Geotechnical Properties of a Copper Slag

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The geotechnical properties of a copper slag are presented. The slag, produced at the American Smelting and Refining Company (ASARCO) plant in El Paso, Texas, is a by-product of refining copper ore in oil-fired reverberatory furnaces. The geotechnical properties include sieve analysis, specific gravity, maximum and minimum dry unit weights, angle of shearing resistance, one-dimensional compressibility, and permeability. The results of laboratory tests on this slag have been compared with the representative values obtained for sands. The comparison shows that the values of the slag are similar to those obtained for medium sands, and it can be used as a construction material in place of sand, such as backfill of retaining walls and landfill for construction of shallow foundations. Toxicity tests on the slag for possible groundwater pollution are also included. Based on the current U.S. Environmental Protection Agency (EPA) regulations governing solid waste characteristics, the slag can be classified as nonhazardous.

Waste materials are being used increasingly as a geotechnical material in construction of highways, buildings, and other structures. The availability and use of fly ash and bottom ash in the United States have been reported by Meyers, Pichumani, and Kapples (1) and Seals, Moulton, and Ruth (2), respectively. Blast furnace slags have been widely accepted in the construction industry as high-quality mineral aggregates.

The purpose of this paper is to report the geotechnical properties of a copper slag and to compare them with the properties of sands to evaluate the feasibility of using the slag as a replacement for granular soil. The copper slag under study is produced by the American Smelting and Refining Company (ASARCO) in El Paso, Texas. These slags are produced by melting copper ore in oil-fired reverberatory furnaces. The chemical composition of this slag as determined by the atomic absorption technique and wet chemical analysis is 40 percent silicon dioxide, 39 percent iron oxides (Fe O and Fe_2 O_3), 5.8 percent zinc oxide, 5 percent aluminum oxide, 5 percent magnesium oxide, 4.5 percent calcium oxide, 0.56 percent copper, and 0.14 percent lead. The copper slag, which has a black, shiny appearance, is partially crushed to smaller particle sizes and is stockpiled after the refining process. This study was conducted to determine if the slag could be used economically in construction so that the aesthetic and environmental problems associated with slag waste disposal dumps could be lessened somewhat.

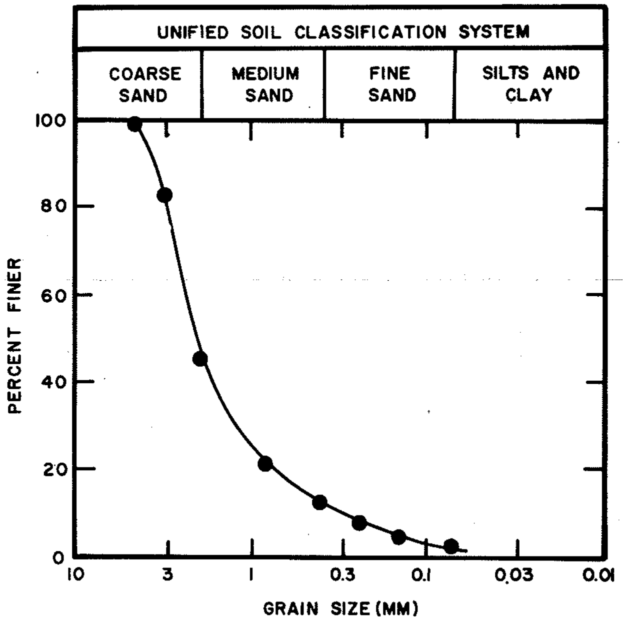
The laboratory test results presented in this study are for highly angular crushed slag particles finer than U.S. sieve No. 4 (4.75 mm), which is the upper limit for sand in the Unified Soil Classification System (3). The fine fraction constituted about 42 percent of the specimen received. Properties of the slag such as grain-size, compaction, angle of shearing resistance, compressibility. permeability, and toxicity, are evaluated.

