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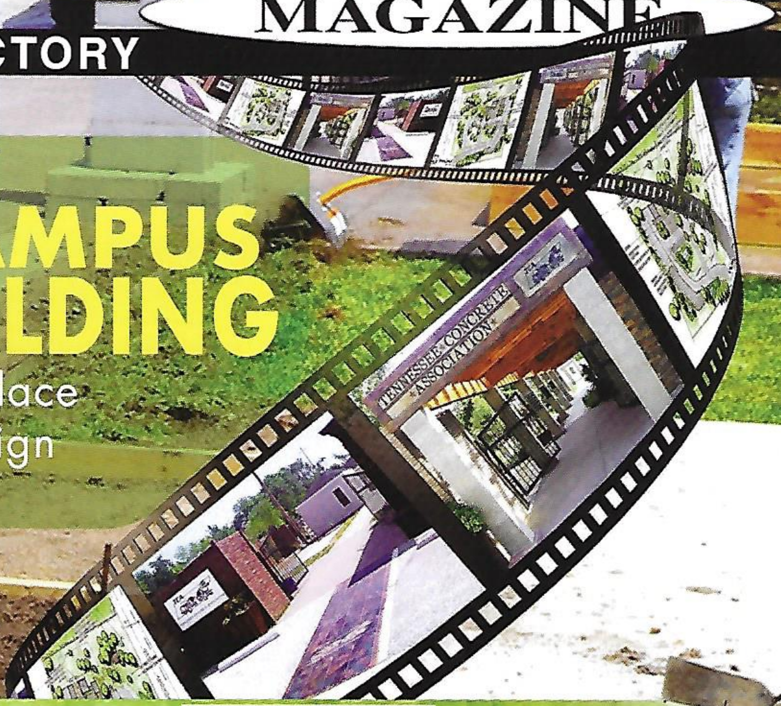

by L. K. Crouch, James Locum, Daniel Badoe and Heather P. Hall

Going Past TDOT Specifications to Lower Concrete Permeability

Part 3: Life in the Fast Lane

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 3, some mixtures that have a good chance of reaching the SR "Very Low" category in 7 days are examined. The final article in the series is titled "New Kid in Town" and will examine ground pumice as an SCM.

TABLE 1. CURING TIME REQUIRED FOR SOME MIXTURES TO REACH SURFACE RESISTIVITY CHLORIDE PERMEABILITY CATEGORIES

CURING DAYS	MODERATE (SR≥12) (2000≤RCP≤4000)	LOW (SR≥21) (1000≤RCP≤2000)	VERY LOW (SR≥37) (100≤RCP≤1000)
7	100PC (Smith) 35SL (Current) 40-55SL (Current) 35SL/15F (Smith)) 30SL/20F (Smith) 35SL25F(Scott) 3.5MK20F (Eagan	60 or 65SL (Current)	
14	5SF25C (Eagan)	35SL (Current) 40-55SL (Current) 35SL/15F (Smith) 30SL/20F (Smith) 35SL25F (Scott) 3.5MK20F (Eagan) 5MK25C (Eagan)	60 or 65SL (Current)
21	–	3.5SF20F (Eagan) 5SF25C (Eagan)	55SL (Current)
28	20 or 25F (Current) 25C (Smith) 50C (Eagan) 30 or 35F (Current)	–	50SL (Current) 35SL25F (Scott)
42	–	30 or 35F (Current)	45SL (Current) 35SL/15F (Smith) 30SL/20F (Smith) 5SF25C (Eagan) 5MK25C (Eagan)
56	–	50C (Eagan)	40SL (Current) 3.5MK20F(TC Fall 2013) 3.5SF20F (TC Fall 2013) 5MK25C (TC W 13/14) 5SF25C (TC W 13/14) 3MK35F (TC W13/14)

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INTRODUCTION

The Need for Speed

Table 1 shows curing time required to reach various SR chloride permeability categories for several mixtures. Mixtures highlighted in yellow met TDOT Class D concrete specifications (1). Words or phrases in parenthesis following the mixtures indicate the various projects analyzed. Projects entitled Current indicate the four part "Going Past TDOT Specifications to Lower SR" study. Names indicate the work of former master's students: Caleb Smith (2), Cory Scott (3) and Blakeslee Eagan (4). TC indicates a past issue of Tennessee Concrete (5, 6). The red fill in Table 1 shows the obvious gap in current mixtures that the authors are attempting to address. TDOT 604.23 require bridge decks to be cured for at least seven days (1). The authors believe it would be ideal to reach the SR "Very Low" category in the TDOT required curing time. The authors believe this to be important since any additional curing is dependent on coating integrity or favorable weather conditions. Eagan (4) provided initial findings investigating this topic.

