Laboratory Characterization of Cement-Stabilized Iron-Rich Slag for Reuse in Transportation Facilities

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An iron process residue aggregate referred to as Iron Rich Material (IRM) was characterized and tested in the laboratory to determine its potential as a highway construction material. Cement-mixed and -stabilized products of IRM were subjected to ASTM-based standard tests to determine and compare their strength, permeability, and durability. The potential reuse capacity of IRM was envisioned as aggregate in making stabilized road base, subbase, or subgrade. The aggregate portion of the material was classified as A-1-b by AASHTO and SW by ASTM. This material was stabilized with cement, lime, and fly ash at varying proportions by weight of the total additives. The resulting products were compacted at their predetermined optimum moisture contents and cured. Then samples of the cured products were tested for unconfined compressive strength, unconfined tensile strength, freeze-thaw durability, and hydraulic conductivity. The best results were obtained with cement-stabilized aggregate for which the 7-day unconfined compressive strength was between 102 and 116 kPa (700 and 800 psi) and the unconfined tensile strength was between 14 and 22 kPa (100 and 150 psi). For these specimens the 12-cycle freeze-thaw test resulted in less than 5 percent material loss. The 45-day cured unconfined compressive strengths of the cement admixture stabilized IRM was over 145 kPa (1,000 psi), which is comparable to approximate strength of 138 kPa (950 psi) of soil cement of sandy gravel with 6 percent cement used in base or subbase courses for heavy traffic. The general conclusion of the work was that the particular residue material, IRM, when stabilized with cement and cementitious substances may be a viable aggregate for reuse in construction of road bases.

The subject of resource recovery and reuse of waste materials has gained much attention within the past decade, principally because of the increased number of environmental statutes and regulations that necessitate the minimization of waste disposal (Comprehensive Environmental Response, Compensation and Liability Act, 96-510, 1980). The benefit of reuse of residual materials of industrial processes should be twofold: (a) compliance with regulations, which helps reduce environmental hazard, and (b) added economy. Effective utilization of these materials as an inexpensive alternative for conventional materials can provide much economy provided that there are no adverse effects to the environment and the created material performs similarly to or equally well as the one it replaces.

Technology for reuse of residue materials needs to be developed independently, aiming at the optimization of the values of a selected number of physical and chemical properties of the end product. Selection of those properties such as permeability, leachability, strength, rigidity, and durability should depend on the intended function of the end product. First, the residue material should be characterized. Then the products of residue materials that are considered for reuse should comply with the following requirements: (a) minimized solubility and mobility (leachability) of toxic substances, (b) minimized permeability and thus leachability and volume change, and (c) physical stability, strength, and durability. In the United States, compliance with the first requirement is assessed by the Environmental Protection Agency (EPA) extraction procedure toxicity (EPT) or the toxicity characteristic leaching procedure (TCLP) tests (*1*,*2*). The physical properties that are often used as indicators of minimized leachability and physical integrity are hydraulic conductivity (permeability), unconfined compressive strength, bulk density, specific gravity, and freeze-thaw and wet-dry durability (*3*).

The objective of this study was to investigate the possible use of a type of kiln slag produced in Pennsylvania. This slag is a steel industry iron residue classified as a non-hazardous material. It is characterized as Iron Rich Material (IRM) and contains metal iron and iron oxides at about 30 percent by weight. The IRM had already been tested by the standard EPA methods of EPT and TCLP and had passed those tests satisfactorily. The reuse capacities of this material were envisioned as filler/aggregate (in making stabilized road base) or filler/binder (in constructing cut-off slurry walls). To accomplish these objectives, three tasks were proposed. Each constituted a phase of the overall project:

1. Testing the material in the laboratory to investigate its suitability for use in each of the capacity given earlier,
2. Modifying chemically or physically the properties of the material to render it suitable for the needs of each capacity, and
3. Proposing appropriate design criteria for large-scale application.

In this paper, only the investigation of reuse of IRM as aggregate in making road bases is considered. The results of testing for physical characterization of the aggregate slag and the aggregate slag stabilized with admixtures (cement and cement mixtures) are presented and discussed in the following sections.

