Stabilization Characteristics of Class F Fly Ash

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Stabilized fly ash is a mixture of fly ash and lime, or fly ash and cement, compacted at optimum moisture content and cured to form a product-like soil-lime or soil-cement. Limited past applications and engineering properties of stabilized class F fly ash are discussed. A research study was undertaken to establish the physical, chemical, compaction, strength, and durability characteristics of class F fly ash stabilized with lime, cement, or lime/cement combinations. Two ashes obtained from West Virginia power plants were included in the laboratory testing program. It was found that although the ashes are quite different in properties, both ashes can be successfully stabilized to produce pozzolanic mixtures of adequate strength and durability for use as base or liner, with the addition of a proper amount of stabilizer and by allowing the mixture to cure for a sufficiently long period. Cement stabilization, in general, produced better strength and durability than lime stabilization for a given stabilizer content for curing periods up to 56 days. Freeze-thaw cycles caused substantial strength losses, and wet-dry cycles resulted in strength gains. Vacuum saturation with water and an acetic acid solution produced intermediate effects. Very good correlations were found between freeze-thaw and water vacuum saturation tests.

Large quantities of fly ash continue to be generated by coal-burning power plants, and the disposal of this material in a safe, economical, and environmentally acceptable manner is becoming increasingly troublesome for the electric utility industry and becoming a public concern. The most desirable way of disposal is utilization, which provides economic benefits by reducing disposal costs and mitigates possible negative environmental effects through proper engineering controls. Fly ash has been used in many types of engineering applications because of its wide availability and desirable pozzolanic (and self-hardening) characteristics and has been used as an admixture in cement and concrete and as a stabilizing agent (in combination with lime or cement) for soils and aggregates in pavement subgrades, bases, and subbases. Fly ash also has been used as a fill material on a limited scale.

The use of fly ash in concrete and aggregate/soil stabilization applications has proven beneficial both technically and economically, but relatively small amounts of fly ash can be exploited in those types of projects because, in most cases, fly ash constitutes a small percentage of the total material composition. This suggests that, in view of the economic and environmental concerns mentioned, further benefits and incentives remain for establishing utilization schemes that will incorporate larger amounts of ash. One such scheme is "stabilized fly ash," defined here as a pozzolanic mixture of fly ash and lime or cement compacted at optimum moisture content to form a product-like soil-lime or soil-cement that can serve as a base or subbase course for pavements or as a low permeability liner or cut-off material when designed (proportioned) to meet pertinent performance criteria. Because this material does not contain any aggregate or soil, the use of fly ash is maximized per ton or cubic yard of base, subbase, or liner material constructed. Fly ash in such an application serves the dual role of pozzolan and aggregate.

Detailed technical information is not available on stabilized fly ash although an abundance of information exists on the technology for pozzolanic base courses employing mixtures of lime, fly ash, and aggregate (LFA); cement, fly ash, and aggregate (CFA); and lime, cement, fly ash, and aggregate (LCFA) (*1–3*), as well as the use of fly ash in soil stabilization (*3,4*). A research study was performed to review and document the limited existing information from the literature on material properties and applications and to produce new information on material properties through an organized laboratory study. Two class F (bituminous coal based) fly ashes from West Virginia were included in the laboratory study. Those ashes were first characterized by subjecting them to standard ASTM tests for pozzolans. Next, the ashes were mixed with hydrated lime and portland cement at varying stabilizer contents to investigate compaction characteristics (optimum moisture content and maximum dry density). Then, the specimens were fabricated, cured for different lengths of time, and tested for strength and durability. Findings of those investigations are reported in this paper. Permeability and leachate characteristics of the stabilized fly ash mixtures were also studied as part of this research project. However, relevant information and findings concerning those aspects are presented elsewhere (*5*) and are discussed by Bowders et al. in a companion paper in this Record.

PAST RESEARCH AND UTILIZATION

Material Properties

It is known that the most unique and outstanding characteristics of fly ash are pozzolanic reactivity and being self-hardening. Pozzolanic reactivity relates to the ability of fly ash to form cementitious products at ordinary temperatures when combined with alkali and alkaline earth hydroxides in the presence of moisture. The alkali and alkaline earth hydroxides needed to achieve pozzolanic reactions are provided by adding lime or cement to fly ash. If they are internally

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present in sufficient amounts (e.g., as CaO or MgO), then the fly ash exhibits self-hardening behavior in addition to pozzolanicity. Fly ash is designated as class F or class C depending on the parent coal source. Class F ash is derived from bituminous or anthracite coals burned mostly in the eastern, midwestern, and southern United States. Class C ash comes from subbituminous or lignite coals predominantly mined in the western United States. It is almost always necessary to combine class F fly ash with lime or cement to produce pozzolanic reactions, but this may not be needed with class C ashes, which contain significant amounts of CaO. However, many class C ashes also produce better stabilization characteristics when lime or cement is added (*3,6*).

Pozzolanic reactions between lime and fly ash are complex. According to Minnick (*7*), those reactions involve various combinations of the hydrated calcium or magnesium in lime with the amorphous silica and alumina in fly ash or both. Reaction products may include tobermorite (calcium silicate hydrate), ettringite (high-sulfate calcium sulfoaluminate: $3CaO\ Al_2O_3\ CaSO_4\ 12H_2O$), and the low sulfate form of calcium sulfoaluminate ($3CaO\ Al_2O_3\ CaSO_4\ 12\ H_2O$). The extent and rate of the reactions will be affected by the fineness and chemical composition of fly ash, the type and amount of stabilizer, moisture content, temperature, and age. When cement is used in lieu of lime to stabilize fly ash, it hydrates relatively quickly on contact with moisture and produces its own cementitious compounds and also releases some free lime that can further react with fly ash in a pozzolanic manner. Consequently, cement enhances short-term strength.

