Properties of Cement and Lime-Fly Ash Stabilized Aggregate

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ABSTRACT

Potential application of cement-fly ash-aggregate, lime-fly ash-aggregate and lime-cement-fly ash-aggregate mixtures in pavement construction is reviewed in this paper. Engineering properties such as moisture-density relationship, compressive strength, flexural strength, dry shrinkage, and freeze-thaw durability are summarized on the basis of past studies. Dry shrinkage and freeze-thaw characteristics of cement and lime-fly ash-aggregate mixtures containing sub-bituminous, self-cementitious Alberta fly ashes were evaluated in the laboratory. The stabilized aggregates are attractive for use in pavement structures because of their high strength and low drying shrinkage characteristics. Lime-fly ash stabilized aggregates are observed to shrink more than cement-fly ash stabilized aggregate. It is also concluded that the materials investigated may perform reasonably well under moderate freeze-thaw conditions in the base courses of pavements. Further research should be conducted to evaluate durability of such materials under appropriate freeze-thaw conditions.

The roadbuilding industry is one of the largest industries in the world. Billions of dollars are spent annually for this purpose. Because demand for more pavement exceeds financing, there is a continuing pressure to use the most economical materials available for pavement construction. Increasing energy and labor costs and depletion of high-quality natural resources are providing the impetus for the development of waste products such as fly ash and bottom ash as construction materials. Available quantities of fly ash are increasing considerably in many areas. A small amount of the total fly ash produced is used at present. Disposal of the millions of tons of remaining ash causes serious environmental problems.

Fly ash has been used for many years in conjunction with lime, cement, and aggregate for roller-compacted materials for road construction. The roller-compacted materials are often referred to as stabilized materials in geotechnical engineering. The term stabilized material is used to describe a family of materials in which a mixture of aggregates (sand, clay, gravel) and cementitious materials such as cement, lime, or fly ash is compacted to a specified density to achieve a strong and durable product. Durability of stabilized materials depends on constituents, method of placement, environment, and exposure conditions.

Lean concrete is another type of stabilized material used in road construction. Lean concrete is produced from washed and graded aggregates of concrete quality. The cement in lean concrete is on the order of 5 to 10 percent by weight of aggregate. The water to cement ratio in lean concrete is maintained low to achieve proper compaction. Lean concrete is evaluated in the laboratory according to concrete technology. Geocrete or cement-fly ash-aggregate (CFA) mixtures described by Joshi and Natt (1) are essentially variations of lean concrete. In geocretes or cement-fly ash-aggregate mixtures, up to 75 percent of the cement is replaced with fly ash and properties of these mixtures are evaluated like stabilized soils.

There has been a substantial increase in the use of lime-fly ash-aggregate (LFA) mixtures in particular and lime-cement-fly ash-aggregate (LCFA) mixtures in some cases in construction during the last decade, but the market is far from fully developed. There are, no doubt, a number of reasons for this including the fact that the behavior properties and technology for the use of such materials is not widely known in the engineering profession.

The suitability of cement-fly ash-aggregate (CFA), LFA, and LCFA mixtures for road construction is judged on the basis of relevant engineering properties. In this paper, a literature review of some of the basic engineering properties of stabilized material is presented. Laboratory test data on the drying shrinkage characteristics of CFA, LFA, and LCFA mixtures are given in detail. The effect of moisture loss (weight loss) on the shrinkage is also presented. Freeze-thaw resistance characteristics of CFA and LFA mixtures are also discussed.

LITERATURE REVIEW

Moisture-Density Relationship

Moisture content and density of stabilized materials have a significant effect on their strength and durability. Roller compactibility and compaction moisture and density of the stabilized mixes is determined from moisture-density relationships. The relationships between dry densities and moisture contents of lime-fly ash-aggregate mixtures have been reported (2) to take a form similar to that found in soils. A similar relationship between dry density and moisture content for CFA and LFA mixtures containing self cementitious Alberta fly ashes has been observed by Joshi and Natt (1).

Compressive Strength

The compressive strength of stabilized materials is commonly considered their most valuable property. Compressive strength usually gives an overall picture of the quality of stabilized materials. The compressive strength characteristics of stabilized materials are generally related to the type and amount of cementitious material used to stabilize them. It is generally assumed that the higher the compressive strength, the better the quality of stabilized mixes (3).

