

# Evaluation of Manufactured Fluidized Bed Combustion Ash Aggregate as Road Base Course Materials

**Chang-Seon Shon<sup>1</sup>, Don Saylak<sup>2</sup>, and Suren Mishra<sup>3</sup>**

<sup>1</sup>Texas Transportation Institute, Texas A&M University, College Station, TX 77845; College Station, TX 77845; <sup>2</sup>Center for By-Product Utilization and Recycling Research, Texas A&M University, College Station, TX 77845; <sup>3</sup>TETRA Technologies, Inc., The Woodlands, Houston, TX 77380

**KEYWORDS:** fluidized bed combustion ash, road base course materials, sulfate attack

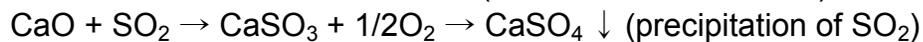
## ABSTRACT

In recent years, there has been renewed interest in synthetic aggregate for flexible or rigid base manufactured with coal combustion by-products because of a scarcity of dependable sources of aggregate and high transportation cost. This creates the need for alternative cost-effective sources for material that are available locally. Although successful use of hydrated ponded Class C fly ash as road-base material has been reported, the utilization of fluidized bed combustion (FBC) ash as flexible or rigid base material is still challenging due to inherent ash properties (high sulfate and carbon contents, angular shape, and free lime, etc.). Therefore, this research was performed to identify and develop the potential of FBC ash as both a synthetic aggregate and a stabilizer in flexible base construction. In the development of the synthetic aggregate, calcium chloride was used as an accelerator for early strength development.

The results have shown that a usable aggregate using FBC fly ash can be manufactured with virtually no potential for sulfate attack in base course application. Furthermore, FBC fly ash as a stabilizer from either naturally stockpiled or manufactured fly ash aggregate blends could be effectively used in flexible base construction without sacrificing its ability to develop high early strength and without causing sulfate swelling due to ettringite formation.

## INTRODUCTION

Recently, the enhanced Environmental Protection Agency (EPA) regulation emphasizes vastly decreasing the emission of combustion pollutants to the atmosphere, especially sulfur oxide ( $\text{SO}_x$ ) from coal combustion power plants. In order to maintain compliance with the Clean Air Act, existing coal-fired plants have increased the use of limestone or dolomite as an absorbent while new plants have adopted a fluidized bed combustion (FBC) process by using limestone as the bed material. The introduction of limestone into the combustion system minimizes the release of  $\text{SO}_2$  into the atmosphere by the following reactions:



The resulting by-products of this reaction (fly ash and bottom ash), However, tend to contain higher calcium, sulfate, and carbon contents than those generated in the conventional process. Consequently, levels of silica ( $\text{SiO}_2$ ), alumina ( $\text{Al}_2\text{O}_3$ ), and ferric oxide ( $\text{Fe}_2\text{O}_3$ ) are somewhat low. Because of these abnormal chemical characteristics, these ashes do not meet ASTM 618 requirements to qualify as either Class C or Class F fly ashes. As a result, these ashes are usually relegated to waste dumps or stockpiled landfills [1]. They are limited in use in roadway construction due to their potential for incurring large-volume swelling even though they inherently have very good binding properties from which excellent strength can be achieved. Therefore, Texas Coal Ash Utilization Group (TCAUG) is confronting the challenge on how to use these ashes in roadway construction. Moreover, the scarcity of land and the high costs of management and treatment associated with disposal of these materials create an additional problem to the Texas Commission on Environmental Quality (TCEQ).

In recent years, there has been renewed interest in synthetic aggregate manufactured with coal combustion by-products for flexible or rigid base because of a scarcity of some sources of aggregate and high transportation cost of aggregate to the construction site [2, 3]. This creates the need for alternative sources for cost-effective material that are available locally. Although successful use of hydrated ponded Class C fly ash as road-base material has been reported, the utilization of high sulfate ash as flexible or rigid base material is still challenging due to inherent ash properties. Therefore, research is needed to identify and develop the possibility of high sulfate ash as a flexible or rigid base material.

## RESEARCH SCOPE AND OBJECTIVE

Since 2003, the By-Product Utilization and Recycling Research Group at Texas A&M University have conducted research on the utilization of fluidized bed combustion (FBC) ash in construction applications [4, 5]. The project included the following: (i) sampling and characterization of both stockpiled and fresh FBC ashes; (ii) application of FBC by-products in 5-concepts of roadway and building construction; (iii) market opportunities

for utilization of stockpiled FBC by-products; (iv) beneficiation of stockpiled fluidized bed cal ash in road base course construction; and development and evaluation of FBC ash aggregate.

As shown in Figure 1 (Phases I and II) a full scale of physical, chemical, and mineralogical characterization of fresh and stockpiled FBC ashes and the use of stockpiled material in base courses have established that stockpile storage can accelerate the aging process of fresh (unstockpiled) fly ash and minimize potential for sulfate attack. Furthermore, it has provided manufacturing aggregates using FBC fresh and stockpiled ashes.

This paper describes a comprehensive laboratory evaluation for the use of manufactured FBC ash aggregate for road base-course construction (Phase III). To assess the performance characteristics of FBC aggregate in a base-course mix design, the laboratory testing protocol includes the determination of optimum moisture content, unconfined compressive strength, evaluation of the moisture susceptibility using the tube suction test, and 3-dimensional swelling test of the fabricated specimens.

