# Preliminary Study of the Potential of a Beneficiated Ultrafine Class F Fly Ash

**L. K. Crouch, Ph.D., P.E.[1], Alex Kelley[1], Samuel Mathews, E.I.[1], Daniel Badoe, Ph.D.[1], and Alan Sparkman[2]**

[1]Tennessee Technological University, Department of Civil and Environmental Engineering, TTU Box 5015, Cookeville, TN 38505; [2] Executive Director, Tennessee Concrete Association, 705 Fort Negley Court, Nashville, TN 37212

CONFERENCE: 2019 World of Coal Ash – (www.worldofcoalash.org)

KEYWORDS: beneficiated fly ash, ultrafine fly ash, Class F fly ash, compressive strength, concrete

## ABSTRACT

As usable fly ash sources dwindle, beneficiation of previously undesirable fly ash is becoming more important. Utilization of this material could provide many benefits. As a first step, a beneficiated ultrafine Class F fly ash (BUFFA) was compared, in similar mixtures, to a popular Tennessee Class F fly ash (F)

Tennessee Department of Transportation (TDOT) Class D (bridge deck) concrete was selected as the application for this preliminary investigation. Two BUFFA mixtures (25% and 35% substitution by weight of cement) were compared to two similar F mixtures from previous research at Tennessee Technological University (TTU). A 100% PC mixture was also generated as a basis for comparison.

Six batches of each mixture were tested. Surface resistivity (chloride permeability) was measured at 7, 14, 28, 42, and 56 days. Compressive strength was measured at 28 and 56 days. Absorption after boiling was measured at 56 days. Both BUFFA mixtures were statistically superior to both F mixtures in all tests after 7 days. The 25% BUFFA mixture was equal or superior to 100% PC mixture at 14 and 28 days and superior thereafter. All mixtures met TDOT Class D plastic and hardened property requirements.

BUFFA costs more than F. However, 25% BUFFA cementing material cost was less than 20% more than 100% PC. The advantage of BUFFA is excellent use of curing time. After 28 days of curing the 25% BUFFA mixture had surface resistivity and compressive strength similar to the 25% F mixture with 72 and 334 day curing times, respectively.

## INTRODUCTION AND RESEARCH SIGNIFICANCE

The use of fly ash in concrete mixes enhances the concrete's strength, durability, and sustainability, and reduces its cost of production. The demand for fly ash remains high while its supply is decreasing, or at least is uncertain in the future. Unfortunately, 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 for fly ash used in concrete. Typically, loss-on-ignition (LOI), a measure of unburned carbon, is too high in fly ashes which fail to meet these standards.
Thermal beneficiation of fly ash typically begins with a fly ash not meeting ASTM or AASHTO standards for LOI and results in a fly ash meeting ASTM and/or AASHTO Class F fly ash requirements for use in concrete.

The Tennessee Concrete Association (TCA) strongly favors the use of thermally beneficiated fly ash as a supplementary cementing material (SCM) in concrete. Thermally beneficiated fly ash would help ensure that fly ash is always available for Tennessee concrete producers. Unfortunately, Tennessee does not currently have thermally beneficiated fly ash available. In an effort to validate the use of thermally beneficiated fly ash, TCA helped Tennessee Technological University (TTU) researchers obtain thermally beneficiated ultrafine Class F fly ash. TTU conducted two comparisons of beneficiated ash and a common Tennessee Class F fly ash known to perform well as an SCM in concrete, one on thermally beneficiated Class F fly ash (described in a separate paper) and one on ultrafine thermally beneficiated Class F fly ash (described in this paper). Finer grinding of Class F fly ash should increase surface area of the fly ash, thus increasing the rate at which pozzolanic reactions occur. 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 ultrafine Class F fly ash (BUFFA) could produce hardened properties (surface resistivity, absorption after boiling, and compressive strength) that were superior to those produced by a typical Tennessee Class F fly ash (F) in similar TDOT Class D concrete.

## LITERATURE REVIEW

Fly ash is a by-product of combustion of coal exhaust fumes produced from coal-fired electric power stations (1). A total of 620-660 million tons of fly ash is produced globally per year. Of this amount produced, only about 54% is currently being utilized, while the remaining amount is distributed to various landfills. The disadvantage of storing fly ash in landfills is it is very costly to fly ash producers and harmful to the environment (2). Fly ash is a pozzolanic SCM, meaning that once it is chemically exposed to water it displays little to no cementitious behavior (3). By substituting fly ash for PC, it can assist in cutting down the emissions associated with producing cement (2).

Regular Class F fly ash is passed through a classifier, removing the coarse particles and collecting only the fines. When the fly ash is processed from the Class F source, it is then classified as ultrafine fly ash (UFFA). Ultrafine fly ash has a maximum particle size of 10 microns, with the average particle size ranging from 2-4 microns (4). Over 90% of UFFA particles have a diameter that is less than 7 microns (5). With a particle size this fine, it provides a larger surface area generating higher early strengths and lower permeability concrete (4).

UFFA positively effects concrete plastic properties by increasing the workability and fluidity of the concrete (2). Fly ash typically reduces water demand and improves concrete durability when used. By using UFFA, this only further improves these properties due to its greater surface area and finer particles. UFFA has more spherical particles than regular fly ash, which reduces friction, thus resulting in a more fluid mixture (5). Fly ash concrete is required by many departments of transportation (DOT's), because it can make concrete more durable and also easier to finish. With fly ash reducing the water demand, and an increase in fine particle content, this enables the concrete mixture to have a decrease in particle segregation (3).

