# A High Volume Fly Ash Concrete Mixture for Tennessee Bridge Decks

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## ABSTRACT

High Volume Fly Ash (HVFA) portland cement concrete (PCC) was developed to compete with the Tennessee Department of Transportation (TDOT) Class D PCC. HVFA PCC is PCC with at least 50 percent of portland cement (PC) replaced with Class C fly ash. The current TDOT allowable PC replacement rate is 25 percent for Class C fly ash. A higher PC replacement rate would greatly increase the use of an industrial byproduct thus making more efficient use of natural resources. However, performance and economy cannot be sacrificed for environmental concerns. This paper addresses the performance of HVFA PCC, excluding the evaluation of its environmental benefits.

HVFA PCCs have lower total cementing materials and water contents than TDOT Class D PCC. HVFA PCC is similar in material costs below a placement temperature of 29.4°C (85°F) and cheaper at a placement temperature of 29.4°C (85°F) and above. The results of the research show first that HVFA PCC meets all TDOT 604.03 Class D PCC property requirements. Second, that HVFA PCC is statistically superior to TDOT Class D PCC in compressive strength (at 7 to 182 days), static modulus of elasticity (28 to 182 days), hardened concrete absorption (28 to 182 days) and rapid chloride permeability (at 91 days). Finally, that above 29.4°C (85°F), hot HVFA PCC hardened properties and rapid chloride permeability are statistically superior to hot TDOT Class D PCC (at 7 to 182 days).

## INTRODUCTION

High Volume Fly Ash (HVFA) portland cement concrete (PCC) is concrete with at least 50 percent of portland cement (PC) replaced with Class C fly ash for this study. The current Tennessee Department of Transportation (TDOT) allowable PC replacement rate is 25 percent for Class C. However, 2006 TDOT standard specification section 604.03 currently allows 50 percent substitution of supplementary cementing materials (SCM) and therefore the proposed research is not without precedent. The higher PC replacement rate greatly increases the use of an industrial byproduct making more efficient use of natural resources. Although the relevant literature indicates that even higher replacement rates may even be viable in some applications, the research team assumed that doubling the current TDOT allowable replacement percentage was a prudent first step. HVFA PCC also requires lower cementing materials and water contents than typical TDOT D PCC mixtures.

Protecting and preserving the environment is a TDOT strategic emphasis area and always a desirable goal. However, neither performance nor economy should be sacrificed for environmental concerns. Unpublished previous research at Tennessee Technological University (TTU) has shown that HVFA initial costs are similar to current TDOT Class D PCC at 70°F (21.1°C) and decrease as placement temperature increases since HVFA PCC does not require chemical retarders. The enhanced durability indicated by previous TTU studies of HVFA PCC mixtures will hopefully result in longer PCC service lives. HVFA PCC exhibited decreased permeability, therefore subsequently leading to reduced reinforcement corrosion in chloride environments – further increasing bridge deck service life. The longer PCC service lives will benefit the department in the following ways:

1. A longer PCC service life will reduce cost to the department;
2. A longer PCC service life will reduce the number of incursions for repair and replacement, thus reducing user delays;

3. The department’s public image will be enhanced by both improved environmental stewardship and reduced traffic incursions for repair and replacement.

## RESEARCH OBJECTIVE

The purpose of the research is to determine if HVFA PCC is an effective warm and hot weather replacement for TDOT Class D. The term effective refers to improved durability and greater sustainability while maintaining adequate plastic properties, compressive strength and static modulus of elasticity and similar costs. With higher fly ash substitution rates, HVFA PCC seems best suited for hot weather. 2006 TDOT standard specifications section 604.03 already requires changes to the chemical admixtures used at 29.4°C (85°F) and above. HVFA PCC mixtures will not require chemical retarders at temperatures above. HVFA PCC mixtures can be used at lower temperatures (perhaps down to 21.1°C (70°F)) to achieve the durability and environmental benefits, but the cost of chemical accelerators would result in higher initial costs for PCC. Longer set times and slow strength development render HVFA PCC less desirable below 21.1°C (70°F).

