CRUSHED AGGREGATES FROM CLASS C FLY ASH

Draft Final Report

to

Combustion Byproducts Recycling Consortium

West Virginia University

by

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I. INTRODUCTION AND EXECUTIVE SUMMARY

Self-cementing class C fly ash is produced in voluminous quantities by utilities in the Midwest as a result of burning sub-bituminous coal from Wyoming. Owing to their self-cementing nature, these fly ashes may be used as cement surrogates. In the proposed research project, the self-cementing nature of these fly ashes is exploited to develop lightweight aggregates that may be used for a wide variety of construction activities.

Hydrated class C fly ash can have compressive strength comparable to low-strength rocks. For example, 7-day air cured samples of class C fly ash-sand mortar have compressive strengths of 10 MPa and above. Furthermore, compressive strengths of some hydrated class C ashes have been reported to be as high as 15 MPa with a specific gravity of less than 2.0. Moreover, additives such as kiln dust, lime and fibers may enhance the strength and other mechanical properties of hydrated class C fly ash. This indicates that class C fly ash could be used to produce lightweight aggregates that would classify as low-strength rocks and could be used as granular base course for highways, as backfill behind retaining structures, as decorative rocks, in specialty concrete, and in other applications. In addition, hydrated class C ponded ash may also be reclaimed from ponds to produce crushed aggregates.

In this research project, we have evaluated class C fly ash aggregates produced by: (1) extruding laboratory cured mixtures of water, class C fly ash, fibers and sand, (2) crushing laboratory cured mixtures of water and class C fly ash, and (2) crushing reclaimed hydrated ponded class C fly ash. A variety of tests were performed to characterize the physical and engineering properties of these aggregates, including particle shape, surface texture, moisture absorption capacity, specific gravity, density, soundness, and durability. The engineering properties of these aggregates for application as pavement base course material, as backfill material and as embankment materials were evaluated by investigating their compaction behavior, and California Bearing ratio (CBR).

This report describes the findings of the research project related to: (1) the literature review of fly ash aggregates and use of fibers in cementitious products, (2) the physical and chemical characteristics of class C fly ash, (3) the determination of optimal ash-sand proportion and optimal ash-fiber-sand mixes, (4) aggregate production and characterization, and (5) ponded ash aggregate characterization. Based upon the results of this research, we find that aggregates produced by exploiting class C fly ash self cementing property have characteristics that are best suited for applications such as road bases, lightweight embankment fills or lightweight granular backfills behind retaining walls. Therefore, ponded class C fly ashes could yield a rich source of crushed aggregates that may be used for these construction applications.

II. LITERATURE REVIEW OF FLY ASH/SYNTHETIC AGGREGATES

The literature review was performed with a focus upon collecting, reviewing, analyzing and summarizing available information concerning: (1) the utilization of class C fly ash for aggregate production; (2) other efforts to produce synthetic aggregates, especially those using cementitious materials; (3) appropriate cut strand fibers and fiber fillers that may be used for ash-fiber-sand aggregate production; and (4) characterization methods for aggregates in various construction applications.

Fly Ash Aggregates: The main finding from the literature review is that little effort has been made to exploit the self-cementing property of ashes to produce aggregates. Most of the aggregate production methods using fly ash that are available in open literature involve some type of high temperature sintering (ACAA 1999). However, Baykal and Doven (1999) from Turkey have attempted to make unsintered fly ash aggregates using a combination of fly ash, Portland cement and lime. They have reported that Portland cement concrete made using this aggregate yielded 28-day strength in the range of 28 MPa to 35 MPa, which is similar to that of structural concrete. Bykal and Doven (1999) used ash that would classify as class F ash and they had to utilize Portland cement and lime as pozzolanic activators to produce the cementation within aggregates. This finding is encouraging and indicates that aggregates may be created without the expense of high temperature treatment. We note that the current research project envisages the exploitation of self-cementing capability of class C fly ashes to produce unsintered aggregates.

Baykal and Doven (2000) have presented further results on manufactured lightweight aggregates produced by pelletizing method using three mixes, 1) fly ash only, 2) fly ash and lime, and 3) fly ash and cement. The production rate and power consumption of the pelletization process depends on the physical properties of the agglomerated materials, the moisture content of the fines and the mechanical parameters. The fly ash used in this study has a specific gravity of 2.18 and a fineness of 24 μm. Based upon the chemical composition, this fly ash would be classified as class F fly ash. The pelletized aggregates were cured at 21°C and 70% humidity. The properties of the aggregates are summarized in the table below. The unit weight of the aggregates with fly ash only was found to be 9.6 kN/m^3. The aggregates formed with the addition of lime and cement had unit weights of 9.8 and 10.4 kN/m^3, respectively, which represent an increase of 2 to 8 %. The specific gravity for the aggregates varied from 2.00 to 2.35, and the absorption capacity varied from 28.8% to 33.9%. The optimum moisture content and maximum dry density from standard Proctor test were found to be 34-34.5% and 11.96-12.56 kN/m^3, respectively. The corresponding CBR values ranged from 58 to 82. The compaction test results show that the optimum moisture content is about 4-4.5 % more than the absorbed amount, which is similar to that for natural aggregates. The soundness test indicated that the loss of weight varies from 6.9% to 9%, which is well below the specified 12%. The finding of Baykal and Doven is encouraging as they indicate that cementitious capacity may be exploited to produce fly ash aggregates.

Properties		Fly ash	Fly ash and Lime	Fly-ash and cement
Unit Weight (kN/m^3)		9.6	9.8	10.4
Specific Gravity		2.00-2.17	2.10-2.28	2.17-2.35
Bulk Specific Gravity		1.19-1.29	1.26-1.33	1.33-1.40
CBR	Optimum Water Content (%)	34.4	34.5	34.0
	Dry Unit Weight (kN/m^3)	11.96	12.16	12.56
	CBR (%)	58	82	82
Soundness	9.5-4.75 mm size	9.0	8.9	7.4
	19-9.5 mm size	7.9	8.2	6.9
Absorption (%)		33.9-31.4	31.6-31.4	29.3-28.8

Along the lines of utilizing self-cementing capacity of class C fly ash, the work done by Kilgour et al. (1988) and Senadheera et al. (1998) has shown encouraging results. For example, ash pellets made in an agglomerator using class C fly ashes have been shown to have sufficient strength and durability for field handling and storage (Kilgour et al. 1988). In addition, compressive strengths as high as 15 MPa have been obtained for hydrated class C fly ash cured under controlled conditions (Senadheera et al. 1998). The samples were hydrated at three different moisture contents with no other additives or fillers, covered with polyethylene bags to prevent moisture loss, and cured at 70^o F. Senadheera et al. reported that the aggregates obtained from fly ash hydrated at 20% moisture content had a specific gravity of 1.85 and satisfied the Wet Ball Mill test specification for Texas Department of Transportation Grade I flexible base materials.

Aggregates obtained from class C fly ashes hydrated in ash ponds have also been successfully used as road base material by the Texas Department of Transportation in experimental projects. These ponded ash aggregate road bases have a tendency to harden into a stiff layer after placement and compaction (Senadheera et al 1998). Similarly, visual inspections of the access road project at the KCPL Hawthorn site show that compacted ponded ash may be used to produce hard, cemented sub-grades. Therefore, it is reasonable to expect that hydrated ponded ashes have some residual cementing capacity, which may be enhanced by pozzolanic activators. Residual cementing capacity has also been observed by Bergeson and Mahrt (2000), who used reclaimed fly ash for fill under PCC pavement.

The paper by Bijen (1986) reviews the processes of manufacturing lightweight aggregates by using fly ash. According to this paper, the agglomeration process may be divide into two categories 1) Agitation granulation and 2) Compacting. The agitation granulation can be divided as disc granulation, drum granulation, cone granulation, and mixer granulation. The density of the pellets produced by compaction agglomeration is higher than that of pellets produced by agitation granulation. The resultant aggregate may be hardened by different processes 1) Sintering, 2) Hydrothermal process and 2) Cold Bonding. In hydrothermal process the bonding is achieved by means of chemical reaction of lime or Portland cement with fly ash and water. The hydrothermal process is more or less related to ore pelletizing. In Cold bonding the bonding is achieved by the reaction of fly ash with calcium hydroxide at ordinary temperature to form a weather-resisting bonding material. But the bonding of the material achieved by this method is less rigid than what is achieved by other method, this negative aspect can over come by using compaction agglomeration technique. This paper doesn’t deal with the test result. Research is conducted to produce a light weight aggregates from a mixture of fly ash, wet desulphurization scrubber sludge and lime. The blocks are made from this composition and are crushed for the production of aggregates. Experiments have been performed to produce crushed aggregates from demolished artificial stone. Here they construct a base with mixture of fly ash, lime, gypsum and water and compacted. After hardening of this material it is crushed into an artificial aggregates.

Fibers in Cementitious Matrix: A variety of fibers have been used in cementitious composites (Balaguru and Shah 1992). In the proposed research project, the purpose of utilizing fibers is to provide the aggregates enhanced properties in terms of toughness, durability, crack resistance and impact strength, and reduced pre-existing shrinkage cracks. Glass, plastic and cellulose fibers have been generally used in cementitious products with varying degree of success. The fiber sizes used in these products vary from 2 mm to 30 mm. Based upon a literature review of fibers utilized with cementitious materials and considering the size of aggregates planned, we have selected three commercially available fibers: (1) milled glass fibers, (2) milled plastic fibers, (3) cellulose fibers. All the three chosen fibers have a size smaller than 1 mm. Of these, the milled plastic fibers are marketed primarily for application in cementitious materials as replacement for asbestos. The others are not marketed directly for cementitious material applications, however, have physical characteristics similar to the milled plastic fibers.

III. PHYSICAL AND CHEMICAL COMPOSITION OF KCPL CLASS C FLY ASH

Fly ash is obtained as a by-product from electricity generating utilities that use pulverized coal powder consisting of 70 to 80% particles passing No. 200 sieve (75 µm). The non-combustible elements in powdered coal evaporate at high temperatures and combine to form a variety of complex inorganic compounds. Upon the cooling of exhaust gases, these compounds precipitate into fine spherical particles. These particles may be collected using a variety of methods such as mechanical collectors, electrostatic precipitators, fabric bag filters and wet scrubbers. The fly ashes from the plants of Kansas City Power and Light Company (KCPL), which this paper focuses upon, are collected using electric precipitators. As part of the current project, a database of physical and chemical properties and their statistical variability has been compiled for the KCPL fly ash being utilized for making aggregate. The database serves as a point of comparison of this fly ash characteristics with other fly ashes reported in the literature. In addition, the database documents the variability of these fly ashes. In the following discussion, we briefly describe the physical and chemical characteristics of KCPL fly ashes. We also briefly discuss the following: (1) the differences between high-calcium fly ashes and low-calcium ashes, and (2) the statistical variability of fly ash properties.

Table 1 summarizes the mean and standard deviations of physical and chemical characteristics based upon data compiled for KCPL fly ashes. Table 1 also contains the data for fly ashes derived from Western or Powder River Basin coal based upon data available in the literature (Misra 1998). Literature data has been grouped into 3 classes based upon the calcium oxide (CaO) content of <10%, 10 to 20% and >20%. It is noteworthy that high calcium (class C) fly ashes, particularly the Western coal fly ashes, show small variability in almost all measures of physical and chemical characteristics. Similarly, the fly ashes obtained from KCPL, which are derived from Western coal combustion, also show a small variability. The low variability is attributable to the awareness of the power plants to control the quality of their combustion by-product as well as the low natural variability of the Western coal. It is also noteworthy that the class C fly ash used in this project has low loss-on-ignition and fineness values, which makes it an excellent cement surrogate.

Particle Morphology, Grain Sizes, Specific Gravity and Bulk Density: In the proposed project we are utilizing class C fly ash obtained from KCPL Iatan plant. This fly ash appears as a fine powdery material with mainly spherical glassy particles, consisting of solid spheres; glass bubbles termed cenospheres; and cenospheres that are packed with smaller spheres termed plerospheres. A small amount of irregular shaped particles are also present that consist of mainly crystalline materials. For fly ashes, the grain sizes are typically specified in terms of: (i) fineness, (ii) specific surface, and (iii) cumulative grain size distribution curves. ASTM C618 specifies the fineness in terms of amount retained on No. 325 (45 µm) sieve, which should be no more than 34% by weight. Figure 1 gives a range grain size distributions observed for various fly ashes. The fineness of KCPL fly ashes is shown by the filled symbol.

Table 1 lists the typical specific gravity values for a variety of fly ashes along with the KCPL fly ashes considered in this project. A review of the literature indicates that the bulk density of different fly ashes also varies over a large range, from 0.5 to 0.9 g/cm^3. The bulk density variations reflect the compaction conditions. The bulk densities of lightly compacted KCPL fly ashes have been measured to vary between 0.75 to 0.8 g/cm^3.

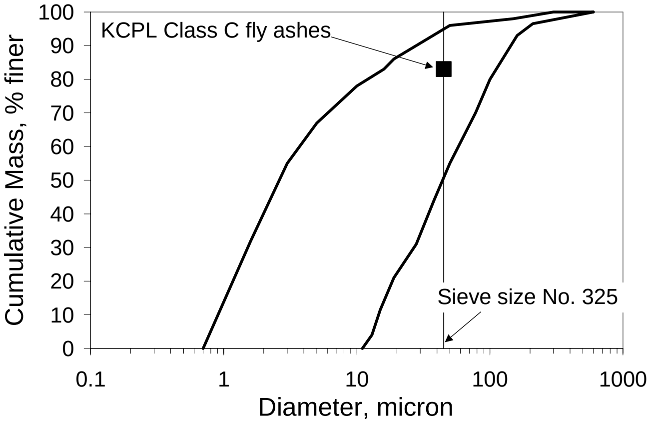


Figure 1. Grain size distribution for fly ashes.

