Stabilized Copper Mill Tailings for Highway Construction

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The results of an investigation to determine the feasibility of using stabilized copper mill tailings in road construction are presented. Properties of three types of tailings were evaluated after preliminary testing of several tailings from Arizona, Idaho, and Utah. The properties of the three tailings are summarized, and detailed results obtained for one type are reported. Index properties of the untreated tailings, including physical and mechanical properties, are given. Engineering parameters of untreated tailings are reported, including compaction characteristics; compressive, tensile, and shear strength; compressibility; permeability; and erodibility by rainfall. Properties of cement-stabilized and asphalt-stabilized tailings are also presented. The results demonstrate that copper mill tailings have excellent engineering properties and can be successfully used in road construction. In particular, the results indicate that there is excellent potential for using tailings as compacted fill in embankments, compacted foundation and subgrade material, cement-treated base, emulsion-treated base, and stabilized material for lining canals, ponds, and reservoirs.

In normal copper-mining operations, the mined ore is crushed in gyratory primary crushers that reduce it to an average 15 cm (6 in) in size. The crushed ore is subjected to secondary and tertiary hydrocone crushers that reduce the final product to a size smaller than 1.27 cm (0.5 in). This fine ore is then wet-ground in ball mills. The ground ore, in an ore-water slurry and conditioned with reagents, is floated in flotation tanks to a rough concentrate of copper and other valuable minerals. Tailings from the flotation process are thickened, and the excess water is recovered from the slurry for reuse in the process. The slurry is either pumped into tailing-disposal ponds or classified for use as a hydraulic backfill in the mine.

More than 1 billion Mg (1.1 billion tons) of mine and smelter waste, including tailings, are produced every year by the basic mineral industry. A 1965 land survey by the U.S. Department of Agriculture showed that the United States contained 0.8 billion hm^2 (2 billion acres) of land despoiled by surface mining. While these millions of megagrams of industrial waste are being produced and stockpiled at high monetary and ecological costs, there is a considerable shortage of conventional construction materials for highway use in many parts of the country.

In view of the available volume and continued enormous rate of production of mill tailings (each unit of copper produced generates about 200 times its weight in waste), it appears that a concentrated effort is needed to evaluate the potential use of mill tailings in various aspects of highway construction and other engineering uses. This paper presents data from a comprehensive investigation that was aimed at determining the feasibility of using tailings as a construction material to replace the more scarce conventional materials.

PROPERTIES OF SELECTED TAILINGS

After a preliminary laboratory evaluation of 11 tailing specimens from Arizona, Idaho, and Utah, the engineering properties of the following three types of tailings were evaluated in detail:

1. Bisbee, obtained from the Cooper Queen Branch of the Phelps Dodge Corporation, Bisbee, Arizona;
2. Duval, obtained from the Sierrita Mine, Duval Sierrita Corporation, Sahuarita, Arizona; and
3. Magma, obtained from the Magma Copper Company, Superior Division, Superior, Arizona.

A summary of some index and engineering properties of the three tailings is given in Table 1. Additional data on these and other tailings are given elsewhere (3).

Because of space limitations, this paper deals only with the properties of compacted, cement-stabilized, and asphalt-stabilized Duval tailings. Similar results, however, were obtained for the Bisbee and Magma tailings and are given elsewhere (3).

UNTREATED DUVAL TAILINGS

Index Properties

The grain-size distribution for the Duval tailings ranged between 1.0 and 0.001 mm with a uniformity coefficient of 21. A large percentage of the materials (41.7 percent) passed the 0.075-mm (no. 200) sieve; this is attributed to the ball-mill grinding of the ore materials during processing. Since tailings are a by-product of rock-crushing processes, the individual particles are very angular in shape when observed under a light microscope.

As data given in Table 1 show, the specific gravity of 2.71 for Duval tailings was the lowest among the three types. The high values of specific gravity obtained for the other two tailings are attributed to large amounts of magnetite: 21.0 and 31.9 percent in Bisbee and Magma, respectively, versus 1.9 percent in Duval.

According to American Association of State Highway and Transportation Officials (AASHTO) classification, Duval tailings are classified as A-2-4 material.

