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16. Abstract This report describes the evaluation of Class C fly ash in sulfate environments. The practical relevance of this is especially critical in regions where high-calcium ash is the only type of fly ash available. Research is needed to identify what specific characteristics of high-calcium fly ash impact sulfate resistance, from a chemical and mineralogical perspective, and guidance is needed on how to incorporate high-calcium fly ash in concrete in sulfate-rich environments.					
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Evaluation of Class C Fly Ash in Sulfate Environments

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Chapter 1. Introduction

This report describes the evaluation of Class C fly ash in sulfate environments. The practical relevance of this is especially critical in regions where high-calcium ash is the only type of fly ash locally available. Research is needed to identify what specific characteristics of high-calcium fly ash impact sulfate resistance, from a chemical and mineralogical perspective, and guidance is needed on how to incorporate high-calcium fly ash in concrete in sulfate-rich environments. The research described is aimed at achieving these objectives.

The use of Class C fly ash is strictly prohibited in certain areas of Texas that have sulfates in soils and groundwater per standard specifications for construction of highways, streets, and bridges. Several experiments have been conducted to determine the effect of Class C fly ash on sulfate resistance. The following items will be discussed throughout the report:

- Outline of testing completed at The University of Texas at Austin and University of New Brunswick
- Results of Class C fly ash in ASTM C 1012 testing including ternary blends
- Recommendations and Future work on the project

Chapter 2. Outline of Testing Completed To Date

2.1 ASTM C 1012 Testing

Eight Class C fly ashes were chosen from Texas for their evaluation in ASTM C 1012 testing. Over 200 mortar mixtures were cast for ASTM C 1012 testing. ASTM C 1012 was selected as the standard testing procedure for this research, not because it is deemed to be the best test or the test most linked to field performance, but rather because it is the test most commonly used, specified, and included in national and international guidelines. As per ASTM C 1012, a standard mortar mixture is cast with 1 part portland Type I cement to 2.75 parts sand. For the control portland cement mixture, the w/cm is fixed at 0.485, and for mixtures incorporating SCMs, water is added to obtain a flow of ± 5 of that of the control portland cement mixture. The mortar bars have dimensions of 1 in. x 1 in x 11.25 in. (25 mm x 25 mm x 286 mm) with stainless steel gauge studs embedded into the ends for length measurements. Nine mortar cubes (2 in x 2 in or 50 mm x 50 mm) are also cast from each mixture. After casting the mortar bars and cubes, they are sealed and placed into a 95° F (35° C) water bath for 23 ± 0.5 hours. After curing, the specimens are de-molded and two of the cubes are tested for strength. Once the compressive strength of the cubes has reached 2850 psi \pm 100 psi (20 MPa \pm 0.70 MPa), the bars are then placed into a 5% sodium sulfate solution (352 moles of Na₂SO₄ per m³). In addition mortars were also placed into magnesium and calcium sulfate solutions. Otherwise, the bars and cubes are placed into a saturated limewater bath until strength is achieved. Upon immersion in the sulfate solution, expansion measurements are taken every 1, 2, 3, 4, 8, 13, 15 weeks and 4, 6, 9, 12, 18 months thereafter.

Expansion limits (and immersion times at which expansion limits are applied) vary considerably from one agency/source to another and also depending on the severity of sulfate exposure. In this dissertation, expansion limits from ACI 201.2R-01 are nominally used to compare and evaluate the performance of mortars exposed to sulfate solutions. Table 2-1 from ACI 201.2R-01, shows the four classes of exposure, increasing in order of severity as one progresses downward in the table. The severity is determined based on the sulfate concentration in either the groundwater or soil. As discussed previously in this dissertation and as will be discussed in more detail later in this chapter, there are several unresolved issues when measuring sulfates in soil, especially when gypsiferous soils are encountered. As one moves from the less severe to more severe exposure classes, more stringent prescriptive guidelines are provided, which include lower w/cm, the use of sulfate-resistant cements, and the use of SCMs. The last column in Table 2-1 shows the different cementitious requirements for each of the exposure classes. A Type II or Type V portland cement (as per ASTM C 150) is specified in Class 1-3 exposures, but “equivalent” materials are allowed for these exposure classes, with equivalency based on ASTM C 1012 test results, as described next.

Table 2-1: Sulfate Exposure classification for water-soluble sulfates in soil or sulfates in water (ACI 201.2R-01)

Severity of potential exposure	Water-soluble sulfate (SO ₄) in soil, percent by mass	Sulfate (SO ₄) in water, ppm	(w/cm) by mass, max.	Cementitious-material requirements
Class 0 exposure	0.00 to 0.10	0 to 150	No special requirements for sulfate resistance	No special requirements for sulfate resistance
Class 1 exposure	>0.10 and <0.20	>150 and <1500	0.50	C 150 Type II or Equivalent
Class 2 exposure	0.20 to <2.0	1500 to <10,000	0.45	C 150 Type V or Equivalent
Class 3 exposure	2.0 or greater	10,000 or greater or greater	0.40	C 150 Type V plus pozzolan or slag