Strength Gain Characteristics and Hydration Moisture Requirements: Tests were conducted on LaCygne class C fly ash to find the strength gain characteristics and hydration moisture requirements of class C fly ash. These tests were conducted according to ASTM D5239**.** Figure 2 shows the relationship between strength gain and curing age, and hydration moisture requirements and curing age. As shown the strength of the fly ash increases as the curing age increase. The rate of strength gain is the highest in the first 7 days. The rate considerably slows down the next 7-days; and there is little strength gain between 7 to 14 days. Beyond 14-days, the strength gain is negligible. Thus, it maybe concluded that most of the hydration reaction in fly ash takes place between 1 to 14 days. A second set of test was conducted by modifying the water-fly ash ratio to be 0.3 as opposed to 0.35 used in the ASTM D5239. As shown in Figure 2, the strengths are generally higher for water-fly ash ratio of 0.3. We also studied the moisture loss during curing. Results show that 13 percent to 17 percent of moisture is needed by fly ash for hydration.

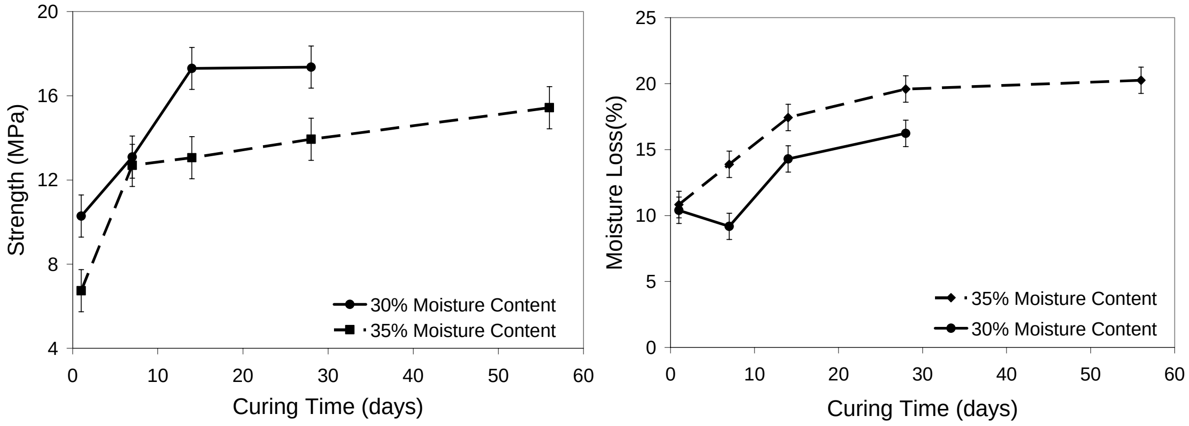


Figure 2. Plot of strength gain and hydration moisture with curing days.

Chemical Composition: Class C fly ash is mainly composed of silicon, aluminum, and calcium oxides as well as complex combinations of these oxides. In addition small amounts of iron and magnesium oxides, active alkalis, such as sodium and potassium oxides, and unburned carbon are also present. Table 1 summarizes the chemical composition of various fly ashes. Considering calcium oxide content, fly ashes are categorized as: (1) low (<10% CaO), (2) medium (10-20% CaO), and (3) high (>20% CaO) calcium fly ash. Furthermore, depending upon the relative amounts of the major chemical constituents, fly ash may be classified as Class C and Class F. Fly ash containing more than 50% but less than 70% of silicon, aluminum and iron oxides (SiO_2+Al_2O_3+Fe_2O_3) are classified as Class C. If the sum of these three oxides exceeds 70% then a fly ash is classified as Class F. Thus the medium and high calcium fly ash are considered as Class C fly ash. As seen from Table 1, the combustion of Western coal (a sub-bituminous coal) typically produces a Class C fly ash. Class C fly ash, such as those obtained from KCPL's Hawthorn, LaCygne and Iatan plants; contain sufficient calcium and other compounds to induce a cementitious reaction in the presence of water, which makes these fly ashes applicable as a cementing agent. As seen from the ternary diagram in Figure 3, which gives the oxide composition of fly ashes along with those of Portland cement, natural cement and quick lime, the KCPL fly ashes have chemical characteristics that are close to natural hydraulic cements.

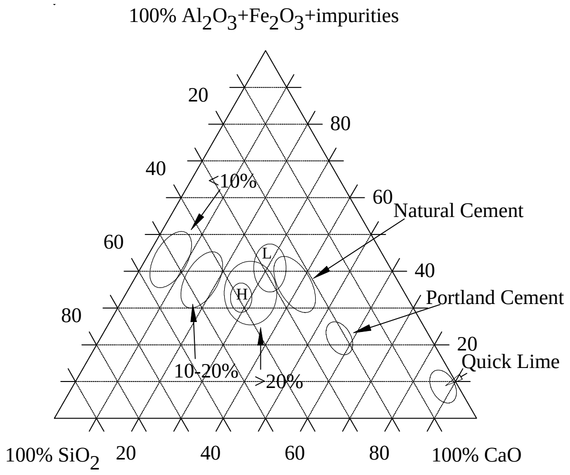


Figure 3. Ternary diagram of oxide composition of fly ashes.

Table 1. Physical and Chemical Characteristics of Fly Ash

Component	Class F fly ash*		Class C fly ash*				Typical Western* coal ash (estimated)		Hawthorn [a] ash		LaCygne [b] ash		Iatan [c] ash	
	< 10 % CaO		10-20 % CaO		>20 % CaO									
	M[d]	D[e]	M	D	M	D	M	D	M	D	M	D	M	D
MC	0.11	0.14	0.1	0.0	0.06	0.06	0.059	0.005	0.091	0.018	0.076	0.025	0.05	0.02
LOI	2.6	2.4	0.5	0.7	0.33	0.05	0.37	0.108	0.316	0.104	0.341	0.147	0.44	1.91
Fineness	23	9	20	7	15	4.9	14	3.4	15.82	1.057	12.28	1.540	20.8	1.99
Specific Gravity	2.19	0.36	2.4	0.14	2.61	0.10	2.6	0.05	2.598	0.027	2.571	0.033	2.52	0.05
SiO_2	52.2	9.6	48.5	4.8	36.9	4.7	35.1	1.52	34.29	2.46	34.09	2.13	41.16	1.76
Al_2O_3	22.8	5.4	19.6	3.6	17.6	2.7	17.6	0.45	23.23	0.75	22.67	0.98	22.28	0.87
Fe_2O_3	7.5	4.3	6.2	2.1	6.2	1.1	5.8	0.35	5.41	0.30	5.86	0.41	5.28	0.33
Sum	82.8	13.1	74.3	4.4	60.7	5.2	58.5	1.62	62.92	2.06	61.67	1.78	68.76	1.53
SO_3	0.6	0.5	1.3	0.8	2.9	1.8	3.1	0.45	1.46	0.20	1.70	0.20	0.93	0.18
CaO	4.9	2.9	15.2	2.5	25.2	2.8	25.9	0.79	25.13	1.29	26.70	1.36	21.99	1.10
AA	0.8	0.9	1.0	0.9	5.1	1.0	2.2	0.45	1.40	0.06	1.38	0.05	1.09	0.10
MgO	-	-	-	-	-	-	-	-	-	-	-	-	4.09	0.27

[a]-------based upon 13 samples collected between February 1996 and June 1996. [b]-------based upon 18 samples collected between February 1996 and June 1996. [c]-------based upon 98 samples collected between January 2001 and May 2001. *-------data from McCarthy et al. 1989[1]. [d]---------Mean. [e]---------Std. Deviation. MC---moisture content. LOI---loss on ignition. Sum---SiO_2+Al_2O_3+Fe_2O_3. AA---available alkalis.

IV. CLASS C FLY ASH AGGREGATES

Class C Fly Ash-Fiber-Sand Mortar

To evaluate the application of class C fly ash as hydraulic cement for making low to intermediate strength material, fly ash-sand mortar mixtures were investigated. Mortar mixes were made for water-fly ash ratios of 0.2, 0.3 and 0.4 and for sand-fly ash ratios of 1.5, 2.0 and 2.5. To ensure uniformity in mix and cube preparation, the mortar was thoroughly mixed in a motorized mixer for exactly 5 minutes and then placed in a mold in three layers with each layer compacted 25-times using a tamper. Three cubes were prepared for each mix proportion and air cured for 7-days at 74±3 ^{o}F (23±1.7 ^{o}C). The cubes yielded very consistent strength results, therefore, three cubes per mixture were deemed to be acceptable for determination of optimum mix proportion. Figure 4 shows the contour plot of 7-day compressive strengths. The optimum mortar mix was found to have the water-fly ash-sand proportion of 0.3:1.0:2.0 with strength in excess of 10MPa.

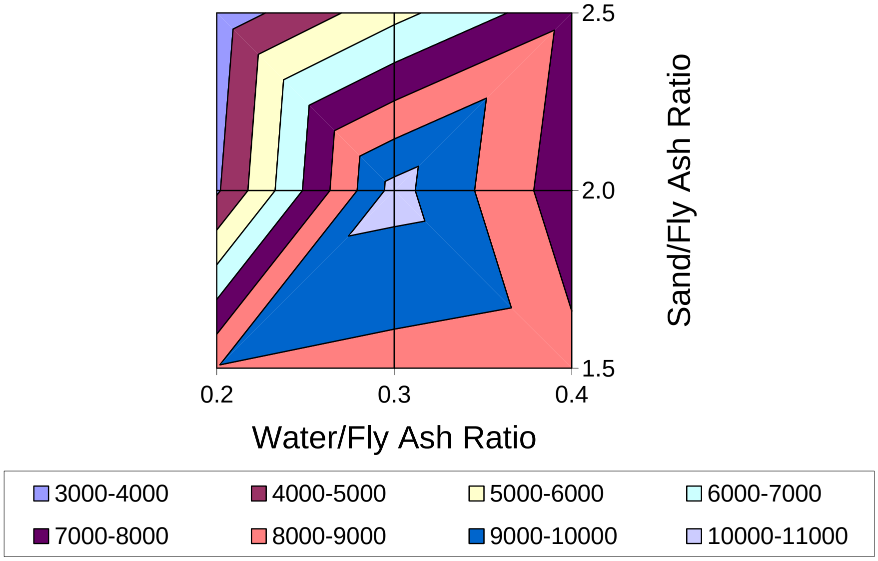


Figure 4. Contour plot of 7-day compressive strengths in kPa.

To further explore the variability of mechanical behavior of fly ash-sand mortar, 21 additional cubes were prepared and cured for 7-days in an environmental chamber at 90% humidity and 95^{o}F (35^{o}C) temperature. Figure 5 gives the histogram of the compressive strength and modulus of elasticity for the mix proportion 0.3:1.0:2.0. The mean and standard deviation of compressive strength was found to be 14.6 MPa and 1.23 MPa, while that for modulus of elasticity was found to be 710 MPa and 60 MPa, respectively. Notably, the coefficient of variation, determined as a ratio of the standard deviation and the mean, is less than 10% indicating low variability in strength and modulus of elasticity.

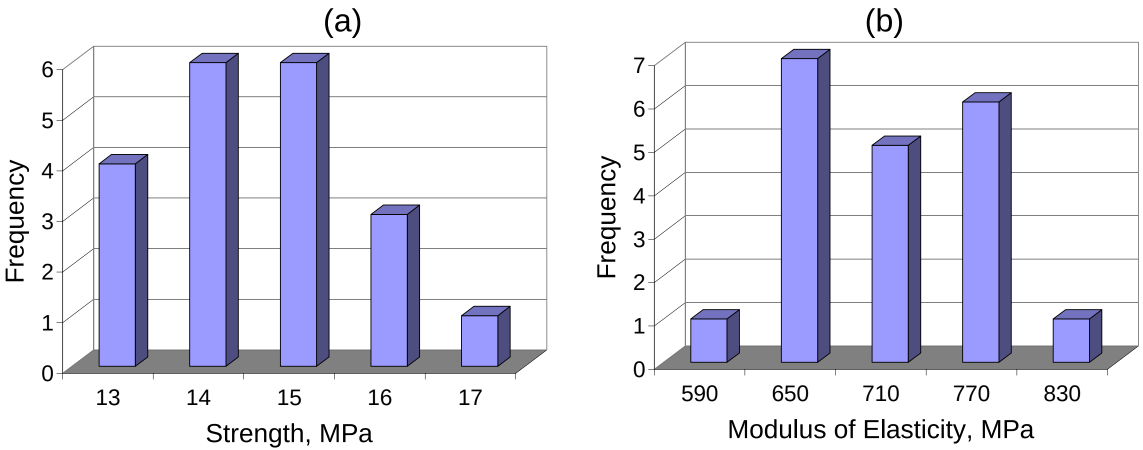


Figure 5. Histogram showing the variability of fly ash-sand mortar, (a) compressive strength, and (b) modulus of elasticity, after 7-day curing.

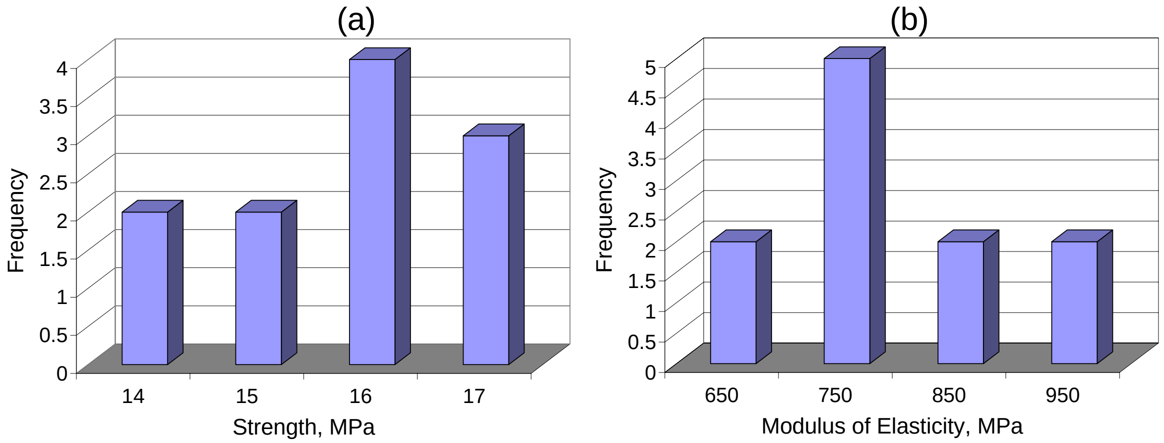


Figure 6. Histogram showing the variability of fly ash-sand mortar, (a) compressive strength, and (b) modulus of elasticity, after 14-day curing.