Limited information has been reported in the literature on the strength characteristics of lime- and cement-stabilized fly ash (*6,8–10*). Evident from those studies for mixtures of lime and fly ash is that normal (70°–75°F) cured unconfined compressive strengths at 7 to 28 days range from 100 psi to 1200 psi and that longer curing periods (90 days and over) may yield strengths exceeding 2000 psi. Cement may produce two to three times higher strengths in the short term, but the differences largely disappear in the long term.

Durability data on stabilized fly ash are very limited. Gray and Lin (*9*) have found that both lime and cement stabilization drastically reduce the frost susceptibility of fly ash. Freeze-thaw durability evaluations by Joshi et al. (*10*) have revealed that mixtures of lime and fly ash have questionable durability in the short term and that mixtures of cement and fly ash produce satisfactory results.

Complete mix-design data for stabilized fly ash could not be found in the literature. Therefore, effects of stabilizer contents on mixture properties cannot be clearly assessed. Evidence exists that increased cement content will increase mixture strength (*11*). However, strength may increase with increasing lime content (*10,11*) or results may be varied (*9*).

According to GAI Consultants (*6*), the standard soil-cement wet-dry and freeze-thaw durability tests, using the brushing technique, are not suitable for cement-stabilized fly ash. Because wet-dry cycles apparently produce negligible effects on durability and freeze-thaw cycles are unduly abrasive, and because test results are dependent on sample preparation techniques, it is suggested that compressive strength tests can be used alone for ensuring adequate durability. For cement-stabilized fly ash, a 7-day normal cured strength between 400 and 800 psi has been specified, along with the requirement that the strength of the mix must increase with time. A minimum 28-day normal cured strength of 550 psi has been recommended for lime-stabilized ash, again with the additional stipulation that there must be strength increase with time. However, stabilized fly ash pavements subjected to extreme service conditions should be tested for durability by observing residual strength after a suitable number of freeze-thaw cycles or after vacuum saturation.

In general, a partial or full replacement of lime by cement in pozzolanic mixtures has been considered advantageous, although this has so far been tried only on pozzolan-aggregate mixes (*2*). In addition to better early strength, cement apparently also enhances durability. It has been suggested that the designer can have better control over the mixture quality (by adjusting cement content) and that nonspecification ashes not highly lime reactive may be effectively stabilized with cement.

Applications

Cement-stabilized fly ash has been successfully used as a base course material in England and France for many years and has been specified and accepted on both public roads and private projects (*4,6*). This type of application is relatively new in the United States but is expected to gain increased attention especially in locations where fly ash can economically compete with alternative aggregate materials. Field trials and demonstration projects have been undertaken in recent years to evaluate the performance of stabilized fly ash pavements (*4,10–13*). Three cases related to cement-stabilized class F fly ash mixes are briefly described here.

- In September 1975 a parking lot pavement consisting of an 8-in.-thick cement-stabilized fly ash base, which was topped by a 3-in. bituminous wearing surface, was constructed at Harrison Power Station in Haywood, West Virginia (*4*). The purpose of the project was to demonstrate cement-stabilized fly ash as an easily constructed and highly serviceable base course. Cement and fly ash were premixed with water in a pugmill at the rate of 83 lb of fly ash and 10 lb of cement per cubic foot of compacted mix. An average in-place density of 98.5 percent of the maximum Standard Proctor of 92.5 pcf was obtained at an optimum water content of 14 percent. Average unconfined compressive strengths of cores taken from the completed base course at 7 and 90 days were 566 and 869 psi, respectively. Strengths of cores taken after a period of 180 days, which encompassed a severe winter, indicated that the pavement had experienced no strength loss. The parking lot has continued to perform well.
- Cement-stabilized fly ash was used in the construction of a base course for a haul road near American Electric Power's Clinch River power plant in southwestern Virginia (*12*). The cement-stabilized fly-ash base course was designed by the procedures presented by GAI Consultants (*4,6*). The resulting pavement consisted of cement-treated fly ash base course 5.5 in. thick overlain by a 1.5-in.-thick emulsified asphalt-stabilized bottom ash surface course. A cement content of 14 percent of the dry weight of the fly ash and a water content of 17 percent were selected for the base-course mix. The haul road was subjected to a low traffic volume, although many of the vehicles were heavy trucks, and the road performed satisfactorily for several years.

- An experimental project, using a 10-in.-thick cement stabilized fly ash as the road base material, was conducted by the Oakland County Road Commission in Michigan in 1983 (*13*). The mix contained 10 percent cement and presented no unique problems during pugmilling and construction. Ease of construction was roughly comparable to the installation of a gravel or bituminous base. Traffic control was also similar, except for a recommendation that the traffic be kept off the completed base during the initial curing period (7 days). Cores taken at 7 and 28 days yielded unconfined compressive strength of 190 psi and 142 psi, respectively. However, early laboratory testing on a sample of fly ash from the plant indicated the design mix would produce a 7-day strength over 400 psi. This difference probably arose from discrepancies between laboratory testing conditions and in-place field conditions. This level of performance, however, was considered unsatisfactory, and this mixture was not recommended for use in the Detroit, Michigan, area.

RESULTS OF THE LABORATORY STUDY

The laboratory studies involved testing of fly ashes in unstabilized and stabilized form. The purpose of the study was to determine the specification conformity of the ashes, the compaction behavior and parameters of the ash-stabilizer mixtures in the freshly mixed condition, and the strength and durability characteristics of the same mixes after curing. All testing in the laboratory was performed on duplicate specimens to obtain average results. If the test results had significant variability, then additional tests were performed before averaging.

Materials

Two fly ashes were used in this study: Harrison, obtained from the Harrison Power Plant in Haywood, West Virginia, and Amos, acquired from the Amos Power Plant, in Nitro, West Virginia. The samples were collected from the dry hoppers in the power plants and were transported to the laboratory for testing. The hydrated lime used in this study was manufactured by the Greer Plant of Morgantown, West Virginia, and the Type I portland cement was produced in Armstrong, West Virginia. Both were bought in paper sacks from local suppliers.

