High Volume Fly Ash Concrete

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ABSTRACT

The use of concrete containing high volumes of fly ash (HVFA) has recently gained popularity as a resource-efficient, durable, and sustainable option for a variety of concrete applications. In this study, two HVFA mixtures, one containing Class C fly ash the other Class F fly ash, were compared with TDOT Class A general use mixtures using the same class of fly ash at a smaller replacement percentage. The HVFA mixtures reached similar to higher long term compressive strengths, due to the pozzolanic properties of the fly ash and the lower w/cm ratios. Also, the water permeable void contents and absorptions were lower for the HVFA mixtures at all ages, indicating that the durability of the HVFA is much better than that of the TDOT mixtures. The setting times for the HVFA mixtures were approximately two hours longer than those of the TDOT Class A mixtures at laboratory conditions (72^{o}F (22 ^{o}C)). Also, the costs of the HVFA mixtures were slightly higher. However, for field placements at warmer temperatures, the time of set and cost of the HVFA mixtures would decrease while the cost of the TDOT Class A mixtures would increase, due to the need for chemical admixtures. Overall, the use of HVFA mixtures would be ideal for warm weather placements; when compared with the TDOT Class A mixtures, the HVFA mixtures exhibit comparable costs, increased compressive strengths, and enhanced durability properties.

INTRODUCTION AND LITERATURE REVIEW

The use of high-volume fly ash (HVFA) concretes has recently gained popularity as a resource-efficient, durable, cost-effective, sustainable option for many types of portland cement concrete (PCC) applications. Any concrete containing a fly ash content that is greater than 50 percent by mass of the total cementitious materials is considered HVFA PCC.[1] The production of portland cement is not only costly and energy-intensive, but it also produces large amounts of carbon dioxide. With large quantities of fly ash available around the world at low costs, the use of HVFA seems to offer the best short term solution to rising cement demands.[2,3] In 2003, 70 million tons of fly ash were produced in the United States, and only 38 percent were recycled into useful applications.[25] Also, LEED points, which are points awarded based on environmental performance, are available for any mixture that replaces up to 40 percent of the cement in concrete with fly ash.[4]

Fly ash is commonly used in concrete in replacements ranging from 0 to 30 percent by mass of the total cementitious material. However, research has shown that using a 50 percent or greater replacement of fly ash can have a wide range of benefits. Fly ash is a by-product and therefore less expensive than portland cement; it is also known to improve workability and reduce internal temperatures.[5] The improved workability is a result of the "ball bearing" action of the spherical fly ash particles. Fly ash improves the grading in the mixture by smoothing out the fine particle size distribution.[6] Also, fly ash has been shown to reduce the amount of water required.[7] Fly ash from modern power plants used in large volumes can reduce the water content by 15 to 20 percent.[1] However, research has shown that the properties of HVFA concrete are strongly dependent on the characteristics of the cement and fly ash used.[8]

While HVFA has a wide range of benefits, possibly the most attractive property of all is durability. The improvements in durability are a result of the reduction in calcium hydroxide, which is the most soluble of the hydration products, and from changes in the pore structure.[5] Research has shown that HVFA concrete is more crack resistant than conventional PCC, due to the decreased shrinkage. This is a result of the decreased mixing water, decreased water to cementitious materials (w/cm) ratio, and also a decrease in the total volume of cement paste that is required in HVFA. Also, the decreased heat of hydration at early ages reduces potential for thermal shrinkage and cracking.[1] One indicator of the durability of concrete is the permeability; the more water that can penetrate the concrete, the more potential for freeze/thaw damage. Also, the rate of water absorption by capillary suction has been shown to be a good measure of the potential durability of concrete.[1] Research has shown that the water permeability of HVFA is lower than that of normal PCC.[8,9]

While HVFA concretes do have a wide range of benefits, they also have a few drawbacks. Generally, the strength development of concretes with high volumes of fly ash is slower than concrete without fly ash.[1] It has been suggested that a compressive strength of 750 psi (5.2 MPa) at one day, which HVFA has been found to obtain, is adequate for formwork removal when no early loads are applied.[10] Also, even though the short term strengths are usually lower than those of normal concrete, the pozzolanic properties of fly ash result in long-term strengths comparable to or better than conventional PCC. The rate of increase in compressive strength is dependent on the level of cement replacement, type of fly ash, and age of the concrete. It has been observed that the rate of early-age strength gain of Class C is higher than that of Class F fly ash. However, the long-term pozzolanic strength contribution for Class F fly ash is greater than Class C, resulting in higher long-term compressive strengths.[3] Overall, higher long term strengths have been observed for HVFA due to the dense microstructure and smaller size of capillary pores, which result from the pozzolanic reactions.[11] Adequate curing is essential to ensure that later-age strength development will occur.[8]