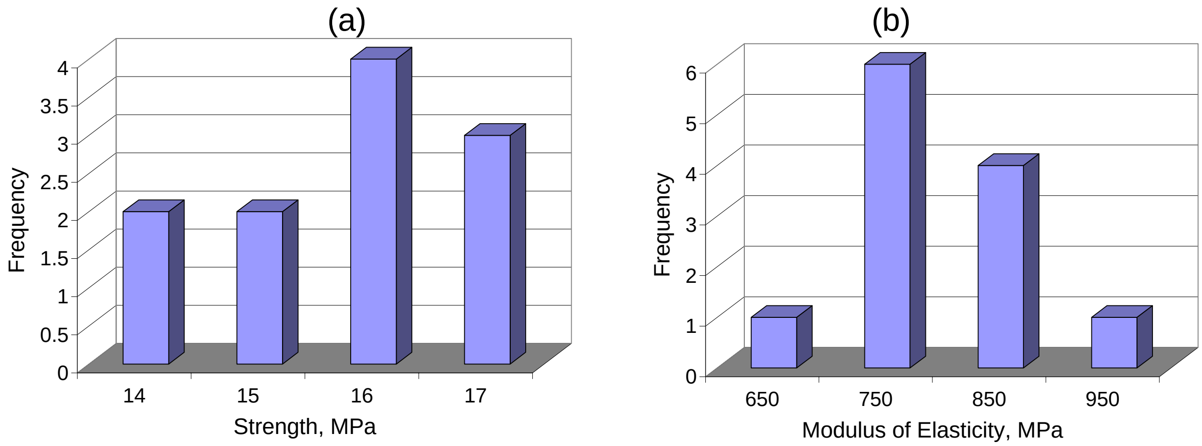


Figure 7. Histogram showing the variability of fly ash-sand mortar, (a) compressive strength, and (b) modulus of elasticity, after 28-day curing.

Furthermore to verify that the 7-day strength is representative of the fly ash-sand mortar behavior, two batches of 21 additional cubes were prepared and cured in an environmental chamber at 90% humidity and 95°F (35°C) temperature and tested for 14 and 28-day strengths. Figures 6 and 7 give the histogram of the compressive strength and modulus of elasticity for 14-day and 28-day cured samples, respectively. As seen from the histograms and Figure 8, the 14-day and 28-day average compressive strength and modulus of elasticity are very close. Clearly a majority of the strength gain occurs within the first 7-days of curing.

Class C fly ash was found to have rapid initial hydration rate and a short set time. Vicat penetration apparatus was utilized to explore the initial hydration rate of fly ash-sand mortar. Since the initial hydration rate is rapid, the needle penetration is recorded every 45 seconds until the needle is unable to penetrate the mortar. This is in sharp contrast to the standard Vicat penetration test used for Portland cement, wherein the penetration is recorded every 30 minutes. Figure 9a gives a record of penetration versus time curve for the optimal fly ash-sand mortar. Again three mortar samples were tested to confirm the repeatability of the penetration tests. An average set time of 12 minutes was recorded for this mortar.

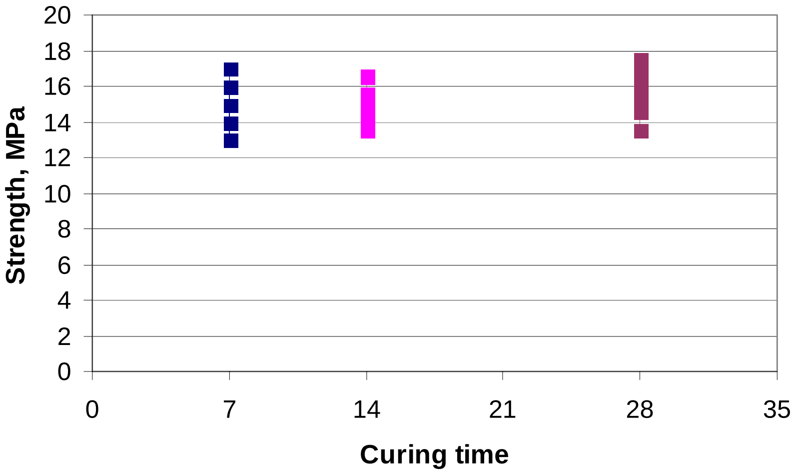
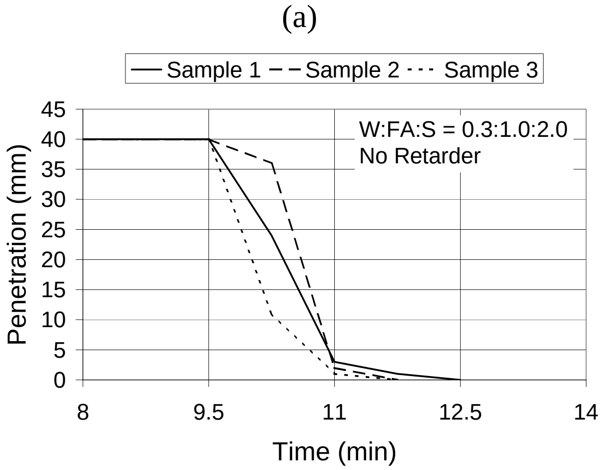


Figure 8. Strength of fly ash-sand mortar versus the time of curing

With the view that the rapid hydration time could be of concern in some application, we evaluated a commercially available retardant used for Portland cements. The retardant was effective in increasing the setting time for the mortars. Figure 8b gives the penetration curve for fly ash-sand mortar prepared with retardant. The retardant used in these tests is marketed for use with Portland cements; therefore the effect of dosage rate on setting time and compressive strength of fly ash-sand mortar was investigated. Figure 10 gives a plot of setting time and compressive strength versus the retardant dosage rate. The retardant has a small effect on compressive strength up to a dosage rate of 150ml/ 100kg of fly ash, while the setting time is increased by almost 50%. At higher dosage rates, the strength falls rapidly and the setting time increases rapidly as well. As a dosage rate of 250ml/ 100kg of fly ash, the strength is decreased by almost 25% to 7.8 MPa, while the setting time is increased by 200% to 36 minutes.



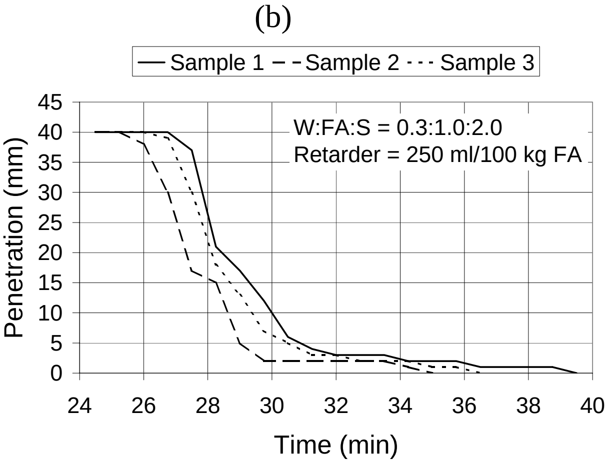


Figure 9. Penetration curve for fly ash-sand mortar.

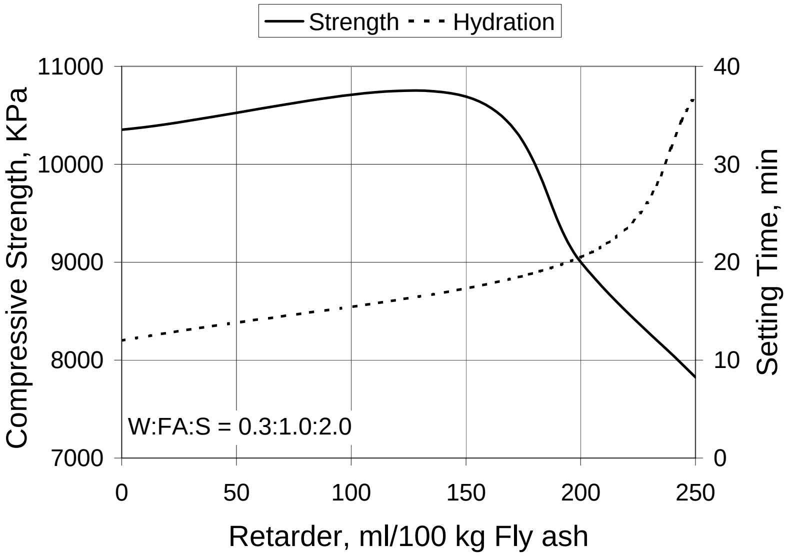


Figure 10. Effect of retardant of fly ash-sand mortar behavior

Class C Fly Ash-Fiber-Sand Mortar

Based upon the above tests, the water-fly ash-sand proportion of 0.3:1.0:2.0 is deemed to be optimal. Further testing is now underway to determine the optimal contents of the three fibers chosen for evaluation. Figures 11 through 16 give the histogram of the compressive strength and modulus of elasticity for mortars prepared by replacing sand with fibers. Glass fibers were used to replace sand at three replacement levels of 5%, 10% and 15%, while polymer fibers were used at the replacement levels of 5% and 10%, and cellulose fibers at the replacement level of 10%.

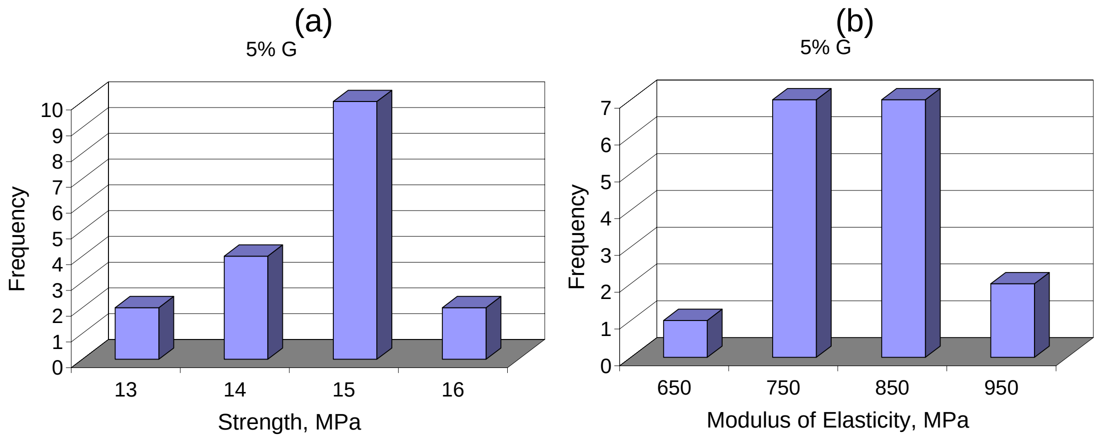


Figure 11. Histogram showing the variability of, (a) compressive strength, and (b) modulus of elasticity for fly ash-fiber-sand mortar containing 5% glass fibers.

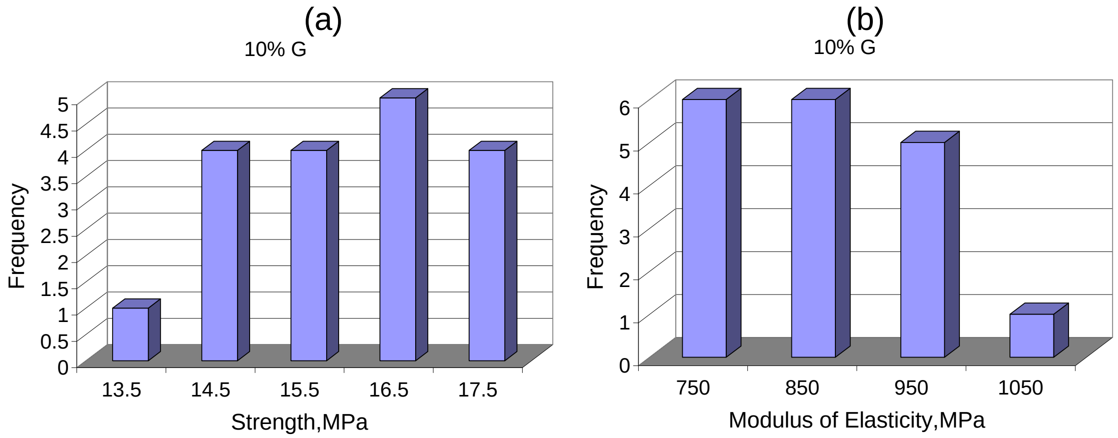


Figure 12. Histogram showing the variability of, (a) compressive strength, and (b) modulus of elasticity for fly ash-fiber-sand mortar containing 10% glass fibers.

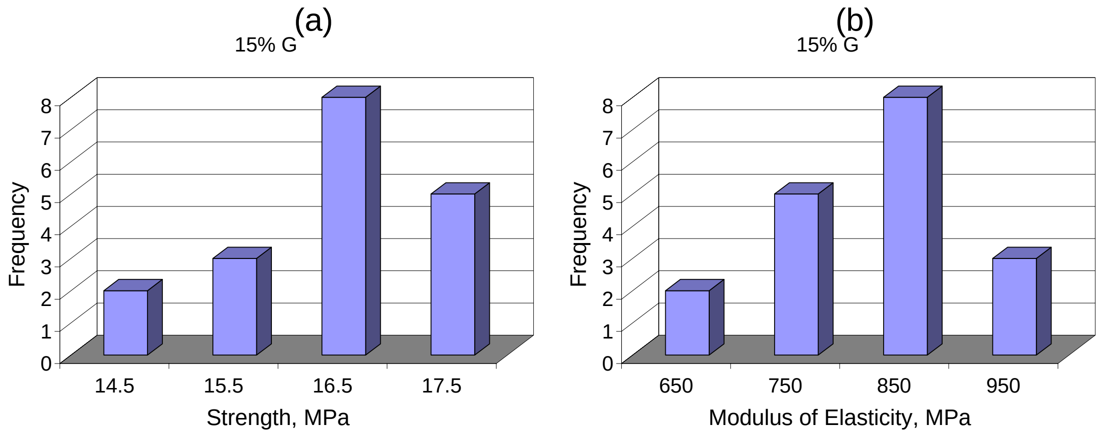


Figure 13. Histogram showing the variability of, (a) compressive strength, and (b) modulus of elasticity for fly ash-fiber-sand mortar containing 15% glass fibers.

