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Effects of Cement Type and Fly Ash on the Sulfate Attack Using ASTM C 1012

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Abstract

The primary factors that affecting concrete sulfate resistance are the chemistry of the Portland cement and the chemistry and replacement level of mineral admixtures.

In order to investigate the effect of those on the sulfate attack the testing program involved the testing of several different mortar mixes using the standardized test, ASTM C1012. Four different cements were evaluated including one Type I cement, two Type I-II cements, and one Type V cement. Mortar mixes were also made with mineral admixtures as each cement was combined with three different types of mineral admixtures. One Class F fly ash and one Class C fly ash was added in various percent volumetric replacement levels. The expansion measurements of mortar bars were taken and compared with expansion criteria recommended from past experience to investigate the effect of each factor.

Keywords : sulfate attack, cement type, fly ash, ASTM C 1012 test method

1. Introduction

As the industry of concrete repair grows it has become critical that engineers emphasize durability and long-term performance in all new construction. Specifications need to be developed to ensure new materials, technologies, and construction practices can be utilized to produce high quality, long-lasting concrete structures. Currently, engineers are limited by the same parameters and guidelines that were developed several years ago. Under today's specifications, if an engineer needed a low permeability concrete to ensure durability in a severe environment, this need would be addressed by keeping the mix design water-to-cementitious material ratio below a specified maximum value.[1)] The specified maximum water-to-cementitious material ratios were derived nearly forty years ago from a correlation that was established between the water-to-cement ratio and permeability. The problem with using this correlation in current specifications is that it does not acknowledge all the factors that affect concrete permeability in today's construction industry.

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2. Factors affecting concrete resistance to sulfate attack

2.1 Chemistry of portland cement

Most research today identifies tricalcium aluminate (C_3A) as the primary measurable component of Portland cement that influences sulfate resistance in concrete.[2)]. The C_3A controls the amount of monosulfoaluminate that is formed in fresh concrete and thus the amount of monosulfoaluminate available to form ettringite in hardened concrete resulting in expansive internal volume changes and the damage that characterize sulfate attack. The need for sulfate resistance in a cement is acknowledged in ASTM C150 via the establishment of maximum C_3A contents for each cement type. The limits address the fact that the C_3A content is the critical property of the cement chemistry that affects sulfate resistance in concrete.

2.2 Mineral admixtures

The obvious benefits of mineral admixtures are the reduction in concrete permeability and the replacement of the

Portland cement. Lowering the permeability slows the penetration of sulfate ions into hardened concrete while replacing the Portland cement reduces the presence of compounds such as C_3A that cause ettringite formation. The mineral admixtures most frequently examined for use in sulfate environments include fly ash, silica fume, and blast furnace slag.

The effect of fly ash, a by-product from the burning of coal, on sulfate attack has been widely researched. The five chemical and mineralogical components of fly ash which affect sulfate resistance are calcium, alumina, iron oxide, silica, and sulfate. The calcium content is the most important of these five components. Low calcium, pozzolanic fly ashes (Class F) are described as pozzolanic because they primarily hydrate by reacting with the calcium hydroxide formed from the Portland cement's calcium silicates. High calcium, pozzolanic and cementitious fly ashes (Class C) are cementitious because they can provide their own source of calcium and thus hydrate independent of the Portland cement. In general, low calcium (F) fly ashes have been shown to improve sulfate resistance while high calcium (C) fly ashes have either shown little improvement or decreased sulfate resistance.

3. Experimental program

3.1 Materials

3.1.1 Portland cement

Four commercially available Portland cements were evaluated in this testing program: one Type I, two Type I-II, and a Type V cement. Chemical analyses for the four cements are provided in Table 1. The most important chemical property reported in Table 1 is the tricalcium aluminate (C_3A) content of the cements. The Type I cement has no ASTM C150 limit for C_3A content and thus the high 12 percent value is acceptable. The Type I-II (A) cement has a C_3A content of 5.1 percent. This value is considerably lower than the maximum limit of 8 percent for Type II cement and is just above the 5 percent limit required for Type V cements. The 7 percent C_3A content of the Type I-II (B) cement is just below the limit of 8 percent for Type II cements. Finally, the Type V cement meets the C_3A content limit of 5 percent for sulfate resistant cement as the cement contains zero C_3A.

3.1.2 Fine aggregate

The fine aggregate used for making the mortars was a graded Ottawa sand meeting the requirements of ASTM C778.[6] The sand has a specific gravity of 2.65 and an absorption capacity of 0.5 percent.

