Comparison of Beneficiated Fly Ash with a Popular Class F Fly Ash in Tennessee

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ABSTRACT

The beneficiation of previously undesirable fly ash is becoming more important due to the amount of available fly ash source dwindling. The utilization of beneficiated Class F fly ash (BFFA) could provide many benefits. The BFFA mixtures were compared to popular Tennessee Class F fly ash (F) mixtures.

TDOT bridge deck (Class D) and general use (Class A) concrete mixtures were selected for this preliminary investigation. Both the Class D and Class A were compared to two similar (25% substitution by weight of cement for both mixes) F mixtures.

Six batches of each mixture were tested. Surface resistivity (chloride permeability) and compressive strength were measured at 7, 14, 28, and 56 days. Static modulus of elasticity was measured at 28 and 56 days. Absorption after boiling was measured at 56 days. The BFFA bridge deck mixture was statistically superior or equal to the corresponding F mixture for all properties except absorption after boiling. The BFFA general mixture was statistically superior or equal to the corresponding F mixture for all properties except surface resistivity at 7-days. All mixtures met TDOT Class D and A plastic and hardened property requirements.

BFFA is expected to cost more than F. However, 25% BFFA cementing material cost less than $2.50 per cubic yard more. The advantage of BFFA is its environmental impact on the use of undesired fly ash by the process of beneficiation. BFFA use cuts down on the amount of fly ash remaining in landfills.

INTRODUCTION AND RESEARCH SIGNIFICANCE

Not only does fly ash enhance concrete strength, durability, and sustainability, it reduces concrete cost as well. There is a continuous demand for fly ash, however, its supply is decreasing or at least it is uncertain in the future. Due to loss-on-ignition (LOI), a measure of unburned carbon, being too high in fly ashes, many sources of fly ash do not meet American Society for Testing and Materials (ASTM) or American Association of State Highway and Transportation Officials (AASHTO) requirements.

When a fly ash has an excessively high LOI and does not meet ASTM or AASHTO standards, this is when the thermal beneficiation process of fly ash typically begins. Thermal beneficiation of fly ash is a proprietary process and so a detailed discussion of it cannot be provided. However, thermally beneficiating a fly ash, will result in a fly ash that meets ASTM and/or AASHTO Class F fly ash requirements for use in concrete.

Studies calling for the use of thermally beneficiated fly ash as a supplementary cementing material (SCM) in concrete are on the rise. Unfortunately, Tennessee does not currently produce thermally beneficiated fly ash. However, if its use becomes more pervasive in the State, it is anticipated that suppliers will ensure its continued availability to Tennessee concrete producers. To validate the use of thermally beneficiated fly ash, thermally beneficiated Class F fly ash was obtained from South Carolina and Tennessee Concrete Association (TCA) contracted with Tennessee Technological University (TTU) to conduct a comparison of its impacts on concrete properties with a Tennessee Class F fly ash known to perform well as a SCM. The two primary target audiences for the comparison are Tennessee concrete producers and the Tennessee Department of Transportation (TDOT).

RESEARCH OBJECTIVES

The primary objective of this research was to determine if a beneficiated Class F fly ash could produce hardened properties (surface resistivity, compressive strength, static modulus of elasticity, and absorption after boiling) that were equal or superior to those produced by a typical Tennessee Class F fly ash in similar TDOT Class A and D concretes.

LITERATURE REVIEW

Due to the thermal beneficiation process being proprietary, a detailed literature review cannot be provided. However, it is known that a Class F fly ash with a higher than allowable LOI, is thermally beneficiated to lower the LOI content to allow the fly ash to pass ASTM and AASHTO fly ash standards for use in concrete.

MATERIALS

Table 1 shows two samples of thermally beneficiated Class F fly ash compared to a typical Tennessee Class F fly ash, known to perform well as an SCM in concrete, meeting ASTM C618-17a (1) and AASHTO M295-11 (2) requirements. Although some chemical differences are apparent, all three fly ash samples met ASTM and AASHTO requirements for use in concrete.

