CODE REQUIREMENTS FOR SULFATE DURABILITY IN RESIDENTIAL CONCRETE

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ABSTRACT

The paper describes the current code requirements for sulfate durability in residential concrete construction. The paper highlights the development of clarifications regarding sulfate durability requirements in ACI 318-08 and other relevant codes. The myths, facts and legal issues in sulfate lawsuits are discussed and the intent of the current ACI and PTI requirements on sulfate durability are clearly described.

KEYWORDS

slab-on-ground; deterioration; sulfate; concrete; cracking

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INTRODUCTION

Significant code changes have been developed recently which apply to the design of residential slabs and foundations for sulfate durability. These changes affect both post-tensioned and non-prestressed residential buildings. They appear in the *International Building Code* (IBC)[1], starting with the 2006 edition, and *Building Code Requirements for Structural Concrete*, published by the American Concrete Institute (ACI 318), starting with the 2008 edition (which is scheduled for publication in January of 2008)[2]. The changes were made to clarify code sulfate durability requirements, to make the codes consistent with long-standing successful practices, to recognize the differences in durability demands between plain concrete residential foundations and reinforced concrete members in commercial buildings, and to avoid misinterpretation, intentional or unintentional, by users of the codes.

One reason for making these code changes involved the many lawsuits that have been filed in southwestern states in which sulfate durability of concrete in residential buildings was an issue. In these lawsuits building code interpretation was a major consideration. It is important for design professionals and contractors involved in residential construction to be aware of the current code criteria for sulfate durability. This paper discusses the current and pending relevant building code requirements governing sulfate durability for both post-tensioned and non-prestressed residential foundation concrete work, and also presents a brief history of the sulfate litigation.

SULFATE LITIGATION HISTORY

Since the early 1990s many hundreds of lawsuits have been filed in California, Nevada, and Arizona alleging that the concrete foundations supporting thousands of single and multi-family wood-framed residences violated code sulfate durability requirements. Some of the homes involved in these lawsuits had post-tensioned slabs and foundations; others had non-prestressed foundations. The specific criteria alleged to be violated are those found in Table 4.3.1 of the ACI codes from the 1983 edition (ACI 318-83) through the 2005 edition (ACI 318-05), and the Uniform Building

Table 1 - Sulfate Table (Table 4.3.1 from ACI 318-05)

TABLE 4.3.1—REQUIREMENTS FOR CONCRETE EXPOSED TO SULFATE-CONTAINING SOLUTIONS

Sulfate exposure	Water soluble sulfate (SO_4) in soil, percent by weight	Sulfate (SO_4) in water, ppm	Cement type	Maximum water-cementitious material ratio, by weight, normalweight concrete*	Minimum f_c', normalweight and lightweight concrete, psi*
Negligible	$0.00 \le SO_4 < 0.10$	$0 \le SO_4 < 150$	—	—	—
Moderate†	$0.10 \le SO_4 < 0.20$	$150 \le SO_4 < 1500$	II, IP(MS), IS(MS), P(MS), I(PM)(MS), I(SM)(MS)	0.50	4000
Severe	$0.20 \le SO_4 \le 2.00$	$1500 \le SO_4 \le 10{,}000$	V	0.45	4500
Very severe	$SO_4 > 2.00$	$SO_4 > 10{,}000$	V plus pozzolan‡	0.45	4500

* When both Table 4.3.1 and Table 4.2.2 ar e considered, the lowest applicable maximum water-cementitious material ratio and highest applicable minimum f_c' shall be used.

† Seawater.

‡ Pozzolan that has been determined by test or service record to improve sulfate resistance when used in concrete containing Type V cement.

Codes into which those ACI codes were incorporated (UBC-85, 88, 91, 94 and 97). Hereinafter ACI 318-05 Table 4.3.1, and the corresponding tables with various table identification numbers incorporated into the Uniform Building Codes, will collectively be called "the sulfate table." The sulfate table appeared in ACI 318-05 as shown in Table 1.

