Green^2: High Volume Slag Substitution in Pervious Concrete

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Abstract

Pervious concrete is already being used for drainage of developed areas. If a high substitution level of ground granulated blast furnace slag (GGBFS) can be used in pervious concrete, it can further increase environmental benefits. However, performance cannot be sacrificed for environmental benefits. Thus, the purpose of the research was to compare the hardened properties of pervious concrete with high volumes of GGBFS to those of similar pervious concrete without GGBFS. Four levels of substitution of GGBFS for portland cement were used in the treatment mixtures: 60, 70, 80, and 90% by volume of total cementing materials. The control mixture had 356-kg/m^3 (600-lbs/CY) of portland cement with a 0.3 w/cm ratio, 1389-kg/m^3 (2,341-lbs/CY) of coarse aggregate near the No. 89 gradation requirements, and 152-kg/m^3 (254-lbs/CY) of river sand. Eight replications of the control mixture yielded average 28-day compressive strength, static modulus of elasticity, effective voids, and constant head permeability values of 20.4-Mpa (2,960-psi), 15.9-GPa (2.30x10^6-psi), 30.2%, and 0.33-cm/sec (468-inches/hour), respectively. The test results from the control and treatment mixtures allowed the effect of high GGBFS substitution on compressive strength, static modulus of elasticity, effective voids, and permeability to be determined.

GGBFS substitution significantly increased the effective voids at all substitution levels compared to the control; the maximum increase in effective voids was less than 10% of the control value. Constant head permeability was increased significantly compared to the control for all cases, but mean permeability remained in the 0.33 to 0.47-cm/sec (468 to 667-inches/hour) range. Twenty-eight day compressive strengths, however, steadily declined as the GGBFS substitution percentage increased. Eight replications of each modified mixture yielded average 28-day compressive strengths of 17.7-Mpa (2,570-psi), 16.6-Mpa (2,410-psi), 15.7-Mpa (2,280-psi), and 13.1-Mpa (1,900-psi), respectively for 60, 70, 80, and 90% substitutions. All compressive strength reductions were statistically significant. Static modulus of elasticity values declined in a similar manner. Seven day compressive strengths were all above 5.2-Mpa (750-psi), indicating no foreseeable problems with form removal. The 80% substitution mixture could be used for most pervious concrete applications. The 90% substitution mixture has the potential for use as sidewalk and bike path applications.

Keywords: Blast Furnace Slag, Pervious Concrete, Ground Granulated Blast Furnace Slag, Slag Cement, Pozzolanic Cement

Introduction

Contractors need to incorporate recycled materials in structures to reduce the impact on the surrounding environment. Thus, incentives have been created for building structures that are "green". Going "green" implies the use of materials that reduce impact on the environment. The use of a by-product like slag, for example, can reduce the carbon footprint of pervious concrete; ground granulated blast furnace slag (GGBFS), when used as a cement substitute, has the potential to remove three million metric tons (3.3-million short tons) of carbon dioxide emissions annually ("Green in Practice 107", NA). Incidentally, pervious portland cement concrete is considered to be one of these "green" materials. Pervious concrete can provide adequate strength for some applications and still be permeable enough to allow for proper dissipation of storm water flows without disturbing local streams and waterways. Pervious concrete also aids in the removal of pollutants from runoff.

The objective of this research is to compare the hardened properties of a pervious concrete containing a high volume of GGBFS to those of a pervious concrete without GGBFS. Specifically, this research will attempt to determine the effects of high substitution levels of GGBFS on compressive strength, static modulus of elasticity, effective voids, and permeability. Therefore, several high substitution levels were used, ranging from 60 to 90%; using various levels of substitution allows for the effect GGBFS has on the hardened properties of pervious concrete to be determined. Pervious concrete pavement is already a material that is used to aid in drainage of developed areas. If a high level of GGBFS substitution can be used in pervious concrete, GGBFS can increase the environmental benefit of pervious concrete use. However, performance cannot be sacrificed for environmental benefits.