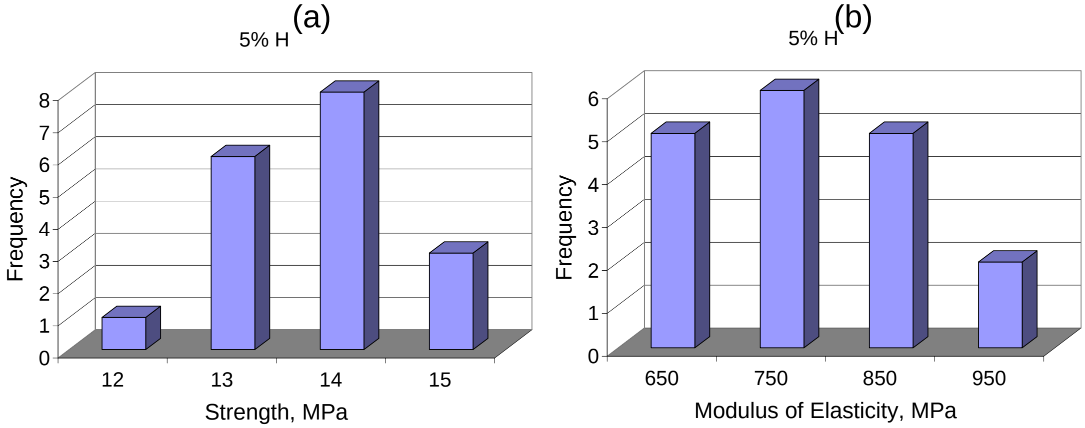


Figure 14. Histogram showing the variability of, (a) compressive strength, and (b) modulus of elasticity for fly ash-fiber-sand mortar containing 5% polymer fibers.

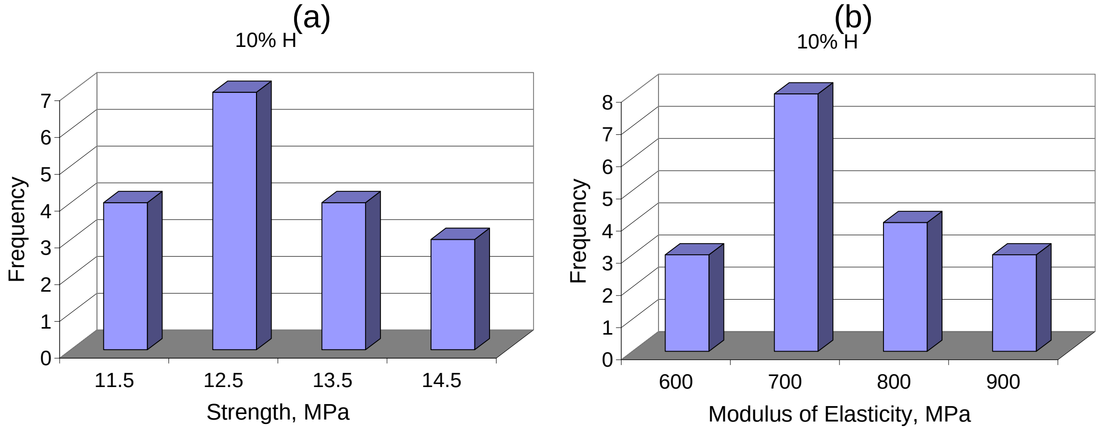


Figure 15. Histogram showing the variability of, (a) compressive strength, and (b) modulus of elasticity for fly ash-fiber-sand mortar containing 10% polymer fibers.

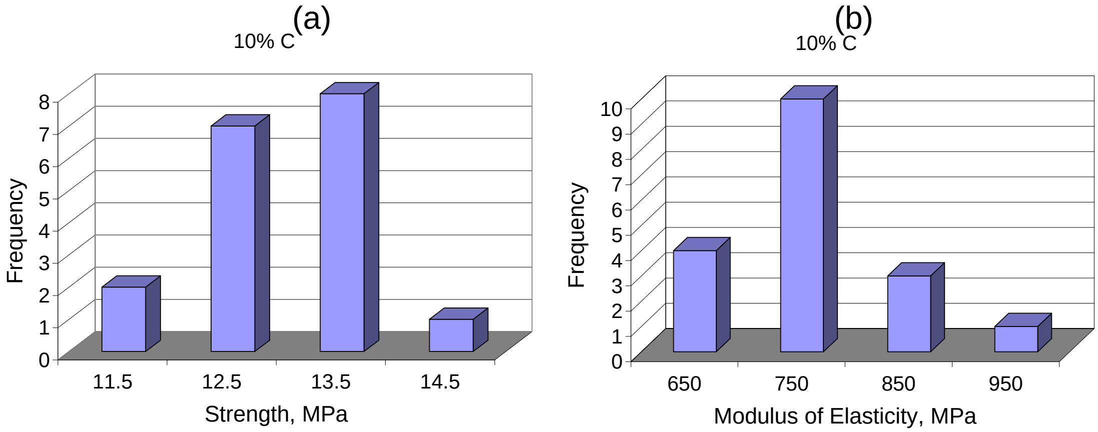


Figure 16. Histogram showing the variability of, (a) compressive strength, and (b) modulus of elasticity for fly ash-fiber-sand mortar containing 10% cellulose fibers.

The histograms in Figures 11 through 16 are based upon tests conducted on 18-cubes for each mix cured for 7-days in an environmental chamber at 90% humidity and 95^{o}F (35^{o}C) temperature. The average and standard deviations of strength and modulus of elasticity are tabulated in Tables 2 and 3. Fairly repeatable results are obtained in all cases. Remarkably, the standard deviations for the strength are in the range of 5% to 8%, indicating repeatability of mix and cube preparation. As seen from Tables 2 and 3, the glass fiber increases both the strength and modulus of elasticity of fly ash-sand mixtures. In contrast, the plastic and cellulose fibers tend to decrease the strength while increasing the modulus of elasticity. Although the change in compressive strengths and modulus of elasticity due to addition of fibers may appear to be low, the durability and toughness are expected to increase considerably. As outlined in the original proposal, we intend to perform toughness and durability tests on the final aggregates produced using these mixes to quantify the toughness and durability parameters.

Table 2. Compressive strength of fly ash-fiber-sand mortar, MPa

% Fiber by volume	Glass Fiber		Hi-Fibe (plastic)		Cellulose Fiber	
	Range	Average (Standard Deviation)	Range	Average (Standard Deviation)	Range	Average (Standard Deviation)
5	13.62-16.34	15.21 (0.75)	11.77-15.45	13.78 (0.84)		
10	12.53-17.65	15.76 (1.32)	11.46-14.79	12.72 (0.95)	11.10-14.27	12.89 (0.74)
15	14.76-17.29	16.37 (0.88)				
50	8.69-10.34	9.55 (0.71)				

Table 3. Modulus of elasticity fly ash-fiber-sand mortar, MPa

% Fiber by volume	Glass Fiber		Hi-Fibe (plastic)		Cellulose Fiber	
	Range	Average (Standard Deviation)	Range	Average (Standard Deviation)	Range	Average (Standard Deviation)
5	686-1002	822 (79.2)	611-933	770 (99.6)		
10	712-1121	855 (105.8)	663-924	740 (96.0)	662-988	749 (79.2)
15	618-944	816 (89.5)				

To further explore the effect of the retardant on behavior of fly ash-fiber-sand mortar, we prepared 5 cubes adding 5% gypsum and additional 6 cubes with 2% gypsum. We cured the cubes for 7-days in an environmental chamber at 90% humidity and 95^{o}F (35^{o}C) temperature. The retardant was a pure white, smooth, slow-setting plaster. The mortar was prepared by replacing fly ash with calcium sulfate and the cubes were prepared in the manner described earlier. The strength and modulus of elasticity of the resulting mortar are given in Table 4.

As seen from Figure 17, the average strength for the mortars with 2% and 5% gypsum are similar - 11.905 MPa and 12.72 MPa, respectively. Therefore additional test was performed to determine which mixture has the better workability. For this purpose, we prepared three fly ash-water samples with 0%, 2% and 5% calcium sulfate. The setting time for the mixtures with 2% and 5% increased. Given that the difference between the setting times of the 2% and 5% were not immense, but the workability for the 2% gypsum improved, we chose the 2% gypsum to be the better amount for aggregate production.

Table 4. Strength and Modulus of Elasticity for mortars with 2% and 5% calcium sulfate.

% Gypsum by volume	15 % Glass Fiber				50 % Glass Fiber			
	Compressive Strength, MPa		Modulus of Elasticity, MPa		Compressive Strength, MPa		Modulus of Elasticity, MPa	
	Range	Average (Stdev)	Range	Average (Stdev)	Range	Average (Stdev)	Range	Average (Stdev)
2 %	11.09-12.41	11.905 (0.49)	579-769	671 (64.2)	8.69-10.34	9.55 (0.71)	391-595	517 (80.8)
5 %	11.38-13.62	12.72 (0.84)	470-918	626 (184)				

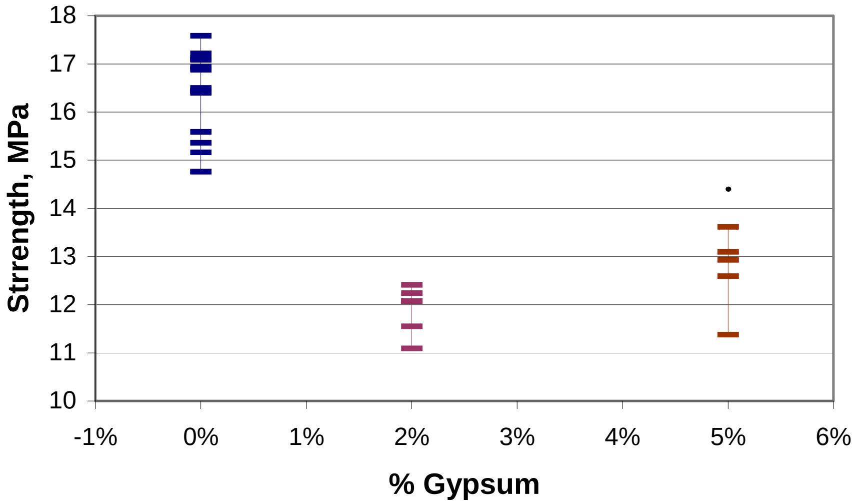


Figure 17. Strength of the samples for 0%, 2% and 5% gypsum

Class C Fly Ash-Fiber-Sand Aggregates:

Extruded Aggregates:

Based upon the results of Task 2 described above, we have determined the optimal mix proportion of water-fly ash-sand proportion to be 0.3:1.0:2.0. Based upon strength consideration, the most effective fiber type identified to be glass fibers at the replacement rates of 15% by volume of sand. However, based upon workability considerations, glass fibers at the replacement rates of 50% by volume of sand were found to be effective. Using these mix-proportions and fiber type and content, aggregate samples were produced utilizing an extrusion process.

The preparation of the extruded mixtures was as follows: first the solid materials (fly ash and fine sand passing # 40 sieve, 0.425 mm) were mixed together with the fibers to get proper dispersion of the fibers in the composite, and then water was incorporated to the mixture. All the components were mixed together manually, since the batches were too small for the mixer. The mixture is subsequently extruded through a die. The extruded aggregates are cured under plastic sheet cover in an environmental chamber at 90% humidity and 95^{o}F (35^{o}C) temperature. After one day the plastic wrapping is removed and the aggregates are cured in the environmental chamber at the same humidity and temperature for 6 days. Another batch of aggregates was cured under plastic cover at room temperature (23 ^{o}C) and 70% humidity. After one day, these aggregates were placed in water to cure at 100 % humidity for at least 6 days. Thereafter the specimens were dried at 70% humidity and room temperature (23 ^{o}C) for 24 hours for aggregate property determination.

A variety of laboratory tests were performed to characterize the properties of the resulting extruded aggregates. We narrowed the number of selected mix proportions to two. Density, specific gravity and absorption capacity tests were conducted on two mix proportions:

- 15 % glass fiber, water-fly ash-sand = 0.3: 1.0: 2.0
- 50% glass fiber, water-fly ash-sand = 0.33-1.0-0.33, 2% gypsum.

The remaining tests were performed on aggregates with 50 % glass fiber, water-fly ash-sand ratio 0.33-1.0-0.33 and 2% gypsum. These tests were performed several times to make the test results statistically meaningful.

Particle shape and surface texture tests were conducted to measure particle angularity and flakiness. These properties are particularly important in the utilization of aggregates as road base course materials. Generally, angular aggregates produce bulk materials with higher stability than rounded aggregates. However, the angular aggregates are more difficult to work into place than rounded aggregates, since its shape makes it difficult for them to slide across each other. The produced crushed aggregates have a rounded shape. Furthermore, surface texture is also an important property that controls the compaction behavior and the shear strength of the bulk material. As such, these properties are important indicators of the aggregate performance. The extruded aggregates have a rough surface, which is desirable for base courses in order to increase the stability of the materials in the field.

Gradation test was performed to document the grain size distribution of the crushed aggregates. The gradation test shows a one-sized distribution. One hundred percent of the aggregate amount retained on 12.5 mm sieve. One-sized graded aggregates have good permeability, but poor stability and could be used for chip seals of pavement.