The rate of strength variation is also dependent upon the consistency and presence of different chemical admixtures.[6] Many researchers agree that the use of a superplasticizer or water reducer is necessary in HVFA to ensure workability, especially when low w/cm ratios are used.[1,8] In cases where frost resistance is necessary, the use of an air-entraining admixture is required.[1] However, special caution must be taken when using air-entrainers and large amounts of fly ash. Fly ashes having very high carbon content require much higher dosages of air-entraining admixtures.[8,12] Also, the effectiveness of air-entrainer decreases with an increase in the fly ash to cementitious materials ratio.[6]

As previously stated, the rate of early strength development is slower for HVFA; therefore, the setting time for HVFA concrete, in general, is longer than conventional concrete using PC alone.[1] The reaction between cement and water is the primary cause of the setting of concrete.[5] Therefore, as the cement content decreases, it makes sense that the time of set would increase. The increased setting time occurs for both fly ash classes and at all levels of fly ash substitution.[7] The delay in setting time can be up to two hours.[1] Initially, it would be expected that Class C fly ash would have less of a reduction in time of set than Class F fly ash, due to the cementitious and pozzolanic properties of C ash. However, Ravina and Mehta found that Class C fly ash has a greater delay in setting time than Class F fly ash, due to its higher sulfate contents.[7] While it is apparent that the setting time is longer for HVFA, results have shown that the amount of retardation is acceptable.[8]

SCOPE

In this study, two different HVFA mixtures were studied, one containing Class C fly ash and the other Class F fly ash. The HVFA mixtures were each compared with a Tennessee Department of Transportation (TDOT) Class A general use mixture containing the same class of fly ash at a much lower replacement percentage. The compressive strength, water absorption, water permeable void content, setting time, and cost were compared. The goal was to produce an HVFA mixture with properties that were comparable to or better than a TDOT Class A mixture.

MATERIALS

The material proportions for the four mixtures are shown in Table 1. The fine aggregate used for all mixtures was Ohio River sand, while the coarse aggregate was a #57 limestone obtained from a local quarry. Both aggregates met the requirements of ASTM C 33.[13] Type 1 portland cement, in accordance with ASTM C 150, was obtained from a local PCC producer from bulk storage.[14] Local tap water was used for all mixtures. Both the Class C and Class F fly ashes were obtained from regional fly ash producers and met the requirements of ASTM C 618.[15] One type of Class F fly ash was used in both mixtures, while a different type of Class C fly ash was used in each of the C Ash mixtures; the chemical analyses are shown in Table 2.

Table 1. Mixture Proportions

Component	**C Ash**		**F Ash**	
	TDOT A	***HVFA***	***TDOT A***	***HVFA***
Coarse aggregate, lb/yd^3 (kg/m^3)	1835 (1089)	1910 (1133)	1790 (1062)	1836 (1089)
Fine Aggregate, lb/yd^3 (kg/m^3)	1259 (747)	1273 (755)	1221 (724)	1224 (726)
Type 1 PC, lb/yd^3 (kg/m^3)	423 (251)	276 (164)	451 (268)	299 (177)
Class C Fly Ash, lb/yd^3 (kg/m^3)	141 (84)	277 (164)	0	0
Class F Fly Ash, lb/yd^3 (kg/m^3)	0	0	113 (67)	300 (178)
Total Cementious, lb/yd^3 (kg/m^3)	564 (335)	553 (328)	564 (335)	599 (355)
Fly ash, % of Total Cementious	25.0	50.1	20.0	50.1
Water, lb/yd^3 (kg/m^3)	225.5 (134)	187 (111)	254 (151)	209 (124)
w/cm	0.40	0.34	0.45	0.35
Air Entrainer, oz/cwt (mL/100kg)	1.125 (73)	2.625 (171)	1.125 (73)	3.75 (245)
Type E Admixture, oz/cwt (mL/100kg)	0	16 (1043)	0	16 (1043)
Type A Admixture, oz/cwt (mL/100kg)	3 (196)	6 (391)	3 (196)	8 (522)

Table 2. Chemical Analyses of Fly Ashes

Component	**F Ash**	**C Ash (TDOT)**	**C Ash (HVFA)**
Silicon Dioxide (%)	49.82	34.72	29.65
Aluminum Oxide (%)	19.24	17.34	15.02
Iron Oxide (%)	19.09	7.93	10.69
Calcium Oxide (%)	4.94	27.78	30.41
Magnesium Oxide (%)	0.97	4.52	5.29
Sulfur Trioxide (%)	1.15	1.99	1.89
Sodium Oxide (%)	0.64	1.43	2.86
Loss on Ignition (%)	0.56	0.90	0.29

