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Utilization of Silo Stored and Ponded Class C Fly Ash in Road Bases

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KEYWORDS: soil stabilization, fly ash, curing time, clay type, curing condition, ponded ash, residual strength

ABSTRACT

Silo stored and ponded class C fly ashes are being increasingly used for soil stabilization as road base and in other civil constructions. These ashes are characterized by their self-cementing property, and therefore, they can be used for clay sub-grade improvement as cement surrogates, or as road sub-grade material. For efficient and economic utilization of silo stored and ponded class C fly ash, the physico-mechanical characteristics of these two ashes must be determined extensively. This paper focuses upon the laboratory evaluation of the (1) stabilization characteristics of clay soils blended with class C fly ash, and (2) residual self-cementation capabilities of ponded class C fly ash. Testing carried out by the authors and other researchers indicated that curing time, curing condition, and the clay mineralogy in the soil-fly ash mix are the three main variables that control stabilization characteristics. In this paper, the stabilization characteristics were evaluated in terms of the gain in the uniaxial compressive strength and stiffness. To examine these effects, 12 set of mixtures of ideal clay soils with known percentages of kaolinite and montmorillonite, class C fly ash and appropriate amount of water were compacted and cured. In the mixed samples, amount of montmorillonite varied from 0, 2, 4 and 6 percent, and the amount of class C fly ash varied from 5, 10 and 20 percent. To investigate the effect of curing condition, three curing environments were used. In the first case, the samples were stored in plastic bags and cured at 38 ^{o}C. In the second case, the samples were kept in a moist chamber at a controlled humidity of 80% and temperature of 27 ^{o}C; and in the third case the samples were kept in a less controlled environment of atmospheric humidity and temperature. In addition to the stabilization characteristics of clay soils-fly ash blend, the residual self-cementation capabilities of ponded class C fly ash were also investigated in terms of unconfined compression and CBR tests performed at 7 and 14 days of curing. Results obtained from these test were encouraging and compared favorably with the typical subgrade materials.

1. INTRODUCTION

Electric utility companies in the United States produce a voluminous amount of class C fly ash by burning coal. According to a survey made by the American Coal Ash Association (ACAA) in 2001 on the production and use of coal combustion by-products, almost 63 million metric tons of fly ash is produced in the United States every year, and the nationwide consumption of dry and stored fly ash is approximately 41 percent of the total production.[1] The percentage consumption decreases to 34% if ponded ashes are also taken into account. The disposal of this huge fly ash poses a serious problem in terms of land use and potential environmental pollution. To overcome this, strong economical and environmental imperatives exist for effective use of this fly ash.

In the past few years, researchers tried to investigate the scope of commercial utilization of fly ash, and a wide variety of applications for high-volume use of fly ash have been conceived.[2, 3, 4, 5, 6] For example, self-cementing class C fly ash is extensively utilized for modification and improvement of road base soil. Class C fly ash has also been utilized as an additive in portland cement concrete, for making controlled low strength materials (CLSM) and flowable fill, or simply as a structural fill.[7] The utility of class C fly ash in these applications has been due to its distinct self-cementing characteristics.[8] However, for efficient and economic utilization, the physico-mechanical characteristics of class C fly ash must be established. To date, very little knowledge on the physico-mechanical characteristics of the class C fly ash are available. Therefore, there is a need to study these characteristics in detail. Moreover, for wide acceptance of fly ash construction material the following aspects need to be addressed:

1) Perception of non-uniformity of the by-product: By their very nature coal combustion by-products have a variation in properties from plant to plant as well as within a single utility plant. Therefore, the statistical variability of fly ash as well as its end products need to be documented.

2) Inadequate design criteria and quality control guidelines for fly ash utilization: Acceptable specifications, design criteria and quality control guidelines that address the local conditions in a manner useful to contractors are needed.

This paper focuses upon the laboratory investigation of the (1) stabilization characteristics of clay soils blended with self-cementing class C fly ash and (2) residual self-cementation characteristics of ponded class C fly ash. Testing carried out by the authors and other researchers indicated that curing time, curing condition, and the clay mineralogy in the soil-fly ash mix are the three main variables that control stabilization characteristics of clay soil blended with class C fly ash. The stabilization characteristics can be measured in terms of strength and stiffness gain, and failure strain. In this paper, the stabilization characteristics were evaluated with respect to the 1) effect of curing time 2) effect of the clay type, and 2) effect of the curing condition. To analyze this, 12 sets of mixtures of ideal clay soils with known percentages of kaolinite and montmorillonite, class C fly ash and appropriate amount of water were compacted and cured. In the mixed samples, amount of montmorillonite varied from 0, 2, 4 and 6 percent, and the amount of class C fly ash varied from 5, 10 and 20 percent. To investigate the effect of curing condition, three curing environments were used. In the first case, the samples were stored in plastic bags and cured at 38 ^{o}C. In the second case, the samples were kept in a moist chamber at a controlled humidity of 80% and temperature of 27 ^{o}C; and in the third case the samples were kept in a less controlled environment of atmospheric humidity and temperature. Samples cured under the first condition were used to investigate the strength and stiffness development of the stabilized clay-fly ash blend with respect to the curing period as well as the clay type. To investigate the effect of curing environment, the strength determined from the samples obtained from all the three curing conditions were compared with respect to the curing period at 7 and 28 days.

For the analyses of residual self-cementation characteristics of ponded fly ash, the grain size distribution, moisture content and density play important roles. Therefore, the grain size distribution, optimum moisture content, unconfined compressive strength and California Bearing Ratio (CBR) were investigated for ponded fly ash. Results obtained from these analyses are discussed in the following sections.

2. SOIL STABILIZATION WITH CLASS C FLY ASH

Class C fly ash behaves like a mixture of cementitious and pozzolanic materials, that is a portion of the fly ash hydrates like portland cement in the presence of moisture, while the rest remains as the reactive aluminous-siliceous oxides like those found in pozzolans.[9] For stabilization of soil with class C fly ash, it is important to determine the moisture-density and moisture-strength relationships to establish the optimum moisture content in the sample[10].

In this paper, the moisture-density relationship was obtained by compaction test with the Harvard miniature apparatus. Four clayey mixtures of kaolinite and 0, 2, 4 and 6 percent bentonite (by weight) were prepared for the analyses. The results obtained from the Harvard miniature compaction tests on soil-fly ash blends are given in Table 1.

Table 1. Index properties and compaction characteristics of clays.[11]

	Clay 1	Clay 2	Clay 3	Clay 4
Kaolinite	0% Bentonite	2% Bentonite	4% Bentonite	6% Bentonite
Liquid Limit	58	70	74	85
Plastic Limit	37	33	34	36
Plasticity Index	21	37	40	49
Optimum Moisture Content (%)	29.8	32.3	25.9	28.6
Maximum Dry Density (KN/m^3)	14.2	13.3	13.2	13.9

2.1. Procedures for Sample Preparation

All samples were prepared with the above clay blends at 5, 10, and 20 percent of fly ash by weight. Before compaction test were performed, the initial moisture content of the air-dried clays were calculated in the laboratory. This initial moisture content was used for calculating the correct moisture content of each compaction specimen. The appropriate amount of fly ash, measured as percent of dry soil was added to the soil blends and mixed thoroughly to produce a homogenous soil-fly ash blend. Then the appropriate amount of water, calculated by weight of the solid mass was sprayed evenly over the soil-fly ash mixture to produce a homogeneous blend. The mixed soil-fly ash sample was placed in a plastic cup and covered in order to avoid evaporation. The mixed sample is then immediately compacted in three equal layers with 25 blows in each layer in the Harvard miniature apparatus before the completion of early hydration reaction of class C fly ash. The samples were then weighed, and the moisture content versus dry density was plotted to determine optimum moisture content of each soil-fly ash blend.

