

Engineering Properties of Phosphogypsum-Based Slag Aggregate

RAMZI TAHA AND ROGER K. SEALS

Between January 5, 1989, and November 15, 1989, Freeport-McMoran, Inc. (FMI) in cooperation with the Davy McKee Corporation operated an experimental pilot plant for the recovery of sulfur dioxide (SO_2) and slag aggregate from the thermal decomposition of phosphogypsum and other materials. The pertinent results collected from FMI's testing program on the slag aggregate are summarized. The research program included physical and chemical characterization; mineralogical, leachate, and radiological analysis; and durability tests. The results indicate that the slag aggregate may find uses in road base/subbase construction, hot mix asphalt paving mixtures, and portland cement concrete mixtures.

Since 1982, the Davy McKee Corporation (DMC) and the Florida Institute of Phosphate Research (FIPR) have been involved in a cooperative research and development program to develop a practical process for the thermal decomposition of phosphogypsum for the production of sulfuric acid and a saleable, solid by-product (1). The process developed to date incorporates the use of a circular grate system that has been successfully applied to the iron and steel industry. The conversion process uses a mixture of phosphogypsum, a solid carbon source (currently petroleum coke), waste phosphatic clays, and other additives depending on certain process parameters. A typical feed composition is given in Table 1. The mixture is fed onto the rotating, circular grate and is processed in a series of sealed zones on the grate. The raw gas, high in SO_2 , is collected for use as the feed gas for a conventional metallurgical-type sulfuric acid plant. The sintered, solid by-product, which remains on the grate after reaction, is discharged in a dry form from the grate by a tilting pan mechanism. The DMC/FIPR conversion process is shown in Figure 1 (12).

Freeport-McMoran, Inc. (FMI), a major materials company located in south Louisiana, constructed a demonstration pilot plant at its Agrico Uncle Sam facility in Donaldsonville, in a joint project with DMC (3). Different experimental burns (Campaigns 1 through 5) were conducted between January 5, 1989, and November 15, 1989. The various campaigns were needed to achieve a better moisture control in the feed mix. Also, inconsistent nodule particle size and poor mixing in the pug mill were dominant in the initial campaigns. However, Campaign 5 was considered a success in terms of quality of aggregate produced. Slag aggregate samples were collected from the five campaigns for future testing.

R. Taha, Civil Engineering Department, South Dakota State University, Brookings, S.Dak. 57007-0495. R. K. Seals, Institute for Recyclable Materials, College of Engineering, Louisiana State University, Baton Rouge, La. 70803-6405.

Although a definite market has not yet been identified for the slag aggregate, the following applications appear to be promising:

1. Phosphatic slimes consolidation (1),
2. Neutralization of phosphate industry waste materials (1),
3. Replacement or supplement to high-grade limestone or lime used in SO_2 scrubber systems (1),
4. Roadbed construction,
5. Portland cement concrete mixtures,
6. Hot mix asphaltic concrete mixtures,
7. Asphalt shingles granules, and
8. Railroad ballast.

Technical, environmental, economic, and regulatory factors will influence the actual use of the slag aggregate in these applications.

OBJECTIVE

The main objective of this paper is to summarize the results of physical, chemical, mineralogical, and engineering properties tests conducted on the slag aggregate. Particular attention is given to the aggregate performance in relationship to the Louisiana Department of Transportation and Development (LDOTD) specifications.

MATERIAL

The feed mix used in the production of SO_2 and the slag aggregate consists of phosphogypsum, petroleum coke, pyrite, bentonite, sand, and returns. The returns include $\frac{1}{4}$ -in. output material from the sintering grate. Currently, there are about 100 tons of slag aggregate from Burn Campaign 5 stockpiled at the Uncle Sam plant (3). Also, smaller quantities of slag aggregate from the other campaigns were collected in 5-gal buckets and are currently stored at the FMI Research and Development Laboratory in Belle Chasse, Louisiana. Characterization of the slag aggregate from these campaigns is discussed later.