Table 1 Chemical properties of portland cements

Cement type (ASTM C150)	Portland cements			
Composition	I	I-II (A)	I-II (B)	V
Silicon dioxide (SiO_2), %	-	20.4	20.9	21.9
Aluminum oxide (Al_2O_3), %	-	4.4	4.5	3.2
Ferric oxide (Fe_2O_3), %	-	3.9	3.2	5.7
Magnesium oxide (MgO), %	1.3	1.1	1.4	0.8
Sulfur trioxide (SO_3), %	3.5	3.0	3.0	3.1
Equivalent alkalies, %	0.6	-	0.4	0.4
Loss on ignition (LOI), %	1.8	0.8	1.3	0.7
Insoluble residue (IR), %	0.2	0.1	02	-
Dicalcium silicate (C_2S), %	-	11.7	-	21.8
Tricalcium silicate (C_3S), %	-	62.1	61	54.2
Tricalcium aluminate (C_3A), %	12	5.1	7	0.0

Table 2 Chemical and physical properties of mineral admixtures

Mineral admixture	ASTM class F fly ash	ASTM class C fly ash
Silicon dioxide (SiO_2), %	47.8	30.59
Aluminum oxide (Al_2O_3), %	22.6	17.78
Iron oxide (Fe_2O_3), %	5.9	5.85
$SiO_2 + Al_2O_3 + Fe_2O_3$, %	76.3	57.22
Calcium oxide (CaO), %	17.3	27.55
Magnesium oxide (MgO), %	2.3	4.65
Sulfur trioxide (SO_3), %	0.7	2.86
Sulfide sulfur (S), %	-	-
Loss on ignition, %	0.1	0.07
Moisture content, %	0.1	0.12
% Retained on #325 sieve	20.4	12.12
Specific gravity	2.53	2.65

3.1.3 Mineral admixtures

Two types of fly ash were used in mixes for this testing. A low-calcium, Class F fly ash; a high-calcium and Class C fly ash were used. The chemical and physical properties of the mineral admixtures reported by the suppliers are shown in Table 2.

3.2 Mixture proportioning

The mixture proportioning for the mortars was adding one part of cement to 2.75 parts of graded standard sand by weight. For the plain Portland cement mortars, the procedures require a water-to-cement ratio of 0.485 for non air-entrained cements and 0.460 for air-entrained cements. Since all the cements used in this test program are non air-entrained cements, a water-to-cement ratio of 0.485 was used for these mixes. The basic mixture proportions for the plain Portland cement mortars are shown in Table 3.

Table 3 Mix proportions for plain portland cement mortars

Material	Content (kgf/m^3)
Water	265
Portland cement	546
Graded sand	1456

Table 4 Compressive strengths and age of mortars at immersion in sodium sulfate solution

Batch name	Cement type	Fly ash (% Rep.)	At immersion into sulfate	
			Age (days)	Compressive strength (MPa)
PC1	I-II (A)	None	2.1	22.4
1FC-1	I-II (A)	C (25%)	4	21.0
1FC-2	I-II (A)	C (35%)	5.9	20.5
1FA-1	I-II (A)	F (20%)	4.9	22.1
1FA-2	I-II (A)	F (30%)	4.9	20.2
PC2	I-II (B)	None	2.0	24.9
2FC-1	I-II (B)	C (25%)	3.9	20.8
2FC-2	I-II (B)	C (35%)	7.0	23.3
2FA-1	I-II (B)	F (20%)	5.9	21.0
2FA-2	I-II (B)	F (30%)	4.8	20.8
PC5	V	None	3.8	22.0
5FC-1	V	C (25%)	6.1	21.4
5FC-2	V	C (35%)	7.1	20.3
5FA-1	V	F (20%)	7.0	20.3
5FA-2	V	F (30%)	11.9	19.7
P1	I	None	1.9	20.3
1C-1	I	C (25%)	4.8	22.3
1C-2	I	C (35%)	4.7	22.2
1F-1	I	F (20%)	5.2	21.4
1F-2	I	F (30%)	6.9	20.3

* In this column, C stands for ASTM class C fly ash and F stands for ASTM Class F fly ash

When mineral admixtures were used, a specified volumetric percent of the cement was replaced by an equivalent volume of the mineral admixture.[3)] The Class F fly ash was used to replace 20 and 30 percent of the cement, the Class C fly ash was used to replace 25 and 35 percent of the cement. For mortars with these blends of Portland cement with fly ash, the required water-to-cementitious material ratio was designated in two manners. Both requirements aimed at ensuring that the flow and consistency of the mortars with admixtures was similar to the plain Portland cement mortars with which they were being compared. The flow of a mortar is quantitatively determined using a flow table test that produces a flow number.

3.3 Specimens

The specimens required for ASTM C1012[7)] are 2.5cm × 2.5cm ×30cm mortar bars for expansion measurements and 5-cm cubes for compressive strength tests(transfer coefficient: 1.2). Five mortar bars were made along with 15 cubes from each batch.

