Fresh and Hardened Properties of Paving Concrete with Steel Slag Aggregate

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Abstract
In 2006 the United States saw the production of 8.6 million tons of steel slag. Although steel slag is currently used as an aggregate in Hot Mix Asphalt surface applications, this paper examines the feasibility of utilizing this industrial by-product as a replacement for both fine and coarse aggregate in conventional concrete mixtures. The first phase of this research examined the effects on the fresh and hardened properties of concrete caused by replacing a percentage of the volume of both fine and coarse aggregate with steel slag available in the Northeastern Ohio area. The basis for comparison was the Ohio Department of Transportations Class C option 1 concrete paving mixture. During this program three types of steel slag were utilized. The slag had been aged and tested for expansion by the producer/supplier, as required by the Ohio Department of Transportation. The fresh concrete properties of workability, air content and unit weight, and hardened properties of compressive and splitting tensile strength were examined per standard ASTM guidelines. This preliminary investigation demonstrates that the specifications called for by the Ohio Department of Transportation can be met. Further study to assure that the performance of the finished pavement is not degraded is on-going.

Introduction
As defined by the American Society for Testing and Materials (ASTM), steel slag is a non-metallic product consisting primarily of calcium silicates and ferrites combined with fused oxides of iron, aluminum, manganese, calcium, and magnesium (National Slag Association). It is a by-product of steel making produced during the separation of the molten steel from impurities in steel-making furnaces. Steel is manufactured in a two step process. First, iron ore is smelted in a blast furnace producing “pig iron”. Next, steel is made from pig iron and/or steel scrap in a Basic Oxygen Furnace (BOF) or Electric Arc Furnace (EAF). The slag floats on the surface while the heavier molten metal lies at the bottom of the container and is poured off in the manufacturing process (Wagman et al, 2005). When using the BOF, 150 to 300 pounds of steel slag is produced per one ton of steel (75 – 150 kg/tonne). About 130 to 160 pounds of steel slag is created per one ton of steel (65 – 80 kg/tonne) produced by utilizing an EAF (National Slag Association). According to the U.S. Geological Survey Mineral Commodity Summaries, the year

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2006 saw the production of 21.5 million tons of iron and steel slag of which 40% would be classified as steel slag (van Oss, 2007).

Research Significance

Beneficial uses of industrial byproducts, in general, promote sustainable development, green building, and environmental responsibility by reducing the quantity of materials that must be land filled, and by replacing other materials such as natural aggregates that must be mined. Natural aggregates are becoming increasingly scarce, and their production and shipment is becoming more difficult and environmentally disruptive.

This research was undertaken to explore the feasibility of utilizing the steel slag produced by steel mills in the Northeastern Ohio region as a replacement for natural aggregate in various concrete mixtures. With transportation being steel slag's most significant cost consideration, a cost savings over natural aggregate concrete could potentially be realized, provided there is no significant performance degradation.

Current Uses and Barriers to Use

According to the National Slag Association pamphlet, *Steel Slag: A Premier Construction Aggregate*, steel slag is currently being used in bituminous asphalt paving, manufacture of Portland cement, roadway bases, and agriculture. The pamphlet does not list its use as an aggregate in concrete. Technical literature on the use of steel slag in concrete is limited and inconclusive, particularly with respect to long term performance. There is the perception, based upon earlier use, that steel slag aggregate concrete exhibits unacceptable durability problems, due to the expansive characteristics of some of its constituents, but much of the information is anecdotal in nature rather than documented in research studies. It has been suggested that free lime (CaO) and magnesium oxide (MgO) in the slag leads to those problems. State DOT's now require much more stringent quality control over steel slag. It is now aged in a moist environment to alleviate its expansive characteristics, and tested for expansion prior to its use, even for asphalt paving applications, where bulking (expansion resulting in material loss or flushing) can occur.

Previous work at Cleveland State University (Obratil et al, 2008)) examined the effects of replacement of various percentages of natural aggregate with aged and expansion tested steel slag in a standard concrete pavement mixture with satisfactory results. Concrete mixes using conditioned EAF slag with good fresh and hardened properties, and acceptable behavior against aggressive environmental conditions have been obtained (Manso, Gonzalez et al, 2004). "Some of the physical properties of steel slag aggregate concrete were better than those of crushed limestone aggregate concrete, though the unit weight of the former was more than the latter (Maslechuddin et al, 2003). Further study (Manso, Polancoz et al, 2006) reaffirmed that with proper mix proportions, both the mechanical strength and durability of slag aggregate concrete is acceptable, but freeze/thaw resistance was still a problem with their sample mixes. It has also been found (Shi, 2004) that "Steel slag can be used as a cementing component in several cementing systems. However some material being able to consume free lime and to eliminate potential expansion must be used together with steel slag." The use of steel slag aggregated with a cement-fly ash binding system (Papayianni et al, 2006) concluded that it was feasible to design low-cost concrete mixtures for pavements using those materials. The performance of carbonated block, which uses steel slag aggregate, in marine environments in Japan has also been investigated (Shinya et al, 2007).

Experimental Program

Protocol. This preliminary experimental investigation made use of an Ohio Department of Transportation (ODOT) Class C option 1 paving mixture as its base. A percentage of the volume of aggregate normally used in the manufacture of concrete in Northeastern Ohio was replaced by steel slag. This replacement was done in approximately 10% increments until the initial supply was exhausted. Before mixing could begin tests were conducted on the gradations of the steel slag samples and compared to those found in the standard aggregates. The gradations were then applied to the mixtures in the proper proportions and the concrete was all mixed in the Concrete Research Laboratory located in the Fenn College of Engineering at Cleveland State University. The properties of both the fresh concrete and hardened concrete were recorded according to the corresponding ASTM standard. The hardened concrete samples were tested at 7 and 28 day intervals. The protocols and methods utilized during the study can be found in Table 1. For the mixture proportions located in Table 2, ODOT 499.03 specifies that this concrete proportioning is based on developing an average concrete compressive strength at 28 days of 4000 pounds per square inch (28.0 MPa) for Class C (State of Ohio, 2005).