Compaction Characteristics

The compaction characteristics of the three types of tailings were determined by using the standard AASHTO (ASTM D 698) and the modified AASHTO (ASTM D 1557) methods. The maximum dry densities and optimum moisture contents are given in Table 1. The resulting wide range in maximum dry densities among the three tailings appears to be attributable essentially to variations in the specific gravities of the tailings. The values of maximum density for Duval tailings are comparable to those of natural soils, whereas those for Bisbee and Magma tailings are significantly higher.

Compressive Strength

The compressive strength of the compacted Duval tailings was determined for specimens compacted at the maximum dry density and optimum moisture content as determined by the modified AASHTO compaction test. In addition, values of compressive strength for the specimens compacted at 95 and 90 percent of the maximum density at their corresponding moisture contents, dry and wet of optimum, were also determined.

All specimens were 10.16 cm (4 in) in diameter and 11.68 cm (4.6 in) in height—i.e., the compaction mold size. The specimens were tested immediately after compaction.

The results of the compressive strength tests are given in Table 2. These values were reached at strain levels lower than 3 percent, which indicates a brittle type of behavior. The compressive strength reaches its maximum value at or slightly below the optimum moisture content and then sharply decreases wet of optimum.

Double-Punch (Tensile) Strength

The tensile strength of compacted Duval tailings was determined by using the double-punch test (4). The test was conducted on compacted specimens similar to those discussed under the compressive strength test. Details of the testing procedure are given elsewhere (3).

The results of the double-punch tests, which are included in Table 2, indicate low values of tensile strength that do not exceed 11.72 kPa (1.7 lbf/in^2). The tensile strength reaches its maximum value at or slightly below the optimum moisture content.

Shear Strength Parameters

Direct shear tests and triaxial tests were conducted in the laboratory on the compacted Duval tailings at maximum dry density as determined by the modified AASHTO compaction test. Drained direct shear tests and consolidated drained and undrained triaxial tests were conducted.

The effective strength parameters for the Duval tailings ranged from $\bar{c}$ = 9.58 to $\bar{c}$ = 15.33 kPa (200-320 lbf/ft^2) and $\bar{\phi}$ = 36° to $\bar{\phi}$ = 37°. All specimens failed with a brittle stress-strain relation with axial strain at failure not exceeding 5 percent and exhibiting well-defined slip planes. The high effective angles of friction for the Duval and other tailings, given in Table 1, are in line with other values reported elsewhere (5, 6) and can be attributed to the high degree of angularity of copper mill tailings and consistency in their production methods.

Table 1. Properties of selected tailings.

Property	Bisbee	Duval	Magma
Color	Light brown	Grey	Dark grey
Specific gravity	3.13	2.71	3.92
Liquid limit	16.5	18.6	13.7
Plasticity index	Nonplastic	Nonplastic	Nonplastic
Shrinkage limit	11.8	16.4	12.0
Percentage passing No. 200 sieve	23.5	31.7	45.3
AASHTO classification	A-2-4	A-2-4	A-4
Optimum moisture content (%)			
Standard AASHTO	11.8	13.1	9.3
Modified AASHTO	8.9	10.8	7.7
Maximum dry density (g/cm^3)			
Standard AASHTO	2.125	1.796	2.566
Modified AASHTO	2.319	1.917	2.917
Effective cohesion, $\bar{c}$ (kPa)	14.37	9.58	7.66
Effective friction angle, $\bar{\phi}$	39°	36°	41°
Compression index, $C_c x10^2$	3.5	3.8	7.5
Swelling index, $C_s x10^2$	1.7	1.1	1.2
Coefficient of consolidation, $C_v x10^{-3}$ (cm^2/s)	13.5	14.6	12.1
Coefficient of permeability, $Kx10^{-6}$ (cm/s)	8.6	22.7	0.2
Rainfall erosion (%)	2.5	2.3	4.5

Note: 1 g/cm^3 = 62.4 lb/ft^3; 1 kPa = 0.145 lbf/in^2; 1 cm^2 = 0.155 in^2; 1 cm = 0.394 in.

Compressibility and Swelling Characteristics

One-dimensional consolidation tests were conducted on specimens compacted at the various density and moisture content conditions described previously under the compressive strength tests. Specimens were 6.35 cm (2.5 in) in diameter and were saturated before testing.