The influential effects UFFA has on hardened concrete properties include: greater long term strength, lower shrinkage, lower water absorption, reduced chloride permeability, increased resistance to sulfate attack, lower heat of hydration, and reduced alkali aggregate reactivity (2). Fly ash reacts to lime curing water to produce additional CSH, which helps increase the overall strength (2, 3). With a decrease in the particle size, the compressive strength of UFFA concrete increases (2). Regular Class F fly ash typically produces lower early strength results up to 28 days after placement, when compared to PCC without SCMs (3). However, UFFA can help produce slightly higher strengths at earlier days due to its particle fineness (2, 5). Like regular Class F fly ash, UFFA concrete has much greater long-term strengths past 28 days when compared to PCC without SCMs (3). A higher cementing material substitution and reduction in water is typically required to have a UFFA concrete sustain an equivalent or better early-age strength compared to regular fly ash (5).

## Previous Research Used in the Study

TTU researchers are writing a four-part series of papers to report the findings of an on-going investigation into TDOT Class D concrete specifications to increase surface resistivity (SR). The investigation explores both exceeding limitations on currently approved TDOT SCMs and using SCMs not currently approved by TDOT. All concrete mixtures used in the investigation met TDOT's Class D concrete plastic and hardened property requirements (6). Further, all concrete mixtures used in the investigation were constrained to meet the following criteria:

- Water-cementing materials-ratio (w/cm) = 0.37
- Design air content of 7%
- Total cementing materials = 620-lbs/CY
- Same brand and type of Portland cement
- Same source and size (no.57) of coarse aggregate
- Same source of fine aggregate
- Fine aggregate as a percentage of total aggregate by volume (FA/TA) of approximately 38%
- Same three TDOT-approved chemical admixtures

The additional constraints facilitated an easier comparison of the concrete mixtures used. It is important to note that the w/cm = 0.37 and FA/TA ~ 38% are not considered optimal, but rather that these values met TDOT Class D concrete specifications and have worked well for the authors. Two mixtures (25% and 35% Class F fly ash) from Part 1 (7) of the study were used as comparison mixtures for the current study of beneficiated ultrafine Class F fly ash. Further, a long-term study of 25% Class F fly ash (as of yet unpublished Part 4 of the Tennessee Concrete series) SR and compressive strength development was also used as a comparison for the current study.

## MATERIALS

The TDOT-approved materials used in the previous four part study were also used in the new study, with the exception of BUFFA. Specifically, the same type and brand of cement, fine aggregate, coarse aggregate, and chemical admixtures were used to produce one additional comparison mixture and two BUFFA variable mixtures. Table 1 shows a comparison of the BUFFA and the F used in the previous four part study. Although some chemical differences are apparent, both fly ashes met ASTM and AASHTO requirements for Class F fly ash. The primary difference in the two fly ashes was particle size.

**Table 1: Fly Ash Properties and Requirements**

| **Property** | **Beneficiated Ultrafine Class F (BUFFA)** | **Typical Popular TN Class F (F)** | **ASTM C618-17a** | **AASHTO M295-11** |
|---|---|---|---|---|
| Silicon Dioxide (%) | 51.3 | 42.9 | — | — |
| Aluminum Oxide (%) | 28.7 | 17.3 | — | — |
| Iron Oxide (%) | 8.97 | 20.34 | — | — |
| $SiO_2 + Al_2O_3 + Fe_2O_3$ (%) | 88.96 | 80.5 | 70 min. | 70 min. |
| Calcium Oxide (%) | 2.9 | 7.4 | — | — |
| Magnesium Oxide (%) | 1.1 | 1.7 | — | — |
| Sodium Oxide ($Na_2O$) | 0.33 | 0.60 | | |
| Potassium Oxide ($K_2O$) | 2.49 | 2.07 | | |
| Sodium Oxide Equivalent ($Na_2O+0.658K_2O$) | 1.97 | 1.96 | | |
| Sulfur Trioxide (%) | 0.21 | 2.72 | 5 max. | 5 max. |
| Loss on Ignition (%) | 1.0 | 1.0 | 6 max. | 5 max. |
| Moisture Content (%) | 0.1 | 0.2 | 3 max. | 3 max. |
| Alkalies as $Na_2O$ (%) | | | — | 1.5 max. |
| Fineness (Amount Retained on #325 Sieve) | 0.4 | 19.0 (15.4 Average) | 34 max | 34 max |

## PROCEDURE

Table 2 shows the proportions of two mixtures from the previous four part study, (25% and 35% Class F fly ash) as well as the one new comparison mixture (100% PC) and the two BUFFA mixtures (25 and 35%). An effort was made to ensure the similarity of the F and BUFFA mixture proportions. The proportions of the five mixtures used in the study (see Table 2) were determined by trial batching. All five final mixtures met TDOT Class D concrete plastic and hardened property requirements. Table 3 shows TDOT requirements for minimum cementing materials, w/cm ratio, FA/TA, and allowable SCM replacement percentages. The 0% and 25% fly ash mixtures met all criteria in Table 2. The 35% fly ash mixtures met all Table 3 criteria except for the maximum SCM replacement percentage. The 25% BUFFA would meet TDOT requirements except that the BUFFA is not on the TDOT approved products list.

