Preliminary Investigation of Higher Grade 100 Slag Substitutions in a Tennessee Bridge Deck Concrete Mixture

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ABSTRACT

ASTM C 989M-18 Ground granulated blast furnace slag (GGBFS) can be substituted for ASTM C 150M-18 Portland cement (PC) in concrete mixtures to reduce the amount of carbon emissions from PC production and make the concrete mixture more environmentally sustainable. This preliminary study investigates if higher substitution rates ($\geq 35\%$) of GGBFS improve concrete properties for bridge deck applications, as well as reduce carbon emissions.

Tennessee Department of Transportation (TDOT) Class D (bridge deck) concrete was selected as the application for this preliminary investigation. Seven mixtures with different substitution rates (35% to 65%) of Grade 100 GGBFS meeting TDOT Class D plastic property requirements were used to characterize the effect of higher GGBFS substitutions. A TDOT Class D mixture with a 100% PC binder was used as a basis for comparison.

Six batches of each mixture were tested. Surface resistivity, AASHTO T358-17, was measured at 7, 14, 28, 42, and 56 days. Compressive strength, ASTM C 39M-18, was measured at 28 and 56 days. Absorption after boiling, ASTM C 642-13, was measured at 56 days.

All mixtures met TDOT 28-day Class D compressive strength requirements of 4000-psi (27.6-MPa). The surface resistivity results of the Grade 100 GGBFS mixtures were statistically superior to the 100% PC mixtures at all testing intervals. All absorption after boiling results for variable and control mixtures were below the 5% maximum for high performance concrete (HPC). The majority of GGBFS replacement rates showed no significant difference or were inferior to the 100% PC mixture absorption after boiling.

Introduction

Approximately four percent of the worlds Carbon Dioxide emissions are generated from producing PC [1]. By incorporating supplementary cementitious materials (SCM’s), like Grade 100 GGBFS, these emissions can be reduced dramatically and conserve natural resources. The use of GGBFS not only has an environmental impact, but also helps save money due to the high cost of PC. By incorporating GGBFS in concrete, the cost of storing the by-products in waste landfills, which in return is beneficial to the environment. The incorporation of SCM's in concrete is also highly beneficial to concrete properties.

The Slag Cement Association recommends slag substitution levels of 25 to 65% to lower concrete permeability [2]. Therefore, the research team decided to start with a 35% slag substitution since it is the highest substitution currently allowed by TDOT Class D concrete specifications [3].

Literature Review

The search for a lower permeability Portland Cement Concrete (PCC) to be used for bridge decks has been long ongoing at TDOT. By decreasing the permeability in TDOT's Class D (bridge deck) concrete, this lowers the amount of degrading chloride ions from salt deicers to penetrate the concrete, causing the reinforcing steel to corrode. When steel corrodes, the rust that is formed creates tensile stresses in the concrete. These stresses can lead to cracking and spalling and decrease the service life of the bridge deck. This increases the need for continued maintenance, which results in higher tax increases for Tennessee residents. A study performed by the Federal Highway Administration (FHWA) in 2013 showed that in order to repair all the bridges in America that need rehabilitation, it would cost over 31.6 billion dollars [4]. With the use of lower permeability PCC bridge decks, there would be a delay in the need for bridge rehabilitation, maintenance, and reconstruction. If there are fewer reconstruction periods, this would result in less traffic issues and also allow the government to save money for use on other projects. With the cost of repair and reconstruction on the rise, there is a greater motivation to lower concrete permeability. By increasing the durability of PCC, this allows infrastructure to have a longer service life.

The use of a test method called Surface Resistivity (SR), is slowly becoming adopted instead of the Rapid Chloride Permeability Test (RCPT). SR was adopted by the American Association of State Highway and Transportation Officials (AASHTO) in 2017 as a standardized test method, T 358. SR is a non-destructive test method that measures the chloride penetration resistance of concrete [5]. SR is a very desirable test method that has proven to require less time, resources, money, and manpower.

High durability and strength, and low permeability concrete are three of the most important factors for bridge decks. Low permeability concrete slows chloride ions from infiltrating through the concrete and corroding the reinforcing steel. High strength and durability concrete allow bridge decks to withstand more abrasion and higher loading for longer periods of time.

