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Title:
Evaluation of the Strength of Cement-Treated Aggregate for Pavement Bases

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Supplementary Notes

Abstract

Cement-treated aggregate (CTA) is commonly used to provide a stable base for pavements that are placed over weak soil subgrades. Because CTA reduces the thickness of the aggregate required to provide a durable base by approximately one-half, using it as a bearing layer for pavement can limit the quantity of unsuitable soil that must be excavated and removed, and can reduce the erodability of the stabilized soils. However, the field performance of CTA is variable, even when prepared according to set standards.

This laboratory-based investigation explored the effects of fines content, cement content, mineralogy, and freeze/thaw cycling on the unconfined compressive strength of cement-treated aggregate. The mineralogy of the base aggregate was found to make a significant difference in the strength of the CTA, with strength increasing in the following order: mica, limestone, and diabase. The granite aggregate yielded variable results, but the strengths were generally on the order of those determined for the diabase aggregate. The pH of the samples also correlated well, with the measured strengths increasing as the pH increased. As was anticipated, increasing the cement content increased the measured unconfined compressive strength of cylinders that were not subjected to freeze/thaw cycling. The same basic trend was observed in cylinders that were subjected to freeze/thaw cycling; however, the increase was less pronounced in the cylinders that were subjected to physical abrasion during thaw cycles. The fines content did not significantly influence the unconfined compressive strength of the cylinders that were not subjected to freeze/thaw cycling; however, the fines content appeared to confer a protective effect to the durability of the cylinders that were subjected to freeze/thaw. For the freeze/thaw test conditions, the unconfined compressive strength increased as the fines content was increased.

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ABSTRACT

Cement-treated aggregate (CTA) is commonly used to provide a stable base for pavements that are placed over weak soil subgrades. Because CTA reduces the thickness of the aggregate required to provide a durable base by approximately one-half, using it as a bearing layer for pavement can limit the quantity of unsuitable soil that must be excavated and removed, and can reduce the erodability of the stabilized soils. However, the field performance of CTA is variable, even when prepared according to set standards.

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INTRODUCTION

Cement-treated aggregate (CTA) is commonly used to provide a stable base for pavements that are placed over weak soil subgrades. CTA consists primarily of coarse-grained aggregate, with a minimal fines content, mixed with a specified percentage of cement by weight, and field compacted at moisture contents slightly greater than the optimum moisture content. It is desirable to use CTA as a pavement subgrade because it reduces the thickness of the aggregate required to provide a durable pavement base by approximately one-half. Additionally, using CTA as a bearing layer for pavement can also limit the quantity of unsuitable soil that must be excavated and removed, and reduces the erodability of the stabilized soils (Salehi and Shiells, 1997).

Cement-treated aggregate is appealing as a low-cost construction material, and investigations have examined the use of marginal aggregates, such as low-grade laterite in combination with sand and cement, for use in low-cost pavement bases (Majumder et al. 1999). Researchers have also studied the use of recycled concrete in CTA (Lim and Zollinger 2003), quantifying the change in strength and modulus of elasticity in cement-treated aggregate bases as a function of time, using both crushed limestone and recycled concrete as the aggregate.

Additionally, soil cement is also an area of active research with studies investigating the application of sulfate-resistant cement stabilization to reduce sulfate-induced soil heave (Puppala et al. 2004), to increase the strength and stiffness of soft clays or peats (Chew et al. 2004; Hernandez-Martinez and Al-Tabbaa 2004; Lee et al. 2005), and as low-cost pavement bases (Mohammad et al. 2000).

PURPOSE AND SCOPE

In some cases, the field performance of CTA is variable, and poor performance is often attributed to a variety of factors including fines content, aggregate mineralogy, and chemical deterioration of the cement matrix due to the presence of expansive clays and ettringite formation (Scullion and Harris 1998). This work presents the results of a laboratory-based investigation of the effects of aggregate mineralogical composition, fines content, cement content, and freeze-thaw cycling on the performance of cement-treated aggregate. Performance of the aggregate was quantified by measuring the unconfined compressive strength of the CTA under a variety of experimental conditions.

CURRENT SPECIFICATION FOR CEMENT-TREATED AGGREGATE

Currently, the Virginia Department of Transportation (VDOT) plans specify the preparation of cement-treated aggregate as "Aggregate Base Material, Type I, Size No. 21A pugmill mixed with 4% hydraulic cement by weight" (from plan sheet no. 2). The design size range for aggregate 21A is shown in Table 1 and Figure 1. Additionally, "Type I shall consist of crushed stone, crushed slag, or crushed gravel, with or without soil mortar or other admixtures. Crushed gravel shall consist of particles of which at least 90 percent by weight of the material retained on the No. 10 sieve shall have at least one face fractured by artificial crushing" (VDOT, 2002). The 21A standard also calls for a well-graded material, with a coefficient of uniformity ($C_u = D_{60} / D_{10}$) greater than four and a coefficient of curvature ($C_c = D_{30}^{\ 2} / (D_{10} D_{60})$) between one and three, and for a fines content with liquid limit equal to 25 or less.

Table 1. Design Range for Dense Graded Aggregate (from Road and Bridge Specifications 2002)

			Amounts Finer Than Each Laboratory Sieve (Square Openings*) (% by Weight)			
Size No.	**2 in**	**1 in**	**3/8 in**	**No. 10**	**No. 40**	**No. 200**
21A	100	94-100	63-72	32-41	14-24	6-12

*In inches, except where otherwise indicated. Numbered sieves are those of the U.S. Standard Sieve Series.

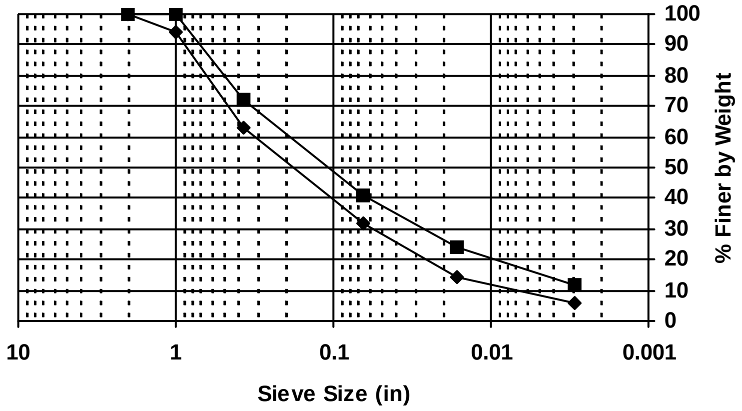

Figure 1. Grain Size Distribution for Aggregate 21A with Minimum and Maximum Particle Sizes Shown

EXPERIMENTAL MATERIALS AND METHODS

Materials

Aggregate was obtained from four quarries commonly used as source material for CTA by the Virginia Department of Transportation (VDOT). The quarries were located in Dale, Virginia; Lynchburg, Virginia; Manassas, Virginia; and Skippers, North Carolina, and will be referred to as Dale, Lynchburg, Manassas, and Skippers, respectively. The primary mineral constituent of the aggregates from each quarry were: mica (Dale), limestone (Lynchburg), diabase (Manassas), and granite (Skippers). Aggregate was delivered to the Virginia Transportation Research Council (Charlottesville, VA) in 22.7 kg (50 lb) bags which were then sieved with a number 200 mesh sieve to remove the fines. Fines were added back into the samples at 4, 7, 10, and 14% by weight in order to control the proportion of fine material in the samples as a variable during the testing program. Test specimens were then prepared with Type I portland cement at contents of 3, 4, 5, and 6% by weight, at each fines content, yielding 16 test conditions for the aggregate from each quarry (Table 2). Three samples were prepared for each test condition, and the data were averaged for analysis.

Table 2. Test Conditions for Minerals from Each Quarry

Specimen Number	Fines Content	Cement Content
1	4	3
2	7	3
3	10	3
4	14	3
5	4	4
6	7	4
7	10	4
8	14	4
9	4	5
10	7	5
11	10	5
12	14	5
13	4	6
14	7	6
15	10	6
16	14	6

Methods

Chemical characterization of the aggregates included x-ray diffraction for the identification of the predominant mineral phases and measurement of aggregate pH. X-ray diffraction samples were disaggregated and powdered using a SPEX 8000 tungsten carbide ball mill, and back-packed sample mounts of the fine powder were used for XRD analysis. X-ray diffraction patterns were generated using Cu$K\alpha$ radiation on a PanAlytical, Theta-Theta X-ray diffractometer, using a "Spinner Sample Stage" operating at 45 kV and 40 mA, between 5 and 75º (2θ) at a step size of 0.0330. X'Pert High Score search/match software was used for sample phase identification. X-ray diffraction analysis was performed at James Madison University (Harrisonburg, VA).

The pH of the aggregate samples was determined using EPA method 9045C (SW-846) (Lancaster Laboratories; Lancaster, PA). The predominant form of ions present in each of the mineral phases was determined by Lancaster Laboratories, Lancaster, PA using EPA method 6010B (SW-846). Analyzed ions were aluminum, calcium, magnesium, potassium, and sodium, and with concentrations determined using Inductively Coupled Argon Plasma Spectroscopy (ICAP) with a Thermo Jarrell Ask ICAP 61E Trace Analyzer.

Physical characterization tests for the four soil samples included a particle-size analysis performed according to ASTM D422 and determination of the liquid limit for the fine materials according to ASTM D4318. Standard Proctor compaction tests were conducted according to ASTM D698 and unconfined compression tests (7-day compressive strength) were conducted according to ASTM D1633-96 Method A. According to the guidelines established in ASTM D1633, the cylinders were prepared in a standard Proctor mold (101.6 mm diameter and 116.4 mm in height), as recommended for aggregate samples with particles retained on the No. 4 sieve. Method A is also used more commonly in practice, yielding results that are more consistent with historically measured values (ASTM D1633). Freeze-thaw testing was conducted according to ASTM D560.

Optimum moisture content for each test condition was determined according to standard Proctor (ASTM D698), and ranged between 5.2 and 12.5% for the 64 combinations tested (16 test variations times four quarries). Unconfined compression test specimens were then compacted at optimum moisture content, in three layers with 25 blows per layer using an automatic soil compactor. Specimens were extruded with a hydraulic jack, and cured in a moisture room at 100% relative humidity and 20 ºC for seven days. Specimens were soaked in tap water for four hours prior to measurement of the unconfined compressive strength, according to ASTM D1633. Compression testing was performed at a loading rate of approximately 64 kPa/sec (9.3 psi/second).

The Manassas aggregate was chosen to quantify the effect of freeze-thaw cycling on the compressive strength of the CTA. Freeze-thaw testing was designed to test a specimen’s endurance and strength under simulated temperature cycling. Each cylinder was made identically to those of the compression cylinders and then stored in the moist cure room for seven days. For freeze-thaw testing, two separate cylinders were tested:

> *Freeze-Thaw Cylinder 1*: After the 7-day storage period, the cylinders were placed on 6.5 mm (0.25 inch) water saturated felt pads and placed into a freezer at a temperature of -23º Celsius (-9º Fahrenheit) for a period of 24 hours. At this time, each cylinder was removed from the freezer, and weighed and measured for average height and diameter. Then the cylinder was moved to the moist cure room to thaw for 23 hours at 20º Celsius (68º Fahrenheit), where the only source of free water was through capillary action. At the end of the thaw cycle, the cylinders were again weighed, and average height and diameter readings were taken. This completed the first of twelve identical cycles. At the

completion of cycle twelve, the cylinders were oven dried at 110° Celsius (230° Fahrenheit) and then weighed, which yielded the changes in mass and volume over time.

Freeze-Thaw Cylinder 2: The process for the second cylinder was the same, except at the end of each thaw cycle, the specimens were brushed with a wire brush with 18-20 strokes on all sides and 4 strokes on each end, and weighed again.

RESULTS AND DISCUSSION

Geochemical Composition

X-ray diffraction analysis confirmed the aggregate compositions (Table 2), with biotite mica being identified in the mineral phase for the Dale aggregate, along with albite, quartz, and clinochlore, minerals known to occur geologically with biotite. X-ray diffraction identified calcite and dolomite in the limestone Lynchburg sample, along with commonly associated quartz. The diabase Manassas aggregate contained pyroxene, as well as albite, quartz, and clinochlore. Finally, the granite Skippers aggregate contained quartz, albite, microcline, and mica, all mineral constituents of granite. Additional other minerals in minor proportions were found to occur in the samples as well. The primary ions identified in the mineral phase supported the results of the x-ray diffraction analysis (Figure 2).