As shown in Table 2-1, “equivalent” cementitious materials can be used in lieu of Type II or Type V cements, which is particularly important for Type V equivalency as there exist very few Type V cements in the United States. Equivalency is judged based on ASTM C 1012 testing, with various expansion limits and test durations, depending on the specific exposure class. An equivalent for a Type II cement in Class 1 exposure would be any type of ASTM C 150 or C 1157 cement with fly ash, silica fume or slag that yields an expansion less than 0.10% after 6 months. An equivalent for Type V cement in Class 2 exposure has two criteria. The first criterion requires the expansion to be less than 0.05% percent after six months, provided that these materials were previously qualified by performance testing. If the materials were not previously qualified, an expansion limit of 0.10% after one year is specified. For Class 3 exposure, an ASTM C 150 Type V or ASTM C 1157 Type HS cement must be used with a suitable dosage of SCM to achieve an expansion less than 0.10% after 18 months of testing using ASTM C 1012.

2.2 Physical sulfate testing

There is not a standardized test method or procedure for testing physical sulfate attack. In order to create physical sulfate damage to specimens, the samples were subjected through temperature cycles ranging from 5-40°C in order to cross over the solubility curve of sodium sulfate to create precipitation of a salt. In order to perform these tests, a series of mortar mixtures were cast into discs measuring 2 in. (50 mm) in diameter and 1 in. (25 mm) thick. Twenty-four hours after casting the discs were demolded and placed into solutions containing 10, 20, and 30% sodium sulfate and 10, 20, and 30% magnesium sulfate. These high concentrations were chosen to ensure that physical sulfate testing occurs within the samples. Eight mortar mixtures were made with Type I and Type V cement at either 0.4 or 0.7 w/cm. Corresponding air-entrained mixtures were also cast. The mortar discs in the containers were enclosed with a lid

and were subjected to 150 temperature cycles. The cycle time was 11 hours which had a holding time of 1 hour at 5 °C then ramped to 40 °C in 5 hours and back down to 5 °C in 5 hours.

More than 20 concrete mixtures have been tested at UNB on wet/dry cycles on prisms placed in either sodium or calcium sulfate. In addition, corresponding static prisms have been made to correlate the physical damage that occurs during the cycling tests.

2.3 Outdoor exposure site testing

Thirty concrete mixtures, each comprised of 24 concrete prisms, were cast for placement in the outdoor sulfate exposure site. The exposure site consists of three 13 ft x 16 ft (4 m x 5 m) trenches, each having a depth of 18 in (450 mm). After excavation, a 0.045 in (1.14 mm) ethylene propylene diene terpolymer (EPDM) pond liner made by Firestone was placed for confinement of sulfates in each trench. A sandy loam used for residential foundations in Austin, Texas was used as the fill material in the trenches, filled to a depth of 8 in (200 mm). Testing of this loam confirmed sulfates were not present. Sulfate solutions (sodium, magnesium and calcium) were then added to each of the three trenches. The trench containing sodium sulfate was filled with solution to obtain a concentration of 5% sodium sulfate, which matches the sulfate concentration used in ASTM C 1012. The other two trenches for the current study were matched to the total sulfate concentration contained in the sodium sulfate trench, but contained calcium sulfate and magnesium sulfate. The sulfate solutions were initially kept at a height 3 in (75 mm) above the soil. The trenches were subsequently monitored and allowed to evaporate until the solutions just reached the soil level and were then filled with water. As such, the concentrations of sulfates in the trenches are at a minimum when the levels are at their highest (and initial) level and at a maximum when the water has evaporated to the point where the solution reaches the soil level.

Details of these concrete mixtures are provided later in this chapter. Concrete prisms with dimensions of 3 in. x 3 in. x 11.25 in. (75 mm x 75 mm x 285 mm) were selected, to allow for expansion measurements, mass loss, and dynamic modulus testing in standard laboratory equipment. The prisms were demolded 24 hours after casting. After demolding, the prisms were cured in a fog room (73° F (23° C), 100% RH) for 28 days. At 28 days of age the prisms were placed in either the outdoor exposure site or in a modified ASTM C 1012 testing regime. The standard ASTM C 1012 testing regime specifies mortar and sodium sulfate while these concrete prisms were cast of concrete and placed into magnesium and calcium sulfate solutions as well.

2.4 Analytical Techniques

2.4.1 X-ray diffraction

Samples for x-ray diffraction (XRD) were taken from mortar bars at 18 months after storage in sodium sulfate solutions. A single mortar bar was tested from each mixture. The bars that had fully deteriorated had a sample carefully removed with most of the entire cross-section preserved. A 2- in. (51mm) section near the center of the mortar bar was crushed with a mortar and pestle to pass through a #325 sieve (45 microns). The majority of the sample passed through the sieve; however, sand particles did not successfully pass through the sieve. Once the sample passed through the sieve, it was placed into vials and stored under vacuum until tested.

