed to distilled water were 73.6 lbf/in. lengthwise and 70.9 lbf/in. crosswise. For comparison, the minimum tensile strength for a Class A vapor barrier material in accordance with ASTM E1745, “Standard Specification for Plastic Water Vapor Retarders Used in Contact with Soil or Granular Fill under Concrete Slabs,” is 45 lbf/in.

The average elongations of the five samples exposed to the sulfate solution were 1731% lengthwise and 1678% crosswise. The average elongations of the five samples exposed to distilled water were 1759% lengthwise and 1693% crosswise. The two samples exposed to the sulfate solution and further tested for water vapor permeance exhibited an average permeance of 0.008 perms.

The tests showed no significant changes in mass and volume of the vapor barrier samples exposed to either the sulfate solution or distilled water. The difference in results for samples in the two exposure conditions was not statistically significant, based on a t-test at a 95% confidence level.

The differences in the ultimate tensile strength and elongation of specimens immersed in the sulfate solution and distilled water were also not statistically significant based on a statistical t-test at a 95% confidence level. Based on the similarity of water vapor permeance test results for vapor retarder material in different exposures, the material is not affected by exposure to significantly high concentrations of sulfate solution. The vapor barrier material properties were not affected after being soaked in a severe sulfate solution for 28 days, supporting the use of a vapor retarder/barrier to provide protection to concrete from the potential for sulfate attack from subgrades with high sulfate contents.

Is It a Vapor Retarder or a Vapor Barrier?

In this article, we have used the terms “vapor retarder,” “vapor barrier,” and “vapor retarder/barrier.” It is unclear how the vapor sheet was classified in the tests conducted for Baker Concrete, but in the tests conducted for Stego Industries, a vapor barrier was used. The 2021 International Building Code (IBC)¹⁴ separates vapor retarder materials into three classes: I, II, and III:

- Class I with a perm rating of 0.1 or less;
- Class II with a perm rating greater than 0.1 but less than 1.0; and
- Class III with a perm rating greater than 1.0 but less than 10.0.

For a vapor retarder/barrier to meet ASTM E1745, a perm rating of 0.1 or less is required. ACI 302.1R-15,¹⁵ Section 5.2.3.1, states that “the industry has not established a permeance level that serves as the dividing point between materials classed as vapor barriers or vapor retarders. It is most likely that when a dividing point between barrier and retarder is established it will be at 0.01 perms or less.” Stego Industries recognizes vapor barriers as having a perm rating of 0.01 or less. Consequently, we recommend the use of a vapor barrier with a perm rating of 0.01 as protection for concrete against sulfate exposure.

Edges, Joints, Penetrations, and Punctures

It is recognized that during construction, installation of vapor retarders can result in isolation that can be compromised due to tears, edges, and overlaps. ASTM E1643, “Standard Practice for Selection, Design, Installation, and Inspection of Water Vapor Retarders Used in Contact with Earth or Granular Fill Under Concrete Slabs,” covers procedures for selecting, designing, installing, and inspecting flexible, prefabricated membranes in contact with earth or granular fill used as a vapor retarder/barrier under concrete slabs. This standard is typically referenced in construction specifications for slab-on-ground construction. Further, a granular capillary break, which is generally required in project specifications, will prevent sulfate ions from being in contact with the vapor retarder/barrier. Thus, moisture vapor transmission should be the only concern at the lap joints because dissolved sulfates are not transmitted through water vapor.

Other Benefits

ACI 302.1R-15 and ACI 360R-10¹⁶ recommend a vapor retarder/barrier below concrete slabs that are to receive moisture-sensitive floor coverings. Even if moisture-sensitive floor coverings are not used, a below-slab vapor retarder/barrier can be used to minimize sweating slab syndrome.^{17,18} Vapor retarders provide other potential benefits, including reduction of unwanted moisture ingress that can lead to mold growth in susceptible building materials, reduction of moisture contributing to interior RH levels (and associated latent loads), reduction of alkali-silica reactivity potential by

reducing slab RH, and reduction in slab curling.^{19,20}

It can sometimes be difficult to provide a consistent hard-trowel finish on concrete with a w/cm of 0.40 and 0.45 that would be specified with Exposure Classes S2 and S3 based on soil sulfate concentration, as these mixtures may require the use of high quantities of admixtures that result in sticky mixtures or high cementitious materials contents that could reduce bleeding. ACI 302.1R recommends a w/cm in the range of 0.47 to 0.55 for concrete floors to receive a hard-troweled finish. The use of a vapor retarder/barrier to isolate the slab from the soil for sulfate resistance would allow the w/cm to be that recommended by ACI 302.1R.

Although this article does not explicitly address the use of vapor retarders/barriers for limiting exposure to soil containing chlorides, or to protect concrete in contact with water, these can be considered as other potential benefits associated with the use of a vapor retarder/barrier.

One Answer to Sulfate Exposure for Slabs-on-Ground

The ACI 318 Building Code requires the licensed design professional to assign exposure categories and the appropriate class for each category, and ACI 301-20²¹ requires the

designer to designate the exposure classes or specify requirements for concrete mixtures for portions of the structure requiring concrete resistant to sulfate attack in project specifications. We believe that information provided in this article can assist design professionals in addressing requirements of ACI 318 and ACI 301 with respect to sulfate resistance of concrete for slabs-on-ground.

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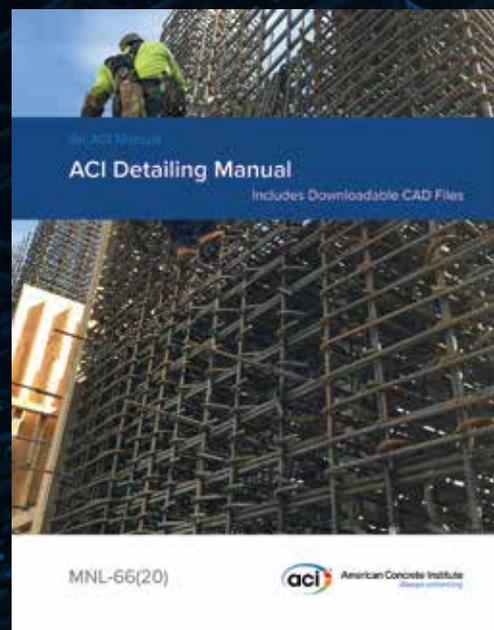
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Note: Additional information on the ASTM standards discussed in this article can be found at www.astm.org.

Selected for reader interest by the editors.



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