TABLE 1 Testing Program

Test	Protocols and Methods	Number of Tests
Aggregate		
Gradations	ASTM C 136	18 (6ea. Of 3 types)
Fresh Concrete Properties		
Workability	ASTM C 143	1
Air content	ASTM C 231	1
Unit weight	ASTM C 138	1
Hardened Concrete Properties		
Compressive strength	ASTM C 39, 4" x 8" cylinders	2 each age, total of 4
Splitting tensile strength	ASTM C 496, 4"x 8" cylinders	4 each age, total of 8

Gradations. The steel slag aggregate samples provided by Stein Inc. consisted of 600 pounds of 3/4-inch steel slag, 560 pounds of 1/2-inch steel slag, and 600 pounds of "C" Fines steel slag. The initial visual examination of the steel slag samples determined that they consisted of a mixture of both fine and coarse aggregates. Six samples averaging 2kg each were taken from each of the three types of steel slag and sieve tested according to ASTM C 136. The average results of the percentage passing each screen for the three types of steel slag were compared to the mix curves determined by J.M. Shilstone (State of Ohio, 2005)).

TABLE 2 Concrete Mixture Proportions (Quantities per Cubic Yard (m^3))

Research Mixture Design									
Mixture Type	SSD Aggregate Weight						Cement Content		Water-Cement Ratio
	Fine Aggregate		Coarse Aggregate		Steel Slag Aggregate				
	lb	kg	lb	kg	lb	kg	lb	kg	Max.
ODOT Class C High	1270	753	1610	955	-	-	600	356	0.50
¾" @ 20%	1020	463	1249	567	675	306	600	356	0.50
¾" @ 30%	893	405	1093	496	1013	459	600	356	0.50
¾" @ 40%	765	347	937	425	1350	612	600	356	0.50
¾" @ 50%	638	289	781	354	1688	766	600	356	0.50
¾" @ 60%	510	231	625	284	2025	919	600	356	0.50
¾" @ 70%	393	178	468	212	2363	1072	600	356	0.50
¾" @ 80%	255	116	312	142	2700	1225	600	356	0.50
¾" @ 100%	0	0	0	0	3375	1531	600	356	0.50
½" @ 20%	1020	463	1249	567	675	306	600	356	0.50
½" @ 40%	765	347	937	425	1350	612	600	356	0.50
½" @ 50%	638	289	781	354	1688	766	600	356	0.50
½" @ 60%	510	231	625	284	2025	919	600	356	0.50
½" @ 70%	383	174	468	212	2363	1072	600	356	0.50
½" @ 80%	255	116	312	142	2700	1225	600	356	0.50
½" @ 100%	0	0	0	0	3375	1531	600	356	0.50
"C" Fines @ 10%	1148	521	1405	637	338	153	600	356	0.50
"C" Fines @ 30%	893	405	1093	496	1013	459	600	356	0.50
"C" Fines @ 40%	765	347	937	425	1350	612	600	356	0.50
"C" Fines @ 50%	638	289	781	354	1688	766	600	356	0.50
"C" Fines @ 100%	0	0	0	0	3375	1531	600	356	0.50

Fresh Concrete Properties. Prior to mixing a batch of concrete each aggregate to be used was weighed and placed into an oven at 105^{o}C for 24 hours to determine the moisture content. As noted in Table 1 above, the fresh concrete properties tested for in this research were workability, air content, and unit weight. For this mixing program it was decided to use 15 plastic cylinders with dimensions of 4 inch by 8 inch. Each cylinder consisted of two lifts loaded according to the American Society for Testing and Materials (ASTM) requirements for testing. The tops were then troweled level and the cylinders set aside to cure for 24 hours under a plastic covering. The specimens were removed from their molds after the 24 hours and submerged in a lime bath per ASTM C 511 until the time of testing.

Hardened Concrete Properties. Due to the limited quantity of steel slag available during this phase of testing it was decided to examine the splitting tensile strength of the concrete mixtures for the flexural properties with a batch of four specimens tested at 7 days and another batch tested at 28 days. Compressive strength tests utilized two batches of two specimens each also tested at 7 and 28 days. The three remaining specimens were utilized as a backup for any of the primary cylinders and for later testing at either 56 or 90 days. Both tests utilized a hydraulic loading machine to apply the loads. Each specimen's compressive strength was derived by dividing the ultimate applied load by the cross-sectional area of the cylinder and recorded along with the type of fracture observed. The splitting tensile strength was determined indirectly by use of the following equation;

$$T = \frac{2P}{\pi l d}$$

where T equals the splitting tensile strength in psi (kPa), P is the maximum applied load in lbf (kN), and both l and d are the length and diameter of the specimens in inches (m). By this formula the splitting tensile strength would equal the maximum applied load divided by 50.2655 in U.S. units (64.4 in SI).

Material Properties

Base Mixture. The base mixture selected for this research was the ODOT Class C option 1 concrete paving mixture. The materials used for this research remained constant throughout the experiment cycle only the volumetric amounts were varied. All materials aside from the steel slag are those utilized by ODOT District 12 in Northeastern Ohio on their road projects. All mixtures maintained a water to cement ratio of 0.5 throughout the testing.

Cement. The cement used for this experiment was the Type I Portland cement obtained from both St. Marys Cement and Lafarge Corporation. Both of these cements met ASTM standards for Portland cement composition.

Fine Aggregate. The fine aggregate that made up our concrete was Shalersville natural sand from Lafarge Corporation and supplied by Cuyahoga Concrete and Stone. This sand has absorption of 1.18%. The Bulk Specific Gravity was 2.60 and the SSD Specific Gravity of 2.63.

Coarse Aggregate. A #57 Marblehead limestone with a nominal maximum size of 1 inch (25mm) was selected as the high absorption coarse aggregate and was also supplied by Cuyahoga Concrete and Stone. The absorption of the coarse aggregate was specified as 3.03%. The Bulk Specific Gravity provided by the supplier was 2.49 with an SSD Specific Gravity of 2.57.

Chemical Admixtures. Two chemical admixtures were applied to the mixtures in some degree. All concrete mixtures except for the 100% and 80% ¾ inch steel slag replacements contained 15mL of the air entrainment admixture MB-AE 90 and some mixtures required the use of the high range water reducer Glenium 3030 NS. These chemicals were provided by BASF/Master Builders.