Concrete prisms tested, as per the modified version of ASTM C 1012, were removed at 18 months and progressively milled to a depth of 0.12 in. (3 mm) to generate concrete powder

samples to be analyzed by x-ray diffraction for the presence of hydration products and potentially detrimental reaction products from sulfate attack. In addition, over 150 XRD samples have been conducted at the University of New Brunswick. Those include identifying deteriorated products and investigations into the mineralogy of Class C fly ash.

2.4.2 Scanning electron microscopy

Mortars were imaged and analyzed with the use of a scanning electron microscope (SEM) after 18 months of storage. The sample was then placed under vacuum for at least 24 hours prior to epoxy impregnation with a two-part epoxy resin from Logitech. The epoxy was allowed to cure at least 24 hours at 73° F (23° C) prior to grinding. The sample was then grinded with #180-, 400-, 800-, 1200-grit sandpaper on a Buehler Ecomet 6 grinder-polisher. The progression towards finer grit sandpaper depended on scratches on the surface of the specimen. The time spent on each size depended on the amount of scratches. Typically, it took 15 minutes per grit size. After grinding the same instrument, the samples were polished with 3, 1, and ¼ micrometer diamond paste. The samples were polished with an automated Buehler Automet 2000 Powerhead. The 3 and 1 micrometer diamond pastes were used for 1 hour each followed by the ¼ micrometer diamond paste for 1.5 hours. After polishing, the sample is cleaned with ethanol and stored under vacuum until analyzed under the SEM. SEM work at UNB has been used to evaluate the glassy phase of Class C fly ash to determine its reactive phases that creates the poor sulfate resistance.

Chapter 3. Evaluation of Class C Fly Ash

3.1 Mortar Mixtures

Mixtures containing Class C fly ash exhibited faster deterioration and often higher expansions compared to the control specimens. Figure 3.1 shows the behavior of mortar containing fly ash FA1. This mixture begins to expand earlier than the control, and the onset of expansion occurs earlier as the dosage of fly ash is increased. Only the mixture containing 20% FA1 (by mass replacement of portland cement) was intact at the end of the 18-month test; all other mixtures with higher dosages of FA1 deteriorated prior to this time and subsequent measurements were not possible. The increased storage duration of the mortar bars for 18 months shows that 20% FA1 lasts for that period unlike the other replacements; however, it has the highest ultimate expansion compared to the other replacement levels at 18 months. Increasing the dosage of FA1 tended to increase the expansions. In fact, the mixture containing 40% FA1 “failed” the 0.1% expansion limit at 6 months. The increasing replacement dosages of Class C fly ash deteriorated the mortar bars at faster rates due to greater amounts of reactive phases placed into the system.

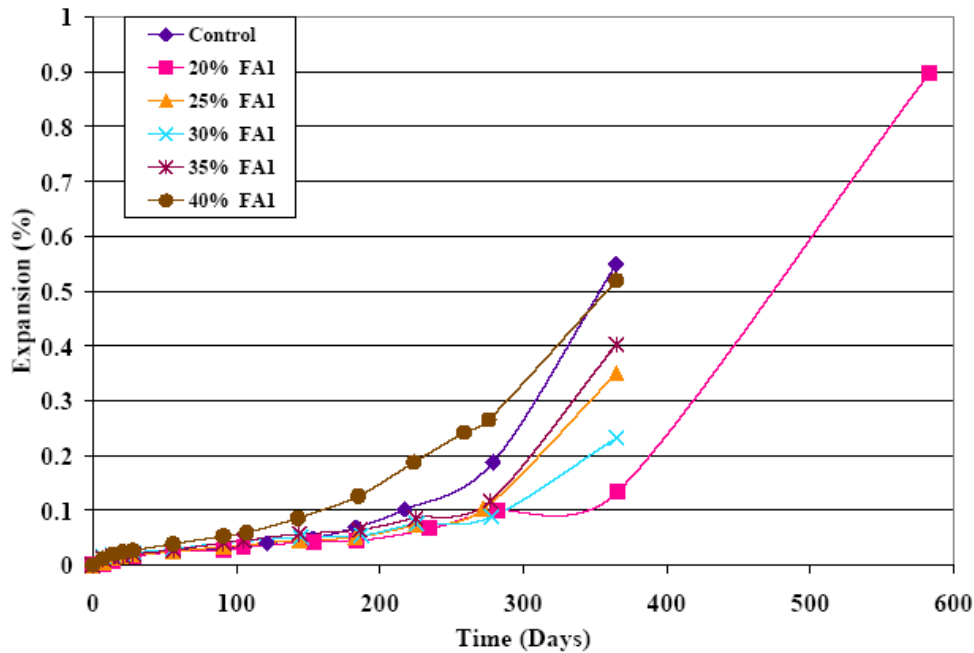


Figure 3.1: Expansions of FA1 at various replacement dosages

All but one of the other Class C fly ashes tested in this program performed similarly to FA1, with increasing fly ash dosages leading to increasing deterioration. The only exception was FA2, which had similar bulk chemistry to FA1, but performed quite differently in ASTM C 1012 testing. Ongoing work on the project is focusing on the behavior of these two Class C fly ashes focusing on the glassy phase of the fly ash. Figure 3.2 shows an SEM and EDS spectrum of a

mixture containing 40% FA1 after 18 months in ASTM C 1012 testing. In the SEM images of 40% FA1, there are many cracks throughout the hydrated paste. Ettringite formation is visible throughout the paste, with small amounts of gypsum near aggregates. The EDS spectrum confirms the small area of gypsum occurring near the aggregate.