Literature Review

Pervious Concrete. Pervious portland cement concrete (PPCC) is described by the Portland Cement Association (PCA) as a combination of cementitious material and water that creates a thick paste to coat the aggregate. Very little, if any, fine aggregate is present in a PPCC, which allows for sizeable voids to form. The sizeable voids and thick paste help to bind the aggregate together, allowing the concrete to be more permeable. With the increased void structure, however, a reduction in strength will occur when compared to conventional concrete mixtures (Tennis, 2004).

Ground Granulated Blast Furnace Slag. GGBFS is created as a by-product of liquefying iron to create steel; it consists mostly of a crystalline mixture of calcium silicates and alumino-silicates ("Green in Practice 107", NA). GGBFS is classified in one of three grades: 80, 100, and 120, as per ASTM C 989; the grade denotes the reactivity level and is determined by a slag activity test (ASTM C 989, 2006). GGBFS provides a multitude of benefits in normal concrete, for both the plastic and hardened states; it can improve workability of the concrete in the plastic state, while improving compressive and flexural strength in the hardened state. GGBFS also improves durability by increasing resistance to chloride intrusion and corrosion ("Green in Practice 107", NA).

GGBFS in Pervious Concrete. Previous research conducted by Phillips (Phillips, 2009) at Tennessee Technological University (TTU) involved several lower substitution levels of grade 120 GGBFS in pervious concrete; these substitution levels were 12.5%, 25%, 37.5%, 50%, and 62.5%. The objective of this earlier research was to discover possible areas for future research. It was found that the sample compressive strength was higher, on average, than the control, which used only portland cement as the cementing material, for all substitution levels except 62.5% (Phillips, 2009). The compressive strength was lower at 62.5% level, but remained within 1.4-MPa (200-psi) of the control.

Compactive Effort in Pervious Concrete. Iowa State University in Ames, IA conducted research concerning the effect of compaction on pervious concrete. Two compaction methods were compared: one used a roller screed and the other used a weighted roller in which the number of passes made with the weighted roller was varied. The results showed that increasing the number of passes increased the unit weight of the pervious concrete. A higher unit weight, however, tends to decrease the amount of effective voids (Kevern, 2006).

Various compaction methods were employed in a research project conducted at TTU in an effort to examine the effect on the hardened properties of pervious concrete. The results showed that a higher compactive effort, combined with low cementitious content and a uniform aggregate gradation, creates the possibility of higher compressive strengths and higher permeabilities (Crouch[3], 2006). Research was also done to determine if current methods for preparation of pervious concrete specimens in the laboratory were appropriate. It was determined that rodding the cylinders did not correlate well with roller compacted field specimens; pneumatically pressed cylinders, however, did show a good correlation to roller compacted field specimens (Mahboub, 2009).

Methodology

Table 1 shows the gradation of the coarse aggregate used for the research and ASTM C33 requirements (ASTM C 33, 2006). Similarly, Table 2 shows the gradation of the fine aggregate used and ASTM C 33 fine aggregate requirements. The coarse aggregate used for the research was sold locally as a 9.5-mm (3/8-inch) crushed limestone; the fine aggregate used was river sand not meeting ASTM C 33 fine aggregate requirements, but commonly used as a concrete fine aggregate in middle Tennessee.

The objective of this research was to compare the hardened properties of a pervious concrete containing a high volume of GGBFS to those of a pervious concrete without GGBFS. Variable mixture designs were developed with GGBFS substitutions of 60, 70, 80, and 90% by volume of total cementing materials. The control mixture design (containing no GGBFS) is shown in Table 3. The cementing material proportions for all mixtures are shown in Table 4.

Table 1. Coarse Aggregate Used for the Project (% Finer by Mass)

Sieve Size, mm (sieve number)	Coarse Aggregate	ASTM C33 No. 8 Stone	ASTM C 33 No. 89 stone
12.5 (1/2-inch)	100	100	100
9.5 (3/8-inch)	99	85 - 100	90 - 100
4.75 (No. 4)	45	10 - 30	20 - 55
2.36 (No. 8)	3	0 - 10	5 - 30
1.18 (No. 16)	2	0 - 5	0 - 10
0.3 (No. 50)	1	…	0 - 5

Table 2. Fine Aggregate Used for the Project (% Finer by Mass)