The wording of the older codes was not clear as to the applicability of the sulfate table to residential concrete work. The codes could be wordsmithed both ways, either that the sulfate table did apply or that it did not apply to residential buildings. Plaintiffs in these lawsuits argued that the sulfate table did apply; defendants argued that it did not apply. The plaintiff argument was simple: the sulfate table is right there in the code. The plaintiffs, in trials and presentations, often displayed large pictures of the sulfate table, which was obviously felt to support their position. The defense acknowledged that the table was in the code, but they argued that it was in a part of the code which applied only to reinforced concrete, one of the two ACI code categories for structural concrete. Residential foundations, the defense argued, were almost always designed under the code category of structural plain concrete, and they cited code wording that suggested that the sulfate table did not apply to structural plain concrete. Billions of dollars changed hands in these lawsuits. Some settlements exceeded the market value of the homes. In one early case the plaintiffs were paid $640,000 per home for homes with a market value of about $400,000. To the best of the author's knowledge, the repairs proposed as necessary by the plaintiff to remedy the alleged sulfate attack have never been executed in any of the roughly 5,000 plaintiff homes involved in these lawsuits. That fact sheds some light on the seriousness of sulfate attack in residential foundation concrete work, and the merits of the claims in the lawsuits.

WHAT HAPPENS IN PRACTICE?

There has been no lack of clarity in the historical practice of residential concrete design and construction; clearly in practice the sulfate table, particularly its requirements for water-to-cementitious materials ratio (w/cm), did not apply. Prior to the filing of the first of these lawsuits, design professionals rarely required full conformance to the sulfate table for residential concrete work, and building officials virtually never enforced the table. This established standard of practice was the reason why the plaintiff attorneys were able to find hundreds of residential projects on which they correctly alleged that the concrete work failed to satisfy the requirements of the sulfate table. At issue in these cases was whether residential concrete work was required to satisfy the sulfate table, either by code or by standard practice.

The sulfate table first appeared in an ACI code in 1983 (it was mentioned in the Commentary to ACI 318-77), and its first appearance in a Uniform Building Code was in 1985. The sulfate table establishes four categories of soil sulfate exposure, negligible, moderate, severe, and very severe, each defined by the percentage of water-soluble sulfates contained by weight in the soil. For the severe and very severe categories, the sulfate table requires the use of a sulfate-resistant cement (Type V or equivalent) and an upper limit on water-to-cementitious materials ratio (w/cm) of 0.45.

For decades prior to the first appearance of the sulfate table in building codes, geotechnical and structural engineers designing residential buildings in areas of high soil sulfates normally specified the use of sulfate-resistant cements, but did not require any limitations on w/cm beyond that inherent in the specified concrete compressive strength f'c. Typical concretes used in residential slab and foundation work were specified to have compressive strength between

2,000 and 3,000 psi, and those strengths were roughly consistent with w/cm ratios between 0.8 and 0.6 respectively.

This established standard of practice for sulfate durability predated the first appearance of the sulfate table in a building code by about 20 years (I first became aware of it in the late 1960s), and, judged by the lack of structural distress related to sulfate deterioration in residential slabs and foundations, the practice was successful and cost-effective for the homeowner. The heart of the many sulfate lawsuits is the allegation that the design and construction of the foundation concrete, in high soil sulfate environments, violates the code because the w/cm ratio is higher than the upper limit of 0.45 specified in the sulfate table. As described below, current codes are changing to unambiguously state, consistent with long-standing successful standard practice, that the w/cm ratio limitations of the sulfate table are in fact not required in residential concrete work.

THE SULFATE LAWSUITS AFFECTED STANDARD ENGINEERING PRACTICES

By the mid 1990's most residential designers and developers had become aware of the wave of sulfate-related lawsuits which had been filed on residential projects. As a result of this knowledge design practices changed. Designers and developers began, for the first time, to require full conformance to the sulfate table on residential projects when soil sulfates were identified, including the reduced w/cm ratios. This change in design practice occurred not because of any performance deficiencies in residential concrete; rather it happened simply to avoid being sued.