The use of GGBFS as an SCM can be traced back to 1774 when it was combined with slaked lime to be used as a mortar. The production of GGBFS in the United States was started in 1896 [6,7]. When iron is being produced, blast furnaces are loaded with iron ore, coke, and fluxing agents. The iron ore is made up of iron oxides, silica, and alumina. When the products form together with the fluxing agents, molten iron and slag are produced [8]. Blast-furnace slag (BFS) is the nonmetallic product that is formed in a liquefied condition simultaneously with iron in a blast furnace. GGBFS is the glass-like granular material that is formed when molten BFS is cooled rapidly [9]. This cooling process is achieved by quenching the molten slag with water jets [8,9].

GGBFS has three grade classifications. These classifications consist of Grade 80, 100, and 120. These are determined in accordance to the slag's performance in the slag activity test. To determine the reactivity of the GGBFS, a compression test is performed on mortar cubes consisting of PC and compared to cubes consisting of equal portions of GGBFS and PC [9]. Comparing the three grades of slag to PC: Grade 120 slag produces lower early strengths but increased strengths at 7 days or later, Grade 100 slag produces lower early strengths but equal or greater strengths at 21 days, and Grade 80 slag produces reduced strengths at all ages [7]. The use of Grade 100 Slag can outperform typical PCC in early and later ages due to the rapid silica and calcium hydration properties [10]. GGBFS has a greater surface area compared to PC which allows the GGBFS concrete to have a lower permeability and a higher durability.

Not only is GGBFS a highly effective cementitious material, it also greatly improves the environmental effects by lowering the greenhouse gas and embodied energy levels that are attributable to concrete [11]. Slag is highly beneficial to most concrete properties when a 30-45% substitution is used in place of PC [11,12].

Slag exhibits both pozzolanic and cementitious properties, meaning slag itself hardens when chemically reacted with water [13]. Some appealing plastic property attributes GGBFS provides, when it is used as a partial cement replacement, are workability and an increased ability to pump GGBFS concrete [13]. These workability improvements are due to the smooth, glass-like surface characteristics of the slag particles. The surface and chemical properties of GGBFS allow small amounts of water to be absorbed, resulting in the paste to be more fluid, workable, and a reduction in water demand [7,11]. This phenomenon also allows the setting time to be slower than regular PCC. The curing effects GGBFS has on concrete is very similar to a basic PCC. Curing can possibly take longer for GGBFS concretes due to the fact that GGBFS concrete typically develops strength more slowly. When GGBFS is combined with PC and water, a greater calcium-silicate hydrate (CSH) enriched binder is produced. The pores in concrete naturally contain calcium hydroxide and are filled in part with CSH. This results in a denser cement paste, reduces the permeability, and increases the durability of the hardened concrete [11].

GGBFS also greatly benefits the hardened properties of concrete [11,13]. The hardened concrete properties GGBFS can improve are as follows: heat of hydration, salt scaling, resistance to alkali-aggregate reactivity, and resistance to sulfate attack [11,13]. Two other important hardened properties slag can increase are lowering permeability and high strength development [13]. Slag can also reduce the internal heat buildup in concrete structures because it lowers the internal heat of hydration. This is especially beneficial in mass concrete structures, like dams, because it helps prevent cracking. The use of GGBFS can reduce the amount of reactive elements, like calcium, thus improving the concrete's ability to resist sulfate attack. Lastly, GGBFS can reduce the potential of concrete expansion due to alkali-silica reaction (ASR). The additional CSH that slag helps produce, chemically ties up alkali-s in the concrete by decreasing its reactivity [13].

Materials and Procedure

TDOT-approved materials used in the study are shown in Table 1, column 1. The proportions of the eight mixtures used in the study (see Table 1) were determined through trial batching. After trialing, all eight mixtures met TDOT Class D concrete plastic and hardened property requirements. Table 2 shows TDOT requirements for minimum cementing materials, w/cm ratio, fine aggregate percentage by total aggregate volume, and allowable SCM replacement percentages. The first two mixtures, 0 and 35% Slag, met all Table 2 criteria, whereas mixtures 40% through 65%, indicated in red, met all criteria except maximum TDOT allowable SCM replacement percentage. Six batches of each mixture were made and tested as per Table 3.