3.4 Testing procedures

Upon reaching the strength of 19.7MPa, the mortar bar specimens were measured for their initial length. Length measurements were made using a length comparator following the procedures of ASTM C490. A 30-cm reference bar made of a low coefficient of thermal expansion steel alloy was used to zero the gage on the comparator.

Following test requirements, the sodium sulfate solution was prepared at least one day before its use. The solution designated by ASTM C1012 was a 0.352 molar, 5 percent sodium sulfate (Na_2SO_4) solution. Length measurements were taken for each batch at 1, 2, 3, 4, 8, 13, and 15 weeks after the bars were initially placed in the sodium sulfate solution. Long-term measurements were taken after 4 and 6 months of soaking.

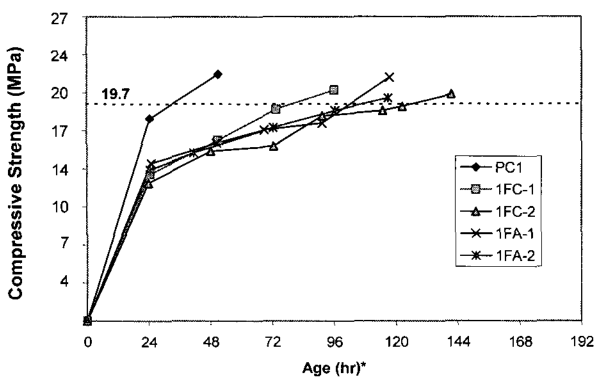
4. Test results

4.1 Compressive strengths results

Figs. 1~ 4 show the compressive strength development of the mortars for the four different cements. Also Table 4 shows the compressive strengths of the mortars at the time of immersion in the sulfate solution and the age of the mortars at immersion. No mortar had reached the 19.7-MPa compressive strength after this initial 24 hours of curing and thus all the batches required additional curing time in the room temperature saturated limewater curing tanks.

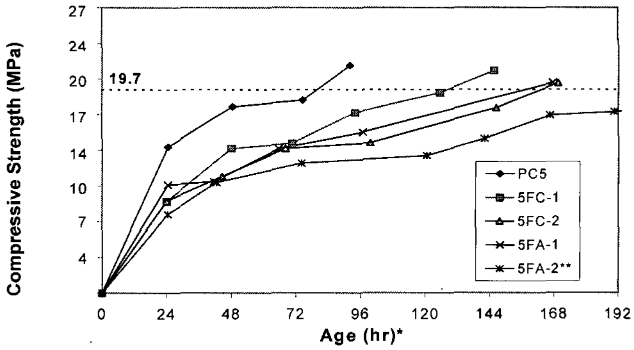
For each cement type, the plain Portland cement mortars reached strengths of 19.7-MPa or higher much quicker than the mortars with fly ash. The plain Type I-II cement mortars gained strength the quickest as each reached strengths above 20.7MPa after approximately one day in the room temperature limewater. The mortar with the Type I-II (A) Portland cement had a strength of 22.4MPa after approximately 48 hours of total curing while the mortar with the Type I-II (B) cement had a strength of 24.9MPa after the same amount of curing.

The Type I cement had comparable early strength gain to the Type I-II cements as it reached a compressive strength of 20.3MPa in less than 48 hours. The Type V cement mortar, PC5, had the slowest strength development as it took nearly 96 total hours of curing before a strength of 22.0 MPa was reached. The mortars with fly ash required much more curing time as no mortar reached a 19.7-MPa com-



* Cured at 35 ± 3°C for first 24 hours and at room temperature for remainder of time

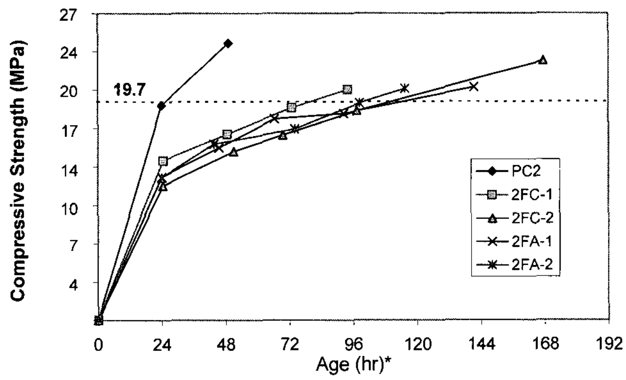
Fig. 1 Compressive strengths of mortars with type I-II (A) cement



* Cured at 35 ± 3°C for first 24 hours and at room temperature for remainder of time