**Table 2: Mixture Proportions**

| **Material Type** | **25% Class F** | **35% Class F** | **100% PC** | **25% Ultrafine Class F** | **35% Ultrafine Class F** |
|---|---|---|---|---|---|
| Type I PC | 465 | 403 | 620 | 465 | 403 |
| Class F Fly Ash | 155 | 217 | 0 | 0 | 0 |
| Ultrafine Class F Fly Ash | 0 | 0 | 0 | 155 | 217 |
| No. 57 Limestone | 1883 | 1887 | 1890 | 1861 | 1850 |
| River Sand | 1118 | 1110 | 1135 | 1119 | 1112 |
| Water | 229.5 | 229.5 | 229.5 | 229.5 | 229.5 |
| Design % Air | 7 | 7 | 7 | 7 | 7 |
| Air Entrainer | 0.6 | 1 | 0.4 | 1.0 | 1.1 |
| Mid-range Water Reducer | 3 | 1.3 | 3.7 | 3.5 | 3.5 |
| High Range Water Reducer | 2 | 2.3 | 4.4 | 2.6 | 2.7 |

Six batches of each mixture were tested as per Table 4. The specimens were de-molded the day after casting and cured using lime-water immersion according to ASTM C 192 (8). The 56-day compressive strength specimens were used for all SR tests. Compressive strength testing was conducted in accordance with ASTM C 39 (9). Hardened concrete absorption after boiling was conducted in accordance with ASTM C642 (10). Surface resistivity was conducted in accordance with AASHTO T 358-17 (11).

### Table 3: Comparison of Mixtures Used with TDOT Class D Mixture Requirements

| | **TDOT 604.3** | **25% Class F** | **35% Class F** | **100% PC** | **25% Ultrafine Class F** | **35% Ultrafine Class F** |
|---|---|---|---|---|---|---|
| Total Cementing Materials | 620 minimum | 620 | 620 | 620 | 620 | 620 |
| Water to cementing materials ratio | 0.40 maximum | 0.37 | 0.37 | 0.37 | 0.37 | 0.37 |
| Percent Fine Aggregate by Total Aggregate by volume | 44 maximum | 38.3 | 37.8 | 38 | 38 | 38 |
| Percent Class F Fly Ash Substitution (by weight) for Portland Cement | 25 maximum | 25 | 35 | 0 | 25 | 35 |

### Table 4: Testing Protocol Used to Evaluate the Beneficiated Ultrafine Class F Fly Ash Mixtures

| **Test Method** | **Frequency** | **Specimens** |
|---|---|---|
| Compressive Strength (AASHTO T22) (11) | 3 @ 28 and 56 days | 4 x 8 cylinders |
| Surface Resistivity (AASHTO T 358-17 (12) | 3 @ 7, 14, 28, 42 and 56 days | 56-day compressive strength 4 x 8 cylinders |
| Hardened Concrete Absorption ASTM C642 (10) | 3 @ 56 days | 3 x 6 cylinders |

## RESULTS

Tables 5 and 6 show the SR results and ranges for each mixture. Similarly, compressive strength results and ranges are shown in Tables 7 and 8. Tables 9 and 10 show the absorption after boiling results and ranges.

**Table 5: Surface Resistivity Results (kilohm-cm) of Comparison Mixtures**

| Age (days) | 25% Class F Mean | 25% Class F Range | 35% Class F Mean | 35% Class F Range | 100% PC Mean | 100% PC Range |
|---|---|---|---|---|---|---|
| 7 | 9.7 | 1.1 | 8.3 | 0.3 | 12.6 | 1.4 |
| 14 | 10.3 | 0.7 | 10.0 | 0.8 | 13.6 | 1.6 |
| 28 | 13.5 | 1.8 | 15.3 | 3.9 | 16.0 | 0.7 |
| 42 | 16.4 | 1.2 | 22.2 | 5.8 | 19.3 | 1.3 |
| 56 | 19.7 | 2.0 | 28.8 | 6.2 | 20.1 | 1.1 |

**Table 6: Surface Resistivity Results (kilohm-cm) of Ultrafine Fly Ash Mixtures**

| Age (days) | 25% Ultrafine Class F Mean | 25% Ultrafine Class F Range | 35% Ultrafine Class F Mean | 35% Ultrafine Class F Range |
|---|---|---|---|---|
| 7 | 9.4 | 1.0 | 7.8 | 0.3 |
| 14 | 12.5 | 1.1 | 12.1 | 0.5 |
| 28 | 24.9 | 3.2 | 25.6 | 1.1 |
| 42 | 37.2 | 4.1 | 40.6 | 2.8 |
| 56 | 53.5 | 1.7 | 54.5 | 1.5 |

**Table 7: Compressive Strength Results (psi) of Comparison Mixtures**

| Age (days) | 25% Class F Mean | 25% Class F Range | 35% Class F Mean | 35% Class F Range | 100% PC Mean | 100% PC Range |
|---|---|---|---|---|---|---|
| 28 | 5020 | 600 | 4300 | 580 | 7687 | 1405 |
| 56 | 5907 | 500 | 5265 | 590 | 8230 | 1280 |

**Table 8: Compressive Strength Results (psi) of Ultrafine Fly Ash Mixtures**

| Age (days) | 25% Ultrafine Class F Mean | 25% Ultrafine Class F Range | 35% Ultrafine Class F Mean | 35% Ultrafine Class F Range |
|---|---|---|---|---|
| 28 | 8250 | 1010 | 7010 | 3800 |
| 56 | 9547 | 680 | 7997 | 4280 |

**Table 9: Absorption after Boiling Results (%) of Comparison Mixtures**

| Age (days) | 25% Class F Mean | 25% Class F Range | 35% Class F Mean | 35% Class F Range | 100% PC Mean | 100% PC Range |
|---|---|---|---|---|---|---|
| 56 | 5.43 | 0.43 | 5.46 | 0.08 | 4.27 | 0.2 |

**Table 10: Absorption after Boiling Results (%) of Ultrafine Fly Ash Mixtures**

| Age (days) | 25% Ultrafine Class F Mean | 25% Ultrafine Class F Range | 35% Ultrafine Class F Mean | 35% Ultrafine Class F Range |
|---|---|---|---|---|
| 56 | 3.55 | 0.86 | 4.34 | 0.24 |

## Quality of Results

Tables 11 through 14 show comparisons of actual and acceptable ranges of results for hardened properties. The acceptable range was determined by first multiplying the test method multi-laboratory COV by a factor from ASTM C 670 (13) for the number of results. Finally, the product was multiplied by the mean result to obtain the allowable range. When available, the multi-laboratory precision was used since AASHTO T 22 (11) states that preparation of cylinders by different operators would probably increase the variation above multi-laboratory precision criteria. All SR results met the acceptable range requirements. Three of the four compressive strength results of the F, from a previous study met the allowable range requirements and the fourth was close (see Table 13). The 25% BUFFA compressive strength results met allowable range requirements. However, 100% PC and 35% BUFFA compressive strength results did not meet allowable range results. The reason for the large range is not known.