EXPERIMENTAL RESULTS

Chemical (Elemental) Composition

Chemical characterization of the slag aggregate was carried out as part of the research program (3). The chemical break-

TABLE 1 TYPICAL COMPOSITION OF FEED MATERIALS USED IN THE CIRCULAR GRATE SYSTEM PROCESS (1)

Raw Materials	Percentage Weight Composition (Dry Basis)
Phosphogypsum (w/ hydration water)	53.1
Petroleum Coke	5.0
Pyrite	18.8
Bentonite	1.1
Sand	5.0
Returns ^a	17.0

^aReturns include minus 1/4 inch output material from the sintering grate.

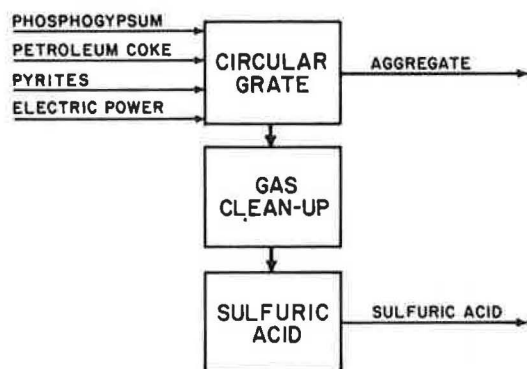


FIGURE 1 DMC/FIPR conversion process of phosphogypsum to sulfuric acid and aggregate (2).

down of the material is given in Table 2. Also, a number of trace elements such as As, Ba, Cd, Cr, Pb, Ag, Hg, and Se are present in the slag aggregate.

Mineralogical and Morphological Analysis

Examination of the slag aggregate by X-ray diffraction and microscopy indicates the following original phases of crystallized materials in the approximate order of decreasing abundance: Magnetite (Fe_3O_4) plus hematite (Fe_2O_3), amorphous/glassy constituents, belite ($\beta\text{-}2\text{CaO}\cdot\text{SiO}_2$), and quartz (SiO_2). Table 3 presents a compositional analysis of selected samples from the Campaign 2 slag aggregate. Gamma C_2S was not detected by X-ray diffraction (4). Microscopy studies of a polished section of reference sample indicated magnetite, dicalcium ferrite (angular crystals in matrix), and belite (round to dendritic crystals with multidirectional lamellae). Initial comments by Campbell and Tang (5) indicated that "the application of the slag aggregate in road base and embankments does not appear to have problems as suggested by its phase composition and volume stability."

Physical Analysis

Physical tests performed on the slag aggregate include particle size distribution, unit weight, specific gravity, percent absorption, ignition loss, Los Angeles abrasion, accelerated polish, aggregate freeze-thaw, and others.

TABLE 2 RESULTS OF THE ELEMENTAL ANALYSIS OF THE SLAG AGGREGATE (3)

Constituent	Content (%)
Na_2O	0.16
CaO	39.3
SiO_2	22.0
Al_2O_3	0.86
TiO_2	0.10
MgO	0.14
C_{tot}	0.21
C_{org}	0.07
F	0.40
Pb	0.03
As	0.094
Zn	0.74
Fe_2O_3	29.2
Total S	3.04
SO_4	1.10
L.O.I. (weight gain)	-3.06

TABLE 3 MINERALOGICAL COMPOSITION ANALYSIS OF CAMPAIGN 2 SLAG AGGREGATE (4)

Crystal Type	Composition (%)
Magnetite (Fe_3O_4) + Hematite (Fe_2O_3)	35
Amorphous/Glassy Constituents	30
Belite ($\beta\text{-}2\text{CaO}\cdot\text{SiO}_2$)	25
Quartz (SiO_2)	8
Calcium Ferrite ($\text{Ca}_2\text{Fe}_2\text{O}_7$)	minor
Pyrrhotite (Fe_7S_8)	minor
Alkali Sulfate ($\text{Ca, K, Na}\cdot\text{SO}_4$)	minor

Specific Gravity, Unit Weight, and Percent Absorption

The slag aggregate can be described as a nonplastic material. The aggregate particles have an irregular shape. Their surface texture can be generally described as rough and honeycombed (visible pores and cavities). Table 4 presents typical specific gravity, unit weight, and percent absorption data on the material from Campaigns 2, 3, and 5 (Houston, unpublished data). The specific gravity and percent absorption values reported in this table were determined in accordance with ASTM C127. The unit weight values were determined using ASTM C29. Currently, there are no specification limits set on specific gravity or percent absorption by LDOTD. Material specifications place limits on unit weight only. ASTM and AASHTO specify minimum dry rodded unit weights from 60 to 70 lb/ft³ depending on the type of application. The data of Table 4 indicate compliance with these requirements.