Steel Slag. The steel slag used in this study was BOF steel slag produced by Mittal Steel USA, and provided by Stein Inc., located in Cleveland, Ohio. It was processed in compliance with ODOT Construction and Material Specifications. Section 703.01E of the Specifications requires that Steel Slag Aggregate (steel slag) from open-hearth (OH), BOF and EAF be supplied from sources according to ODOT Supplement 1071 Quality Control Requirements for Steel Slag Aggregate Producers/Processors. Section 703.14 D of the Specifications provides aging and stockpiling requirements, which include the requirement that water be added to stockpiled materials "to provide a uniform moisture content not less than their absorbed moisture", and that it be "maintained in a moist condition during the required stockpiling period." At the time of this study, the minimum aging time was six months, but it has since been decreased to a minimum of three months. Section 703.14E Expansion Testing specifies that expansion testing be performed on the aged material, according to Pennsylvania Department of Transportation PTM No. 130 Method of Test for Evaluation of Potential Expansion of Steel Slags. PTM 110 is similar to ASTM D 4792 – 00 Standard Test Method for Potential Expansion of Aggregates from Hydration Reactions which is referenced for expansion testing of steel slag fine aggregate in Supplement 1071. "The maximum allowable total expansion for each test is less than 0.50 percent."

Three sizes of steel slag were provided by Stein Inc. The first sample was labeled as ¾" x 0 and came from Republic Engineered Products Inc. (R.E.P.), located in Lorain Ohio, which manufactures both hot-rolled and cold finish bar stock. The other two samples were labeled as ½" x 0 and as "C" Fines. Both of these were from Mittal Steel USA located in Cleveland, Ohio which is involved in the manufacture of many types of steel. Stein Inc. also provided an analysis report compiled by Alternative Testing Laboratories Inc. which provided information on the chemical composition of the steel slag (Table 3) along with the percent absorption and SSD Specific Gravity (Table 4).

TABLE 3 Steel Slag Chemical Composition

	¾" R.E.P.	½" MITTAL	"C" FINES MITTAL
Aluminum oxide (Al_2O_3)	4.07 %	5.84 %	3.09 %
Calcium oxide (CaO)	45.2 %	30.7 %	28.6 %
Chromium oxide (Cr_2O_3)	0.30 %	0.28 %	0.25 %
Iron oxide (FeO)	14.4 %	35.6 %	37.5 %
Magnesium oxide (MgO)	10.1 %	9.95 %	9.82 %
Manganese oxide (MnO)	3.14 %	3.99 %	3.88 %
Phosphorus oxide (P_2O_5)	0.33 %	0.61 %	0.62 %
Potassium oxide (K_2O)	0.01 %	0.05 %	0.02 %
Silicon oxide (SiO_2)	15.3 %	12.0 %	10.7 %
Sodium oxide (Na_2O)	0.05 %	0.09 %	0.07 %
Titanium oxide (TiO_2)	0.40 %	0.65 %	0.63 %
Vanadium oxide (V_2O_5)	0.12 %	0.21 %	0.21 %

TABLE 4 Steel Slag Properties

Type of Aggregate	Absorption (%)	SSD Specific Gravity
R.E.P Steel Slag ¾" x 0	2.61	3.09
Mittal Steel Slag ½" x 0	3.37	3.09
Mittal Steel Slag "C" Fines	3.37	3.09

Experimental Results

Batch Size. The amount of concrete mixed for each batch was 1.05ft^3 (0.029m^3). The experimental results of this preliminary research are as follows.

Gradations. The sieve analysis of the steel slag samples revealed this material to be a combination of both fine and coarse aggregate for the ¾ inch and ½ inch. The "C" Fines was also found to be a combination however it was closer to a fine aggregate with very little coarse. The results of the sieve analysis are shown in Table 5 and are compared to that of the Shalersville fine aggregate and the Marblehead #57 course aggregate. All the mixtures replaced the fine and coarse aggregates with steel slag by volume in roughly 10% increments until the supply was exhausted.

TABLE 5 Sieve Analysis Results Compared to Course and Fine Aggregates

Sieve		Percent Passing				
#	**(mm)**	**¾" Steel Slag**	**½" Steel Slag**	**"C" Fines**	**Marblehead #57**	**Shalersville Sand**
1 ½	**37.5**	100	100	100	100	100
1	**25**	100	100	100	100	100
¾	**19.500**	99.95	100	100	83	100
½	**12.700**	90.92	98.88	99.75	38	100
3/8	**9.500**	71.33	96.02	99.02	13	100
4	**4.750**	44.93	79.13	90.25	4	99
8	**2.360**	30.52	52.37	68.77	3	82
16	**1.180**	21.48	30.83	42.6	0	63
30	**0.425**	12.6	17.8	12.8	0	48
50	**0.300**	5.77	8.43	4.65	0	31
100	**0.150**	1.28	1.78	1.32	0	4
200	**0.075**	0.33	0.38	0.5	0	1.8

Fresh Concrete Properties

Workability. As the steel slag replaced the fine and coarse aggregates each batch became harsher. As Table 6 illustrates, the slump of the replacement steel slag mix became smaller and smaller unless increasingly larger amounts of admixture were applied. According to the ODOT Construction and Material Specifications Manual the nominal slump for Class C concrete pavement is 1 inch to 3 inches (25 to 75 mm) but "may be increased to 6 inches (150 mm) provided the increase is achieved by adding chemical admixture" (State of Ohio, 2005)). The maximum slump allowed is 4 inches (100 mm) but can also be increased by using approved admixtures to 7 inches (180mm) according to ODOT 499.03-1 (State of Ohio, 2005)).

Table 6 Fresh Concrete Properties and Admixture Dosage

Mixture Design (steel slag type@ percent replacement)	Amount of Water Reducer Admixture (mL)	Measured Slump		Meets Nominal Slump Specs. (ODOT 499.03-1)	Meets Maximum Slump Specs. (ODOT 499.03-1)	Measured Air Content (%)
		(in)	(mm)			
c-57	-	3.00	76.2	yes		5.50
¾” @ 20%	-	3.25	82.6		yes	5.20
¾” @ 30%	-	5.00	127.0			7.00
¾” @ 40%	-	2.00	50.8	yes		4.50
¾” @ 50%	-	2.25	57.2	yes		5.00
¾” @ 60%	-	0.50	12.7			3.50
¾” @ 70%	-	1.25	31.8	yes		4.10
¾” @ 80%	100	1.00	25.4	yes		5.00
¾” @ 100%	80	0.50	12.7			4.50
½” @ 20%	-	1.25	31.8	yes		4.75
½” @ 40%	-	0.75	19.1			5.25
½” @ 50%	-	2.75	69.9	yes		8.00
½” @ 60%	31	0.75	19.1			5.50
½” @ 70%	35	0.75	19.1			7.75
½” @ 80%	60	0.25	6.4			5.50
½” @ 100%	70	0.50	12.7			8.75
“C” Fines @ 10%	-	8.50	215.9			8.50
“C” Fines @ 30%	-	1.50	38.1	yes		5.00
“C” Fines @ 40%	-	1.50	38.1	yes		6.00
“C” Fines @ 50%	30	0.25	6.4			5.00
“C” Fines @ 100%	350	8.00	203.2			4.50