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INVESTIGATION

Characterization of Aggregate

The aggregate samples received from the source were identified as new and old, on the basis of their age in stockpile. The new material is the fresh slag from the kiln, and the old material is slag that had been stockpiled for approximately 2 years. Both of the slags had been characterized as heterogeneous and vesicular. Mineralogical composition of the slags was determined to be mostly metal iron (Fe) and iron oxides (FeO-wustite, Fe_3O_4-magnetite, and Fe_2O_3-hematite), calcium, aluminum and magnesium silicates, and glass. Earlier investigations on the IRM material showed that the metal oxide content of the material was approximately 30 percent by weight (approximately 1 part of iron oxides to 2 parts of crystalline silicates). The specific gravities of the iron oxides present in the IRM slag are near 5.0 and above. The crystalline silicates have average specific gravity of 3.0. Abundance of glass would lower the overall specific gravity of the mineral mixture in the slag.

Gradation

According to Unified Soil Classification System (USCS, ASTM D2488), both of the materials were classified as well-graded or gravelly sand with little or no fines (SW). According to AASHTO specifications, they were classified as A-1-b, the significant constituent materials of which are stone fragments, gravel, and sand. Figure 1 shows the generated gradation curves for these materials along with the soil gradation ranges recommended for bases and subbases by ASTM D448 specifications. ASTM D448 specification gives the upper and lower ranges of gradation sizes for processed aggregate used in road construction. Superimposed on the same graph are the grading requirement ranges for final mixtures of aggregates to be used in construction of bases and subbases according to ASTM D2940. Both of the slag materials are well graded and have good portions of their components from the large size. The old material contains more large and fine particles than the new material. The increased fines portion may be due to the working of the old material, which could result in crushing and production of more fines. The old material also has a significant portion of large particles above # 4 sieve size, possibly because of the particular processing of the material at the time of production or the agglomeration and cementing of particles with age. Both of the materials appear to comply with ASTM D2940 gradation requirements below 1-mm particles, but the curves need to be pulled down into the range by addition of mid-size coarse material.

Aggregate Index Properties

Table 1 presents a summary of some of the physical and chemical index properties measured for the new and the old aggregates. Each of these measurements represents the average of three or more tests. The bulk specific gravities of the new material were calculated to 2.90 for the fine (passing #4 sieve) and 2.94 for the coarse fractions. These values indicate heavier material than aggregates of rock types such as granite (2.61 to 2.68), limestone (2.59 to 2.71), or sandstone (2.43 to 2.96). The old material was even heavier, with average bulk specific gravity of 3.01. This was attributed partially to oxidation and the formation of iron oxide hydrates (rust or limonite) by aging of the material. Another reason for the difference may be possible variation in the original chemical composition and metal content of the old aggregate slag. The water absorption of the old material was less for both the fine and the coarse portions. This may indicate that the water absorption capacity of this material is partially satisfied by the production of iron compounds.

The unit weight and percentage void space determination was conducted on samples of compacted mixed aggregates. It should be noted that the typical compaction effort used in

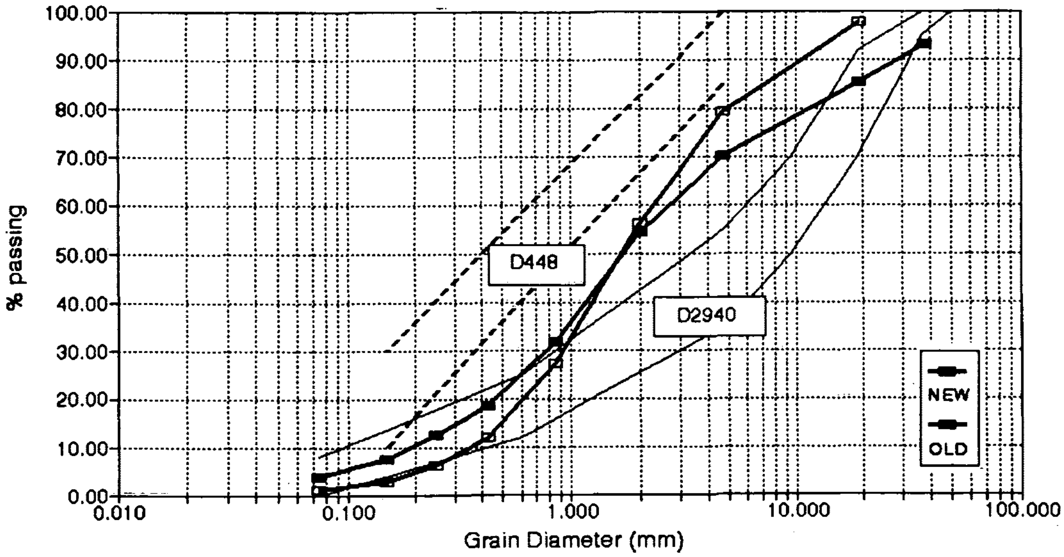

FIGURE 1 Particle-size distribution curves for IRM aggregates.