Table 3. X-ray Diffraction Analysis and Chemical Composition of Aggregates

Quarry	Mineral	Chemical Formula
Dale	Mica (Biotite)	$K(Mg_{1.48}Fe_{1.28}Ti_{0.24})Al_{1.2}Si_{2.8}O_{10}(OH)_{1.4}$
	Albite (Na-plagioclase Feldspar)	$(Na,Ca)Al(Si,Al)_3O_8$
	Quartz	SiO_2
	Clinochlore	$(Mg,Fe)_6(Si,Al)_4O_{10}(OH)_8$
	Microcline (Potassium Feldspar)	$KAlSi_3O_8$
Lynchburg	Calcite	$Mg_{0.03}Ca_{0.97}\ CO_3$
	Dolomite	$CaMg\ (CO_3)_2$
	Quartz	SiO_2
	Clinochlore	$(Mg,Fe)_6(Si,Al)_4O_{10}(OH)_8$
	Muscovite	$H_2KAl_3(SiO_4)_3$
Manassas	Pyroxene (Diopside or Augite)	$(Mg_{0.992}Fe_{0.008})(Ca_{0.97}Mg_{0.022}Fe_{0.008})(Si_2O_6)$
	Albite (Na-plagioclase Feldspar)	$(Na,Ca)Al(Si,Al)_3O_8$
	Quartz	SiO_2
	Clinochlore	$(Mg,Fe)_6(Si,Al)_4O_{10}(OH)_8$
Skippers	Quartz	SiO_2
	Albite (Na-plagioclase Feldspar)	$(Na,Ca)Al(Si,Al)_3O_8$
	Microcline (Potassium Feldspar)	$KAlSi_3O_8$
	Mica (Phlogopite or Biotite)	$K(Mg,Fe)_3(Al,Fe)Si_3O_{10}(OH,F)_2$

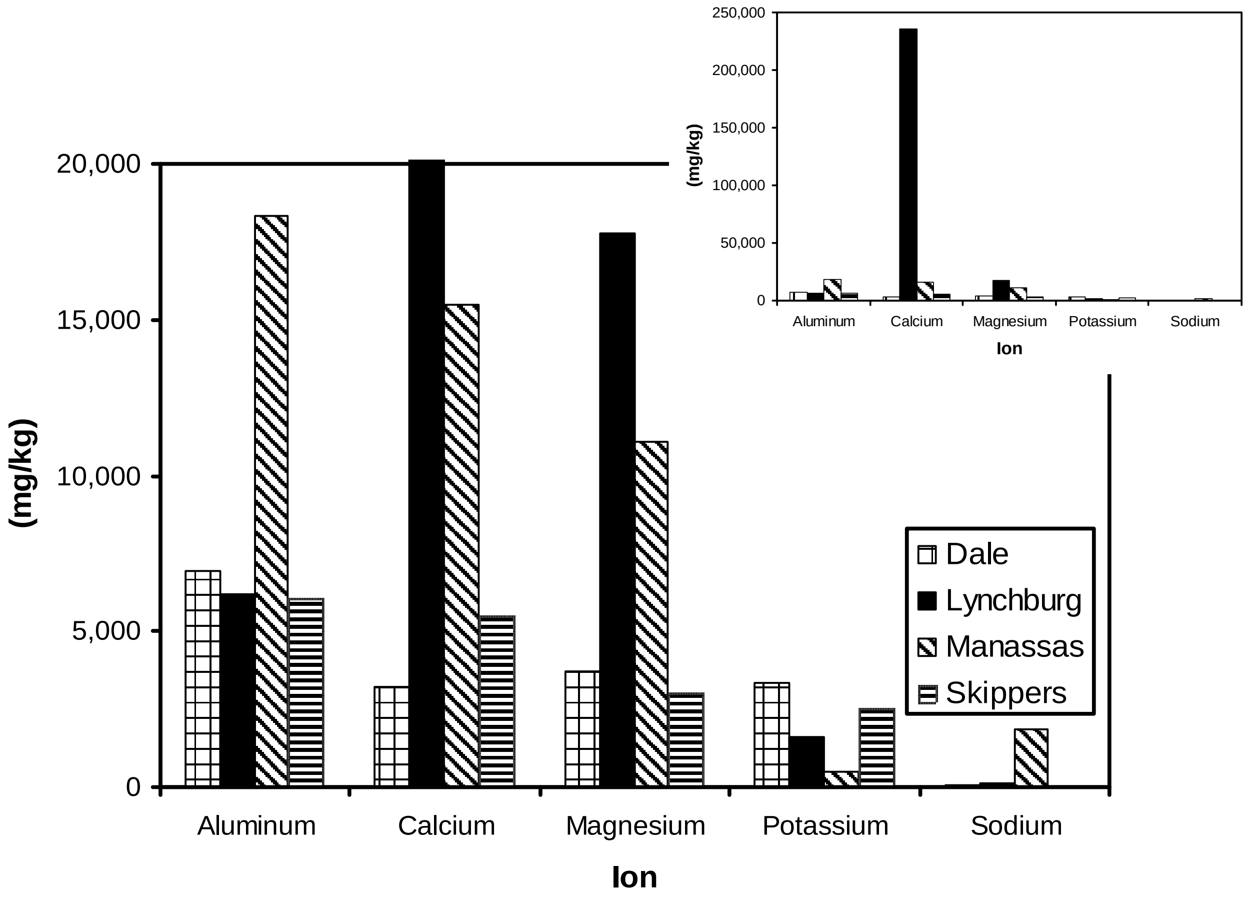

Figure 2. Concentration of Major Exchangeable Ions in Aggregate Samples.

The pH of the four aggregates did not differ significantly, ranging from 8.9 to 9.3: Dale (mica) pH = 8.9, Lynchburg (limestone) pH = 9.0, Manassas (diabase) pH = 9.3, and Skippers (granite) pH = 9.2. Similarly, the liquid limits measured for the fines contents for the four aggregates did not differ significantly, ranging from 23-25.

The sieve analysis on the as-delivered aggregate samples demonstrated that the aggregate did not meet grain size specifications as required by VDOT standard 21A, generally falling below the specified range (Figure 3 and Table 4). However, because the fines were removed by sieving, and added back to the coarse aggregate to achieve the desired fines content, the lack of conformance to the VDOT standard did not affect this investigation, although it could be a factor in the field performance. It is not known why the samples delivered to VTRC did not meet the specified grain size distribution, and it is recommended that the grain size for aggregate in CTA applications be field verified to guarantee that the as delivered samples are within standards.

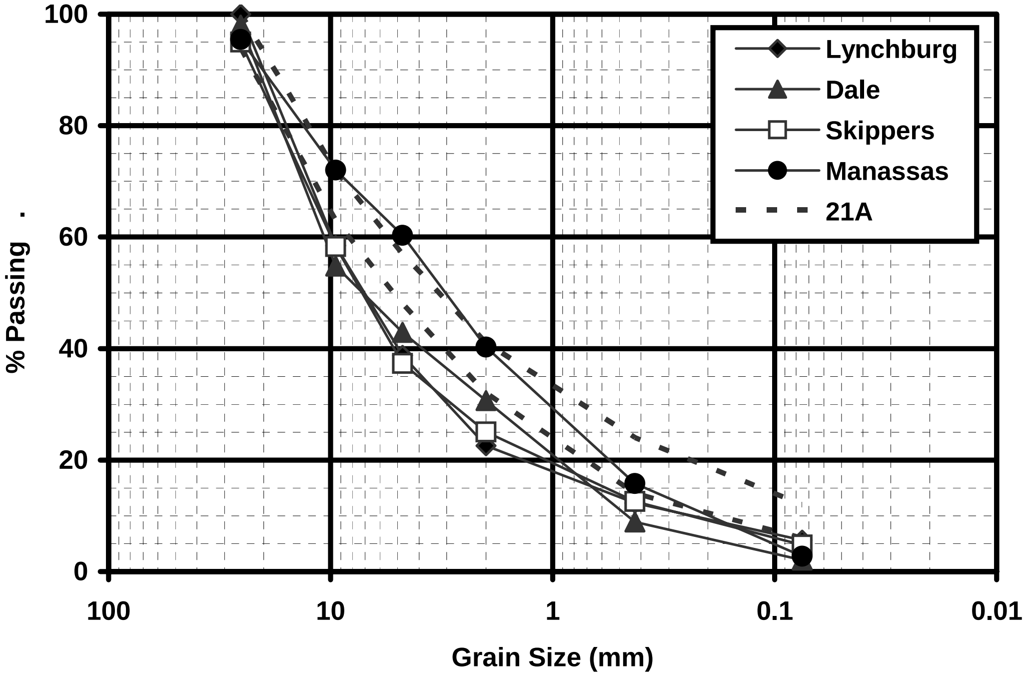

Figure 3. Sieve Analysis Results on the As-Delivered Aggregate Samples.

Table 4. Sieve Analysis for All Sites

Sieve	Sieve Size (mm)	% Passing				
		21A Standard	Lynchburg	Dale	Skippers	Manassas
1	25.4	94-100	100.00	98.07	95.01	95.46
3/8	9.5	63-72	58.48	54.83	58.33	72.05
4	4.75	48-57	38.79	42.91	37.35	60.32
10	2	32-41	22.57	30.68	25.07	40.28
40	0.425	14-24	12.29	8.91	12.58	15.78
200	0.075	6-12	5.63	2.06	4.79	2.79

Coefficients of uniformity ($C_u = D_{60} / D_{10}$) and curvature ($C_c = D_{30}{}^2 / (D_{10} D_{60})$) were tabulated for the four aggregates under analysis (Table 5). Only the Manassas aggregate met the requirements of the 21A standard, with a C_u greater than 4, and a C_c between 1 and 3, although the results for the other three quarries were reasonably close to the required values.

Table 5. Coefficients of Curvature and Uniformity

	C_u	C_c
Dale	23	0.7
Lynchburg	34	3.5
Manassas	17	1.6
Skippers	34	3.1

Unconfined Compressive Strength

Effect of Cement Content

All strengths reported are 7-day compressive strengths. The unconfined compression results show similar trends for the aggregates from Dale, Lynchburg, and Manassas, with the aggregate from Skippers demonstrating significantly different behavior (Figure 4 - Figure 7). For all aggregates, the data demonstrate that the compressive strength increases essentially linearly as a function of cement content, as was anticipated. The aggregates from Dale (mica), Lynchburg (limestone), and Manassas (diabase) showed an approximate doubling of unconfined compressive strength as the cement content was increased from its lowest value of 3% to the highest tested value of 6%, while for the Skippers (granite) quarry, the strength at 6% cement content increased two to three times the strength measured at 3% cement content.

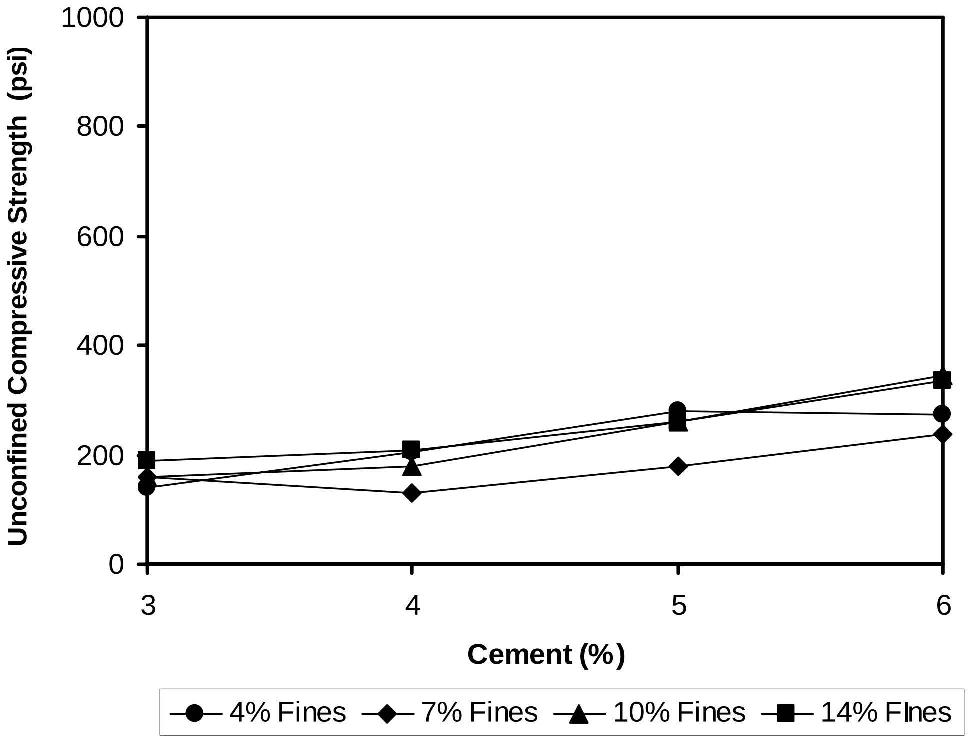

Figure 4. Unconfined Compressive Strength of Dale Aggregate as a Function of Cement Content.