Air Content. Due to the climate experienced in Northeastern Ohio, ODOT specifications call for Class C option 1 paving concrete to have an air content of 6 +/- 2% (State of Ohio, 2005)). As can be seen in Figure 1 each type of slag used had one mixture fall outside of the requirement. However this may be attributed to the mixing process or to the quantities of admixture placed in the mixture. All concrete mixtures except for the 100% and 80% ¾-inch replacements contained 15mL of the air entrainment. In the case of the 100% ¾-inch steel slag replacement 20 mL was used and for the 80% 18mL was used. Both of these batches were mixed at the start of the program.

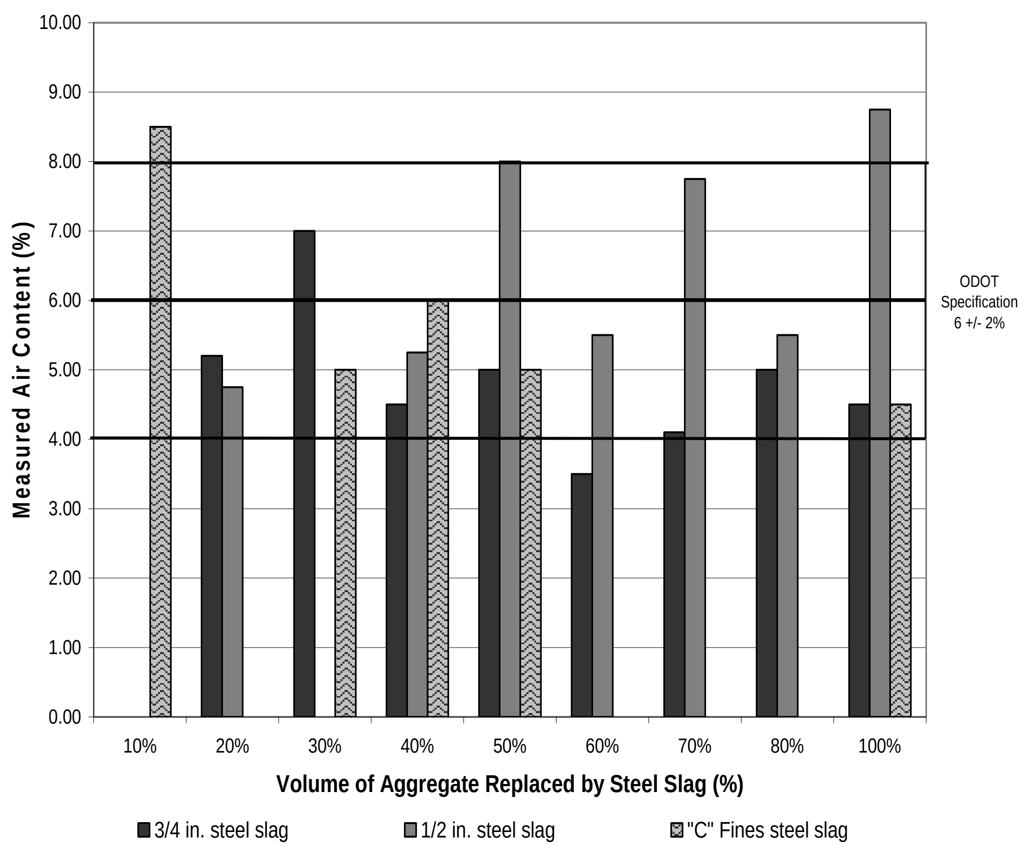

FIGURE 1 Percent replacement versus measured air content.

Unit Weight. As can be seen in Figure 2 the measured unit weight was higher for the ¾-inch replacements on most its mixtures. Similar trends between the measured unit weight and the designed unit weight was found also with the “C”Fines and ½-inch steel slag.

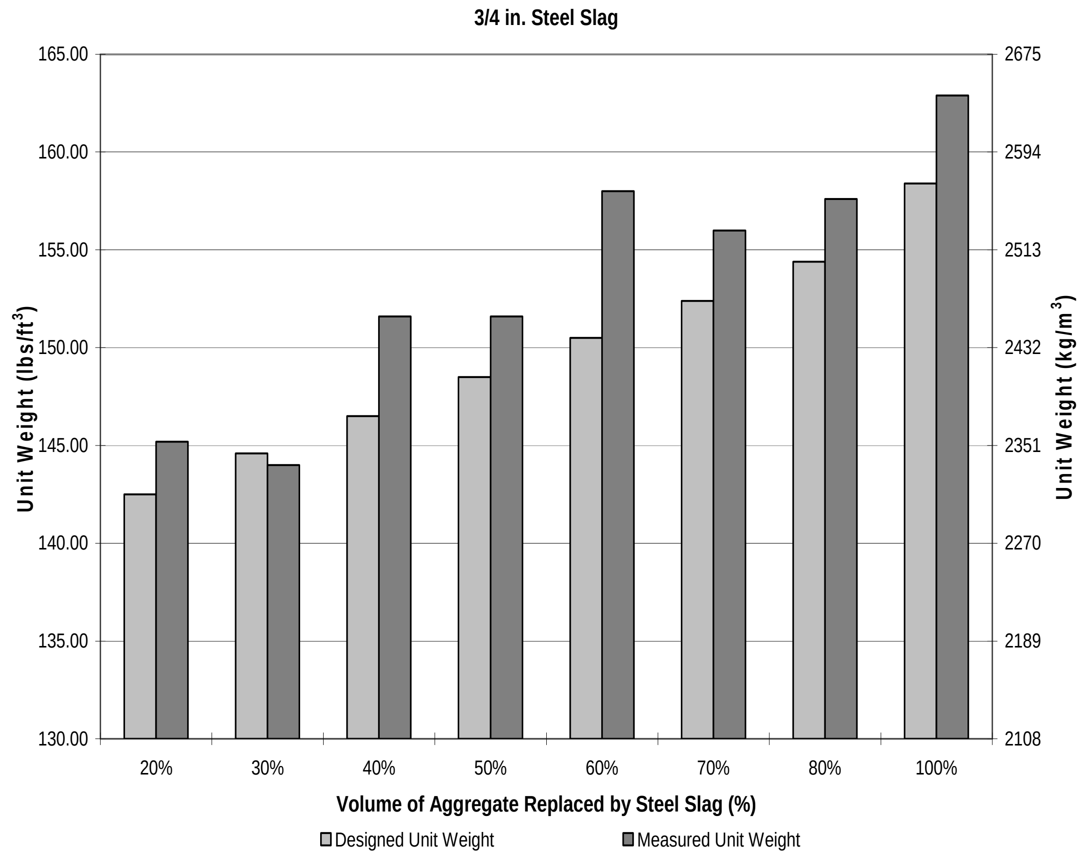

FIGURE 2 Percent replacement versus unit weight.

