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SUSTAINABILITY
WORKFORCE BUILDING CODES
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COMPLIANCE ENVIRONMENT
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WORKFORCE COMPLIANCE
DURABILITY INFRASTRUCTURE
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ENVIRONMENT WORKFORCE
RESILIENCE ENVIRONMENT
COMPLIANCE INFRASTRUCTURE
INFRASTRUCTURE DURABILITY
ENVIRONMENT
SUSTAINABILITY COMPLIANCE
RESILIENCE WORKFORCE
WORKFORCE COMMUNITY
COMPLIANCE
DURABILITY COMMUNITY
RESILIENCE SUSTAINABILITY COMPLIANCE
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SUSTAINABILITY BUILDING CODES WORKFORCE

by L. K. Crouch, Caleb Smith, William C. Scott, James Locum, Daniel Badoe and Heather P. Hall

Going Past TDOT Specifications to Lower Concrete Permeability

PART 1: TAKE IT TO THE LIMIT

SERIES OVERVIEW

This four-part series of papers report the findings of an ongoing investigation into Tennessee Department of Transportation (TDOT) Class D concrete specifications (1) to increase surface resistivity (SR). The investigation explores both exceeding limitations on currently approved TDOT supplementary cementing materials (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 (1). 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 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

These additional constraints should facilitate 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. The authors hope mixture designers and concrete professionals find the information useful.

In Part 1, the effect of increasing the Class F fly ash replacement dosage on SR is examined. Subsequent articles in the series will examine:

2. Already Gone – Slag Dosage Effect on SR
3. Life in the Fast Lane – SCM Dosages for Rapidly Reaching the SR "Very Low" Category
4. New Kid in Town – Ground Pumice as an SCM

INTRODUCTION

The work described herein is a combination of master's research of former graduate students Caleb Smith and Cory Scott. Smith (2) looked at the SR of seven different TDOT approved Class D concrete mixtures including two mixtures containing only Class F fly ash as an SCM. Scott investigated the effect on SR of going past current TDOT Class F fly ash specifications.

MATERIALS AND PROCEDURE

TDOT-approved materials used in the study are shown in the first column of Table 1. The proportions of the four mixtures used in the study (see Table 1) were determined by trial batching. All four final mixtures met TDOT Class D concrete plastic and hardened property requirements. Table 2 shows TDOT requirements for minimum cementing materials, w/cm ratio, FA/TA, and allowable SCM replacement percentages. The first two mixtures, 20 and 25, met all criteria in Table 2. The second two mixtures, 30 and 35, met all Table 2 criteria except for the maximum SCM replacement percentage. Six batches of each mixture were produced and tested as per Table 3.

RESULTS AND DATA QUALITY

Tables 4 and 5 show 28-day compressive strength and 56-day absorption results, respectively. SR results for 7, 14, 28, 42 and 56 days are shown in Table 6. The acceptable range of hardened properties was determined by obtaining the standard deviation or coefficient of variation from the appropriate test method and multiplying by an ASTM C 670 factor for the number of test results (6). The multi-laboratory precision was used for 4×8-inch cylinders since AASHTO T 22 states that preparation of cylinders by different operators would probably increase the variation above multi-laboratory precision criteria (3). All hardened property test results met the acceptable precision criteria except the 30% and 35% Class F fly ash compressive strengths (indicated in red in Table 4). Unfortunately, no precision criteria are available for hardened concrete absorption after boiling.

ANALYSIS OF RESULTS

Statistical Comparison of SR Results

Tables 7 and 8 present the results of the test of hypothesis of equality of SR for different mixtures at a given curing time and the same mixture over various curing times, respectively. A statistical t-test under the assumption of unequal variances was performed. Where the estimated t-value was less than the critical t-value at the corresponding degree of freedom and 5 percent significance level, the compared mixes were deemed to have statistically equal SR values. Where the estimated t-value exceeded the critical t-value at the corresponding degree of freedom and 5 percent significance level, the compared mixes were deemed to have statistically significant different SR values.