Sieve Size (mm)	River Sand	Limestone Manufactured Sand	ASTM C 33 Fine Aggregate Requirements
9.5 (3/8-inch)	100	100	100
4.75 (No. 4)	98	100	95 - 100
2.36 (No.8)	91	96	80 - 100
1.18 (No.16)	82	66	50 - 85
0.6 (No. 30)	63	39	25 - 60
0.3 (No. 50)	9	20	5 - 30
0.15 (No. 100)	1	10	0 - 10
0.075 (No. 200)	0.3	6.3	Varies

Table 3. Control Pervious PCC Mixture Design

Component	Amount
Type I PC, kg/m³ (lbs/CY)	356 (600)
Limestone Coarse Aggregate, SSD, kg/m³ (lbs/CY)	1389 (2341)
River Sand, SSD, kg/m³ (lbs/CY)	151 (254)
Water, kg/m³ (lbs/CY)	107 (180)
Hydration Stabilizer, L/m³ (oz/CY)	0.93 (24)
Mid-Range Water Reducer, L/m³ (oz/CY)	1.16 (30)
Viscosity Modifier, L/m³ (oz/CY)	0.46 (12)

Table 4. Cementing Material Proportions

	Control	Variables			
Component	0%	60%	70%	80%	90%
Type 1 PC, kg/m^3 (lbs/CY)	356(600)	140 (240)	107 (180)	71.2 (120)	35.6 (60)
Grade 120 Slag, kg/m^3 (lbs/CY)	0	195 (329)	228 (384)	260 (439)	293 (494)

Eight batches of each mixture were produced. Each batch was mixed in an electric mixer according to ASTM C 192 (ASTM C 192, 2008). Six 100 x 200-mm (4 x 8-inch) cylinders were cast in reusable steel molds; each cylinder was cast in two layers and compacted using four blows per layer with a Marshall hammer (AASHTO T 245, 1998). The cylinders were then allowed to sit undisturbed for 2 days and, subsequently, de-molded and submerged in limewater until testing. The two day wait period for de-molding the specimens was used to ensure the specimens had acquired enough strength to not be damaged.

Two cylinders from each batch were used for both permeability testing and effective void determination and four cylinders were tested for compressive strength and modulus of elasticity. Permeability testing was conducted approximately 14 days after casting using a constant head triaxial flexible-wall permeameter, as described by Crouch (Crouch[2], 2006). These same cylinders were subsequently oven-dried for seven days and tested for effective void content, as per ASTM D 7063 (ASTM D 7063, 2005). The four remaining cylinders were sulfur capped according to ASTM C 617 (ASTM C 617, 2008) before each respective test, compressive strength or static modulus of elasticity. Compressive strength testing was performed at seven and 28 days according to ASTM C 39 (ASTM C 39, 2008); seven day compressive strength was done to ensure adequate strength was available for form removal. Static modulus of elasticity was determined at 28 days, as per ASTM C 469 (ASTM C 469, 2008).

Results

The average results from each test, permeability, effective voids, compressive strength, and static modulus of elasticity, are shown in Table 5. Seven-day compressive strength was not conducted on the control mixture since slow strength development was not a concern without supplementary cementing materials (SCMs).

Table 5. Engineering Property Results

Mixture	Mean Permeability, cm/sec (inches/hour)	Mean Effective Void Content, (%)	Mean 7-day Compressive Strength, MPa (psi)	Mean 28-day Compressive Strength, MPa (psi)	Mean 28-day Static Modulus of Elasticity, GPa (psi)
Control - 0%	0.33 (468)	30.2	Not Available	20.4 (2960)	15.9 (2.30×10^6)
60% Slag	0.44 (626)	31.9	12.8 (1860)	17.7 (2570)	16.0 (2.32×10^6)
70% Slag	0.40 (567)	31.3	13.4 (1950)	16.6 (2410)	14.1 (2.05×10^6)
80% Slag	0.47 (666)	32.9	10.9 (1590)	15.7 (2280)	13.5 (1.95×10^6)
90% Slag	0.38 (536)	32.7	9.6 (1390)	13.1 (1900)	12.5 (1.81×10^6)

Data Quality

Average Range of Individual Values. The authors wanted to determine the quality of the data prior to analysis. Unfortunately, no current ASTM pervious concrete test methods exist for the procedures performed in the research. Therefore, the authors subscribed to a “best currently available" philosophy. Table 6 shows the average range of values used to obtain a result for the test methods used in the research. The effective voids method chosen was for porous hot-mix asphalt. The static modulus of elasticity and compressive strength methods are for conventional (non-pervious) concrete. No ASTM test method was available for anything close to constant head laboratory permeability of pervious concrete.