Table 1: Fly Ash Properties and Requirements

Property	Thermally Beneficiated Class F Fly Ash (Samples a & b)		Typical Popular TN Class F Fly Ash	ASTM C618-17a	AASHTO M295-11
Silicon Dioxide (%)	53.9	52.8	42.9	—	—
Aluminum Oxide (%)	27.6	27.5	17.3	—	—
Iron Oxide (%)	9.69	10.08	20.34	—	—
$SiO_2 + Al_2O_3 + Fe_2O_3$ (%)	91.1	90.4	80.5	70 min.	70 min.
Calcium Oxide (%)	1.8	2.2	7.4	—	—
Magnesium Oxide (%)	1.0	1.0	1.7	—	—
Sodium Oxide (Na_2O)	0.31	0.31	0.60		
Potassium Oxide (K_2O)	2.33	2.33	2.07		
Sodium Oxide Equivalent ($Na_2O+0.658K_2O$)	1.85	1.85	1.96		
Sulfur Trioxide (%)	0.14	0.21	2.72	5 max.	5 max.
Loss on Ignition (%)	0.5	0.6	1.0	6 max.	5 max.
Moisture Content (%)	0.1	0.0	0.2	3 max.	3 max.
Alkalis as Na_2O (%)	1.03	1.03	0.82	—	1.5 max.
Fineness (Amount Retained on #325 Sieve)	21.6	21.7	19.0 (15.4 Average)	34 max	34 max

PROCEDURE

Table 2, column 1 shows the TDOT-approved materials for concrete used in the study, except for the thermally beneficiated Class F fly ash that was investigated. The proportions of the four mixtures used in the study (see Table 2) were determined through trial batching. All four mixtures met TDOT 604.03 (3) concrete plastic and hardened property requirements. Tables 3 and 4 show TDOT 604.03 (3) requirements for minimum cementing materials, w/cm ratio, fine aggregate percentage by total aggregate volume, and allowable SCM replacement percentages for Class D and A concrete, respectively.

Table 2: Mixtures Used to Evaluate Thermally Beneficiated Class F Fly Ash

	Control Class D	Thermally Beneficiated Class D	Control Class A	Thermally Beneficiated Class A
Type I PC, (lbs/CY)	465	465	423	423
Popular TN Class F Fly Ash, (lbs/CY)	155	0	141	0
Beneficiated SC Class F Fly Ash, (lbs/CY)	0	155	0	141
No. 57 Stone, (SSD lbs/CY)	1849	1840	1747	1741
River Sand, (SSD lbs/CY)	1112	1106	1270	1263
Water, (lbs/CY)	229.5	229.5	242.5	242.5
Design Percent Air	7	7	6	6
Air Entrainer, (oz/cwt)	2.8	4.0	2.5	2.3
Mid-Range Water Reducer, (oz/cwt)	3.1	3.1	7.6	8.2
High-Range Water Reducer, (oz/cwt)	4.5	4.2	0	0

Table 3: Comparison of Fly Ash Evaluation Mixtures with TDOT Class D PCC Requirements

Property	TDOT 604.03 Class D PCC Requirements	Control Class D	Thermally Beneficiated Class D
Cement content (lb/CY)	620 minimum	620	620
Water-cement ratio	0.40 maximum	0.37	0.37
Percent Fine Aggregate by Total Aggregate Volume	44 maximum	38	38
Percent Class F Fly Ash Substitution (by Weight) for PC	25 maximum	25	25

Table 4: Comparison of Fly Ash Evaluation Mixtures with TDOT Class A PCC Requirements

Property	TDOT 604.03 Class A PCC Requirements	Control Class A	Thermally Beneficiated Class A
Cement content (lb/CY)	564 minimum	564	564
Water-cement ratio	0.45 maximum	0.43	0.43
Percent Fine Aggregate by Total Aggregate Volume	44 maximum	42.5	42.5
Percent Class F Fly Ash Substitution (by Weight) for PC	25 maximum	25	25

Six 0.85-cubic-foot batches of each mixture were made and tested as per the protocol reported in Table 5. The specimens were demolded the day after casting and were cured using lime-water immersion according to ASTM C 192 (4). The 56-day compressive strength specimens were used for all SR tests. Compressive strength testing was conducted in accordance with ASTM C 39 (5). Static modulus of elasticity was conducted in accordance with ASTM C 469 (6). Surface resistivity was conducted in accordance with AASHTO T 358-17 (7). Hardened concrete absorption after boiling was conducted in accordance with ASTM C 642 (8).