TABLE 1: MIXTURES USED TO EVALUATE CLASS F FLY ASH REPLACEMENT PERCENTAGE EFFECT

Component	20% Class F Fly Ash	25% Class F Fly Ash	30% Class F Fly Ash	35% Class F Fly Ash
Type I PC (lbs/CY)	496	465	434	403
Class F Fly Ash (lbs/CY)	124	155	186	217
No. 57 Stone (SSD lbs/CY))	1857	1883	1887	1887
River Sand (SSD lbs/CY)	1118	1118	1118	1110
Water (lbs/CY)	229.5	229.5	229.5	229.5
Design Percent Air (%)	7	7	7	7
Air Entrainer (oz/cwt)	0.5	0.6	0.5	1
Mid-Range Water Reducer (oz/cwt)	0.1	3	3	1.25
High-Range Water Reducer (oz/cwt)	3	2	2.5	2.25

TABLE 2. COMPARISON OF MIXTURES USED TO EVALUATE CLASS F FLY ASH REPLACEMENT PERCENTAGE EFFECT WITH TDOT CLASS D PCC REQUIREMENTS

Quantity/Ratio/Percentage	TDOT 604.03 Class D PCC Requirement	20% Class F Fly Ash	25% Class F Fly Ash	30% Class F Fly Ash	35% Class F Fly Ash
Cementing Materials Content (lbs/CY)	620 minimum	620	620	620	620
W/CM Ratio	0.40 maximum	0.37	0.37	0.37	0.37
Percent Fine Aggregate by Total Aggregate Volume	44 maximum	38.3	38.3	38.0	37.8
Percent Class F Fly Ash Substitution (by weight) for Portland Cement	25 maximum for Class F	20	25	**30**	**35**

TABLE 3. TESTING PROTOCOL USED TO EVALUATE CLASS F FLY ASH REPLACEMENT PERCENTAGE EFFECT

Test Method	Frequency	Specimens
Compressive Strength (AASHTO T22, 3)	3 @ 28 and 56 days	4 x 8 cylinders
Surface Resistivity (AASHTO T 95-11, 4)	3 @ 7, 14, 28, 42 and 56 days	56-day compressive strength 4 x 8 cylinders
Hardened Concrete Absorption (ASTM C642, 5)	3 @ 56 days	3 x 6 cylinders

TABLE 4. 28-DAY COMPRESSIVE STRENGTH RESULTS AND DATA QUALITY (PSI)

% F Ash	Batch 1	Batch 2	Batch 3	Batch 4	Batch 5	Batch 6	Mean	Range	Allowable Range
20	5700	5640	5600	5630	5790	5970	5722	370	732
25	5000	4710	4680	5210	5240	5280	5020	600	643
30	5000	5060	4870	5540	5700	5650	5303	**830**	679
35	4010	4090	4450	4310	4590	4350	4300	**580**	550

by L. K. Crouch, Caleb Smith, William C. Scott, James Locum, Daniel Badoe and Heather P. Hall

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PART 1: TAKE IT TO THE LIMIT

The table cells shaded green indicate a statistically significant difference (SD) between compared SR values while cells shaded red indicate the compared SR values were not statistically significantly different (NSD).

Graphical Comparison of SR Results

A graphical comparison of the SR results is shown in Figure 1. Figure 1 seems to indicate that increasing Class F fly ash from 30% to 35% does not produce an increase in SR. The statistical analysis results shown in Table 7 concur with this observation. The results indicate no significant increase in SR for increasing the Class F fly ash substitution from 30% to 35% at any curing age.