## LITERATURE REVIEW

High volume fly ash (HVFA) concrete is characterized as a concrete that has more fly ash than portland cement by weight in the mix [1, 2]. With the larger than normal replacement of cement with supplementary cementitious material (SCM), HVFA utilizes a much lower water-cement ratio ( $< 0.40$) to achieve adequate early strength requirements [3, 4]. HVFA meets high performance standards due to the spherical shape of fly ash particles which increase workability through the “ball bearing” effect [5]. Utilizing a lower water-cement (w/cm) ratio improves durability aspects of concrete and incorporating HVFA can help enhance positive effects on strength, static modulus, drying shrinkage, and reduced permeability which is favorable to ordinary portland cement concrete [6, 7].

Fly ash is a byproduct that is produced by the combustion of coal in electric or steam generating plants [8, 9]. Fly ash is composed of the same basic components as cement [10]. It contains silica, alumina, calcium, iron, and other trace elements that can negatively affect the properties of concrete such as; sulfur, sodium, potassium, and carbon [8, 10]. American Society for Testing and Materials (ASTM) Specification C 618 has two classifications for fly ash that defines the chemical composition of either a Class C or Class F fly ash that is suitable to be used in concrete [2, 8]. A Class C fly ash is required to have higher calcium oxide contents than a Class F fly ash, which means that the majority of its mineral constituents react in the presence of water allowing for both pozzolanic and cementitious reactions to occur [2, 8, 10].

Setting time, due to low portland cement contents, is slightly prolonged [9]. The reaction process of the fly ash takes longer than that of portland cement [9]. Even with the longer setting time, HVFA concrete does have adequate one day and later age strengths [9, 11]. HVFA mixtures that are designed to meet equivalent early age strength requirements will ultimately surpass ordinary portland cement mix designs [4, 8]. The addition of a pozzolan, like fly ash, binds with the leftover available lime and alkali in the concrete to form additional calcium silicate hydrate (C-S-H), which is essential to reduce permeability and the development of strength in the cement paste [8, 10].

The process primarily by which HVFA improves durability is through a reduction in the size of the pore structure, which in turn causes a reduction in the permeability of the concrete [8, 10, 14, 16, 17]. When a concrete fails in durability, the primary responsibility for this lies with the movement of fluids through the concrete [10]. Fly ash is not as dense as portland cement and requires a higher volume per unit mass; this increase of the overall amount of hydrated cementitious materials will lead to a decrease in permeability over time [10, 12].

ASTM C 1202 is a test method used to evaluate materials used in concrete to determine their chloride ion penetration resistance [13]. In general, ASTM C 1202 is used as an indicator to maintain quality control over construction practices [15]. Concrete surfaces that are exposed to the weather are subject to attack by deleterious agents [18]. It is the presence of carbon dioxide, moisture, and chlorides that can cause rapid deterioration in concrete [18].

HVFA concrete has shown better characteristics that resist the penetration of chloride ions than that of concrete with only ordinary portland cement [9, 19, 20, 21]. With a significant reduction of chloride penetration, HVFA PCC can significantly reduce the risk of corrosion on embedded reinforcing steel to slight or even to undetectable levels [20, 22]. The charge passed through a given specimen incorporating SCMs such as fly ash, silica fume, and ground blast furnace slag may be lower due to a reduction in the alkalinity of the pore structure solution rather than due to a lower permeability [23].

ASTM C 642, otherwise known as the boil test [24, 15], is a test method used to determine durability by measuring the density, percent absorption, and the hardened percent voids in concrete [24, 25]. A portion of the test includes drying the specimen to a constant mass and it is likely that this induces cracking, which leads to an increase in absorption percentages [14]. However, the boil test is considered to be a more consistent test method than the rapid chloride permeability test (ASTM C 1202) [13].

## MATERIALS

A TDOT approved limestone coarse aggregate meeting ASTM C 33 [26] No. 57 gradation specification was obtained from a local quarry. Similarly, a TDOT approved river sand fine aggregate was obtained from a local supplier. Sieve analysis on both coarse and fine aggregates met ASTM C 136 precision criteria [27]. The coarse aggregate average specific gravity and absorption were determined as per ASTM C 127 [28]. Similarly, the fine aggregate average specific gravity and absorption were determined in accordance with ASTM C 128 [29].

Type I portland cement meeting ASTM C 150 [30] was obtained from a regional supplier. A Class C fly ash that met ASTM C 618 [31] was obtained from a regional supplier for use in the HVFA concrete. Results of tests performed by the supplier as well as applicable ASTM C 618 [31] and AASHTO M 295 [32] criteria are shown in Table 1. Similarly, a Class F fly ash that met ASTM C 618 was obtained from a regional supplier for use in the TDOT Class D concrete. Results of tests performed by the supplier as well as applicable ASTM C 618 [31] and AASHTO M 295 [32] criteria are shown in Table 2. Chemical admixtures [33] were provided by the local representative of an international chemical producer. Local tap water was used in all mixtures.

