Utilization of Phosphogypsum-Based Slag Aggregate in Portland Cement Concrete Mixtures

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Phosphogypsum is a by-product of the fertilizer industry, specifically the production of phosphoric acid from phosphate rock. It is produced in large quantities and generally disposed of by stockpiling in large stacks. An alternative to disposal is reuse as a construction material in some form. One such process to convert phosphogypsum to a usable product is the Davy McKee-Florida Institute of Phosphate Research thermal conversion sulfur recovery process, in which sulfur contained in the phosphogypsum is recovered and a slag aggregate by-product is produced. This study centers around the possible utilization of phosphogypsum-based slag aggregate as a substitute for coarse aggregate in portland cement concrete for highway construction. The physical properties of the slag aggregate, such as specific gravity, unit weight, gradation, and absorption, were determined for use in concrete mix design. The durability behavior of the slag aggregate was also explored, exclusive of cold weather performance, which would require further research if the aggregate were exported to northern climates. On the basis of the physical characteristics of the aggregate, a concrete mixture was developed and tested in both the fresh and hardened states. The specific properties evaluated were workability, unit weight, air content, and yield of the fresh concrete along with strength and deformation characteristics of the hardened concrete. The compressive strength, flexural strength, splitting tensile strength, modulus of elasticity, and Poisson's ratio results indicated that the slag aggregate performed well as a coarse aggregate in portland cement concrete and should perform satisfactorily in a highway pavement system.

Phosphogypsum (PG) is a by-product of the production of phosphoric acid, which is a major component in many agricultural fertilizers. It is a light tan, crystalline calcium sulfate powder in the dihydrate form ($CaSO_4 \cdot 2H_2O$) and is more soluble in water than natural gypsum. It is generated at a rate of approximately 4 to 5 Mg/Mg (4.5 to 5.5 tons/ton) of phosphoric acid produced. In the United States, about 31.7 million Mg (35 million tons) of PG is generated each year. There is about 86.2 million Mg (95 million tons) of PG stockpiled in Louisiana and 22.7 million Mg (25 million tons) in Texas, and by the year 2000, about 900 million Mg (1 billion tons) is expected to be stockpiled in Florida. PG is regulated by the Environmental Protection Agency because it contains radioactive Radium-226, which decays to radon gas and is vented into the atmosphere. Environmental concerns and the problems associated with stockpiling have prompted research in Louisiana, Florida, and Texas, as well as in other countries besides the United States, to investigate the utilization of PG (*1*).

There are basically two processes for producing PG-based slag aggregate. The two-stage fluidized bed process uses a fluidized bed reactor with raw PG as the feedstock to produce sulfur dioxide gas (SO_2) and quick lime (CaO). This process is referred to as the flash sulfur cycle process and is copyrighted under the name FLASC (*2*). The circular grate process, developed by the Davy McKee Corporation and the Florida Institute of Phosphate Research (FIPR), mixes predried PG with pulverized coal and silica-bearing minerals for spraying into the flame of the circular grate. Since PG quality varies depending on the source of the phosphate-bearing rock, this mixture can be adjusted to accommodate quality differences and to produce a slag aggregate with consistent quality. Sulfur dioxide gas is released at this point, and the minerals fuse together and drain from the reactor as a molten slag, which is quickly quenched to form the slag aggregate. The sulfur dioxide gas is converted to sulfuric acid and recycled to phosphoric acid production (*1*).

Research programs were initiated in 1982 at FIPR to study the process of thermal decomposition of PG to recover sulfur dioxide and produce a slag aggregate. Since that time, Freeport-McMoRan, Incorporated (FMI), a major producer of phosphoric acid, has constructed a pilot facility at their Uncle Sam Plant in Donaldsonville, Louisiana, in a cooperative venture with the Davy McKee Corporation. The purpose of this joint venture was to investigate the technical feasibility and economic viability of the process as well as the properties of the slag aggregate. Different experimental burns were conducted in an attempt to optimize the production parameters. Eventually, aggregates were produced in five distinct campaigns. Several problems arose during Campaigns 1 through 4 that caused variations in the quality of the slag aggregate produced, but Campaign 5 was judged to have produced successful results.