TABLE 1 Physical Properties of IRM Aggregate

Property	ASTM Procedure	New Aggregate			Old Aggregate		
		Coarse	Fine	Mixed	Coarse	Fine	Mixed
Bulk Specific Gravity (BSG)	C-127 C-128	2.94	2.90		3.00	3.02	
BSG- Saturated Surface Dry	C-127 C-128	3.19	3.18		3.09	3.25	
Water Absorption (%)	C-127 C-128	8.66	9.41		3.0	7.53	
Dry Unit Density (kN/m3)	C29			18.34			21.57
Void Content (%) (by total volume)	C29			36			27
Void Content (%) (by solid volume)	C29			56			37
Weight Loss of Material (%)	C88 (sulfate soundness)			18.26			19.60
Index of Particle Shape and Texture	D-3398			12			15
Index of Aggregate Durability	D-3744			87			84
CaO content (%) (by weight)				13.9			12.5
Volume Expansion (%)	D4792 N/S[b]			ND[a] 0.044			ND 0.044

a Not Detectable, b No surcharge

this test is less than the compaction effort used in a standard Proctor (ASTM D698) compaction test, therefore the unit density achieved is less. The void content of the old material was less than the new material. This is attributed to the larger fines portion and to the formation of iron oxide hydrates in the aged slag.

The sodium sulfate soundness test is used to estimate the soundness of aggregates when subjected to weathering action in concrete or other applications. The sulfate soundness test is often considered a rigorous durability test. In many cases, it has been observed that aggregates that do not satisfy the specified requirements by sulfate soundness test do perform well in the field under severe exposures (*4*). Therefore, the ASTM standard test for freeze-thaw durability (ASTM D666) is often recommended as a check against sulfate soundness test. In the sulfate soundness test, the average total weight losses were estimated at about 18.3 percent for the new material and 19.6 percent for the old material. The observation that these numbers are very close confirms the good repeatability of this particular test.

Particle index is used to indicate the effects of aggregate shape and texture on compaction and strength characteristics of soil-aggregate and asphalt-concrete mixtures (ASTM D3398). This index ranges from 1 to 21. The more angular and rougher the aggregate particles, the higher is this value. It has been shown that the volume of voids in a soil-aggregate mixture of a given gradation under a standard laboratory compaction condition increases more or less linearly with increasing value of the particle index (*5*,*6*). Therefore, the density of a soil-aggregate mixture varies not only with the gradation of the mixture but also with the particle index. The weighted average indexes are 12 for the new material and 15 for the old material. Therefore, the old material is rougher in texture and more angular in shape. These numbers are similar to particle index of crushed stone of bulky, uniform size particles with sharp edges and rough surfaces or gravel with flat particles with sharp edges and rough surfaces. A comparable material designated as glacial gravel with optimum moisture content of 5.8 percent, maximum dry unit weight of 21.8 kN/m^3 (138.9 pcf), and a gradation similar to the slag material has a particle index evaluated as 12.1. The angularity and roughness of the particle increases its shearing resistance, but it may also increase its tendency to crush into smaller particles under load. This type of behavior was observed in compaction of both materials, but more significantly in the old material.

The durability index (ASTM D3744) of an aggregate is a value indicating the relative resistance of the aggregate to production of detrimental clay-like fines when subjected to a prescribed mechanical method of degradation. This index ranges from 0 to 100, 0 being complete deterioration and 100 being no deterioration. Both of the aggregates performed well in this test. The durability indexes were 87 and 83 for the new and old materials, respectively.

Expansion tests (ASTM D4792) were conducted with and without surcharge. In the unsurcharged tests, volumetric expansion of 0.044 percent was measured for both the old and the new materials. The expansion occurred within the first 2 hr of each test and stayed constant for the next 5 days under regulated temperature. No measurable expansion was detected when the materials were surcharged by 10 lb of load, as specified in ASTM D4792. In general, volumetric expansion of soil-aggregate mixtures under 2 percent corresponds to low swelling potential. The measured low expansion is attributed primarily to the low percentage of fines in both of the materials.

The CaO content measurement was conducted to assess the degree of self-hardening of the material and to compare it with other types of calcium containing residue materials. The average CaO content of the new and the old material is about 13 percent by weight. This places the material among the residues bearing moderately high calcium content. Typically, bituminous fly ashes contain 4.5 percent CaO and lime-modified fly ashes contain 33.6 percent CaO by weight.