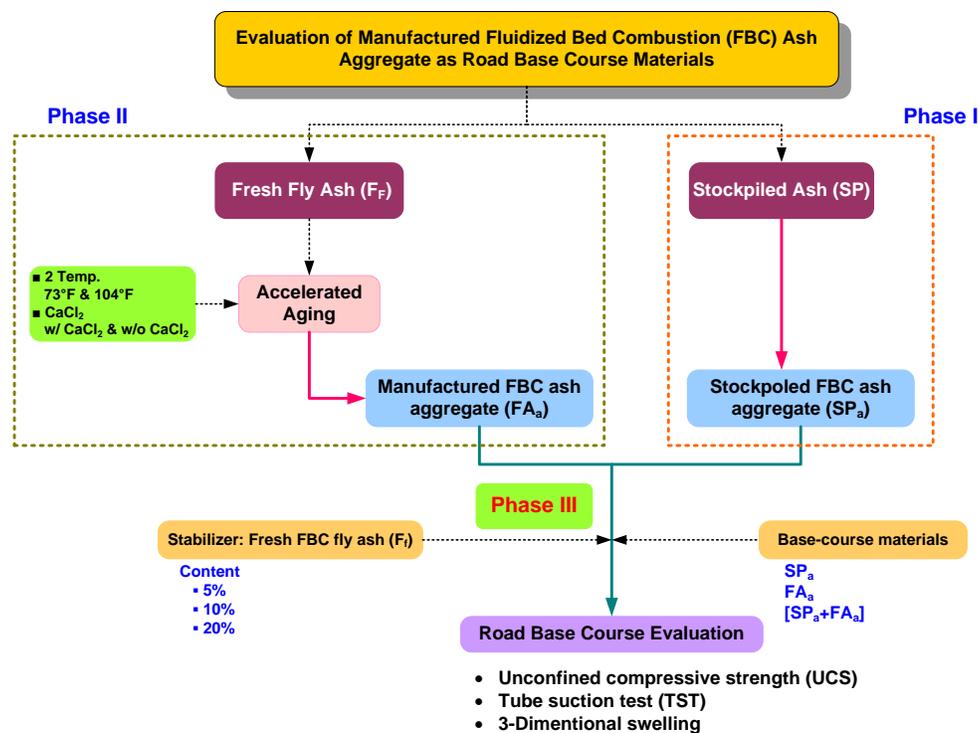


Figure 1. Diagram of research scope and experimental program

## EXPERIMENTAL PROGRAM

### Material

Manufactured fluidized bed combustion (FBC) fly ash aggregate (FA<sub>a</sub>), stockpiled FBC ash aggregate (SP<sub>a</sub>), the combination of FA<sub>a</sub> and SP<sub>a</sub>, and fresh FBC fly ash were used

for laboratory testing in establishing the optimum mix design rationale for base-course applications. As presented in Figure 1, while FA<sub>a</sub> was produced through the process of hydration, hardening, crushing, and sieving, SP<sub>a</sub> was produced after excavation, crushing, and sieving. All physical and chemical properties of these aggregates are given in Table 1.



Figure 1. Manufactured FBC fly ash (a) and stockpiled FBC fly ash (b) aggregates

TABLE 1 Chemical and Physical Properties of Fly Ashes, CaCl<sub>2</sub>, and Limestone

Chemical Compounds (wt %)	Fresh FBC fly ash	Stockpiled FBC ash	Manufactured fly ash aggregate		
			Bulk density	Lb/ft <sup>3</sup>	
SiO <sub>2</sub>	42.52	39.39	Absorption	%	21.9
Al <sub>2</sub> O <sub>3</sub>	13.57	12.80	LA abrasion	Grading	B
Fe <sub>2</sub> O <sub>3</sub>	4.62	3.63		% loss	46.8
Sum	60.71	56.59	Soundness (% loss)	F&T	30.5
CaO	25.12	18.04		Sulfate	17.85
MgO	1.58	2.35			
SO <sub>3</sub>	8.22	6.61	Specific gravity	% loss	1.91
Free CaO	9.90	-			
L.O.I	1.91				
<sup>1</sup> Fineness	32.38				
Specific gravity	2.65				
Strength @ 7d	880				

<sup>1</sup>Amount retained on 325 sieve

## Mix Design and Test Methods

Basically, the laboratory mix design for base-course evaluation was focused on enhancing early strength development and durability. For moisture susceptibility and sulfate attack, three levels of fresh FBC fly ash content (5, 10, and 20%) were tested for base-course mix design. The amount of fly ash was calculated on a dry weight basis.

Laboratory test methods were selected on the basis of satisfying the following Texas Department of Transportation (TxDOT) base-course evaluation criteria (TxDOT Standard Specification Item 276) [6]:

- Unconfined compressive strength (UCS) after 7-day moist-curing:  $\geq 175$  psi min.
- Surface dielectric constant value after the Tube Suction Test (TST):  $< 10$
- Retained UCS after TST:  $\geq 80\%$  7-day UCS
- 3-dimensional swelling:  $\leq 6\%$ .

For durability evaluation, the 3-dimensional swelling test developed by Texas Transportation Institute (TTI) was conducted. This test is used for assessing the volumetric expansion of the sample caused by the ettringite formation ( $\text{Ca}_6 [\text{Al}(\text{OH})_6]_2 (\text{SO}_4)_3 \cdot 26\text{H}_2\text{O}$ ), when exposed to prolonged capillary soak conditions. The primary concern for ettringite formation is brought about by the presence of soluble sulfate ions when FBC fly ash is used both in manufacture of FBC fly ash aggregate and in base-course applications. Because the swell test samples are exposed to deionized water free of sulfates, the only source of the sulfate ions comes from within the base materials themselves. This set-up ideally suits the evaluation of potential sulfate attack of FBC materials.