Data obtained from the moisture-density test showed that the optimum moisture content changes due to the addition of fly ash to the prepared clay mixtures. These changes also depend on the soil blend type as well as on the delay in compaction. The optimum moisture content has an overall tendency to decrease as fly ash is added. This may be due to the hydration reaction of fly ash. Upon exposure to moisture, even at a very short time, class C fly ash quickly hydrates to form a partial cementious structure. Based on the fly ash quality, the hydration reaction may take longer, but in the majority of the situations, it occurs within few hours. Therefore, preparation and compaction of the sample have to occur very rapidly to prevent any early hydration.

Based upon the moisture-density relationship discussed above, samples were compacted for unconfined compressive strength at +/- 3% of optimum moisture content for each soil-fly ash blend. At the time of preparing samples for unconfined compressive strength, the initial moisture content were also measured at compaction using the trimmings of the compacted sample. Immediately after compaction, the samples were then sealed in plastic (Ziploc) bags and placed in the oven at 38 °C (100°F) for curing at 1, 3, 7, 14, 28, 56 and 112 days. The compacted samples were also stored in two other curing environments, namely a) in a moist chamber at a controlled humidity of 80% and temperature of 27 ^{o}C and b) in a less controlled atmospheric humidity and temperature. The cured samples were tested for unconfined compressive strength as per ASTM D2850, and the stress-strain relationships were recorded along with their moisture contents. This was done for comparing the moisture content at cure with that at compaction. This relationship establishes the moisture loss characteristics of the soil-fly ash blends. Further investigations were conducted to establish the physico-mechanical characteristics of the soil-fly ash mixtures with respect to the curing days, curing condition and clay type. The physico-mechanical properties include: 1) moisture content, 2) unconfined compressive strength and stiffness, and 3) failure strain.

2.2. Effect of Curing Time on Physico-Mechanical Properties

The physico-mechanical properties studied in this paper are unconfined compressive strength and stiffness and failure strain. Unconfined compression test of the various soil-fly ash blends compacted at +/- 3% of optimum moisture content were carried out. Figures 1 and 2, respectively show the stress-strain behaviors at 1, 3, 7, 14, 28, 56, and 112 days of curing for 0, 2, 4 and 6 percent bentonite. The stress-strain behavior of clay sample with 0 percent bentonite is more brittle as compared to that of clay samples with bentonite. Also, the increase in percentage of fly ash in the blend typically results in a higher strength. Results also show that every sample failed with a distinct cone or shear failure without any signs of shrinkage cracks.

Figures 3 and 4, respectively show the gain in unconfined compressive strength and stiffness with respect to the curing period for four laboratory clay mixtures with 5, 10, and 20 percent of fly ash. Results show that the samples rapidly gained strength within the 7-day curing period, and the greatest increase occurs in 1-day due to the rapid hydration reaction of class C fly ash. Typically, the strength tends to increase up to the 14-day curing period. Beyond 14 days the strength retards and slightly decreases due to degradation in the long-term curing process. Results also reveals that the long-term strength development occurs in a complex fashion and depends upon the fly ash content and the proportion of smectite (montmorillonite) mineral in the soil. Trends indicate that higher smectite and fly ash contents typically delay the soil strength degradation. For nearly all samples with 5 percent fly ash content, the strength development retards at 14 days, and beyond 14 days, the samples show only some amount of strength degradation. On the other hand, samples with 20 percent fly ash content, strength development continues upto 112 days at comparatively smaller rate. Samples with 0 percent bentonite content, shows the largest amount of strength degradation with time. From the analysis of Figure 3, it may be concluded that higher the fly ash content, lower is the strength loss.

Figure 4 shows the development of Young’s Modulus with the curing time for various soil fly ash samples. Results show that the development of stiffness in majority of the cases occurs within 7 to 14 days of curing. The stiffness gain or degradation beyond this period is at a smaller rate and depends on the amount of fly ash and the smectite materials in the blend. Result also shows that at 0 percent bentonite, there is a significant amount of stiffness degradation with curing time. This indicates that soils with small capacity to hold adsorbed water would develop weaknesses in the form of microscopic cracks with longer curing time. However, with the presence of smectite mineral, samples show either moderate increase or no degradation in stiffness with curing time.

The average percent moisture loss during unconfined compression test of stabilized lab clays 1, 2, 3, and 4 is given in Figure 5. About 1 to 3 percent moisture is lost within 1 day of curing due to hydration (Figure 5). This moisture loss is consistent with the fly ash hydration requirement. Furthermore, about 5 to 10 percent moisture is lost due to evaporation at 14 days of curing. However, strength development is continued even after 14 days of curing and depends upon the moisture content in the sample. Figure 5 also shows that the moisture loss constantly increases as hydration continues with slight fluctuation throughout the curing process, which may be due to irregular evaporation. The moisture loss tends to be slightly greater without bentonite added to the soil-fly ash blends. As moisture loss increases, microscopic shrinkage cracks are anticipated to develop.