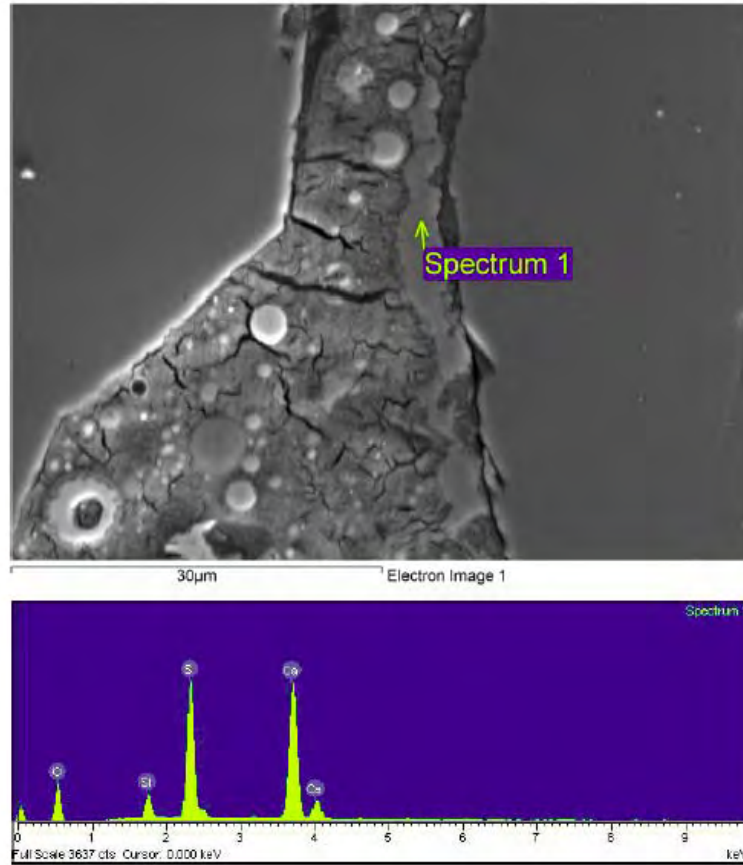


Figure 3.2: SEM image and EDS spectrum of 40% FA1 mortar after 18 months storage in sodium sulfate showing possible conversion of gypsum into ettringite.

ASTM C 1012 testing has clearly shown that binary mixtures with Class C fly ash were not sulfate resistant; however, mixtures with ternary blends with Class C fly ash have performed better. Tables 3.1 and 3.2 provide the expansions of ternary blends from FA1 and FA2 fly ashes after 18 months of storage. Silica Fume (SF), ultra fine fly ash (UFFA) and slag were incorporated with Class C fly ash to provide sulfate resistance. Guidelines still need to be determined for evaluating areas with sulfates. Because the majority of testing with ternary blends from ASTM C 1012 testing calls for sodium sulfate which is far more aggressive than calcium sulfate, it may be deserving to call all sulfate regions a moderate exposure condition and take 12 month criteria. Further testing is needed to determine this equivalent designation between calcium and sodium sulfate solutions. When adding silica fume, ultra-fine fly ash, slag to mortar containing FA1, significant improvements in sulfate resistance were realized. All of these ternary blends reduced expansions at six months below 0.1% expansion criteria at 6 months, and the majority satisfied the Class 2 equivalent sulfate resistance described in section 2.1, as tested per ASTM C 1012.

Table 3.1: Expansion measurements from FA1 in ASTM C 1012 Testing

FA1	Ternary	6 Month	9 Month	12 Month	18 Month
20%		0.043	0.100	0.134	0.900
20%	3% SF	0.060	0.074	0.192	X
20%	5% SF	0.028	0.042	0.074	0.261
20%	6% UFFA	0.037	0.045	0.079	0.244
20%	9% UFFA	0.037	0.038	0.053	0.099
20%	20% Slag	0.028	0.040	0.062	0.106
20%	25% Slag	0.027	0.038	0.052	0.056
25%		0.041	0.092	0.340	X
25%	3% SF	0.036	0.062	0.132	0.395
25%	5% SF	0.027	0.045	0.079	0.194
25%	6% UFFA	0.036	0.044	0.048	0.065
25%	9% UFFA	0.037	0.051	0.069	0.084
25%	20% Slag	0.036	0.054	0.088	0.107
25%	25% Slag	0.039	0.056	0.076	0.091
30%		0.072	0.085	0.229	X
30%	3% SF	0.034	0.058	0.199	0.621
30%	5% SF	0.034	0.051	0.074	0.138
30%	6% UFFA	0.038	0.053	0.077	0.094
30%	9% UFFA	0.028	0.041	0.052	0.057
35%		0.060	0.113	0.398	X
35%	3% SF	0.039	0.062	0.106	0.213
35%	5% SF	0.039	0.047	0.056	0.095
35%	6% UFFA	0.041	0.066	0.084	0.083
35%	9% UFFA	0.038	0.069	0.094	0.097
40%		0.118	0.257	0.511	X
40%	3% SF	0.045	0.072	0.072	0.090
40%	5% SF	0.027	0.046	0.052	0.073
40%	6% UFFA	0.044	0.057	0.073	0.077
40%	9% UFFA	0.040	0.057	0.075	0.071