Tube suction test (TST) also called capillary suction test, Tex-144-E test method, was carried out. The TST was originally developed for assessing the moisture susceptibility of aggregate base materials as “good, marginal, and poor” [7, 8]. The moisture susceptibility is based on the mean surface dielectric value of compacted specimens measured by a percometer after a 10-day capillary soak (Figure 2). The dielectric value is most sensitive and directly related to the amount of unbound water that exists within the aggregate matrix. The specimens with final dielectric values less than 10 are expected to provide a good performance, while those with the dielectric values above 16 are expected to provide a poor performance as base materials. Specimens having final dielectric values between 10 and 16 are expected to be marginally moisture-susceptible.

The residual retained compressive strength was also determined as a part of a modified tube suction test. The residual retained compressive strength test also represents a measure of the moisture susceptibility of the flexible base material. The retained strength of the samples after the capillary soak period is viewed as the most important indicator of the mixtures moisture susceptibility as it simulates field conditions and provides a long-term durability assessment of the base material. The 10-day capillary soaked unconfined compressive strengths of the specimen should also not be less than 80% of the original unsoaked values.



Figure 2. Tube Suction Sample (a) and Percometer (b)

## TEST RESULTS AND DISCUSSIONS

### Particle Size Analysis

TxDOT Item 247 material requirement for flexible base specifies four different grades of aggregates that can be used in flexible base construction. For each grade, the specification defines cumulative amounts of the material retained on certain sieves. Particle size distributions (PSD) of FBC fly ash aggregate ( $FA_a$ ), stockpiled aggregate ( $SP_a$ ), and the combined  $FA_a$  and  $SP_a$  are given in Figure 3. While  $FA_a$  belongs to Grade 1, the  $SP_a$  contained more fines than permitted for Grade 1 through 3. In particular, the most commonly referred sieve No. 4 (4.75 mm) of the specification retained only 34.7%, which is 10.3% less than the required minimum of 45%. This, however, does not eliminate applicability of  $SP_a$  as a base-course material due to Grade 4 regulation of specification, which allows for use of virtually any type of aggregate that does not qualify for Grade 1 through 3. Based on the sieve analyses of  $FA_a$  and  $SP_a$ , they were combined at a 50% to 50% ratio. This allowed for use of Grade 1 of blended aggregate as shown in Figure 3.

### Moisture Content-Density Relationship

The moisture-density relationship is used to determine the optimum moisture content ( $W_{opt.}$ ), at which the each aggregate demonstrates the maximum dry density ( $\gamma_{d-max.}$ ). The  $W_{opt.}$  of the composite materials was determined using Tex-113-E Test Method "Laboratory Compaction Characteristics and Moisture-density Relationship of Base Materials" (similar to ASTM D 698-07e1 Method D) into 6" by 8" height specimens at four different moisture contents using a 9.9 lbs hammer at 18" in height using 50 blows/layer. Each specimen consisted of 4 layers.

The derived moisture-density results are presented in Table 2. Each mixture had a different  $W_{opt.}$  and  $\gamma_{d-max.}$ . In general, the  $W_{opt.}$  for  $FA_a$  mixture is lower than that of  $SP_a$

mixture and the combined FA<sub>a</sub> and SP<sub>a</sub> mixture. In addition, as FBC fly ash content which was used as the binder is increased, W<sub>opt.</sub> is decreased and γ<sub>d-max.</sub> is increased. This might be explained mainly by the stiffening and void-filling effect of the fly ash acting as a filler in the base-course mixture because of the small particle size of fly ash.