LABORATORY TESTS AND INTERPRETATION OF RESULTS

Sieve Analysis

Sieve analysis of a representative oven-dried sample of the copper slag was made in the laboratory. Before the analysis, the coarse fraction (i.e., the fraction retained on No. 4 sieve) was removed. The results of the sieve analysis for the fine fraction are shown in Figure 1: 100 percent passed No. 4 sieve; 46 percent passed No. 10 sieve; 12 percent passed No. 40 sieve; and 2 percent passed No. 200 sieve. Figure 1 gives a comparison of the limits of fine, medium, and coarse sand-size limits as defined by the Unified Soil Classification System (ASTM D 2487). Based on this information the slag sample can be classified as SW, i.e., well-graded sand.

Figure 1. Grain-size distribution of the copper slag used in the study with size limits of sands as given by the Unified Soil Classification System.



Specific Gravity

A number of tests for the specific gravity of the copper slag were run in accordance with ASTM D 854 using a 200-ml volumetric flask, and the average value obtained was 3.2. This high value for the slag was expected because of its high iron content. In contrast, the specific gravity of most natural sands usually falls in a range of 2.64 to 2.67.

Dry Unit Weights

The minimum and maximum unit weights of oven-dried slag were determined in the laboratory to be 1779.4 kg/m^3 and 2180.2 kg/m^3, respectively. This was done by using the test procedure described in ASTM D 2049. The void ratios corresponding to the maximum and minimum dry unit weights were found to be 0.468 and 0.8, respectively. These void ratios correspond to those actually obtained in uniform, clean medium-to-fine sand (4).

A standard Proctor compaction test (ASTM D 698) was also conducted on the slag using a standard Proctor mold and a 24.5 N (5.5 lb) hammer. The maximum dry unit weight obtained was approximately 2020.1 kg/m^3 (126 lb/ft^3) at a moisture content of 18.80 percent. This is somewhat higher than that for most natural sands, which fall within the range of 1682.5 to 1845.7 kg/m^3 (105 to 115 lb/ft^3).

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*Deceased, March 1982

Angle of Shearing Resistance

For estimating the bearing capacity of foundations and the lateral pressure of backfill on retaining structures and checking the stability of embankments, the angle of friction for shearing resistance for granular materials is of considerable importance. For this reason, a number of direct shear tests (ASTM D 3080) were conducted in the laboratory.

The direct shear box used for the tests had a cross-section area of 50.8 x 50.8 mm (2 x 2 in.). The relative density at the beginning of the test was varied by pouring the slag into the direct shear box through a funnel from different heights. All tests were conducted with a normal stress of 70 kPa (10 lb/in.^{2}). The angles of friction obtained at various relative densities of compaction are shown in Figure 2.

The range of friction angles generally obtained for various natural sandy soils is also plotted in Figure 2 (5). A comparison shows that, in general, at a given initial relative density the value of the friction angle for copper slag is considerably higher than that obtained for sandy soils. This can be attributed mostly to the high degree of angularity of the slag particles used in the test. For most natural soils, the angle of friction at the maximum density (relative density = 100 percent) usually ranges between 40 and 45 degrees. However, for the slag under consideration, it is about 53 degrees. Based on the present test results, a conservative estimate of the angle of friction may be given by

$$\phi = 36.5 + 0.165\,D_r \qquad (1)$$

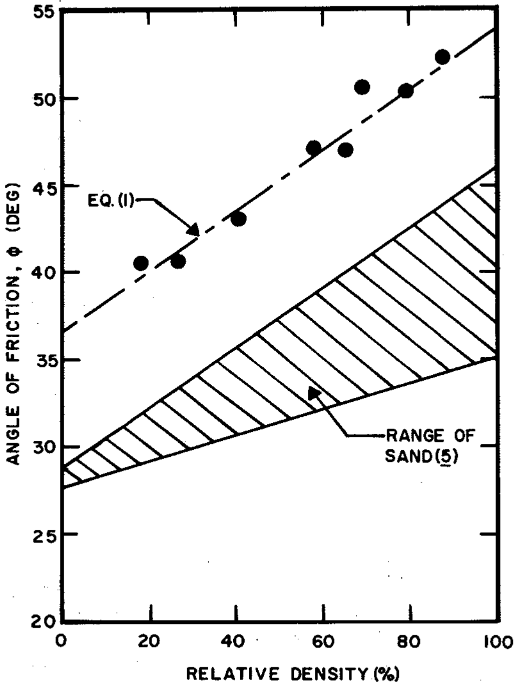
where

ϕ = angle of friction, in degrees, and
D_r = relative density, in percent.