No guidance was found on acceptable variability for the absorption after boiling acceptable range of results. However, the coefficients of variation for absorption after boiling were less than 10% for all mixtures and less than 3.5% for all mixtures except 25% BUFFA.

The SR and absorption after boiling results were determined to be adequate for material comparisons. The compressive strength results, although containing higher variability than desired by the authors, were assumed to be adequate for preliminary comparisons of the materials.

**Table 11: Surface Resistivity Actual and Allowable Ranges (kilohm-cm) of Comparison Mixtures**

| Age (days) | 25% Class F Range | 25% Class F Allowable Range | 35% Class F Range | 35% Class F Allowable Range | 100% PC Range | 100% PC Allowable Range |
|---|---|---|---|---|---|---|
| 7 | 1.1 | 4.9 | 0.3 | 4.1 | 1.4 | 6.3 |
| 14 | 0.7 | 5.2 | 0.8 | 5.0 | 1.6 | 6. |
| 28 | 1.8 | 6.8 | 3.9 | 7.7 | 0.7 | 8.0 |
| 42 | 1.2 | 8.2 | 5.8 | 11.1 | 1.3 | 9.7 |
| 56 | 2.0 | 9.8 | 6.2 | 14.4 | 1.1 | 10.0 |

**Table 12: Surface Resistivity Actual and Allowable Ranges (kilohm-cm) of Ultrafine Fly Ash Mixtures**

| Age (days) | 25% Ultrafine Class F Range | 25% Ultrafine Class F Allowable Range | 35% Ultrafine Class F Range | 35% Ultrafine Class F Allowable Range |
|---|---|---|---|---|
| 7 | 1.0 | 4.7 | 0.3 | 3.9 |
| 14 | 1.1 | 6.3 | 0.5 | 6.0 |
| 28 | 3.2 | 12.4 | 1.1 | 12.8 |
| 42 | 4.1 | 18.6 | 2.8 | 20.3 |
| 56 | 1.7 | 26.7 | 1.5 | 27.3 |

**Table 13: Compressive Strength Actual and Allowable Ranges (psi) of Comparison Mixtures**

| Age (days) | 25% Class F Range | 25% Class F Allowable Range | 35% Class F Range | 35% Class F Allowable Range | 100% PC Range | 100% PC Allowable Range |
|---|---|---|---|---|---|---|
| 28 | 600 | 643 | **580** | 550 | **1405** | 984 |
| 56 | 500 | 756 | 590 | 674 | **1280** | 1053 |

**Table 14: Compressive Strength Actual and Allowable Ranges (psi) of Ultrafine Fly Ash Mixtures**

| Age (days) | 25% Ultrafine Class F Range | 25% Ultrafine Class F Allowable Range | 35% Ultrafine Class F Range | 35% Ultrafine Class F Allowable Range |
|---|---|---|---|---|
| 28 | 1010 | 1056 | **3800** | 897 |
| 56 | 680 | 1222 | **4280** | 1024 |

## Analysis of Results

Tables 15 and 16 show the results of the statistical tests of the hypotheses of equality of the means of various concrete-properties of BUFFA mixtures and the corresponding means of three or four other mixes respectively. The test statistic used was the t-statistic, with the test performed under the assumption of unequal variances in the respective concrete-property data for each pair of mixes compared. To reach a decision on the acceptance or rejection of the null hypothesis which indicates no difference in compared means of concrete properties, a five percent level of significance was used.

In both tables, for the concrete-properties SR and Compressive Strength, where a BUFFA mix had a mean property-value significantly greater than that of the corresponding mean value for any of the other mixes, “Superior” is shown. Where a BUFFA mix had a mean property-value not significantly different from that of the corresponding mean value for any of the other mixes, “No Difference” is shown, and where a BUFFA mix had a mean property-value that was significantly lower than that of the corresponding mean value for any of the other mixes, “Inferior” is shown. In the case of the Concrete Absorption property, where a BUFFA mix had a mean property-value significantly lower than that of the corresponding mean value for any of the other mixes, “Superior” is shown. Where a BUFFA mix had a mean property-value not significantly different from that of the corresponding mean value for any of the other mixes, “No Difference” is shown, and finally, where a BUFFA mix had a mean property-value that was significantly higher than that of the corresponding mean value for any of the other mixes, “Inferior” is shown.