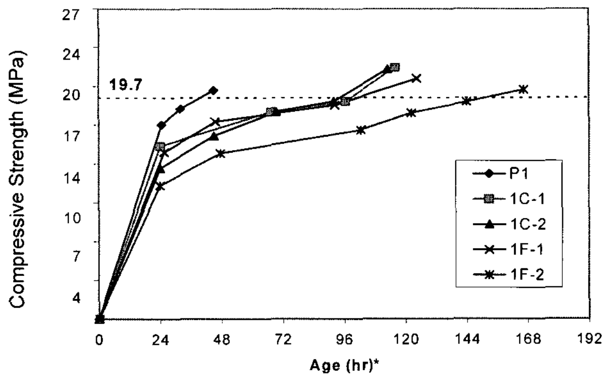
** 5FA-2 reached 19.7MPa after 11.9 days of total curing

Fig. 3 Compressive strengths of mortars with type V cement



* Cured at 35 ± 3°C for first 24 hours and at room temperature for remainder of time

Fig. 2 Compressive strengths of mortars with type I-II (B) cement



* Cured at 95.5 ± 3°F for first 24 hours and at room temperature for remainder of time

Fig. 4 Compressive strengths of mortars with type I cement

pressive strength before 72 hours of total curing. The mortars with combinations of the Type I-II or Type I cements with fly ash usually reached 19.7MPa compressive strengths between 4 and 7 days of curing.

4.2 Sulfate expansion results

4.2.1 Sulfate expansion results for plain portland cement mortars

Fig. 5 and Table 5 outline the expansion results for the mortars containing plain Portland cement. Fig. 5 shows measured bar expansions after 1, 2, 3, 4, 8, 13, and 15 weeks and 4 months (120 days) and 6 months (180 days) of continuous soaking in the sodium sulfate solution.

The expansion limits defined for ASTM C1012 are depicted graphically in Fig. 5 by horizontal gridlines.

According to the limits, mortars having 180-day expansions of less than 0.05 percent meet the requirements for a severe sulfate environment, mortars with a 180-day expansion of 0.10 or less meet the requirements for a moderate sulfate environment, and mortars with 180-day expansions exceeding 0.10 percent are only applicable in mild environments. On the other hand, as the 180-day expansions are lower the mortars can be used for more severe sulfate environment.

The mortar bars containing the Type I-II (A) cement had average 180-day expansions slightly above 0.05 percent as an average 180-day expansion of 0.060 percent was obtained for the mortar. The Type I-II (B) cement mortar had higher expansions exceeding 0.10 percent at 180 days as the average 180-day expansion for the mortar was 0.113 percent.

The mortar mix, PC5, for the Type V cement had the lowest average 180-day expansion as the 0.037 percent average expansion was well below 0.05 percent. The mortar mix, P1, containing the Type I cement had the highest expansions of the plain Portland cement mortars as an average 180-day expansion of 0.199 percent was obtained.

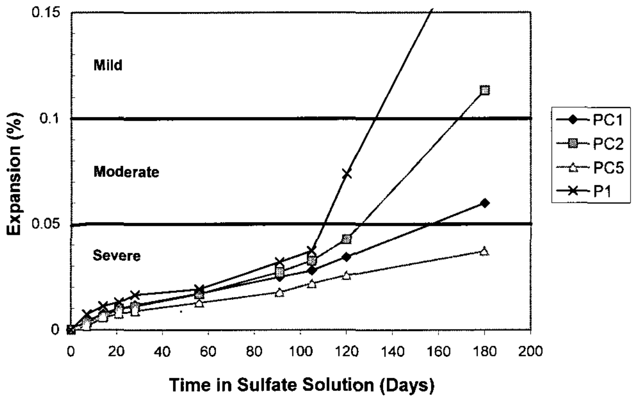


Fig. 5 Sulfate expansions of plain portland cement mortars

Table 5 180-day sulfate expansions of plain portland cement mortars

Batch name	Cement type	C_3A content	No. of bars	Standard deviation, %	Average 180-day expansion, %
PC1	I-II (A)	5.1%	6	0.004	0.060
PC2	I-II (B)	7%	6	0.008	0.113
PC5	V	0%	6	0.001	0.037
P1	I	12%	6	0.018	0.199

4.2.2 Sulfate expansion results for mortars with fly ash

Figs. 6~9 and Tables 6~9 present the expansion results for the mortars containing combinations of cement with fly ash. A Figure is provided for each cement presenting the expansions for the five mortars with different cement-mineral admixture combinations. The expansion of the plain Portland cement mortar is also presented in each figure such that it can be observed whether the mineral admixture increased or decreased sulfate resistance. The effect mineral admixtures had on the sulfate resistance of mortars varied depending on the cement with which they were blended. In general, all mortar mixes containing the ASTM Class C fly ash reached expansions exceeding 0.10 percent or failed due to cracking before 180 days of soaking.

For the Type I-II (A) cement, the mortars containing the Class F fly ash and the slag significantly reduced expansions as the 0.060 percent average 180-day expansion of plain Portland cement mortar was reduced 28 to 38 percent with the addition of the admixtures. A 20 percent volumetric replacement of the cement with the Class F fly ash resulted in the highest reduction while a 30 percent replacement with the fly ash provided the lowest reduction.