The compressive strength characteristics of CFA and LFA mixtures containing self-cementitious Alberta fly ashes have been discussed in detail in another paper by the authors (1). In this study (1), it is concluded that cement and/or lime-fly ash stabilized aggregate develop significantly higher 7- and 28-day strength values than the recommended design strengths for pavements by various investigators and agencies (2,4,5). Cement-fly ash-aggregate mixtures have been reported (1,6) to attain more than 40 percent of their ultimate strength in the first 7 days, whereas lime-fly ash-aggregate (LFA) mixtures attained only about 15 percent of their ultimate strength in the same period. However, ultimate strengths of LFA mixes are indicated to be similar to the ultimate strength of CFA mixes.

Flexural Strength

The tensile strength is also an indicator of the quality of stabilized materials. These materials are significantly stronger in compression than in tension. However, pure tensile strength is difficult to measure in these mixtures. An effective alternate method of evaluating the composite tensile and compressive capacity is through a determination of flexural strength.

Although the flexural strength can be determined directly from tests, most agencies estimate the flexural strength as a fraction of its compressive strength (2). An average value of 20 percent of the compressive strength has been stated (7) to be a good conservative engineering estimate of flexural strength of LFA mixtures.

Flexural strength values of the LFA mixtures investigated by Barenberg (3) were in the range of .125 to .1 of their compressive strengths. In another study (7), flexural strength values of 1.38 MPa at 28 days and 2.2 MPa at 90 days have been reported for LFA mixtures. Flexural strengths of the mixes containing self-cementitious Alberta fly ashes investigated by Joshi and Natt (1) were on the order of 1.5 MPa to 2.5 MPa after 28 days of curing. These flexural strength values were 15 to 25 percent of their respective compressive strength.

Dry Shrinkage

Shrinkage of base and sub-base materials is one of the important factors contributing to the pavement cracking. Infiltration of water through these cracks further damages the pavement base. Shrinkage cracking of soil-cement pavements has been recognized as a serious problem (8-10). The use of stabilized granular materials in base and sub-base construction for roads and airfield pavements runs into billions of tons per year and is increasing every year. However, there is little published information on shrinkage characteristics of stabilized granular materials. Results of some field studies indicate that LFA mixes do exhibit drying shrinkage tendencies (4). Barenberg (11) studied the volume change characteristics of LFA mixtures during alternate cycles of wetting and drying after 20 days of initial moist curing. He reported a maximum expansion of 0.2 percent and shrinkage of 0.1 percent at the age of 80 days.

Nakayama and Handy (8) stated that the type of material stabilized with cement significantly affected shrinkage characteristics. Cement stabilized soils have been reported (8,10) to shrink 0.2 to 0.8 percent depending on the type of soil used. By the addition of lime to these soils, a significant reduction in the tendency of these materials to shrink and swell with a change in moisture content has been noticed (10,11). Moisture content plays a major role in the shrinkage behavior of stabilized materials. George (10) suspected some correlation between shrinkage and evaporation in soil cements.

Freeze-Thaw Resistance

The acceptability of stabilized materials is determined by applying both strength and durability criteria. Many agencies have specified the minimum cured compressive strength criteria for a durable and economical use of stabilized materials, whereas some agencies such as the Ohio Department of Transportation and the Federal Aviation Administration have also specified maximum weight loss criteria along with minimum cured compressive strength (2). According to these agencies, the specified maximum weight loss for LFA and LCFA mixes should not be more than 10 to 14 percent after 12 cycles of freeze-thaw (i.e., ASTM D 560 Method). On the other hand, many researchers (12-14) advocate the use of residual strength (compressive strength after freeze-thaw cycles) approach for establishing freeze-thaw durability criteria.

George and Davidson (14) suggested a minimum residual strength of 3.16 ± 0.28 MPa and an index of the resistance (i.e., the ratio of the average unconfined compressive strength of freeze-thaw specimens to that of control specimen) of 80 percent.

TEST MATERIALS

Fly ash, lime and cement, or mixtures of fly ash-cement, fly ash-lime, and fly ash-lime cement are referred to as cementitious materials in this study. Two sub-bituminous fly ashes from Sundance and Forestburg power plants in Alberta were selected for this study. The Alberta fly ashes possess pozzolanic property as well as self-cementitious property. Chemical properties of these fly ashes are given in Table 1. Normal portland cement CSA Type 10 from the Exshaw (Alberta) plant and high calcium hydrated lime from the Crowsnest (B.C.) plant were used. Locally available washed and screened aggregate of concrete quality was used. Maximum size of coarse aggregate used was 14 mm .625 in.