Table 5: Testing Protocol for Fly Ash Comparison Mixtures

Test Method	Frequency	Specimens
Compressive Strength, ASTM C39 (5)	3 @ 7, 14, 28 and 56 days	4 x 8 cylinders
Static Modulus of Elasticity ASTM C 469 (6)	1 of 3 @ 28 and 56 days	4 x 8 cylinders
Surface Resistivity, AASHTO T 358-17 (7)	3 @ 7, 14, 28, and 56 days	56-day compressive strength 4 x 8 cylinders
Hardened Concrete Absorption, ASTM C642 (8)	3 @ 56 days	3 x 6 cylinders

RESULTS

Tables 6 and 7 show compressive strength results and result ranges for TDOT Class D and A, respectively. Tables 8 and 9 show static modulus of elasticity results and result ranges for TDOT Class D and A, respectively. Tables 10 and 11 show surface resistivity results and result ranges for TDOT Class D and A, respectively. Table 12 shows 56-day absorption after boiling results and result ranges for TDOT Class D and A, respectively

Table 6: TDOT Class D Compressive Strength Results (psi)

Mixture	Batch 1	Batch 2	Batch 3	Batch 4	Batch 5	Batch 6	Mean	Range
	7-days							
Class D Control	5500	5280	5780	5530	5730	5890	5618	610
Class D Beneficiated	5470	5660	5760	5740	5730	5350	5618	410
	14-days							
Class D Control	6190	6190	6500	6090	6210	6470	6275	410
Class D Beneficiated	6490	6420	6190	6320	6200	6160	6297	330
	28-days							
Class D Control	6780	6750	7110	6750	7230	7240	6977	490
Class D Beneficiated	6870	6830	6810	6910	7260	6990	6945	450
	56-days							
Class D Control	7800	7610	7890	7630	7650	8200	7797	590
Class D Beneficiated	7670	7480	7930	7600	8220	7790	7782	740

Table 7: TDOT Class A Compressive Strength Results (psi)

Mixture	Batch 1	Batch 2	Batch 3	Batch 4	Batch 5	Batch 6	Mean	Range
	7-days							
Class A Control	3990	4250	4180	4260	4110	4720	4252	730
Class A Beneficiated	4360	4510	4480	4280	4410	4330	4395	230
	14-days							
Class A Control	4650	4780	4490	4700	4460	5250	4722	790
Class A Beneficiated	4830	5180	4970	4970	4970	4870	4965	340
	28-days							
Class A Control	5080	5080	5080	5120	5190	6030	5263	950
Class A Beneficiated	5610	5710	5580	5600	5900	5400	5633	500
	56-days							
Class A Control	5880	5980	5910	5990	5970	6520	6042	640
Class A Beneficiated	6190	6430	6420	6760	6550	6170	6420	590

Table 8: TDOT Class D Static Modulus of Elasticity Results (10^6-psi)

Mixture	Batch 1	Batch 2	Batch 3	Batch 4	Batch 5	Batch 6	Mean	Range
	28-days							
Class D Control	3.95	4.05	4.20	3.95	4.00	4.05	4.03	0.25
Class D Beneficiated	4.45	4.20	4.10	4.35	4.00	4.20	4.22	0.45
	56-days							
Class D Control	4.25	4.10	4.15	4.20	4.30	4.55	4.26	0.45
Class D Beneficiated	4.30	4.20	4.50	4.30	4.30	4.20	4.30	0.30

Table 9: TDOT Class A Static Modulus of Elasticity Results (10^6-psi)

Mixture	Batch 1	Batch 2	Batch 3	Batch 4	Batch 5	Batch 6	Mean	Range
	28-days							
Class A Control	3.60	3.75	3.55	3.55	3.60	3.90	3.66	0.35
Class A Beneficiated	3.85	4.15	3.95	3.90	3.90	3.80	3.93	0.35
	56-days							
Class A Control	4.30	3.85	4.10	3.90	3.95	4.15	4.04	0.40
Class A Beneficiated	3.80	3.95	3.95	4.05	4.10	3.95	3.97	0.30

Table 10: TDOT Class D Surface Resistivity Results (kilohm-cm)

Mixture	Batch 1	Batch 2	Batch 3	Batch 4	Batch 5	Batch 6	Mean	Range
	7-days							
Class D Control	9.7	9.2	9.3	9.6	9.8	9.5	9.5	0.6
Class D Beneficiated	9.6	9.7	9.4	10.1	9.3	9.3	9.6	0.7
	14-days							
Class D Control	10.9	10.4	10.6	11.2	11.0	10.8	10.8	0.8
Class D Beneficiated	11.4	11.2	11.0	11.9	10.9	11.0	11.2	1.0
	28-days							
Class D Control	13.8	13.3	13.7	14.5	14.3	14.1	14.0	1.2
Class D Beneficiated	15.2	14.9	14.9	15.2	14.6	14.8	14.9	0.6
	56-days							
Class D Control	20.8	20.4	20.3	21.2	20.7	21.3	20.8	1.0
Class D Beneficiated	24.4	24.3	22.6	24.8	24.6	24.4	24.2	2.0