Table 1: Mixtures Used to Evaluate Slag Replacement Percentage Effect

	0% Slag	35% Slag	40% Slag	45% Slag	50% Slag	55% Slag	60% Slag	65% Slag
Type I PC, lbs/CY (kg/m^3)	620 (368)	403 (239)	372 (221)	341 (202)	310 (184)	279 (166)	248 (147)	217 (129)
Grade 100 Slag, lbs/CY (kg/m^3)	0	217 (129)	248 (147)	279 (166)	310 (184)	341 (202)	372 (221)	403 (239)
No. 57 Stone, SSD lbs/CY (kg/m^3)	1890 (1121)	1867 (1108)	1870 (1109)	1867 (1108)	1865 (1106)	1865 (1106)	1866 (1107)	1865 (1106)
River Sand, SSD lbs/CY (kg/m^3)	1135 (673)	1128 (669)	1127 (669)	1126 (668)	1125 (667)	1124 (667)	1125 (667)	1125 (667)
Water, lbs/CY (kg/m^3)	229.5 (136)	229.5 (136)	229.5 (136)	229.5 (136)	229.5 (136)	229.5 (136)	229.5 (136)	229.5 (136)
Design Percent Air	7	7	7	7	7	7	7	7
Air Entrainer, oz/CY (mL/m^3)	2.5 (97)	2.2 (85)	3.7 (143)	3.7 (143)	3.7 (143)	3.7 (143)	3.7 (143)	4.7 (182)
Mid-Range Water Reducer, oz/CY (mL/m^3)	22.9 (887)	18.6 (720)	24.8 (960)	22.9 (887)	24.8 (960)	24.8 (960)	24.8 (960)	24.8 (960)
High-Range Water Reducer, oz/CY (mL/m^3)	27.0 (1045)	24.8 (960)	23.9 (925)	19.2 (743)	21.1 (817)	22.9 (887)	23.9 (925)	24.8 (960)

Table 2: Comparison of Study Mixtures with TDOT Class D PCC Requirements

Mixture ID	Cementing Materials Content, lbs/CY (kg/m^3)	W/CM Ratio	Percent Fine Aggregate by Total Aggregate Volume	Percent Grade 100 Slag Substitution (by Weight) for PC
0	620 (368)	0.37	38	0
35	620 (368)	0.37	38	35
40	620 (368)	0.37	38	**40**
45	620 (368)	0.37	38	**45**
50	620 (368)	0.37	38	**50**
55	620 (368)	0.37	38	**55**
60	620 (368)	0.37	38	**60**
65	620 (368)	0.37	38	**65**
TDOT 604.03 Class D PCC Requirements	620 (368) minimum	0.40 maximum	44 maximum	35 maximum for Grade 100 Slag

Table 3: Testing Protocol for the Study

Test Method	Frequency	Specimens
Compressive Strength, AASHTO T22 [14]	3 @ 28 and 56 days	4 x 8-inch (100 x 200-mm) cylinders
Surface Resistivity, AASHTO T 358 -17 [15]	3 @ 7, 14, 21, 28, 42 and 56 days	56-day compressive strength 4 x 8-inch (100 x 200-mm) cylinders
Hardened Concrete Absorption, ASTM C642 [16]	3 @ 56 days	3 x 6 (75 x 150-mm) cylinders

Results and Data Quality

Tables 4 and 5 show 28-day compressive strength and 56-day absorption results, respectively. The SR results are shown in Table 6 for 7, 14, 21, 28, 42 and 56 days. The acceptable range of the hardened properties results was determined by obtaining the standard deviation or coefficient of variation from the appropriate test method and multiplying by the corresponding ASTM C 670 factor for the number of test results [17]. The multi-laboratory precision was used for the 4×8-inch (100×200-mm) cylinder results, since AASHTO T 22 states that the preparation of cylinders by different operators would probably increase the variation above multi-laboratory precision criteria [14]. All hardened property test results met the acceptable precision criteria except the 0 and 40 percent slag compressive strengths, indicated below in red in Table 4. Unfortunately, no precision criteria are available for hardened concrete absorption after boiling.