OBJECTIVE AND SCOPE

The objective of this study was to determine the technical feasibility of using PG-based slag aggregate, specifically slag aggregate produced from Campaign 5 at the Uncle Sam pilot plant facility, as a coarse aggregate in portland cement concrete (PCC) mixtures. In Phase One of the study, previous research on the properties and characteristics of the slag aggregates, primarily from Campaigns 1 through 4, was reviewed to gain an understanding of the nature and behavior of these materials. The physical properties of the aggregates, such as specific gravity, gradation, absorption, and porosity, were summarized, and comparisons were made with conventional aggregates to provide insight concerning their suitability for concrete production. The durability aspects of the slag aggregate were also critically reviewed in this phase to

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assess its potential performance in PCC exposed to moderate climates. Additional research would be required to assess cold weather performance, however, if the aggregates were employed in northern climates. Finally, previous work regarding the environmental concerns of PG-based slag aggregates was reviewed in Phase One to assess the possibility of any unaccountable radiation emanation and leachate that might result from the embedment of the slag aggregate in a cement matrix.

Phase Two of the study supplemented the physical characterization studies of Campaign 5 material reported by Taha and Seals (*3*) and investigated the durability characteristics of the aggregate to determine its suitability for use as a coarse aggregate in PCC. Various physical tests, such as specific gravity and unit weight, absorption, porosity, and gradation, were performed on the slag aggregate to provide a basis for the design of PCC mixes. This test series was followed by soundness and freeze-thaw tests to assess the long-term durability potential of the aggregate. Phase Three of the project investigated the performance of the slag aggregate-based concrete using a variety of tests on the fresh and hardened states of the mixture. Comprehensive workability, strength, and elasticity measurements were performed and compared with typical representative properties of concrete made using conventional aggregates.

In this study the physical aspects of PG slag aggregate-based concrete were explored; the environmental and economic aspects of the use of this new material is the subject of companion studies currently under way. These studies will address such concerns as alkali-aggregate and sulfate reactions, chemical compatibility with portland cement, radiation emanations, and energy costs associated with the production of the aggregate. It must be emphasized, however, that this aggregate is a by-product of a process whose primary purpose is to recover the sulfur content of raw PG for the production of sulfuric acid. Thus, the market value of the aggregate represents a credit against the cost of sulfuric acid production, and the economic feasibility of the process is primarily dependent on the comparative cost of sulfuric acid produced using virgin sulfur versus the cost of production using the Davy McKee/FIPR process. At current virgin sulfur prices, the Davy McKee/FIPR process is not economical in the United States. According to tentative capital and production cost estimates, only when sulfur prices approach \$125/Mg (\$125/long ton) is the sulfur recovery process economical.

CHARACTERIZATION OF CAMPAIGN 5 SLAG AGGREGATE

Morphology

The Campaign 5 aggregate appears dark grey to black in color with a morphology that can best be described from two viewpoints. At the microtexture level, the basic particle is polished and well rounded. At the macrotexture level, however, these basic particles are fused together to form a very rough, angular shape that has a honeycomb appearance. Particle sizes vary from larger than 38 mm ($1^1/_2$ in.) to smaller than 0.075 mm (No. 200 sieve), but only the coarse fraction above 4.75 mm (No. 4 sieve) was characterized.

Specific Gravity and Absorption

The tests to determine the specific gravity and absorption of the slag aggregate were conducted in accordance with ASTM C 127-81 or AASHTO T 85-85 specifications. Table 1 provides the specific gravity and absorption values found for Campaign 5 slag aggregate and compares these values with those for the well-rounded, extremely hard river and pit-run gravels typically used in Louisiana. Apparent and saturated surface dry specific gravities, as well as absorption, were higher for Campaign 5 slag aggregate than for typical river and pit-run gravels. Although the specific gravity information reveals little about the quality of the slag aggregate when used in PCC, it does provide some insight into the expected unit weight of slag aggregate concrete. If the slag aggregate makes up 65 percent of the total volume of concrete and has a saturated surface dry specific gravity approximately 14 percent higher than that of conventional aggregates, the density of slag aggregate concrete should be about 9 percent greater than that of normal concrete. The absorption capacity for the slag aggregate was higher as well, denoting a higher water requirement when used in PCC for the same water-cement ratio.

Unit Weight

Unit weight and void content were determined according to the standard procedures outlined in ASTM C 29-78 or AASHTO T 19-80. Unit weight by compaction through rodding is applicable for the slag aggregate since the maximum size of particles is 25 mm (1 in.). Table 1 shows the results of these tests and a comparison with typical aggregates. Unit weight and void content in aggregates are seldom specification requirements, but ASTM and AASHTO recommend a minimum dry rodded unit weight of 972 to 1134 kg/m^3 (60 to 70 lb/ft^3) for normal weight concrete. The Campaign 5 slag aggregate meets this requirement but is relatively light compared with conventional aggregates. The void content of the aggregate is relatively high at 62.9 percent, reflecting the honeycomb texture of the aggregate particles.