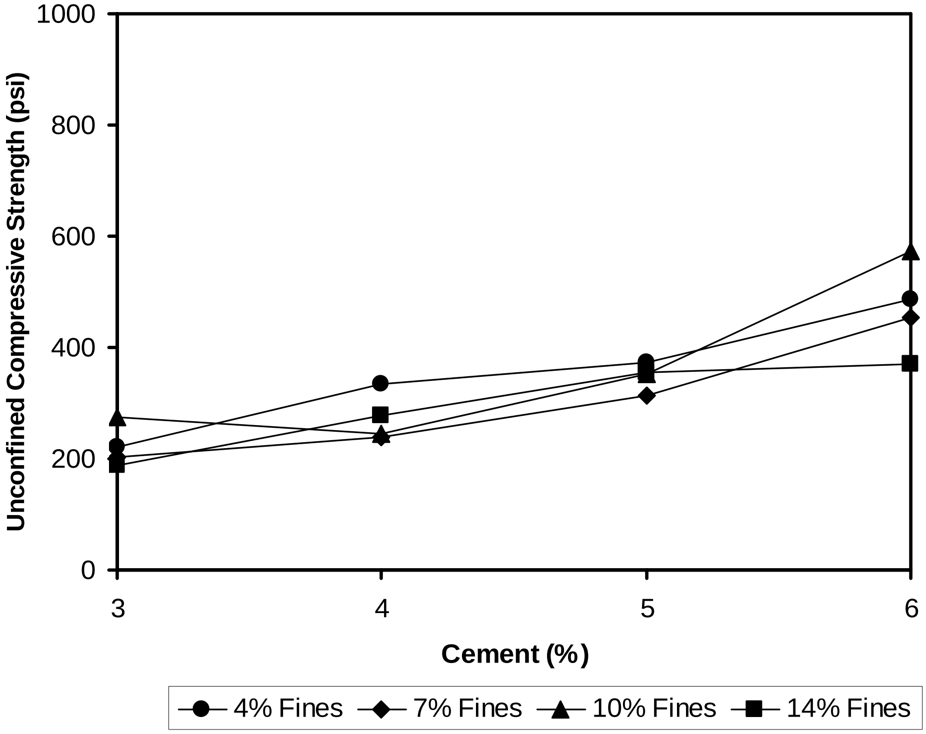

Figure 5. Unconfined Compressive Strength of Lynchburg Aggregate as a Function of Cement Content.

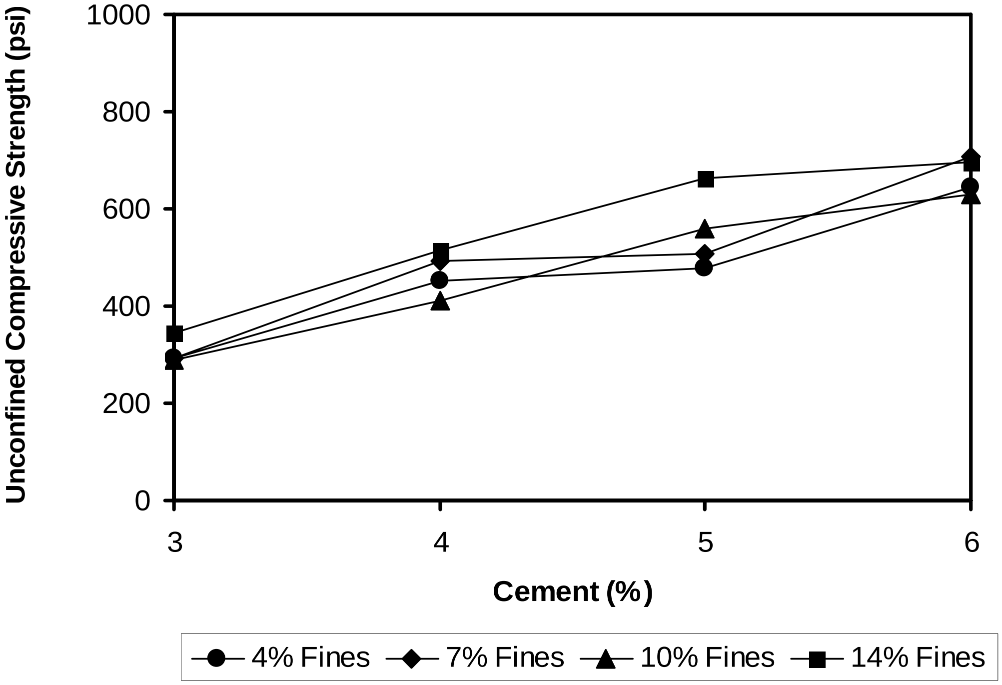

Figure 6. Unconfined Compressive Strength of Manassas Aggregate as a Function of Cement Content.

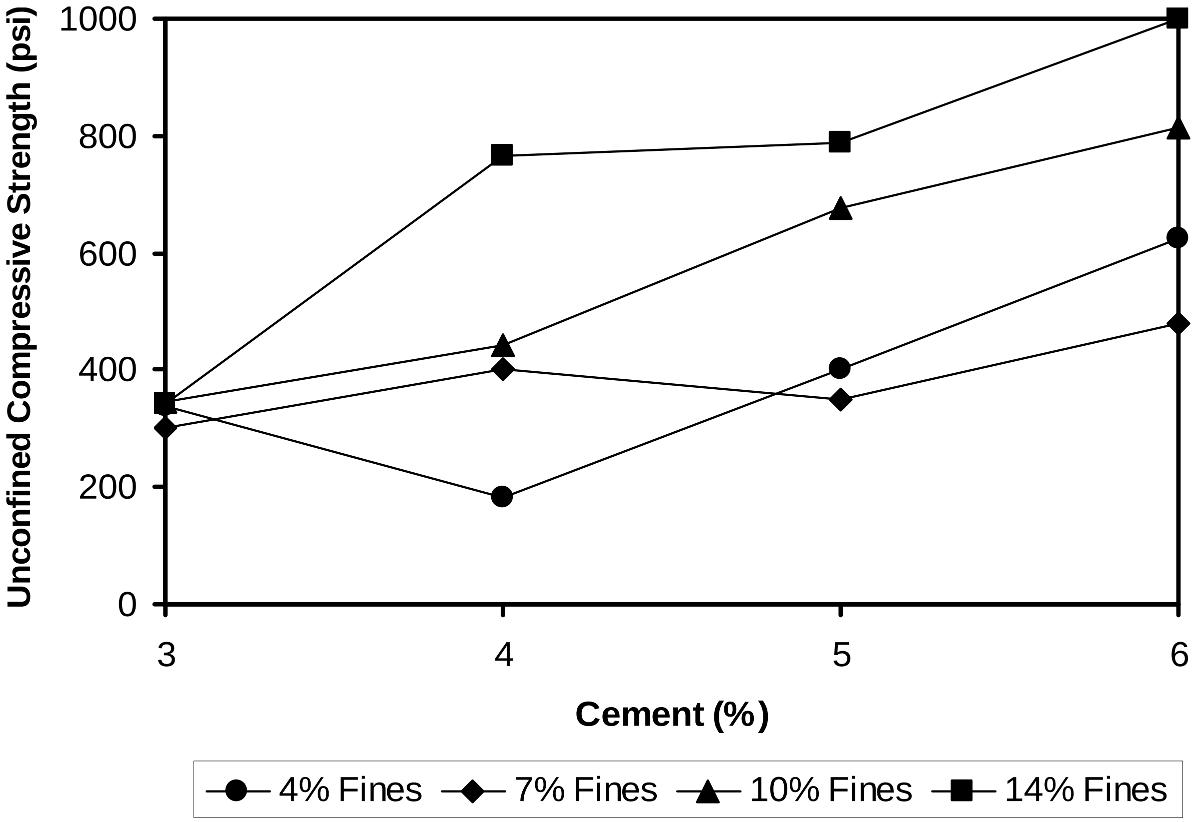

Figure 7. Unconfined Compressive Strength of Skippers Aggregate as a Function of Cement Content.

Of the three aggregates with clearly identifiable trends in unconfined compressive strength (Dale, Lynchburg, and Manassas), the aggregate from the Dale quarry (mica) was consistently the weakest with unconfined compressive strengths in the range of 130-345 psi, Lynchburg (limestone) was the next strongest with values in the range of 190-575 psi, and Manassas (diabase) was consistently the strongest with values of 290-695 psi (Figure 8). In general, the values measured for the Skippers (granite) quarry were equivalent with, or higher than those measured for Lynchburg and Manassas (Skippers data omitted from Figure 8 for clarity).

The pH measured for the aggregates correlates well with the ultimate strength of the CTA, with the Dale mica at the lowest pH (pH = 8.9) and strength, Lynchburg limestone at a pH = 9.0 and intermediate strength, and the Manassas diabase at a pH = 9.3 and the highest strength of the three aggregates. Skippers granite (pH = 9.2), which showed some inconsistency in measured strength, demonstrated an unconfined compressive strength that bounded the values measured for Manassas (pH = 9.3) (Figure 5).

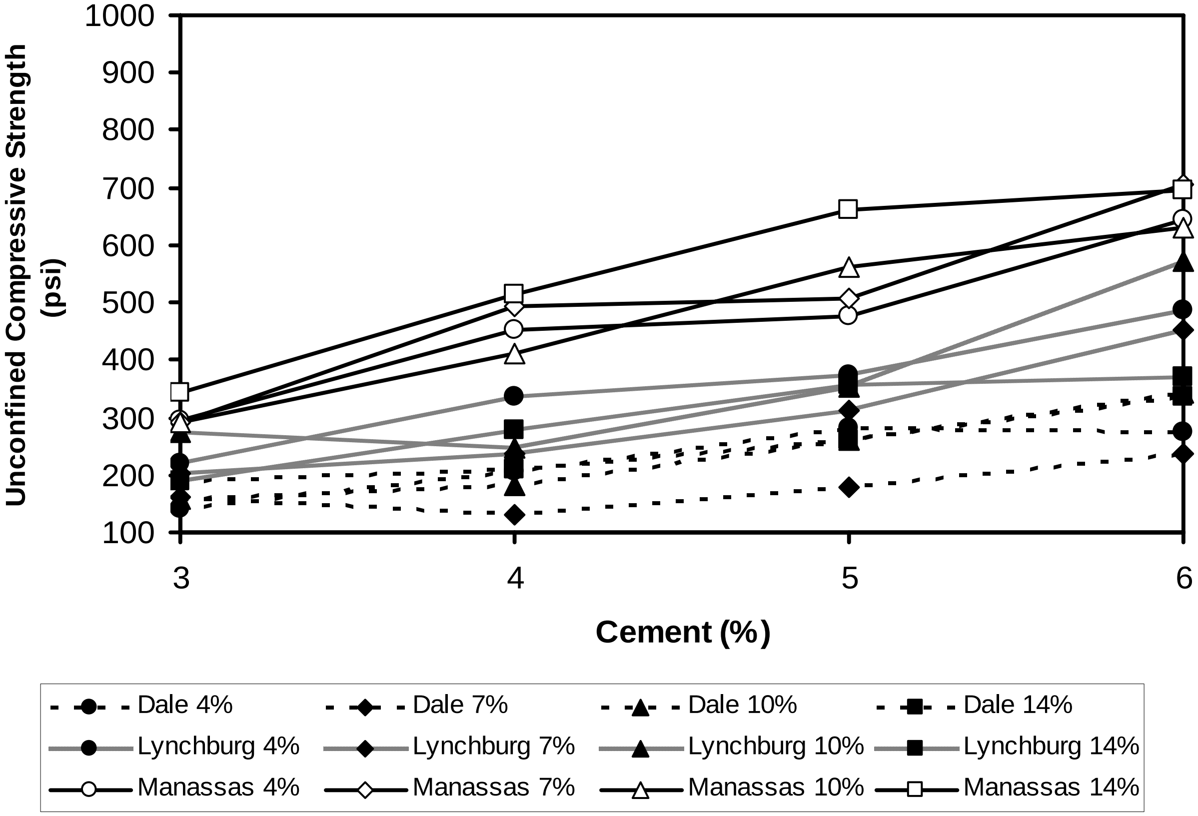

Figure 8. Comparison of Unconfined Compressive Strength of Aggregates as a Function of Cement Content (Skippers Data Omitted for Clarity).