The range of individual values used to produce a result for effective voids met available precision criteria for all mixtures except the 90%; this mixture was very close to meeting the criteria however. The average range of the individual tests used to produce a permeability result was high, but, as mentioned, there are no precision criteria available. The average range of the individual cylinders used to produce a 28-day compressive strength result met precision criteria for all mixtures. Seven day ranges were not computed since seven day results were only used to determine if form removal would excessively damage the pervious concrete. There are no precision criteria available for the range of individual 28-day static modulus of elasticity cylinders.

Table 6. Average Range of Individual Values Used to Obtain a Result

Mixture	Effective Void Content (%)	Permeability (%)	28-day Compressive Strength (%)	28-day Static Modulus of Elasticity (%)
Control	0.5	17.3	3.8	1.0
60% Slag	0.6	23.5	5.0	6.3
70% Slag	0.7	13.5	7.7	2.0
80% Slag	0.8	9.6	3.2	2.1
90% Slag	1.2	5.5	4.6	2.2
Single operator acceptable range of two results	1.0	Not Available	9.0	Not Available

Batch-to-Batch Variation of Results. The authors also wanted to determine the batch-to-batch variability prior to analysis. Table 7 shows the batch-to-batch variability for the test methods used in the research. Unfortunately, no current ASTM pervious concrete test methods exist for the procedures performed in the research. Therefore, the authors again subscribed to a "best currently available" philosophy. No batch-to-batch variability criteria were available for anything close to effective voids or permeability. ACI 214 (ACI 214, 2002) batch-to-batch criteria were selected for compressive strength even though they apply to normal concrete and not pervious concrete. All mixtures were rated either "Excellent" or "Very Good" by ACI 214 criteria. ASTM C 469 batch-to-batch variability criteria were used for static modulus even though they apply to conventional concrete. All of the mixtures, including the control, fell outside the 5% criteria for 28-day modulus of elasticity. The most probable reason for this is the open void surface of the pervious affecting the placement and stability of the compressometer.

Table 7. Batch-to-Batch Variation of Results

Mixture	Effective Void Content COV (%)	Permeability COV (%)	28-day Compressive Strength Overall Standard Deviation, MPa (psi)	28-day Static Modulus of Elasticity Average difference in results (%)
Control	1.3	11.1	0.3 (49)	6.5
60% Slag	2.6	17.2	1.6 (225)	13.0
70% Slag	3.1	17.8	1.7 (245)	12.7
80% Slag	2.7	20.4	1.4 (198)	9.7
90% Slag	2.0	15.6	0.7 (107)	9.0
Criteria	Not Available	Not Available	Excellent < 1.4 (200) Very Good 1.4 to 1.7 (200 to 250)	5.0

Analysis

Table 8 shows the results of the paired t-test at the 5% level of significance for permeability, compressive strength, static modulus of elasticity, and effective voids. A critical t-value of 2.365 was used based on seven degrees of freedom. Table 9 shows the percent difference between the selected average variable mixture property and the same property of the average control mixture. Negative values indicate a reduction in that property compared to the average control mixture.

Effective Void Content. The effective void content of the control mixture was significantly lower than that of all other mixtures. However, the maximum increase in effective voids was less than 10% of the control value. The effective voids of the 60% mixture were significantly lower than those of the 80% and 90% mixtures. The effective voids of the 70% mixture were significantly lower than those of the 80% and 90% mixtures. Figure 1 shows the mean effective void content versus percent slag substitution. The coefficient of determination, 0.73, was not impressive. However, if the 70% mean value is removed, the coefficient of determination increases to 0.97, which is very impressive.