Gradation

Sieve analysis results were used to develop an aggregate blend that conforms with ASTM C 33 and Louisiana Department of Transportation and Development (LDOTD) TR 1003 specifications for coarse aggregate in concrete. Freeport-McMoRan provided approximately 1072 kg (2,400 lb) of randomly sampled Campaign 5 slag aggregate for the research study. The grain size distribution was determined by sieving the entire batch into sep-

TABLE 1 Physical Test Results

	Slag Aggregate	Louisiana Aggregates
Apparent Specific Gravity	3.16	2.62 - 2.65
Saturated Surface Dry Specific Gravity	2.84	2.51 - 2.59
Absorption (%)	7.2	1.0 - 5.0
Rodded Unit Weight (kg/m^3)	1,183	1,540 - 1,702
Void Content (%)	62.9	30-45

1.0 lb/ft^3 = 16.21 kg/m^3

arate sieve fractions and weighing each fraction. The gradation analysis shown in Figure 1 indicates that the slag aggregate does not fall within the range specified by ASTM C 33 and LDOTD TR 1003 for coarse aggregate used in PCC. This does not restrict the material from being used, but merely means that it has to be regraded to meet the specifications.

Durability Analysis

Since the durability of an aggregate has such a profound effect on the performance of PCC, Campaign 5 slag aggregate was subjected to a series of tests in an attempt to identify any potential problems that might arise from its use.

Five-Cycle Sodium Sulfate Soundness

The soundness of aggregates is usually determined by the sodium or magnesium sulfate soundness test procedures given in ASTM C 88-76 or AASHTO T 104-86. The low precision of this test dictates that the results be interpreted carefully. Five test cycles were conducted in which the aggregate was immersed in saturated sodium sulfate solution for 17 hr, drained for 15 min, and then oven dried to reach a constant weight. Test data are shown in Table 2. Upon completion of the test, some disintegration of the aggregate, and in a very few cases splitting of entire aggregate particles, was observed. The results show an average weight loss of about 6 percent on each of the sieve fractions investigated, which is comparable with the degradation experienced by conventional Louisiana aggregates and well below the 15 percent maximum stipulated in the LDOTD specifications. Thus, satisfactory behavior of the slag aggregate with regard to long-term durability is indicated.

Aggregate Freeze-Thaw

A freeze-thaw test is not required for conventional aggregates used in Louisiana, since concrete is not generally subjected to such climatic conditions anywhere in the state. However, such a test is another way to assess the general durability of the slag aggregate. To estimate its behavior, a typical gradation of the slag aggregate used in concrete production was subjected to 50 freezing and thawing cycles using a test procedure developed by the state of Indiana. The aggregate was evaluated using the AASHTO T 103-83, Procedure A, in which the aggregate is totally immersed in water. Results of the test are reported in Table 2. The degradation weight loss after 50 cycles ranged from a high of 19.7 percent for the 2.36-mm (No. 8) sieve to only 1.6 percent for the 25-mm (1 in.) sieve. The weighted average degradation loss due to freezing and thawing for the composite gradation is 4.2 percent and compares favorably with the sodium sulfate soundness results. It should be noted that a hydrogen sulfide odor was evident immediately after the samples were removed from the freezer from the 20th to the 30th cycle. This phenomenon is being studied to determine the underlying cause, but it most likely stems from a residual sulfur impurity from the production process.

Los Angeles Abrasion

LDOTD TR111 and AASHTO T96 test methods describe the procedures for testing different gradations and sizes of coarse aggre-

