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Experimenting with High Volume Fly Ash Concrete in Tennessee

INTRODUCTION

In March 2005, the Tennessee Concrete Association (TCA) sponsored the initial Tennessee Tech research on High Volume Fly Ash (HVFA) concrete. Subsequently, in 2010, the Tennessee Department of Transportation (TDOT) Division of Materials and Tests Division sponsored a project entitled "Higher Volume Fly Ash (HVFA) Portland Cement Concrete (PCC) for Sustainability and Performance". The TDOT project concluded in 2012 and the authors would like to thank TCA for sponsoring the initial "seed" project. Further, we would also like to thank TDOT for sponsoring the second project and share some of the results of the TDOT project.

HVFA Concrete uses approximately 50 percent Portland cement (PC) replacement rate with Class C fly ash. Current TDOT allowable PC replacement rate is 25 percent for Class C fly ash. However, 2006 TDOT standard specification section 604.03 currently allows a 50 percent substitution of all supplementary cementing materials (SCM) combined and therefore the research was not without precedent [1]. The higher PC replacement rate greatly increases the use of an industrial byproduct making more efficient use of natural resources. Protecting and preserving the environment is always a desirable goal; however, neither performance nor economy should be sacrificed for environmental concerns. Therefore, even though the literature indicates that higher replacement rates may be viable in some applications, the research team assumed that doubling the current TDOT allowable replacement percentage was a prudent first step.

TCA SEED PROJECT

The TCA seed project, which began in March 2005, included both a preliminary laboratory evaluation and a field placement at Burgess Falls State Natural Area (near Cookeville, TN). Only the field placement will be discussed herein since the TDOT project laboratory evaluation was much more extensive. TDOT standard specification section 604.03 currently requires a change in chemical admixture types used at 85°F. The concept behind HVFA PCC was to change the supplementary cementing material substitution rate as well as the chemical admixtures at 85°F. The retarding effect of high fly ash substitution might be an effective and more economical answer to hot Tennessee summer days.

Table 1 shows the mixture design used at the Burgess Falls placement compared to a contemporary TDOT Class A mixture design. It is important to note that in the TCA seed project HVFA PCC was assumed to be competing to be a hot weather replacement for TDOT Class A PCC. Later, it was realized that HVFA PCC could move up a weight class (620 vs. 564-lbs/CY) and compete to be a hot weather replacement for TDOT Class D. Figure 1 shows the natural beauty of the big falls at Burgess Falls State Natural Area (a great place to visit or do concrete research). Figures 2 through 4 show placement of and sample fabrication for the Burgess Falls HVFA PCC slab. Figure 5 shows compressive strength development of HVFA PCC mixture used at Burgess Falls (field cast lab cured). Figure 6 shows a birthday cake for the five-year-old HVFA PCC that the first author's youngest daughter baked (concrete is extremely important to the Crouch family). Figure 7 shows the 9-year-old HVFA PCC slab serving (as a base for a handicapped accessible historical information kiosk) without a crack (the few edge dings from mowing are not a mixture design problem in the opinion of the first author).

Figure 1: The Big Falls at Burgess Falls State Natural Area

Figure 2: The Big Picture on Placement Day 4/19/05

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Figure 3: Close Up Showing Grading, Screeding and PCC Sampling

Figure 4: Making Test Cylinders, Finishing and Cleaning Up

TABLE 1. BURGESS FALLS HVFA AND TDOT CLASS A COMPARISON MIXTURE DESIGNS

Component	HVFA PCC for Burgess Falls Placement	Typical TDOT Class A PCC Field Mixture
Type I PC (lbs/CY)	262	451
Class C Fly Ash (lbs/CY)	262	113
No. 57 Limestone SSD (lbs/CY)	1891	1800
River Sand SSD (lbs/CY)	1231	1236
Water (lbs/CY)	222	252
Design Air Voids (%)	6	6
Water-to-cementing-materials ratio	0.424	0.442
Paste volume (% of total volume)	30.3	32.4