MATERIALS AND PROCEDURE

The materials shown in column 1 of Table 2 are TDOT-approved with the exception of metakaolin. The proportions of the six mixtures used in the study (see Table 2) were determined by trial batching. All six 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. All mixtures met Table 3 criteria except for the maximum SCM replacement percentage. Six batches of each mixture were produced and tested as per Table 4.

A Fortunate Near Miss

The authors were attempting to develop "Fast Lane" mixtures that would reach the SR "Very Low" chloride permeability category in 7 days or less. However, Table 1 also shows that there are no current TTU ternary mixtures that reach the "Low" category in 7 days or the "Very Low" category in 14 days. Therefore, even though early indications were that the 45% slag 3% metakaolin mixture would not be a "Fast Lane" mixture, six larger batches were made and tests were conducted out to 14 days.

RESULTS AND DATA QUALITY

Tables 5 and 6 show 7-day compressive strength and 7-day absorption results, respectively. SR results for 3, 5, and 7 days are shown in Table 7. In addition, 10 and 14-day SR results are shown for the 45% slag, 3% metakaolin mixture in Table 7. 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 (10). 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 (7). All hardened property test results met the acceptable precision criteria. Unfortunately, no precision criteria are available for hardened concrete absorption after boiling.

ANALYSIS OF RESULTS

Rate of Increase of SR Results

The curing time required to reach various SR chloride permeability categories are shown in Table 8 for mixtures from parts 1, 2, and 3. "Fast Lane" and "Near Fast Lane" mixtures are highlighted in green and light blue, respectively. Mixtures meeting current TDOT 604.03 Class D requirements for maximum SCM substitution are highlighted in yellow.

Figure 1 shows the development of SR of "Fast Lane" mixtures. A "Fast Lane" mixture is defined as a mixture that reaches the SR "Moderate," "Low," and "Very Low" SR chloride permeability categories by 3, 5, and 7 days, respectively. A ternary mixture (35% Slag / 15% Class F fly ash) and a mixture containing no SCMs meeting TDOT 604.03 Class D requirements are shown for speed references in Figure 1.

The development of SR of the "Near Fast Lane" mixture is shown in Figure 2. A "Near Fast Lane" mixture is defined as a mixture that reaches the SR "Moderate," "Low," and "Very Low" SR chloride permeability categories by 5, 7, and 14 days, respectively. A ternary mixture (35% Slag / 15% Class F fly ash), a 25% Class F fly ash mixture and a mixture containing no SCMs all meeting TDOT 604.03 Class D requirements are shown for speed references in Figure 2. Table 8 suggests that 60 and 65% Grade 120 Slag mixtures (from Part 2) may qualify as "Near Fast Lane" mixtures. Unfortunately, 5-day results are not available for these mixtures.

TABLE 2. MIXTURES USED

COMPONENT	60SL/5MK	55SL/5MK	55SL/4MK	60SL/3MK	45SL/3MK	70SL
Type I PC, (lbs/CY)	217	248	254.2	229.4	322.4	186
Grade 120 Slag, (lbs./CY)	372	341	341	372	279	434
Metakaolin, (lbs/CY)	31	31	24.8	18.6	18.6	0
No. 57 Stone, (SSD lbs/CY)	1862	1863	1864	1863	1865	1863
River Sand, (SSD lbs/CY)	1123	1123	1125	1123	1125	1125
Water, (lbs/CY)	229.5	229.5	229.5	229.5	229.5	229.5
Design Percent Air, (%)	7	7	7	7	7	7
Air Entrainer, (oz/cwt)	2.01	2.01	2.46	2.00	2.30	2.14
Mid-Range Water Reducer, (oz/cwt)	5.0	5.0	5.0	5.0	5.0	5.0
High-Range Water Reducer, (oz/cwt)	4.24	4.24	3.13	3.13	4.85	2.23