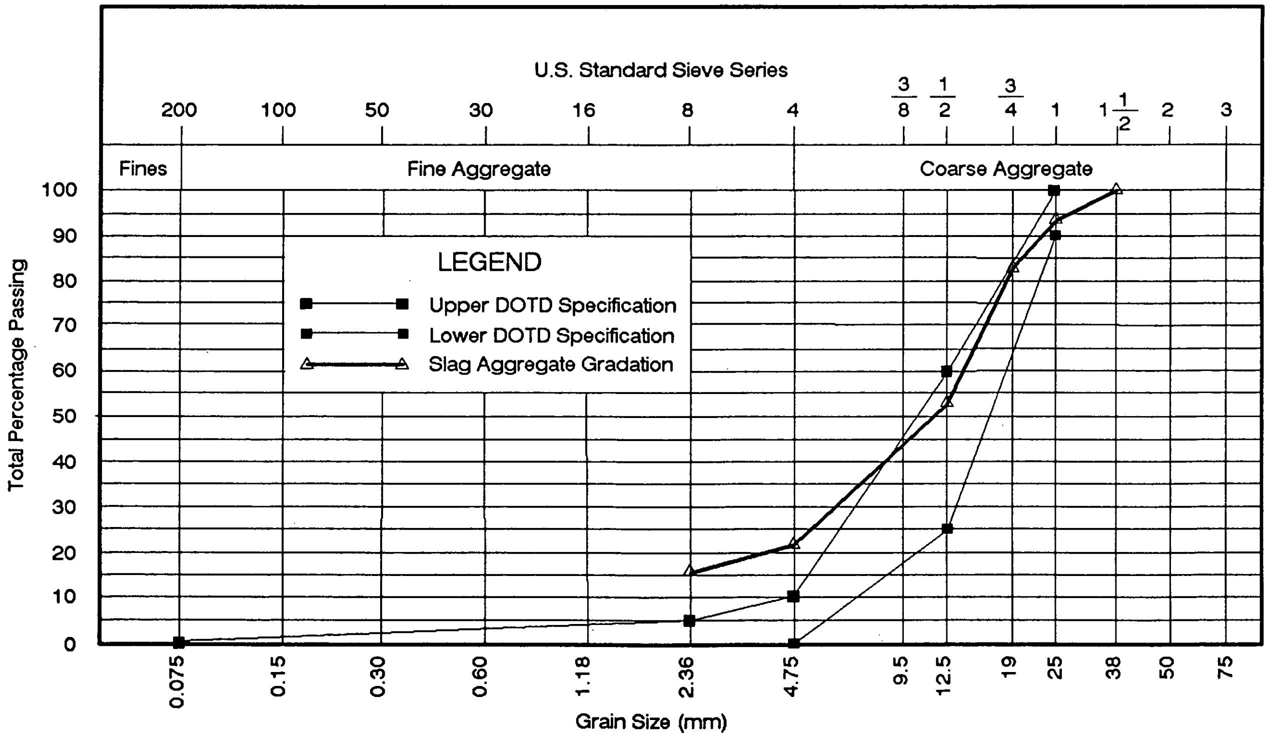

FIGURE 1 Natural gradation for Campaign 5 slag aggregate.

TABLE 2 Durability Test Results

	Sieve Size (mm)					
	2.36	4.75	9.5	12.5	19.1	25.4
Sodium Sulfate Soundness Loss (%)	12.7	4.6	6.3	6.6	8.0	8.0
Freeze-Thaw Soundness Loss (%)	1.6	3.2	4.3	10.6	15.1	19.7

25.4 mm = 1.0 in

gate for resistance to abrasion using the Los Angeles (LA) testing machine. Abrasion losses of selected samples from Campaign 5 ranged between 34.0 and 36.4 percent, values that approach the upper limit of 40 percent established by LDOTD. Additional samples of Campaign 5 slag were also subjected to LA abrasion testing after 4 weeks of immersion in 150°F tap water, and no significant differences in abrasion loss were observed as a result of the soaking.

PG SLAG AGGREGATE-BASED CONCRETE

Background

This portion of the research investigated the use of PG-based slag aggregate as a substitute for conventional aggregates in concrete production. After a mix design for this new material was developed, the study evaluated the engineering properties of fresh concrete, including slump, unit weight, air content, and yield. Attributes of the hardened concrete, such as compressive strength, splitting tensile strength, and flexural strength, were then examined, and an assessment was made of the feasibility of using the slag aggregate in concrete mixes.

Mixture Design

Coarse and Fine Aggregate Proportioning

The gradation of the PG slag coarse aggregate was chosen to meet the ASTM C 33 and LDOTD TR 1003 recommendations and can be seen in Figure 2. Masonry sand was selected for use as the fine aggregate, with 88 percent passing the 1.18-mm (No. 16) sieve and 8 percent passing the 0.075-mm (No. 200) sieve. The