Table 4: 28-day Compressive Strength Results and Data Quality, psi (MPa)

% Slag	Batch 1	Batch 2	Batch 3	Batch 4	Batch 5	Batch 6	Mean	Range	Allowable Range
0	7300 (50.3)	7410 (51.1)	7050 (48.6)	8410 (58.0)	8240 (56.8)	7710 (53.2)	7687 (53.0)	**1405** (**9.7**)	984 (6.8)
35	9330 (64.3)	8800 (60.7)	9120 (62.9)	9050 (62.4)	8680 (59.8)	9170 (63.2)	9025 (62.2)	650 (4.5)	1155 (8.0)
40	9950 (68.6)	9090 (62.7)	9580 (66.1)	9780 (67.4)	8270 (57.0)	9350 (64.5)	9337 (64.4)	**1680** (**11.6**)	1195 (8.2)
45	8970 (61.8)	9030 (62.3)	8360 (57.6)	9050 (62.4)	9280 (64.0)	9360 (64.5)	9008 (62.1)	1000 (6.9)	1153 (7.9)
50	9230 (63.6)	9670 (66.7)	9560 (65.9)	8970 (61.8)	9620 (66.3)	9310 (64.2)	9393 (64.8)	700 (4.8)	1202 (8.3)
55	9300 (64.1)	9200 (63.4)	9730 (67.1)	9040 (62.3)	8860 (61.1)	8810 (60.7)	9157 (63.1)	920 (6.3)	1172 (8.1)
60	8870 (61.2)	8960 (61.8)	9050 (62.4)	9280 (64.0)	9470 (65.3)	9490 (65.4)	9187 (63.3)	620 (4.3)	1176 (8.1)
65	8890 (61.3)	8510 (58.7)	8630 (59.5)	8610 (59.4)	8900 (61.4)	8490 (58.5)	8672 (59.8)	410 (2.8)	1110 (7.7)

Table 5: 56-day Absorption after Boiling Results and Ranges (%)

% Slag	Batch 1	Batch 2	Batch 3	Batch 4	Batch 5	Batch 6	Mean	Range
0	4.26	4.18	4.38	4.28	4.23	4.28	4.27	0.20
35	4.23	4.37	4.26	4.38	4.45	4.72	4.40	0.49
40	4.06	4.11	4.48	4.22	4.38	4.74	4.33	0.68
45	4.80	4.53	4.78	4.36	4.55	4.62	4.61	0.44
50	4.68	4.43	4.60	4.58	4.39	4.63	4.55	0.29
55	4.67	4.87	4.02	4.30	3.47	3.52	4.14	1.40
60	4.22	3.78	3.76	4.28	4.42	4.48	4.16	0.72
65	3.88	3.55	3.60	3.59	3.85	3.57	3.67	0.33

Table 6: Surface Resistivity Results and Data Quality

Slag Substitution (%)	Test Age (days)	Mean Result (kΩ-cm)	Range of Results (kΩ-cm)	Allowable Range of Results (kΩ-cm)
0	7	12.6	1.4	6.3
0	14	13.6	1.6	6.8
0	21	15.3	0.7	7.7
0	28	16.0	0.7	8.0
0	42	19.3	1.3	9.7
0	56	20.1	1.1	10.0
35	7	15.0	2.0	7.5
35	14	34.6	2.6	17.3
35	21	49.0	5.6	24.5
35	28	59.8	5.3	29.9
35	42	74.5	3.4	37.3
35	56	77.6	8.0	38.8
40	7	15.3	1.5	7.6
40	14	38.1	3.2	19.0
40	21	56.0	6.4	28.0
40	28	70.1	6.4	35.0
40	42	78.8	7.0	39.4
40	56	87.0	6.9	43.5
45	7	15.8	1.8	7.9
45	14	38.4	3.3	19.2
45	21	57.9	15.7	28.9
45	28	68.2	7.6	34.1
45	42	77.4	11.1	38.7
45	56	81.0	10.0	40.5
50	7	17.7	3.1	8.9
50	14	43.1	6.5	21.5
50	21	58.1	6.4	29.0
50	28	68.9	5.6	34.4
50	42	79.0	5.0	39.5
50	56	79.7	5.9	39.8

Table 6: Surface Resistivity Results and Data Quality (continued)

Slag Substitution (%)	Test Age (days)	Mean Result (kΩ-cm)	Range of Results (kΩ-cm)	Allowable Range of Results (kΩ-cm)
55	7	24.3	8.7	12.1
55	14	51.8	10.9	25.9
55	21	68.9	7.7	34.4
55	28	80.7	17.6	40.3
55	42	93.9	40.8	46.9
55	56	107.4	30.4	53.7
60	7	21.7	2.7	10.9
60	14	56.5	8.0	28.3
60	21	77.6	12.4	38.8
60	28	92.3	22.7	46.1
60	42	104.6	21.8	52.3
60	56	114.9	8.7	57.5
65	7	19.5	1.3	9.8
65	14	49.4	5.0	24.7
65	21	70.0	7.0	35.0
65	28	78.0	3.3	39.0
65	42	83.1	6.2	41.5
65	56	90.9	3.5	45.5