Table 8. Paired t-tests Results

Mixture	Test Method	60% Slag	70% Slag	80% Slag	90% Slag
Control	permeability	3.633	2.606	3.437	2.391
	strength	4.982	6.431	10.522	51.761
	modulus	0.012	3.331	7.358	13.915
	voids	6.570	3.192	10.315	16.206
60% Slag	permeability	…	0.850	0.496	1.468
	strength	…	1.372	3.136	10.367
	modulus	…	2.386	3.858	5.769
	voids	…	1.465	2.485	2.410
70% Slag	permeability	…	…	1.286	0.500
	strength	…	…	1.265	6.605
	modulus	…	…	1.097	2.894
	voids	…	…	4.152	4.138
80% Slag	permeability	…	…	…	7.839
	strength	…	…	…	6.024
	modulus	…	…	…	2.049
	voids	…	…	…	0.391

Table 9. Percentage Change of Engineering Properties from the Control Mixture Average

Mixture	Mean Effective Void Content (%)	Mean Permeability (%)	Mean 28-day Compressive Strength (%)	Mean 28-day Static Modulus of Elasticity (%)
60% Slag	5.6	25.0	-13.2	0.6
70% Slag	3.6	21.2	-18.6	-11.3
80% Slag	8.9	42.4	-23.0	-15.7
90% Slag	8.3	15.2	-35.8	-21.4

Permeability. The permeability of the control mixture was significantly lower than that of all other mixtures. The permeability of the 80% mixture was significantly different than that of the 90% mixture. Figure 2 shows mean constant head permeability versus percent slag substitution. The coefficient of determination, 0.43, was not impressive. Fortunately, there was no paste drain down evident in any of the cylinders, indicating paste consistency is not a problem with higher GGBFS substitution levels.