Table 11: TDOT Class A Surface Resistivity Results (kilohm-cm)

Mixture	Batch 1	Batch 2	Batch 3	Batch 4	Batch 5	Batch 6	Mean	Range
	7-days							
Class A Control	8.6	8.3	8.5	8.5	7.7	8.2	8.3	0.9
Class A Beneficiated	7.4	7.4	7.0	7.4	7.6	7.8	7.4	0.8
	14-days							
Class A Control	9.5	9.1	9.2	9.3	8.7	9.2	9.2	0.8
Class A Beneficiated	8.6	8.6	8.2	8.7	9.4	9.0	8.8	0.8
	28-days							
Class A Control	12.1	11.7	11.6	11.9	11.5	11.9	11.8	0.6
Class A Beneficiated	12.0	12.5	12.1	12.3	12.1	12.0	12.2	0.5
	56-days							
Class A Control	19.3	19.0	18.6	18.8	18.4	20.0	19.0	1.6
Class A Beneficiated	21.3	22.0	20.5	20.9	21.1	21.6	21.2	1.5

Table 12: 56-day Absorption after Boiling Results and Ranges (%)

Mixture	Batch 1	Batch 2	Batch 3	Batch 4	Batch 5	Batch 6	Mean	Range
Class D Control	4.09	4.21	4.32	4.37	4.58	4.45	4.34	0.49
Class D Beneficiated	4.51	4.89	4.60	4.77	4.39	4.49	4.61	0.50
Class A Control	4.78	4.91	4.78	4.82	4.73	4.41	4.74	0.50
Class A Beneficiated	4.82	4.86	5.05	4.78	4.98	4.86	4.89	0.27

QUALITY OF RESULTS

Tables 13 through 18 show comparisons of actual and acceptable range of results for hardened properties. Table 19 shows the coefficients of variation for the absorption after boiling results. No precision criteria are available for hardened concrete absorptions after boiling. The acceptable range of the hardened property results was determined by first multiplying the test method multi-laboratory coefficient of variation (COV) by a factor from ASTM C 670 for the number of results (9). Finally, the product was multiplied by the mean result to obtain the allowable range. The multi-laboratory precision was used for the 4x8-inch cylinder results, since AASHTO T 22 states that the preparation of cylinders by different operators would probably increase the variation above multi-laboratory precision criteria (10). All hardened property test results met the acceptable precision criteria except the TDOT Class A control compressive strengths at 7, 14, and 28-days. Batch 6 of TDOT Class A control mixture was unusually strong compared to batches 1 through 5 at 7, 14, and 28-days. The reason for the higher strength of batch 6 is not known but is not considered a serious problem.

Table 13: TDOT Class D Compressive Strength Data Quality (psi)

Age (days)	Class D Control Range	Class D Control Allowable Range	Class D Beneficiated Range	Class D Beneficiated Allowable Range
7	610	719	410	719
14	410	803	330	806
28	490	893	450	889
56	590	998	740	996

Table 14: TDOT Class A Compressive Strength Data Quality (psi)

Age (days)	Class A Control Range	Class A Control Allowable Range	Class A Beneficiated Range	Class A Beneficiated Allowable Range
7	730	544	230	563
14	790	604	340	636
28	950	674	500	721
56	640	773	590	822

Table 15: TDOT Class D Static Modulus of Elasticity Data Quality (10^6-psi)

Age (days)	Class D Control Range	Class D Control Allowable Range	Class D Beneficiated Range	Class D Beneficiated Allowable Range
28	0.25	0.68	0.45	0.71
56	0.45	0.72	0.30	0.73

Table 16: TDOT Class A Static Modulus of Elasticity Data Quality (10^6-psi)

Age (days)	Class A Control Range	Class A Control Allowable Range	Class A Beneficiated Range	Class A Beneficiated Allowable Range
28	0.35	0.62	0.35	0.66
56	0.40	0.68	0.30	0.67

Table 17: TDOT Class D Surface Resistivity Data Quality (kilohm-cm)

Age (days)	Class D Control Range	Class D Control Allowable Range	Class D Beneficiated Range	Class D Beneficiated Allowable Range
7	0.6	4.8	0.7	4.8
14	0.8	5.4	1.0	5.6
28	1.2	7.0	0.6	7.5
56	1.0	10.4	2.0	12.1

Table 18: TDOT Class A Surface Resistivity Data Quality (kilohm-cm)