One-Dimensional Compression Test

Crushed copper slag is a granular material. The compression of the slag deposit under load (if used as a landfill) will be elastic in nature, and consolidation settlement will not occur. The constrained secant modulus (i.e., Young's modulus with no lateral deformation) is the parameter from which the elastic settlement of a slag layer used as a fill can be estimated. For this reason, one-dimensional compression tests on the slag were performed using a consolidation ring (ASTM D 2435) in a consolidation loading frame. The consolidation ring had a cross-section area of 100 cm^2 and the specimens molded for the tests were 38.1 mm high. The slag was poured into the consolidation ring through a funnel from different heights to achieve a variation in the relative density of the specimens. The specimen prepared at a relative density of 100 percent needed slight vibration after the pouring of the slag into the consolidometer. Initially the specimens were subjected to a small pressure of 6.9 kPa (1 lb/in.^{2}) and then soaked for 24 hr before further load application. The vertical stress and the corresponding vertical strain obtained from these tests are given in Figure 3. It may be noted that the values of D_r given for each stress-strain curve in Figure 3 are the relative densities at the beginning of the tests.

Figure 2. Angle of friction of copper slag at varying relative densities.



The constrained secant modulus may be defined as

$$M = \Delta\sigma_v/\Delta\epsilon_v = \sigma_{v(2)} - \sigma_{v(1)}/\epsilon_{v(2)} - \epsilon_{v(1)} \qquad (2)$$

where

M = constrained secant modulus,
$\epsilon_{v(1)}$ = vertical strain at a stress level of $\sigma_{v(1)}$, and
$\epsilon_{v(2)}$ = vertical strain at a stress level of $\sigma_{v(2)}$.

The values of constrained secant modulus from zero stress [$\sigma_{v(1)} = 0$] up to various stress levels have been calculated and are also shown in Figure 4. These values are of the same order of magnitude as those obtained from sandy soil. Hassib (6) studied the constrained secant modulus for various sands and these are also reported by Lambe and Whitman (7). Table 1 gives a comparison of the typical values of M for well-graded sand taken from Hassib's study with those obtained from the copper slag. The values appear to be of the same order of magnitude except when the relative density is 100 percent and the level of stress is high. Then the constrained modulus of the slag shows a significantly lower value than the sand. This is probably because of the crushing of angular particles present in the slag.

Coefficient of Permeability

Results of a number of constant head permeability tests (ASTM D 2434) conducted on the slag are shown in Figure 5. These tests were run at varying void ratios. All specimens prepared for testing had a diameter of 63.5 mm (2.5 in.) and their heights varied between 127 and 139.7 mm (5 and 5.5 in.). As in the one-dimensional compression test, the slag was poured through a funnel into the permeameter from various heights to achieve the desired void ratio. The coefficient of permeability, k, varies from about 0.32 mm/sec in a very dense state to about 0.8 mm/sec in a very loose state. The average value of the coefficient of permeability at a relative density of about 50 percent is about 0.47 mm/sec. Table 2 gives a comparison of the average values of k for various sandy soils with those for the slag. Although several factors contribute to the rate of flow of water through granular materials, based on these results it would be reasonable

Figure 3. One-dimensional compression tests—variation of vertical strain versus normal stress.