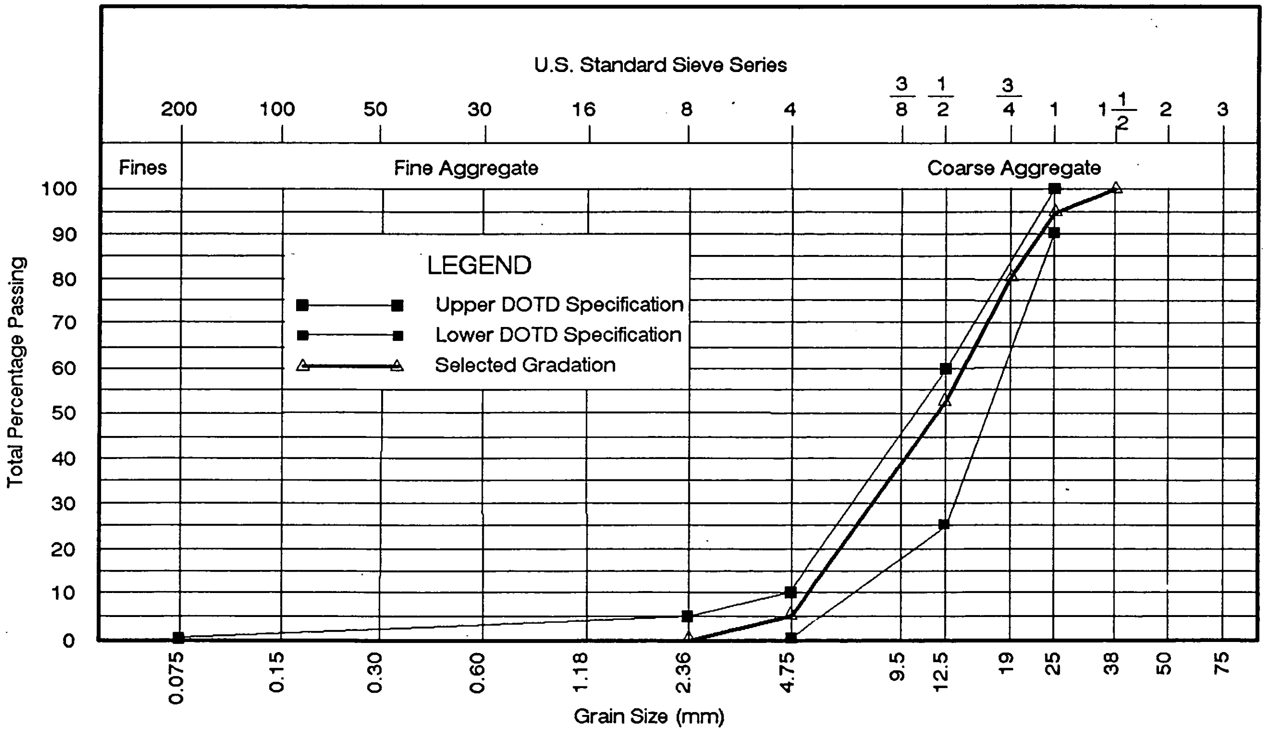

FIGURE 2 Selected gradation for Campaign 5 slag aggregate.

workability of a mixture depends on the volume of the coarse aggregate and the maximum size and fineness of the fine aggregate. Proportions of coarse to fine aggregates that give a workable mix have been developed by experience and are given in the American Concrete Institute (ACI) 211.1 Standard. For coarse aggregate with a maximum size of 25 mm and fine aggregate with a typical fineness modulus of 3.0, the recommended proportion of coarse to fine aggregate is 65 percent. Because of the lack of experience with the slag aggregate, however, four different coarse to fine aggregate proportions were subjectively evaluated for optimal workability, keeping the water content, cement content, and thus the water-cement ratio, constant at typical values for highway construction. The results of the subjective evaluation of the workability, appearance, and finishability of the fresh concrete indicated that a coarse to fine aggregate proportion of 65 to 35 percent was optimum, confirming the recommendations of the ACI and coinciding very well with common experience.

Water and Cement Content Determination

Workability is generally indicated by the slump of a mixture, which is specified for different types of applications. For highway construction, the ACI recommends a slump of 25 to 75 mm (1 to 3 in.) and water content of 193 kg/m^3 (325 lb/yd^3) of concrete. Since the water-cement ratio is a key parameter in determining the quality of concrete, however, four different water-cement ratios were evaluated using 28-day, moist-cured compressive strengths of cylinders 152 mm (6 in.) in diameter by 305 mm (12 in.) high and a 65/35 percent coarse to fine aggregate proportion. The water content was reduced, however, from the ACI recommended level of 193 kg/m^3 (325 lb/yd^3) to 178 kg/m^3 (300 lb/yd^3) to reduce the cement content of the mixes to 396 kg/m^3 (667 lb/yd^3), approximately a seven-bag mix and 0.45 water-cement ratio, and to provide a more economical mix. The mixture proportions used in the water-cement ratio determination and the results of the 28-day compressive strength tests are given in Table 3. Five specimens were cast, cured in water, and then tested in compression for each water-cement ratio.