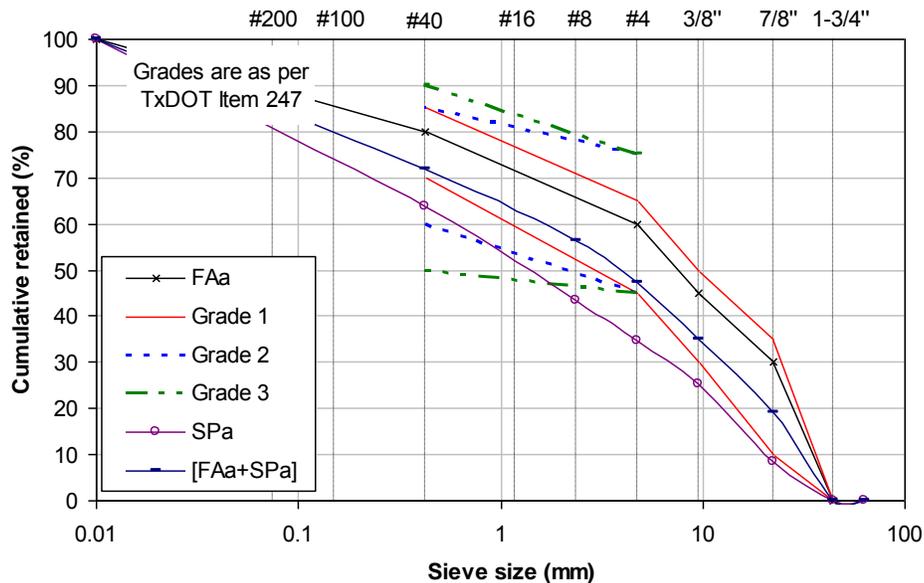


Figure 3. Particle Size Distribution of each material

TABLE 2 Moisture Content-Density Relationship for Each Mixture

Mixture	Optimum moisture content (%)	Maximum dry density (lbs/ft <sup>3</sup> )
0% F <sub>f</sub> + FA <sub>a</sub>	51.2	58.8
0% F <sub>f</sub> + SP <sub>a</sub>	62.4	58.3
0% F <sub>f</sub> + [FA <sub>a</sub> +SP <sub>a</sub> ]	58.9	58.5
5% F <sub>f</sub> + FA <sub>a</sub>	52.2	61.3
5% F <sub>f</sub> + SP <sub>a</sub>	57.2	59.6
5% F <sub>f</sub> + [FA <sub>a</sub> +SP <sub>a</sub> ]	53.0	60.2
10% F <sub>f</sub> + FA <sub>a</sub>	42.1	67.2
10% F <sub>f</sub> + SP <sub>a</sub>	52.0	60.8
10% F <sub>f</sub> + [FA <sub>a</sub> +SP <sub>a</sub> ]	44.2	65.1
20% F <sub>f</sub> + FA <sub>a</sub>	26.4	74.0
20% F <sub>f</sub> + SP <sub>a</sub>	35.4	69.2
20% F <sub>f</sub> + [FA <sub>a</sub> +SP <sub>a</sub> ]	33.6	71.2

### Unconfined Compressive Strength

Figures 4 through 5 show unconfined compressive strength (UCS) development for mixtures containing 5%, 10%, and 20% fresh FBC fly ashes, respectively. As expected, fly ash-treated mixtures have higher strength values than mixtures without containing fly

ash regardless of aggregate type. 5% fly ash mixture shows only marginal improvement of the UCS up at early age while 10% and 20% fly ash mixtures show good early strength. This is probably due to the lack of a binding effect and sustained the pozzolanic reaction in 5% fly ash mixture.

As can be noted, for the mixtures containing 5% and 10% FBC fly ashes, the strength kept gaining up to the recorded curing time of 91 days. However, interestingly, the mixture containing 20% FBC fly ash gained in strength up to 28 days, and then dropped regardless of aggregate types (Figure 5). Shon et al. [9] have explained that this behavior could be attributed to the increased interactive specific surface area (SSA). When fly ash is added to the mixture system, the trivalent cation ( $Al^{3+}$ ) and the divalent cation ( $Ca^{2+}$ ) available from fly ash are attracted to the negatively charged sites at mixture matrix. Furthermore, the introduction of these higher valence cations can normally replace lower valence cations of the system. Highly charged cations tend to be held more tightly than those with less charge. This phenomenon also increases the electrolyte concentration in the matrix and reduces the spacing between individual particles called “the electrical diffuse double layer” (DDL) at the particle-liquid interface (flocculation). This results in increased pore solution surface tension, producing an increase in apparent cohesion between particles in the matrix and promotes strength development. However, an excessive amount of cations in the system diminishes this positive phenomenon and brings the repulsion between matrix particles due to excessive cations. Consequently, this makes the system brittle and subsequently reduces the strength. It should be noted that 20% fly ash provides more surface area than others.

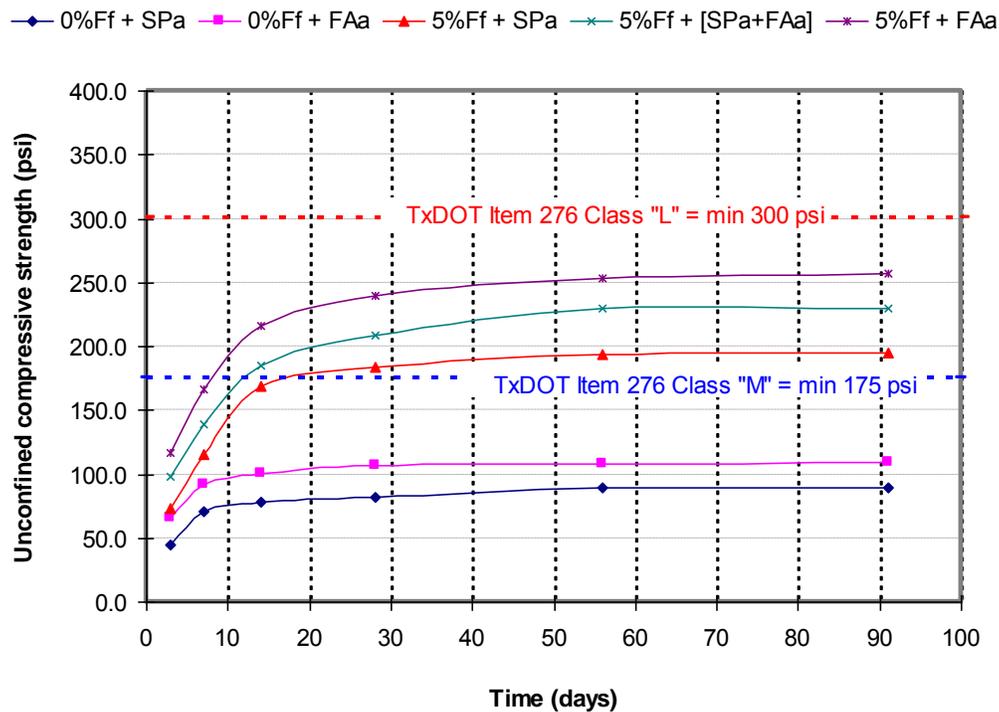


Figure 4. Unconfined Compressive strength of Different Mixture (5% Fresh Fly Ash)