TABLE 1 Chemical Analysis of Two Alberta Fly Ashes

Constituents (Wt.%)	Forestburg	Sundance
Si as SiO_2	48.5	49.0
Aℓ as $A\ell_2O_3$	23.5	24
Fe as Fe_2O_3	5	3.5
Ca as CaO	17	15.5
Mg as MgO	.53	.49
Na as Na_2O	3.16	2.94
K as K_2O	1	.7
S as SO_3	.27	.29
Ti as TiO_2	<1.0	<1.0
LOI	0.43	0.57

TEST PROCEDURES

Dry Shrinkage

Cylindrical specimens 71 mm (2.8 in.) in diameter and 142 mm (5.6 in.) in height were used to study the drying shrinkage. Specimens were prepared by compressing predetermined amounts of each mix to a predetermined volume in a cylinder by two end pistons as per procedure described in ASTM D 1632-63 (reapproved in 1979). Mixes were molded at their optimum moisture contents. Moisture-density relationships for each of the mixes were established according to the ASTM D 1557-78 Method. After 14 days of initial curing in the moist room (23 ±1.7°C), all the specimens were transferred to a controlled room maintained at 50 ±4 percent humidity and a temperature of 23 ±1°C.

To determine the shrinkage, the longitudinal strain was measured with the help of a 102-mm (4-in.) gauge length mechanical strain gauge. In order to measure strain on three gauge lines, three sets of gauge studs were cemented around the periphery of each specimen at equal spacing. The length and weight change measurements on each specimen were taken after specified periods ranging from 0 days (initial reading after 14 days of curing) to 150 days. All measurements were conducted inside the control room.

Freeze-Thaw Resistance

The freeze-thaw durability characteristics of stabilized aggregate were investigated considering the residual compressive strength and index of resistance criteria. Cylindrical specimens of the same size that were molded and initially cured in the same manner as the shrinkage specimens were used in this study.

A programmable chamber was used to subject the specimens to freeze-thaw cycles. Each cycle was 24 hr long of which 12 hr were above freezing up to 23°C and 12 hr were below freezing down to -23°C. The specimens were sealed in plastic wrap and placed in polyethylene bags before being transferred to a freeze-thaw chamber. This was done to avoid moisture loss during freezing and thawing.

A total of nine compressive strength specimens from each mix were prepared. After specified initial curing in the moist room, three specimens were tested for compressive strength. Of the remaining six, three were weighed, sealed, and transferred to the freeze-thaw chamber for cyclic freezing and thawing, and the other three were left in the moist room for standard curing as control specimens. After completion of the specified freeze-thaw cycles and curing, residual strengths and normal strengths were determined by conducting compressive strength tests on the specimens subjected to freeze-thaw and the standard cured specimen, respectively. Freeze-thaw specimens were thawed for at least 8 hours in the moist room and were weighed before testing. Remnants of the crushed specimen were used to determine the moisture content. The index of resistance for each mix of specified age was obtained by taking the ratio of the average residual strength to the average normal strength.

This study was divided in two parts: one for fly ash-cement and aggregate mixtures and the second for fly ash-lime and aggregate mixtures. In the case of CFA mixtures, the initial curing period was 14 days. The residual strength and the index of resistance were determined at 28 days after 14 freeze-thaw cycles. For fly ash-lime-aggregate mixes, the initial curing period of 28 days was selected before subjecting them to the 14 freeze-thaw cycles. Therefore, the residual strength and index of resistance were determined after 42 days.

For fly ash-lime-aggregate mixtures, the study of the strength recovery behavior of freeze-thaw specimens was undertaken. Therefore, at 42 days, one of the freeze-thaw specimens from each mix was saved and cured in the moist room. After 14 days of standard moist curing, the compressive strength values of these specimens were determined and compared with their respective normal 56-day strength values.

RESULTS AND DISCUSSION

As mentioned earlier, strength characteristics of CFA, LFA, and LCFA mixtures containing various proportions of self-cementitious Alberta fly ashes have been discussed in another report by the authors (1). However, moisture contents, dry densities, and compressive strengths of mixes used in the present study are given in Tables 2 and 3. Mix proportions, optimum moisture contents, and maximum dry densities are listed in Table 2. Compressive strengths at 7, 28, 56, and 120 days are listed in Table 3.