Table 15. Statistical Comparison of 25% BUFFA Properties with Those of the Comparison Mixtures in the Study

| Property | 100% PC | 25% Class F | 35% Class F |
|---|---|---|---|
| SR @ 7 days | Inferior | No Difference | Superior |
| SR @ 14 days | Inferior | Superior | Superior |
| SR @ 28 days | Superior | Superior | Superior |
| SR @ 42 days | Superior | Superior | Superior |
| SR @ 56 days | Superior | Superior | Superior |
| Compressive Strength @ 28 days | No Difference | Superior | Superior |
| Compressive Strength @ 56 days | Superior | Superior | Superior |
| Absorption after Boiling @ 56 days | Superior (lower) | Superior (lower) | Superior (lower) |

Table 16 Statistical Comparison of 35% BUFFA Properties with Those of other Mixtures in the Study

| Property | 100% PC | 25% Class F | 35% Class F | 25% BUFFA |
|---|---|---|---|---|
| SR @ 7 days | Inferior | Inferior | Inferior | Inferior |
| SR @ 14 days | Inferior | Superior | Superior | No Difference |
| SR @ 28 days | Superior | Superior | Superior | No Difference |
| SR @ 42 days | Superior | Superior | Superior | Superior |
| SR @ 56 days | Superior | Superior | Superior | Superior |
| Compressive Strength @ 28 days | No Difference | Superior | Superior | No Difference |
| Compressive Strength @ 56 days | No Difference | Superior | Superior | No Difference |
| Absorption after Boiling @ 56 days | No Difference | Superior (lower) | Superior (lower) | Inferior (higher) |

Figure 1 shows a graphical comparison of the mean SR results for mixtures used in the study. The superiority of BUFFA mixtures over the F comparison mixtures (beginning at 14 days) and the 100% PC comparison mixture (beginning at 28 days) is evident.

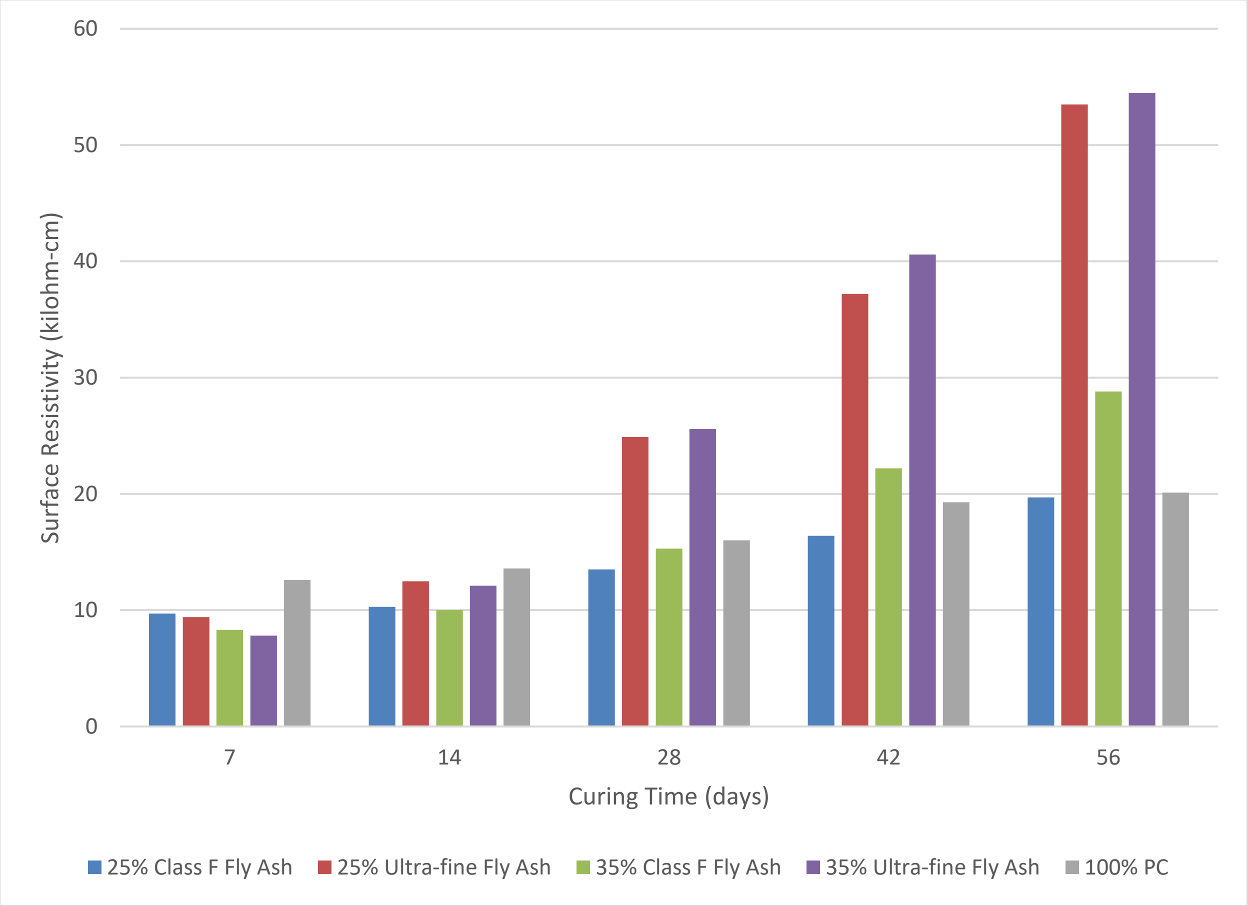

Figure 1. Comparison of SR Results

Similarly, Figure 2 shows a graphical comparison of the mean compressive strength results for mixtures used in the study. The superiority of 25% BUFFA mixture over the F comparison mixtures (beginning at 28 days) and the 100% PC comparison mixture (at 56 days) is evident.