At 18 months, ternary blends at the lower replacement levels of Class C fly ash performed worse than those at higher replacement dosages. In almost all cases, all ternary blends with 6% and 9% UFFA exhibited excellent sulfate resistance. A surprising trend noticed was an increase in protection of ternary blends as the replacement levels of FA1 increased, which was the opposite when FA1 was used separately (without silica fume or ultra-fine fly ash).

Ternary blends with FA2 performed well at 6 months and at 1 year. All the ternary blends passed the 6 month criteria of 0.1% expansion; however, at 1 year, three mixtures containing UFFA barely failed at 0.1%. At 18 months, the performance of ternary blends declined slightly. Many of the mixtures that failed had expansions close to 0.1% expansion. Although the sulfate resistance was improved through the use of ternary blends, FA2 did not respond as well as FA1, and it was difficult to reduce expansions to meet the criteria set forth for Class 3 exposure, as per the ACI 201.2R table shown in section 2.1.

Table 3.2: Expansion measurements from FA2 in ASTM 1012 Testing

FA2	Ternary	6 Month	9 Month	12 Month	18 Month
20%		0.055	0.117	0.359	0.995
20%	3% SF	0.039	0.055	0.075	0.201
20%	5% SF	0.035	0.052	0.074	0.162
20%	6% UFFA	0.024	0.031	0.040	0.069
20%	9% UFFA	0.034	0.042	0.054	0.080
20%	20% Slag	0.038	0.058	0.089	0.133
20%	25% Slag	0.048	0.063	0.077	0.085
25%		0.070	0.130	0.470	X
25%	3% SF	0.028	0.037	0.047	0.103
25%	5% SF	0.032	0.039	0.057	0.073
25%	6% UFFA	0.058	0.068	0.080	0.094
25%	9% UFFA	0.069	0.075	0.099	0.090
25%	20% Slag	0.046	0.064	0.090	0.136
25%	25% Slag	0.047	0.037	0.085	0.237
30%		0.051	0.073	0.098	0.191
30%	3% SF	0.060	0.077	0.092	0.124
30%	5% SF	0.072	0.079	0.087	0.100
30%	6% UFFA	0.053	0.067	0.098	0.110
30%	9% UFFA	0.064	0.063	0.075	0.105
35%		0.046	0.070	0.108	0.161
35%	3% SF	0.042	0.062	0.083	0.135
35%	5% SF	0.026	0.049	0.077	0.087
35%	6% UFFA	0.064	0.070	0.088	0.100
35%	9% UFFA	0.064	0.072	0.088	0.109
40%		0.054	0.074	0.075	0.102
40%	3% SF	0.032	0.037	0.048	0.057
40%	5% SF	0.065	0.080	0.091	0.092
40%	6% UFFA	0.061	0.066	0.080	0.099
40%	9% UFFA	0.067	0.080	0.098	0.144

Figure 3.3 shows a mixture with 40% FA1 and 5% silica fume after 18 months of storage in ASTM C 1012 testing. The image shows a long band of gypsum runs along the sample's edge. This band runs along the entire sample along the edge of the sample nearest to the sodium sulfate solution. The Ca and S in the EDS spectrum confirm the gypsum band in the image. In comparison with 40% FA1 in Figure 3.2, there is much less ettringite in the paste and around aggregates. Ternary blends with 6% and 9% UFFA also did well in suppressing expansion, even at 18 months. The use of these ternary blends significantly reduces the permeability of mortar, minimizing the ingress of sulfates and preventing chemical alterations of the matrix. This physical effect is also accompanied by the chemical effect of the pozzolanic reaction, resulting in lower calcium hydroxide contents and concomitant reductions in attack on this vulnerable phase.