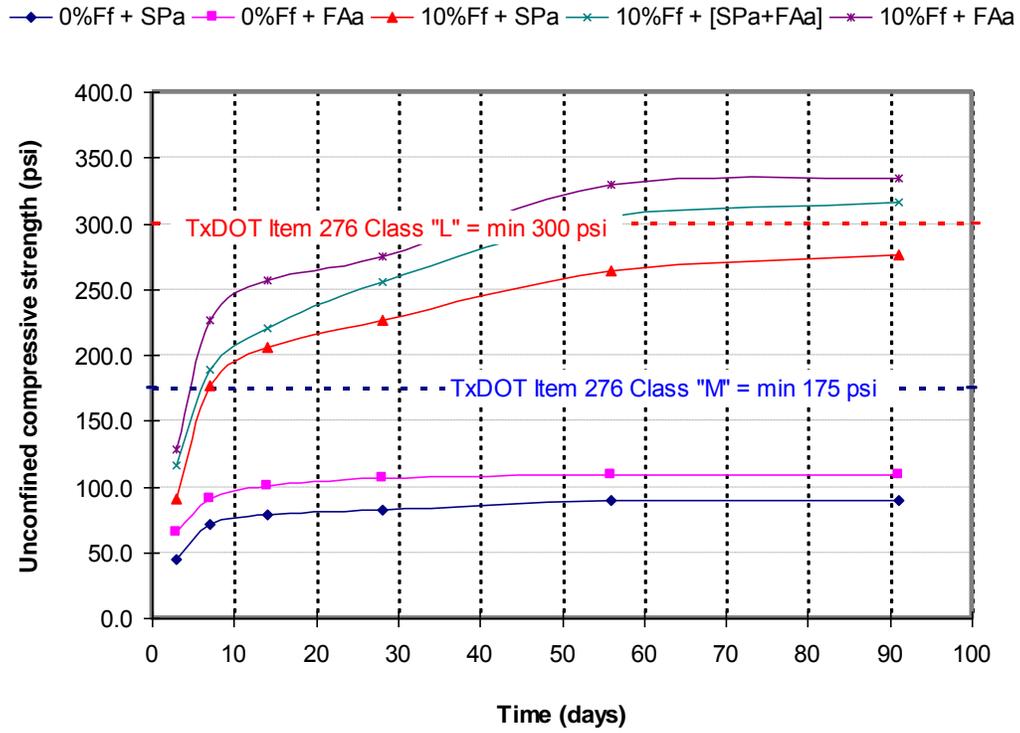


Figure 5. Unconfined Compressive strength of Different Mixture (10% Fresh Fly Ash)

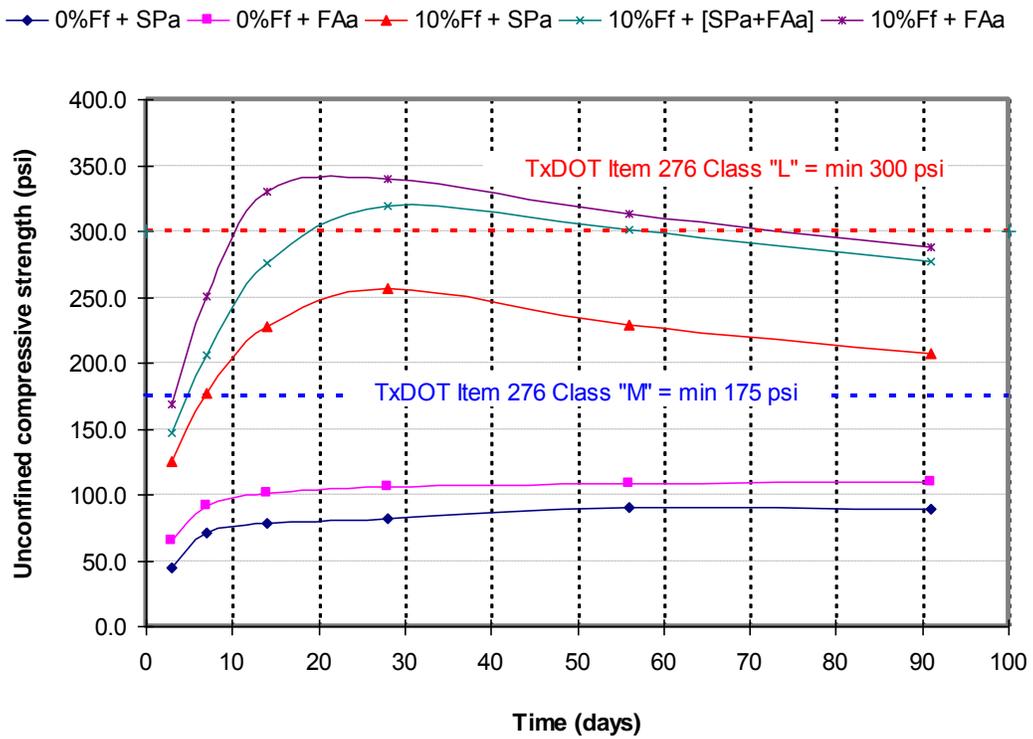


Figure 6. Unconfined Compressive strength of Different Mixture (20% Fresh Fly Ash)

Figures 4 to 6 also present the strength measured for mixtures made with different types of aggregates. FA<sub>a</sub> produces the higher strength while SP<sub>a</sub> has the lowest strength. The combined 50% FA<sub>a</sub> and 50% SP<sub>a</sub> shows the medium strength compared to others irrespective of amount of FBC fly ash used as a stabilizer. This is not surprising because the authors' previous research [10] shows that the FA<sub>a</sub> has higher density and lower porosity than SP<sub>a</sub>.