Gradation Analysis

Particle size distribution curves for the slag aggregate produced in Campaigns 2 through 5 are shown in Figure 2 (Houston, unpublished data). The gradation analysis was performed in accordance with ASTM C136 or LDOTD TR113. The

TABLE 4 SPECIFIC GRAVITY, UNIT WEIGHT, AND PERCENT ABSORPTION TESTS DATA FOR SELECTED SAMPLES FROM CAMPAIGNS 2, 3, AND 5 (Houston, unpublished data)

Campaign No.	K ^a	Sample	Unit ^b Weight (DL lb/ft ³)	Unit ^c Weight (DR lb/ft ³)	SG ^d (SSD)	SG (dry bulk)	Absorption ^e (%)
2	0.77	Bucket (ASTM #56)	67.1	74.2	3.07	2.99	2.49
2	0.77	1/4" x 3/8"	N/A ^f	N/A	2.76	2.61	5.97
3	0.77	1/4" x 3/8"	N/A	N/A	2.83	2.71	4.33
3	0.77	Bucket (ASTM #56)	69.7	73.7	N/A	N/A	N/A
5	0.77	N/A	N/A	N/A	3.05	2.97	N/A

^aK = (CaO)/(Fe₂O₃+SiO₂)

^bDL = dry loose

^cDR = dry rodded

^dSSD = saturated surface dry

^eAbsorption = % of dry weight

^fN/A = not available

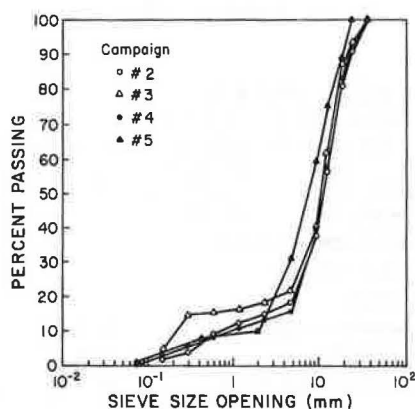


FIGURE 2 Gradation curves for slag aggregate samples selected from Campaigns 2, 3, 4, and 5 (Houston, unpublished data).

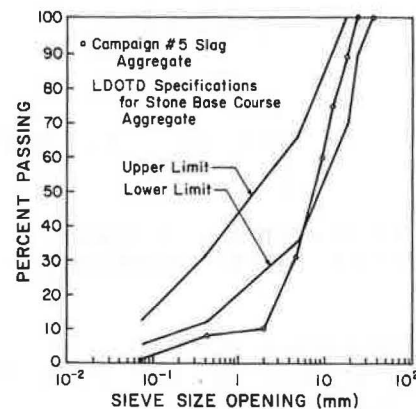


FIGURE 3 Comparison of the Campaign 5 slag aggregate gradation with LDOTD requirements for base course material.

LDOTD gradation requirements for stone used in base course applications are plotted in Figure 3. They indicate that the Campaign 5 slag aggregate will not conform to the gradation requirements for stone unless sufficient fines (< #4 sieve) are added to the slag aggregate. This can be accomplished by adding sand, silt, fly ash, or phosphogypsum size fractions. Gradation can also be improved by crushing some of the slag aggregate itself. The addition of a fine fraction will also be needed when preparing portland cement concrete or hot mix asphaltic concrete mixtures.

Ignition Loss Test

The ignition loss test is generally used as a means of assessing some measure of burn efficiency. The LDOTD TR114 test method covers the procedure for testing coarse aggregate for resistance to loss of weight by ignition. Table 5 presents the ignition loss test results for selected samples from Campaigns 2 and 3 (Houston, unpublished data). All the data indicate

weight gains upon firing the slag aggregate samples. The weight gains may be due to thermally induced reactions with oxidation being a prime mechanism (Houston, unpublished data). Hydration and carbonation reactions are also possible sources of the weight gain.

Durability Studies

The durability tests performed on the slag aggregate encompassed such tests as Los Angeles (LA) abrasion, aggregate freeze-thaw, expansion, hot water immersion, soundness, and accelerated polish.

