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The use of tension testing to investigate the effect of W/C ratio and cement type on the resistance of concrete to sulfate attack

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Abstract

Concrete specimens were cast and partially immersed in a sulfate solution for varying periods of time up to 1 year. The effects of water/cement ratio (0.45 and 0.65) and cement type (ordinary and sulfate resistant) were investigated. Concrete performance was evaluated based on compressive strength and tensile strength, which was measured with the pressure tension test. Results indicated that water/cement ratio had a greater influence on the resistance of the concretes to sulfate attack than did cement type. The pressure tension test appeared to be more sensitive than the compressive strength test in detecting internal damage, particularly at early ages.

Keywords: Sulfate attack; Tensile strength; Sulfate-resistant cement

1. Introduction

Sulfate attack in concrete footings and foundations can be a major problem in areas where the soil contains large quantities of water soluble sulfates. Groundwater, whether natural or provided artificially by such means as irrigation, tends to dissolve these sulfates and carry them into the concrete. In such situations, the bottom of the footing or foundation often becomes completely saturated with sulfate-laden groundwater while the upper portion is exposed and relatively dry. This moisture gradient creates a transport mechanism for the sulfate-laden water as it is drawn into the concrete, permeates upward through the footing to the drier regions, and then evaporates upon reaching the surface. The result is an acceleration in the sulfate attack mechanism induced by larger amounts of sulfates becoming readily available, an effect that is further amplified in arid regions where the evaporation rate is much higher. This cycle is shown schematically in Fig. 1.

The sulfates dissolved in the water are left behind on or near the surface as the water evaporates. In severe cases of prolonged exposure, this type of chemical assault becomes visually evident as a line or band of sulfate crystals and surface scaling just above the grade line. The scaling in this area is due to the formation of sulfate crystals immediately below the surface of the concrete, which results in the development of tensile stresses that literally force the surface skin of the concrete away from the bulk material. Fig. 2 depicts the upper inside surface of a foundation stem wall that is exhibiting this phenomenon.

Although the appearance of such scaling implies that significant damage is occurring at that location, the internal damage caused by sulfate attack can be much more severe. As the sulfate-laden water permeates upward through the concrete, the sulfates chemically attack the hydrated cement paste, inducing microcracking and eventually resulting in degradation of the concrete's mechanical properties and permeability characteristics.

Traditionally, the quality of damaged concrete has been assessed by carrying out standard compression tests on drilled cores. However, compressive stresses tend to close up cracks; in particular, if cracks are preferentially oriented perpendicular to the direction of loading, compression tests will not be a sensitive indicator of internal damage. In this case, tensile tests should provide a much better indicator of internal damage. This phenomenon is depicted schematically in Fig. 3.

In the past, tensile strength testing of concrete has been largely ignored for two reasons. First, structural concrete design assumes that concrete is used only in compression, with reinforcing steel carrying the applied tensile loads.

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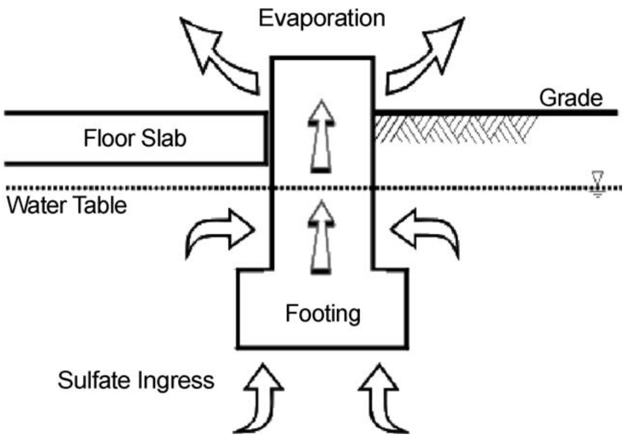

Fig. 1. Sulfate transport mechanism in footings.