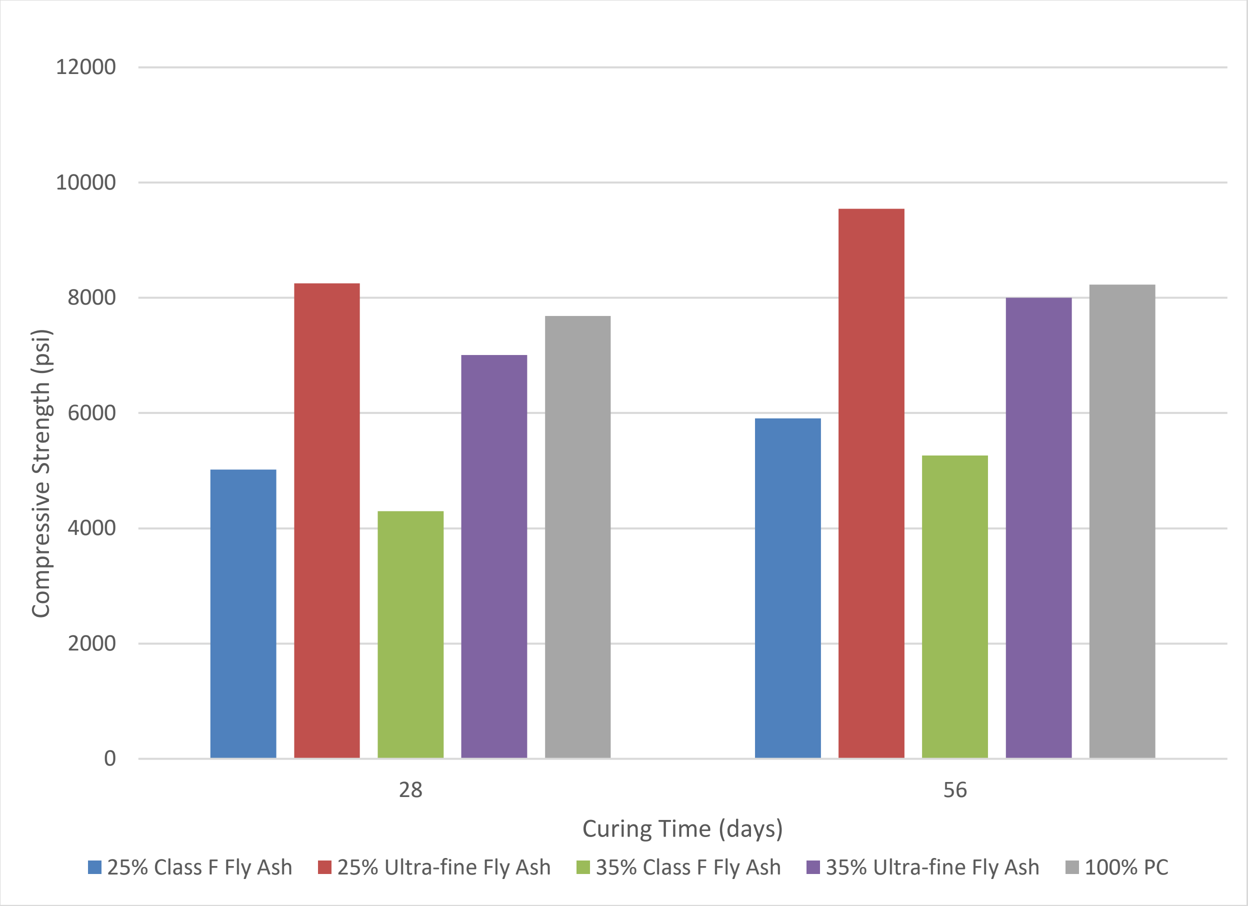

Figure 2. Comparison of Compressive Strength Results

### TDOT 604.03 Specification Compliance

The mean results and all individual batch results of all five mixtures met TDOT Class D compressive strength requirements of 4000-psi at 28-days

.

### Cost

BUFFA costs between 10 and 12 cents per pound. That means a ton of the material costs $200 to $240. A ton of the F costs about $30, while a ton of Type I Portland cement cost about $125. Table 17 shows cementing material cost per cubic yard assuming a cost of $220 a ton (the midpoint) for BUFFA. Although BUFFA is more expensive, the cementing materials cost only increases 19% or 26.6% to change from 100% Portland cement to either 25% or 35% BUFFA.

Table 17 Comparison of Cementing material Costs per Cubic Yard

| Mixture | Cementing Material Costs per Cubic Yard ($) |
|---|---|
| 100% PC | 38.75 |
| 25% Class F | 31.39 |
| 35% Class F | 28.44 |
| 25% Beneficiated Ultrafine Class F | 46.11 |
| 35% Beneficiated Ultrafine Class F | 49.06 |

## Comparison of 25 and 35 Percent BUFFA Mixtures

The small but significant differences in SR at 42 days (means of 40.6 and 37.2) and 56 days (means of 54.5 and 53.5) between 35% and 25% BUFFA do not seem to justify the increase in dosage. Further, the increase in dosage does not significantly increase compressive strength at 28 or 56 days. Finally, and perhaps more importantly, the increased dosage results in a significant increase in percent absorption after boiling (means of 4.34 and 3.55). In summary, there appears to be little to no net benefit in increasing the dosage of BUFFA from 25 to 35%.

## Potential of 25 Percent Beneficiated Ultrafine Class F Fly Ash Mixture

Figures 3 and 4 show as of yet unpublished data from the long term study of 25% F. Figure 3 shows the relationship between SR results and curing time. Similarly, Figure 4 shows the relationship between compressive strength results and curing time. Using the regression equations from these figures, Table 18 shows the property development of the 25% BUFFA compared to the property development of 25% F. The effect of the ultrafine particle size begins to show at 14 days and is very apparent at 28, 42, and 56 days.