**TABLE 1 Fly Ash Test Results for Class C Fly Ash used in HVFA**

| | **Headwaters Class C Fly Ash** | **ASTM C618-08 Class C Requirement** | **AASHTO M295-07 Class C Requirement** |
|---|---|---|---|
| Silicon Dioxide (%) | 38.93 | … | … |
| Aluminum Oxide (%) | 19.57 | … | … |
| Iron Oxide (%) | 6.07 | … | … |
| $SiO_2$ +$Al_2O_3$+ $Fe_2O_3$ (%) | 64.57 | 50 min. | 50 min. |
| Calcium Oxide (%) | 31.68 | … | … |
| Sulfur Trioxide (%) | 1.80 | 5 max. | 5 max. |
| Loss on Ignition (%) | 0.40 | 6 max. | 5 max. |
| Moisture Content (%) | 0.06 | 3 max. | 3 max. |
| Alkalis as $Na_2O$ (%) | 1.4 | … | 1.5 max. |
| Fineness, % Retained on #325 | 16.22 | 34 max | 34 max |
| Strength Activity 7-day % of control* | 93 | 75 min. | 75 min. |
| Strength Activity 28-day % of control* | 102 | 75 min. | 75 min. |
| Water requirement, % of control | 93 | 105 max. | 105 max. |
| Autoclave soundness % | 0.05 | 0.8 max | 0.8 max |
| True Particle Density | 2.49 | … | … |

***Data not applicable***

**TABLE 2 Fly Ash Test Results for Class F Fly Ash used in the TDOT Class D PCC**

| | **Class F Fly Ash** | **ASTM C618-08 Class F Requirement** | **AASHTO M295-07 Class F Requirement** |
|---|---|---|---|
| Silicon Dioxide (%) | 46.49 | … | … |
| Aluminum Oxide (%) | 19.45 | … | … |
| Iron Oxide (%) | 17.99 | … | … |
| $SiO_2$ +$Al_2O_3$+ $Fe_2O_3$ (%) | 83.93 | 70 min. | 70 min. |
| Calcium Oxide (%) | 7.56 | … | … |
| Sulfur Trioxide (%) | 2.33 | 5 max. | 5 max. |
| Loss on Ignition (%) | 1.13 | 6 max. | 5 max. |
| Moisture Content (%) | 0.08 | 3 max. | 3 max. |
| Alkalis as $Na_2O$ (%) | 0.77 | … | 1.5 max. |
| Fineness, % Retained #325 | 15.8 | 34 max | 34 max |
| Strength Activity 7-day % control* | 81 | 75 min. | 75 min. |
| Strength Activity 28-day % of control* | 85 | 75 min. | 75 min. |
| Water requirement, % control | 98 | 105 max. | 105 max. |
| Autoclave soundness % | 0.00 | 0.8 max | 0.8 max |

| | | | |
|---|---|---|---|
| True Particle Density | 2.54 | … | … |

## RESEARCH METHODOLOGY

Table 3 shows a typical TDOT Class D and new HVFA PCC mixture designs for both above and below 29.4°C (85°F) that were used in the study. All mixture designs were obtained by trial batching. Table 4 shows comparisons of TDOT Class D and HVFA PCC attributes with current TDOT 604.03 Class D [34] requirements.