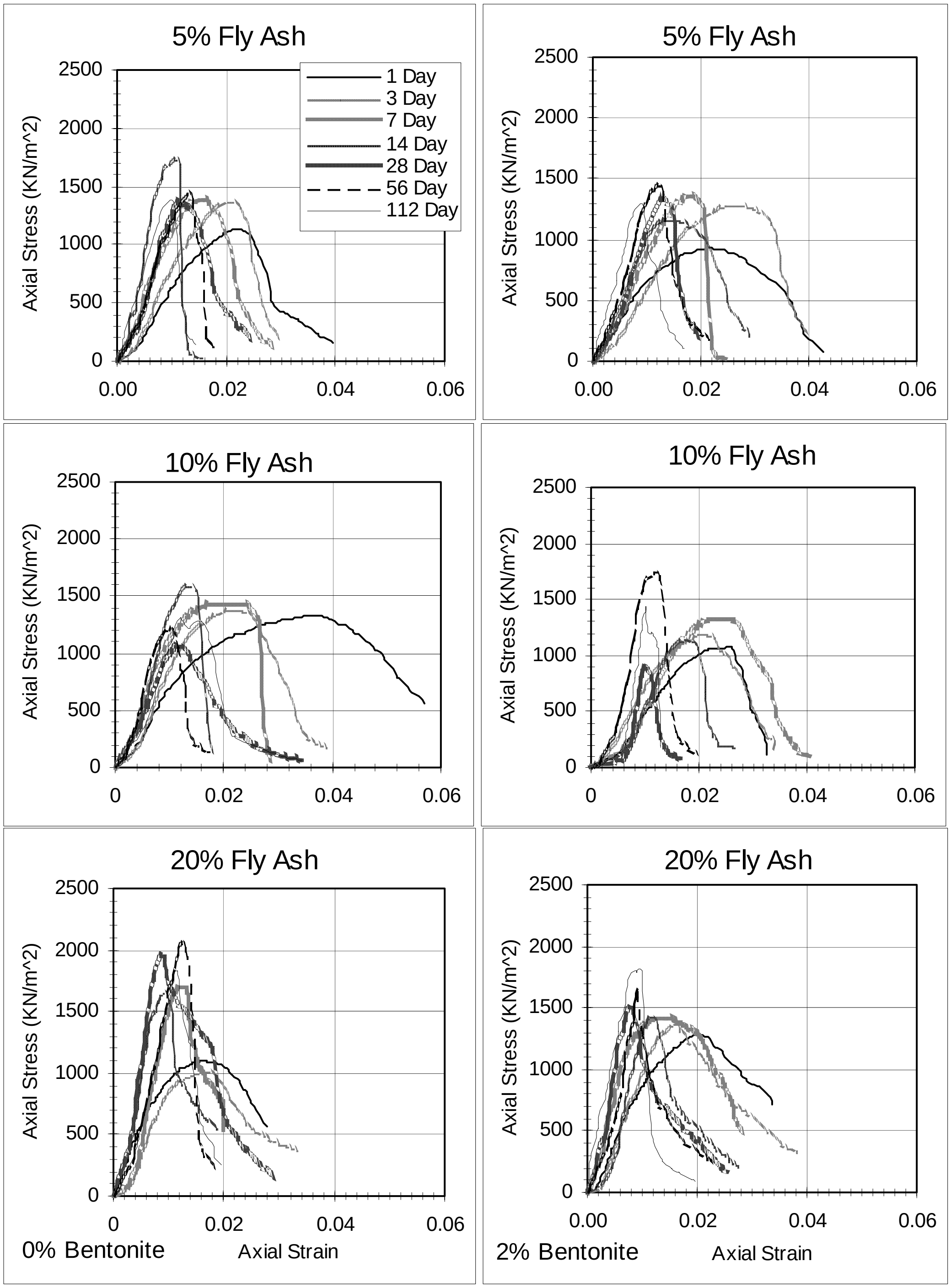


Figure 1. Stress-strain behavior for unconfined compressive strength of stabilized laboratory clay no. 1 and 2.

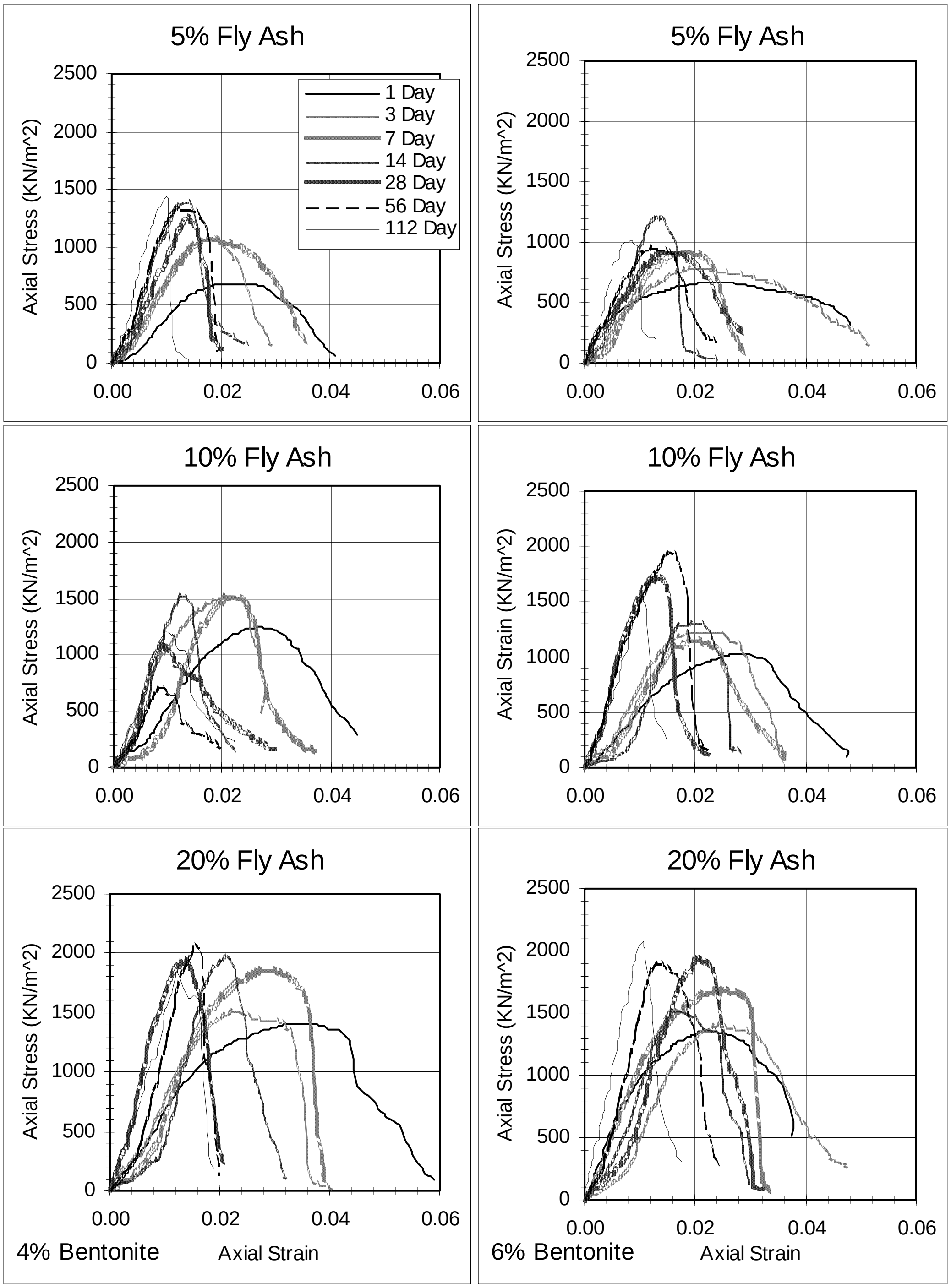


Figure 2. Stress-strain behavior for unconfined compressive strength of stabilized laboratory clay no. 3 and 4.