Dry Shrinkage

A total of 12 mixes, 6 containing the Sundance fly ash and another 6 containing the Forestburg fly ash, were investigated for shrinkage characteristics. The cementitious material consisted of 8 parts of fly ash and 1 part of cement and/or lime. Proportions of cementitious material to aggregate for all mixes were 20 to 80. Aggregates used were either sand or sand plus gravel in proportions of 1 to 1. Shrinkage expressed in percentage is based on the 102-mm (4-in.) gauge length. The weight-loss in specimens is taken equivalent to moisture loss in the discussion.

Shrinkage Versus Age

The shrinkage and percentage shrinkage versus age relationships of CFA, LFA, and LCFA mixes are shown in Figures 1 and 2. These relationships indicate that most of the shrinkage occurred within the first 28 days for various CFA, LFA, and LCFA mixes. After 28 days, little or no shrinkage was observed. A maximum shrinkage value of 800 x 10^{-6} was measured for the mix containing 20 percent cementitious material (1:8 lime:Sundance fly ash) and 80 percent sand. A similar mix proportion containing the Forestburg fly ash in place of the Sundance was found to have a maximum shrinkage value of 600 x 10^{-6} (see Figure 2). In general, shrinkage values of the mixes studied ranged from about 0.04 to 0.08 percent, which are significantly less than the shrinkage values of 0.2 to 0.6 percent of soil cements reported by some researchers (8,10).

A comparison of data in Figures 1 and 2 indicates that the mixes containing Sundance fly ash shrink significantly more than their corresponding mixes containing the Forestburg fly ash. A possible explanation for higher shrinkage of Sundance fly ash mixes could be their higher molding moisture (optimum moisture content) for maximum dry density compared to the Forestburg fly ash mixes (see Table 2).

It is clearly indicated in Figures 1 and 2 that stabilized gravel plus sand (identified with i's) shrunk significantly less than the stabilized sand only (identified with e's). It supports the fact stated by William (5) that coarse aggregate restrains shrinkage.

TABLE 2 Mix Proportions and Their Optimum Moisture Contents and Maximum Dry Densities

Mix Notation	Mix Ingredients and Their Proportions					Optimum Moisture Content	Maximum Dry Density
	20% Cementitious Material			80% Aggregate			
	Cement	Lime	Fly Ash	Sand	Gravel	%	Kg/m^3
BIe	2.22	0	17.78	80	0	8.6	1952
BIi	2.22	0	17.78	40	40	6.75	2080
BIVe	0	2.22	17.78	80	0	9	1988
BIVi	0	2.22	17.78	40	40	7	2120
BVe	1.11	1.11	17.78	80	0	7.25	1981
BVi	1.11	1.11	17.78	40	40	6.5	2129
CIe	2.22	0	17.78	80	0	7.2	2046
CIi	2.22	0	17.78	40	40	5.8	2134
CIVe	0	2.22	17.78	80	0	6.5	2038
CIVi	0	2.22	17.78	40	40	5.5	2139
CVe	1.11	1.11	17.78	80	0	6.25	2063
CVi	1.11	1.11	17.78	40	40	5.5	2147

B's - Sundance Fly Ash, C's - Forestburg Fly Ash

TABLE 3 Compressive Strength at Various Ages of CFA, LFA, and LCFA Mixtures

Mix	Compressive Strength MPa			
	7 days	28 days	56 days	120 days
BIe	3.25	8.95	10	12.4
BIi	5.25	11.1	13.1	16
BIVe	3.3	6.6	10.55	12.5
BIVi	2.15	8.85	12.4	15.2
BVe	4.8	14.2	15.4	17.5
BVi	5.2	16	21.6	22.9
CIe	5.45	13.85	14.75	17.95
CIi	6.35	15.3	17.1	19.65
CIVe	1.75	10.2	13.30	14.4
CIVi	1.5	9.8	14.35	15.65
CVe	4.6	13.25	16.5	17.6
CVi	5.2	12.9	16.2	17.25