Hardened Concrete Properties

The hardened properties of concrete tested for during this phase of research were the compressive strength using two specimens and the splitting tensile strength using four specimens at 7 and 28 days from pouring.

Compressive Strength. As stated in ODOT 499.03 the concrete proportioning utilized for the Class C mixture is based on developing an average compressive strength of 4000 psi (28.0 MPa) after 28 days. As can be seen in figures 3 through 8, the 7 day strength for many of these batches exceeds ODOT's 28 day requirement. It can also be observed that although the steel slag did replace both the fine and coarse aggregates overall strength was not adversely affected. Laboratory batch variability is 200 to 350 psi. (Mindess et al, 2003).

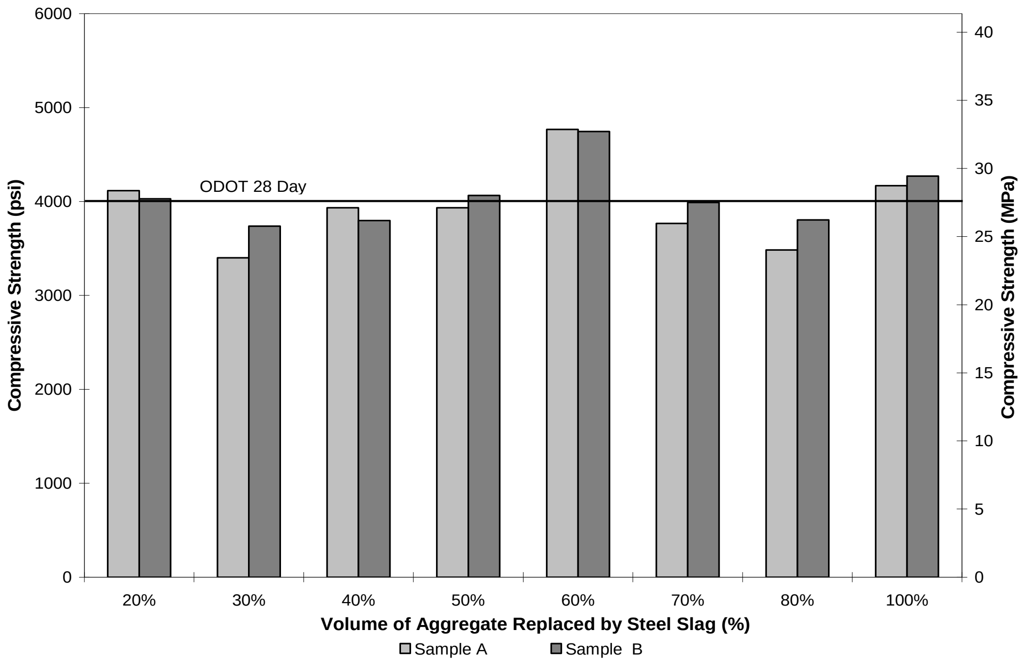

FIGURE 3 ¾-inch steel slag compressive strength at 7 days.

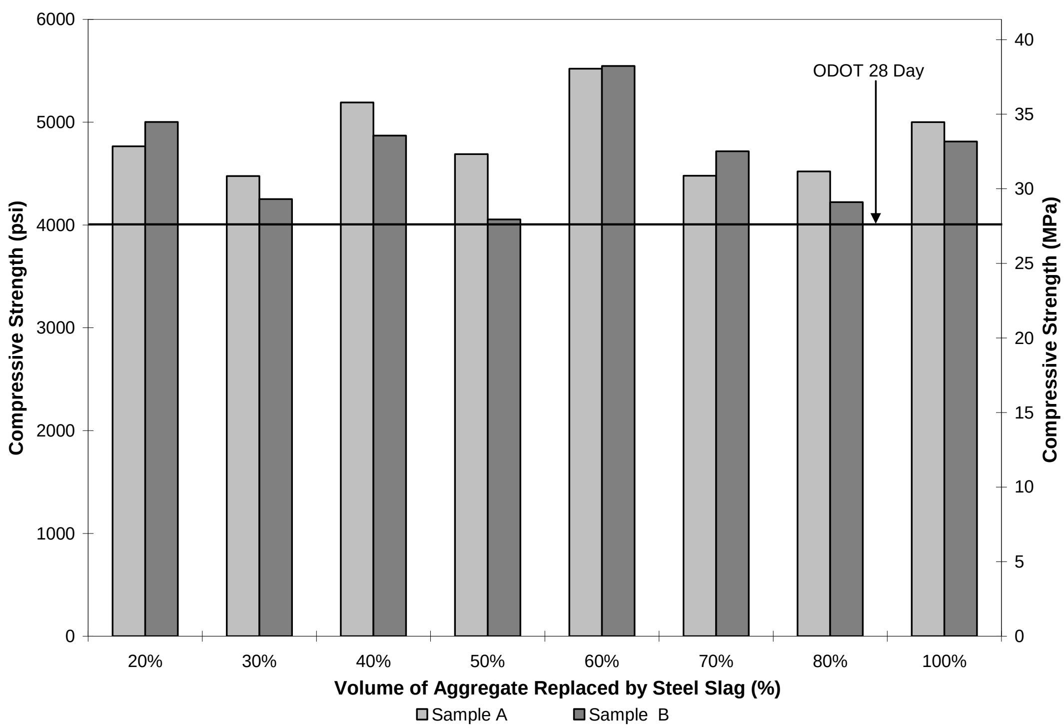

FIGURE 4 ¾-inch steel slag compressive strength at 28 days.