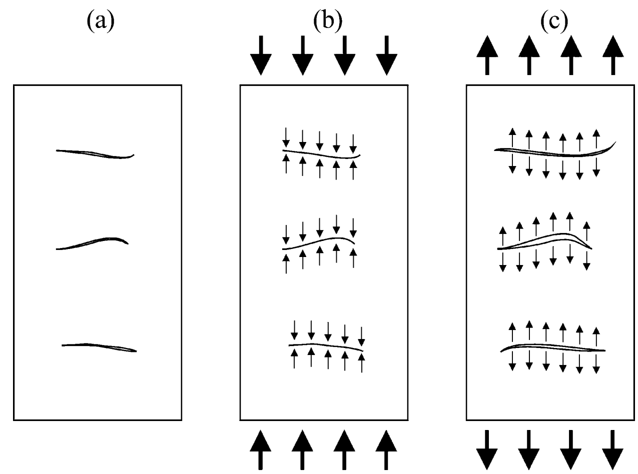

Fig. 3. Cracked concrete under (a) no stress, (b) compressive stress, and (c) tensile stress.

Second, tensile strength of brittle materials is typically very difficult to measure due to stress concentrations developed at the grips, which tend to induce localized failure of the specimen. In reality, the former assertion is valid only on a macromechanical scale. Tensile stresses due to loading are indeed present within the concrete portion of a reinforced concrete member and can also be induced by durability mechanisms involving expansive reactions (i.e., sulfate attack).

Thus, this study utilizes both tension testing and compression testing to examine the effect of sulfate attack on concrete and to better indicate the effect of water/cement ratio and cement type on the concrete's ability to resist such attack.

2. Experimental program

There were two phases to the experimental program. The initial phase was designed to look specifically at the effect of cement type on the sulfate resistance of concrete. The second, more extensive, phase examined the effect of cement type as well, but also investigated the effect of water/cement ratio. The procedure followed in specimen preparation, conditioning, and testing was the same in both phases.

Fig. 2. Sulfate crystal formation and scaling damage on stem wall.

All testing was performed on 100-mm-diameter × 200-mm-long cylinders. Specimens were cast and allowed to remain in the molds for 24 h before demolding. The cylinders were then designated as either control specimens or as exposure specimens. Control specimens were immersed in lime-saturated water, where they remained until removal for testing. Exposure specimens were subjected to a high sulfate environment. They were placed on their ends in plastic containers, into which a 5% sodium sulfate solution was added to a depth of 100 mm. Thus, they were only partially immersed in this sulfate-rich solution, leaving their upper half exposed to laboratory conditions and creating a similar moisture transport mechanism to that described previously for concrete footings in sulfate-laden soils. Additional solution was added to the containers when necessary to maintain the 100-mm depth and account for absorption and evaporation. The exposure specimens were stored in this condition until they were prepared for testing.

Each of the exposure specimens quickly developed a ring of sulfate crystals around its circumference approximately 10–15 mm above the immersion line. This phenomenon was due to the migration and subsequent evaporation of the sulfate solution, which had been drawn up into the cylinders. The sulfate crystals precipitated out as this water evaporated. As time passed, more and more crystals were deposited in this way, with the thickness of the crystal layer increasing. A significant difference in the amount of crystal buildup was noted between the 0.45 W/C ratio mixes and the 0.65 W/C ratio mix, with the latter being much thicker. Fig. 4 shows one set of specimens partially immersed in their exposure bins. The sulfate crystal ring is