**TABLE 3 TDOT Class D and HVFA Mixture Designs**

| **Component** | **TDOT Class D** | **TDOT Class D Hot** | **HVFA PCC** | **HVFA PCC Hot** |
|---|---|---|---|---|
| Type I PC, kg/ $m^3$ (lbs/CY) | 294 (496) | 294 (496) | 164 (276) | 164 (276) |
| Class F Fly Ash, kg/ $m^3$ (lbs/CY) | 74 (124) | 74 (124) | 0 | 0 |
| Class C Fly Ash, kg/ $m^3$ (lbs/CY) | 0 | 0 | 164 (277) | 164 (277) |
| No. 57 Limestone SSD, kg/ $m^3$ (lbs/CY) | 1129 (1904) | 1129 (1904) | 1140 (1922) | 1140 (1922) |
| River Sand SSD, kg/ $m^3$ (lbs/CY) | 676 (1140) | 676 (1140) | 755 (1273) | 755 (1273) |
| Water, kg/ $m^3$ (lbs/CY) | 138(232.5) | 138 (232.5) | 111 (187) | 111 (187) |
| Design Air Voids (%) | 6 | 6 | 6 | 6 |
| Air Entrainer, mL/$m^3$ (oz/cwt) (oz/CY) | 77.3 (0.32) (2) | 85 (0.35) (2.2) | 57.9 (0.28)(1.5) | 46.4 (0.22) (1.2) |
| Mid-range Water Reducer, mL/$m^3$ (oz/cwt) (oz/CY) | 718.9 (3) (18.6) | 0 | 0 | 0 |
| High range Water Reducer, g/$m^3$ (oz/cwt) (oz/CY) | 479.3 (2) (12.4) | 479.3 (2) (12.4) | 749.9 (3.5)(19.4) | 908.4 (4.25)(23.5) |
| Non-chloride Accelerator, mL/$m^3$ (oz/cwt) (oz/CY) | 0 | 0 | 3420.9 (16) (88.5) | 0 |
| Retarder, mL/$m^3$ (oz/cwt)(oz/CY) | 0 | 359.5 (1.5)(9.3) | 0 | 0 |

NOTE: 0.593 kg/$m^3$ = 1 lb/CY; 38.654 mL/$m^3$ = 1 oz/CY

**TABLE 4 Comparison of Mixture Design Attributes and TDOT Class D PCC Requirements**

| **Quantity / Ratio / Percentage** | **TDOT 604.03 Class D PCC Requirements** | **TDOT Class D and Class D Hot** | **HVFA and HVFA Hot** |
|---|---|---|---|
| Cementing materials content | 367.7 kg/$m^3$ minimum (620 lbs/CY) | 367.7 kg/$m^3$ (620 lbs/CY) | 328 kg/$m^3$ (553 lbs/CY) |
| Water-cementing-materials ratio | 0.40 maximum | 0.375 | 0.338 |
| Percent fine aggregate by total aggregate volume | 44 maximum | 38 | 40.4 |
| Percent fly ash substitution (by weight) for portland cement | 20 maximum for Class F fly ash 25 maximum for Class C fly ash | 20 Class F fly ash | 50 Class C fly ash |

NOTE: 0.593 kg/m$^3$ = 1 lb/CY

Ten batches of each normal temperature mixture and three batches of each hot mixture were produced and tested as per Table 5. All batches were mixed in an electric rotary mixer as per AASHTO R39 [35]. Slump testing was performed on each batch as per AASHTO T119 [36]. Unit weight and gravimetric air content testing was performed on each batch as per AASHTO T121 [37]. Air content of each batch was also determined as per AAASHTO T152 [38, 39] with the exception that no aggregate correction factor was used. Compressive strength cylinders were cast as per AASHTO R39 [35] and tested as per AASHTO T22 [40] with ASTM C 1231 [41] neoprene caps. Fifty durometer neoprene pads were used for all cylinders at ages of one and seven days. Seventy durometer pads were used at all other testing ages. Static modulus of elasticity testing was conducted as per ASTM C 469 [42] with the exception that all cylinders were capped with seventy durometer neoprene pads in steel retainers [41].

**TABLE 5 Testing Protocols**

| | |
|---|---|
| Size of each batch (cubic meter) (cubic feet) | 0.05 (1.73) |
| Slump (AASHTO T 119) | 1 per batch |
| Unit Weight and Gravimetric Air Content (AASHTO T 121) | 1 per batch |
| Air Content by Pressure Method (AASHTO T 152) | 1 per batch |
| Compressive Strength * @ 1, 7, 28, 56, 91, and 182 days (AASHTO T 22) | 3 4x8 cylinders per date per batch |
| Static Modulus of Elasticity @ 28, 56, 91, and 182 days (ASTM C 469) | 2 of the 3 4x8 compressive strength cylinders per date per batch |
| Rapid Chloride Permeability @ 91 days (AASHTO T 277) | 2 samples cut from separate 4x8 cylinders per batch |
| Absorption and Voids in Hardened Concrete @ 28, 56, 91, and 182 days (ASTM C 642) | 2 3x6 cylinders per date per batch |

NOTE: 0.028 m$^3$ = 1 ft$^3$

Material cost is always an important concern; the cost assumptions obtained in an informal, unpublished survey of unidentified regional suppliers used for the TDOT HVFA research are shown in Table 6. Applying the cost assumptions in Table 6 to the mixture designs in Table 3 produces the material costs per cubic yard shown in Table 7.