Effect of Fines Content

No significant effect of fines content was identified for the Dale, Lynchburg, and Manassas quarries (Figure 9). However, the effect of fines content was pronounced on the Skippers aggregate, with the strength increasing as the fines content was increased, with the exception of the 3% cement content samples (Figure 10). The reason for this effect on the Skippers aggregate is unknown.

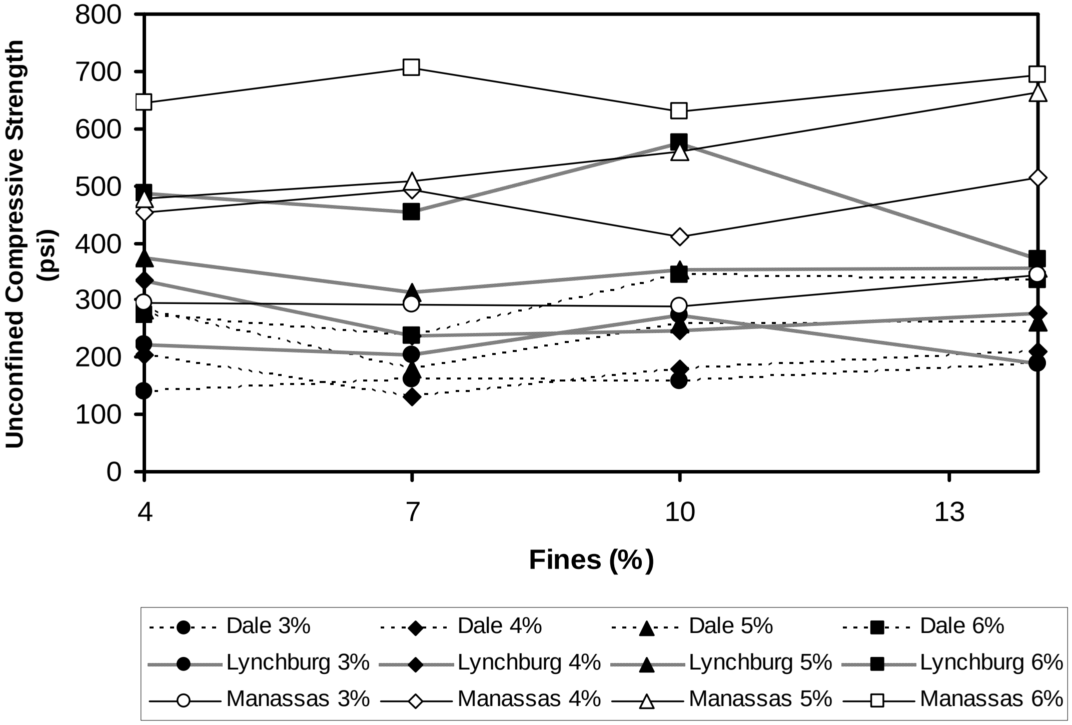

Figure 9. Effect of Fines Content on the Strength of Dale, Lynchburg, and Manassas Aggregates.

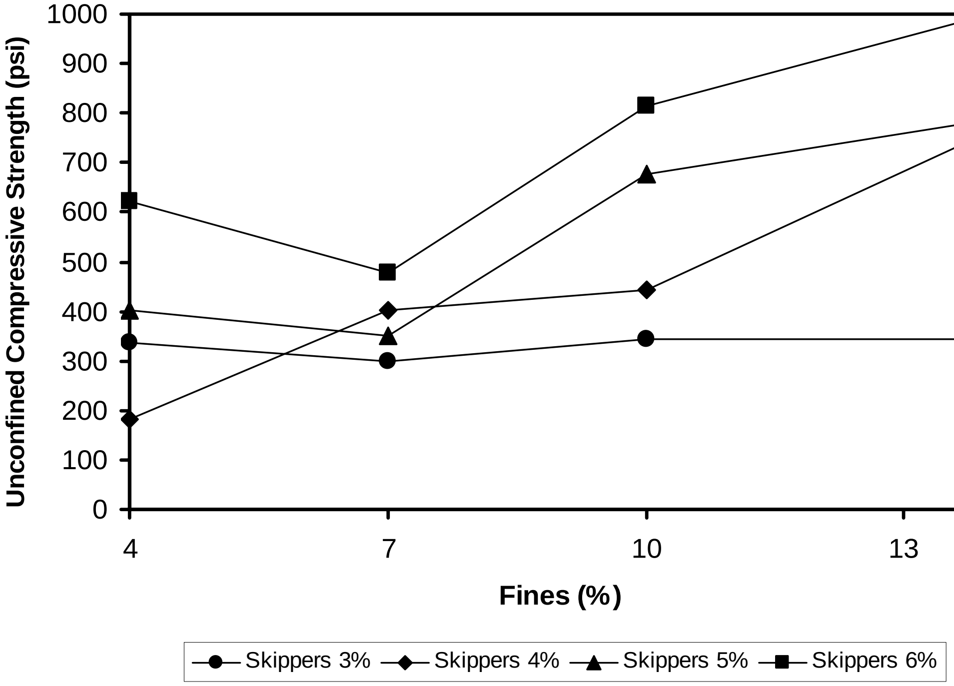

Figure 10. Effect of Fines Content on the Strength of Skippers Aggregate.

Effect of Molding Water Content

The tests performed at -2% optimum moisture content demonstrated a lower unconfined compressive strength than did the specimens constructed at optimum moisture content; however, the trends are somewhat obscured due to the variability of the tests performed at optimum moisture content (Figure 11). Figure 12 shows the data collected at minus 2% optimum moisture content, with the data from optimum moisture content omitted for clarity. In general, the tests performed on the Skippers aggregate at -2% optimum moisture content demonstrated a weak dependence on the fines content.

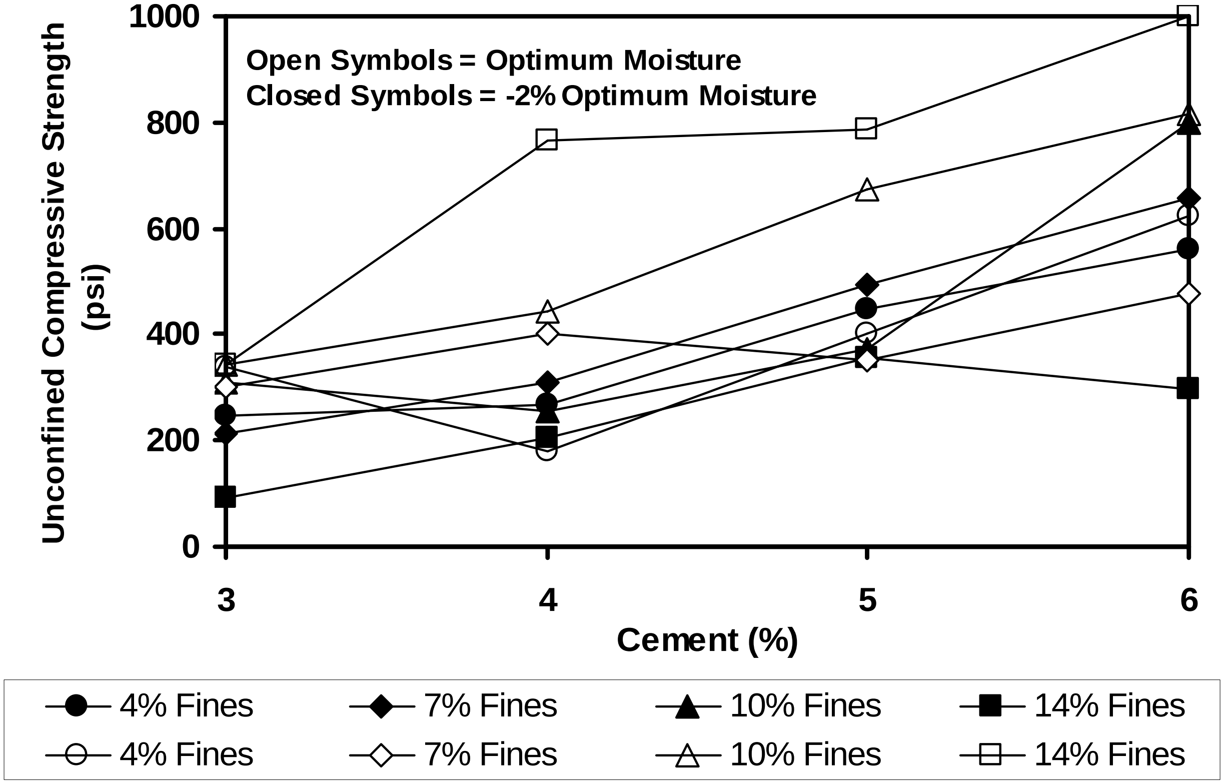

Figure 11. UC Strength of Skippers Aggregate (Optimum and -2% Optimum Water Content) as a Function of Cement Content.

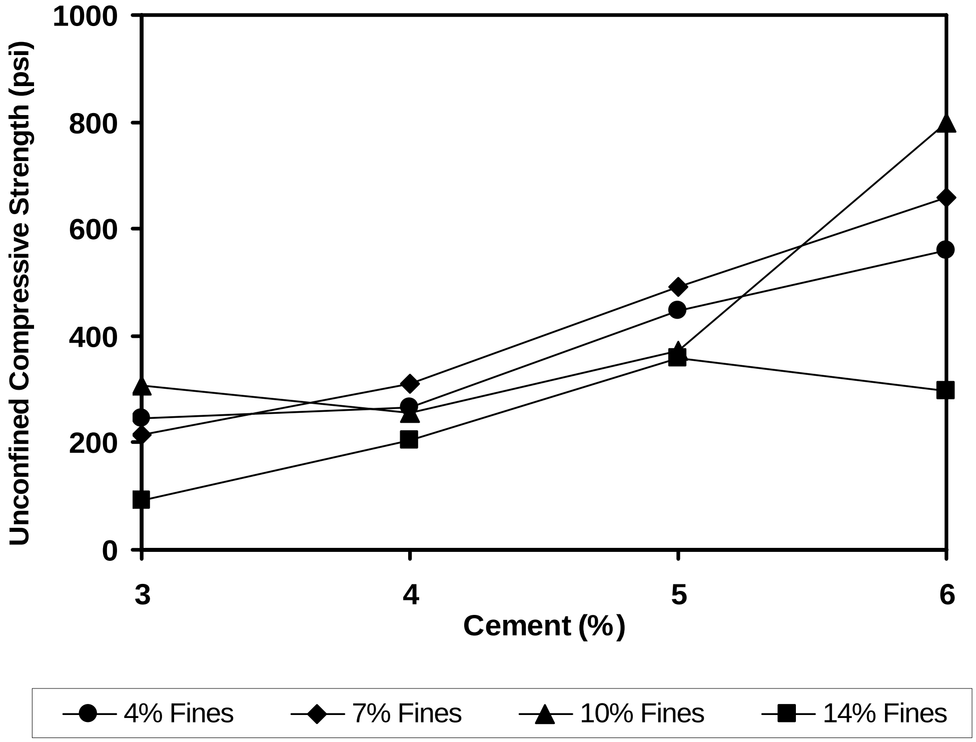

Figure 12. UC Strength of Skippers Aggregate (-2% Optimum Water Content)

Freeze-Thaw Cycling

Freeze-thaw specimens using the Manassas (diabase) aggregate were made identically to the unconfined compression cylinders, with two specimens prepared for two different procedures. Specimen #1 was tested for changes in mass and volume. No physical changes were made to the cylinders in any of the stages of this test; it acted as the control specimen. In contrast, specimen #2 underwent brushing after each thaw cycle, which resulted in a continuously decreasing mass. This specimen was used to test the cylinder's resistance to simulated loading under weather and moisture variations.

In contrast to the strength behavior of the cylinders that were not subjected to freeze-thaw cycling, the measured unconfined compressive strength of the freeze-thaw cycled specimens exhibited a dependence on the fines content, with the strength increasing between 50% to 100% as the fines content was increased (Figure 13). As the fines content of the specimens increased from 4% to 14%, the unconfined compressive strength also increased, with exception of 14% fines/6% cement, which appears to be a bad data point. Increasing the fines content of the cylinders yielded an increase in the unconfined compressive strength for both the cylinder with no abrasion and for the cylinder with physical abrasion (Figure 14), although it was most pronounced in the cylinder with no abrasion.