TABLE 2. TDOT CLASS D AND HVFA MIXTURE DESIGNS

Component	TDOT Class D	TDOT Class D Hot	HVFA PCC	HVFA PCC Hot
Type I PC (lbs/CY)	496	496	276	276
Class F Fly Ash (lbs/CY)	124	124	0	0
Class C Fly Ash (lbs/CY)	0	0	277	277
No. 57 Limestone SSD (lbs/CY)	1904	1904	1922	1922
River Sand SSD (lbs/CY)	1140	1140	1273	1273
Water (lbs/CY)	232.5	232.5	187	187
Design Air Voids (%)	6	6	6	6
Air Entrainer, oz/cwt (oz/CY)	0.38 (2)	0.35 (2.2)	0.28 (1.5)	0.22 (1.2)
Mid-range Water Reducer, oz/cwt (oz/CY)	3 (18.6)	0	0	0
High-range Water Reducer, oz/cwt (oz/CY)	2 (12.4)	2 (12.4)	3.5 (19.4)	4.25 (23.5)
Non-chloride Accelerator, oz/cwt (oz/CY)	0	0	16 (88.5)	0
Retarder, oz/cwt (oz/CY)	0	1.5 (9.3)	0	0

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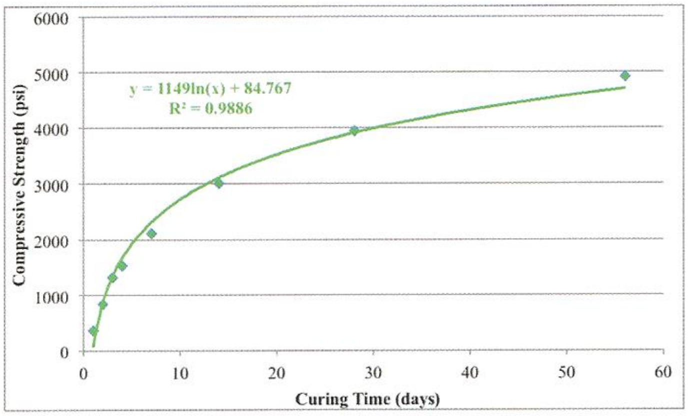

Figure 5: Compressive Strength Development of Burgess Falls HVFA PCC

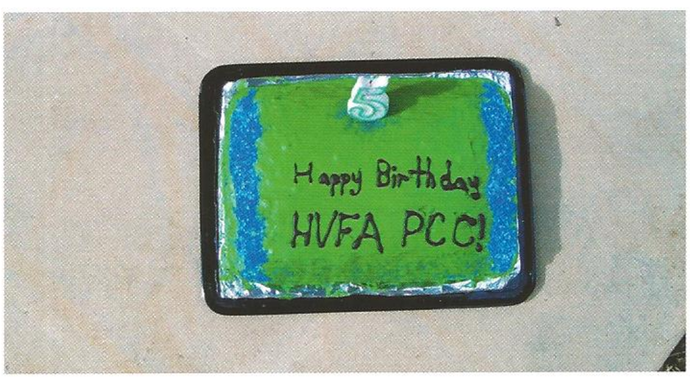

Figure 6: Birthday Cake for Five Year Old HVFA PCC Slab 4/19/10

Figure 7: Nine Year Old HVFA PCC Slab without a Crack 4/20/14

TDOT PROJECT 2010: HVFA AND TDOT CLASS D MIXTURE DESIGNS

Table 2 shows TDOT Class D and HVFA PCC mixture designs for both above and below 85°F that were used in the study. Table 3 shows comparisons of TDOT Class D and HVFA PCC attributes with 2010 TDOT 604.03 Class D requirements.

Material cost is always an important concern; the cost assumptions used for the TDOT HVFA research are shown in Table 4. Applying the cost assumptions in Table 4 to the mixture designs in Table 2 produces the material costs per cubic yard shown in Table 5.