Moisture-Density Relationships for Aggregate

Standard Proctor test results showed good repeatability for moisture-density relation of the new aggregate. The average optimum moisture content and the average maximum dry unit weight were determined as 5 percent (coefficient of variance = .002) and 21 kN/m^3 (133.8 pcf). For the old material, the repeatability of the moisture-density data were not as good because of the nonuniformity of the portion above #4 sieve. The average optimum moisture content was determined to be 8 percent (coefficient of variance = .01), and the average maximum dry unit weight was 24 kN/m^3 (153.2 pcf).

Testing of Aggregate with Admixtures

The IRM slag was mixed with binding agents to improve its physical properties and strength. Three types of admixtures were selected: portland cement, lime, and fly ash. The fly ash was classified as bituminous; lime was commercially obtained hydrated lime (Ca[OH]$_2$), and cement was Type I portland cement.

The proportions of these admixtures used in mixing with the slag aggregate were either based on recommended proportions by ASTM or selected as trial proportions initially. Three percentages of total admixture were selected as 6, 12, and 18 by dry weight of the aggregate. The relative proportions of each admixture used in these series of tests are given in Table 2. The combinations of admixtures were tested both with the new and the old IRM aggregates. The aggregate portion of each mixture was prepared by mixing the appropriate amounts of various aggregate sizes to achieve a predesignated gradation curve. This curve was selected to pass through the mid-section of the range of gradation suggested by ASTM D2940 for base and subbase materials. The follow-

TABLE 2 Compressive Strength and Density of Trial Mixtures of New and Old IRM Aggregates with Additives

Percent Additive by Weight			Moisture Density Relationship Optimum Moisture and Maximum Dry Unit Weight				7-day UCS[a] at Optimum Moisture, (kPa)	
			New IRM		Old IRM			
Cement	Lime	Flyash	ωopt (%)	γdry (kN/m^3)	ωopt (%)	γdry (kN/m^3)	New IRM	Old IRM
6 %								
2	1	3	11.5	23.9	8.8	27.3	1089.3	1420.2
2	2	2	11.3	23.5	11.0	27.4	1227.1	1627.0
4	1	1	12.5	23.6	9.0	27.3	1158.2	2723.1
12%								
2	4	6	-	-	11.0	26.5	-	875.5
2	5	5	13.0	24.2	10.6	27.0	861.8	1482.2
2	6	4	13.0	24.7	11.0	26.5	1096.1	586.0
4	2	6	12.0	24.8	10.0	27.0	1709.7	2275.0
4	4	4	12.3	25.0	11.3	26.2	2426.7	1702.8
4	6	2	13.0	24.2	11.0	27.0	1833.8	2151.0
6	2	4	11.0	24.9	10.0	27.5	4136.4	3722.8
6	3	3	12.0	24.6	10.0	27.2	4184.7	4839.6
6	4	2	12.0	23.7	10.9	27.9	3888.2	4081.2
18 %								
2	4	12	12.0	24.2	10.0	25.7	875.5	668.7
2	8	8	14.0	23.1	11.8	25.5	923.8	1123.7
2	12	4	14.5	23.1	12.8	25.1	717.0	372.3
4	6	8	12.0	23.4	11.0	25.7	2144.0	1992.3
4	7	7	13.5	23.2	10.8	24.5	2330.2	2393.3
4	8	6	11.5	23.2	12.7	24.4	2764.5	3095.4
6	3	9	11.6	24.1	10.8	24.6	2854.1	2854.1
6	4	8	11.5	24.1	11.8	24.0	4370.8	3729.7
6	6	6	12.3	24.0	11.5	24.7	4832.7	4295.0
6	8	4	13.5	23.6	12.3	25.0	3943.4	3784.8
6	9	3	14.0	23.0	11.8	24.7	3722.8	3516.0

[a] Unconfined compressive strength

ing tests were conducted on the laboratory-mixed specimens in duplicate:

1. Moisture density: ASTM D558 and ASTM D698,
2. Unconfined compressive strength: ASTM C593 (7, 28, and 45 days cured),
4. Hydraulic conductivity: ASTM D5084 (7 days cured), and
5. Freeze-thaw durability: ASTM D593 (7 days cured).

The strength, permeability, and durability tests were conducted on samples of each mixture prepared at their optimum moisture content as determined from the moisture-density relation tests. All samples were cured in airtight plastic bags for the appropriate duration before testing. Table 2 gives a summary of the results pertaining to these tests of the 7-day cured old and new aggregate mixtures.