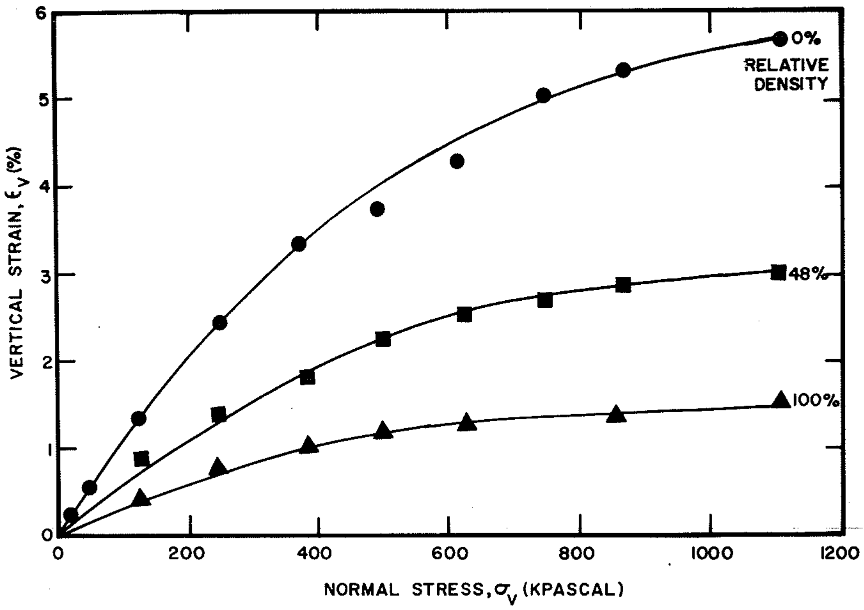


Figure 4. One-dimensional compression test results—variation of secant constrain modulus with normal stress.

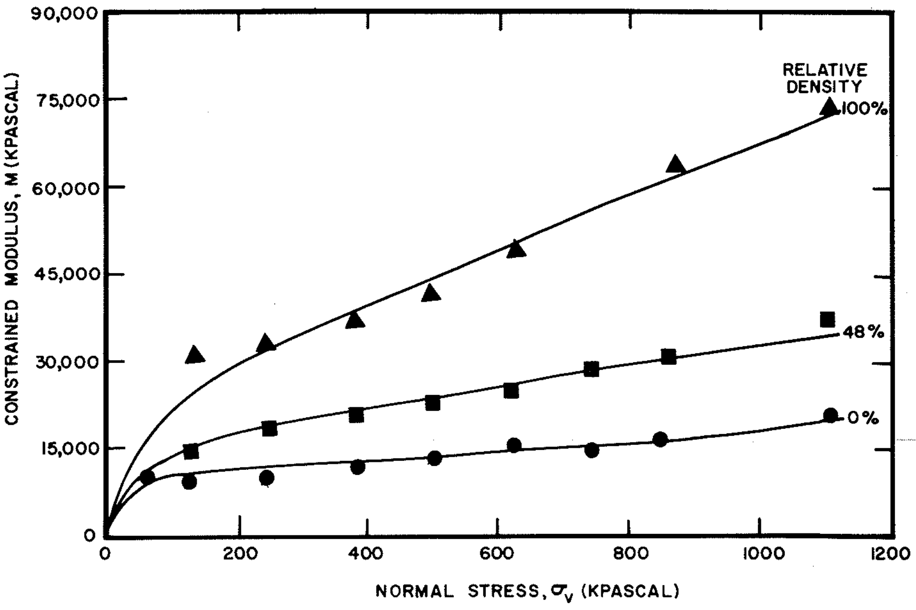


Table 1. Secant constrained modulus of the slag and well-graded sand (virgin loading).

Relative Density (%)	$\Delta\sigma_v$		$M = \Delta\sigma_v/\Delta\epsilon_v$			
			Copper Slag		Well-graded sand[a] 0.02 mm < D[b] < 1 mm	
	kPa	lb/in.^{2}	kPa	lb/in.^{2}	kPa	lb/in.^{2}
0	62.1	9	12,500	1,812	13,800	2,000
	to	to				
100	103.5	15	41,400	6,000	51,750	7,500
0	200.1	29	17,300	2,507	25,530	3,700
	to	to				
100	510.6	74	62,100	9,000	121,440	17,600

[a] Hassib (6) and Lambe and Whitman (7).

[b] D = particle size.