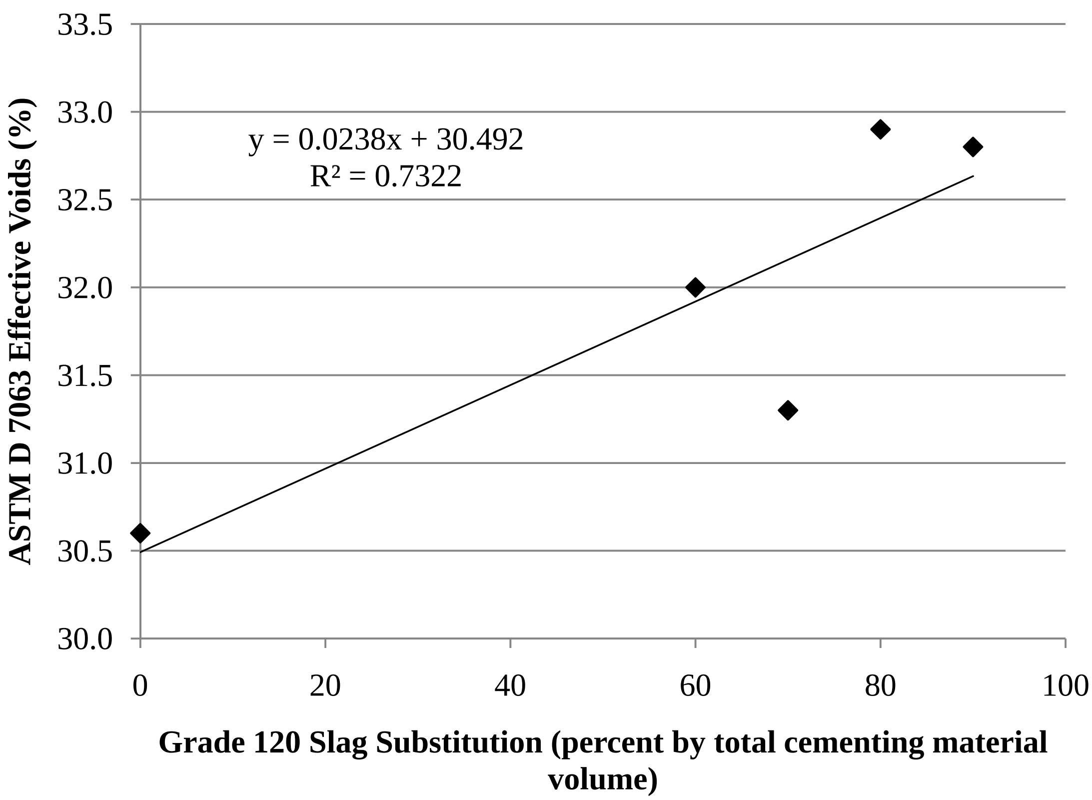

Figure 1. Mean Effective Void Content versus Percent Grade 120 Slag Substitution

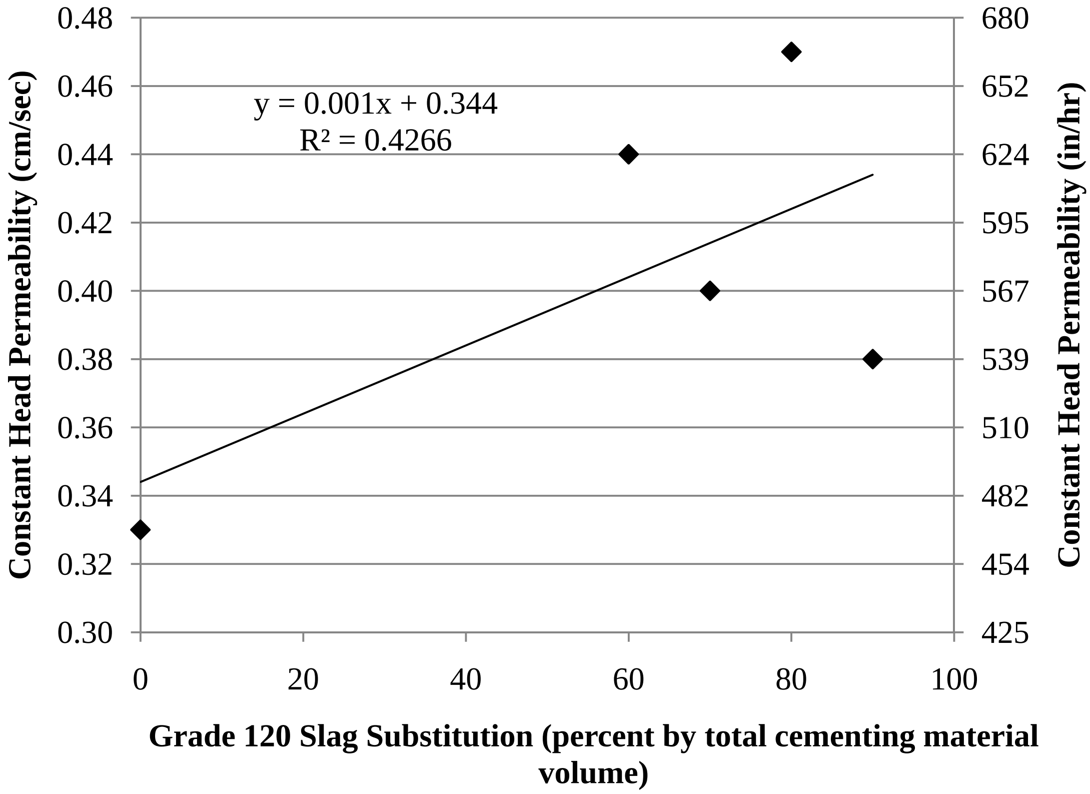

Figure 2. Mean Constant Head Permeability versus Percent Grade 120 Slag Substitution

7-Day Compressive Strength. High substitution levels of SCMs can sometimes slow compressive strength gain. Obla (2003) stated that concrete needs to have a compressive strength of at least 5.2-MPa (750-psi) in order to remove forms without excessive damage. All mixtures in this research exceed this compressive strength recommendation.

28-Day Compressive Strength. The compressive strength of the control mixture was significantly higher than that of all the other mixtures. The compressive strength of the 90% mixture was significantly lower than that of all the other mixtures. A graphical comparison of the compressive strengths is shown in Figure 3; a clear negative correlation between compressive strength and the level of substitution can be seen. It is important to note that the average compressive strength of the 80% mixture was sufficient for most pervious concrete applications, such as parking lots. The 90% mixture could still be used for applications, such as sidewalks or foot paths, where a lower strength is acceptable.