**TABLE 6 Material Cost Assumptions**

| **Component** | **Assumed Cost Delivered to Ready Mix Producer** |
|---|---|
| Type I Portland Cement ($/Mg) ($/ton) | 121.28 (110.00) |
| Class F Fly Ash ($/Mg) ($/ton) | 55.13 (50.00) |
| Class C Fly Ash ($/Mg) ($/ton) | 55.13 (50.00) |
| No. 57 Limestone ($/Mg) ($/ton) | 19.85 (18.00) |
| River Sand ($/Mg) ($/ton) | 16.54 (15.00) |
| Air Entrainer ($/L) ($/gallon) | 1.19 (4.50) |
| Mid-range Water Reducer ($/L) ($/gallon) | 2.25 (8.50) |
| Accelerator ($/L) ($/gallon) | 2.38 (9.00) |
| Retarder ($/L) ($/gallon) | 1.98 (7.50) |

| | |
|---|---|
| High-range Water Reducer ($/L) ($/gallon) | 3.17 (12.00) |

NOTE: 0.907 Mg = 1 ton=; 3.785 L = 1 gallon

**TABLE 7 Material Cost per Cubic Yard**

| Component | TDOT Class D | HVFA PCC | TDOT Class D Hot | HVFA PCC Hot |
|---|---|---|---|---|
| Type I Portland Cement ($/m$^3$) ($/CY) | 35.66 (27.28) | 19.84 (15.18) | 35.66 (27.28) | 19.84 (15.18) |
| Class F Fly Ash ($/m$^3$) ($/CY) | 4.05 (3.10) | 0 | 4.05 (3.10) | 0 |
| Class C Fly Ash ($/m$^3$) ($/CY) | 0 | 9.06 (6.93) | 0 | 9.06 (6.93) |
| No. 57 Limestone ($/m$^3$) ($/CY) | 22.41 (17.14) | 22.61 (17.30) | 22.41 (17.14) | 22.61 (17.30) |
| River Sand ($/m$^3$) ($/CY) | 11.18 (8.55) | 12.48 (9.55) | 11.18 (8.55) | 12.48 (9.55) |
| Air Entrainer ($/m$^3$) ($/CY) | 0.09 (0.07) | 0.08 (0.06) | 0.10 (0.08) | 0.07 (0.05) |
| Mid-range Water Reducer ($/m$^3$) ($/CY) | 1.62 (1.24) | 3.05 (2.33) | 0 | 0 |
| High range Water Reducer ($/m$^3$) ($/CY) | 1.53 (1.17) | 2.38 (1.82) | 1.53 (1.17) | 2.89 (2.21) |
| Accelerator ($/m$^3$) ($/CY) | 0 | 8.14 (6.23) | 0 | 0 |
| Retarder ($/m$^3$) ($/CY) | 0 | 0 | 0.72 (0.55) | 0 |
| Estimated Total Material Cost (excluding water) in $/m$^3$ ($/CY ) | 76.54 (58.55) | 74.60 (57.07) | 75.65 (57.87) | 66.95 (51.22) |

NOTE: 0.765 m$^3$ = 1 CY

## RESULTS

Table 8 shows the results of plastic property tests on TDOT Class D and HVFA PCC for mixtures above and below 29.4°C (85°F).

**TABLE 8 TDOT Class D and HVFA Plastic Properties and TDOT Class D Requirements**

| Property | TDOT 604.03 Class D PCC Requirement | TDOT Class D Mean Value of 10 batches | HVFA PCC Mean Value of 10 batches | TDOT Class D Hot Mean Value of 3 batches | HVFA PCC Hot Mean Value of 3 batches |
|---|---|---|---|---|---|
| Slump after HRWR (mm) (inches) | 203.2 maximum (8) | 174 (6.85) | 144.8 (5.70) | 175.3 (6.90) | 134.6 (5.30) |
| Air content by pressure method (%) | 5 to 8.5 | 6.15 | 5.82 | 6.10 | 6.70 |
| Air content gravimetric (%) | None | 6.09 | 5.73 | 6.20 | 6.80 |
| Unit Weight (kg/m$^3$) (pcf) | None | 2338.1 (144.2) | 2370.5 (146.2) | 2336.4 (144.1) | 2344.5 (144.6) |

| | | | | | |
|---|---|---|---|---|---|
| Temperature (°C) (°F) | Normal < 85<br>Hot ≥ 85 | 22.8 (73.0) | 23.1 (73.5) | 33.5 (92.3) | 29.6 (85.3) |