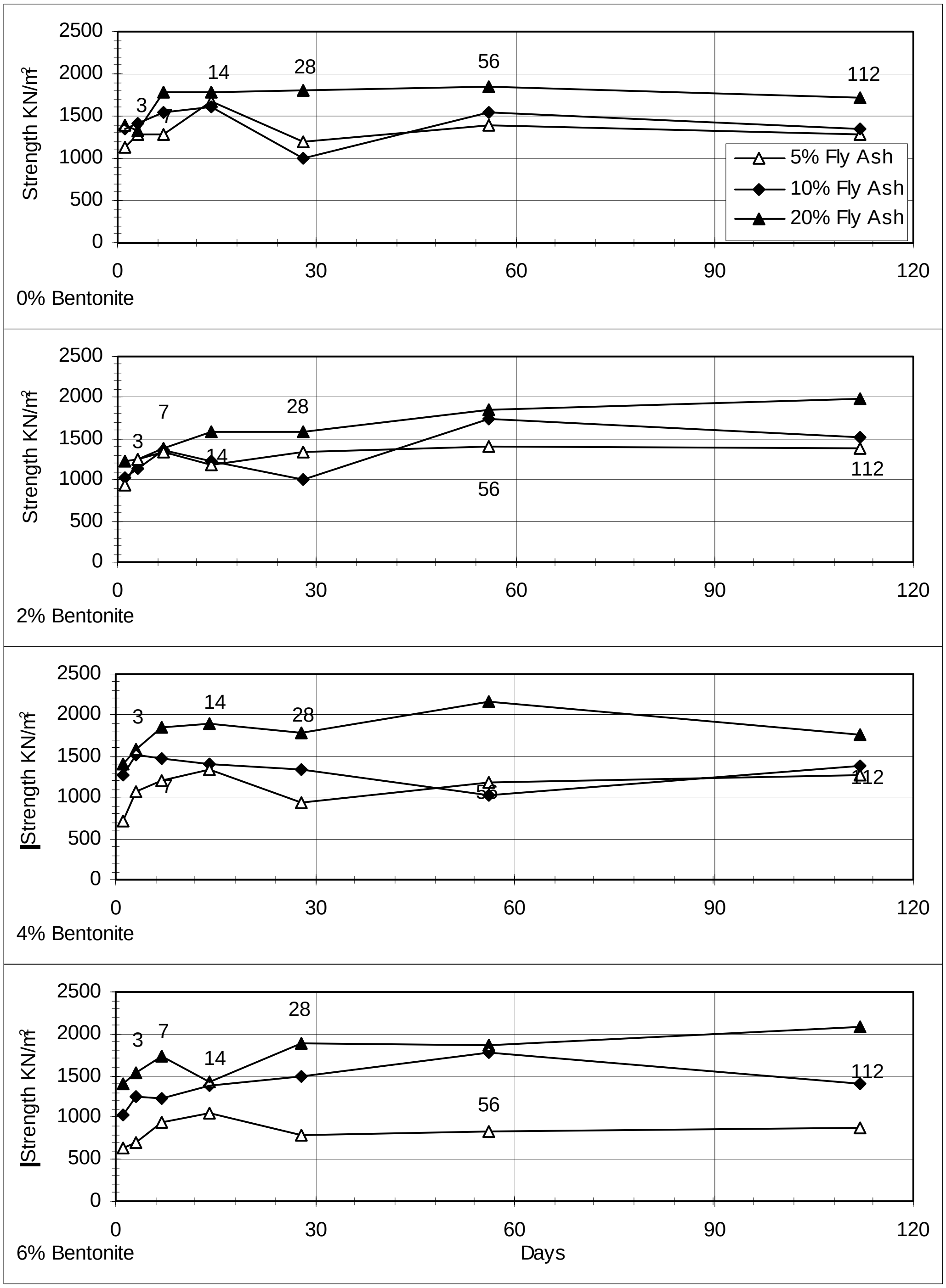


Figure 3. Strength development for unconfined compressive strength of stabilized laboratory clay nos. 1, 2, 3, and 4.

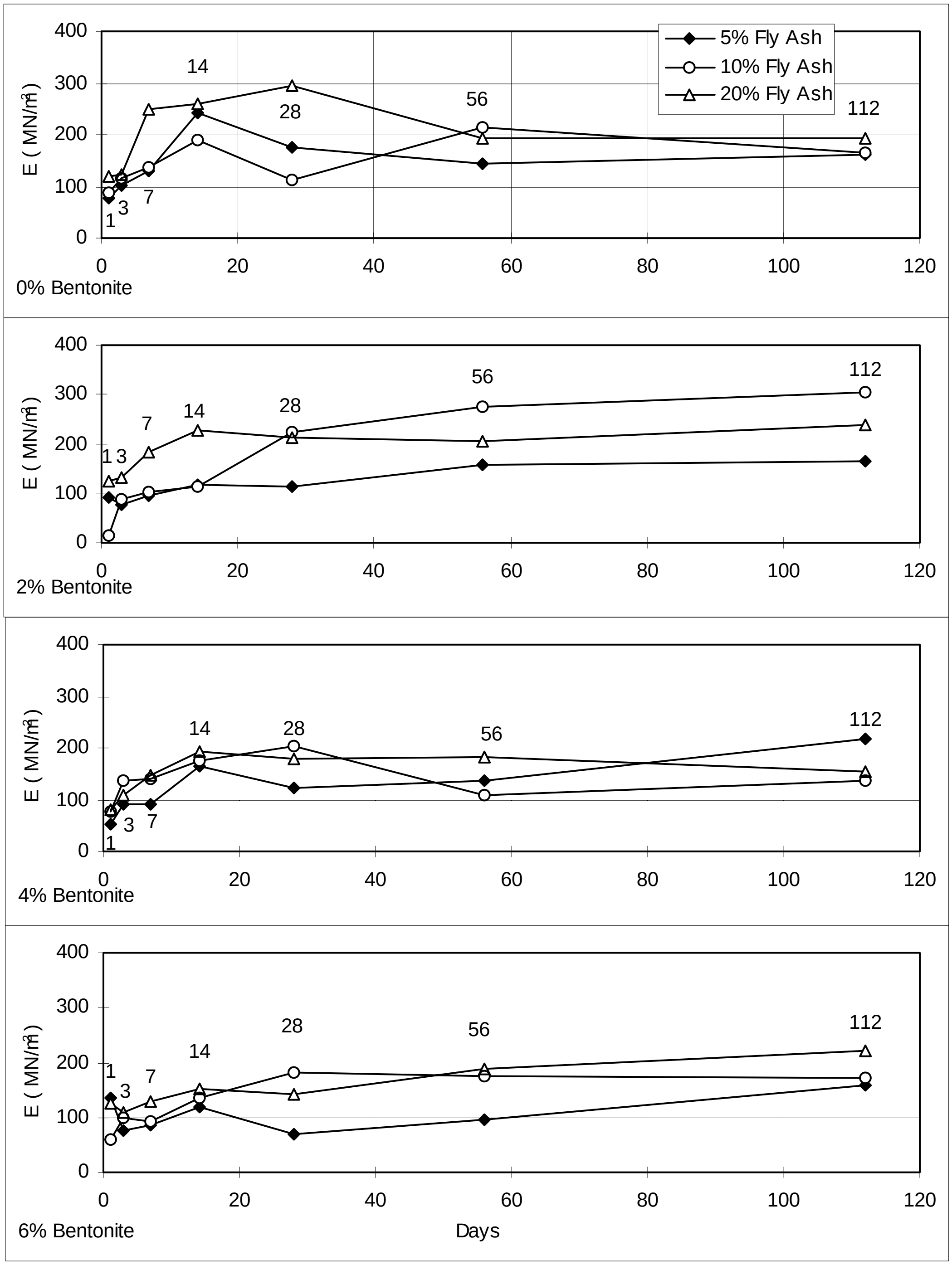


Figure 4. Modulus of Elasticity (stiffness) development of stabilized laboratory clay nos. 1, 2, 3, 4.