As previously stated, TxDOT Item 276 specifies four classes, L, M, N, and O of the cement stabilized bases with 7-day UCS requirements of "300 psi", "175 psi", "as shown on the plans", and "deleted," respectively. An UCS requirement of 175 psi is the minimum value currently used in base-course design. Figure 7 shows the average unconfined compressive strength (UCS) results for each mixture after 7-day curing. Whereas 5% fly ash-treated mixtures did not satisfy the Class L requirement, mixtures containing 10% and 20% fly ash met the minimum allowable strength (175 psi) for base-course design irrespective of aggregate type.

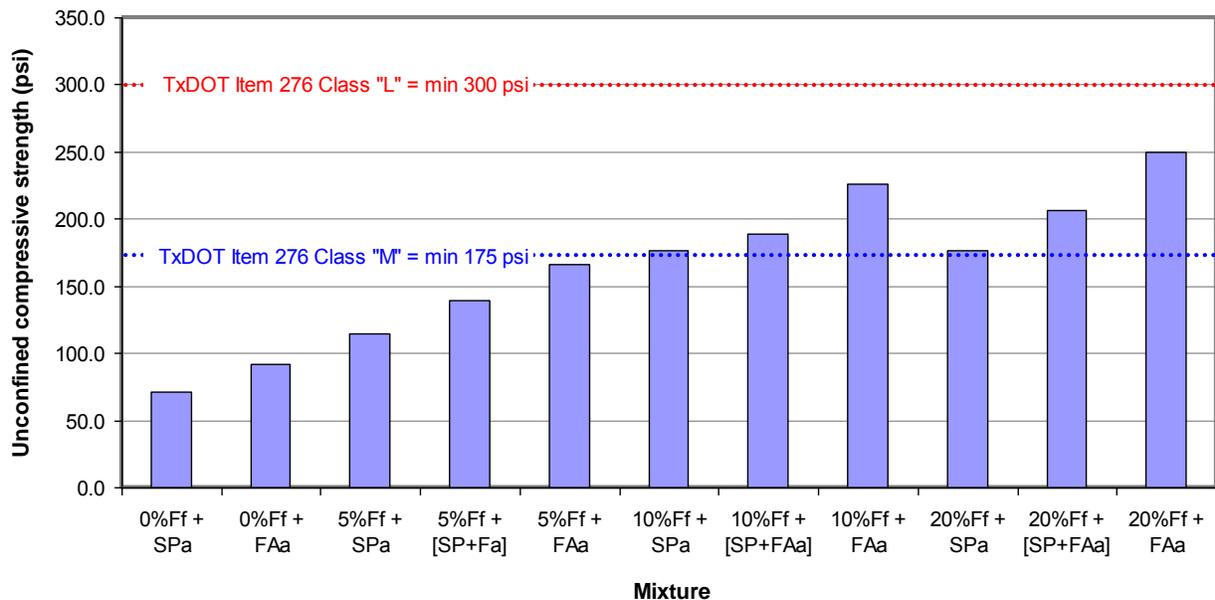


Figure 7. Unconfined Compressive strength of Different Mixture for TxDOT Item 276

### Tube Suction (Capillary Suction) Test

Tube suction (capillary suction) test was conducted for assessing the moisture susceptibility of base-course mixture when exposed to prolonged capillary soak conditions. The development of both a dielectric value (DV) and absorbed moisture content is shown in Figures 8 and 9. For 10% FBC fly ash-treated mixtures, SP<sub>a</sub> mixture exhibited higher average DV, 12.1 at 10-day, whereas FA<sub>a</sub> and a blend of SP<sub>a</sub> and FA<sub>a</sub> mixtures stayed below 10 at the same age. As stated earlier, this indicates that

mixtures containing FA<sub>a</sub> has lower moisture susceptibility composed with the corresponding poor DV which was below 10.

Increasing FBC fly ash content deteriorated the moisture susceptibility resistance of base-course mixture and resulted in DV nearly twice of that exhibited by 10% fly ash-treated mixture.