RESULTS

Table 6 shows the results of plastic property tests on TDOT Class D and HVFA PCC for mixtures above and below 85°F. The research team wanted a fair fight and attempted to produce mixtures with very similar plastic properties. For the mixtures below 85°F, the HVFA PCC has statistically significantly different slump and unit weight from TDOT Class D, but air contents (according to both pressure meter and gravimetric results) are not statistically significantly different. For the mixtures above 85°F, the HVFA PCC has statistically significantly lower slump than TDOT Class D PCC. Other properties measured were not significantly different.

Figure 8 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 750-psi at one day, as recommended for form wrecking without excessive damage [2]. Although HVFA PCC required a chemical accelerator to achieve the compressive strength in the 70°F range, as the temperature increased above 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 9 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 [3]. Figure 10 shows the development of PCC absorption after boiling over time for HVFA and TDOT Class D PCC as well as the PCA HPC upper limit. Figure 11 shows the mean 91-day rapid chloride permeability of HVFA and TDOT Class D PCC.

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TABLE 3. 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	620 lbs/CY minimum	620 lbs/CY	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

TABLE 4. MATERIAL COST ASSUMPTIONS

Component	Assumed Cost Delivered to Ready Mix Producer
Type I Portland Cement ($/ton)	110.00
Class F Fly Ash ($/ton)	30.00
Class C Fly Ash ($/ton)	50.00
No. 57 Limestone ($/ton)	18.00
River Sand ($/ton)	15.00
Air Entrainer ($/gallon)	4.50
Mid-range Water Reducer ($/gallon)	8.50
Accelerator ($/gallon)	9.00
Retarder ($/gallon)	7.50
High-range Water Reducer ($/gallon)	12.00

TABLE 5. MATERIAL COST PER CUBIC YARD

Component	TDOT Class D	HVFA PCC	TDOT Class D Hot	HVFA PCC Hot
Type I Portland Cement ($/CY)	27.28	15.18	27.28	15.18
Class F Fly Ash ($/CY)	1.86	0	1.86	0
Class C Fly Ash ($/CY)	0	6.93	0	6.93
No. 57 Limestone ($/CY)	17.14	17.30	17.14	17.30
River Sand ($/CY)	8.55	9.55	8.55	9.55
Air Entrainer ($/CY)	0.07	0.06	0.08	0.05
Mid-range Water Reducer ($/CY)	1.24	0	0	0
High range Water Reducer ($/CY)	1.17	1.82	1.17	2.21
Accelerator ($/CY)	0	6.23	0	0
Retarder ($/CY)	0	0	0.55	0
Estimated Total Material Cost (excluding water) in $/CY	57.31	57.07	56.63	51.22

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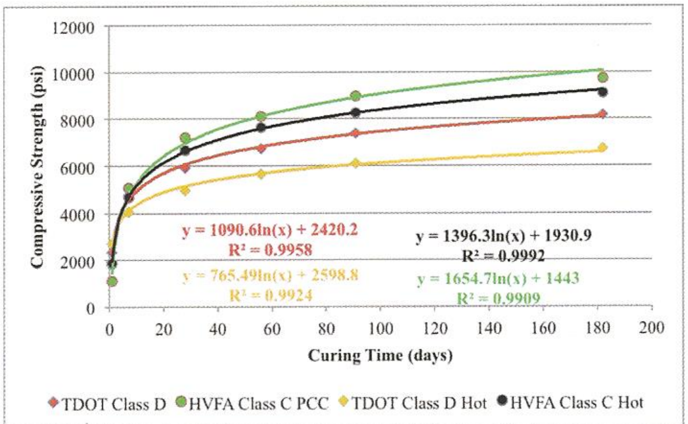