The soil fly-ash blends cured at 1, 3, 7, 14, 28, 56, and 112 days also established deformation characteristics as shown in Figure 6. This has an indication whether the failure of the sample would be gradual or catastrophic. The four clay samples with addition of 5, 10, and 20 percent fly ash by weight are very ductile (plastic) up to 28 days of curing. After 28 days, the specimens became very brittle. The initial ductility caused due to large amount of moisture in the sample. As the hydration reaction of class C fly ash proceeds, the sample becomes brittle over a long period of time. It is also observed that the samples with upto 4 percent bentonite have a failure strain of about 1 percent within 14 days of curing, while the samples with 6 percent bentonite have failure strains greater than 1 percent upto 56 days of curing (Figure 6). From this it may be concluded that the rate at which samples loose ductility depends upon the smectite material content in the specimen.

2.3. Effect of Curing Condition

The curing condition plays a very important role for both short term and long term strength development. Three types of curing conditions were considered in this analyses, namely, (1) stored in plastic bags and cured at 38 ^{o}C, (2) in an moist chamber at a controlled humidity of 80 percent and temperature of 27 ^{o}C, and (3) in a less controlled environment at atmospheric humidity and temperature. Figure 7 shows the strength development after 7 and 28 days of curing for a mixture with 2 percent bentonite and 10 percent class C fly ash.

Though most of the hydration process is completed for the fly ash soil blend within the initial few hours of curing, the moisture in the blend reacts with the fly ash to provide continued strength gain in the blend. Figure 7 shows that the strength gain occurs at the most controlled curing situation. At atmospheric curing, the samples gain the least strength as compared to most controlled curing condition.

2.4. Effect of Clay Mineralogy

Clay mineralogy is one of the most important parameter for both short-term and long-term strength gain. Figure 8 shows that strength of the blend increases as the amount of montmorillonite (bentonite) increases in the blend for 20 percent fly ash and after 7 and 28 days of curing. This is because the clay blends with montmorillonite tends to absorb and retain moisture due to its characteristics.[12, 10] This absorption provides moisture to fly ash hydration process for a longer period. In contrast, cementitious products used for soil stabilization was predicted to develop detrimental shrinkage cracks over a long period of time. The failure strain also increases with the increased amount of montmorillonite (bentonite) (Figure 8). This is obvious because with increased amount of montmorillonite, the samples retain more moisture, and hence behave more like a ductile material.

The samples prepared in this research did not develop visual shrinkage cracks or effect on strength characteristics in detail. Although conclusions are not clear, trends indicate that higher smectite and fly ash contents usually delay the strength degradation, due to an increase moisture absorption prolonging the hydration reaction. The curing time may need to be increased to develop a more significant strength characteristic for strength gain and loss.

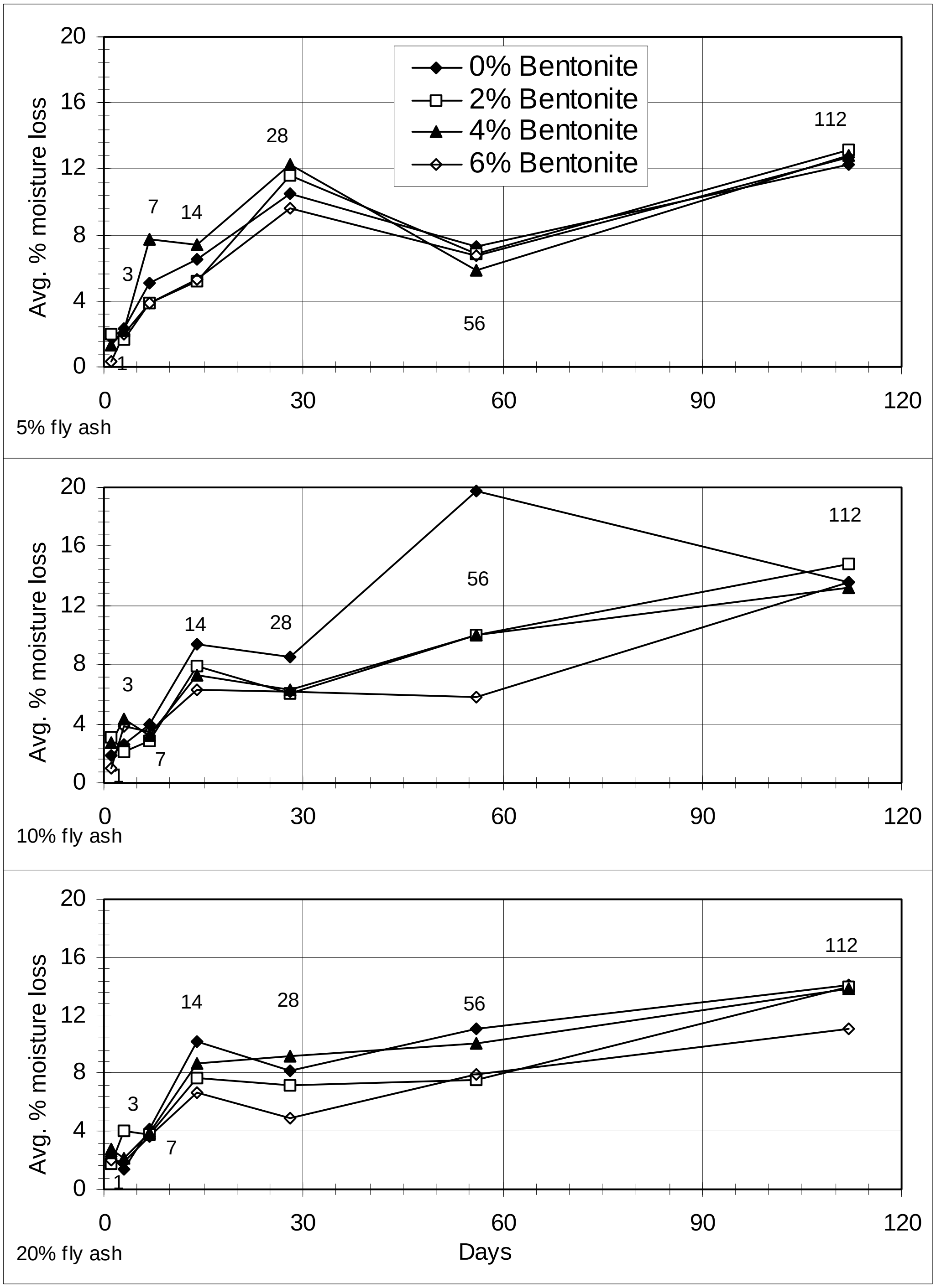


Figure 5. Average percent moisture loss for unconfined compressive strength of stabilized lab clays 1, 2, 3, and 4.