Moisture absorption capacity, specific gravity and density tests were performed to measure the weight-volume characteristics of the aggregates. The density of the aggregates was determined according to ASTM D 1556. The specific gravity tests and the absorption test were conducted according to ASTM C127. Prior to the test, the aggregates were immersed in water at room temperature for 24 hours. Afterwards the aggregates were removed from the water and rolled in a towel until all visible films of water were removed. The test sample in saturated-surface dry condition were weighted and recorded. Following, the aggregates were placed in a wire basket and the weight was determined while it was submerged in water at a temperature of 23 ^{o}C. Finally the test sample was dried to a constant temperature of 110 ^{o}C and weighted. Table 10 shows the density, bulk specific gravity and apparent specific gravity as well as the absorption capacity of the tested aggregates. We can see how the results vary for the different mortar ratios, besides the bulk specific gravity.

Table 5. Extruded fly ash-sand-fiber aggregate properties.

Aggregate	Density [g/cm^3]	Bulk spec. Gravity (SSD)	Apparent spec. Gravity	Bulk spec. Gravity	Absorption [%]
15 % glass fiber, water-fly ash-sand = 0.3: 1.0: 2.0	1.163	3.37	3.64	1.78	90.5
50% glass fiber, water-fly ash-sand = 0.33-1.0-0.33, 2% gypsum	0.95	1.34	1.59	1.78	18

Soundness and durability tests were performed to determine the weathering resistance of the aggregates. We performed both, the sulfate resistance test (ASTM C88) and the freeze-thaw test (AASHTO T103) to determine the soundness of the fly ash-fiber-sand aggregates. The sulfate resistance test was performed according to ASTM C88 by using sodium sulfate. The samples were immersed in the prepared solution of sodium sulfate for not less than 16 h, nor more than 18 h. After the immersion period, the aggregate samples were removed from the solution and placed in the drying oven at 230 ^{o}F (110 ^{o}C). After constant weight has been achieved, the samples were cooled to room temperature and afterwards they were again immersed in the prepared solution. The process of alternate immersion and drying was repeated until 5 cycles were obtained. After completion of the required numbers of immersion and drying cycles, the sulfate salt was washed out of the sample and the aggregate sample was dried. The sample then was sieved trough 8 mm sieve, which is smaller than the original sieve (12.5 mm) on which the size fraction was retained. The resulting weighted average loss for the size fraction is used as indication of durability of the aggregate. The weight loss was found to be 89.8% indicating that these aggregates are especially susceptible to sulfate attack. The freeze-thaw test also resulted in large weight loss of 91.3%.

Crushed Aggregates:

After performing extensive laboratory test on extruded aggregates, we found that the material lost during soundness and durability test is excessive, absorption capacity is very high in some cases, and the abrasion resistance is low. Consequently, we decided to make crushed lightweight aggregates and perform laboratory test to find the weight –volume characteristics and engineering properties of these aggregates. We have produced crushed aggregates with three different methods. The two most critical aspects of crushed aggregate production are (1) curing of aggregates, and (2) crushing of aggregates to get dense-graded aggregates.

Three methods of crushed aggregate production have been investigated:

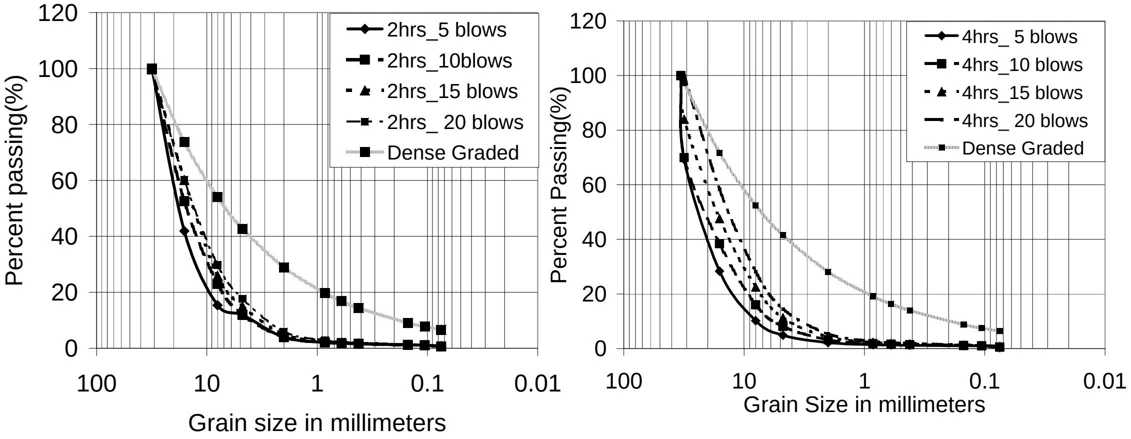
Procedure 1) Fly ash was mixed with 20 % moisture content by weight in a mixer for 2 to 3 minutes. The mix was then placed in a circular mold of size 3.0 inch in diameter and 1.5 inch in height and compacted at 1000 psi for 1-minute. Subsequently, a seating pressure of 600 psi was applied on the sample for 10 minutes to achieve proper compaction and to ensure that there is minimal rebound upon removal of seating pressure. The sample is then wrapped in plastic and aluminum foil and cured at 38^{o}C and 75% humidity for 7 days. Thereafter the specimens were dried at room temperature (23^{o}C) for 24 hours and crushed with 20 blows by 2.5 kg rammer.

Procedure 2) The samples were molded and cured using the method described in procedure 1. Subsequent to curing, the specimen was dried for a day at room temperature and then fired in a furnace at a temperature of 850^{o}C for 2 hrs to bake. The sample was the crushed by the same method discussed in procedure 1.

Procedure 3) The samples were molded and cured using the method described in procedure 1. Subsequent to curing, the specimen was dried for a day at room temperature and then fired in a furnace at a temperature of 850^{o}C for 4 hrs to bake. The sample was the crushed by the same method discussed in procedure 1.

The size and weight of the samples were measured after the samples were demolded prior to curing. The compacted sample had a size 3.0 inch diameter and 1.47 inch height. The unit weight of the compacted samples came out to be 124 pcf. Samples were also weighed after they were cured and baked. It was seen that approximately 60 grams weight was lost during the baking process and the resultant unit weight of the sample was 102 pcf.

Figure 18a and 18b below shows the gradation of aggregates of 2 hrs and 4 hrs-baked samples, with different number of blows. It is seen that both the samples have approximately same percentage of fines passing through 2 mm sieve. Figure 19 below shows the comparison of gradation of aggregates made by 3 different methods with 20 blows.



(a) (b)

Figure 18. Grain size distribution of crushed aggregates crushed at different input energy.

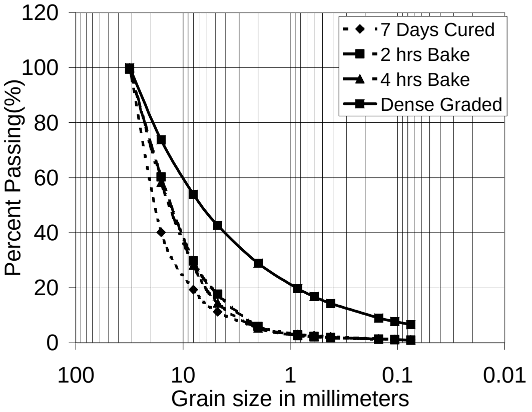


Figure 19. Comparison of grain size distribution of crushed aggregates.

Figure 20 shows the picture of 3 different samples made by different methods after 20 blows of 2.5 kg rammer. After examining the grain size distribution of different kinds of aggregates made with the above procedures, we have concluded that the aggregates made using procedure 1 have an applicable grain size distribution. Moreover, procedure 1 is expected to be more economical compared to the other two procedures, which require sintering at 850 ^{o}C. Therefore, the less energy intensive procedure 1 was further investigated for aggregate production. The aggregate properties were characterized with a view of grading these aggregates for quality and application.

Method 1 Method 2 Method 3

Figure 20. Pictures of crushed aggregates after 20 blows.

Specific Gravity, Bulk Density and Absorption Capacity

The crushed aggregates obtained from procedure 1 were used to determine the specific gravity, bulk density and absorption capacity. Specific gravity is the characteristic generally used for calculating the volume occupied by the aggregates in various mixtures that are proportioned or analyzed on an absolute volume basis. The test conducted on the lab-crushed aggregate was according to ASTM C127 standards. The specific gravity of material ranges between 1.73-1.75. The bulk density test on the lightweight aggregate was done according to ASTM C29 standards. The compact bulk density was determined by the rodding procedure during our laboratory test. The bulk density of aggregates ranges from 1.31 Mg/m^3 – 1.46 Mg/m^3. Absorption Capacity test was conducted according to ASTM C127. It was found that fly ash aggregate made by procedure 1 has an absorption capacity of 20%-22 %.

Index of Aggregate particle shape and texture

This test was conducted in accordance with (ASTM D 3398-00). To determine the particle index of aggregate we used sample, which passed through 9.5 mm sieve and retained on 4.75mm sieve due to short of sample. We selected this fraction of sample because from the grain size distribution curve we can see that our bulk sample have nearly have 40-50% of aggregates size which comes under this range. Void ratio for this fraction at 10 blows per layer was 35% and for 50 blows per layer was 29%. Particle index for this fraction of aggregate was 4.6.

Dry density and Moisture content relationship

The moisture-density relationship of the fly ash aggregates was determined according to ASTM D 1556. Figure 21 shows dry density and misture content relationship for light weight aggregates. The maximum dry density obtained was 1.61 Mg/m^3, at the optimum moisture content of 19%

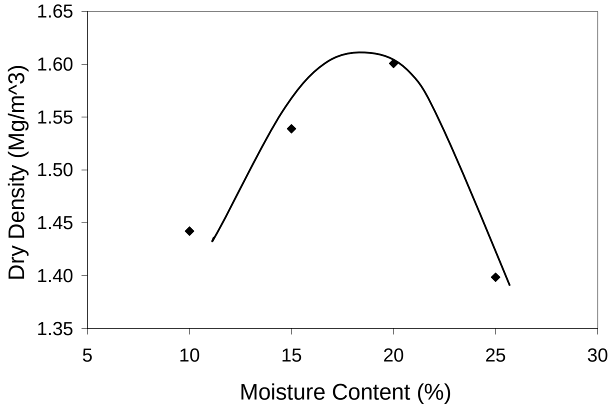


Figure 21: Compaction curves for aggregates.

California Bearing Ratio (CBR)

The California Bearing ratio (CBR) test (ASTM D1883) was performed on samples compacted in the Modified Proctor mold. Samples were immediately tested upon compaction. Four specimens were compacted at different moisture contents with the intent of achieving densities higher than a certain predetermined density. Figure 22 gives the compaction curves obtained from CBR test. A maximum dry density of 1.65 Mg/m^3 was obtained at optimum moisture content of 18%. Figures 23, give the CBR load-displacement relations for the four samples compacted at different moisture content.

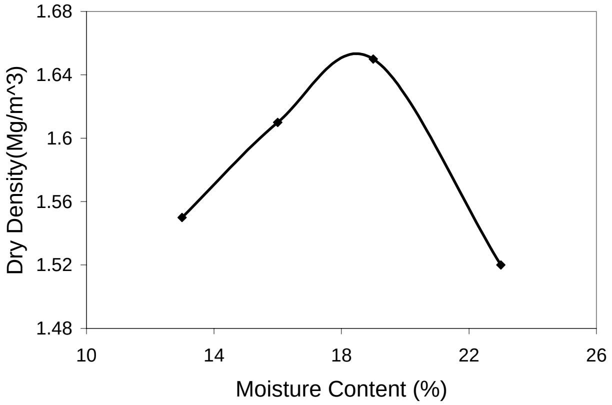


Figure 22: Dry density and moisture content relationship curve based on CBR test.

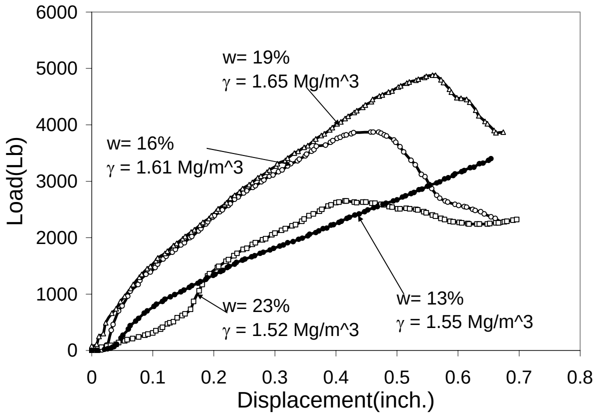


Figure 23. CBR load-displacement relationship for aggregates

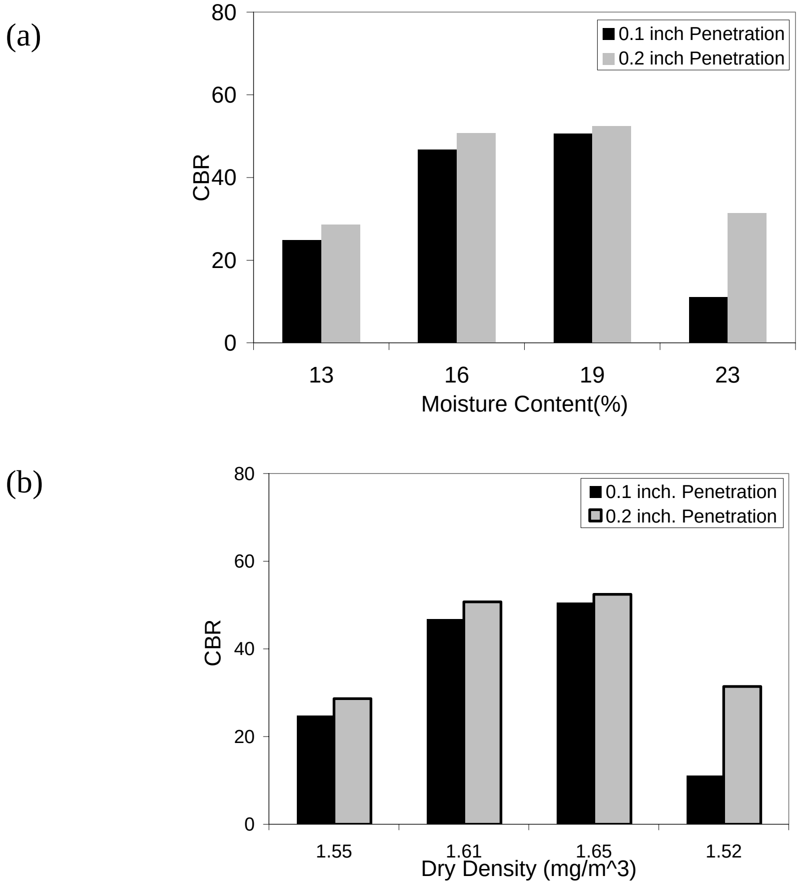


Figure 24. CBR values for aggregates

Figures 24a and 24b give plots of CBR value versus dry density and moisture content for the light weight aggregates tested immediately after compaction. CBR values were in the range of 28 to 52. As seen, the CBR value depends both upon the moisture content and the dry density of the compacted aggregates. Higher moisture content, especially that well above the optimum moisture content, leads to both low dry density as well as low CBR value. Table 6 tabulates the result of CBR values, dry density and moisture content of light weight aggregates