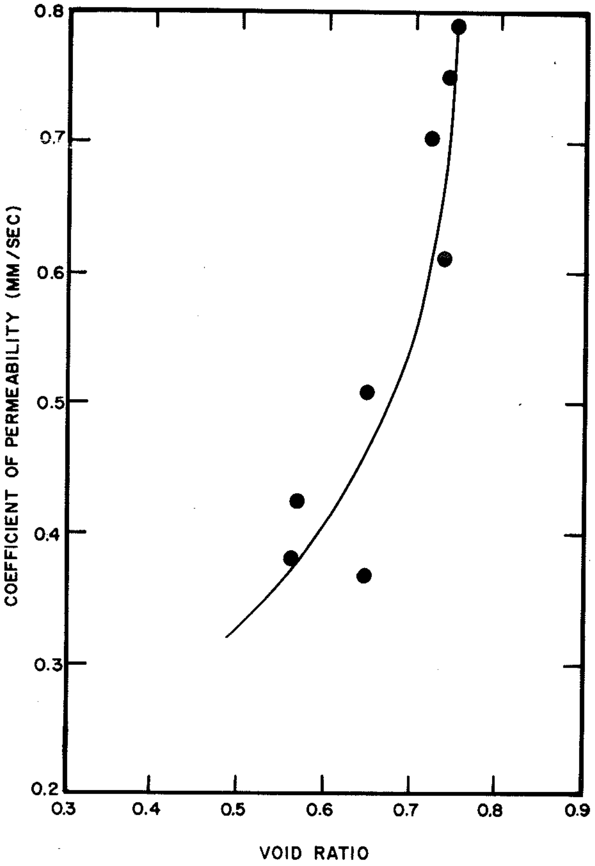
Table 2. Comparison of typical values of permeability coefficient, k, of sands with those of the copper slag.

Soil Type	D_{10}(mm)[a]	k(mm/sec)
Uniform, coarse sand[b]	6	4
Uniform, medium sand[b]	3	1
Clean, well-graded sand and gravel[b]	1	0.1
Uniform, fine sand[b]	0.6	0.04
Copper slag		
Very loose	0.35	0.3
Very dense	0.35	0.8
$D_r \approx 50\%$	0.35	0.47

[a] D_{10} = effective size; i.e., the sieve size through which 10 percent of the soil specimen will pass.

[b] B.K. Hough (4).

Figure 5. Variation of the coefficient of permeability of the slag with the void ratio.



to conclude that the permeability of uniform, medium-to-fine sands is comparable to the slag sample.

Toxicity Test

To evaluate the possible groundwater pollution potential of the slag when used as a geotechnical material, an EPA toxicity test was conducted on a representative 100-g sample. The test was conducted according to procedures specified in the Code of Federal Regulations, 40 CFR 261.24. Table 3 lists the elements that were examined as part of the EPA toxicity test with their respective maximum allowable concentrations. The results obtained from analysis of the slag sample leachate are given in the last column of Table 3.

The data show that the concentrations of all metals in the slag leachate were far below the maximum allowable limit for characterizing a solid waste material as hazardous. Because no organic materials are present in the slag, the material could be characterized as nonhazardous on the basis of the EPA toxicity test. In addition to the EPA toxicity test, the other criteria for characterizing solid wastes as hazardous or nonhazardous were examined, including ignitability, corrosivity, and reactivity. Because the slag does not possess any of these characteristics, it would be considered a nonhazardous waste residue according to the current EPA regulations governing characterization of solid waste.

CONCLUSIONS

Laboratory tests for the physical properties of a copper slag passing No. 4 U.S. sieve have been presented. The portion of slag passing through the sieve was about 42 percent of the crushed slag specimen received. Based on these results, the following conclusions may be drawn:

Table 3. Results of toxicity tests.

Contaminant	Maximum Allowable Concentration (mg/l)	Slag Extract Concentration (mg/l)
Arsenic	5.0	0
Barium	100.0	0.5
Cadmium	1.0	0.002
Chromium	5.0	0
Lead	5.0	0
Mercury	0.2	0
Selenium	1.0	0.08
Silver	5.0	0

1. The copper slag is generally similar to medium sands as far as maximum, minimum, and average void ratios; permeability; and compressibility are concerned.
2. The angle of friction of shearing resistance of the slag is generally higher than that of sands. This is because of the angularity of the slag particles. Even at a relative density of about 20 percent, the friction angle is about 40 degrees. If the slag is used as a backfill material for structures such as retaining walls, the lateral pressure will be less than that encountered with a uniformly graded sand backfill.
3. It appears that the slag can be used as a fill material. Foundations of buildings can be adequately supported over fills constructed by the slag. Of course, slight variations in properties of the slag may be anticipated depending on the source. With proper design and analysis, however, the waste material can be economically used; and the environmental and aesthetic problems associated with waste disposal sites can be reduced.
4. Based on toxicity tests, it appears that the slag examined in this study is a nonhazardous waste as far as the groundwater pollution potential is concerned.

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