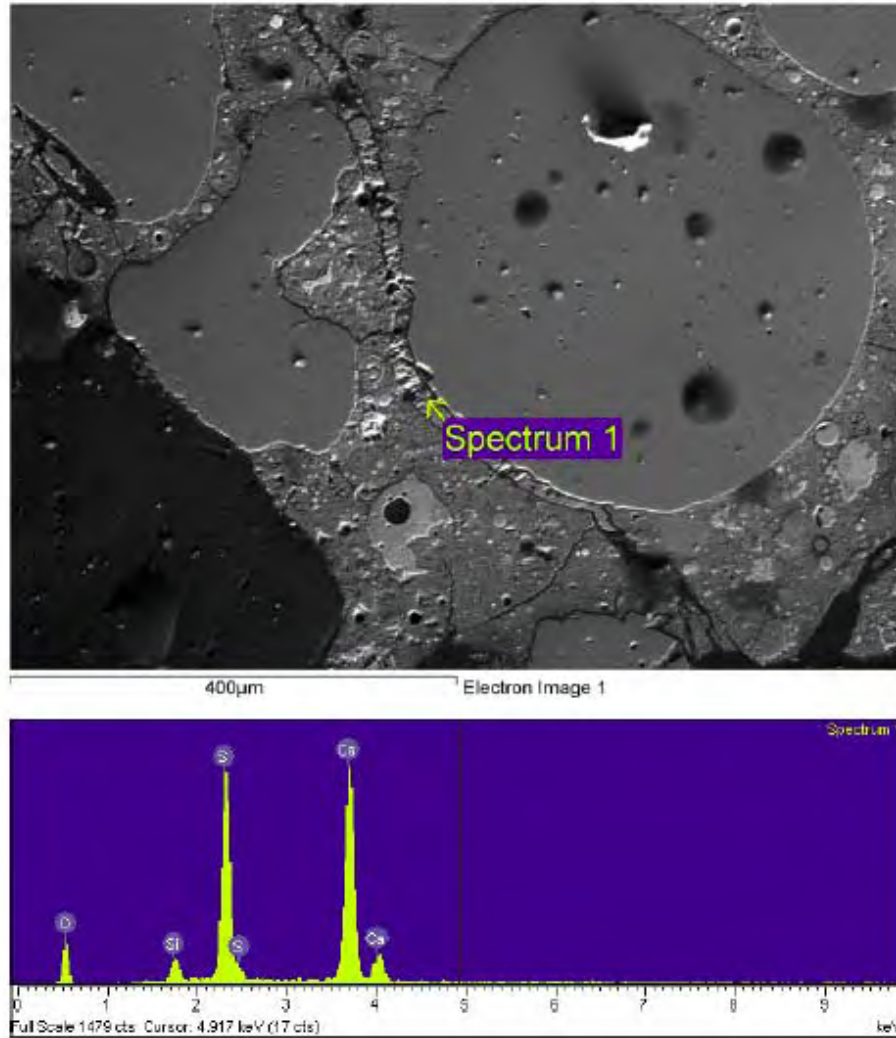


Figure 3.3: SEM image and EDS spectrum of 40% FA1 with 5% SF after 18 months of storage in sodium sulfate showing a gypsum band along the samples edge and around aggregates

3.2 Concrete Mixtures

Concrete mixtures provided a difference in performance compared to mortar mixtures. An interesting trend that was noticed was with the FA1 dosage replacement as it increased. An increasing replacement dosage of Class C fly ash was found to generally cause more deterioration in mortar bars tested using ASTM C 1012, as described earlier. However, the concrete mixtures with 20% Class C fly ash performed worse than those containing 40% Class C fly in both the exposure site and modified ASTM C 1012 testing. One possible explanation is that higher fly ash contents tend to reduce permeability more than lower fly ash contents, and this effect may be even more important for larger, concrete specimens and for specimens exposed to temperature variations and wetting and drying cycles. This included mixtures with Type I, Type I/II and Type V cement in sodium and magnesium sulfate conditions.

FA1 and FA2 exhibit drastically different behavior in ASTM C 1012 testing, despite similarities in crystalline compositions, suggesting strongly that one must evaluate the amorphous or glassy phases to determine if the differences in behavior can be elucidated. FA8,

which was one of the worst performers in ASTM C 1012, was found to have significant differences in its crystalline content and composition, when compared to FA1 and FA2.

3.3 Characterizing Class C Fly Ash

A detailed evaluation of the amorphous or glassy phases is currently underway through the use of scanning electron microscopy to analyze the bulk and glassy phases of the ashes. The chemical analyses of the glassy phases are then plotted onto a calcia-alumina-silica ternary phase diagram. A correlation between the composition of the reactive glassy phases and the sulfate resistance of Class C fly ashes has been found and will be reported in future reports. Fly ashes that exhibited the worst sulfate resistance in ASTM C 1012 testing show a tendency towards containing more calcium aluminates in the glassy phase. This is especially evident for FA8, which exhibited the most significant deterioration in ASTM C 1012. Research at the University of New Brunswick has linked the composition of the glassy phase to early hydration products and ultimately to the mechanism of failure when mortar containing Class C fly ash is exposed to sulfate solutions.

3.4 Field Investigations

A comprehensive evaluation of transportation structures exposed to gypsiferous soils or gypsum-bearing groundwater was conducted with the assistance of TxDOT personnel. To pinpoint areas of possible sulfate attack, agricultural maps identifying sulfate-bearing soils, were utilized. According to these maps, several TxDOT-defined “districts” were selected. The El Paso, Paris, and Childress Districts showed the most promise for areas containing sulfate-bearing soils in the state. Over 200 concrete bridges, culverts, columns, and other transportation structures were visually inspected, and a subset of these were selected for further, detailed investigations.