B's - Sundance Fly Ash, C's - Forestburg Fly Ash

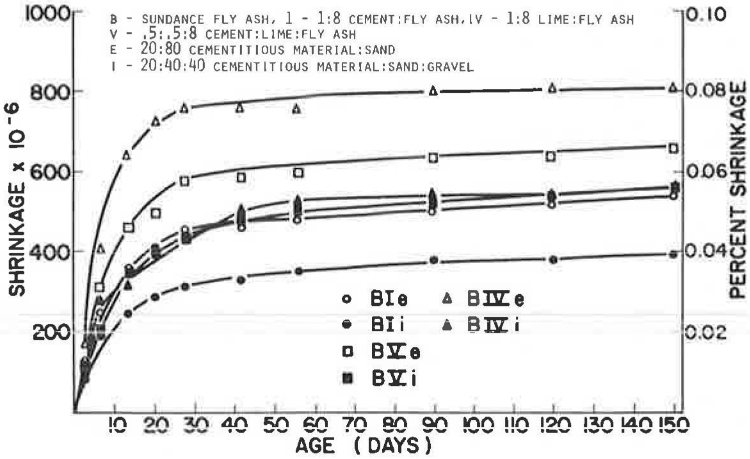

FIGURE 1 Shrinkage percent shrinkage versus age of 20 percent cementitious material (1:8 cement and/or lime : Sundance fly ash) and 80 percent aggregate.

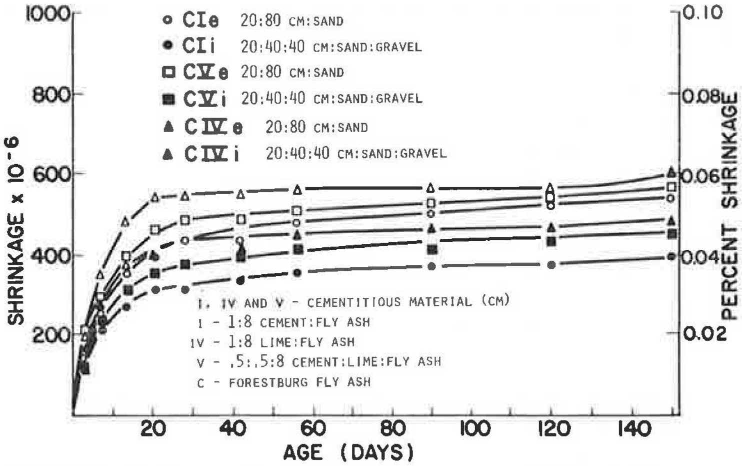

FIGURE 2 Shrinkage and percent shrinkage versus age of 20 percent cementitious material (1:8 cement and/or lime : Forestburg fly ash) and 80 percent aggregate.

The data on shrinkage also indicate that mixes with lime-fly ash shrunk more than the mixes with cement and fly ash and this difference was quite significant in the case of the Sundance fly ash. Because the shrinkage difference between cement-fly ash and lime-fly ash mixes is constant beyond 28 days, it appears that this difference is probably related to variations in water evaporation. The data in Figures 3 and 4 indicate that the percentage of water loss in lime-fly ash mixes is more than in the cement-fly ash mixes. This difference in moisture loss was evident from the first day of drying. A

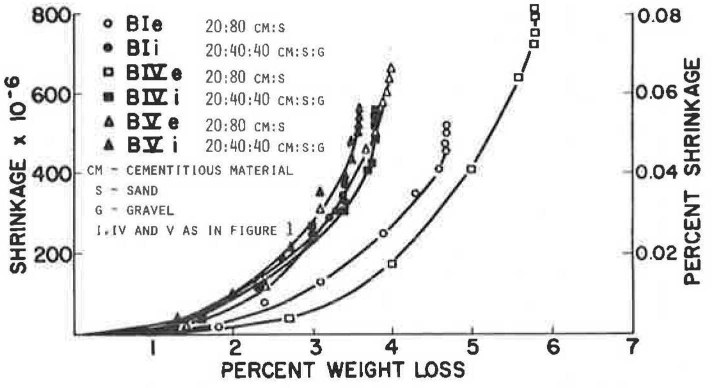

FIGURE 3 Shrinkage and percent shrinkage versus percent weight (moisture) loss of 20 percent cementitious material (1:8 cement and/or lime : Sundance fly ash) and 80 percent aggregate.

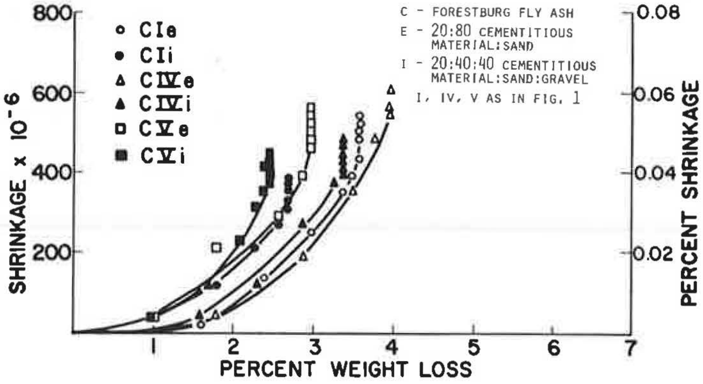

FIGURE 4 Shrinkage and percent shrinkage versus percent weight of 20 percent, cementitious material (1:8 cement and/or lime : Forestburg fly ash) and 80 percent aggregate.

possible reason for the variation in water evaporation could be that more water is used and chemically bound in cement-fly ash hydration than in the lime-fly ash hydration process within the first 14 days (initial curing period).