TABLE 3. COMPARISON OF MIXTURES USED WITH TDOT CLASS D PCC REQUIREMENTS

QUANTITY/RATIO/PERCENTAGE	TDOT 604.03 CLASS D PCC REQUIREMENT	60SL/5MK	55SL/5MK	55SL/4MK	60SL/3MK	45SL/3MK	70SL
Cementing Materials Content (lbs/CY)	620 minimum	620	620	620	620	620	620
W/CM Ratio	0.40 maximum	0.37	0.37	0.37	0.37	0.37	0.37
Percent Fine Aggregate by Total Aggregate Volume	44 maximum	38	38	38	38	38	38
Percent Grade 120 Slag Substitution (by Weight) for PC	35 maximum	60	55	55	60	45	70
Percent Metakaolin Substitution (by Weight) for PC	Not Allowed	5	5	4	3	3	0

TABLE 4. TESTING PROTOCOL USED TO EVALUATE EACH MIXTURE

TEST METHOD	FREQUENCY	SPECIMENS
Compressive Strength, AASHTO T22 (7)	3 @ 7 days	4 x 8 cyinders
Surface Resistivity, AASHTO T 95-11 (8)	3 @ 3, 5, and 7 days	7-day compressive strength 4 x 8 cylinders
Hardened Concrete Absorption, ASTM C642 (9)	3 @ 7 days	3 x 6 cylinders

TABLE 5. 56-DAY MEAN SURFACE RESISTIVITY RESULTS FOR PC AND FLY ASH MIXTURES

MIXTURE	BATCH 1	BATCH 2	BATCH 3	BATCH 4	BATCH 5	BATCH 6	MEAN	RANGE	ALLOWABLE RANGE
60SL/5MK	6610	6560	6690	6670	6060	6370	6493	630	831
55SL/5MK	6440	6150	6480	6000	6270	6420	6293	480	806
55SL/4MK	6060	6030	5770	6290	6330	6200	6113	560	783
60SL/3MK	5920	6220	6280	5940	6010	5810	6030	470	772
45SL/3MK	5880	6230	6300	6360	6390	6130	6215	510	796
70SL	5320	5390	5480	5440	5310	5330	5378	170	688

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Part 3: Life in the Fast Lane

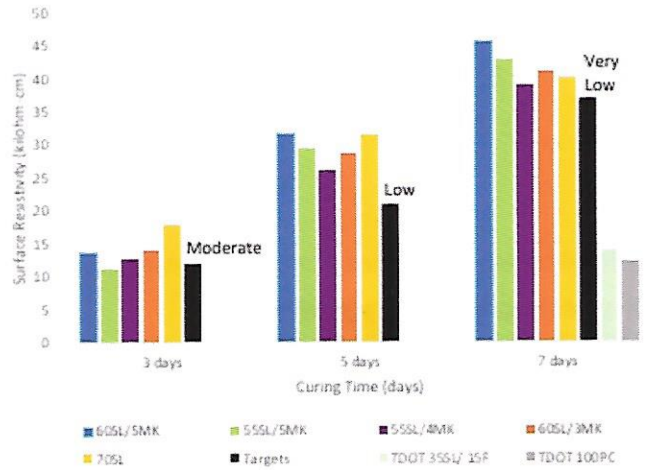

Figure 1: Surface Resistivity Development of Fast Lane Mixtures

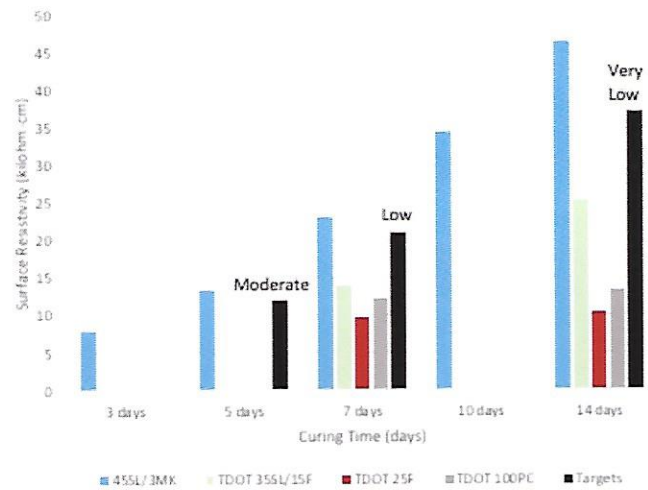

Figure 2: Surface Resistivity Development of the Near Fast Lane Mixture

Table 9 shows an update of the 7 and 14-day rows of Table 1. "Fast Lane" and "Near Fast Lane" mixtures are included in Table 9. "Fast Lane" and "Near Fast Lane" mixtures are highlighted in green and light blue, respectively. Mixtures meeting current TDOT 604.03 Class D requirements for maximum SCM substitution are highlighted in yellow. This update means there is a now a binary and ternary mixture choice for the 7 and 14-day "Low" and "Very Low" SR chloride permeability categories.