It appears that increasing the Class F fly ash replacement percentage slightly, but significantly, reduces SR for 7 and 14-day curing times for all fly ash substitution increases except 30 to 35%. However, the opposite is true for the 28, 42, and 56-day curing times: additional Class F fly ash replacement increases SR for these curing times for all fly ash substitution increases except 30 to 35%. Therefore, increasing Class F fly ash substitution from 30% to 35% does not produce a statistically significant increase in SR and therefore is not a viable means of increasing SR for the given mixture parameters.

Figure 1 shows an increase in SR for all substitution percentages for an increase in curing time increment. The results of the statistical analysis shown in Table 8 support the observation that significant differences exist for all curing ages at every substitution rate tested.

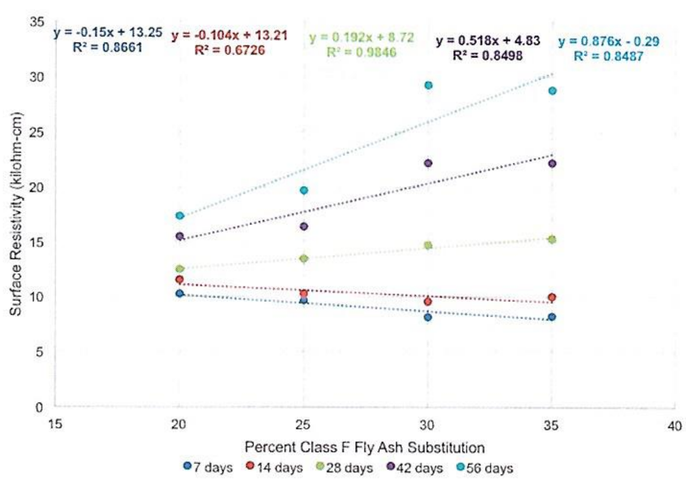

Figure 1: Effect of Class F Fly Ash Substitution on Surface Resistivity

Rate of Increase of SR Results

Table 9 shows the curing time required to reach various SR chloride permeability categories. No mixture in this study reached the "Very Low" category within the allotted time (56 days).

Figure 2 shows 7 and 56-day mean SR results expressed as a percentage of 28-day mean SR results. As expected, mixtures containing Class F fly ash substitution gain SR slowly. Further, the rate of increase is slower as the substitution level increases.

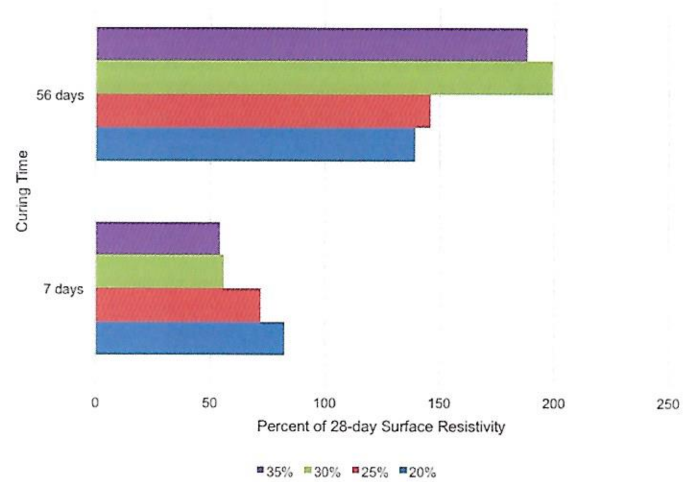

Figure 2: 7 and 56-day Surface Resistivity as a Percent of 28-day Surface Resistivity

Graphical Comparison of Compressive Strength Results

Figure 3 shows a graphical comparison of 28-day mean compressive strength results. The coefficient of determination, 0.7387, is much lower than the authors would prefer. The lower coefficient of determination is most likely due to mixing data from different graduate student projects. These projects were not only conducted by different students, but also at different times of the year. However, the trend of mean results indicates that mean 28-day compressive strength decreases as Class F fly ash substitution increases. The regression equation indicates that the mean 28-day compressive strength should not fall below the TDOT Class D concrete requirement of 4000-psi until the Class F fly ash substitution exceeds 41%. However, the following reasons suggest that perhaps caution should prevail and substitution should be limited to a lower level with the current mixture parameters:

1. Coefficient of determination of the regression equation is not impressive (< 0.9). Therefore, some uncertainty exists.