Moisture-Density Relationships for Aggregate plus Binder

The mixtures were molded in a Standard Proctor compaction mold and tested to determine optimum moisture and maximum dry unit weight according to ASTM D698 and D1557. As observed from the data, maximum dry unit weights did not change significantly for the two materials with the additives. The average maximum dry unit weights are on the order of 25 kN/m^3 (159 pcf) for the new material mixtures and 26 kN/m^3 (165 pcf) for the old material mixtures. The optimum moisture contents for the new material mixtures are consistently higher than the old material mixtures, although not significantly different, being on the order of 12 percent.

The maximum dry unit weight values of 25 and 26 kN/m^3 fall within the high range for typical aggregates mixed with binders (*7,8*). Typically, well-graded crushed stone mixed with lime and fly ash at the lime:fly ash (L:FA) ratio of 1:4 has maximum dry unit weight on the order of 22 kN/m^3 (143 pcf). Similarly, lime-treated river gravel and medium sand would exhibit 21.5 and 19 kN/m^3 (137 and 122 pcf) of maximum dry unit weight, respectively. The relatively higher values are due to the higher specific gravity of the IRM aggregates (average specific gravity = 2.95) than the typical soil aggregates. Therefore the increased unit weight does not necessarily indicate a higher degree of compaction for the IRM aggregate mixtures.

Unconfined Compressive Strength

ASTM suggests that the minimum 7-day cured compressive strength of a stabilized aggregate/soil system be 2760 kPa (400 psi) (ASTM C593) (*10*). Observing from Table 2, the mixtures that meet or come close to the strength value as specified are the aggregate/cement and the aggregate/cement, lime, fly ash (CLFA) mixtures. The 6 percent admixture specimens exhibit low strengths consistently. The specimens of the mixtures that show the highest 7-day strengths are cured up to 45 days and tested for compressive strength.

The results of strength tests on longer cured specimens of both the new and the old IRM slag mixed with 12 and 18 percent admixture are presented in Table 3. The values reported in this table are corrected by the strength correction factor of 0.94 for specimen length/diameter ratio of 1.25 used in this work (ASTM C42). The highest 45-day cured strengths were achieved with the 12 percent total admixture specimens

TABLE 3 Compressive Strength of Long-Term Cured Samples of Selected Mixtures of New and Old IRM Aggregates with Additives

Percent Additive by Weight			Unconfined Compressive Strength at Optimum Moisture (kPa)[a]					
			7 days		28 days		45 days	
Cement	Lime	Flyash	New IRM	Old IRM	New IRM	Old IRM	New IRM	Old IRM
12 %								
4	4	4	2282.0	1599.4	2702.4	2897.1	4177.8	6494.1
6	2	4	3888.2	3502.1	6942.3	5584.1	8603.7	7004.3
6	3	3	3936.5	4550.0	5487.6	5735.8	7052.6	7176.7
6	4	2	3660.7	3833.0	5901.3	6246.0	6645.8	7742.0
18 %								
4	7	7	2192.3	2247.4	5329.1	4880.9	6190.8	5287.7
4	8	6	2337.1	2909.2	2599.0	3853.7	6314.9	4384.6
6	3	9	2681.7	2681.7	4267.4	3626.2	5287.7	3729.7
6	6	6	4543.1	4039.9	5887.5	6218.4	7790.2	8072.9
6	9	3	3502.1	3302.2	4177.8	5391.1	5777.2	6149.4

[a] Strength values are corrected by a factor of 0.94 for specimen :L/D ratio of 1.25

of either aggregate, ranging from 4136 kPa (600 psi) to over 8273 kPa (1,200 psi). The specimens that exhibited 28-day to 7-day strength ratios close to 2 were the aggregate/CLFA mixtures at C:L:FA percentages of 6:2:4, 6:4:2, and 6:6:6.

The variation of unconfined compressive strength with duration of curing are presented in Figures 2 and 3 for the new and the old IRM aggregate mixtures of 12 percent total admixture, respectively. In the overall analysis, the highest strength was achieved with the new aggregate when it was mixed with 12 percent CLFA at a 6:2:4 ratio. The old aggregate required more lime for improved strength with the 12 percent admixture. This is probably due to the slightly less CaO content of the old aggregate initially. The best strength was obtained with a CLFA ratio of 6:4:2 with the old aggregate. For either of the aggregates, lime or fly ash in excess of 6 percent caused strength reduction. This effect was more pronounced with excess fly ash. This was probably due to the unreacting bituminous nature of the particular fly ash used, which did not let it be incorporated in the cemented matrix when applied in excess (*8*).