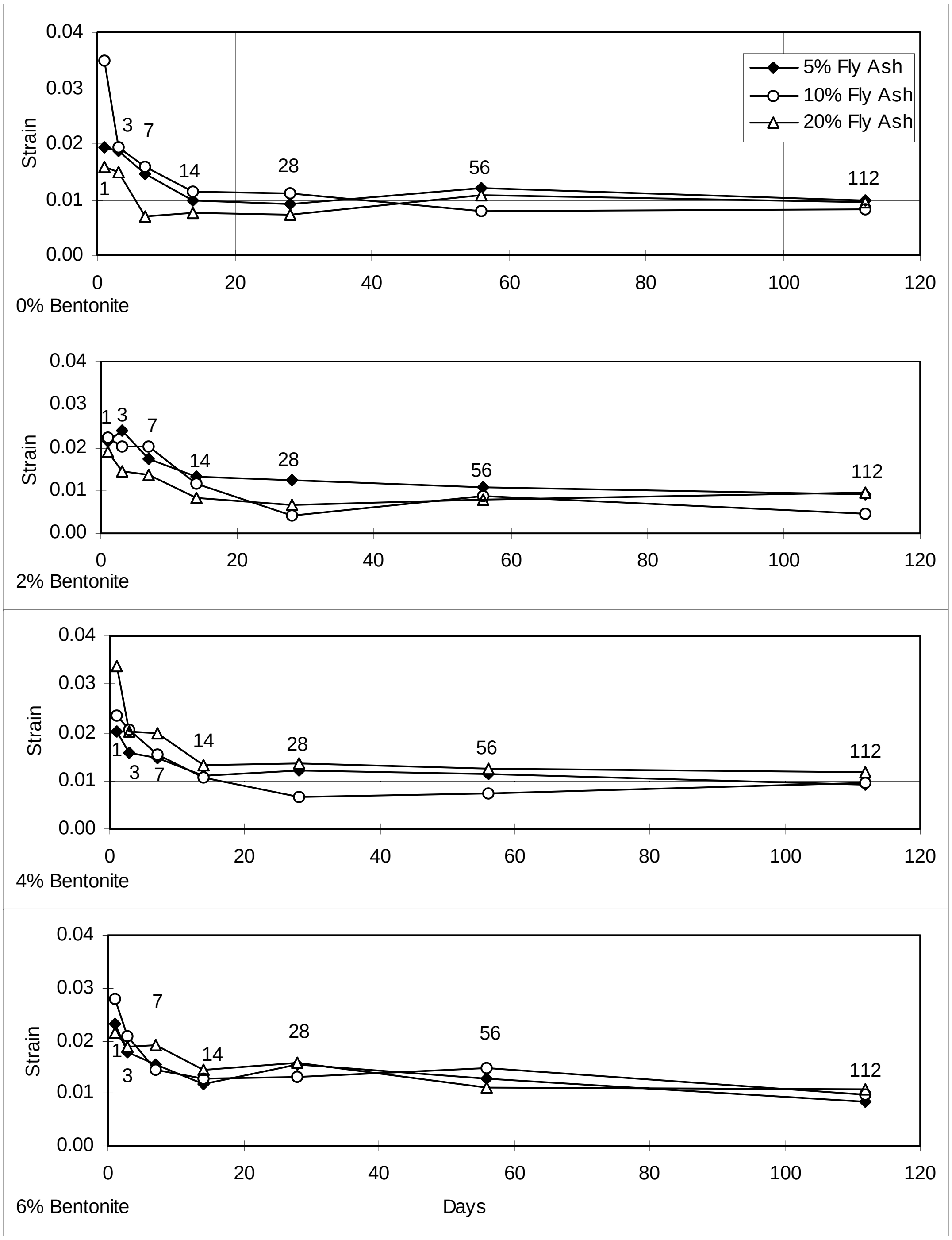


Figure 6. Strain behavior at failure for unconfined compressive strength of stabilized laboratory clay nos. 1, 2, 3, and 4.

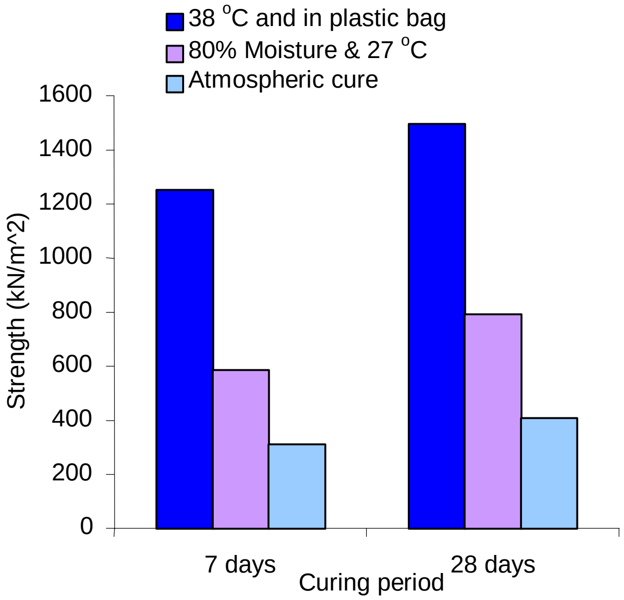


Figure 7. Effect of curing conditions on the strength gain.

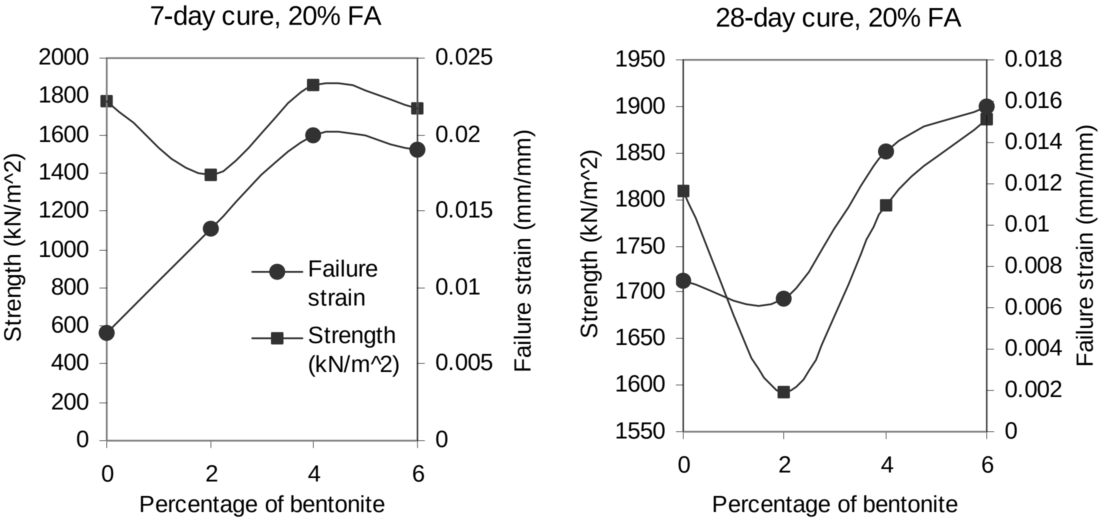


Figure 8. Effect of montmorillonite (bentonite) on the gain in strength and failure strain.