Ash Properties

A variety of ASTM specification tests were performed on the fly ashes and included specific gravity (ASTM D854); fineness, as established by the amount retained when wet-sieved on No. 200 and No. 325 sieves (ASTM D422); pozzolanic activity index with portland cement and pozzolanic activity index with lime (ASTM C311); and lime-pozzolan strength development (ASTM C593). A summary of the test results is presented in Table 1, along with the related ASTM specification criteria. Data on the chemical analyses of the ashes shown in the table were provided by the utility companies, except for the loss on ignition values and CaO contents, which were determined in the laboratory.

The specific gravity values presented in Table 1 indicate that the Harrison ash is much heavier than the Amos because of its high Fe_2O_3 content. The Amos ash conversely has a higher total amount of glassy components (SiO_2, Al_2O_3, and Fe_2O_3) than does the Harrison and has a higher pozzolanic activity index with lime and a higher lime-pozzolan strength development value than does the Harrison. However, both ashes exhibit excellent pozzolanic reactivity with both cement and lime. The sieve analysis results indicate that the Harrison is somewhat finer than the Amos. The loss on ignition values are comparable for both ashes, with the Harrison slightly lower. The values presented in the table indicate that relatively small amounts of carbon and other combustible materials exist in the ashes. The CaO percentage for the Harrison is significantly higher than that for the Amos. Overall, both ashes, although quite different in properties, satisfy the ASTM specification criteria for class F fly ashes for use in cement and concrete and for lime-pozzolan stabilization.

Compaction Characteristics

Compaction characteristics of mixtures of fly ash and lime and of fly ash and cement were investigated by performing Standard Proctor tests (ASTM D698) on materials by using varying stabilizer contents. The maximum dry density (MDD) and optimum moisture content (OMC) were obtained on each mixture. Results are presented graphically in Figures 1 and 2 for Harrison lime (HL), Harrison cement (HC), Amos lime (AL), and Amos cement (AC) mixtures. Results for unstabilized mixtures (zero percent stabilizer) are also included. Some differences exist between the compaction characteristics of the two fly ashes. The Harrison with the higher specific gravity produces higher maximum dry densities when compared with the Amos. However, the Amos, being a lighter weight material, yields higher optimum moisture contents because of the larger surface area it has per unit mass.

The data for both ashes also indicate that increased lime content results in increased OMC and decreased MDD, which can be attributed to the fineness and light weight of lime. Conversely, increased cement content does not appear to produce any clear trends, or any significant variation, relative to OMC and MDD. The moisture-density relationships for individual mixtures were very straightforward to obtain, and the standard laboratory procedures posed no problems or anomalies.

Strength Development

The stabilized fly ash mixtures were first compacted in Proctor molds at their OMC. They were then extracted from the molds and placed in plastic closeable bags and cured in a moist room at 73°F and 100 percent relative humidity. The mixtures were then tested after specified curing periods for unconfined compressive strength in the unsoaked condition to assess the degree of stabilization through progressing pozzolanic reactions between the fly ashes and the stabilizers. The soaking procedure normally employed to determine design strength was omitted to avoid the possibility of negating effects that would obscure the results. (The soaking procedure, however, was

TABLE 1 PROPERTIES OF FLY ASHES

Property	Harrison Ash	Amos Ash	ASTM Specifications
Specific Gravity	2.81	2.25	---
%Retained #200 Sieve	4.4	8.9	ASTM C593 30.0 max.
Fineness, % retained on #325 Sieve	14.4	22.4	ASTM C618 34.0 max.
Moisture Content (%)	0.1	0.1	ASTM C618 3.0 max.
Pozzolanic Activity Index with cement (%)[a]	97.6	86.0	ASTM C618 75 min.
Pozzolanic Activity Index with lime (psi)[b]	944	1003	ASTM C618 800 min.
Lime-Pozzolan Strength Development (psi)[c]	644	979	ASTM C593 600 min.
Silicon Dioxide (SiO_2), %	34	58	---
Aluminum Oxide (Al_2O_3), %	21	30	---
Ferric Oxide (Fe^2O^3), %	24	4	---
Sum of SiO_2, Al_2O_3, and Fe_2O_3, %	79	92	ASTM C618
Loss on Ignition (%)	2.2	2.5	ASTM C618 12 max.
CaO (%)	6.8	1.4	---

[a] - Cured 1 day at 73 F plus 27 days at 100 F

[b] - Cured 1 day at 73 F plus 6 days at 130 F

[c] - Cured 7 days at 130 F

replaced by vacuum saturation, which is reported in the next section.)

The different ash-stabilizer combinations and curing periods employed in this phase of the study and the test results are presented in Table 2. Both ashes were stabilized with 3, 6, 9, 12, and 15 percent lime and with 3, 6, 9, 12, and 15 percent cement. In addition, the Harrison was stabilized with 9 percent cement and 3 percent lime, 6 percent cement and 6 percent lime, and 3 percent cement and 9 percent lime, to study the effects of using combined stabilizers on mixture strength development. The Amos mixtures were tested after 7 and 28 days of curing only, and the Harrison mixtures were tested after 7, 28, and 56 days to assess the effects of longer-term curing. Unconfined compressive strengths for unstabilized ashes (zero percent lime or cement) were also obtained to establish baseline values.

From the results presented in Table 2, increasing cement content causes considerable increases in the strength of both ashes for all curing periods. Increasing lime content, however, may increase or decrease strength. A slight decrease is observed with the Harrison, in general with increasing lime contents at 7 and 28 days. However, the trend reverses at 56 days. This may be caused by unfinished pozzolanic reactions between lime and fly ash in the short term. In the Amos lime mixtures, increased lime content causes negligible strength gain at 7 days, but extended curing effects a notable increase in strength.