Analysis of Results

Statistical Comparison of SR Results

Table 7 shows a statistical analysis on the SR results for the Grade 100 GGBFS PCC versus the 100% PCC mixtures. A two-sample t-test was used to evaluate the hardened property means of both PCCs. It was assumed that the variances were unequal with a 95 percent confidence interval. In order to show any significant statistical differences between the two PCCs, the t-statistic needed to be positive and greater than the corresponding t-critical values for the SR comparison.

Each Grade 100 GGBFS PCC mixture was compared to the single 100% PCC mixture by using a two-sample t-test to determine which mixture had the highest electrical resistance or surface resistivity. The SR testing was performed on each of the PCCs at 7, 14, 21, 28, 42, and 56 days with using the same three cylinders throughout. Since surface resistivity is dependent on the concrete's pore structure, the use of additional SCMs in the Grade 100 GGBFS PCC mixtures reduce the pore connectivity and increases the SR of each cylinder [18]. The results showed that the Grade 100 GGBFS mixtures at all substitution rates were significantly superior to the 100% PC concrete at all testing ages. Lower permeability, should slow the process of chloride ion ingress into bridge decks, ultimately extending the service life of the bridge deck. The green shaded cells in Tables 7 indicate a statistically significant difference with the slag mixture being superior to the 100 percent PC mixture in SR.

Table 7: Statistical Analysis Comparing Slag Mixtures with 100% PC at a Given Curing Time

	7 days	14 days	21 days	28 days	42 days	56 days
35% vs PC	SD	SD	SD	SD	SD	SD
40% vs PC	SD	SD	SD	SD	SD	SD
45% vs PC	SD	SD	SD	SD	SD	SD
50% vs PC	SD	SD	SD	SD	SD	SD
55% vs PC	SD	SD	SD	SD	SD	SD
60% vs PC	SD	SD	SD	SD	SD	SD
65% vs PC	SD	SD	SD	SD	SD	SD

Graphical Comparison of SR Results

Table 6 and Figure 1 show the decline of SR above 60 percent slag substitution for all ages. Therefore, it may not be desirable to consider slag substitution levels greater than 60 percent for TDOT bridge deck concrete mixtures. Figure 2 shows a graphical comparison of mixtures used in the study. The superiority of mixtures containing 35 percent or more slag to 100 percent PC mixtures becomes more apparent with increasing curing age.