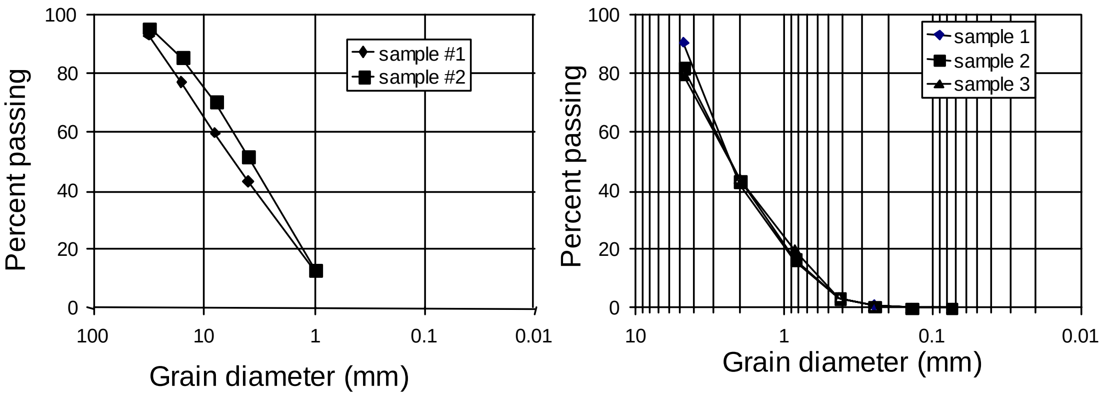
3. RESIDUAL CEMENTING PROPERTY OF PONDED CLASS C FLY ASH

Hydrated ponded ashes have shown some residual cementing capacity, which may be enhanced by pozzolanic activators. Researchers in the past, notably Bergeson and Mahrt observed the residual cementing capacity of ponded ashes for fill under PCC pavement.[13] It has also been used in many road sub-base developments. For example, aggregates obtained from class C fly ashes hydrated in ash ponds have been successfully used as road base material by the Texas Department of Transportation in an experimental project. These ponded ash aggregate road bases have a tendency to harden into a stiff layer after placement and compaction.[14] Similar inspection of the access road project at the KCPL Hawthorn site show that compacted ponded ash may be used to produce hard, cemented sub-grades. Self-cementation may have large variation depending upon the exposure to moisture.

In the present paper, aggregates reclaimed from ponded ash were evaluated for application in road bases, especially for residual cementation capacity and pozzolanic activity. The following analyses were performed to characterize the properties of aggregates reclaimed from ponded ash: (1) sieve analysis, (2) dry density and moisture content tests, (3) unconfined compression test, and (4) California Bearing Ratio (CBR) tests.

3.1. Analysis of Gradation

Analysis of grain size distribution is important as it effects the strength development. Large number of big particles in the sample may always reduce the strength. In the present analysis, grain size distribution was carried out by means of sieve analysis on two samples of ponded ash. Since the ponded ash brought from the plant was partially hydrated, the particle size reached up to 35 mm. The samples were first sieved through the 31.5mm, 16mm, 8mm, 4mm and 1 mm sieves according to ASTM C136 to obtain the coarse aggregate grain size distribution. The portion passing 4 mm sieve was then used for fine aggregate sieve analysis according to ASTM C136. Three tests were performed on fine aggregates using sieves with openings: 4.75mm, 2mm, 0.85mm, 0.425mm, 0.25mm, 0.14mm and 0.075mm. Figure 9a and b show the grain size distribution curves obtained from the tests. The average coarse grain size of the samples obtained is 10-12 mm.



(a) (b)

Figure 9. Grain size distribution of ponded ash: a) coarse fraction, b) fine fraction.

3.2. Analysis of Dry Density and Optimum Moisture Content

The dry density and moisture content of the ponded ash were determined according to ASTM D698 (Standard Proctor Test). The dry density obtained is 1.49 g/cm^3 at the optimum moisture content of 23.47%. Further moisture and density data were recorded during CBR, and unconfined compression tests on material passing no. 4 (4.75 mm) sieve. The intent of these tests was to plot the moisture-density relationships and understand the compactability of these aggregates. Figure 10 shows the results of these analyses. The maximum dry density and optimum moisture content based on the unconfined compression test are 1.44 g/cm^3 and 24.85%, respectively. Based upon CBR tests at 7-day cure, the maximum dry density and optimum moisture content are 1.5 g/cm^3 and 25.44%, respectively, while same at 14-day cure are 1.5 g/cm^3 and 26.66%, respectively (Figure 10).

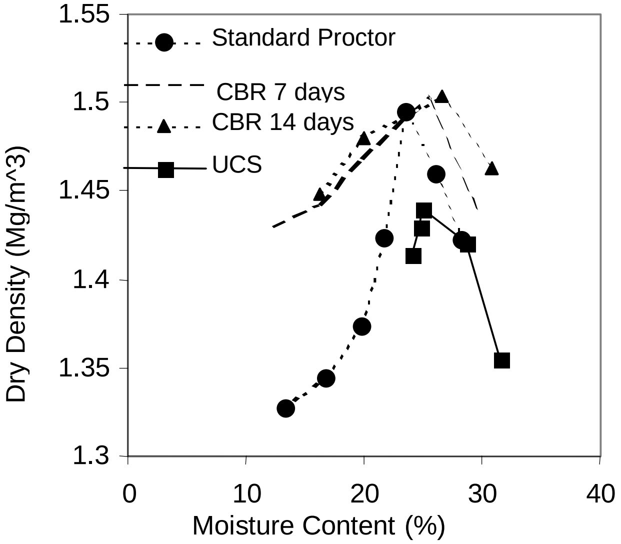


Figure 10. Compaction curves for ponded ash.

3.3. Analysis of Compressive Strength

The analysis of uniaxial compressive strength was carried out to investigate the residual strength of ponded class C fly ash. In the analysis, samples were prepared as per ASTM D1633 procedure with a slight modification in it. At the beginning, samples, which passed through 4.75 mm sieve, were weighed. Then appropriate amount of water, measured as percent of dry ponded ash was added to the ponded ash and mixed thoroughly to produce a homogenous mixture. The percentage of water varied from 24 to 32 percent. The mixed sample was then immediately compacted in three equal layers with 19 blows in each layer in the split molds before the completion of early hydration reaction of class C ponded fly ash. In the present research, the diameter and height of the split molds were 7.63 cm (3 inches) and 15.24 cm (6 inches), respectively. The prepared samples were extruded immediately after compaction and covered in plastic wrap and aluminum foil. The samples were then weighed and kept in the curing chamber at 38 ^{o}C for 7 days. At the time of compaction, some portion of the sample was weighed separately and kept in the oven at 110 ^{o}C for 24 hours to determine the optimum moisture content.

Figure 11 shows the variation of unconfined compressive strength with respect to the moisture content. As moisture content increases, the unconfined compressive strength of the ponded class C fly ash decreases.

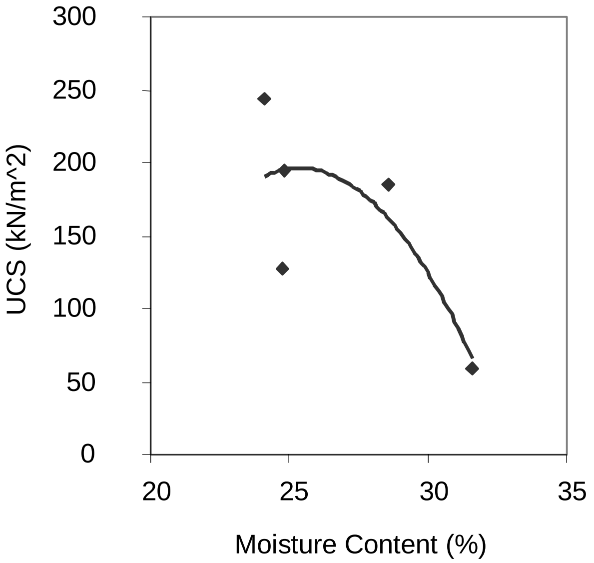


Figure 11. Variation of unconfined compressive strength with the moisture content of the ponded fly ash after 7 days of curing.