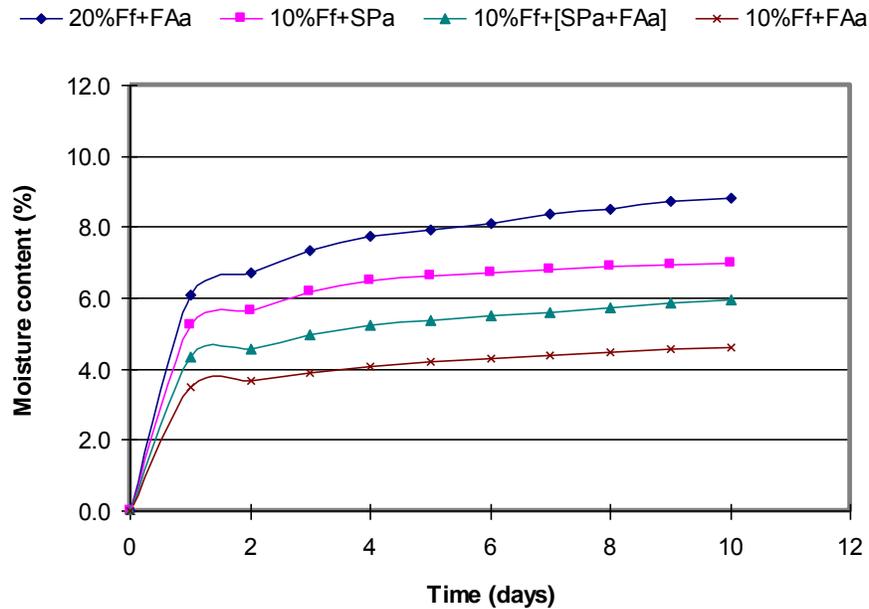


Figure 8. Moisture content changes over time

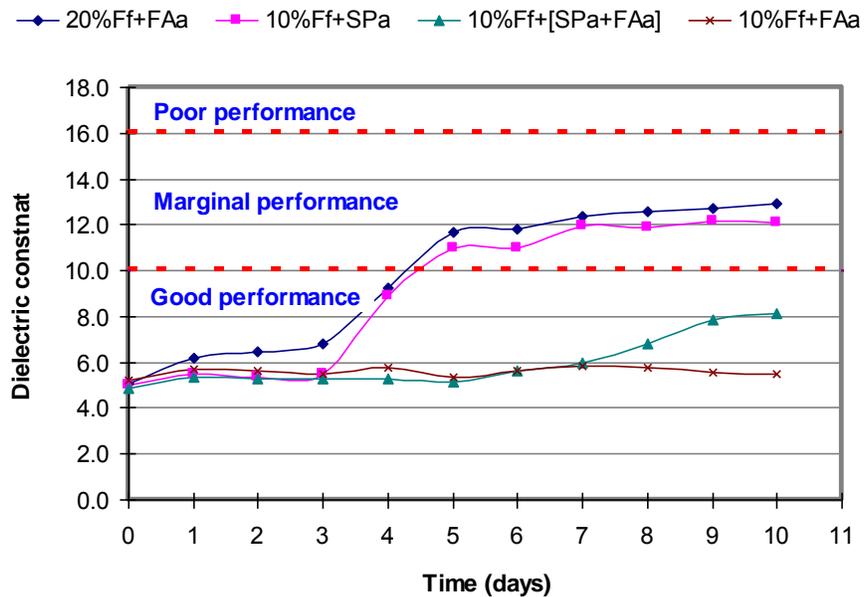


Figure 9. Dielectric value development over time

The average compressive strength values of the mixtures after tube suction test were compared to the baseline strengths after the 7-day moist curing, obtained earlier (Table 3). The relative retained strength values of all mix designs exceeded the threshold value of 80% recommended by TxDOT. The high UCS values of the all mixtures after TST may be attributed to hydration of cementitious material and the pozzolanic reaction between free calcium and silica and alumina.

Mixture	Final		UCS (psi)		Retained UCS (%)
	M.C	D.C	Before TST	After TST	
20%F <sub>f</sub> + FA <sub>a</sub>	10	12.9	250.3	270.3	108.0
10%F <sub>f</sub> + SP <sub>a</sub>	8.8	12.1	176.8	190.5	107.7
10%F <sub>f</sub> + [SP <sub>a</sub> +FA <sub>a</sub> ]	6.0	8.2	188.5	212.4	112.7
10%F <sub>f</sub> + FA <sub>a</sub>	4.6	5.5	226.3	265.6	117.4

### 3-Dimensional Swelling Test

The volumetric expansion results for 10% FBC fly ashes-treated mixtures obtained from TTI swelling test are presented in Figure 10. All mixtures demonstrated excellent performance characteristics with the corresponding average volumetric expansions well under 6.0%. The FA<sub>a</sub> mixture had the highest average volumetric expansion of 4.7%, whereas the SP<sub>a</sub> mixture stayed below an average of 4.0%. At early age, all mixtures presented a decreasing volumetric swelling trend up to 4 days, which can be attributed to the chemical shrinkage of the mixtures due to the hydration of fly ash and consolidation.

Figure 10 also show the volumetric expansion characteristics when large amounts of FBC fly ash are used as a stabilizer. The mixture containing 20% freshly generated (unaged) FBC fly ash exhibited higher average expansion 6.9%. This indicates that the utilization of this FBC fly ash as a binder or stabilizer may have sulfate swell potential with the corresponding high expansion over 6%. Therefore, continuous monitoring of the expansion caused by FBC fly ash should be taken. Based on swell test results, it can be concluded that the utilization of FBC fly ash increases the volumetric expansion of a base-course mixture, but the swelling values are minimal when a certain amount of FBC fly ash is used.