The summary of the test results included in Table 2 indicates very uniform characteristics. For Duval tailings, values of C_c ranged from 0.038 to 0.052, values of C_s from 0.0105 to 0.013, and values of C_v from 0.0125 to 0.0149 cm^2/s (0.08-0.096 in^2/s). The low compressibility (as shown by the low values of C_c and low swelling potential (as shown by the low values of C_s) are similar to those for highly compacted granular fine materials. The low values of C_v are indicative of materials with very low permeability, as will be shown later.

Permeability

The coefficient of permeability for the compacted tailings was determined by a pressurized constant-head permeameter. The permeability tests were conducted on specimens compacted at the density and moisture content conditions described under the compressive strength tests. Specimens were 6.35 cm (2.5 in) in diameter and 10.16 cm (4.0 in) in height.

The summary of the test results given in Table 2 indicates that the coefficient of permeability decreases as density increases, which is a characteristic of granular-type soils. As the dry density increased, the permeability sharply decreased as the moisture content approached optimum. Wet of optimum, as the density decreased the permeability increased again but at lower rates.

The permeability coefficient for the Duval tailings ranged from 22.7 × 10^{-6} to 303 × 10^{-6} cm/s (57.6 × 10^{-6} to 769 × 10^{-6} in/s). The permeability coefficients for the three tailings at maximum dry densities, which are given in Table 1, range from 2 × 10^{-7} to 2.27 × 10^{-5} cm/s (0.2-23.5 ft/year) for the Magma and Duval tailings, respectively. These values cover closely the lower and upper boundaries of the permeability range for soils of very low permeability.

Table 2. Engineering properties of compacted Duval tailings.

At Compaction Condition									
Relative Compaction[a] (%)	Dry Density (g/cm^3)	Moisture Content (%)	Compressive Strength (kPa)	Tensile Strength (kPa)	Compression Index C_c	Swelling Index C_s	Coefficient of Consolidation C_v (cm^2/s)	Permeability Coefficient $Kx10^6$ (cm/s)	Rainfall Erosion (%)
90	1.726	4.2	161.3	7.6	0.052	0.013	0.0135	303	10.5
95	1.822	5.3	266.1	11.7	0.041	0.013	0.0149	177	8.9
100	1.918	10.8	280.6	11.7	0.038	0.011	0.0146	22.7	2.3
95	1.822	14.3	101.4	6.9	0.036	0.0105	0.0128	27.9	5.0
90	1.726	15.7	54.5	2.8	0.040	0.010	0.0125	39.2	5.8

Note: 1 g/cm^3 = 624 lb/ft^3; 1 kPa = 0.145 lbf/in^2; 1 cm^2 = 0.155 in^2; 1 cm = 0.394 in.
[a]Modified AASHTO.

Table 3. Properties of cement-treated Duval tailings.

Amount of Cement by Weight (%)	Compressive Strength by Days of Curing (MPa)			Soaked Strength at 7-Day Cure (kPa)		Durability Loss After 12 Cycles (%)		Permeability Coefficient $Kx10^{-6}$ (cm/s)	Rainfall Erosion (%)
	7	28	90	Tensile Strength[a]	Flexure Modulus	Wet-Dry	Freeze-Thaw		
0	-[b]	-[b]	-[b]	-[b]	-[b]	-[c]	52.9	22.7	100
2	1.55	-	-	172.4	220.6	15.2	14.4[d]	18.2	4.3
4	2.59	3.52	5.31	268.9	296.5	5.7	9.9	8.7	0.0
6	2.79	-	-	330.9	406.8	4.2	5.2	2.3	0.0
8	3.69	5.29	8.96	406.8	489.5	2.3	3.2	-	-
10	4.41	7.15	9.87	496.4	627.4	1.8	2.9	-	-
12	-	7.21	10.03	-	-	-	-	-	-

Note: 1 Pa = 0.000 145 lbf/in^2; 1 cm = 0.394 in. Dry density = 1.918 g/cm^3, and moisture content = 10.8 percent.
[a] Double punch.
[b] Specimens slaked in water.
[c] Specimens disintegrated in one cycle.
[d] Loss of 14.4 percent in five cycles.