3.4. Analysis of California Bearing Ratio (CBR)

The analysis for California Bearing Ratio (CBR) was conducted to investigate the performance of ponded ash as a base course material. The test was performed as per ASTM D1883 on samples compacted in the Modified Proctor mold and air-cured for 7 and 14-days. Figures 12 (a) and (b) show the CBR load-displacement relations.

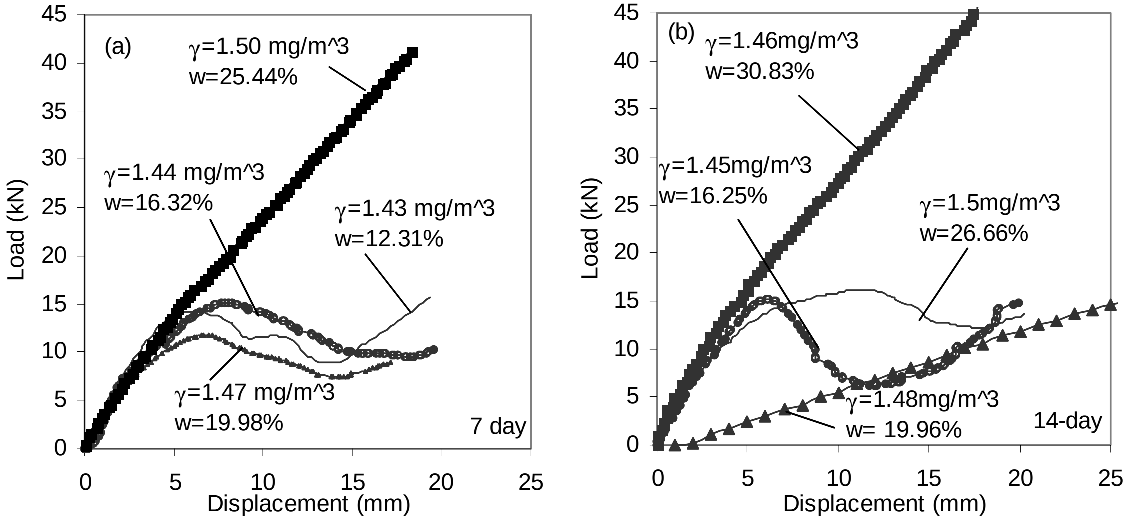


Figure 12. CBR load-displacement relationship for ponded ash.

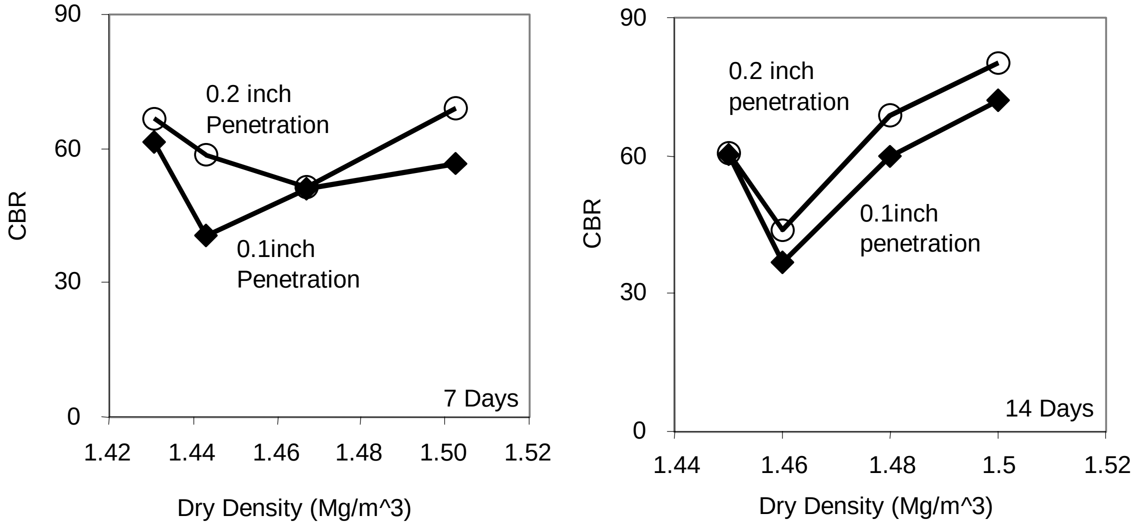


Figure 13. Relation between CBR with the dry density of the ponded fly ash after 7 and 14 days of curing.

Figure 13 shows the relation between the CBR with the dry density of the ponded class C fly ash for each water content. The aim of this investigation is to determine the minimum CBR for the water content range of interest. In the analyses, the minimum CBR value for 7-day is 40, and that for 14-day cure is 37 for 1-inch penetration. The same for 2-inch penetration, respectively are 52 and 44. According to an investigation carried out by a researcher, CBR value of 25 or greater for sub any grade is considered good.[15] Therefore, the results show that the ponded class C fly ash can be a good substitute as a base course material.

4. CONCLUDING REMARKS

This paper has discussed the laboratory investigations of both short-term and long-term strength and stiffness development of stabilized soil with self-cementing class C fly ash. The laboratory investigations discussed in this paper had two main components, namely (1) determination of stabilization characteristics of clay soils blended with self-cementing class C fly ash, and (2) determination of the residual cementation characteristics of ponded class C fly ash.

In the analyses, it was found that the stabilization characteristics are the functions of curing time, curing condition, and the clay mineralogy. The stabilization characteristics in this paper were measured in terms of the (1) gain in the uniaxial compressive strength and stiffness and (2) failure strain. In the analyses, the amount of montmorillonite was varied from 0, 2, 4 and 6 percent, and the amount of class C fly ash was varied from 5, 10 and 20 percent. Three types of curing environments were chosen. In the first case, samples were kept in plastic bags and cured at 38 ^{o}C; in the second case, samples were cured at 80 percent humidity and 27 ^{o}C; and in the third case, samples were cured at atmospheric humidity and temperature. Results obtained from the analyses showed that the optimum moisture content changes due to the addition of fly ash to the prepared clay mixtures. The samples rapidly gained compressive strength and stiffness within 7-day curing period, and the greatest increase occurred in 1-day due to the rapid hydration reaction of class C fly ash. Typically, the strength tends to increase up to 14-day curing period, and beyond 14 days, the strength retarded. Results also suggested that after 28 days, the samples became very brittle. With increased amount of montmorillonite (bentonite), strength of the samples increased significantly. This is because the clay blends of montmorillonite absorbed and retained moisture and provided moisture to fly ash hydration process. During the analysis, it was also observed that in case of most controlled curing situation, samples gained the maximum strength.

In case of ponded class C fly ash, sieve analysis, dry density and moisture content tests, unconfined compression test and California Bearing Ratio (CBR) tests were carried out. CBR value of the ponded class C fly ash was 37 to 52. This suggests that the ponded class C fly ash can be a good substitute as a base course material.

The results obtained from the analyses suggested that class C fly ash has some cementitious property that may effectively replace typical cementitious materials, if proper engineering judgment is given due consideration.

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