A number of structures were damaged from external sulfate attack after conducting forensic evaluations from field specimens. The most prevalent damage were right-of-way (ROW) markers in the El Paso district. These are not concrete structures; however, they do show that gypsum may cause damage to concrete members. A long-term study on ROW markers located in the El Paso District is currently underway at The University of Texas at Austin to investigate the mechanisms of deterioration and to determine if external sulfate attack has occurred. According to preliminary tests, sulfate content in the soils from the district fell into a Class 3 exposure and gypsum was the primary type of sulfate. To allow for a detailed laboratory-based evaluation of deteriorated ROW markers, a total of eight ROW markers were removed for subsequent testing. Six of these ROW markers were replaced with new ROW markers, cast using selected concrete mixtures and constructed as per TxDOT specifications. Two types of fly ashes were tested in addition to different w/cm. A Class C fly ash from the region was used in the testing regime.

Figure 3.4 shows the sulfate content in the soils in this area from six ROW markers that were removed. The sulfate percentage from the 8:1 and 80:1 extraction ratio are shown to highlight the large difference between the two ratios. A difference of magnitude 10 is noticed between the two ratios which suggest gypsum is present in the soil. TEX-135-E, which uses a 20:1 extraction ratio, yielded sulfate contents near 2% for all the locations. Following the ACI 201.2R classification of severity of soils, both 20:1 and 80:1 extraction methods would fall into

the most severe levels of exposure (Class 3 exposure). The 8:1 extraction ratio would be considered a moderate sulfate exposure (Class 2 Exposure).

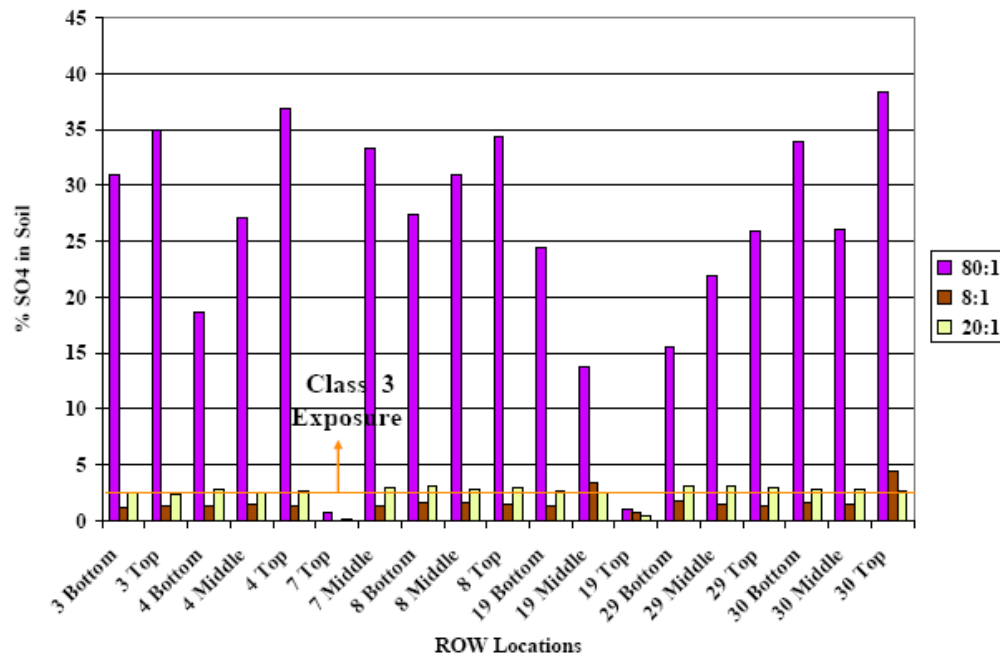


Figure 3.4: Sulfate content of soils taken from each of the ROW locations using ASTM C 1580 and TEX-135-E Test Methods

Preliminary results showed signs of sulfate-related deteriorations occurring in the ROW markers. Figure 3.5 provides the XRD Rietveld analysis from the ROW markers. Concrete powder was taken near the ground level of the marker. Chemical attack from gypsum (calcium sulfate) is known to produce ettringite formation. All but one of the markers removed showed significant ettringite and gypsum formation. The high level of sulfates in the soil and the deleterious products formed indicate damage induced by external sulfate attack from gypsiferous soils.