Mortars containing the Type I-II (A) cement combined with the Class C fly ash had extremely high expansions as the mortar, 1FC-1, that contained a 25 percent volumetric replacement of the Class C fly ash had an average 180-day expansion of 0.711 percent. A 35 percent replacement with the fly ash resulted in even higher expansions such that the bars for the mortar, 1FC-2, expanded at a faster rate than the 1FC-1 bars before becoming severely deteriorated and immeasurable after 180 days of soaking.

The 180-day expansion reductions by the Class F fly ash and the slag were even greater for mortars containing the Type I-II (B) cement as the 0.113 percent average 180-day expansion of the plain Portland cement mortar was reduced 57 to 77 percent. The 2FA-1 mix containing a 20 percent volumetric replacement of the Class F fly ash reduced the plain cement mortars 180-day expansion 64 percent to an average of 0.041 percent. Expansion reductions were even more dramatic when a replacement of 30 percent was used for this fly ash as the 2FA-2 mix reduced expansions 77 percent to an average 180-day expansion of 0.026 percent.

The use of the Class C fly ash with the Type I-II (B) cement resulted in the same dramatic increases in expansions observed earlier. The mix with the Type I-II (B) cement and 25 percent fly ash replacement, 2FC-1, had bar expansions as high as 1.3 percent as an average 180-day expansion of 0.974 percent was obtained. This high value is nearly 9 times the expansion of the plain cement mortar. The mix with 35 percent fly ash replacement expanded at an extremely high rate as all bars had become immeasurable after 13 weeks of soaking.

The reductions in 180-day expansions provided by the Class F fly ash and slag were relatively small when the admixtures were used in combination with the Type V cement. With 20 percent Class F fly ash replacement, mix 5FA-1 had an average 180-day expansion of 0.030 percent reducing the expansion of the plain Portland cement mortar 19 percent. Mix 5FA-2 with a 30 percent fly ash replacement showed the same improvement as the same average 180-day expansion was obtained.

The use of the Class C fly ash with the Type V cement once again resulted in dramatic expansion increases as the 5FC-1 mix containing a 25 percent fly ash replacement expanded 5 times as much as the plain cement mortar after 180 days of soaking. The 5FC-2 mix with a 35 percent replacement expanded approximately 12 times as much as an average expansion of 0.459 was obtained.

The most drastic level of reductions in sulfate expansions provided by the Class F fly ash and slag came when the admixtures were used with the Type I cement. The 1F-1 with a 20 percent Class F fly ash replacement provided the greatest improvement as a 180-day expansion of 0.028 percent was obtained. This was a reduction of 86 percent from the expansion found for the plain cement mortar. The 1F-2 mix with a 30 percent Class F fly ash reduced expansions 77 percent as a 180-day average expansion of 0.045 percent was obtained.

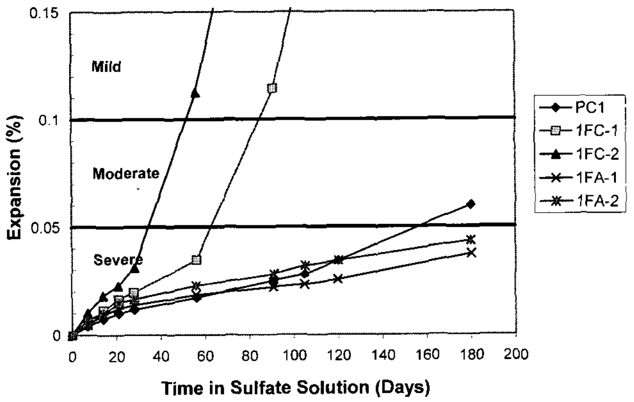


Fig. 6 Sulfate expansions of mortars containing combinations of Type I-II (A) cement with mineral admixtures

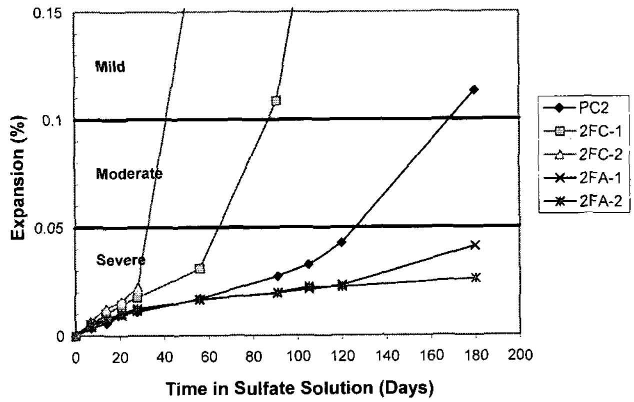


Fig. 7 Sulfate expansions of mortars containing combinations of Type I-II (B) cement with mineral admixtures