Rain Erodibility

The erodibility of compacted tailings under the effects of rainfall was evaluated by using the Rotadisk Rainulator machine (7-9). In this study, an average rainfall intensity of 3.25 cm/h (1.28 in/h) was used for 15 min. These tests were conducted on specimens compacted at the conditions of density and moisture content described under the compressive strength tests. Details of the testing procedure are given elsewhere (3).

The summary of the test results given in Table 2 indicates that the least erosion occurred at the highest compacted density. Erosion was significantly greater dry of optimum than wet of optimum, at equal compacted dry densities. The erodibility values given in Table 1 correspond to those for specimens at maximum dry density values.

Discussion of Results

The tailings consistently included large, though nonplastic, percentages of fine particles. These particles are highly angular and thus contribute to very high angles of internal friction in such fine materials. When compacted, the tailings show high stability with relatively high compacted densities, particularly those tailings that have extremely high specific gravities. Their soil classification and their strength properties and compacted densities indicate their potential use as good to fair subgrade, foundation, and embankment materials. Because of their high erodibility by water (rainfall), they should be stabilized when exposed at the surface. The compacted tailings also exhibited very low compressibility, which indicates potential successful use in high embankments.

The very low permeabilities of the compacted tailings qualify them for potential use as reservoir and canal linings, particularly when they are protected with filter layers and not subjected to wet-dry conditions. These limitations can be removed when the tailings are stabilized with cement, as shown later in this paper.

CEMENT-STABILIZED DUVAL TAILINGS

Compaction Characteristics

The compaction characteristics of the cement-tailing mixes were determined by using the modified AASHTO compaction test. The compaction curve for the Duval tailings did not vary much in comparison with that obtained for the untreated tailings. This behavior is very common in most soils (10, 11). The cement used met the specifications of type 1 and type 2 portland cement as determined in accordance with ASTM designation C 150.

Compressive Strength

Compacted cement-treated tailing specimens were prepared by statically compacting mixtures of the Duval tailings with 2, 4, 6, 8, and 10 percent cement, at the optimum moisture content and maximum dry density, for the modified AASHTO compaction test. Specimens were 10.16 cm (4.0 in) in diameter and 11.68 cm (4.6 in) in height. The specimens were moist-cured for 7 days in a humid room, after which they were soaked for 4 h in tap water. After soaking, specimens were tested in compression according to ASTM designation D 1633. Other specimens with 4, 8, 10, and 12 percent cement were moist-cured for 28 days and 90 days, soaked, then tested in compression.

A summary of the test results is given in Table 3. The data indicate that the soaked compressive strength increased as the amount of cement and the length of the curing period increased. However, at cement contents greater than 10 percent, the increase in strength was not significant for the same curing period. A compressive strength of about 3.45 MPa (500 lbf/in^2) was achieved after 7 days of curing with about 8 percent cement.

Double-Punch (Tensile) Strength

Another group of specimens similar to those discussed above were tested in double punch after being soaked for 4 h in tap water and after curing for a 7-day period only. The test results, which are summarized in Table 3, indicate an increase in tensile strength as the amount of cement increased.

Flexural Strength (Rupture Modulus)

The flexural strength of cement-treated Duval tailings was tested according to ASTM designation D 1635. Beam specimens were statically compacted to the required density and moisture content. The beams measured 7.62x7.62x28.58 cm (3x3x11.25 in). After 7-day humid curing, the beams were soaked before testing in the third-point loading position.

The summary of the test results included in Table 3 indicates that rupture modulus R increased as the amount of cement increased.

Durability Losses (Freeze-Thaw and Wet-Dry Cycles)

The test procedures for the freeze-thaw cycles and the wet-dry cycles followed closely those outlined under

ASTM D 560 and D 559, respectively, except that the specimens were compacted to the maximum dry density at optimum moisture content under the modified and not the standard AASHTO compaction effort.

The summary of the test results in Table 3 indicates that the Duval tailings satisfied the recommended durability requirement of the Portland Cement Association (PCA) for soil-cement mixes used in base courses (12). PCA recommends that durability losses for A-2-4 soil-cement mixes should not exceed 14 percent after 12 cycles. The cement mixes with Duval tailings satisfied this criterion with the addition of only 4 percent cement by weight.