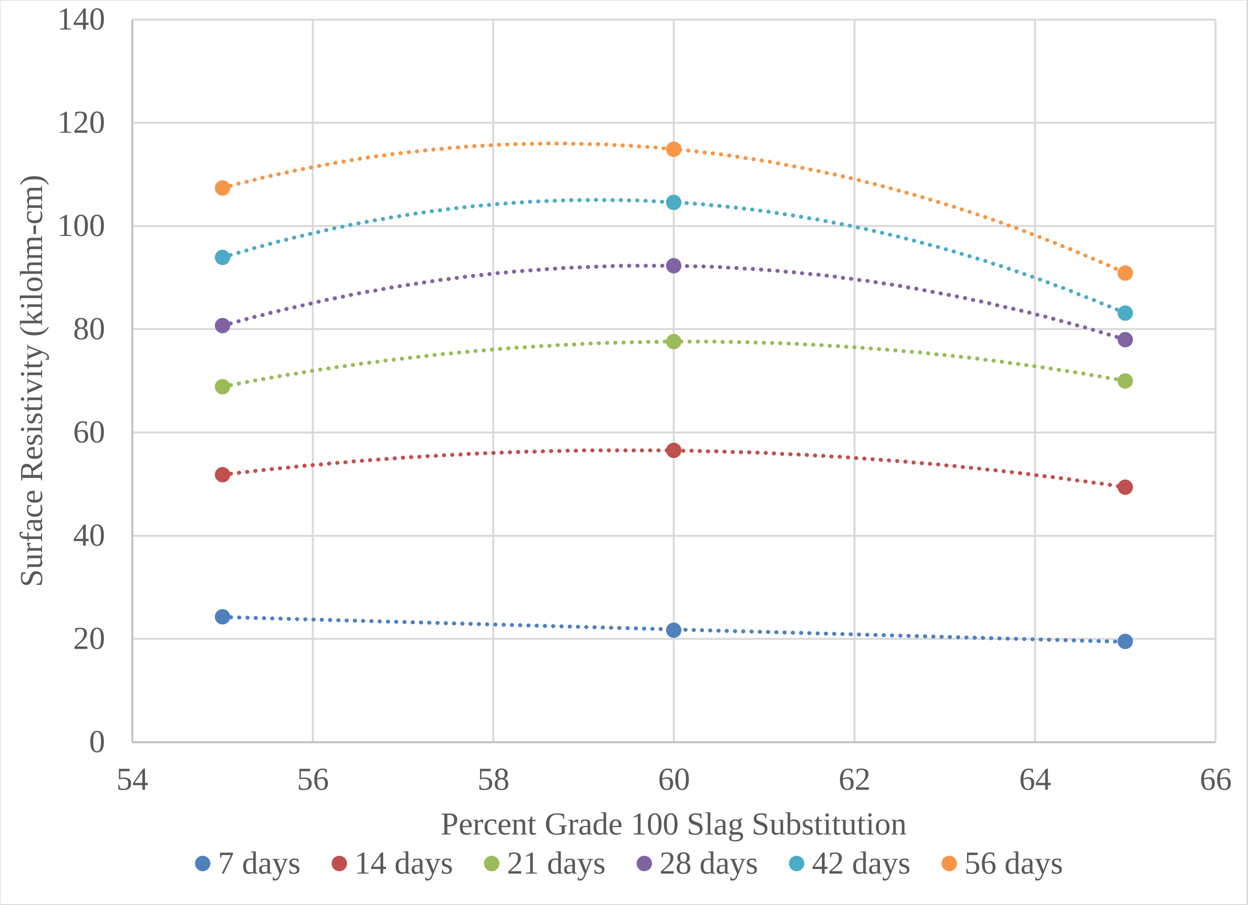

Figure 1: Surface Resistivity Decline in Slag Substitution above 60 Percent

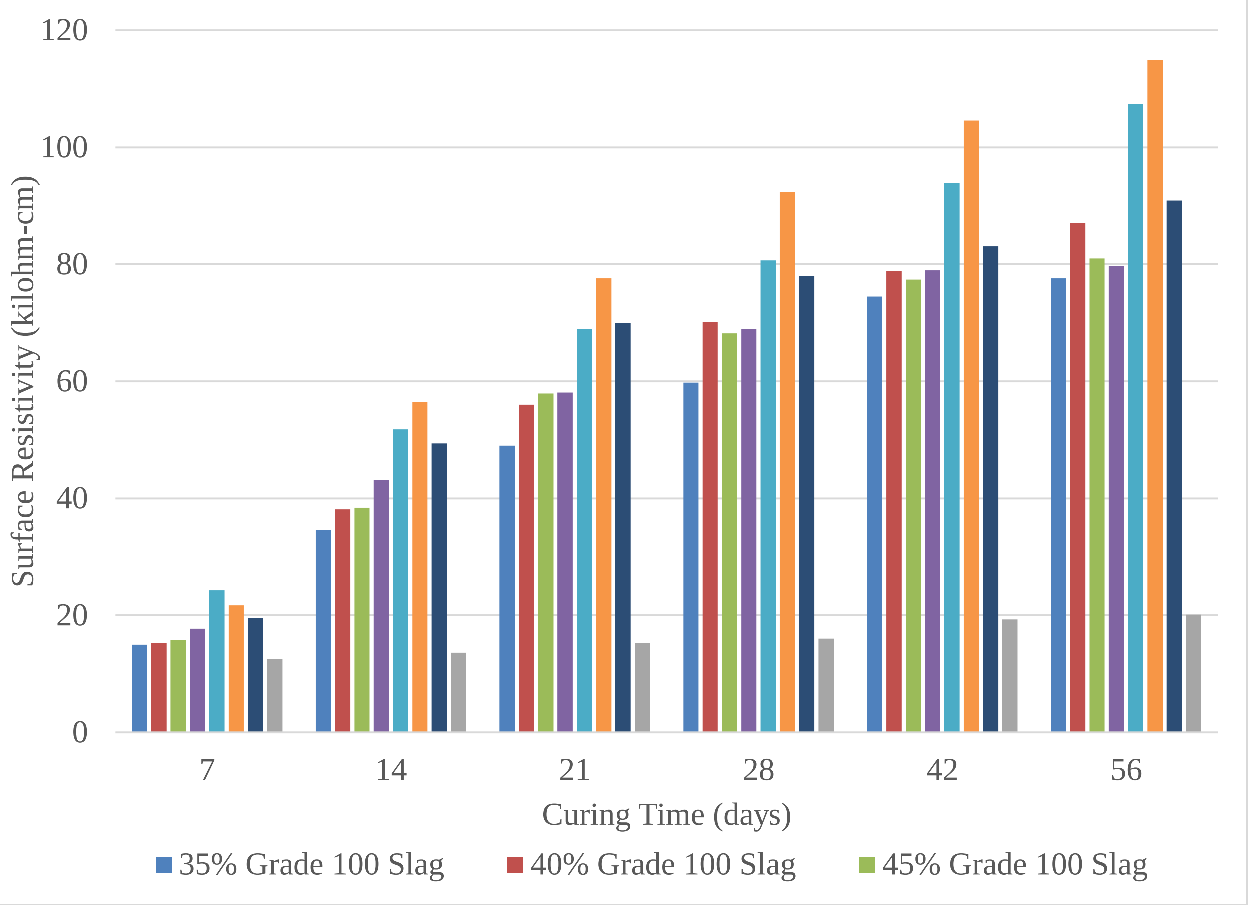

Figure 2: Effect of Slag Substitution on Surface Resistivity

Compressive Strength Analysis

A statistical analysis was not performed to compare the compressive strength of each mixture. The reason for this is, both the Grade 100 GGBFS and 100% PC mixture met TDOT 604.03 standards for hardened properties [3]. Due to the focus of this research being about the chloride ion ingress rate and permeability, it was only desired to get each mixture to at least meet the minimum allowable TDOT 604.03 standards, in which they all complied [3]. Table 4 shows that each concrete mixture surpassed the TDOT 4,000-psi (27.6-MPa) minimum compressive strength requirement at 28 days of curing [3].

Absorption Analysis

Table 5 shows that the 56-day absorption after boiling results are all below the five percent upper limit for high performance concrete [19]. Therefore, it is important to point out the absorption after boing results for all mixtures were very good. Each Grade 100 GGBFS PCC mixture was compared to the single 100% PCC mixture by using a two-sample t-test to determine which mixture had the lower absorption after boiling. Table 8 shows how each Grade 100 GGBFS mixture compared to the 100% PC concrete at 56 days. The absorption results coincide with other studies that the use of SCMs may decrease permeability but not necessarily porosity, therefore, this explains why most of the absorption results are inferior or NSD [20].

Table 8: Statistical Analysis Comparing Slag Mixtures Absorption after Boiling Results to 100% PC Results at 56-days

	35%	40%	45%	50%	55%	60%	65%