NOTE: 25.4 mm = 1 inch; 16.214 kg/m$^3$ = 1 lb/CF; °C = (°F – 32)/1.8

Figure 1 shows a graphical comparison of compressive strength development of HVFA and TDOT Class D PCC. The figure shows that the compressive strength of all mixtures was greater than 5167.5-kPA (750-psi) at one day, as recommended for form wrecking without excessive damage [3]. Although HVFA PCC required a chemical accelerator to achieve the compressive strength in the 21.1˚C (70˚F) range, as the temperature increased above 29.4°C (85°F) HVFA PCC mixtures no longer required the chemical accelerator, and had no need of a chemical retarder to maintain plasticity for placement and finishing operations. Figure 2 shows a graphical comparison of static modulus of elasticity development of HVFA and TDOT Class D PCC. Durability is the key to a long service life for PCC. Reducing the amount of water absorbed should reduce freeze-thaw damage to PCC mixtures. The Portland Cement Association (PCA) indicates that the upper limit of water absorption after boiling for high performance concrete (HPC) is five percent [4]. Figure 3 shows the relationship between concrete absorption after boiling and curing time for HVFA and TDOT Class D PCC as well as the PCA HPC upper limit. For TDOT Class D, TDOT Class D Hot, and HVFA concrete absorption declined with curing time. However, for HVFA Hot, it increased.