Compressive Strength Analysis

The 7-day compressive strength results shown in Table 5 all exceed the 28-day TDOT Class D specification requirement by at least 1300-psi. The results for the six mixtures in the study appear to have no discernable trend on compressive strength as percent slag substitution increases.

Absorption Analysis

The hardened concrete absorption after boiling results shown in Table 6 are acceptable but not exceptional when compared to high performance concrete results of less than 5.0% (11). The results for the all six mixtures in the study range from 5.60 to 6.04% and appear to have no discernable trend on the absorption after boiling as percent slag substitution increases.

Material Cost Analysis

Table 10 (*see page 28*) shows material cost assumptions for concrete materials except water. Calculations using Table 2 mixture proportions and Table 10 cost assumptions were used to generate Figure 3. Slag mixture costs from Part 2 and 25% Class F fly ash mixture costs from Part 1 of the study are shown in Figure 3 for comparison. The ternary "Fast Lane" mixtures all have a higher cost than the Grade 120 Slag mixtures from Part 2. Using the TDOT-approved 25% Class F fly ash mixture from Part 1 as a standard for reference, "Fast Lane" and "Near Fast Lane" mixtures ranged from 3.5 to 17.7% higher in cost. Therefore, material cost would not be a major factor in mixture choice.

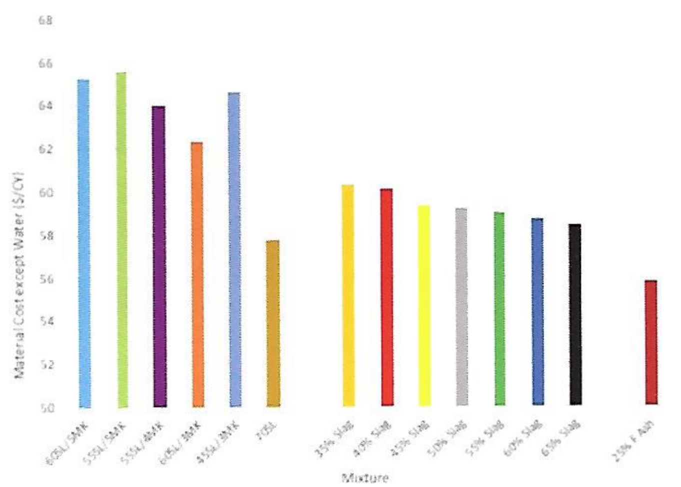

Figure 3: Material Cost Comparisons

TABLE 6. 7-DAY ABSORPTION AFTER BOILING RESULTS AND RANGE (%)

MIXTURE	BATCH 1	BATCH 2	BATCH 3	BATCH 4	BATCH 5	BATCH 6	MEAN	RANGE
60SL/5MK	5.48	5.78	5.76	5.70	5.92	5.55	5.70	0.44
55SL/5MK	5.63	5.39	5.81	5.52	5.65	5.59	5.60	0.42
55SL/4MK	5.88	6.02	5.96	6.22	5.95	6.23	6.04	0.35
60SL/3MK	5.78	5.79	5.85	5.74	5.70	5.69	5.76	0.16
45SL/3MK*	5.66	5.56	5.71	5.42	5.65	5.61	5.60	0.29
70SL	5.98	6.05	5.93	5.98	6.10	6.19	6.04	0.26

*7-day not available, 14-day results shown

TABLE 7. SURFACE RESISTIVITY RESULTS AND DATA QUALITY

MIXTURE	TEST AGE (DAYS)	MEAN RESULT (kΩ-CM)	RANGE OF RESULTS (kΩ-CM)	ALLOWABLE RANGE OF RESULTS (kΩ-CM)
60SL/5MK	3	13.7	1.5	6.9
60SL/5MK	5	31.7	1.7	15.9
60SL/5MK	7	45.5	2.2	22.7
5SL/5MK	3	11.2	1.3	5.6
5SL/5MK	5	29.3	1.2	14.7
5SL/5MK	7	42.8	1.5	21.4
55SL/4MK	3	12.6	0.8	6.3
55SL/4MK	5	26.0	2.0	13.0
55SL/4MK	7	38.9	4.2	19.4
60SL/3MK	3	14.1	0.8	7.1
60SL/3MK	5	28.7	1.8	14.3
60SL/3MK	7	40.9	2.3	20.5
45SL/3MK	3	7.9	0.8	4.0
45SL/3MK	5	13.3	0.7	6.7
45SL/3MK	7	23.1	0.8	11.5
45SL/3MK	10	34.5	1.5	17.2
45SL/3MK	14	46.4	2.3	23.2
70SL	3	17.8	2	8.9
70SL	5	31.5	3.6	15.8
70SL	7	40.0	3.6	20.0