Hydraulic Conductivity Tests

The 7-day cured specimens of the mixtures compacted at their optimum moisture contents were subjected to a Constant Rate of Flow Flexible Wall Permeameter Test (ASTM D5084). The specimens were water-saturated under a confining pressure of 34 kPa (5 psi), and the coefficients of hydraulic conductivity were measured at constant rate of flow of water under. The coefficient of hydraulic conductivity for the unstabilized control specimens were on the order of 10^{-2} cm/sec, whereas for the stabilized specimens it ranged from approximately 10^{-4} to 10^{-5} cm/sec for all the mixtures tested. This range places the stabilized material in the category of moderate to low permeability systems. The lowest hydraulic conductivities were measured for the aggregate and LFA mixtures, and the highest permeabilities were measured for the aggregate and cement mixtures.

The hydraulic conductivity measurements can be useful in judging erodibility and frost susceptibility of earthen materials. Low permeabilities may indicate low potential for erosion, frost heave and leaching of material, since water inflow is restricted and the quantity of water available for frost formation may be less (*7,8*).

Durability Tests: Freeze-Thaw

The cumulative percentage weight loss per cycle of freeze-thaw is presented for four specimens in Figure 4. As observed, the maximum weight loss occurred for the new aggregate and CLFA mixture. The average weight loss for the samples of this mixture was 10 percent at the end of the 12th cycle; the others showed total weight losses of about 4 percent at the end of the 12th cycle. The standard durability criterion for typical admixture-stabilized bases and subbases ranges from 10 to 14 percent maximum weight loss (i.e., ASTM, FAA,

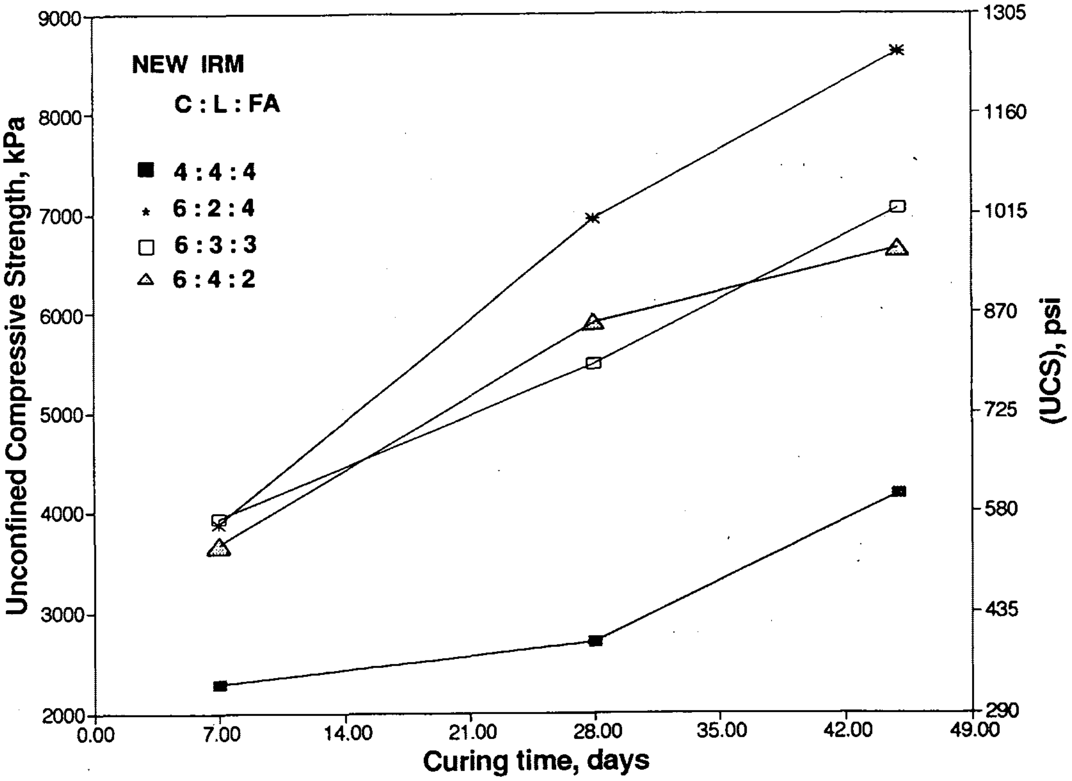

FIGURE 2 **Unconfined compressive strength versus curing time variation for new IRM mixtures with cement, lime, and fly ash (12 percent total additive by weight).**