Thus the sulfate litigation has resulted in a significant increase in the cost of many new homes in California, Nevada, and Arizona, with no related benefit. While the attorneys and consultants involved in this litigation benefited financially, the plaintiff homeowners, the supposed beneficiaries of these lawsuits, received surprisingly little of the billions of dollars which changed hands. Payments to homeowners, after all other costs and fees were paid, were rarely enough to accomplish the repairs the plaintiff consultants claimed were necessary. The fact that these repairs were never done has left many homeowners with future disclosure problems when they sell their homes.

While plaintiff homeowners generally believed, or were led to believe, that there was no risk or downside involved for them in filing these lawsuits (the plaintiff attorneys generally front all the costs until a settlement or judgment has been realized and funds disbursed), that has been proven untrue. In one recent 2005 case[4], after a long bench trial (no jury), the sulfate allegations were found baseless by a California Superior Court judge who rendered a complete defense verdict, and the owners of the 19 plaintiff homes in the case were ordered to pay over $500,000 in costs incurred by the defendants in proving their case.

It remains to be seen whether the clarification in building code requirements discussed herein will result in a return to long-standing and successful sulfate durability practices, established decades before the first of the sulfate lawsuits, or whether these lawsuits have caused an irreversible increase in the cost of housing.

WHY DIFFERENT DURABILITY REQUIREMENTS FOR RESIDENTIAL CONCRETE?

Foundations for light, one and two-story wood-framed residential buildings have limited life-safety considerations (they cannot collapse and fall to the ground as can elevated concrete members, they are always built in or on the ground), and they support much lighter loads than commercial buildings of reinforced concrete or structural steel. The entire weight of a typical two-story wood-framed California residence could be supported, without failure, on a single 8-in. diameter concrete core removed from its foundation. Because of the light applied loading and the minimum sizes used in residential foundations (often limited by construction equipment), tension, compression, and shear stresses in plain concrete residential foundations are much lower than they are in reinforced concrete members found in larger commercial buildings. Reinforced concrete members are typically designed with a factor of safety (failure (factored) load divided by service (unfactored) load) of roughly 1.4 (based on current ACI code load factors of 1.2 on dead load and 1.6 on live load.) Factors of safety in residential foundation concrete are often in the range of 30, almost always controlled by the bolted connection between the wood superstructure and the concrete rather than the concrete itself. In a typical wood-framed residential building it is the wood that establishes the critical loading on the foundation, not the concrete.

In addition to the lower in-service stresses applied in residential foundations, the structural materials supported by residential foundations (wood, wallboard) inherently have shorter service lives than even the lowest quality concrete used structurally. Thus a hypothetical increase in service life from say, 150 to 200 years in a residential concrete foundation, accomplished by reducing its w/cm from 0.6 to 0.45, results in increased cost but no benefit to the homeowner, when the superstructure materials themselves have a service life of only 75-100 years.

Thus it is fully rational for plain concrete foundations in residential buildings to have different durability criteria than for reinforced concrete members in other types of buildings. Indeed, from a structural engineering analysis of demand versus capacity and the related economics, it is irrational not to have different criteria.

CODE REQUIREMENTS FOR POST-TENSIONED FOUNDATIONS

Starting in IBC 2006[1] sulfate durability requirements for residential post-tensioned foundations have been specified in Section 1805.8.2, which is repeated in its entirety as follows:

> ***1805.8.2 Slab-on-Ground foundations**. Moments, shears and deflections for use in designing slab-on-ground, mat or raft foundations on expansive soils shall be determined in accordance with WRI/CRSI Design of Slab-on-Ground Foundations or PTI Standard Requirements for Analysis of Shallow Concrete Foundations on Expansive Soils[5]. Using the moments, shears and deflections determined above, nonprestressed slabs-on-ground, mat or raft foundations on expansive soils shall be designed in accordance with WRI/CRSI Design of Slab-on-Ground Foundations[7] and post-tensioned slab-on-ground, mat or raft foundations shall be designed in accordance with PTI Standard Requirements for Design of Shallow Post-Tensioned Concrete Foundations on Expansive Soils. It shall be permitted to analyze and design such slabs by other methods that account for soil-structure interaction, the deformed shape of the soil support, the plate or stiffened plate action of the slab as well as both center lift and edge lift conditions. Such alternative methods shall be rational and the basis for all aspects and parameters of the method shall be available for peer review.*