Table 6 180-day sulfate expansions of mortars with combinations of type I-II (A) cement with mineral admixtures

Batch name	Fly ash/ slag *	% Rep.	No. of bars	Standard deviation, %	Average 180-day expansion, %
PC1	None	0	6	0.004	0.060
1FC-1	C	25	4	0.121	0.711
1FC-2	C	35	-	-	-
1FA-1	F	20	6	0.003	0.038
1FA-2	F	30	6	0.003	0.044

* In this column, C denotes ASTM Class C fly ash and F denotes ASTM Class F fly ash

Table 7 180-day sulfate expansions of mortars with combinations of type I-II (B) cement with mineral admixtures

Batch name	Fly ash/ slag *	% Rep.	No. of bars	Standard deviation, %	Average 180-day expansion, %
PC2	None	0	6	0.008	0.113
2FC-1	C	25	6	0.129	0.974
2FC-2	C	35	-	-	-
2FA-1	F	20	6	0.004	0.041
2FA-2	F	30	6	0.001	0.026

* In this column, C denotes ASTM Class C fly ash and F denotes ASTM Class F fly ash

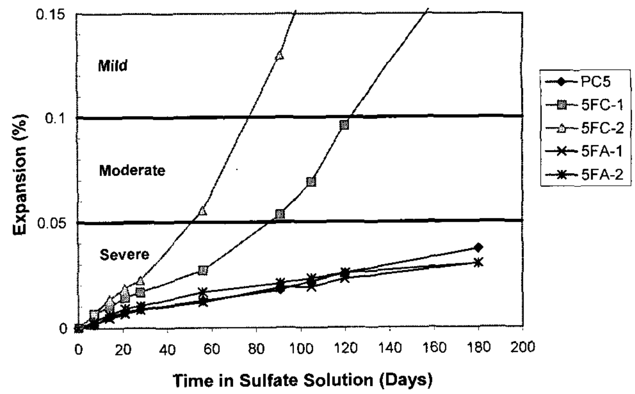


Fig. 8 Sulfate expansions of mortars containing combinations of Type V cement with mineral admixtures

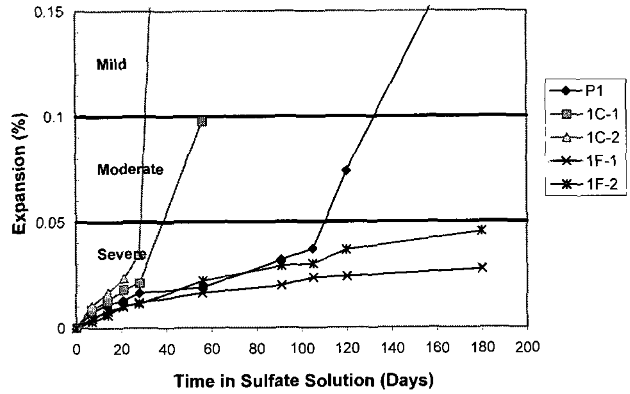


Fig. 9 Sulfate expansions of mortars containing combinations of Type I cement with mineral admixtures

Table 8 180-day sulfate expansions of mortars with combinations of type V cement with mineral admixtures

Batch name	Fly ash/ slag *	% Rep.	No. of bars	Standard deviation, %	Average 180-day expansion, %
PC5	None	0	6	0.001	0.037
5FC-1	C	25	5	0.039	0.185
5FC-2	C	35	6	0.034	0.459
5FA-1	F	20	5	0.001	0.030
5FA-2	F	30	6	0.002	0.030

* In this column, C denotes ASTM Class C fly ash and F denotes ASTM Class F fly ash

Table 9 180-day sulfate expansions of mortars with combinations of type I cement with mineral admixtures

Batch name	Fly ash/ slag *	% Rep.	No. of bars	Standard deviation, %	Average 180-day expansion, %
P1	None	0	6	0.018	0.199
1C-1	C	25	-	-	-
1C-2	C	35	-	-	-
1F-1	F	20	6	0.001	0.028
1F-2	F	30	5	0.001	0.045

* In this column, C denotes ASTM Class C fly ash and F denotes ASTM Class F fly ash

The combination of Class C fly ash with a Type I cement resulted in mortars that deteriorated quickly as all bars for the 1C-1 mix containing 25 percent of the fly ash became immeasurable after 8 weeks of soaking. The bars for the 1C-2 mix with 35 percent of the fly ash became immeasurable after between 4 and 8 weeks of soaking.

5. Discussion and analysis

5.1 Effects of cement type on sulfate resistance

In this study, four cements with C_3A contents ranging from 0 to 12 percent were tested. Fig. 10 provides a plot of the average 180-day expansions that were obtained for the four plain Portland cement mortars versus the C_3A contents of the cements used in each mortar.