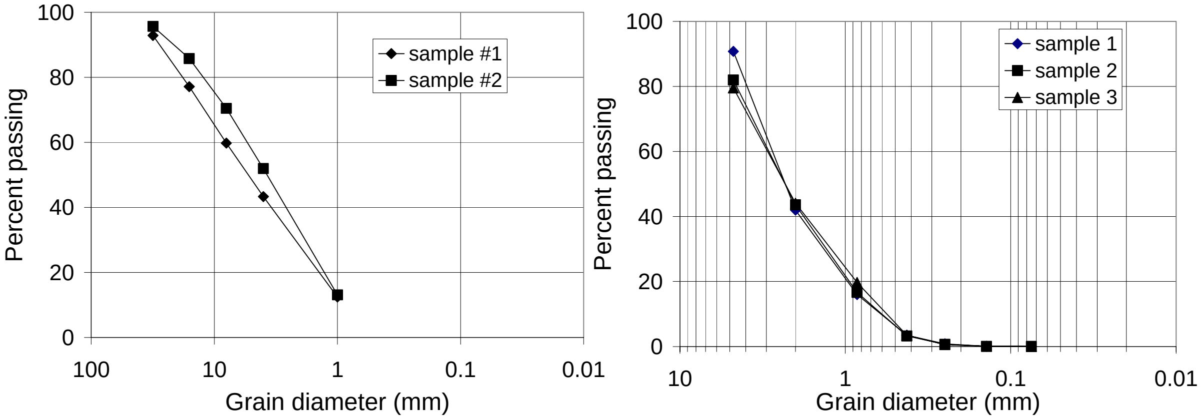
Table 6. Results of fly ashaggregates

Properties		Fly ash
SPT	Maximum Dry Density (Mg/m^3)	1.61
	Optimum Moisture Content (%)	19
Specific Gravity		1.73-1.75
Bulk Specific Gravity Mg/m^3		1.31-1.46
CBR	Optimum Moisture Content (%)	18
	Maximum Dry Density (Mg/m^3)	1.65
	CBR (%)	52
Absorption (%)		20 %- 22%

Ponded Ash Aggregates:

Based upon the literature review, we believe that not only dry scrubber ash but also ponded hydrated class C fly ash may be utilized to produce lightweight aggregates with adequate mechanical properties, such that they may be applied in various construction activities. Consequently, we have documented the following physical and engineering properties: grain size distribution, density, specific gravity, compaction characteristics and the CBR test results, for two samples of ponded fly ashes.

Grain size distributions were obtained from the sieve analysis on two samples of ponded ash. Since the ponded ash brought from the plant was partial hydrated, the particles sized 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. The grain size distribution curves obtained from the tests are shown in Figures 25a and 25b.



(a) (b)

Figure 25. Grain size distribution of ponded ash.

Ponded Ash Sample 1: The density of the ponded ash was determined according to ASTM D 1556, the moisture content test was conducted according to ASTM 2216 and the specific gravity test was conducted according to ASTM 128. The density is obtained to be 1.016 g/cm^3, the moisture content is 27.3%, and specific gravity is 2.56. Furthermore, compaction tests have been performed using both Standard Proctor (ASTM D698) and Modified Proctor (ASTM D1557) test methods on material passing the 3/4-inch sieve. The intent of these tests is to characterize the compaction moisture-density relationships and understand the compactability of these aggregates. The test results are given in Figure 26. The maximum dry density and optimum moisture content based on the Standard Proctor compaction tests are 1.35 g/cm^3 and 28%, while those based upon the Modified Proctor test are 1.41 g/cm^3 and 28%, respectively.

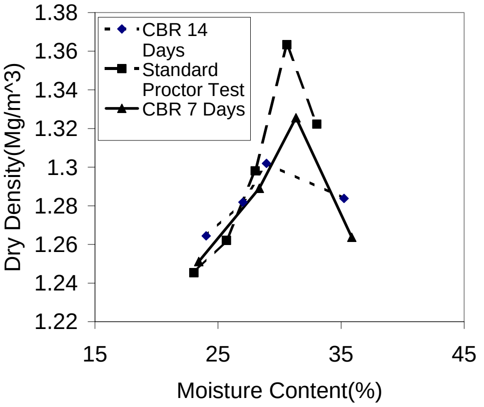
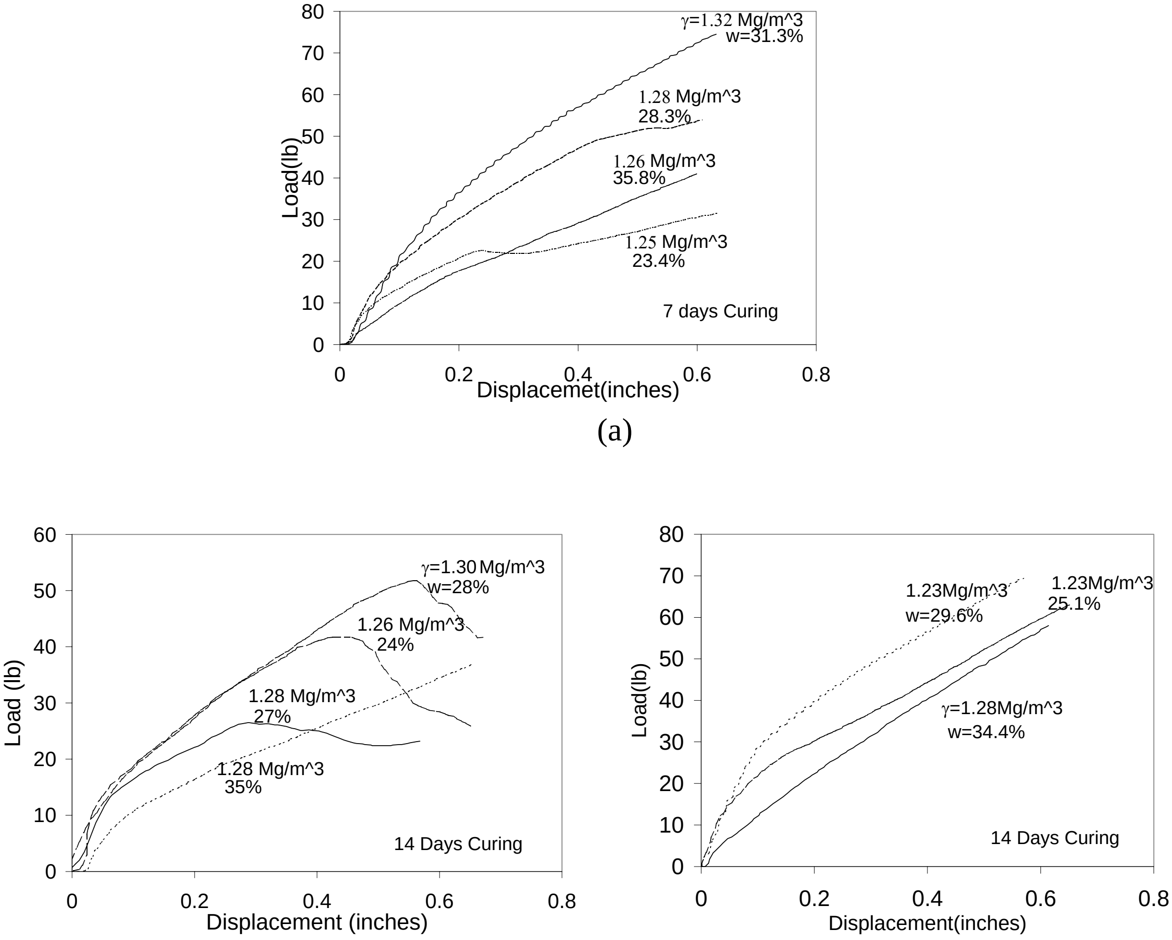


Figure 26. Compaction curves for ponded ash sample 1.

The California Bearing ratio (CBR) test (ASTM D1883) was performed on samples compacted in the Modified Proctor mold and air-cured for 7 and 14-days. Four specimens were compacted at different moisture contents with the intent of achieving densities higher than a certain predetermined density. Figures 27 a, b and c give the CBR load-displacement relations for the four samples.



(a)

(b)

(c)

Figure 27. CBR load-displacement (10^2 lb) relationship for ponded ash sample 1.

The CBR load-displacement relationship is used to obtain the CBR value, which is used as an indicator of performance as a sub-base course material. CBR values greater than 15 indicate an excellent sub-base course material, while CBR values of 5-15 indicate a good sub grade. Class C fly ash used for soil stabilization has shown CBR of as high as 25 (Senol et al. 2002). The specimens were compacted to a density similar to the average density of stabilized soil in the field, and the samples cured in a wet room for seven days before test was performed. Figures 28 and 29 gives the CBR value versus dry density and moisture content for the compacted ponded ash specimens after 7 and 14-day curing. Encouragingly, the CBR values for all the samples are above 30 and may be as high as 82 for favorable moisture and compaction conditions. As seen, the CBR value depends both upon the moisture content and the dry density of the compacted ash. Higher moisture content, especially that well above the optimum moisture content, leads to both low dry density as well as low CBR value. For this ponded ash sample, curing time does not lead to a gain in CBR value. The effect of curing time is not unexpected since fly ashes typically have most strength gain within the first 7-days.

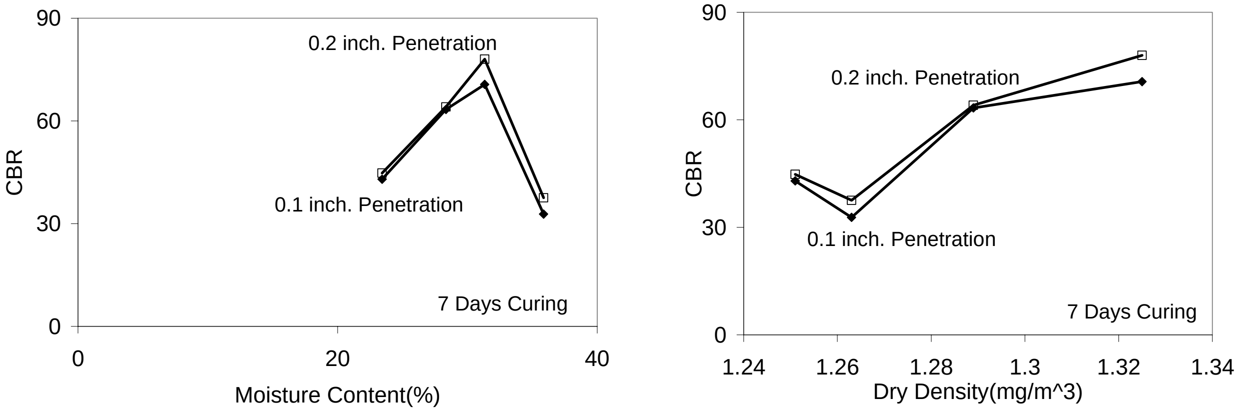


Figure 28. CBR values for 7-day cure for ponded ash sample 1.

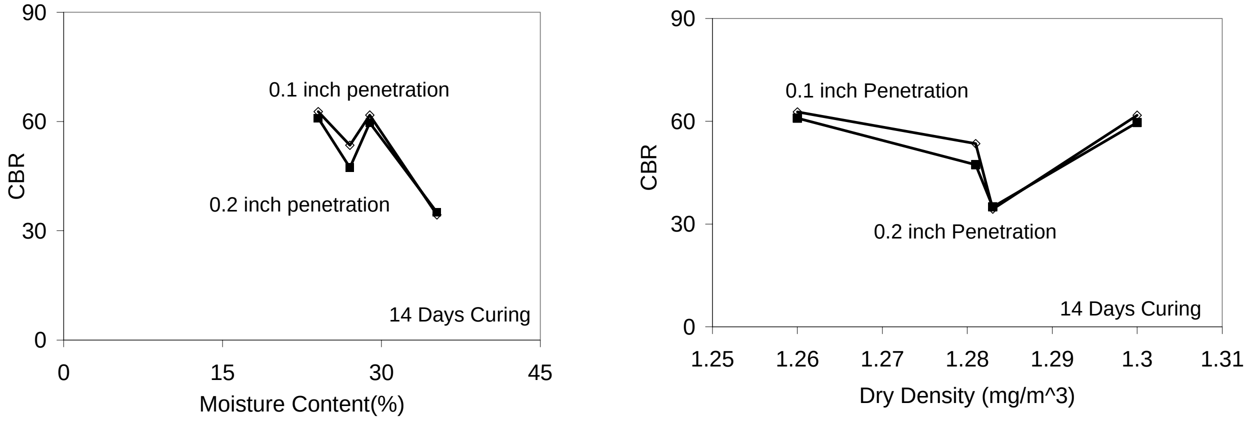


Figure 29. CBR values for 14-day cure for ponded ash sample 1

Ponded Ash Sample 2: The physical properties, such as grain size distribution, density, moisture content and specific gravity are similar to that of sample 1. Compaction tests were performed using both Standard Proctor (ASTM D698) and Modified Proctor (ASTM D1557) test methods on material passing the 3/4-inch sieve. The moisture-density relationship is given in Figure 30. The maximum dry density and optimum moisture content based on the Standard Proctor compaction tests are 1.49 g/cm^3 and 23.47%, while those based upon CBR test sample compaction are 1.50 g/cm^3 and 28%, respectively.