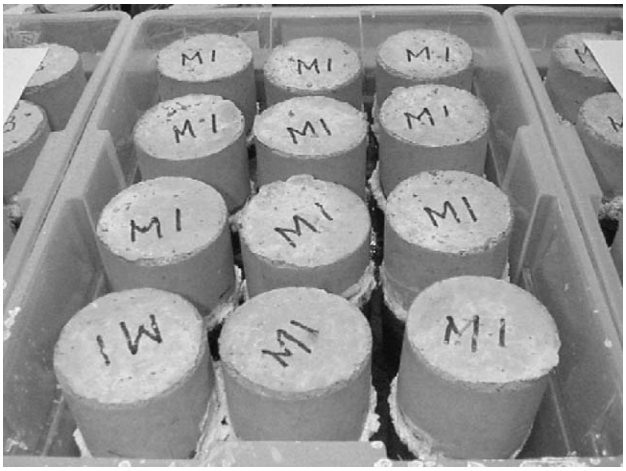

Fig. 4. Laboratory sulfate exposure conditions; specimens are 2 weeks old.

already apparent on these specimens after only 2 weeks of exposure.

At each of the three testing ages (varying from about 50 to 365 days), a set of specimens from each subgroup was tested. For the control specimens, this simply involved removal of the specimens from their curing tank just before testing. The exposure specimens, on the other hand, were removed from their exposure containers 2 days before testing, cleaned of built up sulfate crystals, and fully immersed in lime saturated water. This was done so that all specimens would be tested in the saturated condition.

The pressure tension test is a relatively new test originally developed by the British Research Establishment in the UK [2]. In this test, gas pressure is applied to the curved surface of a cylinder, but not to the ends, which remain open to the atmosphere. This induces tensile stresses parallel to the longitudinal axis of the specimen. Failure eventually occurs on a plane perpendicular to this axis. Further development of this technique and subsequent use for the quantification of damage due to alkali-aggregate reactivity [3–5] and sulfate attack [6] has indicated that the test is indeed more sensitive to internal damage than compressive strength testing. At each testing interval, both the compressive strength and pressure tensile strength were measured for each specimen subgroup. Three specimens were tested in compression while six were made available for the pressure tensile strength test to ensure that a minimum of three specimens could be tested. (Some specimens could not be tested due to irregularities in shape or air pocket location that led to leakage problems with the pressure chamber.)

2.1. Phase 1

In Phase 1, the objective was to examine the effect of cement type on sulfate resistance. Cement types included in this phase were CSA Type 10 ordinary Portland cement and CSA Type 50 sulfate-resistant Portland cement. Four sets of cylinders were cast using the mix proportions shown in Table 1. All mixes were designed in accordance with the absolute volume method described by the Canadian Portland Cement Association [1] using a fine aggregate proportion equal to 40% of total aggregate mass.

Table 1
Concrete mix proportions—Phase A

Component	Proportions (kg/m^3)
	W/C = 0.66
Water	215
Cement	325
Fine aggregate	785
Coarse aggregate	1025

The first two sets were cast using Type 10 cement, with the second set varying from the first in that it contained 5% sodium sulfate (by mass) in the mix water. The third and fourth sets were cast using Type 50 cement. Again, the latter of these two sets (Set 4) contained 5% sodium sulfate in the mix water.

2.2. Phase 2

In Phase 2, the objective was to reexamine the effect of cement type (Type 10 vs. Type 50) and also to investigate the effect of water/cement ratio on sulfate resistance. Three sets of cylinders were cast using the mix proportions shown in Table 2. The first mix was cast with a water/cement ratio of 0.45 and Type 10 cement. The second mix was also cast with a 0.45 water/cement ratio, but in this case, the cement was changed to Type 50. The third and final mix possessed a water/cement ratio of 0.65 and also contained Type 50 cement. All mixes were again designed in accordance with the absolute volume method described by the Canadian Portland Cement Association [1].