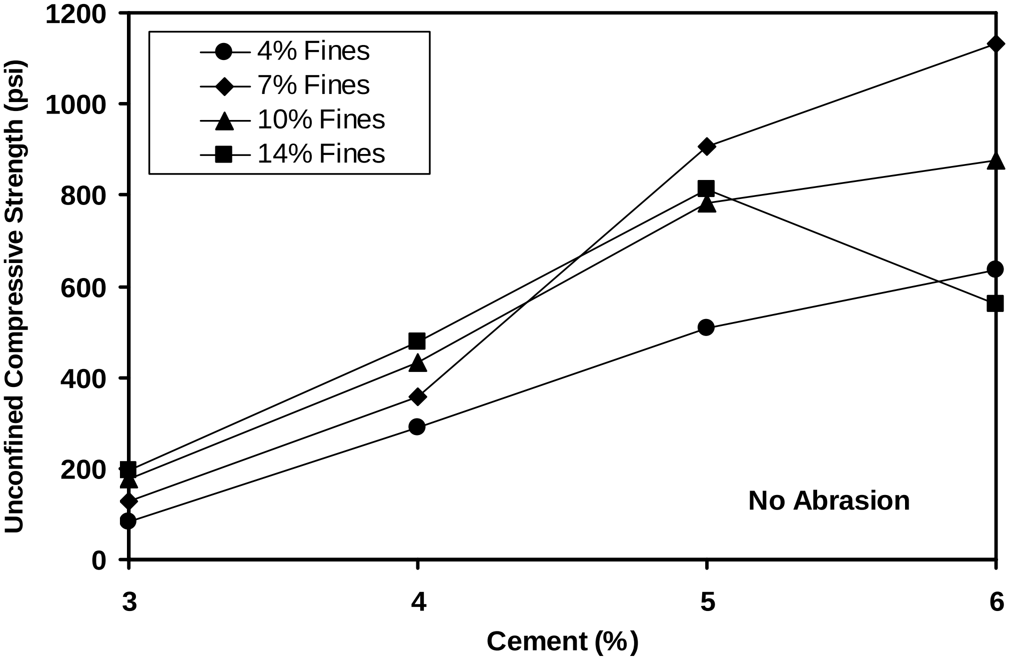

Figure 13. Unconfined compressive strength of Manassas aggregate after freeze-thaw cycling; as a function of cement content with no physical abrasion.

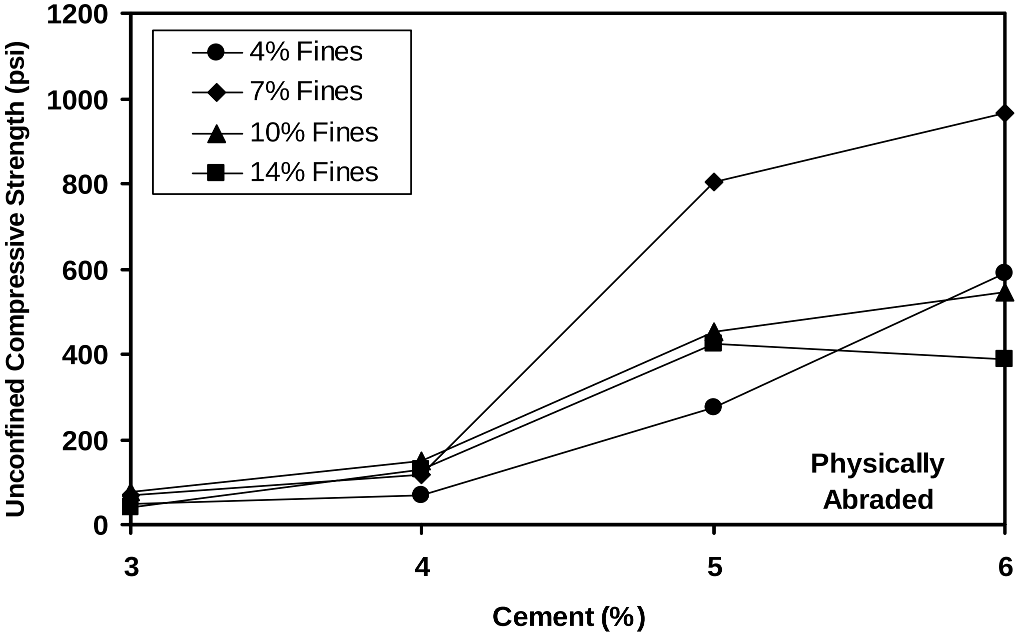

Figure 14. Unconfined compressive strength of Manassas aggregate after freeze-thaw cycling; as a function of cement content with physical abrasion after each cycle.

Comparison of the unconfined compressive strengths for the freeze-thaw samples that were not physically abraded to that of the cylinders that were physically abraded demonstrates that in all cases, the abrasion decreased the measured unconfined compressive strength, as would be anticipated (Figure 15).

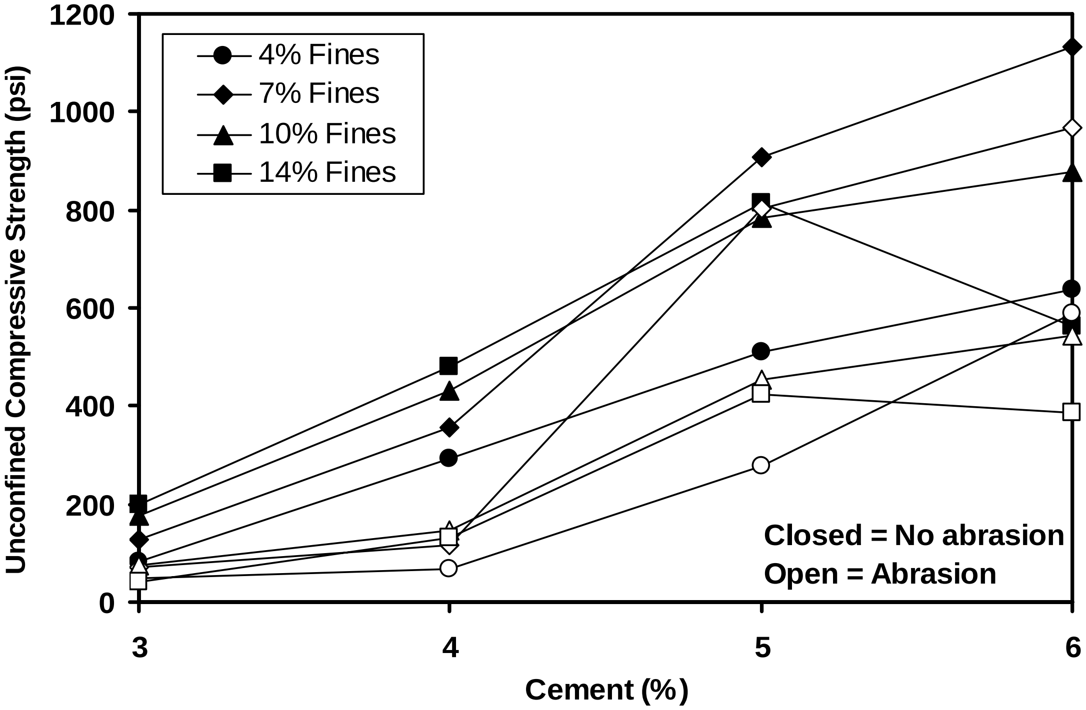

Figure 15. Comparison of performance of Manassas freeze-thaw cylinders without abrasion (closed symbols) and with abrasion (open symbols); plotted as a function of cement content.

In general, the specimens that were subjected to freeze-thaw cycling, but were not physically abraded, demonstrated a clear dependence on the cement content of the samples, with unconfined compressive strengths increasing as cement content was increased. Similarly, the specimens that were subjected to physical abrasion demonstrated similar dependence of unconfined compressive strength on the cement content.

Comparison of the unconfined compressive strength measured for cylinders that were not subjected to freeze-thaw cycling with the cylinders that were subjected to freeze-thaw cycling with abrasion demonstrates that, for the most part, a lower unconfined compressive strength was obtained for the cylinders that underwent freeze-thaw (Figure 16), as would be anticipated. In two of the instances, higher strengths were measured for the cylinders that were subjected to freeze-thaw; however, this is attributed to the experimental difficulty of working with an inherently variable particulate material. The unconfined compressive strength was particularly sensitive to freeze-thaw cycling when the cylinders were constructed at low cement content (3% and 4% cement), demonstrating approximately 10% of the strength of the cylinders that were not subjected to freeze-thaw cycling. However, at the highest fines and cement contents, the cylinders that were subjected to freeze-thaw cycling demonstrated approximately two-thirds the unconfined compressive strength of the cylinders that were not subjected to freeze-thaw cycling.

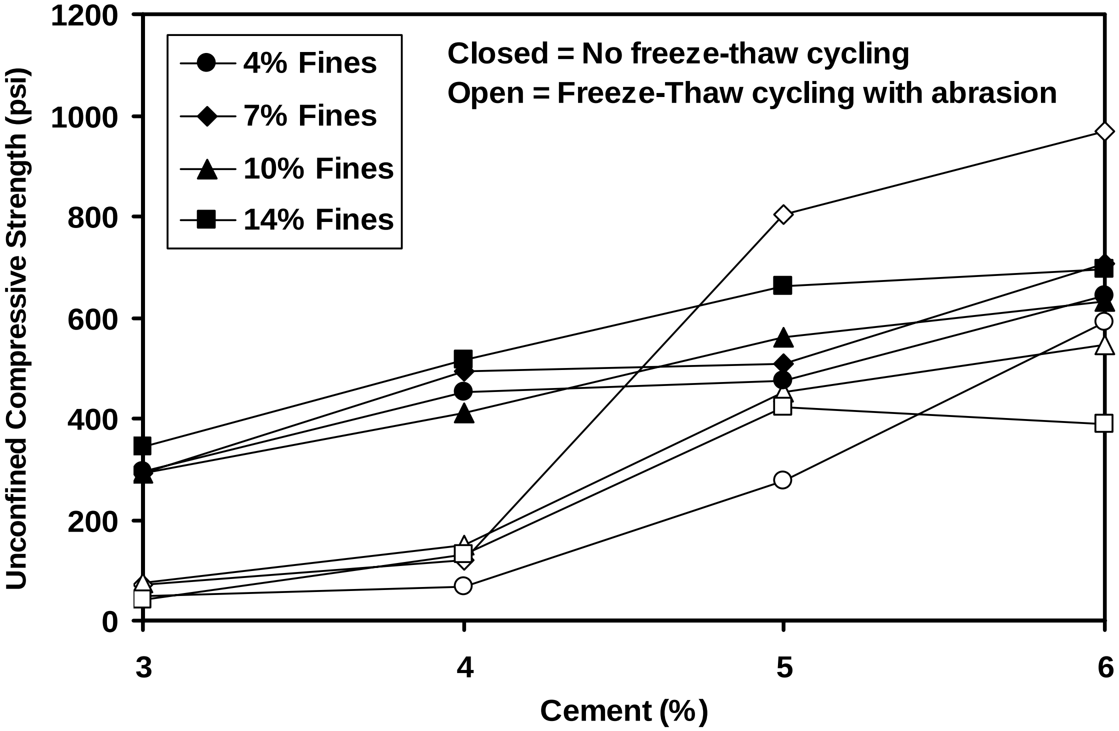

Figure 16. Comparison of performance of Manassas aggregate with (closed symbols) and without (open symbols) freeze-thaw testing.

Cylinders made from the Manassas aggregate were also monitored for mass and volume loss as a function of the number of freeze thaw cycles. The data consistently demonstrated that the cylinders constructed with 4% fines are sensitive to mass loss through freeze-thaw cycling (Appendix A and Appendix B). The effect is most pronounced at low cement contents, demonstrating a lower mass loss at 5% and 6% cement content than at the lower cement contents (3% and 4%). In contrast, cylinders constructed with 7%, 10%, and 14% fines content show little variability in mass loss as a function of cement content, indicating that a critical level of protective fines is achieved between 4% and 7% fines content. Similarly, the recorded volume loss demonstrates a strong dependence on the fines and cement contents, with the cylinders made from 3% cement/ 4% fines exhibiting significant (~10%) losses in volume. Cylinders made with more than 3% cement or 4% fines exhibit little significant difference in their mass and volume loss resistance to freeze-thaw.