ASTM Type A and E admixtures were used, along with an air-entrainer.[16] Type E admixtures are both accelerating and water-reducing; this was added to the HVFA mixtures in an attempt to reduce the delay in setting time associated with high amounts of fly ash. The HVFA mixtures contained higher dosages of air-entrainer than the TDOT Class A mixtures. As stated in the literature, this was necessary due to the reduced effectiveness of air-entrainer that results from high volumes of fly ash.[6] The HVFA mixture containing F Ash also required a greater dosage of air-entrainer than the C Ash mixture due to the higher carbon content.[8,12]

PROCEDURE

Two batches were made for each of the four mixtures shown in Table 1. All batches were mixed in a 3 ft^3 (0.08 m^3) nominal capacity electric mixer. The first batch was 2 ft^3 (0.06 m^3) while the second batch consisted of 1.5 ft^3 (0.04 m^3). After mixing each batch, the slump was determined as per ASTM C 143, the unit weight was determined as per ASTM C 138, and the air content was determined using a Type B pressure meter, as per ASTM C 231.[17,18,19]

The first batch from each mixture was used for cylinders for testing; all cylinders were cast in accordance with ASTM C 192.[20] For each batch, twenty 4x8-inch (10.2x20.4-cm) and ten 3x6-inch (7.6x15.2-cm) cylinders were cast. The 4x8-inch (10.2x20.4-cm) cylinders were used for compressive strength testing, while the 3x6-inch (7.6x15.2-cm) cylinders were used for density, absorption, and water permeable voids determination. Twenty-four hours after casting, all cylinders except those used for 1 day compressive strength testing were de-molded, labeled, and placed in a lime-water curing tank maintained at 73.5 ± 3.5°F (23.0 ± 2.0°C) as per ASTM C 192.[20] All cylinders remained in the tank until time for testing. Compressive strengths were determined using 4x8 inch (10.2x20.4-cm) cylinders at 1, 2, 3, 4, 7, 14, 28, 56, 91, and 182 days as per ASTM C 39 using 70 durometer neoprene pads in accordance with ASTM C 1231.[21,22] The density, absorption, and water permeable voids were determined in accordance with ASTM C 642 at 7, 28, 56, 91, and 182 days.[23]

The second batch of each mixture was used to determine the setting time as per ASTM C 403.[24] The second batch of the HVFA and TDOT A mixtures containing Class C ash were cast on the same day, while those containing Class F ash were both cast the next day. Mixing on the same day ensured that laboratory conditions were consistent for both mixtures, allowing for a more accurate comparison of the setting time. The initial temperature in the laboratory was 72^{o}F (22.2°C) and the finish temperature was between 72^o (22.2°) and 73^{o}F (22.8°C) on both days.

RESULTS

The plastic properties for the first batch of each mixture are shown in Table 3. The results for the compressive strength development of the TDOT A and HVFA mixtures containing C ash and F ash are shown in Figures 1 and 2, respectively. The water absorption and the water permeable void contents for all mixtures are shown in Figures

3 and 4, respectively. The individual material costs, as well as the total cost for each of the mixtures, are shown in Table 4. The plastic properties and the setting times for the second batch of each mixture are shown in Table 5. A comparison of the time of set for the mixtures containing Class C ash is illustrated in Figure 5, while a comparison of the Class F ash mixtures is shown in Figure 6.

ANALYSIS OF RESULTS

Compressive Strength

The plastic properties for the batches used for compressive strength testing are given in Table 3. The slump and air content for the Class C ash mixtures were similar, as were those for the Class F ash mixtures. As shown in Figure 1, the HVFA mixture containing Class C ash obtained greater compressive strengths than the TDOT Class A mixture with 25 percent C ash replacement. The strength of the HVFA mixture was greater than that of the TDOT Class A mixture at all ages. It would seem that the HVFA mixture would have lower strengths at early ages, due to the decreased cement available for reactions. However, it appears that the low w/cm ratio and the increased Type A admixture overcome the adverse effect of increased fly ash. Class C fly ash also has some cementitious properties which contribute slightly to the compressive strengths at early ages. As expected, the long term strengths were greater for HVFA due to the pozzolanic properties of the Class C ash and the lower w/cm ratios.   The rate of strength gain for the two mixtures appears to be similar.