It should be noted that none of the mixes in Phase 2 contained sulfates in the mix water. This ingredient was eliminated in order to allow both control and exposure specimens to be taken from the same mix for each of the three mix variations. After demolding, the cylinders from each of the three mixes were divided into two sets for a total of six subgroups. One of these subgroups acted as an in-group control and was cured by immersion in lime-saturated

Table 2
Concrete mix proportions—Phase B

Component	Proportions (kg/m^3)	
	W/C = 0.45	W/C = 0.65
Water	146	211
Cement	325	325
Fine aggregate	815	757
Coarse aggregate	1220	1100

Table 3
Test results—0.65 W/C ratio, Type 10 cement

Approximate age (days)	Control specimens			Exposed to sulfates		
	Strengths (MPa)		Ratio (%)	Strengths (MPa)		Ratio (%)
	CS	PT	PT/CS	CS	PT	PT/CS
50	42.8	3.8	8.9	35.1	3.7	10.5
150	37.8	4.4	11.8	38.5	3.2	8.3
300	42.9	3.9	9.1	42.3	3.5	8.2

Table 5
Test results—0.45 W/C ratio, Type 10 cement

Approximate age (days)	Control specimens			Exposed to sulfates		
	Strengths (MPa)		Ratio (%)	Strengths (MPa)		Ratio (%)
	CS	PT	PT/CS	CS	PT	PT/CS
90	71.8	5.3	7.4	48.0	4.1	8.4
230	72.4	5.9	8.1	61.6	5.0	8.2
365	76.6	8.7	11.4	61.5	5.1	8.3

water while the others were exposed to the 5% sodium sulfate solution described previously.

3. Results

3.1. Phase 1

The test results for each mix in Phase 1 are presented in Tables 3 and 4, with each table containing all of the results for one concrete variation (W/C ratio and cement type). The two test methods are designated as CS for compressive strength and PT for pressure tensile strength. Each value in these tables represents the average result for that particular group of specimens. The ratios of tensile to compressive strength have also been provided. Unfortunately, test data are unavailable for the later ages of the Type 50 cement control mix.

Examining these results, a number of trends become evident. First, there is a significant drop in strength between the Type 10 cement mixes and their Type 50 counterparts. Second, the compressive strength of all mixes, whether exposed to sulfates or not, tended to increase over time while the tensile strength tended to remain fairly constant. The combination of these two trends resulted in a drop in the tensile/compressive strength ratio with prolonged exposure.

3.2. Phase 2

The test results for each mix in Phase 2 are presented in Tables 5–7, with each table containing all of the results for one concrete variation (W/C ratio and cement type).

For the low water/cement ratio mix with ordinary Type 10 cement (Table 5), all of the strength values increased over time. The specimens exposed to sodium sulfate, though still gaining strength, exhibited much lower strength values at all ages. The tensile/compressive strength ratio either increased or stayed constant for the control group and the exposure specimens, respectively.

In the low water/cement ratio mix with a Type 50 cement (Table 6), the overall strengths are again lower than they were for the Type 10 cement. Though the trends are not as consistent as those reported for the previous mix, this concrete also continued to gain small amounts of strength over time, even when subjected to sulfates. The control specimens again exhibited an increasing tensile/compressive strength ratio. However, the exposure specimens exhibited a definite downward trend in tensile strength, with a negative trend indicating that the tensile strength was dropping faster than the compressive strength.

Maintaining the Type 50 cement but increasing the water/cement ratio to 0.65 produced some very definitive trends (Table 7). The overall strength values were much lower than for the 0.45 water/cement ratio mixes, which is not surprising. Now, however, a significant downward trend also appeared in the compressive strength values of the specimens exposed to sulfates, though the tensile strength dropped even faster as evidenced by the decrease in tensile/compressive strength ratio. These specimens lost over 40% of their compressive strength and nearly 60% of their tensile strength.

Moreover, the compressive strength in these specimens actually showed an increase between 90 and 230 days of exposure, while the tensile strength had already begun to drop. This appears to indicate that the pressure tension test was more susceptible to early stages of damage than was compression testing.

It is also interesting to note that the proportions of tensile to compressive strength are very similar between the control specimens of the two low W/C ratio mixes (Tables 5 and 6) but significantly larger in the high W/C mix (Table 7). This seems to indicate that tensile strength is less sensitive to water/cement ratio than is compressive strength.