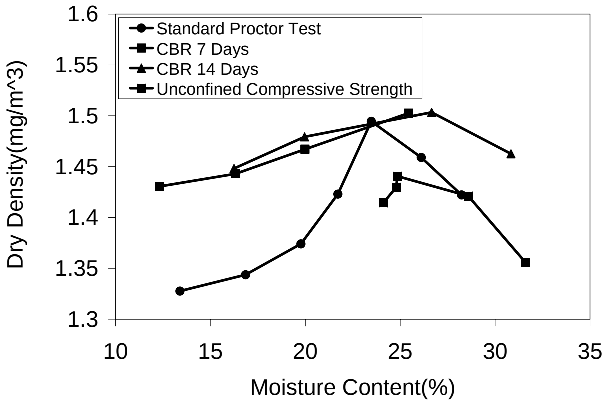


Figure 30. Compaction curves for ponded ash sample 2.

Unconfined compressive strength test was performed on ponded ash by compacting the ash in a 3-inch diameter and 6-inch high mold. The compacted samples were wrapped in a plastic wrap and cured in a humidity chamber at 38^{o}C and 75% humidity. Figure 31 gives a comparison plot between the unconfined compressive strength at 7 days and 14 days curing at optimum moisture content.

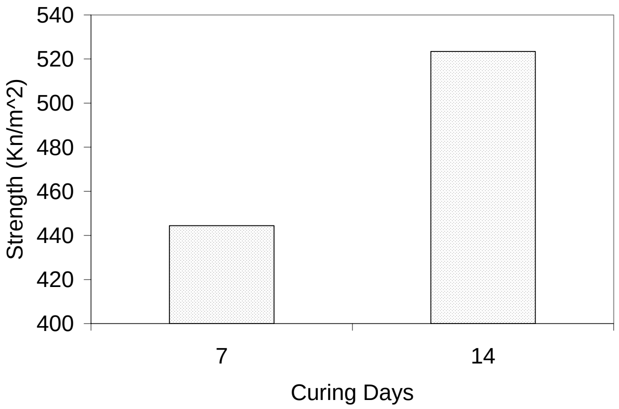


Figure 31. Unconfined compressive strength versus curing days for 7 and 14day cured samples.

The CBR tests were also performed on ponded ash sample 2. Figure 32 gives the CBR load-displacement relationship for 14 days curing and 7 days curing. Interestingly, specimens compacted at higher moisture contents (>~25%) show a ductile behavior in contrast to those compacted at low moisture content which show a brittle behavior characterized by a peak in the load-displacement curve.

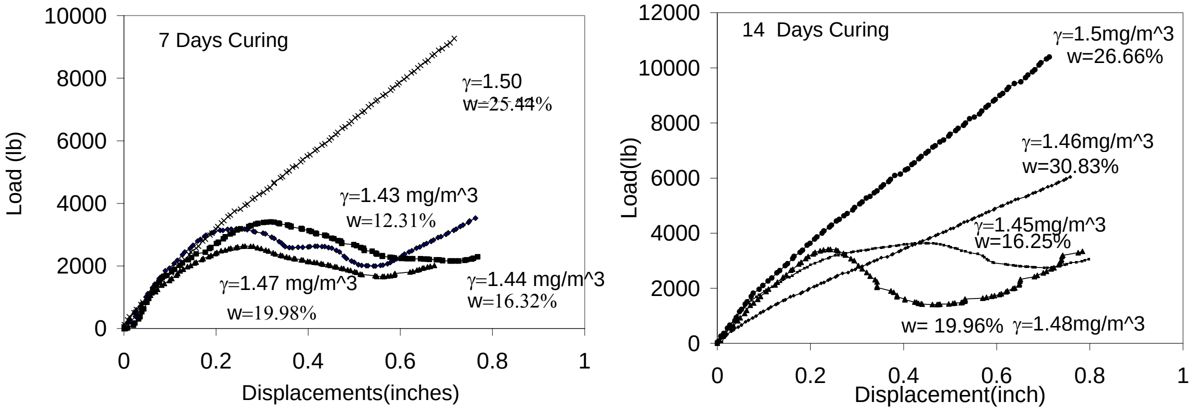


Figure 32. CBR load-displacement relationship for ponded ash sample 2.

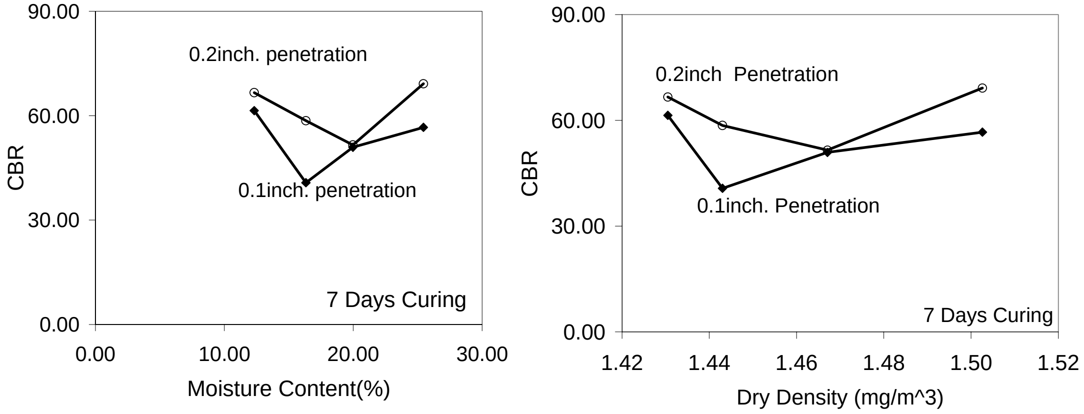


Figure 33. CBR values for 7-day cure for ponded ash sample 2.

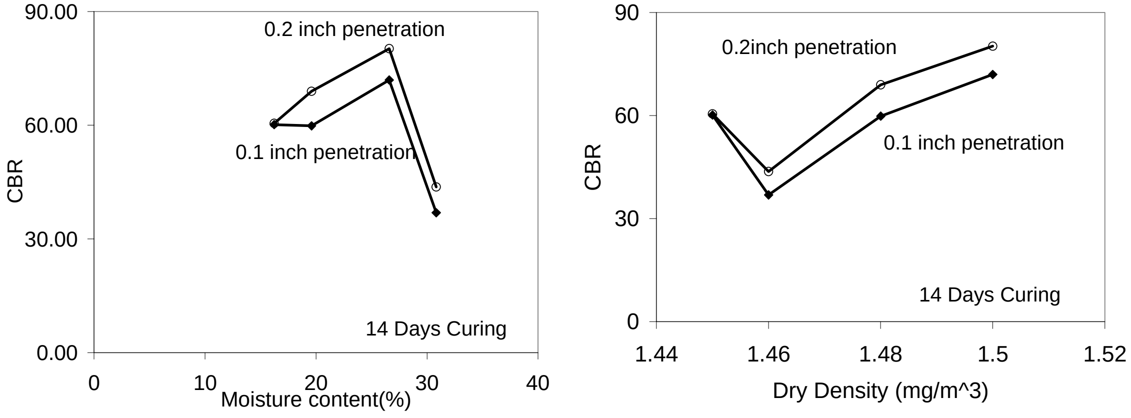


Figure 34. CBR values for 14-day cure for ponded ash sample 2.

CBR and DCP correlation for ponded fly ash

The dynamic cone penetrometer (DCP) test is increasingly utilized for assessing the California bearing ratio (CBR) values. The purpose of this laboratory investigation was to see whether these correlations also exist for ponded fly ash. The testing program to develop CBR-DCP correlations for ponded fly ash included the determination of the following moisture-density relationships of the ponded.fly ash, and California Bearing Ratio (CBR) and Dynamic Cone Penetrometer (DCP) penetration rates. These tests were conducted in accordance with the methods specified by the American Society of Testing and Materials (ASTM) and the American Association of State Highway and Transportation Officials (AASHTO). In this study five samples were prepared at varying moisture contents.

Moisture-Density Relationship

Compaction tests were performed using CBR molds according to (AASHTO T 193-99) test methods on material passing the 19mm sieve. The moisture-density relationship for the ponded fly ash is shown in Figure 35. The maximum dry density is found to be 1.54 Mg/m^3 at optimum moisture content of 23%.

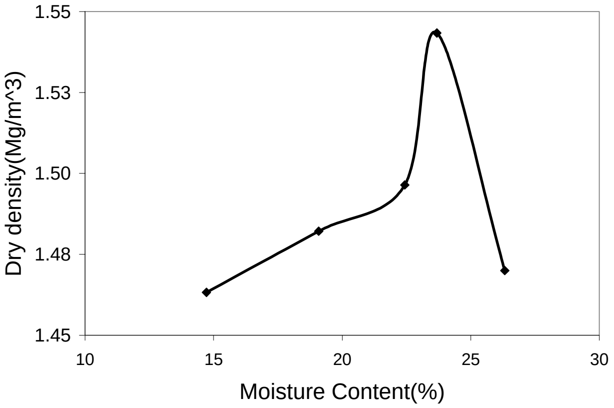


Figure 35. Dry density and moisture content relationships for Ponded fly ash.

California Bearing Ratio

CBR tests were conducted in accordance with the methods described in AASHTO T 193-99, which is the standardized test method. This test measures the resistance to penetration using a loading device such that penetration rate is 0.05 inch/min. As described earlier, the samples were compacted in three layers in the CBR molds at 56 blows per layer. CBR tests were performed for the varying moisture content. The load-displacement data gathered from the CBR tests are plotted in Figure 36. The CBR values obtained from these load-displacement data are tabulated in Table 7. As seen, the CBR values from 95-126 depending upon the moisture content. Also, from the load-displacement curves and the tabulated CBR-values, it may be observed that ponded fly ash experience brittle failure.

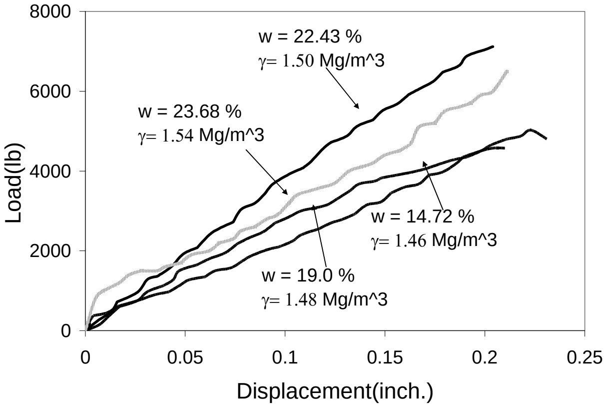


Figure 36. Load-penetration curves for Ponded fly ash.

Table 7. Dry density and CBR values for ponded fly ash at different moisture content.

Test Number	Ponded Fly ash			
	W (%)	γ (Mg/m^3)	CBR (0.1 inch)	CBR (0.2 inch)
1	14.7	1.46	67	95
2	19.08	1.48	91	95
3	22.43	1.50	125	149
4	23.68	1.54	102	125

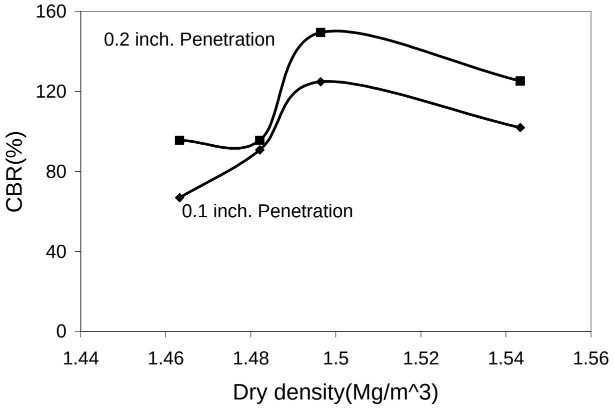


Figure 37. CBR versus dry density

Figure 37 shows plots of CBR with dry density. We observe that the CBR values are, typically, higher for the moisture contents that are less than the optimum moisture contents. From Figure 37 we also note that: for the ponded fly ash, the maximum CBR of 149 corresponds to a dry density of 1.50 Mg/m^3, which is not the maximum dry density. The maximum dry density in this case was 1.54 Mg/m^3 and the corresponding CBR value is 125.

Dynamic Cone Penetrometer Test

The Dynamic Cone Penetrometer (DCP) test was completed using standard testing methods specified in the new ASTM test D6951-03. This test is a measurement of the penetration rate of the dynamic cone penetrometer through an undisturbed soil sample. The standard test uses a DCP device with an 8-kg hammer, which is dropped from a height of 22.6 inches for a given number of blows. The penetration depth of the cone tip into the soil is then recorded for the number of blows. For these experiments, two blows per recording were used with a maximum penetration of 10 cm. For the DCP test, the cumulative penetration is plotted in Figure 38 as a function of cumulative number of blows for each sample. A regression analysis was performed to fit a line to the data points.

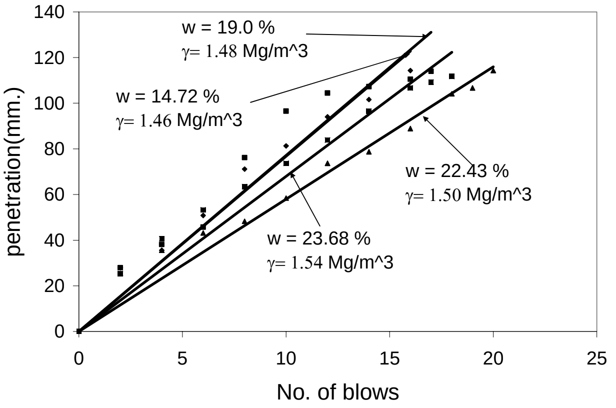


Figure 38. Cumulative penetration versus cumulative number of blows.