On the basis of the results shown in Table 3, a mixture with a water-cement ratio of 0.45 was chosen for all further testing. This water-cement ratio provides good, workable concrete and 28-day compressive strengths well in excess of the 27,560 kPa (4,000 psi) minimum required by LDOTD for paving applications. Thus, a 1-m^3 (1.31-yd^3) batch of slag aggregate-based concrete for the study contains 178 kg (300 lb) of water, 396 kg (667 lb) of cement, 1424 kg (2,401 lb) of slag aggregate, and 658 kg (1,109 lb) of fine aggregate.

Characteristics of Fresh Concrete

Production Considerations

The PG-based slag aggregate used in this research effort as coarse aggregate in the production of PCC was blended according to the selected gradation shown in Figure 2, immersed in water for 24 hr, and then air dried to reach a saturated surface dry condition. Masonry sand was used as the fine aggregate in the concrete. The free moisture content of the sand was determined to be 1.5 percent and was taken into account in the calculation of the water added to the mixture. Type I portland cement was used for all batches produced. The properties of fresh concrete were determined primarily to control the quality of the mixture produced. The slump test was used to evaluate the workability of the mix, and unit weight, air content, and yield were measured to determine expected production quantities.

Workability

The slump test was performed in accordance with ASTM C 143 for each batch of the selected design mixture. The slump was found to be 1 in. for each batch, somewhat lower than expected but remarkably consistent, demonstrating that workable, consistent-quality concrete can be produced using PG-based slag aggregates.

Unit Weight

Unit weight or density of concrete depends on the amount and relative density of the aggregates, the amount of entrapped or purposely entrained air, and the water and cement contents. Determination of the unit weight for slag aggregate concrete followed ASTM C 138 procedures, using a 0.014-m^3 (0.5-ft^3) container, and was found to be approximately 2513 kg/m^3 (155 lb/ft^3).

TABLE 3 Compressive Strengths After 28 Days for Different Water-Cement Ratios

	Water - Cement Ratio			
	0.40	0.45	0.50	0.55
Water (kg/m^3)	178	178	178	178
Cement (kg/m^3)	445	445	445	445
Coarse aggregate (kg/m^3)	1,392	1,424	1,450	1,471
Fine Aggregate (kg/m^3)	642	658	669	679
Slump (mm)	25	25	38	38
28-Day Strength (kPa)	38,100	37,570	28,330	28,640

1.0 lb/yd^3 = 0.593 kg/m^3, 1.0 in = 25.4 mm, 1.0 psi = 6.89 kPa

Air Content

The non-air-entrained air content of the mix was determined using the pressure method specified in ASTM C 231. The pressure method is the most common method for measuring air content of fresh concrete and measures the changes in volume of the concrete when subjected to a given pressure. The air content of the slag aggregate concrete measured with a Press-Ur-Meter was 3.0 percent, a relatively high air content compared with the 1 to 2 percent for typical mixtures and probably is due to the honeycomb nature of the slag aggregate and the difficulty of filling those voids with fine aggregate and cement paste.

Yield

The yield of concrete is the amount of fresh concrete produced per sack of cement and is usually expressed in cubic meters per sack. On the basis of the batch proportions used, the specific gravities of the materials used, and the air content from above, approximately 0.110 m^3 (3.95 ft^3) of concrete can be produced for each sack of cement used, somewhat lower than the 0.112 to 0.126 m^3 (4.0 to 4.5 ft^3) per sack for typical aggregates.

Characteristics of Hardened Concrete

The characteristics of the PG slag aggregate and fresh concrete discussed to this point are certainly critical to the production and placement of quality concrete, but clearly the characteristics of the hardened mass must be thoroughly examined to assess the performance of slag aggregate-based concrete. In the next several paragraphs, the preparation, curing, and testing of the concrete specimens used in the study are briefly described.

Preparation and Curing of Test Specimens

Different sizes and shapes of test specimens were used for the various tests performed on the hardened concrete. For compressive strength, splitting tensile strength, and elastic modulus tests, cylindrical specimens with a diameter of 152 mm (6 in.) and a height of 305 mm (12 in.) were used. Beams 152 mm by 152 mm in cross section by 508 mm (20 in.) in length were used for flexural strength tests. For the compressive and splitting tensile strength tests, five cylinders were produced for each test series. For the flexural strength test, seven beams were cast. All test specimens were left in the molds for approximately 24 hr, unmolded, and then placed in a curing tank filled with water and kept at a temperature of 73.4 ± 3°F for the required duration of curing. The cylindrical specimens were removed from the curing tank at the proper time and capped for compressive strength, modulus of elasticity, and Poisson's ratio tests.