Table 4
Test results—0.65 W/C ratio, Type 50 cement

Approximate age (days)	Control specimens			Exposed to sulfates		
	Strengths (MPa)		Ratio (%)	Strengths (MPa)		Ratio (%)
	CS	PT	PT/CS	CS	PT	PT/CS
50	29.4	3.0	10.3	21.9	2.4	11.1
150	–	–	–	28.7	2.2	7.8
300	–	–	–	34.6	2.2	6.4

Table 6
Test results—0.45 W/C ratio, Type 50 cement

Approximate specimen age (days)	Control specimens			Exposed to sulfates		
	Strengths (MPa)		Ratio (%)	Strengths (MPa)		Ratio (%)
	CS	PT	PT/CS	CS	PT	PT/CS
90	62.5	5.1	8.2	50.1	3.7	7.3
230	69.8	5.9	8.5	52.5	3.6	6.9
365	71.5	7.3	10.3	60.7	4.0	6.5

Table 7
Test results—0.65 W/C ratio, Type 50 cement

Approximate specimen age (days)	Control specimens			Exposed to sulfates		
	Strengths (MPa)		Ratio (%)	Strengths (MPa)		Ratio (%)
	CS	PT	PT/CS	CS	PT	PT/CS
90	36.1	4.0	11.0	31.5	2.7	8.5
230	39.3	4.4	11.1	31.9	2.0	6.1
365	40.0	4.5	11.3	18.5	1.1	6.0

A number of other observations were made during this study as well. When using the pressure tensile strength test, it was found that the variation in results increased dramatically between undamaged specimens and those exhibiting severe sulfate attack. This variability also tended to increase as the damage grew worse. For the pressure tension test, undamaged control specimens typically exhibited a coefficient of variation in the 5–10% range while sulfate damaged specimens produced values as high as 20% or more.

The location of the failure plane induced by the pressure tension test varied with specimen type, and even more, with exposure condition. For the control specimens from all three mixes (and most of the exposure specimens tested at early ages), the failure locations appeared to occur randomly and seemed to be evenly distributed over the entire cylinder length. As sulfate exposure length increased, however, the exposure specimens developed an extremely consistent trend.

All of the prolonged exposure specimens from both low W/C ratio mixes failed within the damaged region immediately above the immersion line. There was a significant amount of surface scaling evident in this region, resulting in a slightly smaller cross-sectional area, thus contributing to failure in this locale. Cylinders from the high W/C ratio mix, without exception, failed in the bottom half of the specimen, below the immersion line, even though the specimens showed no visible signs of damage in this area. Following prolonged exposure, the concrete became weaker in the high sulfate exposure region below the immersion line than in the zone of surface scaling just above the immersion line.

Combined with the previously mentioned observation that sulfate crystal buildup was less extensive on the low W/C mixes, this observation indicates that internal damage was more significant in the high water/cement ratio mix. It also indicates that the pressure tensile strength test is very sensitive to internal damage such as that present in sulfate attack. This is especially true for localized or directional damage as is the case in this study.

4. Conclusions

When exposed to the damaging influence of expansive mechanisms that tend to induce microcracking, such as sulfate attack, the tensile strength of concrete drops off more quickly than does its compressive strength. This phenomenon is due to the higher sensitivity of tensile strength to cracking, as compared with compressive strength, and means that it is more applicable to the detection and evaluation of such damage. As such, it has the potential to be a useful tool in the identification of damaged concrete at earlier ages.

The use of a lower water/cement ratio appears to be far more effective than the use of a sulfate-resistant cement in offsetting the detrimental effects of sulfate attack on concrete. Not only are the benefits of using a sulfate-resistant cement type less evident than those produced by a lower W/C ratio, there is also a significant drop in strength associated with high W/C ratios.

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