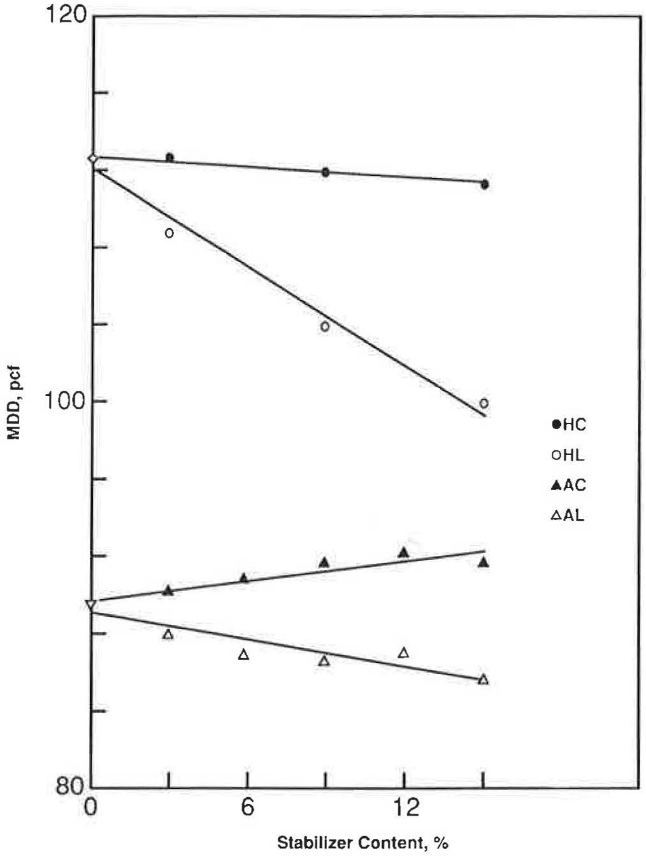

FIGURE 1 MDD versus stabilizer content for ash mixtures.

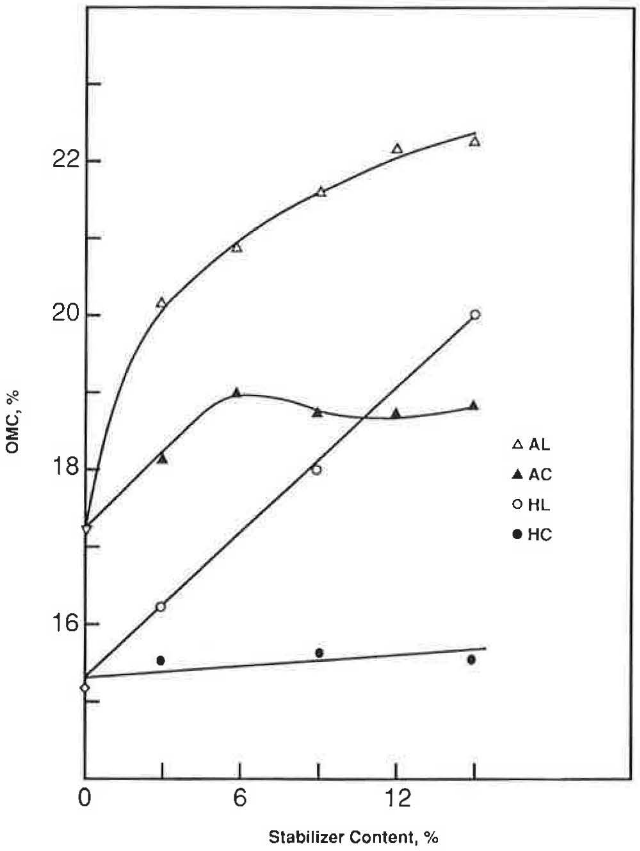

FIGURE 2 OMC versus stabilizer content for ash mixtures.

Overall, the results show that cement-stabilized ashes exhibit higher strengths than their lime-stabilized counterparts, regardless of the length of curing period. However, as the curing period gets longer the differences between the cement- and lime-stabilized fly ash mixes at a given stabilizer content become somewhat smaller.

When comparing the strengths of the two ashes, the Harrison has developed higher strengths for both lime and cement stabilization. This, unfortunately, cannot be readily predicted from the pozzolanic reactivity test results presented in Table 1, because the Amos appears to have higher pozzolanic reactivity with lime than does the Harrison. However, the test results presented in Table 1 are based on accelerated curing at high temperatures. Further, the high CaO content and the fineness of the Harrison can be important factors that contribute to high strength. The results in Table 2 indicate that the Harrison ash shows very satisfactory strength values with both lime and cement for all stabilizer contents and curing periods. The Amos exhibits relatively low strengths with lime in the short term, but extending curing results in appreciable strength gains and reaches satisfactory levels at higher lime contents, a favorable characteristic. The length of curing, actually, has a very dramatic effect on all mixtures. The longer the curing period, the higher the strengths.

Finally, the dominance of cement in the strength development of stabilized fly ash mixes is quite evident from the results given in Table 2 for the Harrison stabilized with combined lime and cement. As the cement/lime ratio increases in the combined stabilizer, the strength of the total mixture also tends to increase. The mixtures containing combined stabilizers indicate strengths much higher than those stabilized with lime only. When compared with cement-stabilized mixtures, the differences are much less and become quite insignificant at high cement/lime ratios.

Durability Evaluation

Durability of lime- and cement-stabilized fly ash mixtures was evaluated by obtaining the residual strength q_r of the cured specimens after subjecting them to different exposure conditions and then comparing this value to the original (pre-exposure) strength q_0. Three levels of stabilizer contents were used in the preparation of the mixes: 3, 9, and 15 percent. However, part of the Amos specimens was prepared only with 9 percent stabilizer to economize on time and materials. Two curing periods, 7 and 28 days, were selected for specimen preparation.