Permeability

Cement-treated specimens were tested in the pressurized constant-head permeameter. Amounts of 2, 4, and 6 percent by weight were used. Specimens were statically compacted to the maximum dry density and optimum moisture content obtained by using the modified AASHTO compaction test. After compaction, the specimens were humid-cured for 7 days before testing.

The results, summarized in Table 3, indicate a reduction in permeability with the increase of cement additive.

Rain Erodibility

Cement-treated specimens were tested in the Rotadisk Rainulator. Amounts of 2, 4, and 6 percent by weight were used. Specimens were compacted statically to the maximum dry density and optimum moisture content obtained by using the modified AASHTO compaction test. Specimens were humid-cured for 7 days after compaction. After curing, the specimens were subjected to six rain-dry cycles, each of which consisted of 1 h of rain at 3.25 cm/h (1.28 in/h) followed by 23 h of drying in an environmental room at 21°C (70°F) and 50 percent relative humidity.

The test results, summarized in Table 3, indicate a significant reduction in the rain erodibility of the tailings with the addition of cement. When 4 percent cement was added, no erosion was detected, and even when only 2 percent cement was added, a tolerably low level of erosion resulted.

Discussion of Results

The results given in Table 3 indicate that cement treatment significantly increased the compressive, tensile, and flexural strength of the compacted Duval tailings. With the addition of merely 4 percent cement by weight, the Duval tailings satisfied the PCA durability criteria for soil-cement mixes used in base courses. Cement treatment also significantly reduced rainfall erodibility and the permeability of the compacted mixes. These results indicate that cement-treated tailings could potentially be successfully used in embankments, for slope protection, in bases and subbases, and as reservoir and canal linings.

ASPHALT-EMULSION-STABILIZED DUVAL TAILINGS

The effect of asphalt stabilization of the Duval tailings was also evaluated. Because of the high amount of fines [material passing the 0.075-mm (no. 200) sieve], a slow-setting cationic emulsion (CSS-1) was considered for stabilization. No consideration was given to the use of liquid asphalt cutbacks from an energy conservation viewpoint, since petroleum fuel products are used as solvents in cutbacks whereas water is used in processing emulsified asphalts.

In the following tests, various percentages of emulsion (total weight of emulsion as percentage of dry tailing weight) were mixed with the tailings and compacted. For preparation of compacted tailing-emulsion mixtures, additional moisture of about 3 percent above the optimum moisture content was needed during the mixing operation to obtain uniform and homogeneous mixes. Before compaction, the samples were allowed to dry back to the required moisture content (at molding). The drying time required was obtained from charts developed by drying various mixes for various periods of time in the environmental room. The charts showed the relations between moisture content and time for various mixes. This procedure was followed in preparing all specimens used in the tests discussed below.

Compressive Strength

Compacted emulsion-treated tailing specimens were prepared by static compaction with 4, 8, 12, 16, and 20 percent emulsion at the maximum dry density and optimum moisture content for the modified AASHTO test. Specimens were 10.16 cm (4.0 in) in diameter and 11.68 cm (4.6 in) in height. After compaction, the specimens were cured for 7 days and 28 days in the environmental room. After curing, one set of specimens was tested immediately in compression and another set was soaked in tap water for 4 h before testing in compression.

Table 4 gives a summary of the test results, which indicate the following:

1. There is an optimum amount of emulsion at which the highest compressive strength occurs. When greater amounts of emulsion are used, lower strengths develop because of flow of the asphalt. When lesser amounts of emulsion are used, lower strengths result because of lack of bonding or adhesive forces.
2. The optimum percentage of emulsion is not necessarily the same for soaked and unsoaked compressive strengths. The optimum value is 4 percent for unsoaked strength and 8 percent for soaked strength.
3. At the optimum percentage of emulsion, values of compressive strength increased significantly in comparison with those for untreated tailing specimens.
4. Emulsion provides good waterproofing qualities to the tailing and thus protects it from disintegration while it soaks in water.
5. The values for unsoaked strength, however, are consistently higher than those for soaked strength.
6. The higher the amount of emulsion used, the higher is the axial strain at failure; this indicates increased plastic deformation and less brittle behavior.
7. The longer the curing time is, the higher is the compressive strength for both the soaked and unsoaked conditions.