Table 3. Plastic Properties

Component	C Ash		F Ash	
	TDOT A	***HVFA***	***TDOT A***	***HVFA***
Slump, in. (cm)	4.5 (11.4)	4 (10.2)	5.75 (14.6)	5.5 (14.0)
Unit Weight, lb/ft^3 (kg/m^3)	145.2 (86.2)	146.94 (87.2)	142.92 (84.8)	141.56 (84.0)
Air content, %	6	6	7	7.75

The long term compressive strengths for the HVFA mixture containing Class F ash were similar to those of the TDOT Class A mixture with 20 percent F ash replacement, as illustrated in Figure 2. Unlike the C ash mixture, the strengths of the HVFA mixture containing F ash were slightly lower than those of the TDOT Class A mixture at early ages. This was the expected behavior due to the large amount of Class F fly ash, which possesses pozzolanic properties but no cementitious properties. Even though the early strength of the HVFA mixture was lower, it still exceeded 750 psi (5.2 MPa) at one day, which has been suggested as an acceptable limit for formwork removal.[10] After approximately three weeks, the compressive strength of the HVFA mixture surpassed that of the TDOT Class A mixture, due to the pozzolanic properties of the F ash. However, at later ages, the compressive strength of the HVFA mixture dropped slightly below that of the TDOT Class A mixture; an explanation for the drop in strength is unclear. It appears from the graph that the rate of strength gain for the HVFA mixture was equal to that of the TDOT Class A mixture, due to the pozzolanic properties.

Figure 1. Compressive Strength vs. Time – C Ash Mixtures

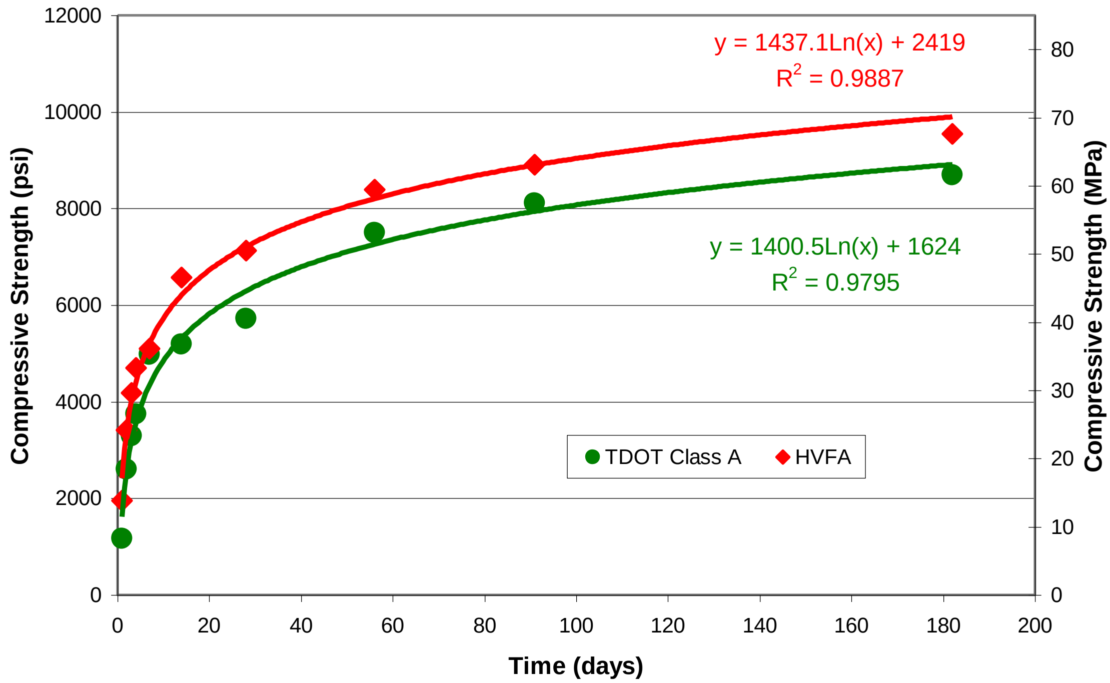
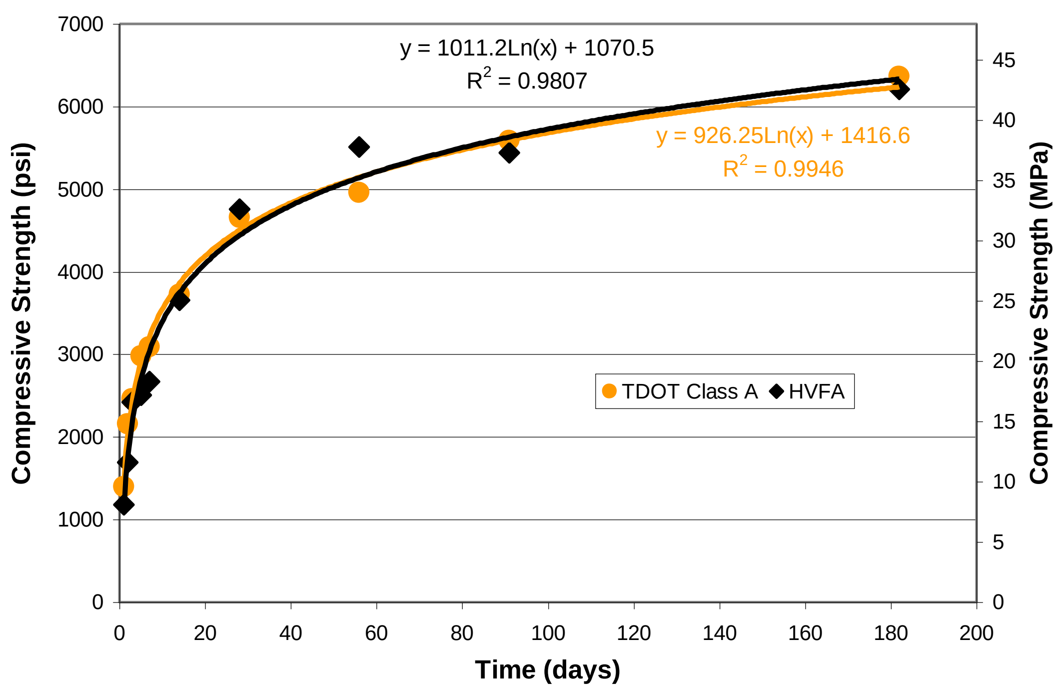