LA Abrasion Test

LDOTD TR111 and AASHTO T96 test methods cover the procedure for testing different sizes of coarse aggregate for resistance to abrasion using the Los Angeles testing machine.

TABLE 5 IGNITION LOSS TEST RESULTS FOR SELECTED SAMPLES FROM CAMPAIGNS 2 AND 3 (Houston, unpublished data)

Campaign No.	K ^a	Sample	Ignition Weight Change (%) ^b
2	0.77	1/4" x 3/8"	+3.2
2	0.77	1/4" x 3/8"	+4.1
2	0.77	+5/8"	+3.9
2	0.77	+5/8"	+5.6
3	0.77	3/8" x 5/8"	+3.9
3	0.77	1/4" x 3/8"	+5.4
3	0.77	+ #4	+5.0

^aK = (CaO)/(Fe₂O₃+SiO₂)

^bHeating Conditions: 900°C for 30 minutes in a muffle furnace.

Data summarizing the results of LA abrasion testing of selected aggregate samples from Campaigns 1 through 5 are given in Table 6 (Houston, unpublished data). The LDOTD specifications require an LA abrasion loss not to exceed 40 percent (6). The differences in the abrasion loss data obtained for samples for Campaigns 1 through 5 and for Gradings A and B were relatively insignificant. However, the results were high compared with the 40.0 percent specification limit. Grading C test data exceed the 40 percent limit in all burn campaigns except Campaign 5. Such data indicate the presence of poorly burned nodules in the Grading C test fraction, which is composed of #4 × 3/8-in.-sized material (Houston, unpublished data).

For Campaign 3, with an increase in the K value, there seems to be an increase in the abrasion loss values for A grading tests. However, such a conclusion is not validated for Grades B and C.

Selected slag aggregate samples from Campaigns 2 and 5 were also subjected to LA abrasion testing after 4 weeks of immersion in 5-gal buckets containing approximately 12,500

cc of 150°F tap water. Table 7 gives the LA abrasion losses before and after the hot water treatment of the slag aggregate (Houston, unpublished data). The results indicate that the 4-week hot water immersion test had no significant adverse effect on the abrasion resistance of these samples. The slight improvement indicated for the soaked samples is considered insignificant (Houston, unpublished data).

Five-Cycle Sodium Sulfate Soundness Test

The sulfate soundness test (AASHTO T104), using the sodium sulfate procedure, was conducted on slag aggregate samples from Campaigns 2 and 3 (Houston, unpublished data). Table 8 presents a summary of the soundness test results. As noted in the table, the LDOTD specifications specify a maximum degradation loss of 15 percent. It is therefore concluded that the slag aggregate samples will meet the requirements of typical sulfate soundness tests for use as a construction aggregate.

Aggregate Freeze-Thaw Test

The aggregate freeze-thaw test is not currently required by LDOTD. The test was conducted to provide another measure of long-term durability. Failure criteria for rating aggregate resistance to disintegration by freezing and thawing are generally related to the failure criteria established for judging the sulfate soundness for aggregates (AASHTO T104). LDOTD sets a 15 percent loss limit for all aggregates when tested by the five-cycle magnesium sulfate soundness test (6). Indiana uses a 50-cycle aggregate freeze-thaw test. Its specification limits on degradation losses are 12 to 16 percent for the top four classes of construction aggregates and 20 to 25 percent for the two lowest classes of aggregate allowed for use in the state.

Both 25- and 50-cycle aggregate freeze-thaw tests were performed on selected slag aggregate samples from Campaign 2. The results are presented in Table 9 (Houston, unpublished data). The data indicate that the smaller aggregate fractions (#4 × 3/8 in. and 3/8 × 3/4 in.) were much more resistant to freeze-thaw cycles than was the 3/4 × 1 1/2 in. sized fraction. The latter failed to meet the Indiana specification limits or the LDOTD magnesium sulfate soundness test requirements. Furthermore, with an increase in the number of freeze-thaw cycles, there is an increase in the percentage of degradation loss.