Compressive Strength

Tests after 1, 3, 7, 28, and 90 days were conducted to determine the strength increase of the concrete mixture with time. Specimens were tested according to ASTM C 39 or AASHTO T 22 while still in a moist condition. Five cylinders were produced and tested for compressive strength for each of the five curing periods. Table 4 presents a statistical summary of the load and deformation data collected in this phase of the study. Most of the cylinder breaks exhibited the classic conical shape indicative of uniaxial loading, and in general, the breaks occurred through the aggregate particles, indicating that the cement paste was controlling the strength of the hardened mass rather than the coarse aggregate, even at early stages of curing. However, the desired minimum compressive strength of 27,560 kPa (4,000 psi) specified by LDOTD for paving concrete was easily achieved at 28 days.

Figure 3 shows the strength increase with age for the PG slag aggregate-based concrete and for conventional concrete with approximately the same 28-day compressive strength. The curve for PG slag aggregate-based concrete generally follows the typical strength gain pattern for concrete produced with conventional aggregate. Strength at 28 days is considered to be 100 percent strength for most practical purposes and is the value used for structural design. The increase in compressive strength between 28 and 90 days for the slag aggregate concrete was 4000 kPa (583 psi) or about an additional 11.6 percent strength gain. Typical concretes will gain an additional 20 percent compressive strength between 28 and 90 days of moist curing.

Flexural Strength

Two test methods have been well established to assess the tensile strength of concrete. These are the splitting tensile strength test

TABLE 4 Compressive Strength Test Results

Curing Period (days)	Average Peak Load (kN)	Average Peak Strain ($\mu\epsilon$)	Average Compressive Strength (kPa)	Standard Deviation of Strength (kPa)
1	214	4,390	11,713	703
3	349	5,620	19,085	2,204
7	473	3,204	25,906	4,665
28	645	7,610	35,277	8,406
90	716	7,750	39,273	9,908

1.0 lbf = 0.00445 kN, 1.0 psi = 6.89 kPa and the flexure test. The flexural strength test is the most common method to estimate the resistance of concrete against tension and is widely used as a design criterion in many states for road construction. Seven beam specimens were tested according to ASTM C 78-84 or AASHTO T 97-86 after they had been cured for 28 days. The standard third-point loading method was used, and loads were applied at a rate of 556 N/sec (125 lbf/sec). Seven specimens were tested as compared with five for compressive strength because the results of tests for modulus of rupture of concrete beams typically have a higher standard deviation. The results of the flexural strength tests are shown in Table 5. The results of the flexural strength tests range from a low of 3730 kPa (541 psi) to a high of 5860 kPa (850 psi), giving a mean of 4940 kPa (717 psi) and a standard deviation of 2030 kPa (295 psi). The modulus of rupture for slag aggregate-based concrete is about 14 percent of the 28-day compressive strength, which compares very favorably with the typical flexural strength-compressive strength ratios for conventional aggregates of 13.5 percent found in the literature (*4*).

TABLE 5 Flexural Strength Test Results

Beam No.	Load at Failure (kN)	Modulus of Rupture (kPa)
1	36.0	4,650
2	44.9	5,795
3	36.5	4,706
4	28.9	3,727
5	45.4	5,857
6	32.9	4,244
7	43.6	5,622
Average	38.3	4,940

1.0 lbf = 0.00445 kN, 1.0 psi = 6.89 kPa

Splitting Tensile Strength

For splitting tensile strength tests, the cylindrical specimens were loaded on their side in diametral compression according to ASTM C 78-84 or AASHTO T 97-76. Five specimens were loaded to failure with a loading rate of 75.6 kN/min (17,000 lbf/min). The results are shown in Table 6. The splitting tensile strength of the slag aggregate-based concrete specimens varied between 2520 kPa (567 psi) and 3500 kPa (786 psi), with a mean of 2960 kPa (665 psi) and a standard deviation of 716 kPa (161 psi). Therefore, the splitting tensile strength of the concrete is 13.0 percent of its 28-day compressive strength. This value is slightly higher than the range of typical values between 7 and 11 percent reported in the literature (*4*).

Modulus of Elasticity and Poisson's Ratio

The tests to determine the static modulus of elasticity and Poisson's ratio were conducted according to ASTM C 469-87a using extensiometer and compressiometer measurements. Cylinders were moist cured for 90 days, capped, and then tested in axial compression. Table 7 gives the results of these tests. The average value for the modulus of elasticity was found to be 23.4 × 10^6