Figure 2. Compressive Strength vs. Time – F Ash Mixtures



Durability Properties

The water absorption and permeable void contents were determined as per ASTM C 642. The water absorption for each of the four mixtures is shown in Figure 3. Both of the HVFA mixtures had significantly less absorption than the TDOT Class A mixtures. Also, Figure 4 illustrates the water permeable void content for each of the mixtures. The HVFA mixtures also had a lower percentage of water permeable voids than the TDOT Class A mixtures. This indicates that the HVFA mixtures will probably exhibit better durability than the TDOT Class A general use mixtures. This is consistent with the literature, which states that the durability of concrete containing large amounts of fly ash is superior to that of normal PCC. The high volumes of fly ash provide a denser microstructure that is less permeable, resulting in enhanced durability.

Figure 3. Water Absorption vs. Time

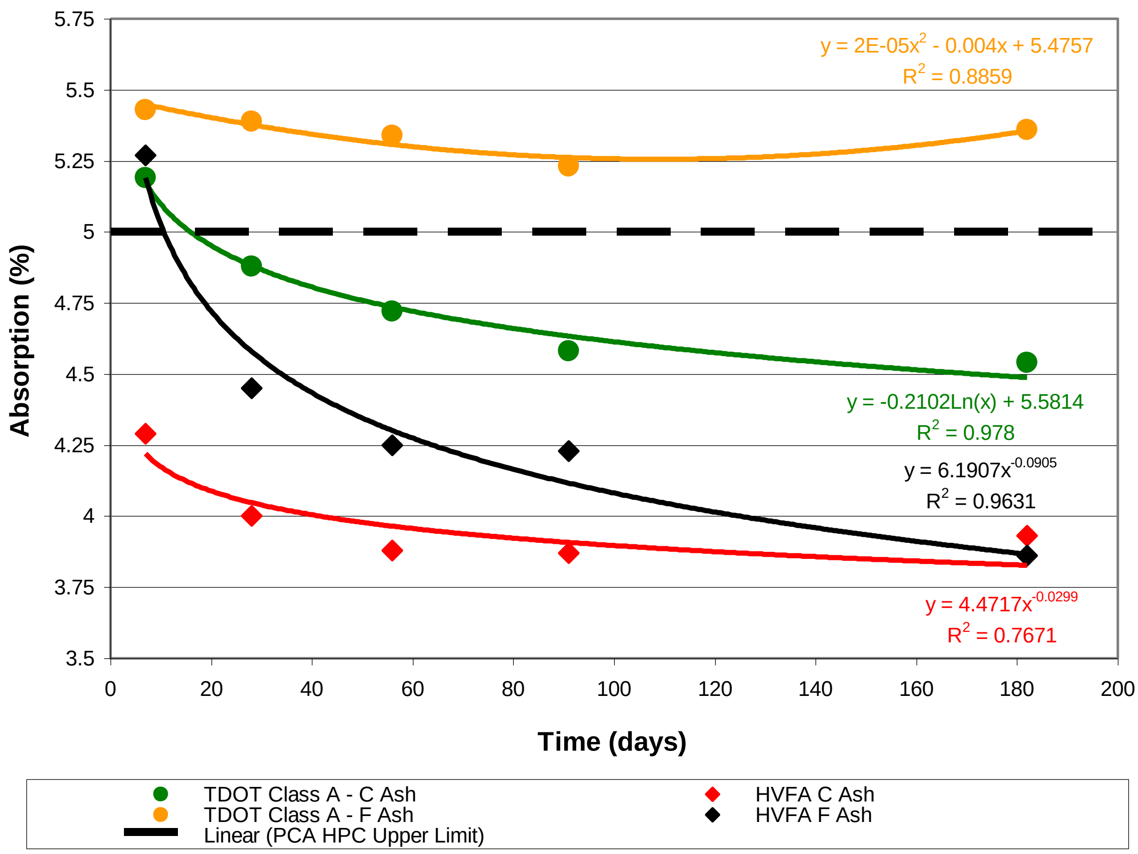
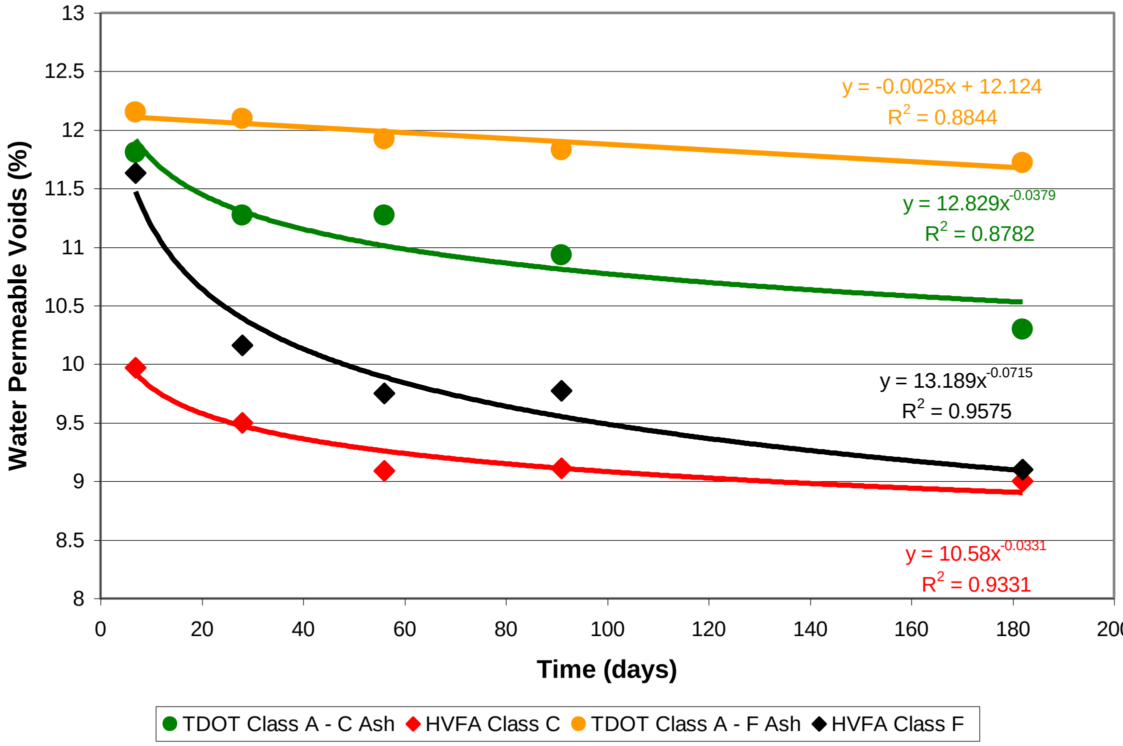


Figure 4. Water Permeable Void Content vs. Time



Cost

The cost per cubic yard for each of the four mixtures is given in Table 4. These costs are estimates based on prices obtained from regional suppliers. Water costs were considered negligible. Each of the HVFA mixtures was slightly more expensive than the TDOT Class A mixture containing its respective class of fly ash. However, upon inspection, it is evident that the increased cost is mainly due to the chemical admixtures. The admixtures in each of the TDOT Class A mixtures accounted for $1.12 of the total cost, while in the HVFA C and F ash mixtures the admixture cost was $5.79 and $7.40, respectively.

All mixtures in the laboratory were cast at approximately 72^{o}F (22 ^{o}C). When casting in the field at temperatures greater than this, the need for Type E (accelerating) admixtures would be reduced in the HVFA mixtures. Also, as the temperature increases, the TDOT Class A mixtures would require Type B (retarding) admixtures to regulate setting. Therefore, even though the HVFA mixtures are slightly more expensive at laboratory conditions, the cost would be significantly less than the TDOT Class A mixtures in warm weather placements.