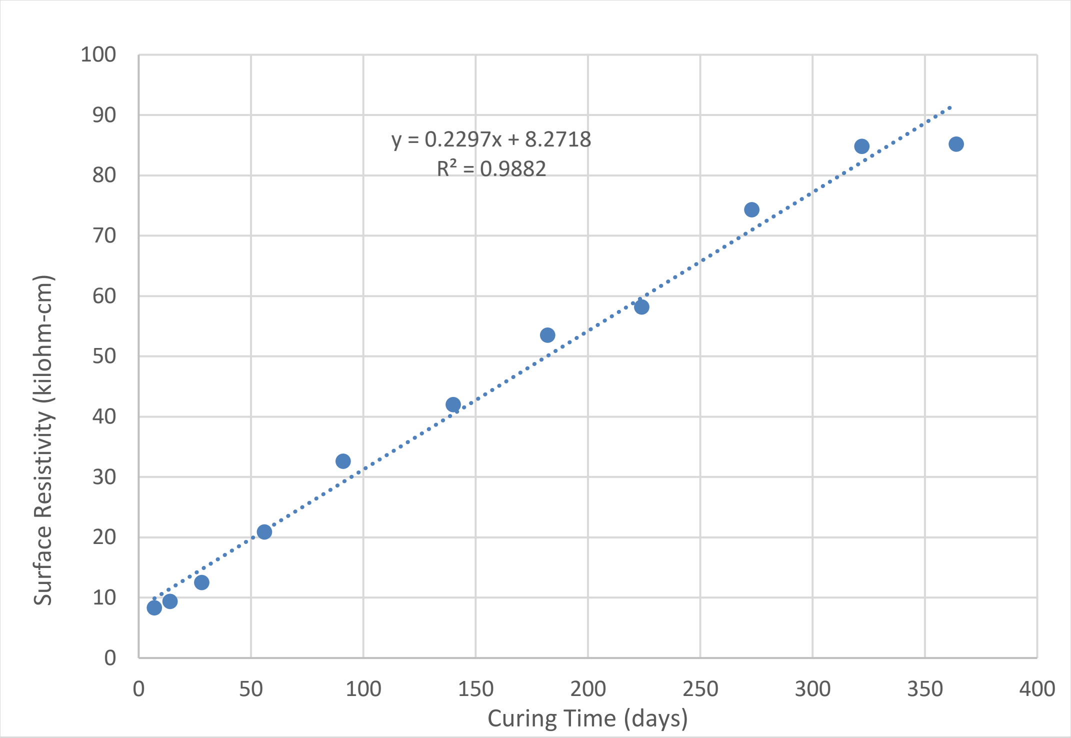

Figure 3. Development of SR of 25% F from a Previous Study

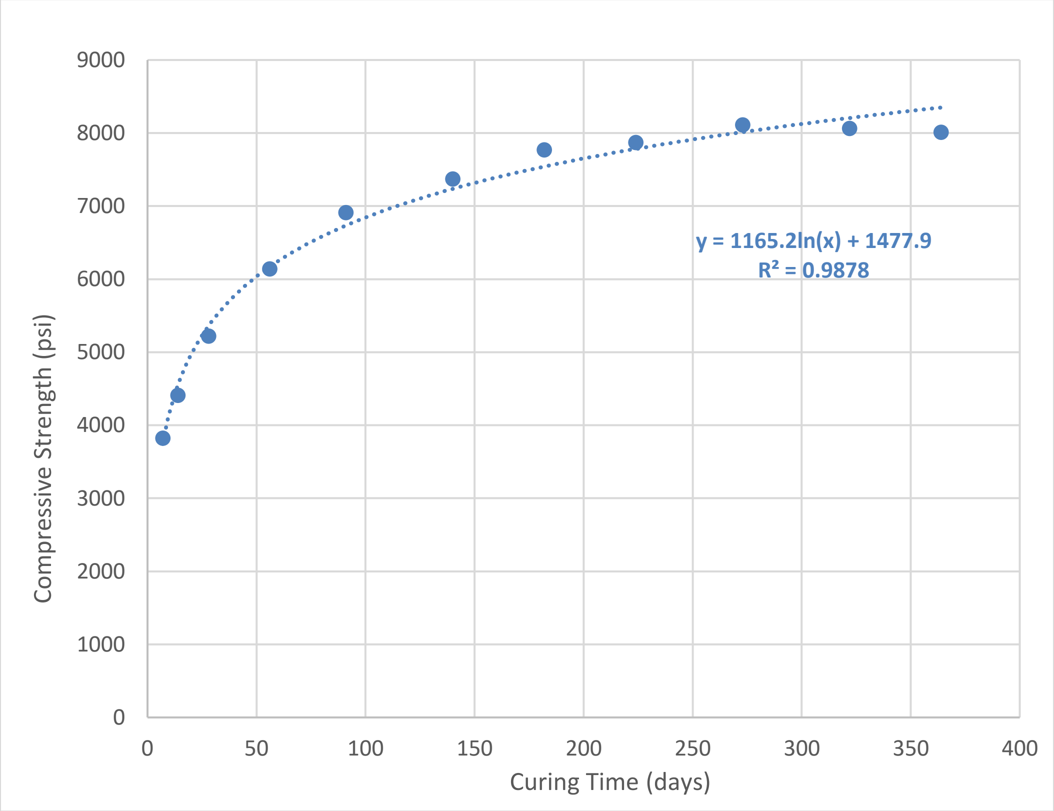

Figure 4. Development of Compressive Strength of 25% F from a Previous Study

Table 18 Comparison of 25% BUFFA with 25% F Property Development

| 25% Beneficiated Ultrafine Class F Fly Ash Age (days) | 25% Beneficiated Ultrafine Class F Fly Ash Mean SR (kilohm-cm) | 25% Beneficiated Ultrafine Class F Fly Ash Mean Compressive Strength (psi) | Age for 25% Class F Fly Ash to Achieve a Similar SR (days) | Age for 25% Class F Fly Ash to Achieve a Similar Compressive Strength (days) |
|---|---|---|---|---|
| 7 | 9.4 | Not Measured | 4.9 | — |
| 14 | 12.5 | Not Measured | 18.4 | — |
| 28 | 24.9 | 8250 | 72.9 | 334.3 |
| 42 | 37.2 | Not Measured | 125.9 | — |
| 56 | 53.5 | 9547 | 196.9 | Out of Data Range |