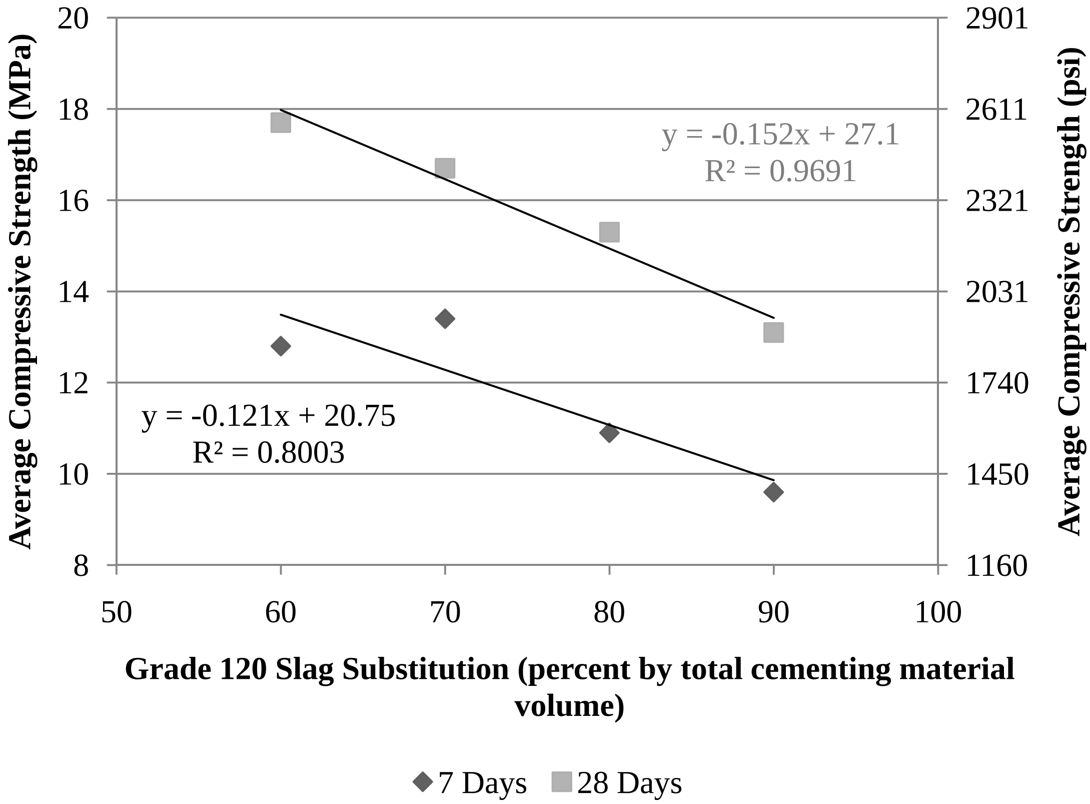

Figure 3. Mean Compressive Strength versus Percent Grade 120 Slag Substitution

28-Day Static Modulus of Elasticity. The static modulus of elasticity of the control mixture and 60% substitution mixtures were significantly higher than that of the 70, 80, and 90% substitution mixtures. A graphical comparison of the average static modulus of elasticity values is shown in Figure 4. As the level of substitution increased above 60%, the average static modulus of elasticity decreased.