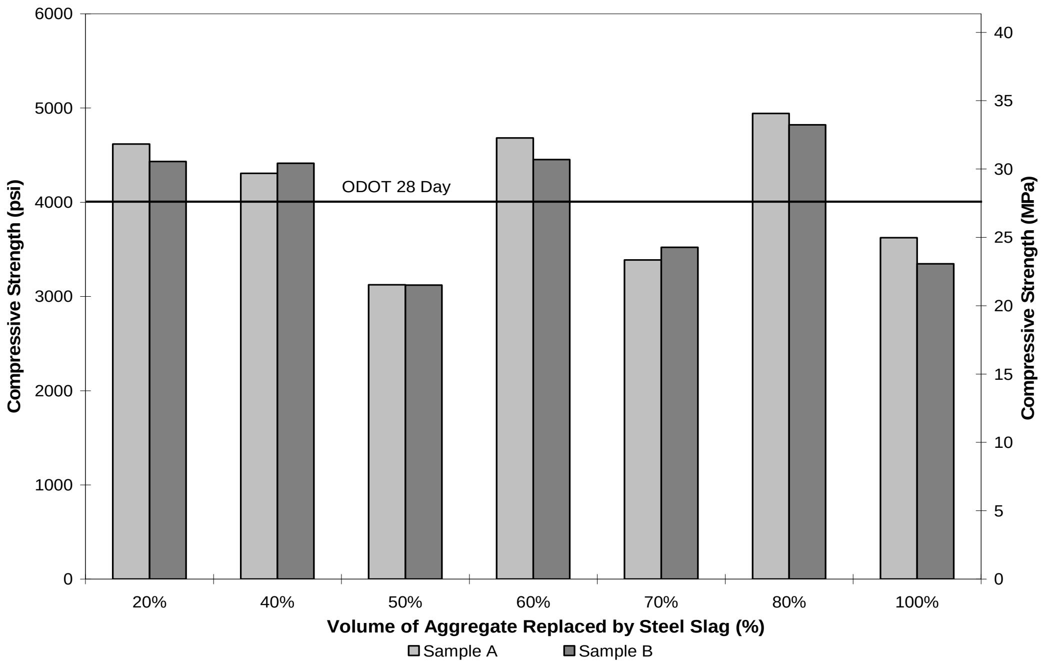

FIGURE 5 ½-inch steel slag compressive strength at 7 days.

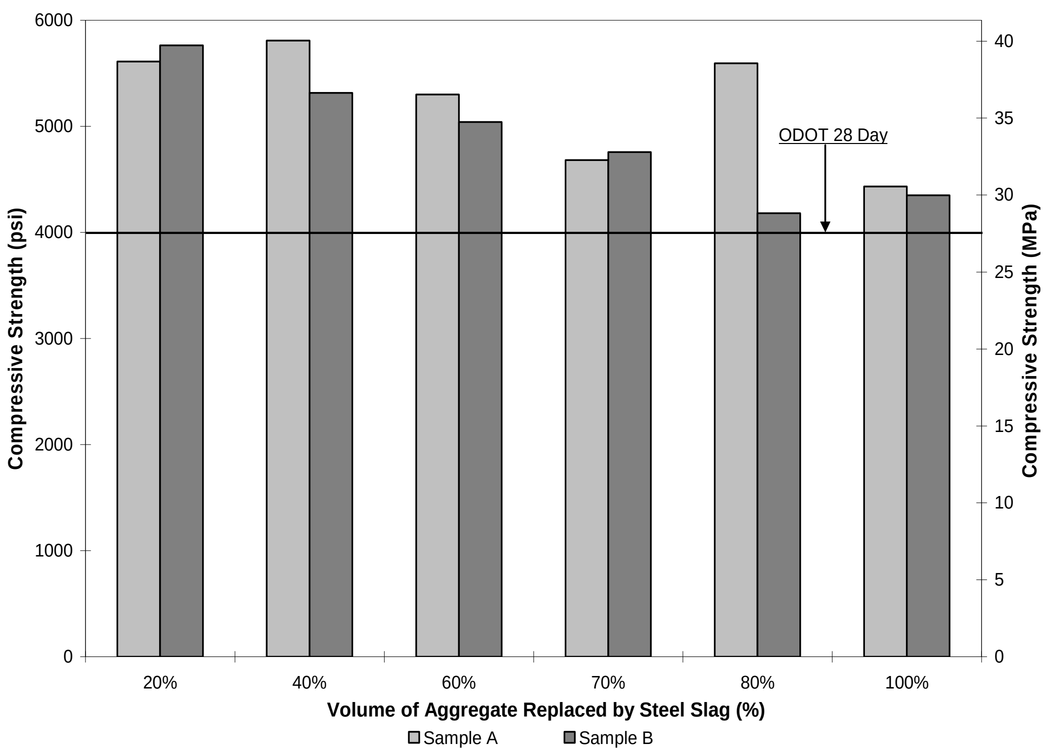

FIGURE 6 ½-inch steel slag compressive strength at 28 days.