CONCLUSIONS

This laboratory-based investigation explored the effects of fines content, cement content, mineralogy, and freeze-thaw cycling on the unconfined compressive strength of cement-treated aggregate. The mineralogy of the base aggregate was found to make a significant difference in the strength of the CTA, with strength increasing in the following order: mica (Dale), limestone (Lynchburg), and diabase (Manassas). The Skippers aggregate, composed primarily of granite, yielded variable results, but the strengths were generally on the order of those determined for the Manassas diabase aggregate. The performance of a lab based investigation allowed comparison of the experimental variables under controlled boundary conditions, facilitating more efficient field-scale implementation of CTA testing.

The pH of the samples also correlated well with the measured strengths increasing as the pH increased: mica (Dale pH =8.9), limestone (Lynchburg pH = 9.0), and diabase (Manassas pH = 9.3). Skippers granite, with strengths on the order of those measured for Manassas had a pH = 9.2. As was anticipated, increasing the cement content increased the measured unconfined compressive strength of cylinders that were not subjected to freeze-thaw cycling. The same basic trend was observed in cylinders that were subjected to freeze-thaw cycling; however, the increase was less pronounced in the cylinders that were subjected to physical abrasion. The fines content did not significantly influence the unconfined compressive strength of the cylinders that were not subjected to freeze-thaw cycling; however, the fines content appeared to confer a protective effect to the durability of the cylinders that were subjected to cycles of freezing and thawing. For freeze-thaw test conditions, the unconfined compressive strength increased as the fines content was increased, with strengths between 50% and 100% greater as the fines content was increased.

For cylinders tested at 4% cement content (current specification) and *not* subjected to freeze-thaw cycling, the unconfined compressive strength increased in the following order: Dale (130-210 psi), Lynchburg (240-335 psi), Manassas (410-515 psi), and Skippers (400-765 psi) (neglecting apparently unreliable data at 4% cement/4% fines). The results represent the expected values that would be obtained on cylinders tested during field construction. The minimum acceptable unconfined compressive strength of the cement-treated aggregates is a function primarily of: mineral type and cement content. It is known that the Lynchburg aggregate has performed successfully under the current standards of 4% cement content (with significant quality assurance and quality control in the field); consequently, it is recommended that the 7-day unconfined compressive strength of cylinders not subjected to freeze-thaw testing be 250 – 300 psi.

RECOMMENDATIONS

All recommendations are to be implemented by VDOT's Materials Division.

1. The 7-day unconfined compressive strength of cement-treated aggregate cylinders (not subjected to freeze-thaw testing) should meet a minimum standard of 250 psi.

2. The cement content of CTA from the Manassas (diabase) and Skippers (granite) quarry should be a minimum of 3%, and the cement content for the Lynchburg (limestone) quarry should be a minimum of 4%. However, the current standard that specifies 4% cement content will produce CTA that is too weak with the Dale (mica)

used as the aggregate; consequently, a cement content of 6% should be used for CTA with mica as the aggregate.

3. In the cases where the mineralogy of the source quarry is unknown, the mineralogy should be tested and the minimum cement contents as outlined in recommendation 2 should be followed.

4. Pavement test sections should be constructed to field-verify that the fines content provides a protective effect to cement-treated aggregate that is subjected to freeze-thaw cycling. Based on the results of the laboratory strength tests, the field test section should use CTA constructed with 7% - 10% fines content for the best expected performance.

COSTS AND BENEFITS ASSESSMENT

Reducing the required cement content for the Manassas and Skippers quarries from 4% to 3% will result in a cost savings. Assuming an average dry unit weight of 135 lb/ft^3, which was representative of the material used in this study, results in a reduction in cement from 5,400 lb per 1,000 ft^3 at 4% cement content to 4,050 lb per 1,000 ft^3 at 3% cement content, reflecting a savings of 1,350 pounds of cement for every 1,000 ft^3 of CTA. At a price of \$0.04 per pound of portland cement, the reduction in cement content would save \$54 per 1,000 ft^3 of CTA.

In order to meet the minimum recommended strength standard, the cement content in CTA made with the Dale aggregate must be increased. For the Dale aggregate, with an average dry unit weight of approximately 125 lb/ft^3, increasing the cement content from 4% to 6% will result in an increase of 2,500 pounds of cement required in every 1,000 ft^3 of CTA (5,000 pounds/1000 ft^3 at 4% cement content versus 7,500 pounds/1000 ft^3 at 6% cement content). At a price of \$0.04 per pound of portland cement, the increase in cement content would cost \$100 per 1,000 ft^3 of CTA. Although the increase in the required cement content will increase the cost, it will result in improved field performance for the Dale aggregate in CTA.

ACKNOWLEDGMENTS

The authors thank Arthur Wagner, Bill Ordel, Michael Burton, and Marshall Davis for their assistance with the laboratory portion of this investigation and Susan Warr for her extensive testing at the beginning of the investigation.

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APPENDIX A

Mass Loss as a Function of Time

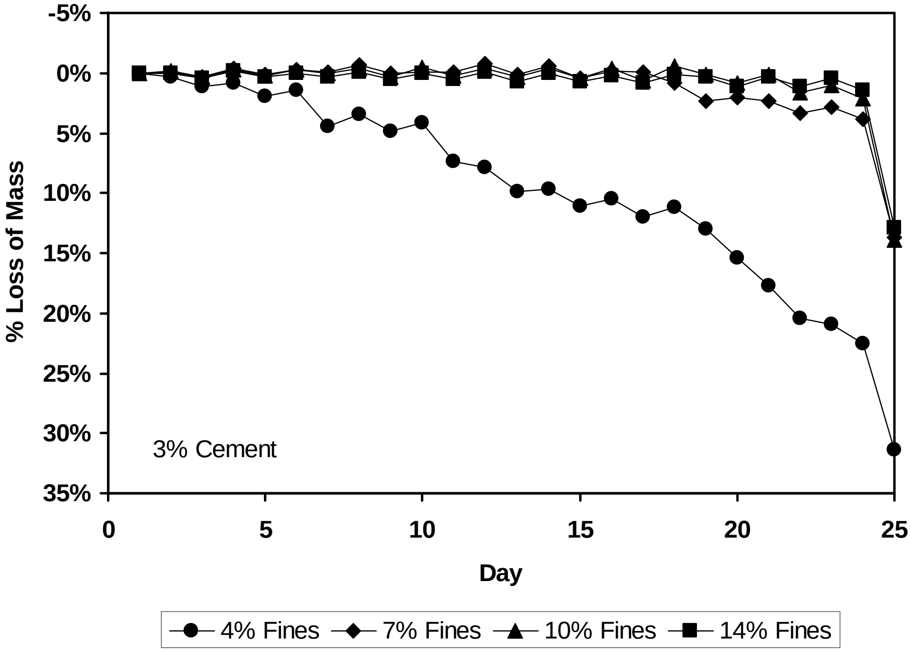


Figure A-1. Mass loss for Manassas aggregate at 3% cement as a function of time.

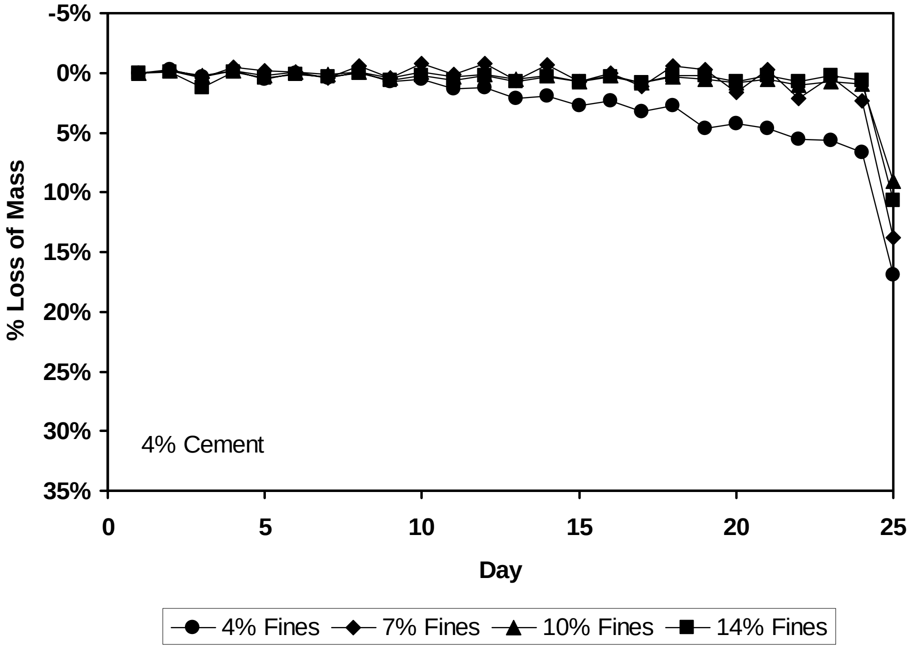


Figure A-2. Mass loss for Manassas aggregate at 4% cement as a function of time.

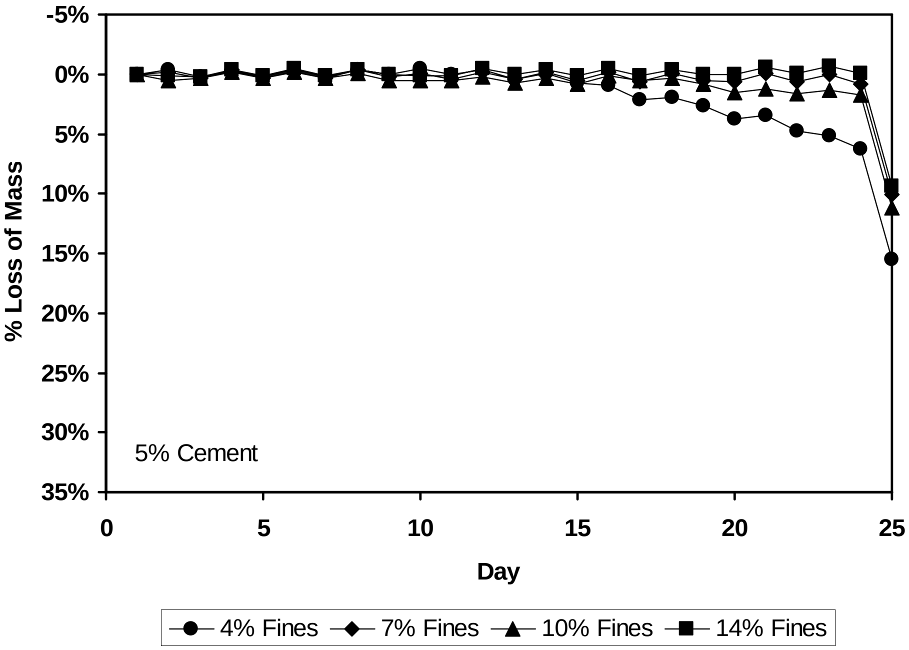


Figure A-3. Mass loss for Manassas aggregate at 5% cement as a function of time.