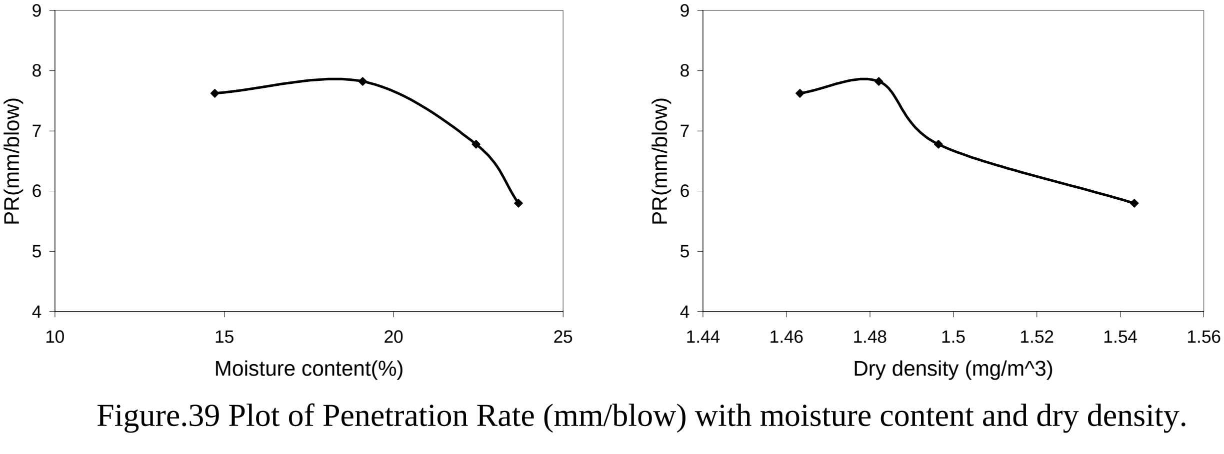


Figure.39 Plot of Penetration Rate (mm/blow) with moisture content and dry density.

Figure 38 shows the dependence of the penetration rate, given by the slopes of the linear fits. From figure 39 it was observed that penetration rate is decreasing with increase in moisture content. Interestingly, the penetration rate was found to decrease rapidly after moisture content of 20 % and dry density of 1.48 Mg/m^3.

<u>Correlation between CBR and DCP Penetration Rate</u>

Figure 40 shows the variation of CBR as a function of the DCP penetration rate measured in the laboratory on a log-log scale. Based upon the linear regression analysis of this data, the following correlations are obtained for CBR and PR (mm/blow):

$$LogCBR = 2.98 - 1..09(LogPR) \quad (1)$$

The goodness-of-fit coefficient R^2 for these relationships is 0.46. Interestingly, the intercept and slopes for the correlations in Equations 1 are very similar to those for Class C fly ash stabilized clay soils given by Misra et al (2004). The correlation is also similar to that of subgrade materials given by Webster et al. (1992), who obtained an intercept of 2.465 and a slope of 1.12, for a wide range of granular and cohesive materials.

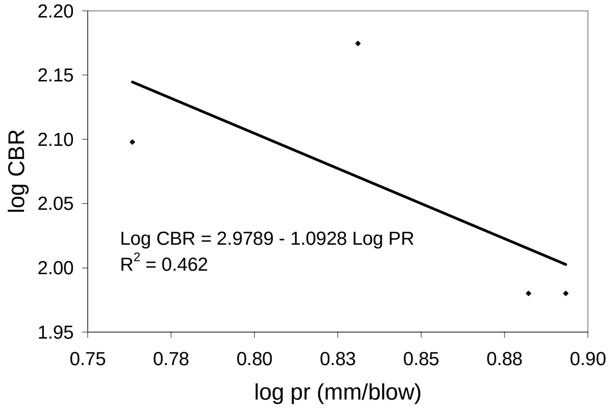


Figure 40. CBR-DCP correlations for ponded fly ash penetration rate data.

Leaching Potential of Fly Ash Aggregates:

Data available in the literature shows that Class C fly ash derived from Wyoming coal, generally, leaches only very small quantities of contaminants of concern (Garcez and Tittlebaum 1984, EPRI 1995). Nevertheless, leaching behavior of each fly ash must be examined on a case-by-case basis in relation to the background water quality. These leaching tests must be standardized with respect to the leaching fluids that best represent the fluids in nature, such as, simulated groundwater or rainwater leachates. In absence of these standards, the TCLP test provides a method for evaluating the leaching potential of a fly ash. Therefore, in this report, the leaching behaviors of the LaCygne ash utilized in this project are examined based upon the TCLP test results. Results of the TCLP tests are give in Table 8 and Figure 41 along with the Drinking Water Standards (DWS) and the RCRA standards. We have included test results from samples obtained in 1994 and 1995, in addition to those in 1998 to demonstrate that the fly ash leaching characteristics are quite uniform.

Table 8: TCPL Test Results – LaCgyne fly ash

Element	LaCygne fly ash (mg/l) TCPL Test				DWS Standards (mg/l)	RCRA Standards (mg/l)
	Sampled 01/15/94	Sampled 02/03/95	Sampled 1998 (10 Samples)			
				Avg		
Lead	<0.05	<0.05	8 samples < 0.05 avg of 2 samples 0.115	0.063	0.05	5
Chromium	0.09	0.18	4 samples < 0.01 avg of 6 samples 0.158	0.098	0.05	5
Cadium	<0.01	<0.01	8 samples < 0.01 avg of 2 samples 0.205	0.049	0.01	1
Barium	0.76	0.5	avg of 10 samples 0.534	0.534	1	100
Sliver	<0.03	<0.02	10 samples < 0.02	<0.02	0.05	5
Selenium	0.224	0.19	5 samples < 0.01 avg of 5 samples 0.214	0.112	0.01	5
Arsenic	0.048	0.12	5 samples < 0.01 avg of 5 samples 0.018	0.014	0.05	5
Mercury	<0.0002	<0.005	10 samples < 0.005	< 0.005	0.002	0.2

As shown in Table 8 and Figure 41, none of contaminants of concern exceed the RCRA standards. Data from literature indicates that it is quite likely that the extracted concentrations of the various contaminants are highest in the TCLP test. Thus in most cases these TCLP numbers represent the worst case scenario and may be used to judge the leaching potential of the fly ash. Quite clearly, the ash utilized in this project leach very low quantities of most contaminants of concern.

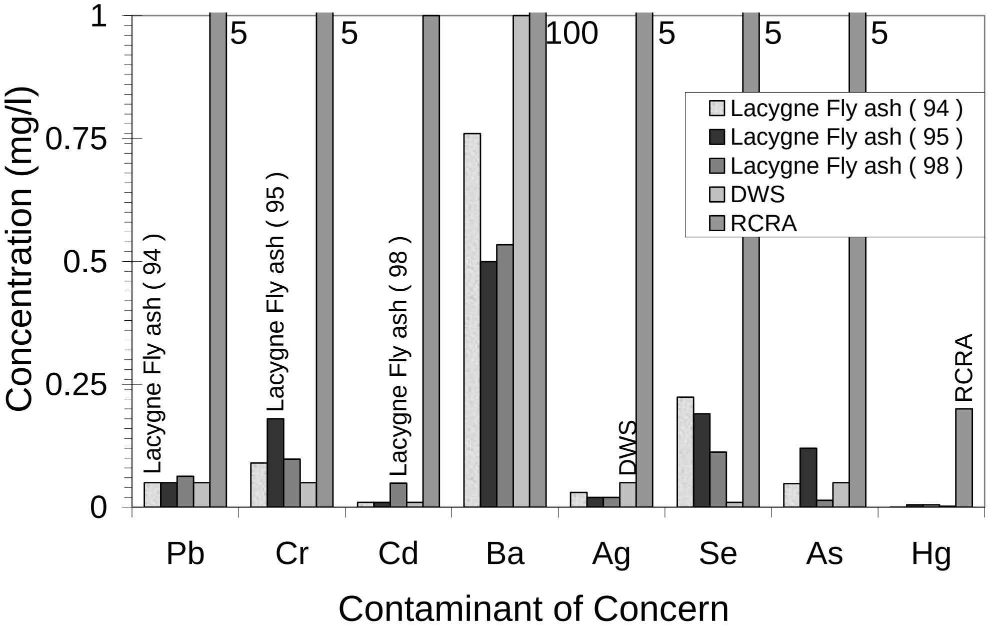


Figure 41. Leaching behavior of LaCygne Class C fly ash

V. SUMMARY AND CONCLUSIONS

Literature review

A literature search was performed with a focus upon collecting, reviewing, analyzing and summarizing available information concerning: (1) appropriate cut strand fibers and fiber fillers that may be used for ash-fiber-sand aggregate production; (2) the utilization of class C fly ash for aggregate production; (3) other efforts to produce synthetic aggregates, especially those using cementitious materials; and (4) characterization methods for aggregates in various construction applications.

Based upon the literature review, we have noted that little effort has been made to exploit the self-cementing capacity of fly ashes for producing aggregates. Most fly ash aggregate production methods employ some type of high temperature sintering process. A few efforts that have aimed at producing unsintered aggregates have yielded encouraging results. Therefore, we believe that the self-cementing properties of class C fly ashes can be exploited to produce lightweight aggregates with adequate mechanical properties, such that they may be utilized in various construction activities.

Fly ash-fiber-sand mix proportions

Based upon the literature review and cost and availability of appropriate fibers, three candidate fiber fillers were selected for ash-fiber-sand mixes. Fine sand was sieved from locally available construction sand. 2-inch cube samples for several fly ash-sand-fiber mix proportions were prepared by varying the fiber content. The cubes were allowed to harden for 1 day in a moisture cabinet, then de-molded and cured for at least 7 days in an environmentally controlled chamber. Unconfined compressive strength test is performed to obtain the 7-day compressive strength.

Based upon the tests performed, the optimal mix proportion for water-fly ash-sand mortar was found to be 0.3:1.0:2.0. Under controlled curing, this mortar proportion yields an average 7-day compressive strength of 14.6 MPa, with a coefficient of variability of less than 10%. Moreover, the addition of fibers, generally, results in a higher modulus of elasticity, however, the behavior for different fiber types are different. Optimal fiber content is, therefore, a function of the fiber type and we expect to define that content for the three fiber types selected for the proposed project. Based upon the strength results, mixtures with the glass fibers at 15% replacement rates yield the best strength.

Characterization of fly ash-fiber-sand aggregate engineering properties

Using the optimal mix proportion and fiber type, batches of fly ash-fiber-sand aggregate have been extruded. The extruded aggregates were used to perform particle shape and surface texture tests, gradation tests (ASTM C136), moisture absorption capacity, and specific gravity and density tests (ASTM C29 and ASTM C127). The aggregates had very high absorption capacity and also had a propensity to abrade easily. Consequently, the mix proportion was modified and additional aggregate batches extruded. These aggregates were then used to perform particle shape and surface texture tests, gradation tests (ASTM C136), moisture absorption capacity, specific gravity and density tests (ASTM C29 and ASTM C127) and finally soundness and durability tests (ASTM C88 and AASHTO T103). The results show that aggregates meet the properties of base course and sub-grade material, however, the soundness and durability performance were not up to the specification. Low sulfate resistance could be due to high absorption capacity, which in-turn may be a caused by the sand content. Consequently, the mix proportion and the production technique were revised to reduce the porosity of the aggregates. The sand content was reduced and the fiber content was increased. Extruded aggregates using the new mix-proportion were prepared and found to have improved absorption capacity. These aggregates were also found to be susceptible to sulfate attack, which could also be attributed to the somewhat high absorption capacity. Therefore, it was decided to completely eliminate sand from the mix and produce crushed samples from samples that have been compacted.

A production methodology that considers pressure compacted samples with precision moisture control which are subsequently oven cured at low temperature was also evaluated.

Three methods of crushed aggregate production based upon compacted samples were investigated. After examining the grain size distribution of different kinds of crushed aggregates made with the above procedures, we concluded that the aggregates made using procedure 1 have an applicable grain size distribution. Moreover, procedure 1 is expected to be more economical compared to the other two procedures, which require sintering at 850 ^{o}C. Therefore, the less energy intensive procedure 1 was further investigated for aggregate production. Fly ash briquettes were compacted using this compaction methodology. These briquettes were crushed to produce sufficient amount of aggregate for investigating the aggregate properties for its application. Grain size distribution, specific gravity and bulk density, and particle shape and texture were determined. The moisture-density relationship and the CBR values were also determined. The specific gravity of these aggregates are 1.73-1.75 and the maximum compacted dry density is ~1.6 Mg/m^3. Thus, these aggregates fall within the category of lightweight aggregates. The CBR values are obtained in the range of 28-52 depending upon the compaction moisture content. Even at low CBR values of 28, the compacted aggregate material would provide a competent road base or sub-base.

Characterization of ponded ash aggregate engineering properties

The above results indicate that ponded class C fly ashes could yield a rich source of crushed aggregates that may be used for road bases, lightweight embankment fills as well as lightweight granular backfills behind retaining walls. A number of tests were performed to characterize crushed aggregates derived from ponded fly ashes. We have documented the following physical and engineering properties: grain size distribution, density, specific gravity, compaction characteristics and the CBR test results, for two samples of ponded fly ashes. The density of ponded ash is found to be low, thus it would result in a lightweight road base/sub-base material. The CBR values are obtained in the range of 40-90 depending upon the compaction moisture content. Even at low CBR values of 40, the compacted ponded ash material would provide a competent road base or sub-base. We have also found that the 14-day cured samples provided higher values than the 7-day cured samples, indicating that the ponded ash have some residual cementation capacity. Given that the 7-day strengths and CBR values are sufficiently high for road base or sub-base applications, it is expected that ponded ash will provide even better performance in the long-term.

Fly ash aggregate leaching behavior

Leaching tests have been performed on the fly ash using the TCLP procedure. TCLP test result show that the self cementing fly ash utilized in this project leach very low quantities of most contaminants of concern. Since TCLP test likely represents the worst case scenario, the leaching potential of contaminants of concern from the fly ash aggregates is expected to be low.

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