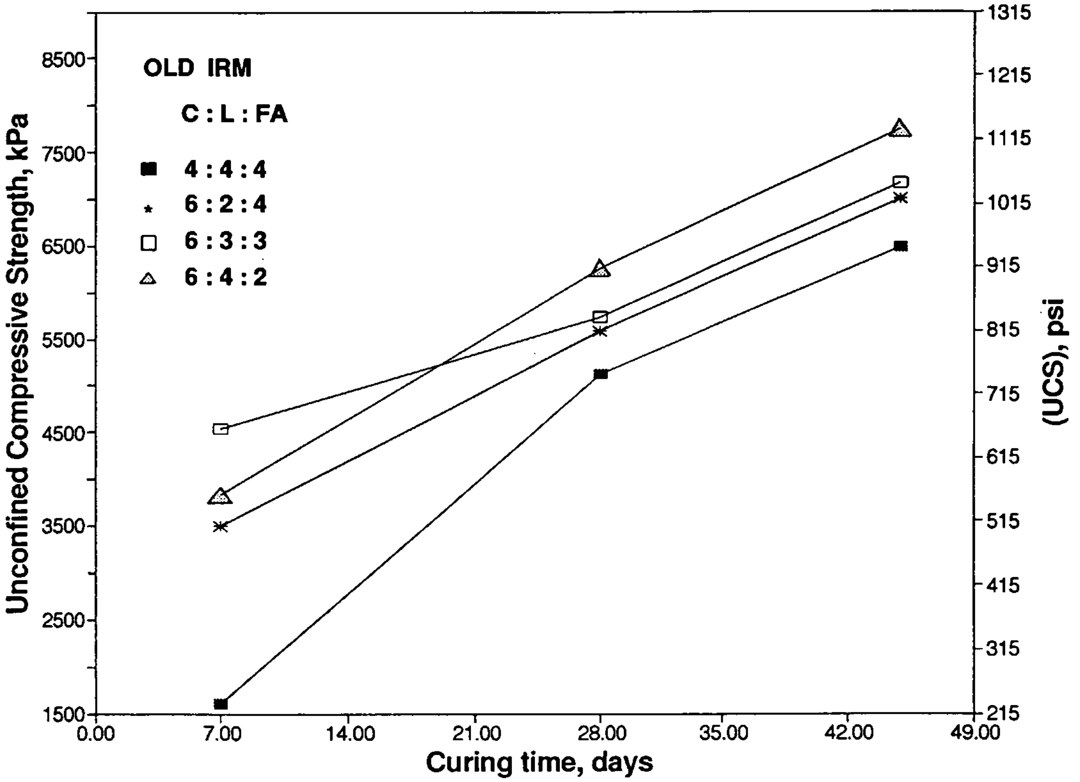

FIGURE 3 Unconfined compressive strength versus curing time variation for old IRM mixtures with cement, lime, and fly ash (12 percent total additive by weight).

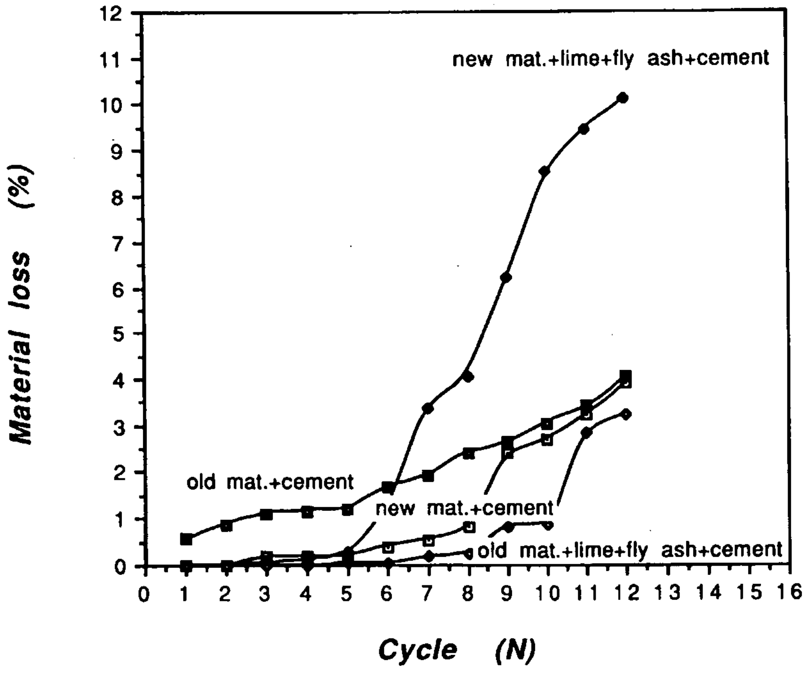

FIGURE 4 Material loss versus freeze-thaw cycles of stabilized new and old IRM aggregates.