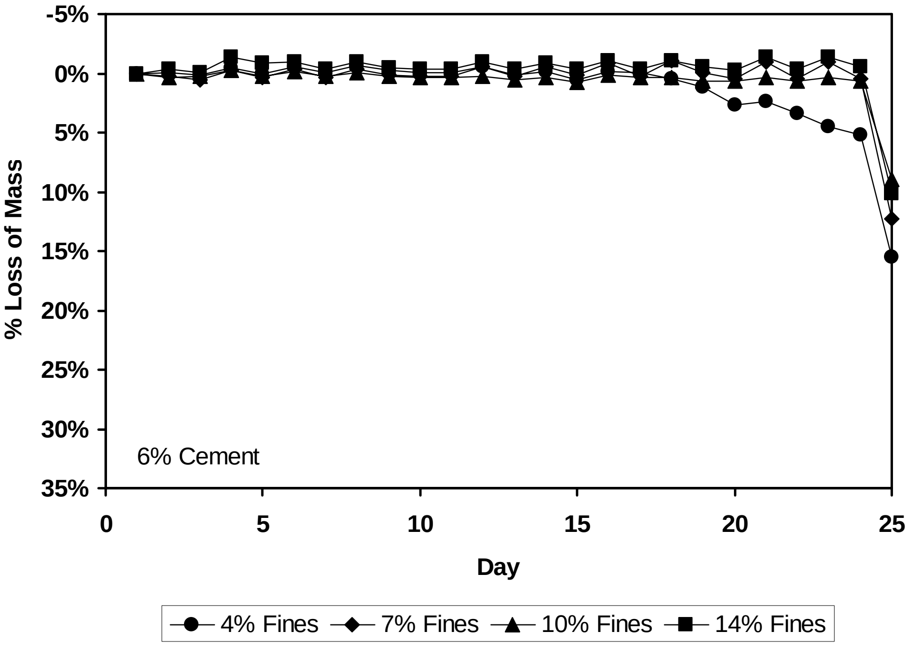
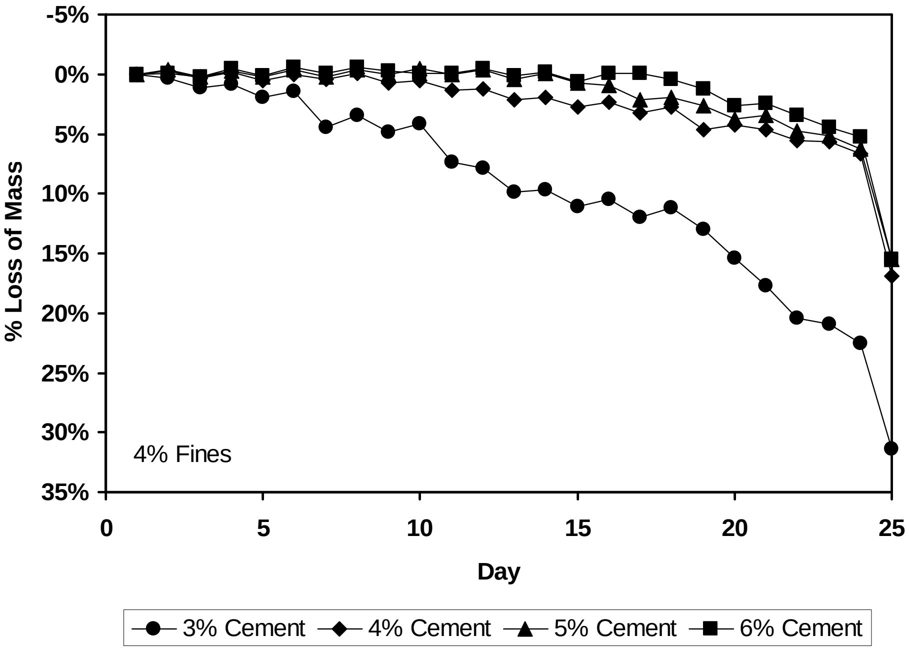


Figure A-4. Mass loss for Manassas aggregate at 6% cement as a function of time.



FigureA-5. Mass loss for Manassas aggregate at 4% fines as a function of time.

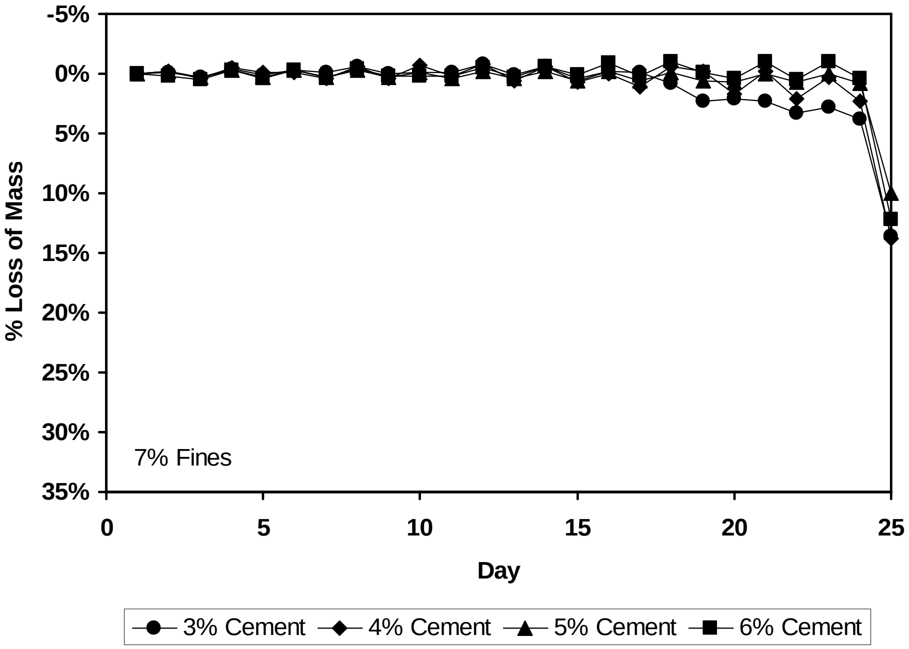


Figure A-6. Mass loss for Manassas aggregate at 7% fines as a function of time.

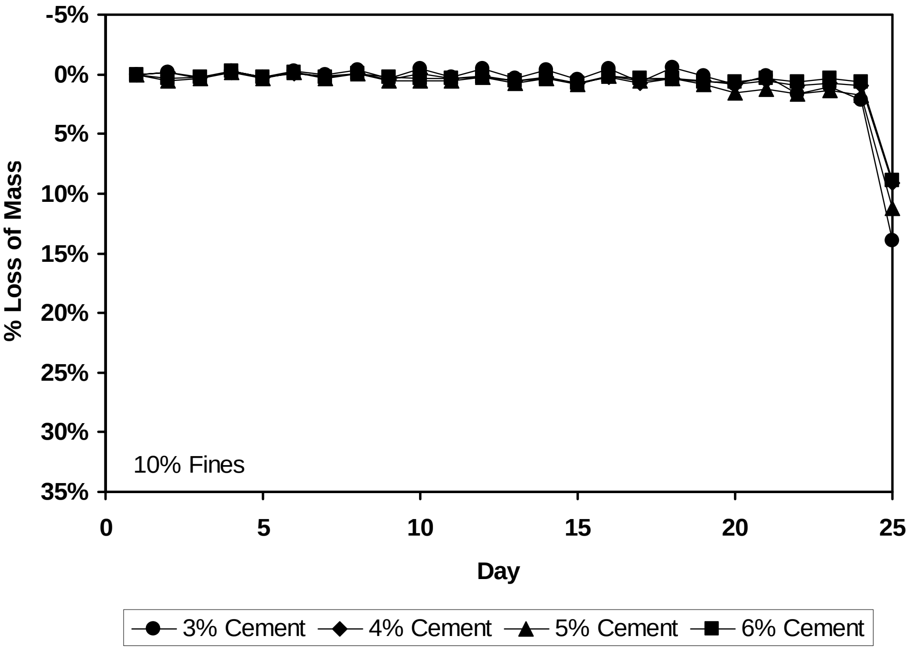


Figure A-7. Mass loss for Manassas aggregate at 10% fines as a function of time.

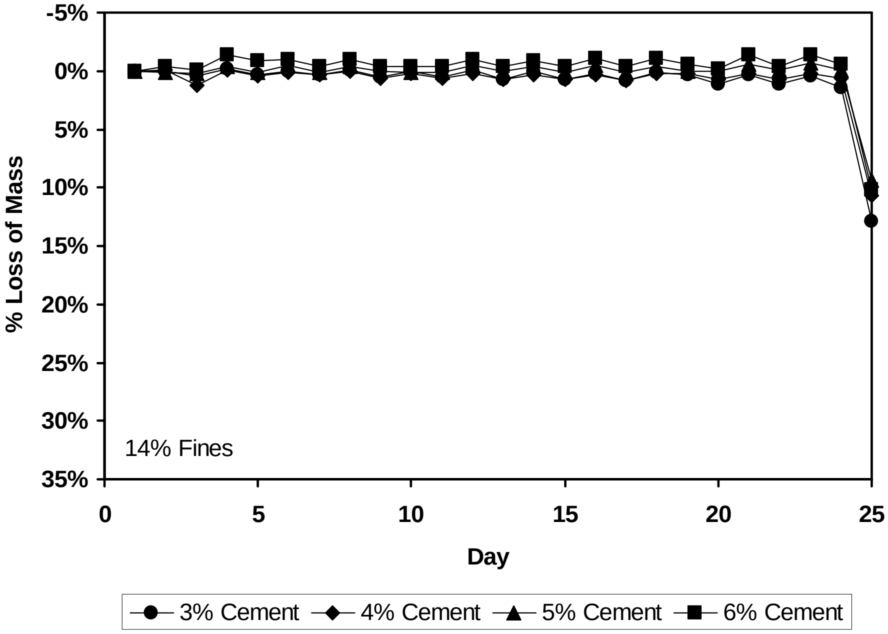


Figure A-8. Mass loss for Manassas aggregate at 14% fines as a function of time.

APPENDIX B

Volume Loss as a Function of Time

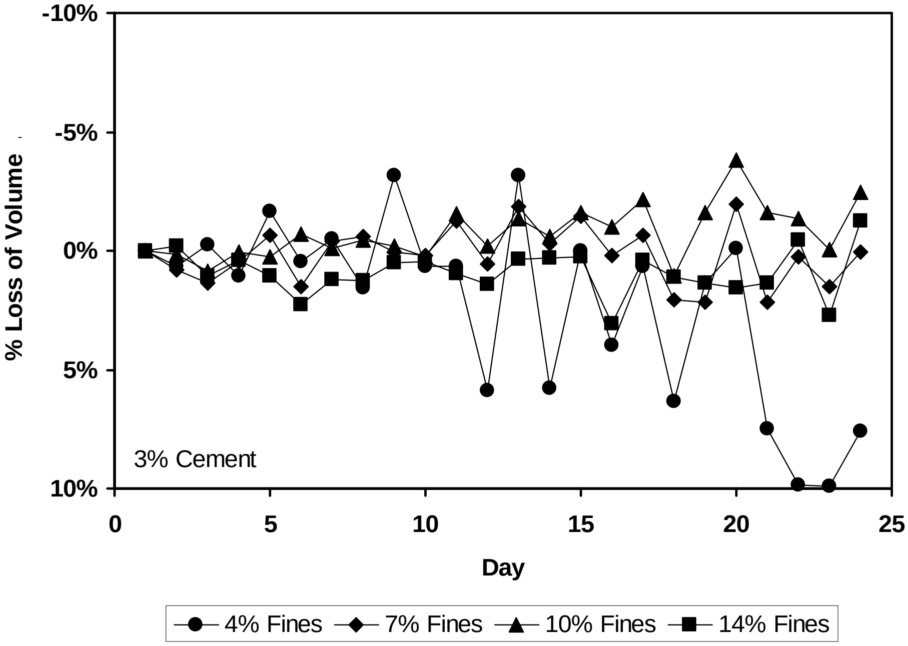


Figure B-1. Volume loss for Manassas at 3% cement content as a function of time.

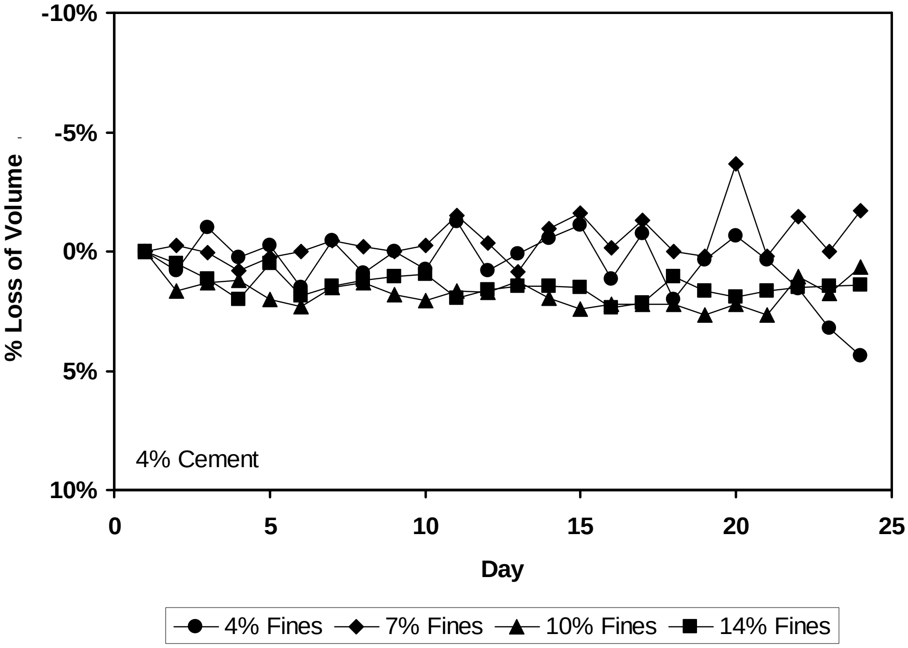


Figure B-2. Volume loss for Manassas at 4% cement content as a function of time.