Figure 8: Compressive Strength Development of HVFA and TDOT Class D Mixtures

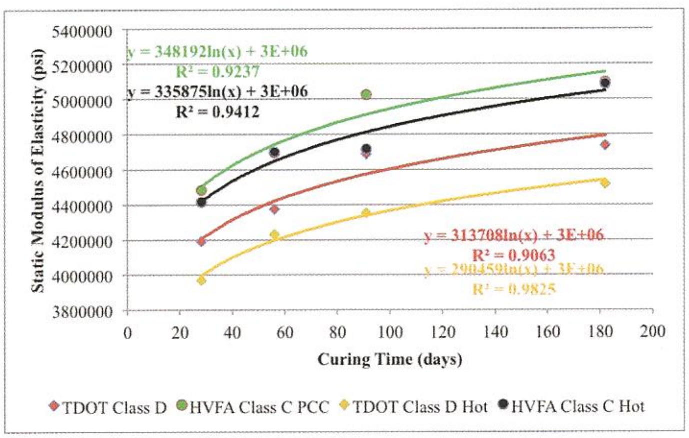

Figure 9: Static Modulus of Elasticity Development of HVFA and TDOT Class D Mixtures

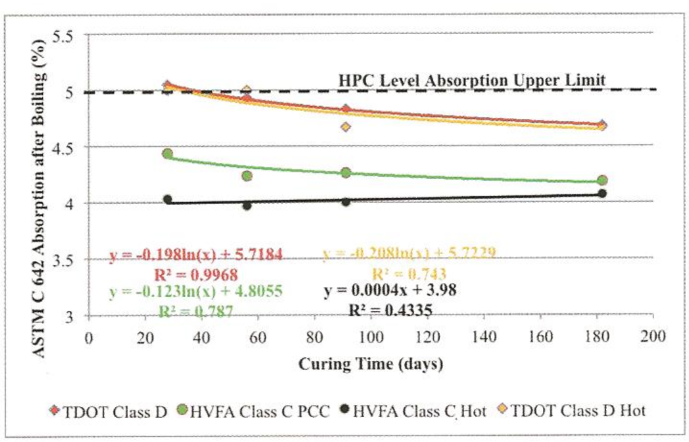

Figure 10: Concrete Absorption Development of HVFA and TDOT Class D Mixtures

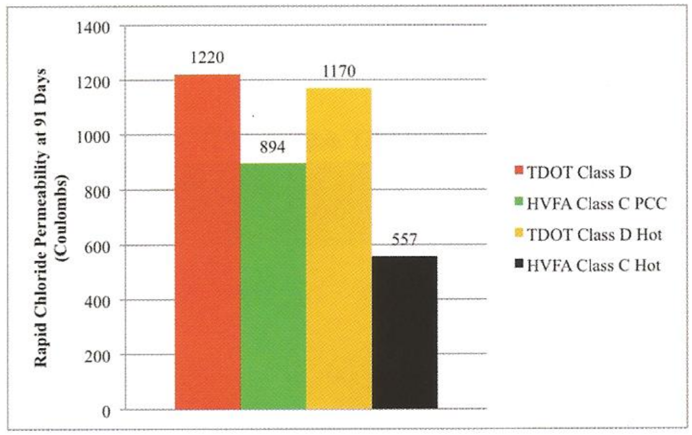

Figure 11: 91-day Rapid Chloride permeability of HVFA and TDOT Class D Mixtures

ANALYSIS OF RESULTS

Table 7 shows the relative mean values of properties of HVFA and TDOT Class D PCC. Thus, the numbers shown are a percentage of the mean TDOT Class D PCC results that the mean HVFA PCC results obtained. A cell shaded in blue indicates that at a specified age, TDOT Class D PCC was significantly different and superior to HVFA PCC. A cell shaded in yellow 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 8 is a similar comparison of hot HVFA and hot TDOT Class D PCC.