Illinois DOT, Pennsylvania DOT). The weight loss values obtained for the materials tested in here are either at or well below this criterion. It appears that the cement-stabilized aggregates, both new and old, best satisfy the durability criterion. The ratio of the unconfined compressive strength after and before the freeze-thaw were also determined. The highest ratio was 0.68, which was exhibited by the new aggregate/cement mixture. The average of this ratio for the aggregate/CLFA mixtures was 0.35.

DISCUSSION OF RESULTS

As stated earlier, the primary objective of the experimental work, results of which presented here was to investigate the feasibility of using the iron-rich kiln residue in a typical cement-stabilized earth construction. The two possible applications envisioned were use of the aggregate portion in stabilized road subgrade or subbase/base construction. The end product of the investigation was recommendations for design mix formulas of these materials and admixtures to be used in the capacities stated earlier.

IRM Aggregate in Stabilized Road Subgrade, Subbase, or Base

The IRM aggregates were classified as A-1-b type, according to the AASHTO classification system. Subgrade characteristics such as subgrade modulus, k; California bearing ratio (CBR); and resistance value, *R* are determined through field or laboratory tests. For light traffic conditions, broad relationships between soil classification and these parameters can be used to estimate the subgrade strength (*10*). Accordingly, the minimum modulus of subgrade reaction for A-1-b soils is 68 MPa/m (250 psi/in.), and the minimum CBR value is 25. The optimum moisture content and maximum dry density of a typical nonplastic well-graded sand with 2 percent clay content are 7 percent and 21.2 kN/m^3, respectively (*11*). These values compare well with the 5 percent, 21 kN/m^3 and 8 percent, 24 kN/m^3 for the new and the old aggregate measured in standard Proctor test. The C:L:FA mixed IRM may also be considered for construction of modified subgrades. In such cases, recommendations on determining minimum compacted thickness of modified subgrades (*12*) may be used as guide lines to establish protocol for use of IRM in subgrade applications.

Subbase or Base Characteristics of IRM

If the CLFA modified IRM is considered for construction of base and subbase courses, thickness design procedures established for soil-cement (*10*) or soil-lime: fly ash layers (*13*) may be used as guidelines to develop specific protocol to IRM in such applications. This is suggested by the similarities between some of the mechanical properties of the soil-cement, soil-lime, and fly ash layers and the modified IRM material.

CONCLUSIONS

This paper presents the results of a two-phase work to establish the feasibility of using an iron-rich kiln slag (IRM) produced in Pennsylvania in construction of earthen structures. In the first phase, the IRM slag was characterized physically and some preliminary tests were conducted to establish its potential for construction material when stabilized with binders. In the second phase, admixture modification of the aggregate (IRM) was undertaken to obtain suitable physical properties of the final products to use them in construction of stabilized road subgrade or base/subbase courses. The general conclusion of the work is that the iron-rich kiln slag tested in this program may be a viable material for reuse in construction of highway earthen structures. However, further investigations are recommended to establish field performance of the stabilized aggregate in a typical road base.

The admixture modification of the pregraded aggregate showed that addition of cement at 6 percent by dry weight of the aggregate produced 7-day cured strengths above the National Ash Association recommended value of 400 psi for aggregate mixtures stabilized with cement, lime, and fly ash. Addition of either lime or fly ash in excess of 6 percent resulted in lower strengths and poor strength increase with curing time. The best results with respect to the final 45-day strength and also with respect to strength increase with curing time were achieved with addition of cement, lime, and fly ash at the ratios of 6:4:2; 6:2:4; 6:3:3, and 6:6:6 for both the fresh (new) and the aged (2 years old). The average 45-day cured unconfined compressive strength value of these specimens was 158 kPa (1090 psi), which is comparable to approximate strength of 138 kPa (950 psi) for soil-cement of sandy gravel and 6 percent cement. The 45-day strength achieved is also above the typically recommended value for soil-cement layers used in base or subbase courses for either light or heavy traffic.

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