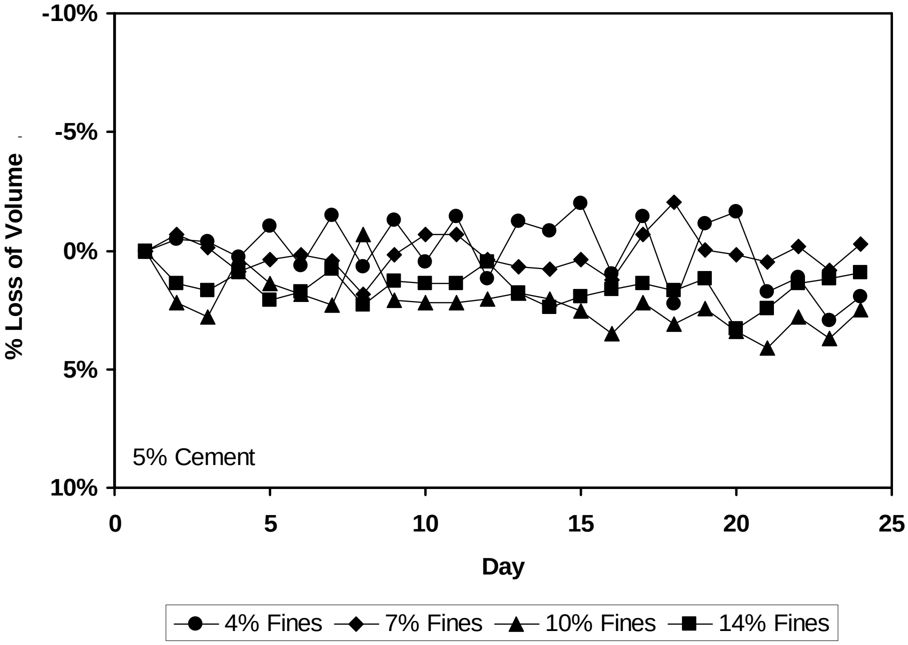


Figure B-3. Volume loss for Manassas at 5% cement content as a function of time.

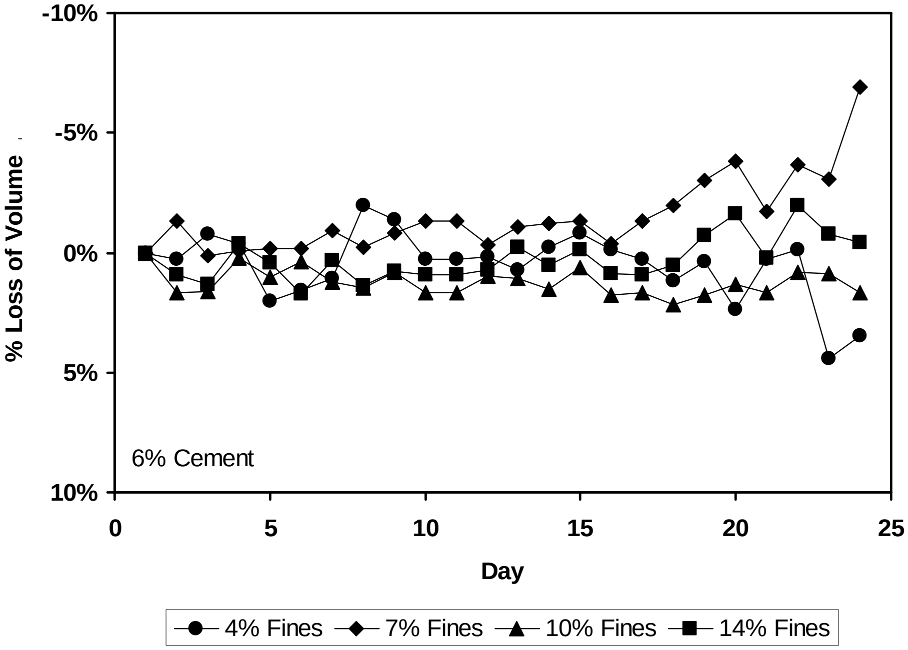


Figure B-4. Volume loss for Manassas at 6% cement content as a function of time.

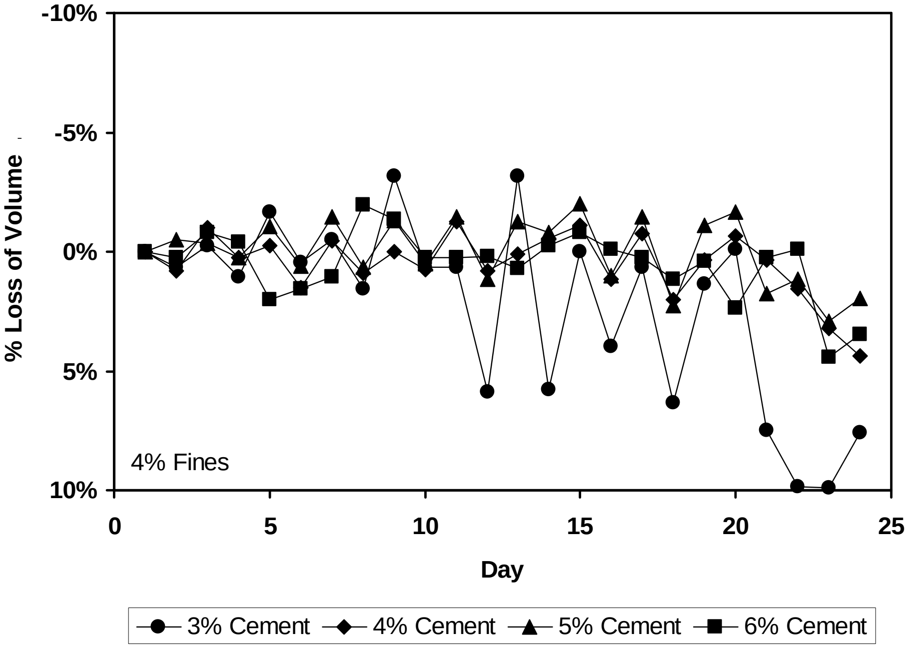


Figure B-5. Volume loss for Manassas at 4% fines content as a function of time.

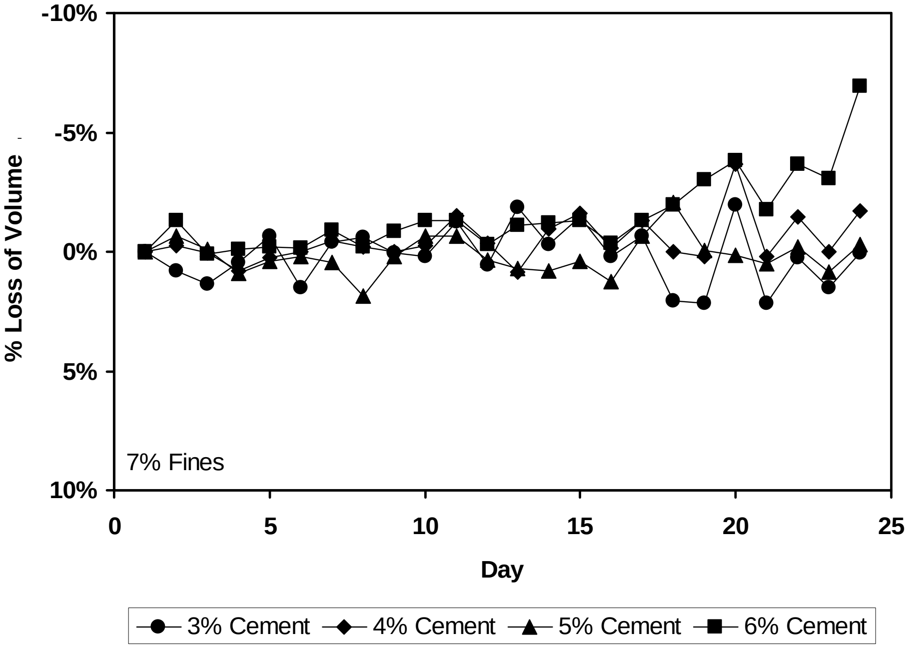


Figure B-6. Volume loss for Manassas at 7% fines content as a function of time.

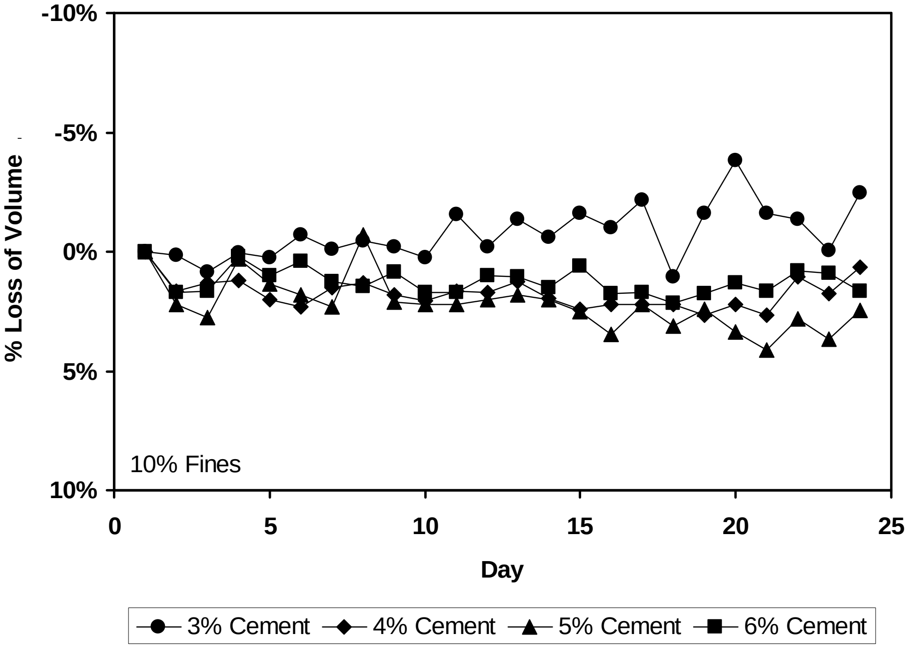


Figure B-7. Volume loss for Manassas at 10% fines content as a function of time.

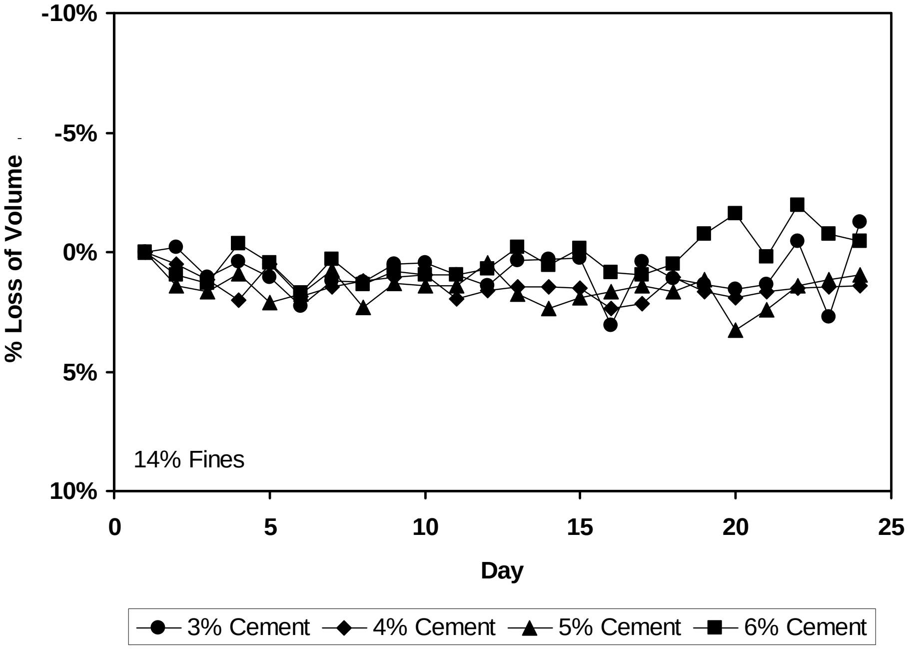


Figure B-8. Volume loss for Manassas at 14% fines content as a function of time.