During the freeze-thaw testing of the slag aggregate, a white precipitate formed in the water during the thaw cycles. A sample of the white precipitate was collected and analyzed by X-ray diffraction (Houston, unpublished data). The analysis indicated that the precipitate was more than 90 percent calcium carbonate (CaCO₃). It is probable that readily soluble calcium compounds within the slag are leached to the surface when the aggregate is exposed to moisture during the thaw cycles (Houston, unpublished data). The development of such reaction product upon wetting is undesirable since it may prevent contact or adhesion between the slag aggregate and liquid asphalt or cement paste, respectively, in hot mix asphaltic concrete mixtures or portland cement concrete. Fur-

TABLE 6 AVERAGE LA ABRASION TEST RESULTS FOR SELECTED SAMPLES FROM CAMPAIGNS 1 THROUGH 5 (Houston, unpublished data)

Campaign No.	K ^a	Abrasion Loss (%)			LDOTD Specification Limit (%)
		Grade A	Grade B	Grade C	
1	0.66	37.7			40
2	0.77	38.1			
2	0.77		36.2		40
2	0.77			53.8	
3	0.77	30.8			
3	0.82	37.4			40
3	0.86	39.8			
3	0.77		36.2		
3	0.82		34.2		
3	0.86		35.1		
3	0.77			45.5	
3	0.82			41.0	
3	0.86			44.6	
4	0.77	39.9	38.8	48.5	40
5	0.77	36.4	34.0	38.6	40

^aK = (CaO)/(Fe₂O₃+SiO₂)

TABLE 7 EFFECT OF HOT WATER IMMERSION ON LA ABRASION FOR SELECTED SAMPLES FROM CAMPAIGNS 2 AND 5 (Houston, unpublished data)

Campaign No.	K ^a	Abrasion Loss (%)						LDOTD Specification Limit (%)
		Pretreatment Sample			Hot Water Immersion Sample			
		Grade A	Grade B	Grade C	Grade A	Grade B	Grade C	
2	0.77	37.3	--	49.6	36.7	--	46.6	40
5	0.77	36.4	--	38.6	33.5	--	40.7	40

$$^aK = (\text{CaO})/(\text{Fe}_2\text{O}_3 + \text{SiO}_2)$$

TABLE 8 FIVE-CYCLE SODIUM SULFATE SOUNDNESS TEST RESULTS FOR SELECTED AGGREGATE SAMPLES FROM CAMPAIGNS 2 AND 3 (Houston, unpublished data)

Campaign No.	K ^a	Particle Size	% Loss	LDOTD ^b Specification Limit (%)
2	0.77	#4 x 3/8"	0.87	15
2	0.77	3/8" x 3/4"	0.16	15
2	0.77	3/4" x 1-1/2"	1.01	15
3	0.77	#4 x 3/8"	0.16	15
3	0.77	3/8" x 3/4"	0.29	15
3	0.77	3/4" x 1-1/2"	0.67	15

$$^aK = (\text{CaO})/(\text{Fe}_2\text{O}_3 + \text{SiO}_2)$$

^bThe 15% loss limit is set by the LDOTD for all aggregates when tested by the 5 cycle magnesium sulfate soundness test.

ther testing and evaluation are necessary to investigate this phenomenon.

Pennsylvania DOT Test for Expansion of Slag Aggregate

Since slag-type aggregates generally exhibit some expansion due to hydration of free oxides, the Pennsylvania DOT test for expansion was used to evaluate slag samples from Campaigns 2, 3, and 5. Slag aggregate samples were presized and then compacted in accordance with Pennsylvania DOT specifications to determine optimum moisture and maximum dry density values. Compacted specimens were then submerged in a 160°F water bath to accelerate the potential expansion reactions. Following a 7-day immersion period, the specimens were removed from the water but kept saturated for an additional 7 days curing in air at 160°F.

The results of the expansion tests are given in Table 10. The measured expansion is reported as a percentage of the original length of the compacted specimen (Houston, unpublished data). The 14-day expansion values varied from a low of 0.04 percent to a high of 0.11 percent. These values are within the Pennsylvania DOT specification limit of 0.5 percent.