Table 4. One Cubic Yard Price Comparison

Materials	C Ash		F Ash	
	TDOT A	***HVFA***	***TDOT A***	***HVFA***
Type 1 Portland Cement	$21.15	$13.80	$22.55	$14.95
Class C Fly Ash	$2.68	$5.26	$0.00	$0.00
Class F Fly Ash	$0.00	$0.00	$1.36	$3.60
Coarse aggregate	$5.51	$5.73	$5.37	$5.51
Fine Aggregate	$9.44	$9.55	$9.16	$9.18
Air Entraining Admixture	$0.19	$0.43	$0.19	$0.66
ASTM Type E Admixture	$0.00	$2.77	$0.00	$3.00
ASTM Type A Admixture	$0.93	$2.59	$0.93	$3.74
Total Cost	**$39.89**	**$40.12**	**$39.54**	**$40.63**

Time of Set

Table 5 shows the slump, air content, and concrete temperature, as well as the initial and final set times, for each of the batches used for determining the time of set. The plastic properties for both mixtures containing C ash were similar, as were those for the mixtures containing F ash. A comparison of the time of set for the C ash and F ash mixtures is shown in Figures 5 and 6, respectively. The HVFA mixtures had delays in setting times ranging from 1 hour 47 minutes to 2 hours 9 minutes. This is consistent with the literature, which stated that HVFA mixtures have delays in setting times around two hours.[1] The laboratory was maintained at approximately 72^{o}F (22 ^{o}C) for the duration of testing. When placing in the field at temperatures greater than this, the time required for setting would decrease for the HVFA mixtures. Therefore, it appears that the HVFA mixtures would be ideal for warm weather placements.

Table 5. Time of Set Properties

Property	C Ash		F Ash	
	TDOT A	***HVFA***	***TDOT A***	***HVFA***
Slump, in. (cm)	4.25 (10.8)	5.25 (13.3)	7 (17.8)	7.25 (18.4)
Air %	6.75%	6.50%	7.75%	7.50%
Concrete Temp,^{o}F (^{o}C)	73 (22.8)	72 (22.2)	73 (22.8)	73 (22.8)
Initial Set (hr:min)	7:01	8:48	6:27	8:36
Final Set (hr:min)	8:51	10:45	8:14	10:20
Delay of Initial Set	---	1:47	---	2:09
Delay of Final Set	---	1:54	---	2:06