SUMMARY

This was certainly not a close fight (almost a knockout). Going to the judge's scorecard (Table 9), HVFA PCC is the clear winner. However, the "cooler" mixtures (below 85°F) were cast, cured and tested in the 70s. At lower casting and curing temperatures TDOT Class D would probably have prevailed (due to HVFA requiring more chemical accelerator) in either cost or early age compressive strength. TDOT Class D is therefore much more widely applicable (over a wider range of temperatures) than HVFA PCC at lower temperatures.

The fight was a knockout for HVFA PCC above 85°F. As the mixing, casting and curing temperature rises, hot HVFA PCC's advantage over hot TDOT Class D PCC would certainly increase. Fortunately, one of the many, many advantages of living in Tennessee is a climate favorable for extensive hot HVFA PCC usage.

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TABLE 6. TDOT CLASS D AND HVFA PLASTIC PROPERTIES AND TDOT CLASS D REQUIREMENTS

Property	TDOT 604.03 Class D PCC Requirements in 2010	TDOT Class D Mean Value of 10 Batches	HVFA PCC Mean Value of 10 Batches	TDOT Class D Hot Mean Value of 3 Vatches	HVFA PCC Hot Mean Value of 3 Batches
Slump after HRWR (inches)	8 maximum	6.9	5.7	6.9	5.3
Air content by pressure method (%)	5 to 8.5	6.2	5.8	6.1	6.7
Air content gravimetric (%)	None	6.1	5.7	6.2	6.8
Unit Weight (pcf)	None	144.2	146.2	144.1	144.6
Temperature (°F)	Normal < 85 Hot ≥ 85	73.0	73.5	92.3	85.3

TABLE 7. COMPARISON OF MEAN RESULTS (HVFA/TDOT CLASS D) *100

Age	Compressive Strength	Static Modulus of Elasticity	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 8. COMPARISON OF MEAN RESULTS (HOT HVFA/HOT TDOT CLASS D) *100

Age	Compressive Strength	Static Modulus of Elasticity	Absorption after Boiling	Rapid Chloride Permeability
1	69			
7	116			
28	135	111	81	
56	135	111	79	
91	135	108	86	48
182	119	113	87	

TABLE 9. FINAL SUMMARY COMPARISON OF HVFA & TDOT CLASS D

Property of Attribute	< 85°F	≥ 85°F
Compressive Strength	HVFA	HVFA Hot
Static Modulus of Elasticity	HVFA	HVFA Hot
Absorption after Boiling	HVFA	HVFA Hot
Chloride Permeability	HVFA	HVFA Hot
Shrinkage	No Clear Winner	—
Material Cost	No Clear Winner	HVFA Hot
Overall Superiority	HVFA	HVFA Hot

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HVFA PCC can be an effective tool for mixture designers if used correctly. Always use the right tool for the job (never hammer with a crescent wrench – use a hammer). Tennessee summer heat is an excellent time to consider HVFA PCC.

RECOMMENDATION

Consider using HVFA PCC for summer placements, it has both environmental (higher byproduct usage) and performance advantages (improved durability and compressive strength) when used appropriately. For more information on using HVFA PCC (especially at higher temperatures) contact the Tennessee Concrete Association (TCA) or a local TCA producer member. Go "green" and help improve both the environment and PCC performance simultaneously.

DISCLAIMER

The opinions expressed herein are those of the authors and not necessarily the opinions of the Federal Highway Administration, the Tennessee Department of Transportation, or the Tennessee Concrete Association.

REFERENCES

[1] TDOT Section 604.03, "Classification, Proportioning and Quality Assurance of Concrete," in *Tennessee Department of Transportation Standard Specifications for Road and Bridge Construction*, 2006, p. 397.

[2 K. H. Obla, R. L. Hill and R. S. Martin, "HVFA Concrete - An industry Perspective," *Concrete International,* vol. 25, no. 8, pp. 29-34, 2003.

[3] S. H. Kosmatka, B. Kerkhoff and W. C. Panarese, Design and Control of Concrete Mixtures 14th Edition, Skokie: Portland Cement Association, 2002, p. 300.

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