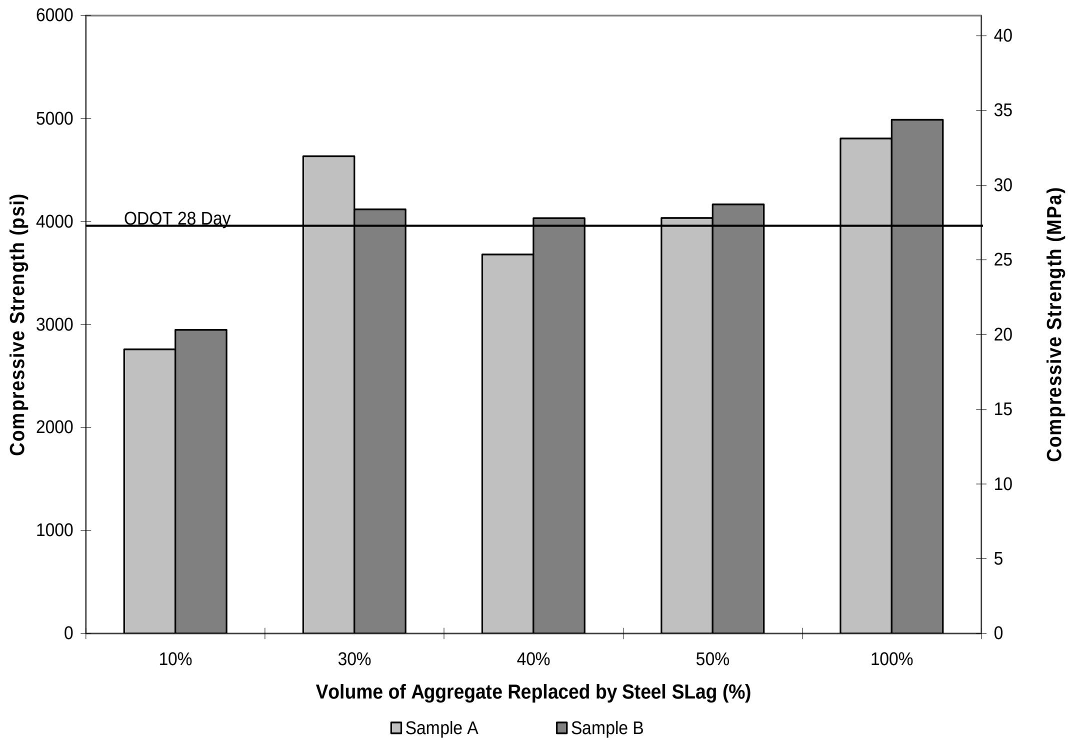

FIGURE 7 "C" Fines compressive strength at 7 days.

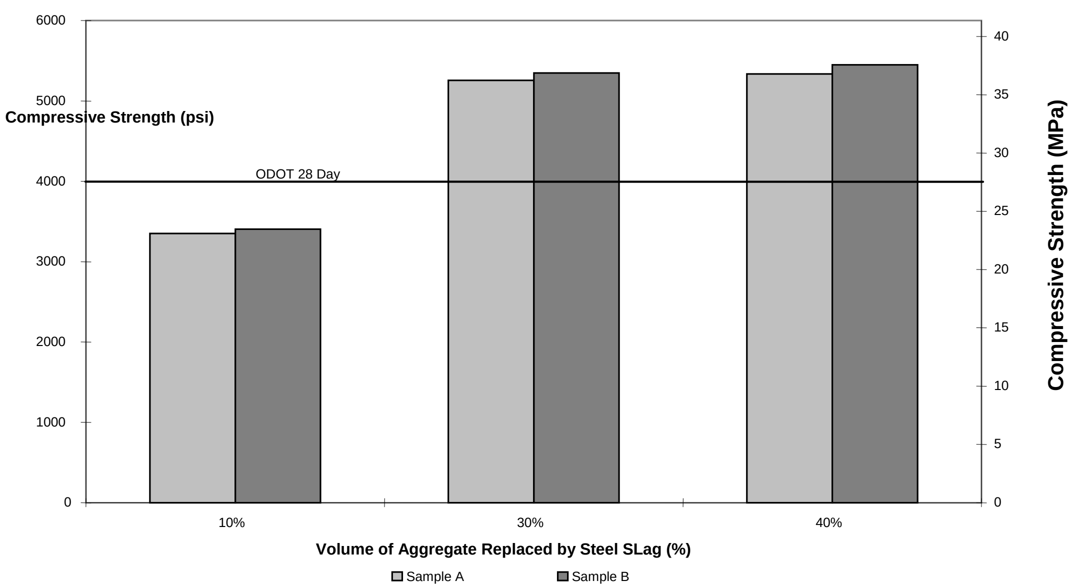

FIGURE 8 "C" Fines compressive strength at 28 days.

Splitting Tensile Strength. Figures 9 through 11 display the splitting tensile strengths of the samples at 7 and 28 days. The results indicate that any inclusion of steel slag results in an improved mix over those using a weak limestone aggregate. The splitting tensile strength data obtained also suggests a flexural strength of 450 to 550 psi, which would be an acceptable strength for many paving applications.

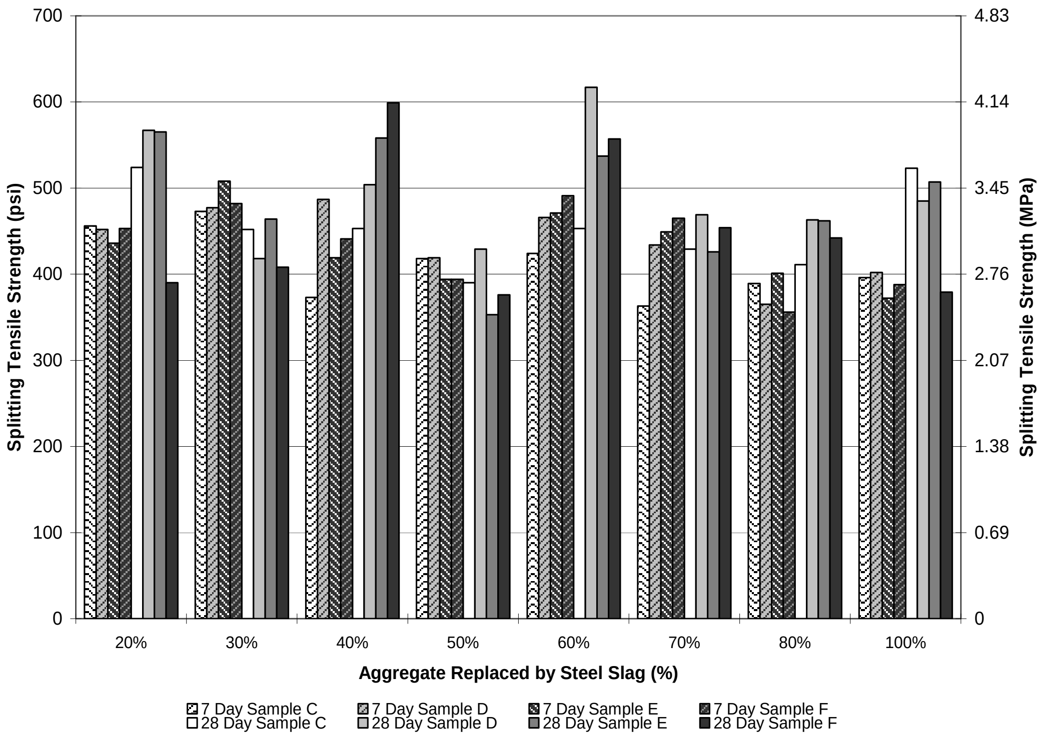

FIGURE 9 Splitting tensile strength of ¾-inch steel slag replacement.