The horizontal gridlines in Fig. 10 represent the ASTM C1012 expansion limits. The line at a 180-day expansion of 0.1 percent delineates between mild and moderate sulfate environment resistance while the line at an expansion of 0.05 percent delineates between moderate and severe sulfate resistance. The vertical gridlines represent the Portland cement C_3A content limits established in the ASTM C150 specifications for categorizing sulfate resistant cements. A line is provided at 5 percent C_3A representing the maximum allowable C_3A content of severe sulfate resistant Type V cements and another line is provided at 8 percent representing the maximum allowable content for the moderate sulfate resistant Type I-II or Type II cements.

The testing of plain Portland cement mortars confirmed the well-supported fact that the C_3A content of a cement greatly impacts its sulfate resistance. The second-degree polynomial trendline shown in Fig. 10 that was developed using the four test data points displays a clear increase in expansion and thus decrease in sulfate resistance as the cement C_3A content increased. The rate of expansion increase increased as the C_3A contents increased.

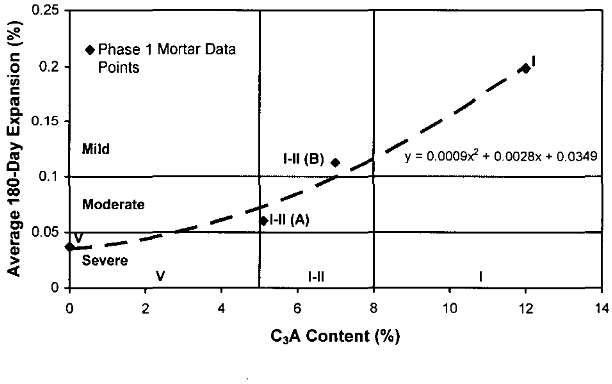


Fig. 10 Average 180-day expansions vs. cement C_3A contents for plain portland cement mortars

In comparing the levels of sulfate resistance determined for the four Portland cements using the ASTM C1012 expansion criteria versus the ASTM C150 C_3A content limits, three out of the four cement evaluations came up with the same results. The Type I cement was found to be only adequate in mild sulfate environments according to ASTM C1012 because of its high average 180-day expansion of 0.199 percent and according to ASTM C150 because of its high C_3A content of 12 percent. The Type V cement proved to be adequate for severe sulfate environments according to ASTM C1012 because its average 180-day expansion was a low 0.037 percent and according to ASTM C150 because of its C_3A content of zero percent. The Type I-II (A) cement met the requirements for moderate sulfate environments according to ASTM C1012 because of its average 180-day expansion of 0.060 percent and according to ASTM C150 because of its C_3A content of 5.1 percent.

The one case where ASTM C1012 sulfate resistance evaluations did not match ASTM C150 evaluations was for the Type I-II (B) cement. The cement had a C_3A content of 7 percent that placed it within the category of a moderate sulfate resistant cement according to ASTM C150 specifications. However, tests on the plain Portland cement mortar containing the Type I-II (B) cement produced an average 180-day expansion of 0.113 percent. This expansion is above 0.1 percent and thus makes the cement inadequate for moderate sulfate environments according to ASTM C1012 expansion criteria.

According to the test results, especially those concerning the Type I-II (B) cement, the expansion criteria established for ASTM C1012 can be conservative in comparison to the ASTM C150 specifications when used to determine Portland cement sulfate resistance levels. The second-degree equation corresponding to the trendline shown in Fig. 10 can be used to calculate 180-day expansion criteria that directly correspond with ASTM C150 limits according to the test results. According to the trendline equation, an average 180-day expansion of 0.071 percent corresponds to a C_3A content of 5 percent and thus the borderline between severe and moderate sulfate resistance. An average 180-day expansion of 0.115 percent corresponds to a C_3A content of 8 percent and thus the borderline between moderate and mild sulfate resistance. The expansion values are 0.021 and 0.015 percent higher than the ASTM expansion limits. Results indicate that borderline cements with C_3A contents between 7 and 8 percent that are considered moderate sulfate resistant cements according to ASTM C150 specifications may be categorized as mild sulfate resistant cements according to current ASTM C1012 expansion limits. Also, ASTM C150 Type V severe sulfate resistant cements with C_3A contents between 4 and 5 percent may be found to only meet moderate sulfate resistance requirements when ASTM C1012 is used.

5.2 Effects of fly ash on sulfate resistance

5.2.1 Class F fly ash

Despite the relatively high calcium content of the Class F fly ash used in the testing, most sources show this fly ash can also be expected to improve sulfate resistance. Results of ASTM C1012 testing on mortars containing the Class F fly ash confirmed that the fly ash did indeed improve sulfate resistance. Fig. 11 shows the average 180-day sulfate expansions of all the mortars containing the Class F fly ash and the corresponding plain Portland cement mortars. All mortars containing the Class F fly ash had improved sulfate resistance compared to their respective plain Portland cement mortar. All Class F fly ash mortars had average 180-day expansions below 0.05 percent such that each mortar met the requirements for severe sulfate resistance according to ASTM C1012 expansion criteria.