Double-Punch (Tensile) Strength

Another group of specimens similar to those discussed above were tested in double punch. The test results, summarized in Table 4, indicate the following:

1. There is an optimum amount of emulsion at which the highest tensile strength occurs.
2. For both soaked and unsoaked tensile strength, the optimum amount of emulsion was 8 percent.
3. At the optimum percentage of emulsion, tensile strength values increased significantly in comparison

Table 4. Properties of emulsion-treated Duval tailings.

Amount of Cement by Weight (%)	Compressive Strength by Days of Curing (kPa)				Tensile Strength by Days of Curing (kPa)				Permeability Coefficient $K x 10^{-6}$ (cm/s)
	Soaked		Unsoaked		Soaked		Unsoaked		
	7	28	7	28	7	28	7	28	
0	-[a]	-[a]	281	297	-[a]	-[a]	12	21	22.7
4	-[a]	-[a]	1160	1992	-[a]	-[a]	74	185	19.8
8	983	1723	1070	1833	67	210	123	255	11.3
12	621	1229	886	1251	81	145	99	166	7.4
16	559	980	564	1146	53	112	79	127	4.2
20	419	794	435	911	36	95	42	99	-

Note: 1 kPa = 0.145 lbf/in^2; 1 cm = 0.394 in. Dry density = 1.918 g/cm^3, and moisture content = 10.8 percent.
[a]Specimens slaked in water.

Table 5. Hveem strength test results for asphalt-treated Duval tailings.

Property	Value by Amount of Asphalt Emulsion				
	9 Percent	9.5 Percent	10 Percent	10.5 Percent	11 Percent
Bulk specific gravity	1.92	1.81	1.82	1.87	1.81
Air voids (%)	22.5	26.8	25.7	23.5	25.8
Stabilometer value S	34.6	34.7	45.1	31.0	31.1
Resistance value R	92.6	93.5	93.6	92.4	93.2
Cohesiometer value C	507	527	625	374	438
Swell (cm)	0.033	0.034	0.046	0.017	0.049

Note: 1 cm = 0.394 in.

with those for the untreated tailing specimens.

4. The values for unsoaked tensile strength are consistently higher than those for soaked strength.

5. The longer the curing period is, the higher is the tensile strength for both the soaked and unsoaked conditions.

Permeability

Compacted emulsion-treated tailing specimens were tested in the pressurized constant-head permeameter. Specimens were statically compacted to the maximum dry density at the optimum moisture content obtained from the modified AASHTO compaction test. Compacted specimens were cured for 7 days in the environmental room before testing.

The summary of the test results given in Table 4 indicates a reduction in permeability with increasing amount of asphalt. However, a comparison of the permeability coefficients for the asphalt-treated mixes (Table 4) and those for the cement-treated mixes (Table 3) indicates that, at an equal percentage of additive, lower permeabilities were obtained by using cement stabilization than by using asphalt stabilization. This can be attributed to the less efficient mixing of asphalt with such a fine-grained material, which results in a lower degree of uniformity.

Rain Erodibility

Emulsion-treated specimens were tested in the Rotadisk Rainulator. Specimens with 12 percent emulsion were compacted statically to maximum dry density and optimum moisture content obtained under the modified AASHTO compaction test. Compacted specimens were cured for 7 days in the environmental room before testing for six rain-dry cycles, as described earlier.

The results indicated an erosion loss of 2.33 percent at 12 percent emulsion, compared with 100 percent erosion for the untreated tailings. It is apparent, however, that cement is more effective than emulsion in eliminating erosion losses, with 4 percent cement additive (Table 3). This can be attributed to the nature of the asphalt in stabilizing aggregations of fine particles and not individual particles. Thus, when an aggregation is eroded, a large number of particles are dislodged from the asphalt-treated specimens, which results in the higher erosion level.

Hveem Strength Tests

The strength of the emulsion-treated mixtures (ETMs) was evaluated by using the Hveem procedure given by the Asphalt Institute (13) and modified as discussed below.