IBC 2006 thus permits, actually for all practical purposes, mandates the design of post-tensioned residential foundations by *Standard Requirements for Design of Shallow Post-Tensioned Concrete Foundations on Expansive Soils*[5] developed and published by the Post-Tensioning Institute, where sulfate durability requirements are found in Section 6.2 (pp. 11-12), repeated in its entirety as follows:

> ***6.2** Foundation concrete in direct contact with native soils containing water-soluble sulfates shall conform to the following:*
>
> ***R6.2** When a polyethylene vapor retarder is placed between the concrete and the native soil, the concrete is not considered to be in direct contact with native soils within the context of Sections 6.2 and 6.3.*
>
> ***6.2.1** For soil sulfate concentrations greater than or equal to 0.1% but less than 0.2% by weight, concrete shall be made with Type II or V cement.*
>
> ***6.2.2** For soil sulfate concentrations equal to or greater than 0.2% by weight, concrete shall be made with Type V cement (or approved equivalent) and shall have a minimum compressive strength of 3,000 psi at 28 days.*
>
> ***6.2.3** Concentrations of water-soluble sulfates shall be determined by California DOT Test 417[8] or other current test method recognized in the governing general building code or commonly used in the geographic area of the project.*

It is seen that IBC 2006 requires, by reference to the PTI Standard[6], the use of a sulfate-resistant cement (Type II or V) for soil sulfate concentrations between 0.1% and 0.2% (corresponding to the "Moderate" exposure category of the sulfate table), with no specific limitation on concrete strength or w/cm (other than the minimum IBC permissible compressive strength of 2,500 psi for structural concrete). For soil sulfate concentrations greater than 0.2% (corresponding to the "Severe" and "Very Severe" categories of the sulfate table) IBC 2006 requires the use of Type V cement (or an approved equivalent, such as Type II with an appropriate flyash) and a minimum concrete compressive strength of 3,000 psi. No specific limitation on w/cm is required. IBC 2006 thus indirectly addresses w/cm by limiting compressive strength, which is much easier to measure and control than is w/cm, particularly in hardened concrete. There is no generally accepted method for determining w/cm in hardened concrete[9]

It is also important to recognize that IBC recommends the use of the California DOT Test 417[8] for determining the concentration of water-soluble soil sulfates. Different tests for determining soil sulfate concentrations can yield different results, depending on the extraction ratio (the weight of water divided by the weight of soil), particularly when the primary soil sulfate compound is gypsum. Thus it is important to use a standardized test for determining soil sulfate concentration.

It should also be noted that ACI 318-08[2] does not govern the design of residential post-tensioned foundations, instead it refers their design to PTI "*Design of Post-Tensioned Slabs-on-Ground*", 3rd Edition, 2004[10], which incorporates the PTI Standard discussed above (see ACI 318-08 Section R1.1.7).

CODE REQUIREMENTS FOR NON-PRESTRESSED FOUNDATIONS

ACI 318-08 in Section 1.1.4 permits the use of the ACI 332 code for residential concrete work:

> ***1.1.4** — For cast-in-place footings, foundation walls, and slabs-on-ground for one- and two-family dwellings and multiple single-family dwellings (townhouses) and their accessory structures, design and construction in accordance with ACI 332-0411 shall be permitted.*

The most current published version of the ACI residential code is ACI 332-04, which in Section 4.2.5 assigns responsibility for sulfate durability, on a performance basis, to the licensed design professional:

> ***4.2.5** Concrete sulfate exposure — Mixture proportions for concrete exposed to sulfate-containing solutions with concentrations greater than 1500 ppm, or exposed to water-soluble sulfate in soil greater than 0.20% by weight, shall be determined based on the requirements provided by a registered design professional.*