Five types of exposure conditions were chosen for durability evaluations. The first series of tests employed vacuum saturation with water and was performed in accordance with ASTM C593. The second series used a freeze-thaw cycles exposure and was performed as outlined in ASTM D560, except for employing 10 cycles instead of 12 and for substituting unconfined compressive strength testing at the end of the exposure period for the brushing and weighing procedures. A similar

TABLE 2 COMPRESSIVE STRENGTHS OF STABILIZED ASHES

Mixture	Compressive Strength (psi)		
	7-day	28-day	56-day
Unstabilized Harrison	80	95	----
Harrison + 3% Lime	559	909	1116
+ 6% Lime	543	780	1182
+ 9% Lime	439	761	1220
+12% Lime	394	895	1277
+15% Lime	372	758	1138
Harrison + 3% Cement	193	422	----
+ 6% Cement	442	756	792
+ 9% Cement	917	1209	1353
+12% Cement	1074	1675	1773
+15% Cement	1341	1803	2423
Harrison + 9% Lime and 3% Cement	694	1251	1695
Harrison + 6% Lime and 6% Cement	756	1361	1687
Harrison + 3% Lime and 9% Cement	959	1635	1928
Unstabilized Amos	40	40	
Amos + 3% Lime	104	148	
+ 6% Lime	116	239	
+ 9% Lime	126	360	
+12% Lime	130	482	
+15% Lime	142	669	
Amos + 3% Cement	217	251	
+ 6% Cement	307	508	
+ 9% Cement	488	764	
+12% Cement	637	1112	
+15% Cement	826	1492	

approach was adopted in the third series, which involved wet-dry cycles. In this case, the procedures specified in ASTM D559 were modified so as to include 10 cycles of wetting and drying rather than 12 and compressive strength testing instead of brushing and weighing. The fourth and fifth series of durability testing involved a vacuum saturation exposure, this time using an acetic acid solution (0.575 M with a pH of 2.5) instead of water. The vacuum saturation period was extended to 2 hours for both series to ensure better pervasion of the acid solution into the specimens. This procedure was devised to test the durability of the mixtures in an acidic environment (i.e., as a landfill liner).

Two sets of specimens were tested, one directly after vacuum saturation, another after 48 hours, to assess the effects of prolonged exposure while the specimens were sealed in plastic bags. The weights of all specimens were monitored throughout the durability testing program to study moisture changes and material loss owing to possible sample deterioration. Visual observations were also performed to supplement quantitative evaluations.

Durability test results for the mixtures and exposure conditions are summarized in Tables 3 and 4 for 7 and 28 day curing periods, respectively. Results are presented in terms of q_r values and q_r/q_0, which is the ratio of the residual strength and the original strength. The original strength values used in computing these ratios are those given in Table 2 for the same mixtures. A q_r/q_0 ratio of less than 1.0 indicates a strength decrease as a result of the exposure, and a q_r/q_0 ratio of greater than 1.0 signifies a strength increase as a result of the exposure. If any of those exposures and testing procedures are adopted for durability evaluations, then the particular criterion to be met by those parameters should be determined for the anticipated field conditions to which the pavement or liner material will be subjected. Low q_r values and q_r/q_0 ratios might indicate a need to critically evaluate the potential durability problems for the given case.

TABLE 3 DURABILITY TEST RESULTS FOR STABILIZED ASHES (7 DAYS)

Exposure Condition	Vac. Saturation with Water		Freeze-Thaw Cycles		Wet-Dry Cycles		Vac. Saturation with Acetic Acid Tested Immediately		Vac. Saturation with Acetic Acid Tested after 48 Hours	
Mixture	q_r[a] (psi)	q_r/q_o[b]	q_r (psi)	q_r/q_o	q_r (psi)	q_r/q_o	q_r (psi)	q_r/q_o	q_r (psi)	q_r/q_o
Harrison + 3% Lime	446	0.80	373	0.67	1540	2.75	394	0.70	400	0.72
+ 9% Lime	346	0.79	129	0.27	2666	6.07	359	0.82	320	0.73
+15% Lime	317	0.85	56	0.15	2845	7.67	276	0.74	283	0.76
Harrison + 3% Cement	169	0.88	295	1.53	812	4.21	241	1.25	103	1.05
+ 9% Cement	736	1.00	844	1.14	3462	4.69	1166	2.09	1096	1.96
+15% Cement	1069	1.03	1106	1.07	2348	2.26	977	1.33	858	1.17
Amos + 3% Lime	64	0.62	0	0	---	---	---[c]	---	---	---
+ 9% Lime	60	0.48	26	0.21	1313	10.42	64	0.51	58	0.46
+15% Lime	86	0.61	34	0.24	---	---	---	---	---	---
Amos + 3% Cement	155	0.71	54	0.25	---	---	---	---	---	---
+ 9% Cement	346	0.71	213	0.44	1393	2.85	201	0.41	243	0.50
+15% Cement	585	0.71	549	0.66	---	---	---	---	---	---

a - q_r = Residual compressive strength (post-exposure)

b - q_o = Original compressive strength (pre-exposure)

c - --- indicates that test was not performed

TABLE 4 DURABILITY TEST RESULTS FOR STABILIZED ASHES (28 DAYS)