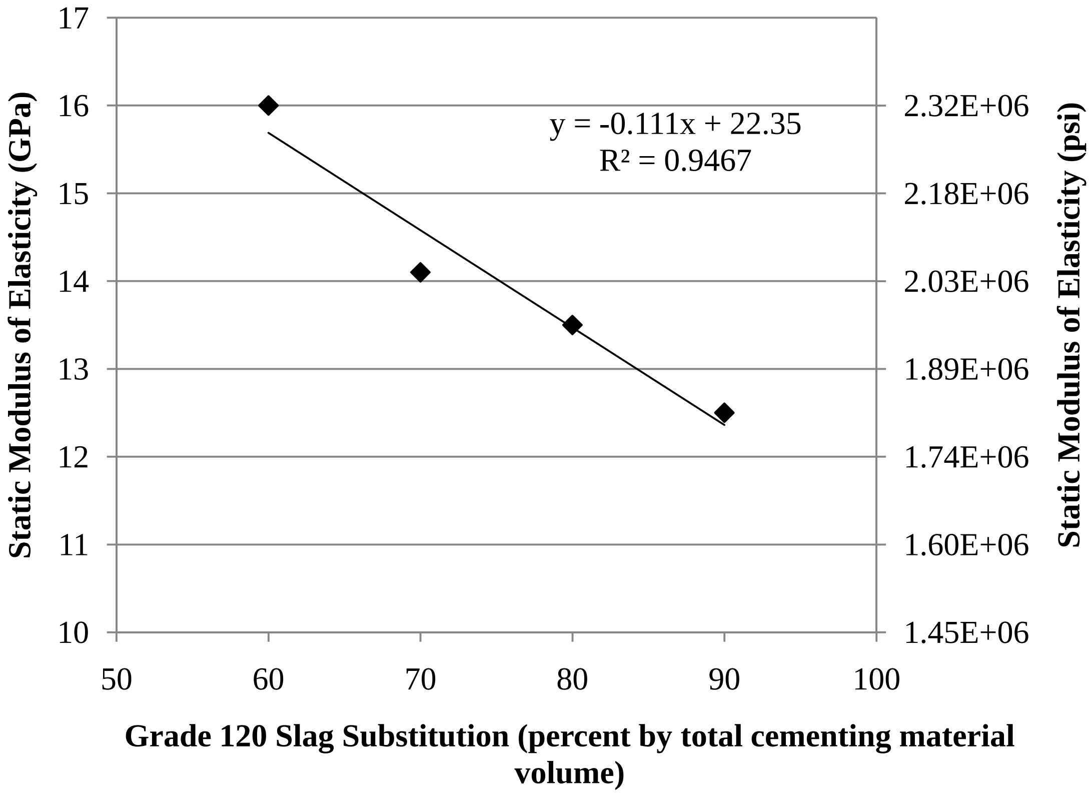

Figure 4. Mean Static Modulus of Elasticity versus Percent Grade 120 Slag Substitution

Conclusions

Based on the results of the limited research performed, the following conclusions can be drawn:

1. Grade 120 Slag substitutions at 60, 70, 80, or 90% levels by volume of total cementing materials significantly increased effective void content of pervious concrete. However, the maximum average increase in effective voids was less than 10% of the control value.
2. Grade 120 Slag substitutions at 60, 70, 80, or 90% levels by volume of total cementing materials significantly increased constant head permeability of pervious concrete. There was no paste drain down evident in any of the cylinders indicating paste consistency is not a problem with higher GGBFS substitution levels.
3. Grade 120 Slag substitutions at 60, 70, 80, or 90% levels by volume of total cementing materials did not prevent seven day compressive strengths from reaching 5.2-MPa (750-psi). Therefore, excessive damage to pervious concrete during form removal should not be a concern
4. Grade 120 Slag substitutions at 60, 70, 80, or 90% levels by volume of total cementing materials significantly decreased 28-day compressive strength of pervious concrete. However, the maximum average decrease in 28-day

compressive strength was less than 36% of the control value. It is important to note that the average compressive strength of the 80% mixture was sufficient for most pervious concrete applications, such as parking lots. The 90% mixture could still be used for applications, such as sidewalks or foot paths, where a lower strength is not required.

5. Grade 120 Slag substitutions at 70, 80, or 90% levels by volume of total cementing materials significantly decreased 28-day static modulus of elasticity of pervious concrete. However, the maximum average decrease in 28-day static modulus of elasticity was less than 22% of the control value.

Acknowledgements

We sincerely appreciate the assistance provided by former TTU graduate students Cameron Williams, Jason Phillips, Steven Matheny, Lindsay Smith Bryant, and John Hendrix. We also greatly appreciate the materials provided by Denny Lind of BASF Admixtures, Inc., Clark Simpson of Builder's Supply, and George C. Zima of Lafarge North America. Thanks to Jeff Holmes and Perry Melton for equipment repair and fabrication. Thanks to Dr. Daniel Badoe for help with proofing and editing. We also gratefully acknowledge the financial support, financial project management, and computer assistance of the TTU Center for Energy Systems Research. Thanks to the TTU Department of Civil and Environmental Engineering for providing supplies and equipment for the project.

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