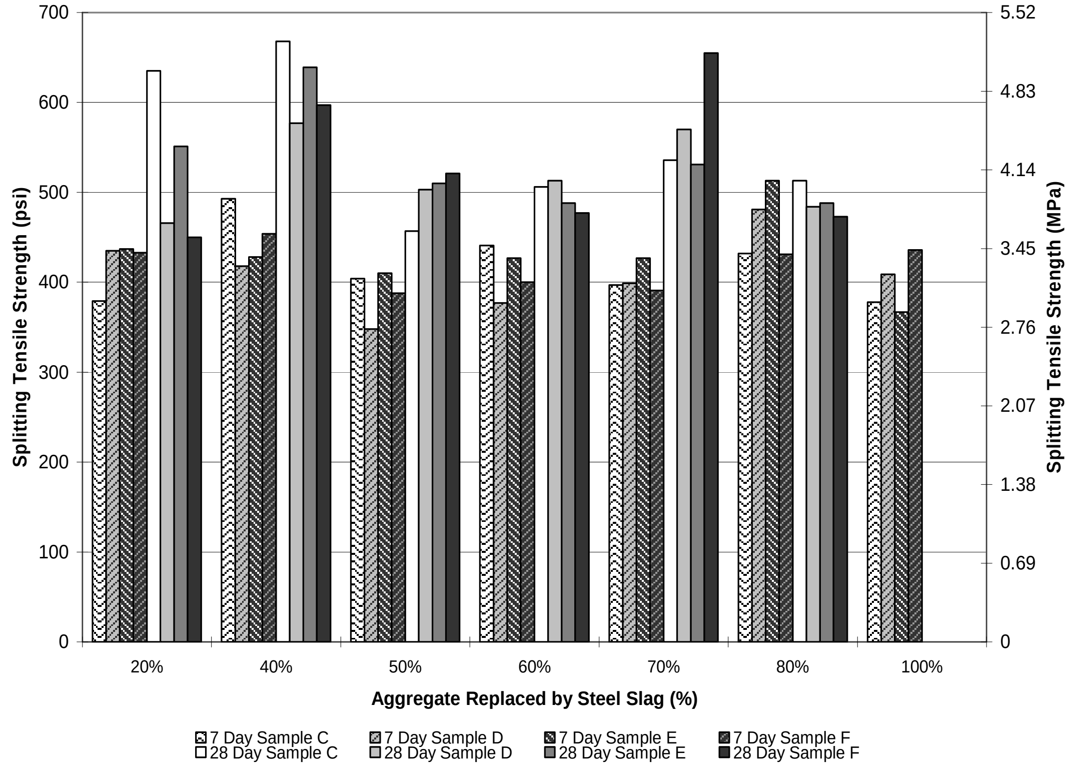

FIGURE 10 Splitting tensile strength of ½-inch steel slag replacement.

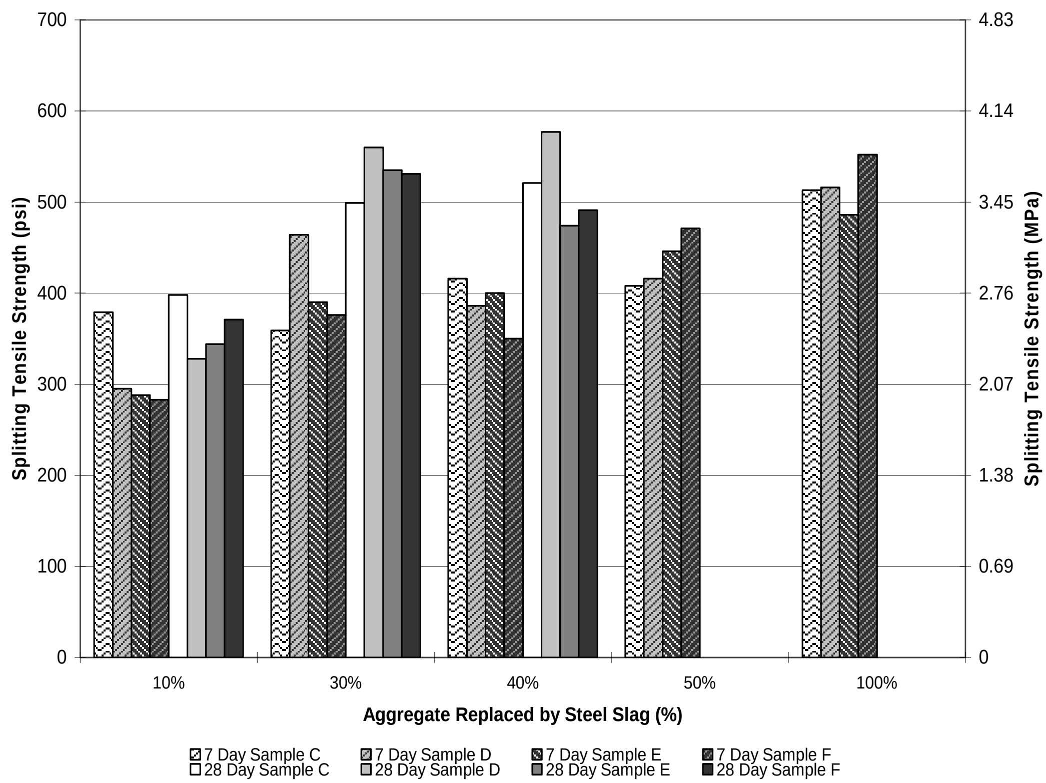

FIGURE 11 Splitting tensile strength of "C" Fines steel slag replacement.

CONCLUSIONS

By replacing a percentage of both the fine and coarse aggregates normally used in the ODOT Class C option 1 paving mixture no degradation in strength was observed. What was observed during the course of this preliminary investigation was that as the amount of slag increased, greater amounts of water reducer were required to obtain better workability as these mixtures tended to be harsh. From an economic standpoint any cost savings realized in using the steel slag above a 40% replacement might be offset by the greater quantities of chemical admixture that would be required to keep the mixture within acceptable workability specifications. It should be noted that further research as outlined below, examining other properties of the steel slag replacement, is necessary.

FUTURE STUDY

Further study of these steel slag aggregate replacement mixture properties will include:

- Thermal coefficient.
- Shrinkage and expansion.
- The effects of freeze/thaw.
- Resistance to polishing and loss of surface friction over time.
- Pouring and testing of flexural beams to establish flexural strength.

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