Accelerated Polish Test (Skid Resistance)

The accelerated polish test was conducted on slag aggregate samples from Campaign 5. The aggregate tested should pass the 1/2-in. sieve and be retained on the No. 4 sieve. LDOTD TR116 covers the procedure for determining a relative mea-

sure of the extent to which aggregate in the wearing surface of the roadway will polish under traffic. The accelerated polish test is a relative one, and it is an indicator of aggregate performance rather than a required criterion. LDOTD has four classes for skid resistance rating. The scheme is given in Table 11 (6). A skid resistance rating of I corresponds to the best aggregate type for use in a wearing course asphaltic mixture. Generally, good quality sandstone will have a skid resistance rating of I. A material with a skid resistance rating of IV will still be used in designing wearing course mixtures. However, the quantity of coarse aggregate used will be considerably less than a material with a skid resistance rating of I. The initial and final polish values for the slag aggregate were 37 and 32, respectively, as determined by LDOTD laboratory personnel (LDOTD, unpublished data). Therefore, a skid resistance rating of III was assigned to the slag aggregate in accordance with Table 11.

Environmental Analysis

The environmental testing program consisted of leachate and radiological testing.

Leachate Testing

The leachate analysis of the trace elements present in the slag aggregate from Campaign 5 was conducted using the EP Toxicity and the TCLP tests. The results are given in Table 12 (3). The results indicate that the leachate quality is well within the EPA leachate standards.

Radiological Testing

Radiation assays were also performed on slag aggregate samples obtained from Campaign 3 (Scott, unpublished data). This material should not be significantly different from the products from other campaigns in its radiological characteristics. Table 13 gives the results of the radiation assay measurements. As noted, the radium-226 content increased in the slag aggregate compared with the raw phosphogypsum. This is a significant finding and certainly represents a cause of concern, particularly in light of the existing Environmental Protection Agency ban on the use of raw phosphogypsum. This ban, which encompasses research studies as well as practical uses, is currently under reconsideration by EPA. Previously, exemptions have been made to allow the phospho-

TABLE 9 AGGREGATE FREEZE-THAW TEST DATA FOR CAMPAIGN 2 (Houston, unpublished data)

Aggregate Size	K ^a	Freeze-Thaw Degradation %			Average (%)	State of Indiana Specification Limits (%)	LDOTD Specification Limit (%)
		Test Cycle	Test #1	Test #2			
#4 x 3/8"	0.77	25	1.3	1.7	1.5	12-25	15
		50	3.8	5.2	4.5		
3/8" x 3/4"	0.77	25	2.1	5.0	3.5	12-25	15
		50	5.0	5.7	5.4		
3/4" x 1-1/2"	0.77	25	20.3	28.8	24.6	12-25	15
		50	55.5	42.4	29.0		

^aK = (CaO)/(Fe₂O₃+SiO₂)^bThe 15% loss limit is set by the LDOTD for all aggregates when tested by the 5 cycle magnesium sulfate soundness test.

TABLE 10 PENNSYLVANIA DOT TEST DATA FOR EXPANSION OF SELECTED SAMPLES FROM CAMPAIGNS 2 AND 3 (Houston, unpublished data)

Campaign No.	Test No.	K ^c	Optimum Moisture (%)	Maximum Dry Density (lb/ft ³)	Molded Moisture (%)	Molded Dry Density (lb/ft ³)	Expansion after 14 Days (%)	Penn. DOT, Specification Limits (%)
2 ^a	1	0.77	12.2	118.6	11.5	118.2	0.11	0.5
	2		--	--	11.5	118.1	0.04	
3 ^a	1	0.77	11.8	118.2	12.3	117.8	0.04	0.5
	2		--	--	11.4	118.0	0.04	
5 ^b	1	0.77	8.0	135.1	8.5	126.4	0.09	0.5
	2				8.0	130.4	0.07	

^aCompaction: ASTM D698 (standard Proctor)^bCompaction: ASTM D1557 (modified Proctor)^cK = (CaO)/(Fe₂O₃+SiO₂)

TABLE 11 LDOTD SKID RESISTANCE RATING FOR COARSE AGGREGATES (6)

Polish Value	Skid Resistance Rating
> 37	I
35 to 37	II
30 to 34	III
< 30	IV

TABLE 13 RADIATION ASSAY MEASUREMENTS ON SLAG AGGREGATE SAMPLES FROM CAMPAIGN 3 AND RAW PHOSPHOGYPSUM (Scott, unpublished data)

Material	Radium-226 (pCi/g)	Radon 222 Emanation Power (%)	Gamma (uRem/h)
Slag Aggregate	51	0.25	20
Raw Phosphogypsum	29 ^a	10	30 ^b

^aLouisiana phosphogypsum (sample was tested in the laboratory).^bFlorida phosphogypsum (measurement was done over an actual stack).