TABLE 5. 56-DAY ABSORPTION AFTER BOILING RESULTS AND RANGE (%)

% F Ash	Batch 1	Batch 2	Batch 3	Batch 4	Batch 5	Batch 6	Mean	Range
20	5.20	5.09	5.31	5.29	5.13	5.20	5.20	0.22
25	5.56	5.47	5.45	5.49	5.78	5.33	5.51	0.45
30	5.31	5.50	5.67	5.55	5.30	5.24	5.43	0.43
35	5.69	5.50	5.46	5.32	5.34	5.47	5.46	0.37

TABLE 6. SURFACE RESISTIVITY RESULTS AND DATA QUALITY

Class F Fly Ash Substitution (%)	Test Age (days)	Mean Result (kΩ-cm)	Range of Results (kΩ-cm)	Allowable Range of Results (kΩ-cm)
20	7	10.3	.09	5.1
20	14	11.5	1.0	5.7
20	28	12.5	1.6	6.2
20	42	15.5	0.9	7.8
20	56	17.4	1.9	8.7
25	7	9.7	1.1	4.9
25	14	10.3	0.7	5.2
25	28	13.5	1.8	6.8
25	42	16.4	1.2	8.2
25	56	19.7	2.0	9.8
30	7	8.2	0.7	4.1
30	14	9.6	0.7	4.8
30	28	14.7	1.9	7.4
30	42	22.2	3.0	11.1
30	56	29.3	2.7	14.6
35	7	8.3	0.3	4.1
35	14	10.0	0.8	5.0
35	28	15.3	3.9	7.7
35	42	22.2	5.8	11.1
35	56	28.8	6.2	14.4

by L. K. Crouch, Caleb Smith, William C. Scott, James Locum, Daniel Badoe and Heather P. Hall

Going Past TDOT Specification to Lower Concrete Permeability

PART 1: TAKE IT TO THE LIMIT

TABLE 7. STATISTICAL ANALYSIS COMPARING SR FOR DIFFERENT MIXTURES AT A GIVEN CURING TIME

	7 Days	14 Days	28 Days	42 Days	56 Days
20% vs. 25%	SD	SD	SD	SD	SD
20% vs. 30%	SD	SD	SD	SD	SD
20% vs. 35%	SD	SD	SD	SD	SD
25% vs. 30%	SD	SD	SD	SD	SD
25% vs. 35%	SD	NSD	SD	SD	SD
30% vs. 35%	NSD	NSD	NSD	NSD	NSD

2. The 30% and 35% fly ash substitution compressive strengths (see Table 4) had considerable scatter and failed to meet ASTM acceptable range criteria. Therefore, additional uncertainty exists.
3. Some compressive strength safety margin is usually desirable to avoid low breaks.

Therefore, the authors think it would be wise to limit Class F flay ash substitution to 30% for the given mixture parameters.