Exposure Condition	Vac. Saturation with Water		Freeze-Thaw Cycles		Wet-Dry Cycles		Vac. Saturation with Acetic Acid Tested Immediately		Vac. Saturation with Acetic Acid Tested after 48 Hours	
Mixture	q_r[a] (psi)	q_r/q_o[b]	q_r (psi)	q_r/q_o	q_r (psi)	q_r/q_o	q_r (psi)	q_r/q_o	q_r (psi)	q_r/q_o
Harrison + 3% Lime	718	0.79	690	0.76	1791	1.97	527	0.58	495	0.54
+ 9% Lime	756	0.99	374	0.49	3084	4.05	541	0.71	549	0.72
+15% Lime	611	0.81	362	0.48	3064	4.04	543	0.72	573	0.76
Harrison + 3% Cement	291	0.69	304	0.72	1055	2.50	605	1.43	645	1.53
+ 9% Cement	798	0.66	614	0.51	2646	2.19	1717	1.42	1631	1.35
+15% Cement	1202	0.67	868	0.48	3870	2.15	1733	0.96	2171	1.20
Amos + 3% Lime	90	0.61	28	0.19	---	---	---[c]	---	---	---
+ 9% Lime	229	0.64	36	0.10	1811	5.03	201	0.56	185	0.51
+15% Lime	374	0.56	44	0.07	---	---	---	---	---	---
Amos + 3% Cement	183	0.73	121	0.48	---	---	---	---	---	---
+ 9% Cement	655	0.86	691	0.40	1353	1.77	584	0.76	603	0.79
+15% Cement	1212	0.81	1431	0.96	---	---	---	---	---	---

a - q_r = Residual compressive strength (post-exposure)

b - q_o = Original compressive strength (pre-exposure)

c - --- indicates that test was not performed

Several observations can be made from the data presented in Tables 3 and 4. First, stabilized mixtures of the Harrison ash have produced much better durability in most cases than the stabilized Amos mixtures. Residual strengths are invariably higher for the Harrison primarily because the original strengths were higher to start with and underscores the importance of obtaining sufficiently high strength in stabilized ash mixtures before their exposure to possible detrimental service environments. The Harrison has also produced higher q_r/q_0 ratios with few exceptions. Cement-stabilized Harrison, in particular, shows excellent durability with respect to all exposures, with an exception observed in the q_r/q_0 ratios for the freeze-thaw test. Cement-stabilized Amos may have done better than lime-stabilized Amos, producing satisfactory durabilities in many cases, particularly at relatively higher cement contents (greater than 9 percent) and longer curing periods (28 days). Lime-stabilized Amos also has performed better after the 28-day curing period when compared with the 7-day curing. This is true for most exposures. However, this mixture failed in freeze-thaw after both curing periods.

Overall, increased stabilizer contents and extended curing periods enhance the durability of the stabilized ash mixtures, and cement-stabilized mixtures perform better in most of the durability exposure conditions. The freeze-thaw cycles test produces the severest exposure and results in substantial strength losses in most cases. The wet-dry cycles test, however, invariably results in very high strength gains for the specimens, indicating that this type of exposure will not be critical in terms of the durability evaluation of stabilized fly ash.

Weight changes of 28-day cured specimens during the freeze-thaw and wet-dry cycles are presented graphically in Figures 3, 4, 5, and 6 to augment the results given in Table 4. The HL, HC, AL, and AC symbols used in those figures denote Harrison lime, Harrison cement, Amos lime, and Amos cement mixtures, respectively, and the numbers at the end of each symbol designate the stabilizer contents. Similar curves were obtained for 7-day curing. Evident from Figures 3 and 4 is that both lime- and cement-stabilized ashes have gained significant amounts of moisture after the first freeze-thaw cycle. Afterward, an approximately constant weight is maintained for cement-stabilized ashes, but moisture gains continue in varying degrees in the lime-stabilized ashes. Weight losses observed in the higher cycles indicate material loss owing to cracking, scaling, and spalling; and continued moisture gain is indicative of internal deterioration. Extreme deterioration was observed in specimens of 3 and 9 percent lime-stabilized Amos after the first few cycles, and the specimens were tested for strength without completing all the cycles. The curves in Figures 5 and 6 reveal that substantial moisture losses occur in all specimens during the first wet-dry cycle, followed by a more or less constant weight achieved through the next one or two cycles and maintained the rest of the way. Because the dry cycle involves the exposure of the specimens to an environment maintained at 160°F, accelerated curing

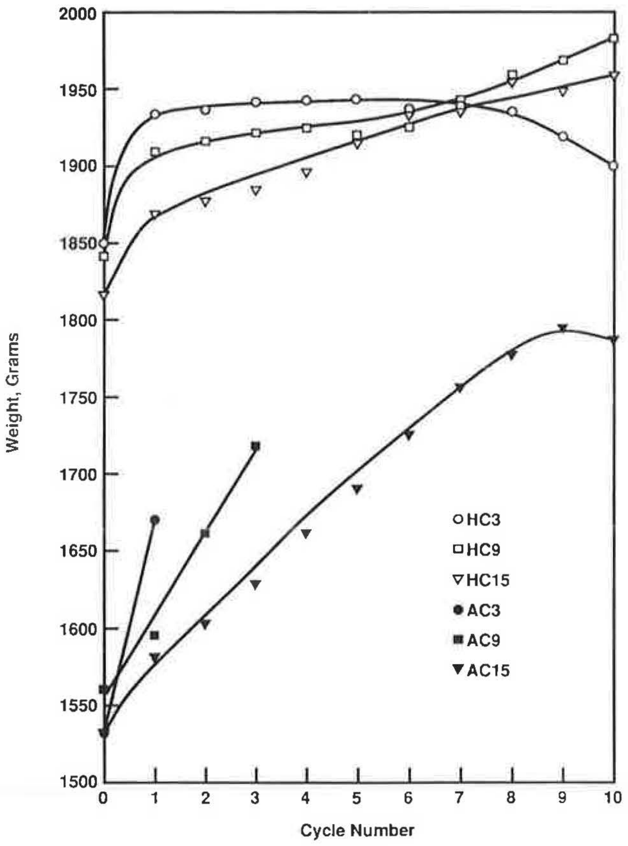

FIGURE 3 Weights of lime-stabilized ashes exposed to freeze-thaw cycles (28 days).