The specimens were mixed and compacted statically by using various amounts of emulsion. Tests of the compacted specimens were done in the following order: (a) swell test, (b) stabilometer test, (c) determination of bulk density, and (d) cohesiometer test. In addition to using static compaction instead of kneading compaction, the mixing, drying back, compaction, curing, and testing were all done at ambient temperatures of 21°C (70° ± 2°F). This is becoming an accepted technique for testing ETMs as indicated by Jimenez (14). Before testing, the specimens were fully cured in the mold for 72 h and then saturated. Curing beyond 72 h did not cause any significant reduction in moisture content.

Results of the Hveem strength test given in Table 5 indicate high strength parameters for the emulsion-treated tailings. The Asphalt Institute has presented interim guidelines for properties of ETMs in bases and surface courses (16). Using applicable data (for testing at 73° ± 3°F), the Asphalt Institute (15) recommended for fully cured and soaked specimens that minimum R-values of 78 and minimum cohesiometer values of 100 be accepted for base courses or temporary surface courses. The R-values and C-values given in Table 5 are significantly higher than the corresponding minimum values given above. The swell values given in Table 5 are consistently less than 0.762 mm (0.03 in), which is the limiting value for base courses as recommended by the Asphalt Institute (13, 4th ed.). The high values of percentage air voids for the tailing mixes in Table 5 are attributed to the relatively uniform grain-size distribution of the tailing.

Jimenez (14) reported Hveem test results for aggregate-emulsion mixes that were mixed, cured, soaked, and tested at ambient temperatures. These values were an R-value of 88, an S-value of 27, and a C-value of 540. The data given in Table 5 are in the range of magnitudes given by Jimenez.

Resilient Modulus

Specimens of emulsion-treated tailings were compacted by using a vibratory kneading compactor and tested under repetitive loading conditions to evaluate their fatigue properties. Details of the compaction and testing equipment are given elsewhere (3, 16, 17). The specimens measured 44.45 cm (17.5 in) in diameter and 3.80 cm (1.5 in) in thickness. One set of specimens was cured in the environmental room for 7 days, and another set was cured for 28 days before testing.

A summary of the test results for two sets of specimens at 8 and 12 percent emulsion content is given below (1 Pa = 0.000 145 lbf/in²):

Property	Curing Period (days)	8 Percent Emulsion	12 Percent Emulsion
Radial stress σ_r (kPa)	7	554	523
	28	635	607
Radial strain ϵ_r ($\times 10^{-3}$)	7	1.615	3.954
	28	0.963	1.524
Resilient modulus E_r (MPa)	7	343	132
	28	659	399

The results indicate the following:

1. As the emulsion content increased from 8 to 12 percent, radial strain ϵ_r increased significantly and radial stress σ_r decreased but at a much lower rate.
2. Increasing emulsion content significantly decreased the resilient elastic modulus E_r.
3. The longer the curing period was, the better were the mix properties—i.e., E_r and σ_r increased and ϵ_r decreased.

Note that the elastic moduli obtained for the tailing-emulsion mixes appear to be comparable to those usually accepted for surface, base, and subbase courses. Jimenez (18) has presented a summary review of reported moduli for surfaces, bases, stabilized bases, and subgrades. Because of the variability of mixes, materials, methods of testing, and temperatures at testing, among other factors, a very wide range of E-values is reported by Jimenez (18). The ranges given below, however, can be considered representative of the majority of the reported data (1 MPa = 145 lbf/in²):

Course	E (MPa)
Surface	690-1380
Untreated base	55-138
Stabilized base	138-690
Subgrade	1.7-138

A major concern in the tailing-emulsion mixes tested above is the high amount of voids caused by the high degree of uniformity in the grain size of the tailing. This may affect the durability of the mixes when they are used in surface courses. In view of the good E-values obtained, however, field verification of the use of the tailing-emulsion mixes should be done under actual traffic conditions.