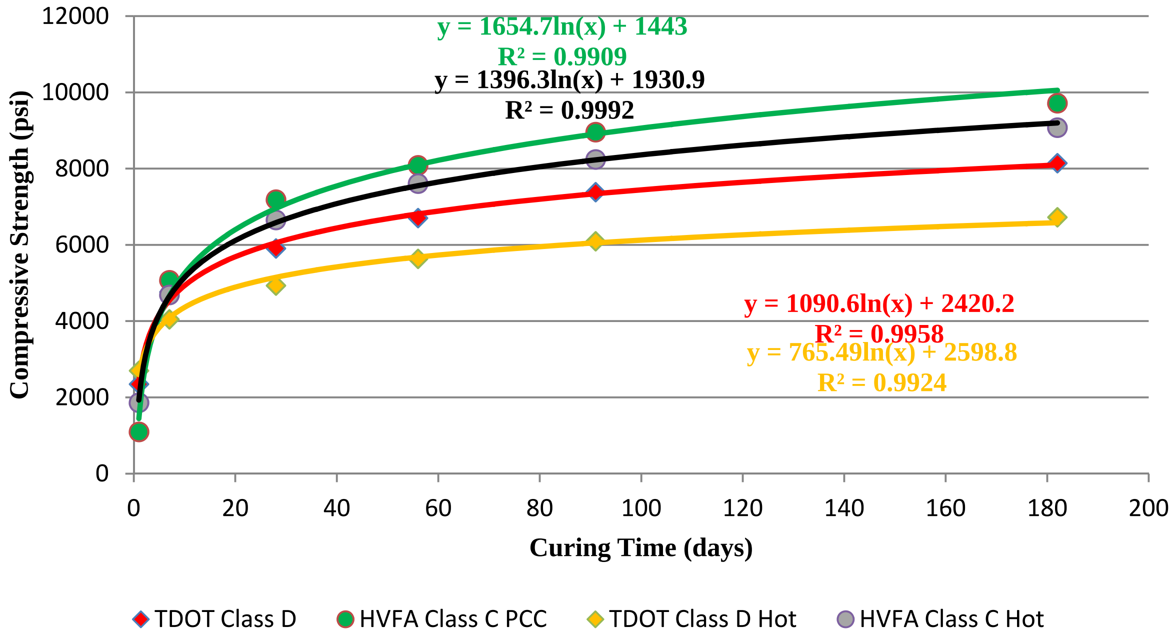

**FIGURE 1 Compressive Strength Development of HVFA and TDOT Class D Mixtures**

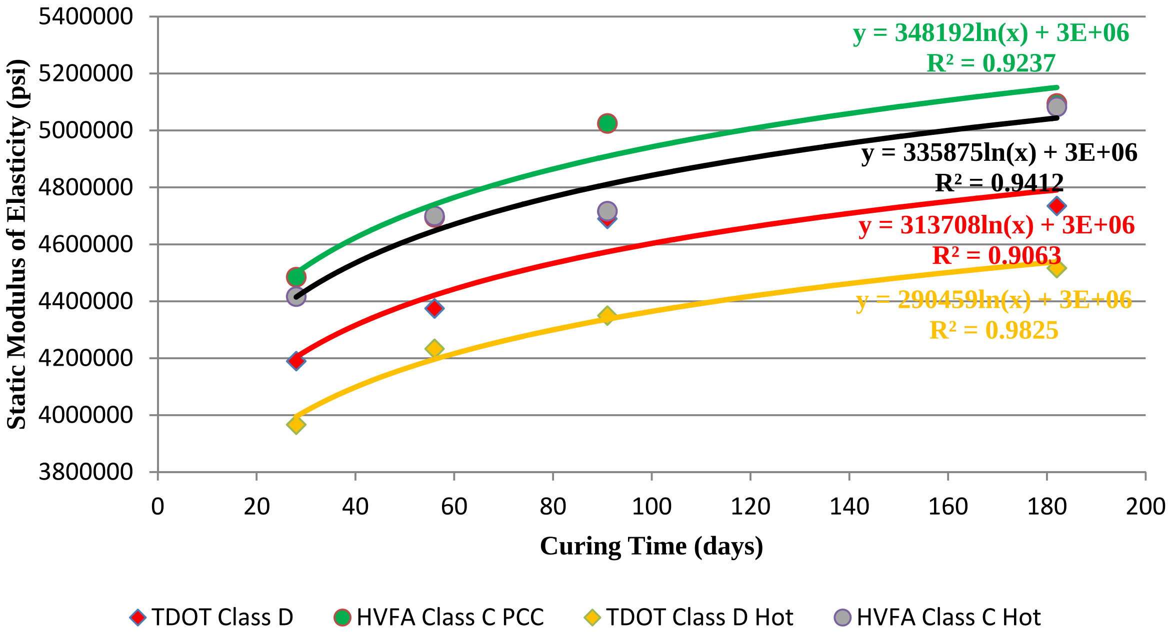

FIGURE 2 Static Modulus of Elasticity Development of HVFA and TDOT Class D Mixtures

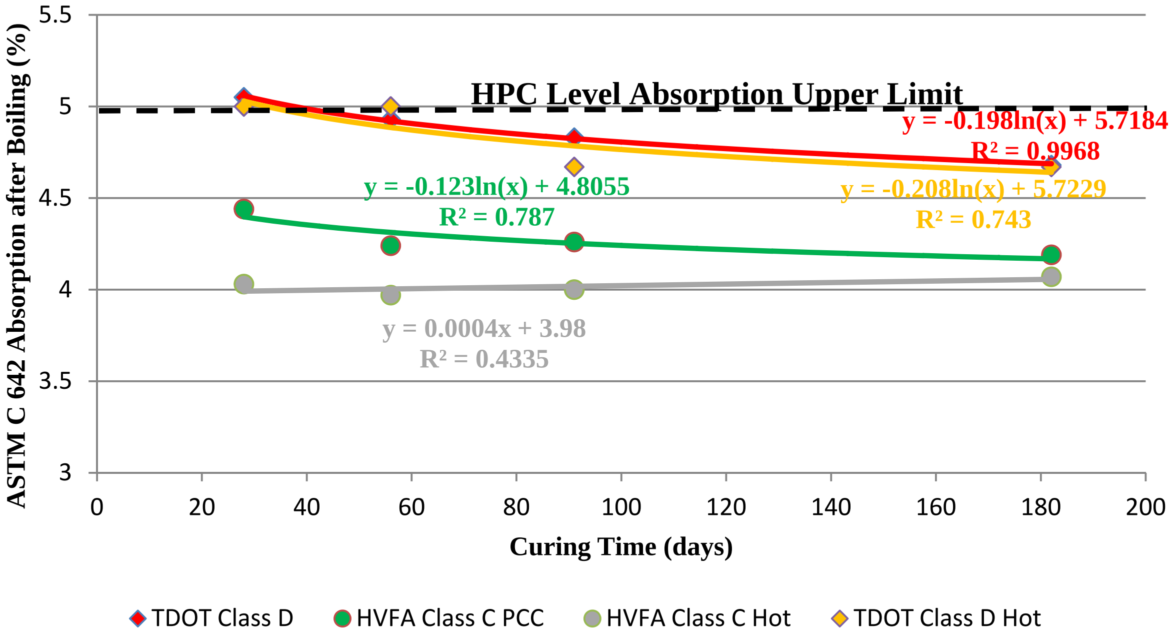

FIGURE 3 Development of Concrete Absorption after Boiling for HVFA and TDOT Class D Mixtures