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Part 3: Life in the Fast Lane

Cautionary Statement

Life in the "Fast Lane" can be very exciting. However, caution should be exercised to maintain control over the situation. "Fast Lane" and "Near Fast Lane" mixtures are considerably diverse when compared to current TDOT Class D mixtures. "Fast Lane" and "Near Fast Lane" mixtures should be thoroughly verified in the laboratory prior to use. If the laboratory investigations are deemed acceptable, an experimental field placement should be placed and monitored for further verification.

CONCLUSIONS

Life in the fast lane (low permeability) is possible. Four ternary and one binary concrete mixture were developed that achieved "Moderate," "Low," and "Very Low" SR permeability categories at 3, 5 and 7 days, respectively. The mixtures developed could reach the SR "Very Low" permeability category within the 7-day minimum curing period required by TDOT 604.23 specifications. Doing so, these mixtures would not be dependent on coating integrity or favorable weather for additional curing. All of the mixtures met and exceeded TDOT 604.03 Class D plastic and hardened concrete property requirements while exceeding the specification's allowable SCM substitutions.

DISCLAIMER

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

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Continued on page 28▶

TABLE 8. COMPARISON OF CURING TIMES REQUIRED TO REACH SURFACE RESISTIVITY CHLORIDE PERMEABILITY CATEGORIES FOR CURRENT STUDY MIXTURES

MIXTURE	MODERATE (SR ≥ 12) (2000 ≤ RCP ≤ 4000)	LOW (SR ≥ 21) (1000 ≤ RCP ≤ 2000)	VERY LOW (SR ≥ 37) (100 ≤ RCP ≤ 1000)
60SL/5MK	3 days	5 days	< 7 days
55SL/5MK	< 5 days	5 days	< 7 days
55SL/4MK	3 days	5 days	7 days
60SL/3MK	3 days	5 days	7 days
45SL/3MK	5 days	7 days	< 14 days
70% Grade 120 Slag	< 3 days	< 7 days	7 days
65% Grade 120 Slag	< 7 days	7 days	14 days
60% Grade 120 Slag	< 7 days	7 days	14 days
55% Grade 120 Slag	7 days	14 days	21 days
50% Grade 120 Slag	7 days	14 days	28 days
45% Grade 120 Slag	7 days	14 days	42 days
40% Grade 120 Slag	7 days	14 days	56 days
35% Grade 120 Slag	7 days	14 days	Did Not Reach
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 9. CURING TIME REQUIRED FOR SOME MIXTURES TO REACH SURFACE RESISTIVITY CHLORIDE PERMEABILITY CATEGORIES

CURING DAYS	MODERATE (SR ≥ 12) (2000 ≤ RCP ≤ 4000)	LOW (SR ≥ 21) (1000 ≤ RCP ≤ 2000)	VERY LOW (SR ≥ 37) (100 ≤ RCP ≤ 1000)
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14	5SF25C (Eagan)	35SL (Current) 40-55SL (Current) 35SL/15F (Smith) 30SL/20F (Smith) 35SL25F (Scott) 3.5MK20F (Eagan) 5MK25C (Eagan)	60 or 65SL (Current) 45SL/3MK

See Table 10 on page 29 ►

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TABLE 10. COST ASSUMPTIONS

COMPONENT	ASSUMED COST FOR READY MIX PRODUCER
Type I PC, ($/ton)	$110.00
Class F Fly Ash, ($/ton)	$30.00
Class C Fly Ash, ($/ton)	$50.00
Grade 120 Slag, ($/ton)	$85.00*
Silica Fume, ($/ton)	$1,000.00*
Metakaolin, ($/ton)	$473.00*
No. 57 Limestone, ($/ton)	$18.00
River Sand, ($/ton)	$15.00
Air Entrainer, ($/gallon)	$4.50
Mid-Range Water Reducer, ($/gallon)	$8.50
High-Range Water Reduced, ($/gallon)	$12.00

*Plus freight