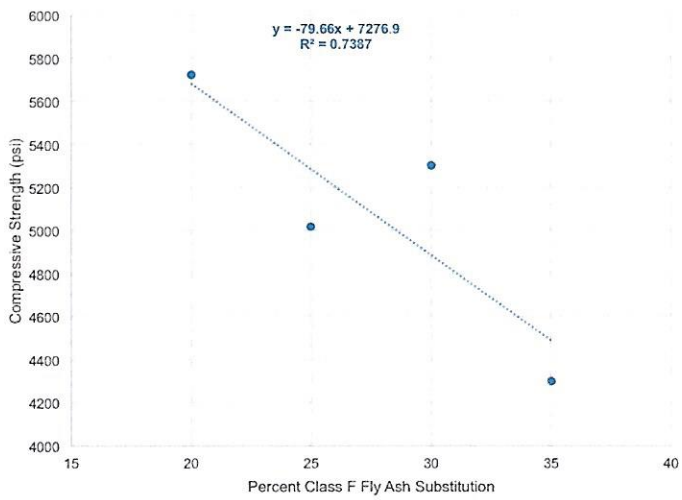

Figure 3: Effect of Class F Fly Ash Substitution on 28-day Compressive Strength

Absorption Analysis

The hardened concrete absorption after boiling results shown in Table 5 are good, but not excellent. High performance concrete absorption after boiling results are typically less than 5.0% (7). The results for the four mixtures in the study range from 5.2% to 5.51% and appear to have no discernable trend as percent Class F fly ash substitution increases.

Material Cost Analysis

Table 10 shows material cost assumptions for concrete materials except water. Calculations using Table 1 mixture proportions and Table 10 cost estimates reveal only a $1.30 maximum difference in material cost for the four mixtures. The 20% fly ash mixture was the most expensive ($56.13/CY without water cost) and the 30% fly ash mixture was the cheapest ($54.83/CY without water cost). Therefore, material cost is clearly not a major factor in choice of mixture.

CONCLUSIONS

Surface resistivity and compressive strength results both suggest that 30% Class F fly ash is the limit for a TDOT Class D mixture with the given mixture parameters. Going past the limit provides additional risk (low cylinder breaks), but no additional benefits (SR does not significantly increase).

DISCLAIMER

The opinions expressed herein are those of the authors and not necessarily the opinions of the Tennessee Department of Transportation or the Tennessee Concrete Association (TCA).

TABLE 8. STATISTICAL ANALYSIS COMPARING SR RESULTS OF THE SAME MIXTURE OVER VARIOUS CURING TIMES

	Batch 1	Batch 2	Batch 3	Batch 4
7 vs. 14 Days	SD	SD	SD	SD
7 vs. 28 Days	SD	SD	SD	SD
7 vs. 42 Days	SD	SD	SD	SD
7 vs. 56 Days	SD	SD	SD	SD
14 vs. 28 Days	SD	SD	SD	SD
14 vs. 42 Days	SD	SD	SD	SD
14 vs. 56 Days	SD	SD	SD	SD
28 vs. 42 Days	SD	SD	SD	SD
28 vs. 56 Days	SD	SD	SD	SD
42 vs. 56 Days	SD	SD	SD	SD

TABLE 9. CURING TIME REQUIRED TO REACH SURFACE RESISTIVITY CHLORIDE PERMEABILITY (RCP) CATEGORY

Mixture	Moderate (SR ≥ 12) (2000 ≤ RCP ≤ 4000)	Low (SR ≥ 21) (1000 ≤ RCP ≤ 2000)	Very Low (SR ≥ 37) (100 ≤ RCP ≤ 1000)
20% Class F Fly Ash	28 days	Did Not Reach	Did Not Reach
25% Class F Fly Ash	28 days	Did Not Reach	Did Not Reach
30% Class F Fly Ash	28 days	42 days	Did Not Reach
35% Class F Fly Ash	28 days	42 days	Did Not Reach

TABLE 10. COST ASSUMPTIONS

Component	Assumed Cost Delivered to Ready Mix Producer
Type I PC ($/ton)	110.00
Class F Fly Ash ($/ton)	30.00
No. 57 Limestone ($/ton)	18.00
River Sand ($/ton)	15.00
Air Entrainer ($/gallon)	4.50
MRWR ($/gallon)	8.50
HRWR ($/gallon)	12.00

by L. K. Crouch, Caleb Smith, William C. Scott, James Locum, Daniel Badoe and Heather P. Hall

Going Past TDOT Specification to Lower Concrete Permeability

PART 1: TAKE IT TO THE LIMIT

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