CONCLUSIONS

The results of the investigation reported here demonstrate that copper mill tailings are an existing mining waste that has excellent engineering properties and can be easily adapted for use in road construction projects. In particular, the study shows the excellent potential for using the tailings as a compacted fill in embankments, a stable engineered fill replacement for poor soil conditions, a compacted foundation and subgrade material, a cement-treated base, an emulsion-treated base, or a compacted impervious layer for lining ponds, reservoirs, and canals. The tailings can also potentially be used as a filler in cement mortar and cement mixes or a cement-tailing grout and to produce high-quality synthetic aggregates (3, 19).

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Use of Energy-Efficient Sintered Coal Refuse in Lightweight Aggregate

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The development and evaluation of a synthetic lightweight aggregate that has particular application to the building and transportation construction industries are described. Bituminous coal refuse, a waste product obtained from five coal-preparation plants in Kentucky, was successfully sintered on a pilot-sized traveling grate to produce lightweight construction aggregate. An improved sintering-grate process was used. A means is thus provided for using a waste product while gaining an economic advantage during processing from the inherent fuel value of the refuse. A thorough laboratory investigation of the aggregate as a material for use in bituminous concrete mixes and structural lightweight portland cement concrete indicated that a satisfactory aggregate for these construction materials was produced. Using lightweight aggregate from sintered coal-mine refuse in concrete construction offers significant technical and economic incentives from the standpoints of reduced weight and the greatly reduced thermal conductivity of the products formed.

The demand for quality aggregates for various construction applications has resulted in shortages of aggregate in many parts of this country. Some areas are experiencing a depletion of all quality natural aggregates (1, 2). Environmental constraints and urban sprawl have curtailed production in some areas where aggregate supplies are abundant. Although U.S. reserves of natural aggregate are virtually inexhaustible, geographic distribution and quality do not necessarily coincide with need. This means high costs for transporting the heavy, bulky commodity.

The manufacture of synthetic aggregates and the use of by-product (waste) materials represent means that are being used to provide locally available aggregates and/or aggregates that have particular characteristics. Blast- and steel-furnace slag, power plant ash, and various mine tailings and wastes are by-product materials in current use. The most commonly manufactured synthetic aggregate is expanded lightweight shale (clay or slate), which is produced by heating the raw product to about 1040°C (2000°F) in a rotary kiln. At this elevated temperature, the gases generated expand (bloat) the material while the high temperatures stabilize it. A less commonly used method for producing synthetic lightweight aggregate is the continuous sintering-grate process, in which the raw material and an added fuel charge are placed on a traveling bed and ignited. As the product sinters (or burns), the particles fuse together and the carbon fuel burns, creating void spaces within the aggregate particles.

The Expanded Shale, Clay, and Slate Institute and the Lightweight Aggregate Producers Association promote the production and use of synthetic lightweight aggregates. All fuel requirements for rotary-kiln processing are provided from an external fuel source, whereas in the sintering operation only minimal external fuel is required and the bulk is contained in the raw feed material.

During the past four years, the Department of Civil Engineering at the University of Kentucky has been involved in research studies to develop uses for materials from bituminous coal refuse (3-9). Similar studies have been conducted in Great Britain, Pennsylvania, and elsewhere (10, 11). In the Kentucky research, the possibilities of converting the refuse into high-quality lightweight aggregate were examined. To determine the technical competence of synthetic lightweight aggregate produced from the sintering of bituminous coal refuse, a thorough laboratory evaluation was conducted on the sintered material. The basic goal of the research was to determine the suitability of the material for use as an aggregate in construction products.

The purpose of this paper is to briefly discuss the origin of coal refuse and the production of lightweight aggregate from sintered coal refuse and to more fully describe laboratory studies conducted on the sintered aggregate to determine its suitability for use in construction products.

COAL REFUSE

Coal refuse is a mixture of fragmented materials that are removed from run-of-mine coal during the cleaning and preparation process so that the quality of the coal will be improved. Sources of refuse materials include thin bands of shale and clay and other impurities and minerals inherent in or adjacent to the coal seam. It is easier and cheaper, with mechanized equipment, to extract a seam of coal with its unwanted impurities than to try to mine only the pure coal (9).

The processing is accomplished in preparation plants, some of which process as much as 18 000 Mg (20 000 tons) of coal a day. Since the coal has a lower specific gravity than the refuse materials, the coarser fractions are normally separated by heavy-media methods. Special frothing agents that attach to and float the coal are com-