Figure 5. Time of Set Comparison – C Ash

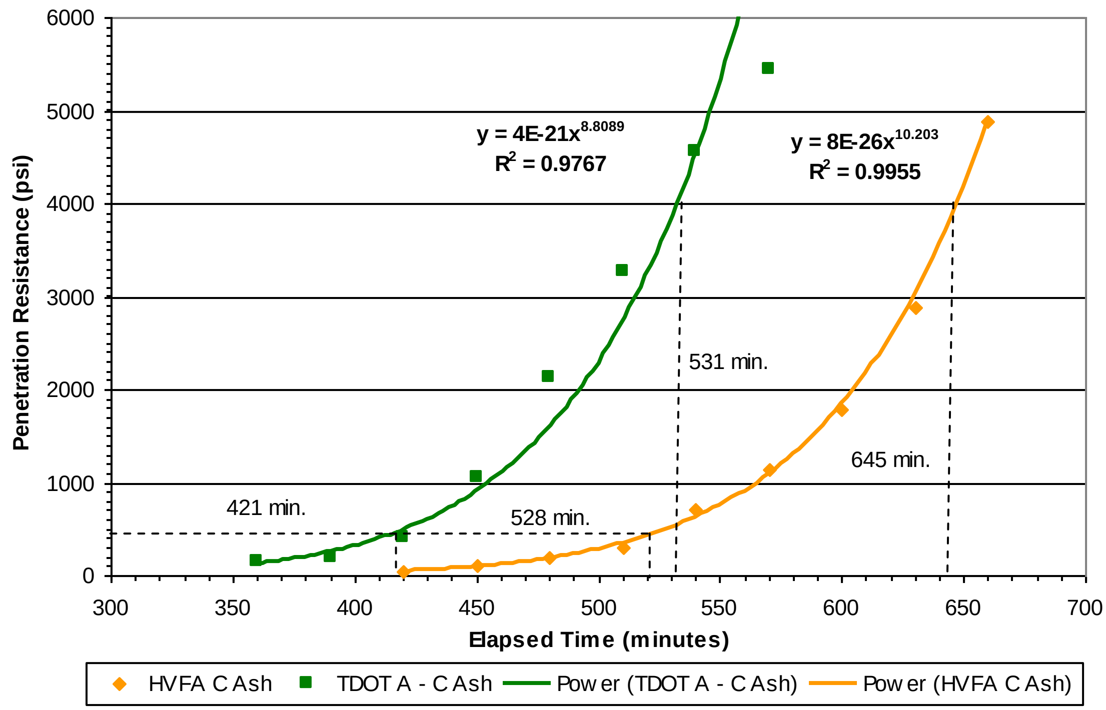
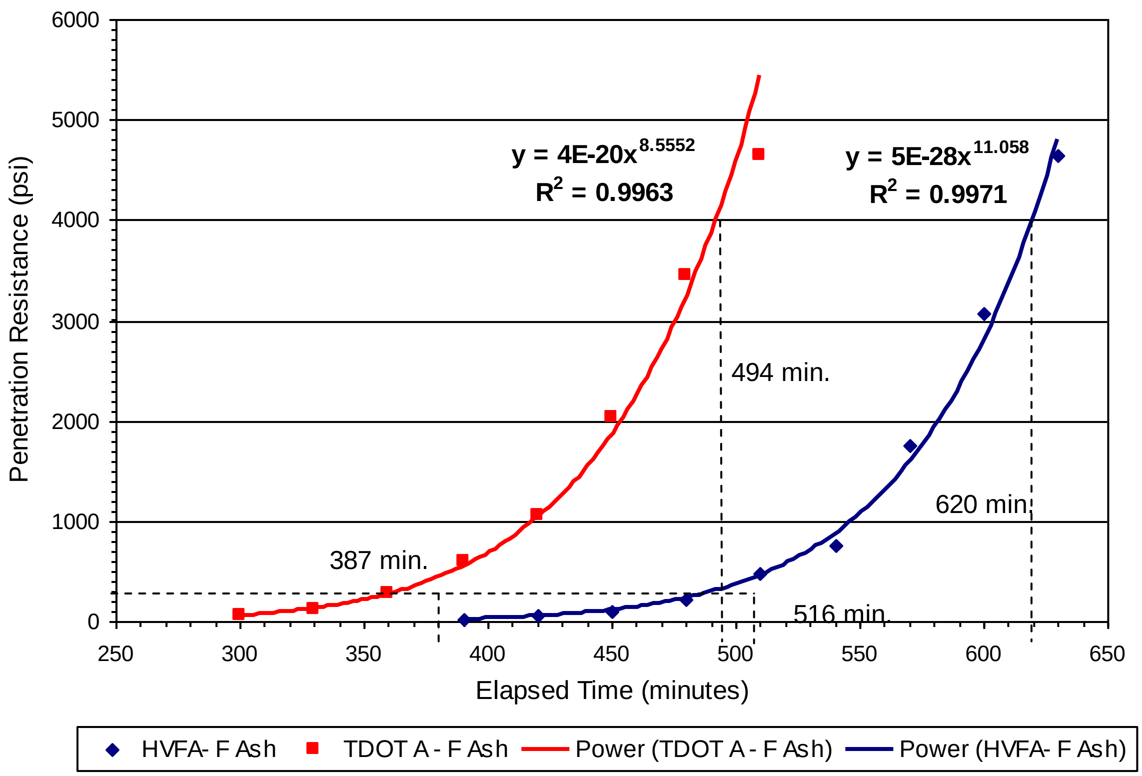


Figure 6. Time of Set Comparison – F Ash



CONCLUSIONS

Based on the limited data available, the following conclusions may be drawn:

1. The ultimate compressive strengths for the HVFA mixtures were similar to or greater than those of the TDOT Class A mixtures. The HVFA C ash mixture had greater compressive strengths at all ages, due to the pozzolanic and cementing properties of the fly ash. The compressive strengths of the HVFA F ash mixture were similar to those of the TDOT mixture after approximately three weeks.

2. The absorptions and water permeable void contents of the HVFA mixtures were lower the TDOT Class A mixtures at all ages. This indicates that the HVFA mixtures would probably be more durable than the TDOT mixtures.

3. The costs of the HVFA mixtures were slightly greater than those of the TDOT Class A mixtures at laboratory conditions. However, in warmer temperatures, the cost of the HVFA mixtures would decrease as the TDOT Class A mixtures increased, due to the need for chemical admixtures. Therefore, HVFA mixtures would be ideal for warm weather placements.

4. The time of set for the HVFA mixtures was approximately two hours longer than those of the TDOT Class A mixtures. However, in warmer temperatures, the delay in setting time for the HVFA mixtures would decrease and therefore be acceptable.

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