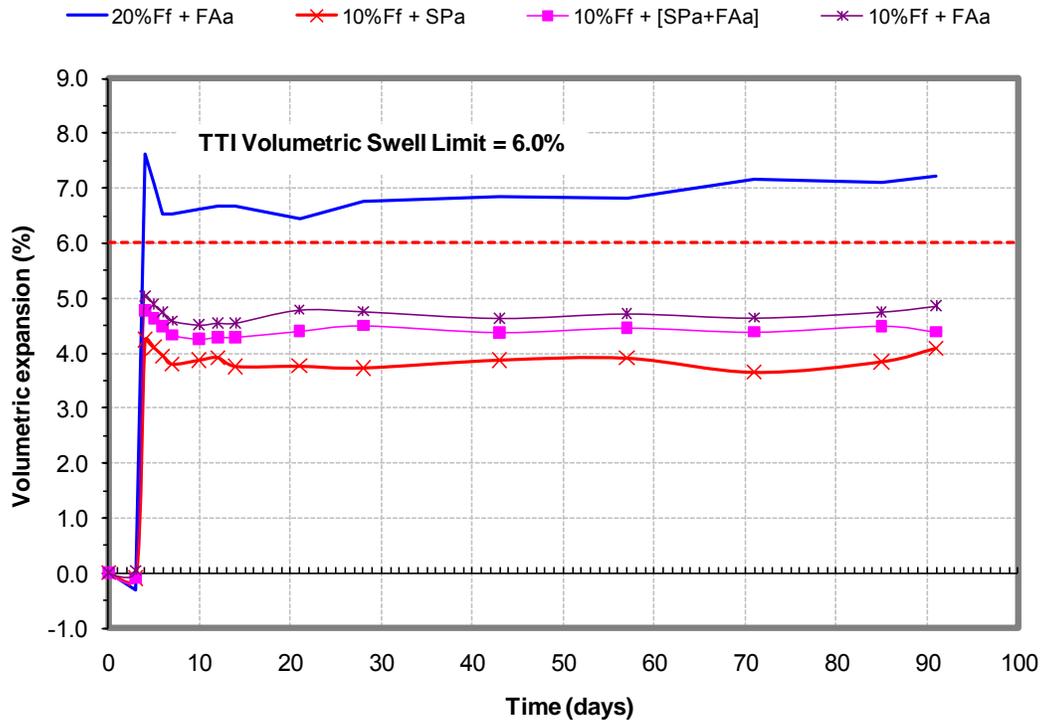


Figure 10. Volumetric expansion results

## CONCLUSIONS

Fluidized bed combustion (FBC) fly ash containing a very good binding characteristic has not been used as extensively in construction applications in comparison with conventional ashes such as Class F and Class C fly ashes because of its inherent properties e.g. in: high free lime and sulfate contents and particles with leafy-flake shaped in irregular morphologies. Authors' previous research indicate that the stockpiled FBC ash would fulfill the aggregate function in the base course mix when cement as an activator to boost binding property is added. In addition, the self-cementing nature of FBC fresh ash could be exploited to develop aggregates that may be used for a wide variety of construction activities. In order to maximize the use of both stockpiled and fresh FBC ashes, a comprehensive laboratory evaluation for the use of manufactured FBC ash aggregate for road base-course construction has been conducted. Based on strength, swelling, and tube suction test results, the mix design containing 10% FBC fly ash for FA<sub>a</sub> and 50/50 blend of SP<sub>a</sub> and FA<sub>a</sub> satisfied the requirements of Class L base as per TxDOT Item 276.

## REFERENCES

- [1] Shon, C.-S., Mukhopadhyay, A.K., Saylak, D., Zollinger, D.G., and Mejeoumov, G. Potential Use of Stockpiled Circulating Fluidized Bed Combustion Ashes in Controlled Low Strength Material (CLSM) Mixture, *Construction and Building Materials*, 2010, 24(5), pp.839-847.
- [2] White, D.J. Reclaimed Hydrated Fly Ash As a Geomaterial, *Journal of Material in Civil Engineering*, 2006, 18(2), pp.206-213.
- [3] Estakhri, C. Field Performance Evaluation of Hydrated, Fly Ash Bases in the Atlanta District-Year 5, Research Report 2966-5, Texas Transportation Institute, TX, 2001, pp. 27-28.
- [4] Mukhpadhyay, A.K., Mejeoumov, G, Shon, C.-S., Saylak, D., and Sarkar, S.L. Finite Characterization of Ashes from a Circulating Fluidized Bed Combustion Thermal Powder Plant, In: *Proceedings of 26<sup>th</sup> International Conference on Cement Microscopy*, San Antonio, 2004, CD-rom.
- [5] Shon, C.-S., Saylak, D., and Zollinger, D.G. Potential Use of Stockpiled Circulating Fluidized Bed Combustion Ashes in Manufacturing Compressed Earth Bricks, *Construction and Building Materials*, 2009, 23(5), pp.2062-2071.
- [6] Sebesta, S., Scullion, T., and Estakhri, C. Field and Laboratory Investigation for Full Depth Reclamation Projects, FHWA/TX-10/0-6271-1, Texas Transportation Institute, TX, 2009, p. 17.
- [7] Scullion, T. and Saarenketo, T. Using Suction and Dielectric Measurements As Performance Indicators for Aggregate Base Materials, *Journal of Transportation Research Record No. 1577*, 1997, pp.37-44.
- [8] Guthrie, S., Hermansson, A., and Scallion, T. Determining Aggregate Frost Susceptibility with the Tube Suction Test.” In: *Proceedings of the 11th International Conference on Cold Regions Engineering: Cold Regions Impacts on Transportation and Infrastructure*, Reston, 1998, pp. 663–674.
- [9] Shon, C.-S., Saylak, D., and Mishra, S. Combined Use of Calcium Chloride and Fly Ash in Road Base Stabilization, *Journal of Transportation Research Record No. 2186*, 2010, pp.120-129.
- [10] Shon, C.-S. and Saylak, D. Development and Evaluation of Base-Course Materials Using Fluidized Bed Combustion Fly Ash, Research Report Phase V, Texas Engineering Experiment Station, Texas A&M University, 2009.