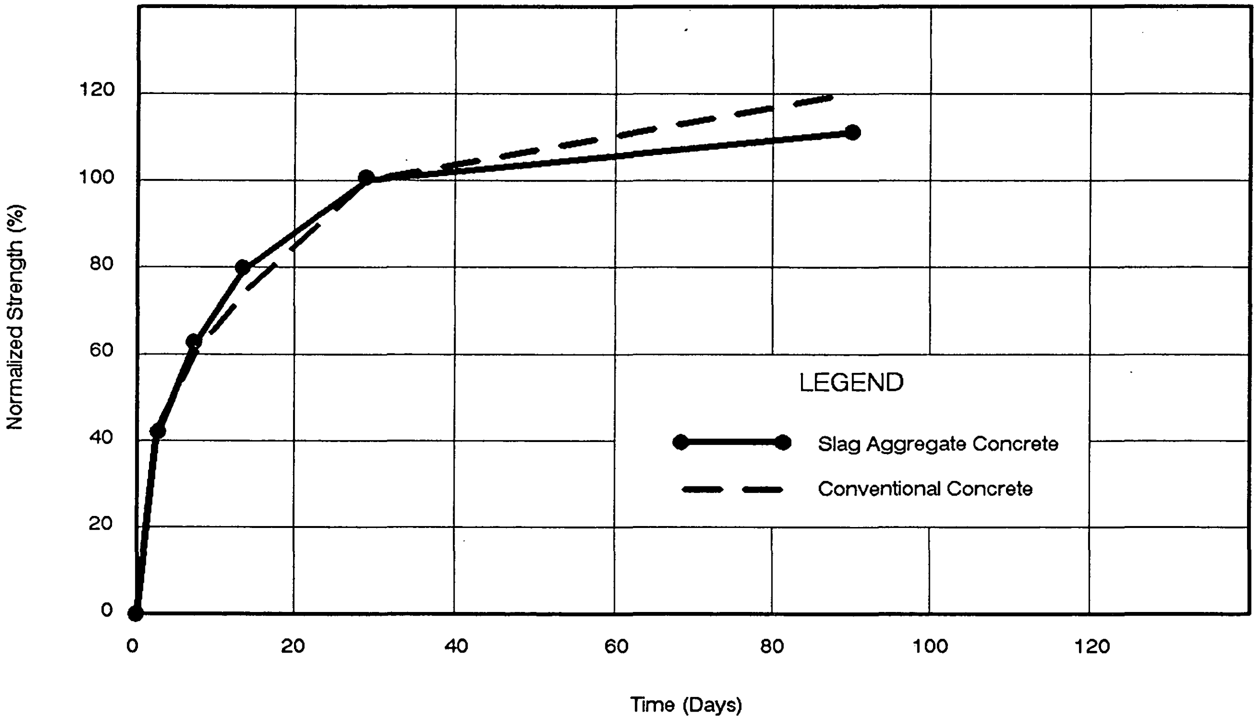

FIGURE 3 Compressive strength gain for slag aggregate-based concrete.

TABLE 6 Splitting Tensile Strength Test Results

Cylinder No.	Load at Failure (kN)	Splitting Tensile Strength (kPa)
1	45,867	637
2	49,620	689
3	55,343	786
4	40,864	567
5	46,587	647
Average	47,656	665

1.0 lbf = 0.00445 kN, 1.0 psi = 6.89 kPa

TABLE 7 Static Modulus and Poisson's Ratio Test Results

Cylinder No.	Modulus of Elasticity (kPa)	Poisson's Ratio
1	$23.4\mathrm{x}10^6$	0.14
2	$26.2\mathrm{x}10^6$	0.12
3	$22.7\mathrm{x}10^6$	0.18
4	$22.0\mathrm{x}10^6$	0.20
Average	$23.4\mathrm{x}10^6$	0.16

1.0 psi = 6.89 kPa

kPa (3.4×10^6 psi), slightly below the typical values reported in the literature that ranged between 24.8×10^6 kPa (3.6×10^6 psi) and 30.3×10^6 kPa (4.4×10^6 psi) for concrete with compressive strengths between 27 560 kPa (4,000 psi) and 41 340 kPa (6,000 psi). The effect of this slightly low modulus value, however, should be minimal in highway applications.

Poisson's ratio is the ratio of lateral strain to axial strain within the elastic range of a material when subjected to axial loading. In Table 7, the average result for Poisson's ratio was 0.16, near the lower boundary of values found in the literature of 0.15 to 0.20 (*4*).

CONCLUSIONS

This investigation has shown that the PG-based slag aggregate possesses physical and durability properties comparable with those of conventional aggregates. The small dissimilarities do not appear to present any significant problems in the production and performance of concrete. It was clearly demonstrated that a concrete mixture using the PG-based slag aggregate as a substitute for conventional coarse aggregate could be developed to meet or exceed the ASTM and LDOTD specifications for concrete used in highway applications.

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