## CONCLUSIONS AND OBSERVATIONS

Based on the testing of one ultrafine beneficiated fly ash, the following conclusions and significant observations were made:

1. The 25% BUFFA mixture was equal or superior to 100% PC mixture at 14 and 28 days and superior thereafter for all tests (SR, compressive strength, and absorption after boiling).
2. The 35% BUFFA mixture was equal or superior to 100% PC mixture at all ages greater than 14 days for all tests (SR, compressive strength, and absorption after boiling).
3. Both BUFFA (25 and 35%) mixtures were statistically superior to both F (25 and 35%) mixtures in all tests (SR, compressive strength, and absorption after boiling) after 7 days.
4. The slight but significant SR superiority of the 35% BUFFA mixture over the 25% BUFFA mixture at 42 and 56 days does not appear justify the increase in cost and absorption after boiling of the higher dosage of BUFFA.
5. The effect of the ultrafine particle size of the 25% BUFFA mixture begins to show at 14 days. The 25% BUFFA mixture obtains SR results that would take approximately three times the curing time for a 25% F mixture to attain. Similarly, the 25% BUFFA mixture obtains compressive strength results that would take more than five times the curing time for a 25% F mixture to attain.

## FUTURE RESEARCH NEEDS

1. Repeat the research using another BUFFA from a different source or process.
2. Perform field testing trials to evaluate the performance of BUFFA use in a TDOT Class D (bridge deck) mixture.

## ACKNOWLEDGEMENTS

The authors greatly appreciate the donation of the thermally beneficiated ultrafine Class F fly ash by Bill Black of Spherix Mineral Products a Division of SEFA. Special thanks to Mark Casey of SEFA Group for providing Cumberland City Class F Fly Ash to serve as control for the research. Thanks also to the Tennessee Concrete Association for their help in locating and procuring research materials. The authors would also like to thank Denny Lind of BASF for his extensive donations of chemical admixtures to the project.

The authors would like to thank Mark Davis and Perry Melton of Tennessee Technological University for their patience and skill in fabrication, maintenance, and repair of the equipment.

The authors appreciate the financial, administrative, and information technology support provided by the TTU Center for Energy Systems Research (CESR). Thanks also to the TTU Department of Civil and Environmental Engineering (CEE) for financial support.

## REFERENCES

1. Myadaraboina, Himabindu, Mochamad Solikin, Indubhushan Patnaikuni, and Sujeeva Setunge. “Development of High Volume Fly Ash Concrete Using Ultra-fine Fly Ash” *Southern Cross University*, 23rd Australasian Conference on the Mechanics of Structures and Materials, 2014, 65-70. Web.

2. Roychand, R., S. De Silva, and S. Setunge. “Micro and Nano Engineered High Volume Ultrafine Fly Ash Cement Composite with and without Additives.” *International Journal of Concrete Structures and Materials*, vol. 10, no. 1, 2016, pp. 113–124.

3. Hanson, Kayla. “SCMs in Concrete.” *National Precast Concrete Association.*, NPCA, 13 Mar. 2017, Web.

4. Foody, Kevin. “Ultrafine Fly Ash.” *National Precast Concrete Association.*, 22 May 2010, Web.

5. Obla, Karthik H., Russell L. Hill, Michael D. A. Thomas, Surali G. Shashiprakash, and Olga Perebatova. “Properties of Concrete Containing Ultra-Fine Fly Ash.” *ACI Materials Journal*, vol. 100, no. 5, Oct. 2003, pp. 1–8.

6. TDOT Section 604.03. “Classification, Proportioning and Quality Assurance of Concrete.” Tennessee Department of Transportation. Standard Specification for Road and Bridge Construction. 2006. 396-403.

7. Crouch, L. K., Caleb Smith, William C. Scott, James Locum, Daniel Badoe, Heather P. Hall. “Going Past TDOT Specifications to Lower Concrete Permeability.” *Tennessee Concrete Magazine*, 2018, pp. 8–14.

8. ASTM Standard C192, 2016, "Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory," ASTM International, West Conshohocken, PA, 2016, DOI: 10.1520/C0192_C0192M-16A, www.astm.org

9. ASTM Standard C39, 2018, "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens," ASTM International, West Conshohocken, PA, 2018, DOI: 10.1520/C0039_C0039M-18, www.astm.org

10. ASTM Standard C642, 2013, "Standard Test Method for Density, Absorption, and Voids in Hardened Concrete." ASTM International, West Conshohocken, PA, 2013, DOI: 10.1520/C0642-13, www.astm.org

11. AASHTO T 22-10 (2011). "Standard Method of Test for Compressive Strength of Cylindrical Concrete Specimens", American Association of State Highway and Transportation Officials. Standard Specifications for Transportation Materials and Methods of Sampling and Testing Part 2A, 33rd Edition 2013.

12. AASHTO T 358-17. "Standard Method of Test for Surface Resistivity Indication of Concrete's Ability to Resist Chloride Ion Penetration". American Association of State Highway and Transportation Officials. Provisional Standards, 2017 edition, April 2017.

13. ASTM Standard C670, 2015, "Standard Practice for Preparing Precision and Bias Statements for Test Methods for Construction Materials". ASTM International, West Conshohocken, PA, 2015, DOI: 10.1520/C0670-15, www.astm.org