## ANALYSIS

### Plastic Properties

Referring to Table 8, the research team wanted a fair contest and attempted to produce mixtures with very similar plastic properties. For the mixtures below 29.4°C (85°F), the HVFA PCC has statistically significantly higher unit weight and significantly lower slump than TDOT Class D. Both pressure meter and gravimetric air contents were not significantly different. For the mixtures above 29.4°C (85°F), the HVFA PCC has statistically significantly lower slump than TDOT Class D PCC. Other properties measured were not significantly different.

## Hardened Properties

Table 9 shows the relative mean values of properties of HVFA to and TDOT Class D PCC. Thus, the number in each cell shows the ratio of the mean property value obtained for HVFA PCC to the mean property value obtained for TDOT Class D PCC multiplied by a hundred. A cell shaded in yellow indicates that at a specified age, TDOT Class D PCC was significantly different and superior to HVFA PCC. A cell shaded in green indicates that at a specified age, HVFA PCC was significantly different and superior to TDOT Class D PCC. It is important to note that sometimes "greater" is superior and sometimes "greater" is inferior depending on the property being measured. Table 10 is a similar comparison of hot HVFA and hot TDOT Class D PCC.

**TABLE 9 Comparison of Mean Results (HVFA / TDOT Class D) * 100**

| Age | Mean Compressive Strength | Mean Static Modulus of Elasticity | Mean Concrete Absorption after Boiling | Rapid Chloride Permeability |
|---|---|---|---|---|
| 1 | 47 | | | |
| 7 | 107 | | | |
| 28 | 122 | 107 | 88 | |
| 56 | 121 | 107 | 86 | |
| 91 | 121 | 107 | 88 | 73 |
| 182 | 119 | 108 | 90 | |

**TABLE 10 Comparison of Mean Results (Hot HVFA / Hot TDOT Class D) * 100**

| Age | Mean Compressive Strength | Mean Static Modulus of Elasticity | Mean Concrete Absorption after Boiling | Rapid Chloride Permeability |
|---|---|---|---|---|
| 1 | 69 | | | |
| 7 | 116 | | | |
| 28 | 135 | 111 | 81 | |
| 56 | 135 | 111 | 79 | |
| 91 | 135 | 108 | 86 | 48 |
| 182 | 135 | 113 | 87 | |

## Summary

Table 11 shows a summary of HVFA and TDOT Class D comparisons with the mix that emerged to be superior indicated in the row of each property.

**TABLE 11 Final Summary Comparison of HVFA & TDOT Class D**

| Property or Attribute | < 29.4°C (85°F) | ≥ 29.4°C (85°F) |
|---|---|---|
| Compressive Strength | HVFA | HVFA Hot |
| Static Modulus of Elasticity | HVFA | HVFA Hot |
| Absorption after Boiling | HVFA | HVFA Hot |
| Rapid Chloride Permeability | HVFA | HVFA Hot |
| Material Cost | No Clear Winner | HVFA Hot |
| Overall Superiority | HVFA | HVFA Hot |

## CONCLUSIONS

Based on the testing and analysis done, the following conclusions can be drawn:

1. HVFA PCC has a lower cementing materials content and water content and is similar in material cost compared to TDOT Class D PCC.
2. HVFA PCC met all TDOT 604.03 Class D PCC property requirements.
3. HVFA PCC is statistically superior to TDOT Class D PCC in compressive strength (at ages of 7 to 182 days), static modulus of elasticity, hardened concrete absorption and rapid chloride permeability at 91 days.
4. Hot (at or above 29.4°C (85°F)) HVFA PCC is statistically superior to hot TDOT Class D PCC in compressive strength (at ages of 7 to 182 days), static modulus of elasticity, hardened concrete absorption, material cost and rapid chloride permeability at 91 days.

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## DISCLAIMER

Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the Tennessee Department of Transportation or the Federal Highway Administration.

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