Age (days)	Class A Control Range	Class A Control Allowable Range	Class A Beneficiated Range	Class A Beneficiated Allowable Range
7	0.9	4.2	0.8	3.7
14	0.8	4.6	0.8	4.4
28	0.6	5.9	0.5	6.1
56	1.6	9.5	1.5	10.6

Table 19: 56-day Absorption after Boiling Data Quality (%)

Mixture	Range	COV%
Class D Control	0.49	4.0
Class D Beneficiated	0.50	4.1
Class A Control	0.50	3.6
Class A Beneficiated	0.27	2.1

ANALYSIS OF RESULTS

The tests of the hypotheses of equality of corresponding mean values of concrete properties across mixes are represented in Table 20 for the various mixtures at a given curing time and for the same mixture over various curing times, respectively. A statistical t-test with the assumption of unequal variances was performed. The estimated t-value was observed to be less than the critical t-value at the corresponding degree of freedom with a 5 percent significance level. The compared mixes that were deemed to have statistically equal values were denoted as NSD (no significant difference) in Table 20. When the estimated t-value exceeded the critical t-value at the corresponding degree of freedom with 5 percent significance level, the compared mixes were deemed to have significantly different values. The green shaded cells in Table 20 indicate thermally beneficiated Class F fly ash results are statistically significantly different and superior to typical Class F fly ash results. The red shaded cells in Table 20 indicate thermally beneficiated Class F fly ash results are statistically significantly different and inferior to typical Class F fly ash results. Numbers shown in Table 20 are the percent difference in mean results. Positive numbers indicate the percentage by which the mean value of a property of a thermally beneficiated Class F fly ash exceeds that of a typical Class F fly ash.

Table 20: Statistical Analysis Comparing Beneficiated Ash vs. Typical Ash

Property	Thermally Beneficiated Fly Ash Class D Concrete vs. Typical Fly Ash Class D Concrete		Thermally Beneficiated Fly Ash Class A Concrete vs. Typical Fly Ash Class A Concrete	
Surface resistivity @ 7 days	NSD		Inferior	-10.8%
Surface resistivity @ 14 days	NSD		NSD	
Surface resistivity @ 28 days	Superior	6.4%	Superior	3.4%
Surface resistivity @ 56 days	Superior	16.3%	Superior	11.6%
Compressive Strength @ 7 days	NSD		NSD	
Compressive Strength @ 14days	NSD		NSD	
Compressive Strength @ 28 days	NSD		NSD	
Compressive Strength @ 56 days	NSD		Superior	6.3%
Static Modulus of Elasticity @ 28 days	Superior	4.5%	Superior	7.3%
Static Modulus of Elasticity @ 56 days	NSD		NSD	
Absorption after Boiling	Inferior	-6.2%	NSD	

Table 20 shows that in 20 of 22 cases, or 90.9% of the time, thermally beneficiated Class F fly ash was superior or equal to the typical Tennessee Class F fly ash, which is known to perform well as a SCM. This would seem to be strong, if not overwhelming, evidence that the thermally beneficiated Class F fly ash is at least as good as typical Class F fly ash.

TDOT 604.03 SPECIFICATION COMPLIANCE

All compressive strength results, shown in Table 6, exceed the TDOT Class D concrete specification 28-day requirement of 4000-psi. Similarly, all compressive strength results, shown in Table 7, exceed the TDOT Class A concrete specification 28-day requirement of 3000-psi.

COST

It is currently not possible to accurately estimate the cost of thermally beneficiated Class F fly ash in Tennessee. However, if the cost of thermally beneficiated Class F fly ash were double the cost of the typical Tennessee Class F fly ash known to perform well as an SCM, it would still be about 50% the cost of Type I Portland cement or about 67% of the cost of Grade 100 Ground Granulated Blast Furnace Slag.

CONCLUSIONS AND SIGNIFICANT OBSERVATIONS

Based on the testing and statistical analysis done in this project, it appears that the South Carolina thermally beneficiated Class F fly ash evaluated is similar in performance as a concrete SCM to the Class F fly ash typically used in Tennessee.

FUTURE RESEARCH NEEDS

The current project only compared one thermally beneficiated Class F fly ash to a typical Tennessee Class F fly ash known to perform well as an SCM. It seems prudent to make further comparisons with other thermally beneficiated Class F fly ash samples. However, if thermally beneficiated Class F fly ash samples are required to meet the same ASTM, AASHTO, and TDOT requirements as typical Class F fly ash, it seems reasonable to expect similar performance as a concrete SCM.

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