TABLE 12 RESULTS OF THE LEACHATE ANALYSIS ON THE SLAG AGGREGATE (3)

Element	EP Toxicity ^a (mg/l)	TCLP ^b (mg/l)	EPA Leachate Standards (mg/l)
As	1.6	0.882	5.0
Ba	0.52	0.17	100.0
Cd	< 0.01	< 0.01	1.0
Cr	< 0.01	< 0.05	5.0
Pb	< 0.05	< 0.1	5.0
Ag	< 0.01	< 0.05	5.0
Hg	< 0.001	< 0.005	0.2
Se	< 0.01	< 0.1	1.0

^aMethod 40CFR261^bMethods 40CFR268 and 6010/7470

gypsum to be used for agricultural purposes. Future studies must be directed at ascertaining the health-related risks associated with the use of slag aggregate for practical applications such as an unbound base material or as an aggregate in asphaltic concrete or portland cement concrete. The studies must consider both the short time exposure to construction workers and the long-term exposure to users of such facilities. On a more positive note, the radon-222 emanation power in the slag aggregate is about 0.25 percent compared with 10 percent in the raw phosphogypsum. Thus, the potentially negative consequences resulting from radon-222 emanation have been reduced significantly.

CONCLUSIONS

The research studies on the slag aggregate included physical and chemical characterization tests, radiological and leachate analysis, and durability studies. Important findings of the testing program relevant to the slag aggregate properties and performance include the following:

1. The raw mix design, the blending and burning processes, and the methods of handling the grate product will significantly influence the quality of the slag aggregate produced. Therefore, quality control is a necessity. Otherwise, failures in applications may result because of material variability.

2. The results of the EP toxicity and the TCLP leachate tests indicate that the slag aggregate will meet the EPA leachate standards.

3. There is an increase in Ra-226 content in the slag aggregate compared with raw phosphogypsum. However, radon emanation is significantly decreased.

4. There are weight gains rather than weight losses upon firing the slag aggregate during the ignition loss test. Oxidation, hydration, and carbonation reactions are possible sources of the weight gain.

5. Generally, the LA abrasion losses (Grades A and B) for the slag aggregate will meet the LDOTD specification limit of 40 percent. However, these values are relatively close to the 40 percent limit.

6. Hot water immersion had no adverse effect on LA abrasion values for the slag aggregate.

7. The larger slag aggregate fraction ($\frac{3}{4} \times 1\frac{1}{2}$ in.) will not meet the aggregate freeze-thaw specification requirements of Indiana. The smaller slag aggregate fractions ($\#4 \times \frac{3}{8}$ in. and $\frac{3}{8} \times \frac{3}{4}$ in.) were much more resistant to freeze-thaw cycles and will meet the specification requirements.

8. The expansion test results indicate that the slag aggregate will meet the Pennsylvania DOT maximum specification limit of 0.5 percent for expansion. No such test is required by LDOTD.

9. The slag aggregate will meet the 15 percent loss limit set by LDOTD for aggregates tested by the five-cycle sodium sulfate soundness test.

10. A skid resistance of III, based on LDOTD criteria, was assigned to the slag aggregate on the basis of initial and final polish values.

RECOMMENDATIONS FOR FURTHER STUDIES

The data obtained by the FMI studies provide an excellent starting point for research related to the use of slag aggregate

in roadbed applications, in portland cement concrete mixtures, or in hot mix asphalt paving mixtures. A follow-up comprehensive testing program is currently under development at the Institute for Recyclable Materials at Louisiana State University. This program will explore the potential use of slag aggregate in the applications noted.

The scope of work will include both environmental and mechanical testing of the slag aggregate and of the mixtures developed for the unbound base, asphaltic concrete, and portland cement concrete applications. Environmental analysis will include toxicity characteristic leaching procedure, EP toxicity, and radiation assay measurements. The mechanical studies will include dynamic modulus testing, flexural strength relations, fatigue analysis, and creep testing.

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