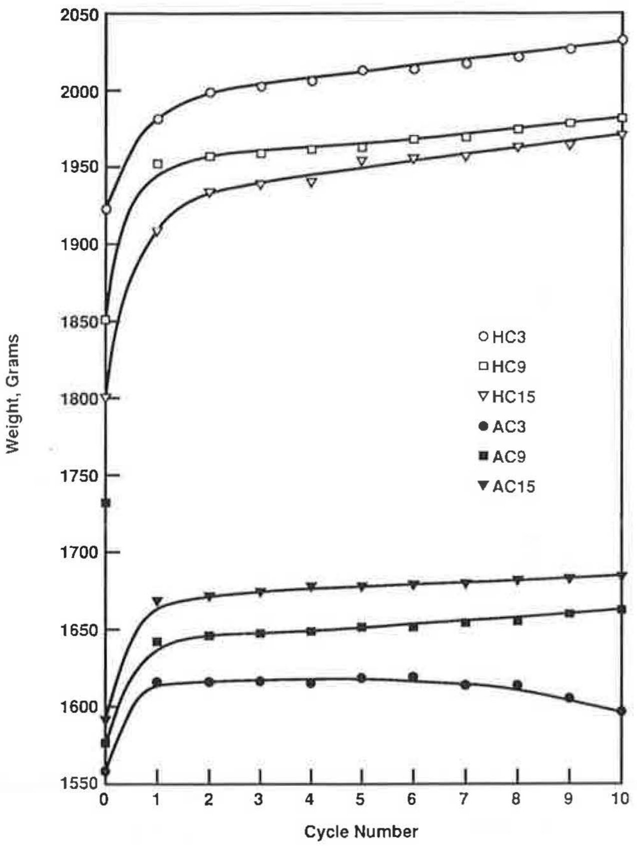

FIGURE 4 Weights of cement-stabilized ashes exposed to freeze-thaw cycles (28 days).

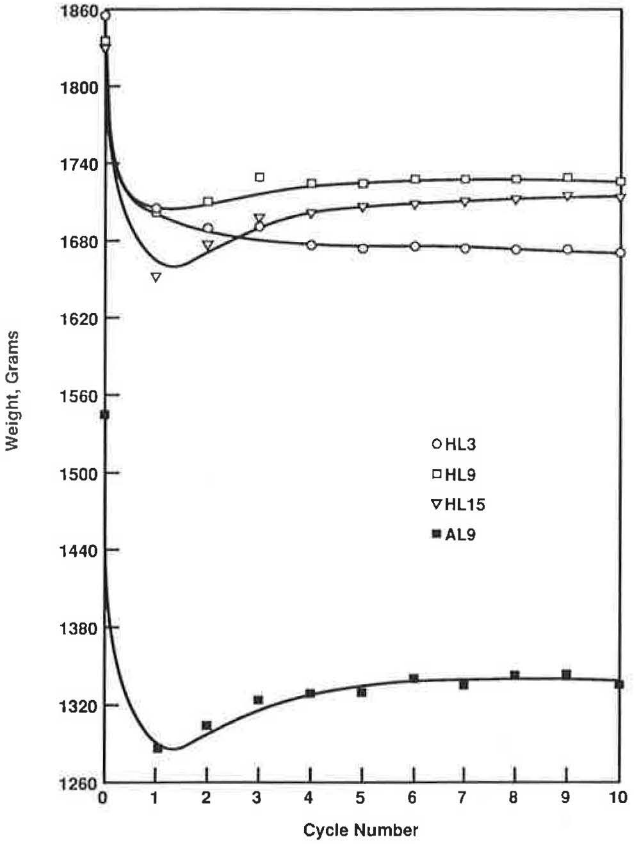

FIGURE 5 Weights of lime-stabilized ashes exposed to wet-dry cycles (28 days).

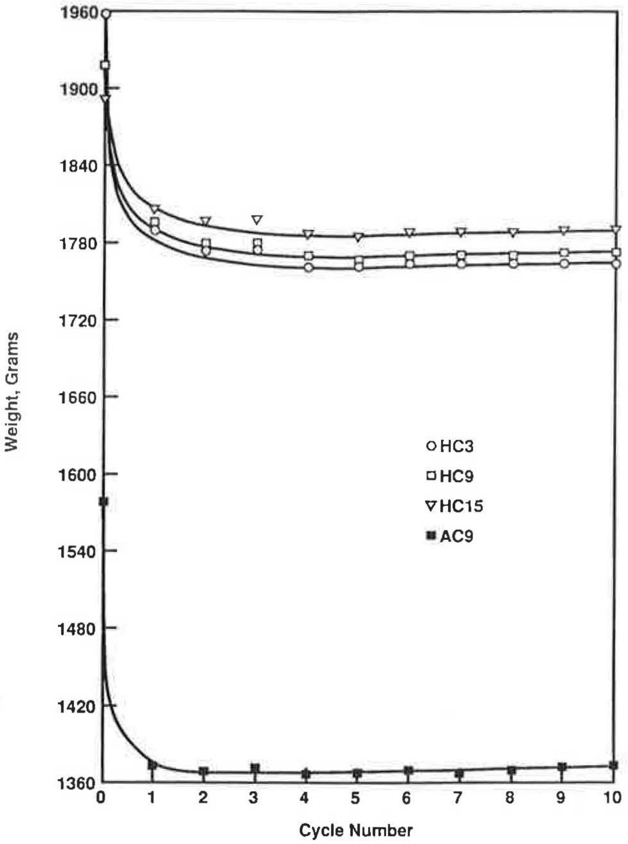

FIGURE 6 Weights of cement-stabilized ashes exposed to wet-dry cycles (28 days).

occurs in the stabilized mixtures, resulting in very high levels of strength gain. Visual observations of the specimens also indicated that none of the specimens experienced detectable shrinkage cracking.