The level of reductions in sulfate expansion depended on the type of cement with which the fly ash was being used as reductions increased as the C_3A content of the cement increased. Reductions in expansion were as small as 0.07 percent when the Class F fly ash was used with the Type V cement and as high as 0.171 percent when the fly ash was used with the Type I cement. No trends were observed concerning the impact of fly ash content on sulfate resistance as sometimes the 20 percent replacement mortar would have lower expansions while other times the 30 percent replacement mortar had the lower value.

5.2.2 Class C fly ash

Due to the high calcium content of Class C fly ashes, most of these fly ashes have been shown to provide little improvement if not reductions in sulfate resistance.

Fig. 12 shows the 56-day expansions of the mortars with Class C fly ash and the corresponding plain Portland cement mortars. After 56 days, sets of mortar bars with Class C fly ash started to become totally deteriorated. The results in Fig. 12 show that Class C fly ash quickly reduced sulfate resistance as the reduction increased with increasing fly ash content. It is considered that the reason is high content of calcium oxide in Class C fly ash which produces C_3A by chemical reaction. Since the content of calcium oxide in Class C and F fly ash are quite different the sulfate resistance can be shown different trends. Fig. 12 also shows that the rate of expansion of the mortars with Class C fly ash increased as the C_3A content of the Portland cement in the mortar increased. In the end, all the mortars containing Class C fly ash showed either significant deterioration or

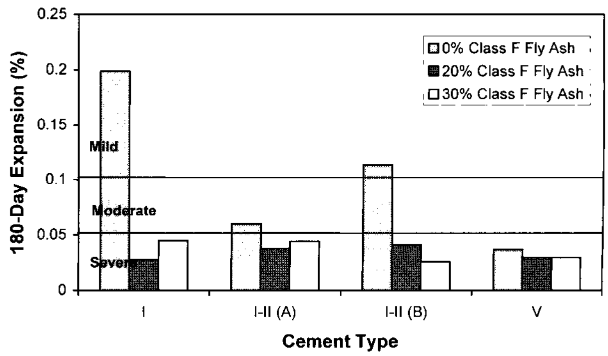


Fig. 11 180-day sulfate expansions of mortars with Class F fly ash

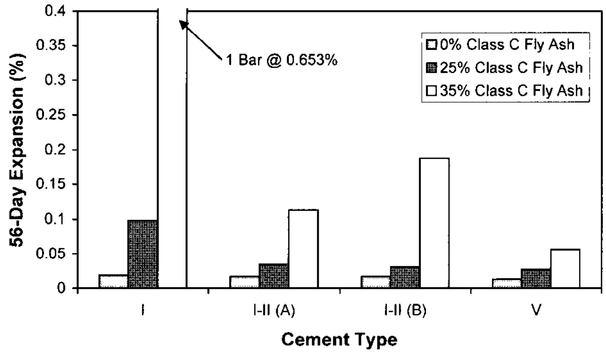


Fig. 12 56-day sulfate expansions of mortars with Class C fly ash

high expansions that indicated the mortars were not suitable for application in a sulfate environment.

6. Conclusions

This research project involved an experimental investigation of the resistances of various mortars to sulfate attack for the purpose of investigating the effect of cement type and fly ash in sulfate environments. Based on the results, the following conclusion can be drawn:

Sulfate expansions of ASTM C1012 tested plain Portland cement mortars confirmed the impact cement tricalcium aluminate (C_3A) contents have on sulfate resistance as increasing C_3A contents yielded increased expansions.

In comparing the ASTM C1012 expansion limits and the ASTM C150 C_3A content limits used for determining levels of sulfate resistance for Portland cements, the expansion limits sometimes proved to be conservative in comparison to ASTM C150 limits. In one case, an ASTM C150 Type I-II moderate sulfate resistant cement was found to be inadequate for moderate sulfate environments according to current ASTM C1012 expansion criteria.

The test results demonstrated that engineers should take caution when using borderline cements with C_3A contents between 7 and 8 percent or 4 and 5 percent in moderate or severe sulfate environments respectively as the cement may be inadequate for the environment.

Test results for mortars containing Class F fly ash showed the fly ash significantly reduced sulfate expansions as each mortar met ASTM C1012 expansion criteria for severe sulfate resistance.

Test results for mortars containing Class C fly ash showed the fly ash significantly increased expansions as each mortar proved to be inadequate for application in any sulfate environment. It is considered that the reason is high content of calcium oxide in Class C fly ash which produces C_3A by chemical reaction.

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