__R4.2.5__ For information regarding proportioning of concrete exposed to elevated sulfate levels, refer to ACI 201.2R.

In the next edition of ACI 332, likely to be published in 2008, Committee 332 has developed expanded prescriptive sulfate durability criteria for residential slab and foundation concrete, which appear as follows at the time of this writing:

4.2.5 Concrete sulfate exposure

__4.2.5.1__ Concrete that is in direct contact with native soils containing water-soluble sulfates as determined according to 4.2.5.2 shall conform to the following:

__4.2.5.1.1__ For sulfate concentrations greater than or equal to 0.1% but less than 0.2% by weight concrete shall be made with ASTM C 150[13] Type II cement, or an ASTM C 595[14] or C 1157[15] hydraulic cement meeting Moderate sulfate-resistant hydraulic cement (MS) designation.

__4.2.5.1.2__ For sulfate concentrations equal to or greater than 0.2% by weight, concrete shall be made with ASTM C 150 Type V cement or an ASTM C 595 or C 1157 hydraulic cement meeting High sulfate-resistant hydraulic cement (HS) designation and shall have a minimum compressive strength of 3000 psi at 28 days.

__R4.2.5.1.2__ For information regarding proportioning of concrete exposed to elevated sulfate levels, refer to ACI 201.2R.

__4.2.5.1.3__ Alternate combinations of cements and supplementary cementitious materials shall be permitted with acceptable service record or test results. The materials shall comply with Section 3.1.1 of this code.

__4.2.5.2__ Concentrations of water-soluble soil sulfates shall be determined by a test method or historical data accepted by the local building official.

__R4.2.5.2__ Tests for soil sulfates can yield different results for the same soil sample, depending primarily on the specified test extraction ratio (the weight of water divided by the weight of soil.) This is particularly true where the predominant soil sulfates are in the form of gypsum. Thus it is preferable that the test used has a history of successful use in the geographic area of the project, and be recognized and approved by the local building official. Test methods may include the Bureau of Reclamation Procedure, California DOT Test 417[8], and ASTM C 1580[16].

These pending ACI 332[11] sulfate criteria are virtually identical to those for post-tensioned residential foundations in IBC 2006, as presented and discussed above. The ACI 332 requirements recognize several alternate sulfate-resistant cements, and mention several additional soil sulfate test protocols, but in every other aspect the requirements are the same. It is important to note that current and pending ACI 332 criteria for non-prestressed foundations, like the criteria for post-tensioned foundations in IBC 2006, contain no specific limitation on w/cm for any sulfate exposure.

SUMMARY AND CONCLUSIONS

IBC 2009, with ACI 318-08 incorporated, will contain, for the first time, clear and unambiguous requirements for sulfate durability in both post-tensioned and non-prestressed residential concrete slabs and foundations. These requirements will be consistent with long-standing successful practices in the design of residential foundation concrete. They will include a requirement for sulfate-resistant cements, but they will not require direct limitations on w/cm, which are difficult to control in fresh concrete and impossible to evaluate precisely in hardened concrete. This will clarify and refute the erroneous allegation that the mere reference to a sulfate-resistant cement by a licensed design professional somehow also triggers a requirement for a limitation in w/cm.† In this model code, w/cm ratios will be indirectly controlled, when necessary, by specifying a minimum concrete compressive strength. These new code criteria are consistent with long-standing successful practices for sulfate durability in residential slabs and foundations. They should help in reducing opportunistic lawsuits which have resulted in increased costs to homeowners with no related benefit, and are based simply on a lack of clarity in code wording rather than a real deficiency in performance.

† *This is an extraordinarily creative allegation. If design professionals had considered a limitation on w/cm to be important, along with sulfate-resistant cement, they would have simply said that, rather than writing their specifications in riddles to await future interpretation by self-serving forensic consultants. It would have taken only a few additional words to state a limitation on w/cm, if one was in fact required or desired.*

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