Results shown in Tables 3 and 4 further indicate, with few exceptions, that the vacuum saturation test by using water produced minor to moderate strength losses. Good durability may be achieved with both lime- and cement-stabilized fly ash by adding a sufficient amount of stabilizer and by providing adequate curing. Interesting results have been obtained with the acetic acid vacuum saturation test. Exposure to acetic acid has caused higher strength losses in lime-stabilized mixtures than in cement-stabilized mixtures, but strength gains are observed with the cement-stabilized Harrison. This may be attributable to the formation of cement-like ionic compounds, such as ferric acetate, resulting from the dissolution of Fe_2O_3 present in the Harrison ash. The same favorable effect as a result of acetic acid exposure was also experienced with the cement-stabilized Harrison ash in the later phase of the testing program involving permeability evaluation. This was manifested as appreciable decreases in permeability (see Bowders et al., this Record).

Vacuum Saturation Versus Freeze-Thaw

The vacuum saturation method is frequently used to evaluate the freeze-thaw durability of the pozzolan-aggregate bases on the basis of the excellent correlations obtained between the results of the vacuum saturation (with water) and cyclic freeze-thaw tests (*14*). The data obtained in this study were used in correlation and linear regression analyses to assess whether this would hold true for stabilized fly ash mixtures. Results presented in Table 5 indicate that the correlations between the two tests are fairly good, as reflected by the relatively high correlation coefficients, and are excellent in the case of cement-stabilized ashes, where the correlation coefficient is 96.7 percent. The regression equations in Table 5 represent the statistical relationships between the residual strengths obtained after vacuum saturation and 10 freeze-thaw cycles. On the basis of these analyses, the vacuum saturation test can be used in lieu of the freeze-thaw test to predict the freeze-thaw durability of stabilized fly ash mixtures.

SUMMARY AND CONCLUSIONS

Limited applications and engineering properties related to the stabilization of class F fly ash were discussed. The findings of the studies lead to the following general observations and conclusions.

1. Class F fly ash can be successfully stabilized with lime, cement, or lime and cement combinations to produce a pozzolanic base course material that does not require the addition of aggregate or soil.

TABLE 5 CORRELATION AND LINEAR REGRESSION ANALYSIS OF FREEZE-THAW AND VACUUM SATURATION RESIDUAL STRENGTHS

Mixture	Curing Period (days)	Correlation Coefficient r	Regression Equation* $q_{FT} = b+aq_{VS}$
Lime-stabilized ashes	7	0.815	$q_{FT} = 118.8 + 0.995\ q_{VS}$
Cement-stabilized ashes	7	0.967	$q_{FT} = 72.3 + 0.858\ q_{VS}$
Lime-stabilized ashes	28	0.863	$q_{FT} = 237.6 + 0.882\ q_{VS}$
Cement-stabilized ashes	28	0.911	$q_{FT} = 141.8 + 0.866\ q_{VS}$
Stabilized Harrison ash	7	0.927	$q_{FT} = 172.7 + 0.733\ q_{VS}$
Stabilized Amos ash	7	0.983	$q_{FT} = 73.3 + 0.977\ q_{VS}$
Stabilized Harrison ash	28	0.844	$q_{FT} = 133.8 + 1.11\ q_{VS}$
Stabilized Amos ash	28	0.973	$q_{FT} = 176.7 + 0.716\ q_{VS}$

*q_{FT} = residual strength after freeze-thaw test

q_{VS} = residual strength after vacuum saturation test

a,b = intercept and shape of the regression equation; constants

2. The two fly ashes evaluated in this study exhibited high levels of pozzolanic reactivity and satisfied all the relevant ASTM specification criteria for pozzolans used in cement and concrete and in lime-pozzolan stabilization. However, considerable differences exist in the compaction, strength, and durability characteristics of the stabilized fly ash mixtures.
3. In standard Proctor compaction, addition of increasing percentages of lime to fly ash resulted in increased OMC and decreased MDD for the mixtures. Addition of increasing percentages of cement did not affect the OMC and MDD appreciably.
4. Studies indicated that adequate strength development and durability levels can be achieved with stabilized fly ash by incorporating sufficient amounts of lime or cement or both and allowing the mixture to cure for a sufficient period. Achieving adequate levels of strength before service exposure is important.
5. In general, cement stabilization produced better strengths than lime stabilization. For cement-stabilized fly ash, increasing cement contents and extended curing resulted in increased strength. For lime-stabilized fly ash, increasing lime content caused an increase or decrease in strength, depending on the stabilizer content and the length of curing. Extended curing, however, increased strength invariably. The difference between the strengths of lime- and cement-stabilized ash at a given stabilizer content diminished somewhat as the curing period got longer.
6. Cement showed a dominant effect in strength development in combined lime- and cement-stabilized fly ash mixtures. Addition of cement to partially replace lime markedly improved the early (7 days) and intermediate strengths (28 to 56 days).
7. Cement-stabilized fly ash mixtures, in general, exhibited better durability characteristics than did the lime-stabilized mixtures after being exposed to different environments. High original (pre-exposure) strengths resulted in relatively high residual strengths. With few exceptions, increased stabilizer content and longer curing period enhanced durability.
8. Freeze-thaw cycles exposure produced the severest effects on durability of both stabilized ashes and resulted in substantial strength losses. Wet-dry cycles, in contrast, did not have any detrimental effect on durability and produced significant strength gains without any shrinkage cracking. Intermediate effects were observed relative to vacuum saturation with water or acetic acid solution. Acetic acid had a positive effect (increased residual strength) on durability with one of the cement-stabilized ashes, indicating enhanced durability after exposure to an acidic environment.
9. Results of the standard vacuum saturation tests (using water) correlate very well with those of the cyclic freeze-thaw tests. Therefore, vacuum saturation can accurately predict the freeze-thaw durability of stabilized fly ash.

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