Portland Cement	NSD	NSD	Inferior	Inferior	NSD	NSD	Superior

Conclusion

Grade 100 GGBFS PCC has been shown to be significantly superior to TDOT Class D 100% PC, for bridge deck use, under ideal laboratory conditions. Both mixes exceeded the 28-day compressive strength TDOT 604.03 specification of 4000-psi (27.6-MPa) [3]. The GGBFS electrical resistance was significantly superior to the 100% PC at all testing intervals. This indicated that the GGBFS PCC had a statistically lower permeability, thus equating a slower rate of water and chloride ion ingress. The GGBFS PCC absorption was either inferior or showed no significant difference when comparing to 100% PCC, except for the 65% GGBFS, which was superior. However, all absorption levels were below the absorption upper limit of 5%. Based on the results, the use of SCMs should produce a more durable concrete when compared to the 100% PCC, along with providing a cheaper more environmentally friendly alternative for bridge deck PCC.

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Acknowledgements

The authors wish to gratefully acknowledge the support Meagan Dangle of Lafarge North America, and Denny Lind of BASF for their extensive donations of slag cement and chemical admixtures to the project. The authors appreciate the procurement help provided by the TCA.

In addition, the authors would like to thank Mark Davis for patience and skill in fabrication, maintenance, and repair of the equipment.

Further, we appreciate the financial support of the TTU Department of Civil and Environmental Engineering.

Finally, the authors appreciate the administrative, financial and information technology support provided by the TTU Center for Energy Systems Research.