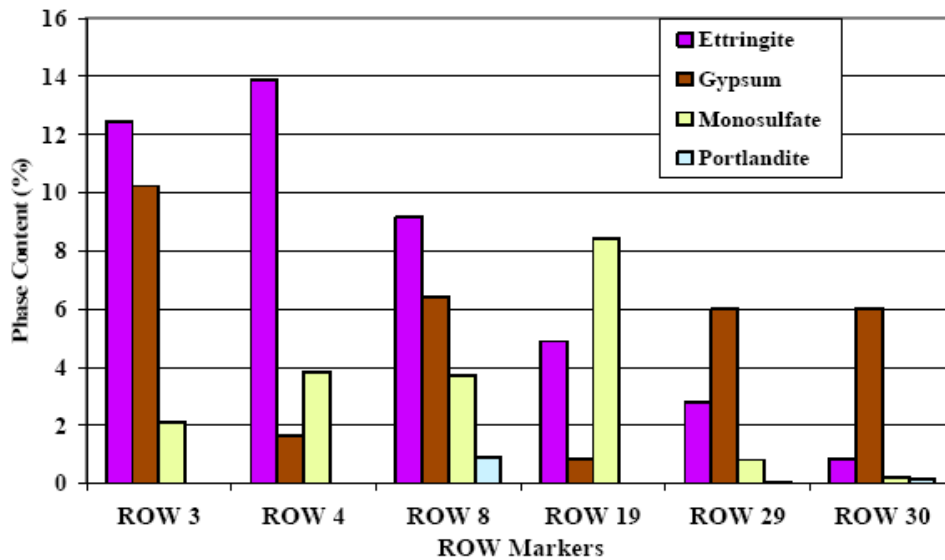


Figure 3.5: Semi-quantitative XRD Rietveld analyses from ROW markers in the El Paso District

Ongoing testing on the ROW markers includes milling for sulfate profiles on three different locations on the marker. Profiling was performed every 0.12 in (3 mm) to a depth of 0.48 in (12 mm) on the following sections of the marker: near the bottom of the marker (bottom of the hole), middle of the marker, (soil level), and top of the marker (exposed area). In addition, samples are being prepared for analysis by scanning electron microscopy.

Chapter 4. Recommendations and Future work

This report summarizes work focusing on developing recommendations on using Class C fly ash for sulfate environments; however, there are many aspects of sulfate attack that are still unresolved, some of which are being pursued already.

- The current recommendation appears that Class C fly ash is not appropriate for use where sulfates are a concern. The use of Class C fly ash has shown poor sulfate resistance in all but one of the fly ashes tested. Analytical techniques are currently being investigated to understand their behavior.
- Some of the Class C fly ash can be mixed with other supplementary cementing materials to create equivalent mixtures to get acceptable results
- The use of proper extraction ratios provide a more accurate understanding of the type of sulfate in soils and its severity which leads to the investigation determining whether sulfates are a concern.

Although significant progress was made in the work described in the report, the following topics are deserving of further attention and investigation:

- Further work on analyzing and characterizing the glassy phase of Class C fly ash should help to shed more light on the linkage between fly ash mineralogy and sulfate resistance. Most of the ashes in this study have been fully characterized (using XRD for crystalline phase and SEM for glassy phase), but it would be ideal to expand this approach to a range of other fly ashes to generate a more definitive link between fly ash mineralogy and sulfate resistance.
- More focused research is needed on accelerated test methods for external sulfate attack. ASTM C 1012 is the most common method, but several issues have been identified with this method through this research. One issue, for example, that deserves further attention is the application of 6-month expansion limits to mortar mixtures. The high C₃A Type I cement used in this study as a control did not expand until after 6 months of immersion in sulfate solution, yet there are current guidelines, such as those put forth in ACI 201 and potentially ACI 318, that allow for performance testing and mixture approval based on 6-month expansion criteria. A wide range of Portland cements should be tested using ASTM C 1012 to determine how many of these perform similarly. If it is found that this behavior is the rule and not the exception, 6-month expansion limits should not be included in guidelines or specifications.
- A wide range of mortar mixtures were evaluated in this project using ASTM C 1012. Based on these findings, other mixtures have been identified that should be evaluated in the future to fill in gaps in the current database. In addition to testing plain cement mixtures it would be quite useful to evaluate a range of ternary blends in combination with fly ashes from this study that showed poor sulfate resistance

(FA1, FA2, and FA3). In addition, higher percentages of silica fume and ultra fine fly ash should be used in the testing. With a better understanding on which ternary systems work for Class C fly ash in ASTM C 1012 testing, it would be beneficial to make concrete prisms with similar mixture proportions and test them in either the outdoor or indoor sulfate conditions.

- Concrete mixtures were cast and evaluated, both indoors and outdoors, that covered the upper and lower bounds of typical w/cm ratios, specifically w/cm values of 0.7 and 0.4. Research is needed to fill in the gaps in this w/cm range, specifically w/cm values of 0.45 and 0.5, as these are cited values in the ACI 201.2R table for different sulfate exposures.
- All of the laboratory and field testing performed in this work has focused on the performance of mortar or concrete in soils or solution with high sulfate concentrations (5% sodium sulfate, for example). Research is needed to evaluate the performance of mortar and concrete in less aggressive environments, such as those defined by Class 1 and 2 exposure in ACI 201.2R which may be more suitable to areas in Texas.
- A more comprehensive evaluation of structures potentially affected by external sulfate attack is needed. This evaluation should extend beyond the state of Texas and should include areas in which sodium sulfate or magnesium sulfate is prevalent. Only through detailed field evaluations can a correlation between laboratory tests and field performance be obtained, and upon achieving this objective, test methods and specifications can be refined to provide a more accurate and rational link between defining severity of exposure and selecting appropriate preventive measures. The placement of known mixtures in the field will help determine if Class C fly ash is a problem in one of the most extreme cases of gypsum in soils in Texas.