Crystallization of reaction products of cement-fly ash takes much before the crystallization of lime-fly ash reaction products (6). At an early age of curing, lime-fly ash reaction products are generally in the form of gel. It appears that less water was available to evaporate from the crystal-like reaction products of cement-fly ash than the gel form of lime-fly ash reaction products. This higher moisture loss from the lime-fly ash specimen is probably responsible for the higher shrinkage rate.

Shrinkage Versus Weight Loss

Shrinkage appears to be caused by the loss of moisture from stabilized aggregate. Data in Figures 3 and 4 indicate that although the majority of the shrinkage was due to weight loss, some shrinkage occurred even after there was no further weight loss. This suggests that although most of the shrinkage in stabilized aggregate is due to moisture loss, it appears that some part of the shrinkage is caused by chemical changes, presumably because of gel formation.

In order to establish a correlation between weight loss and shrinkage in this investigation, the average shrinkage values of all the Sundance and the Forestburg fly ash mixes were plotted against corresponding average percent weight loss values. The plots are shown in Figure 5. A close examination of these plots suggests that one-fourth of the total weight (moisture) loss occurred in one day, whereas little shrinkage occurred during this period. A similar phenomenon has been reported for soil cement by George (9) and for concrete by Neville (15). No definite correlation could be established between shrinkage and weight loss up to the first 3 days of drying. But a linear relationship is found between shrinkage and weight loss from 3 to 28 days and then 28 to 150 days for both the Sundance and Forestburg fly ash mixes. Within the limits investigated, these relationships can be approximated by the following equations:

For mixes containing the Sundance fly ash,

$$y = 2.26 + 0.0039x \text{ (3 to 28 days)} \quad (1)$$

$$y = 3.78 + 7.6 \times 10^{-4}x \text{ (28 to 150 days)} \quad (2)$$

For mixes containing the Forestburg fly ash,

$$y = 1.64 + 0.0038x \text{ (3 to 28 days)} \quad (3)$$

$$y = 3.2 + 2.7 \times 10^{-4}x \text{ (28 to 150 days)} \quad (4)$$

where x is shrinkage in microstrains and y is percent weight loss.

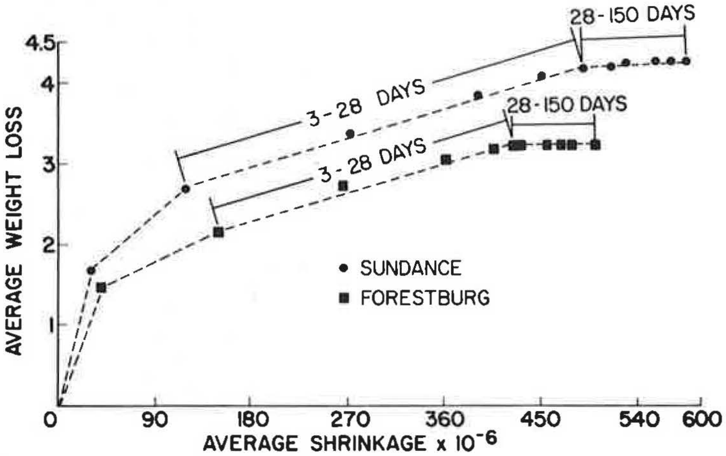

FIGURE 5 Average shrinkage value of all the Sundance and Forestburg fly ash mixes at various ages versus corresponding average percent weight loss.

TABLE 4 Residual Strength, Index of Resistance, and Strengths of Control Specimens for the Various CFA Mixes

Mix	Compressive Strength (MPa)				Index of Resistance (4)/(3)	Weight Loss during F/T cycle, %
	7 days** cured in fog room (1)	14 days cured in fog room (2)	28 days cured in fog room (3)	28 days* after 14 F/T Cycles (4)		
CIe	5.45	6.40	13.65	9.85	0.72	-0.11
CIi	6.35	6.90	15.45	8.30	0.54	-0.1
BIe	3.25	4.15	8.95	6.95	0.78	+ .07
BIi	5.25	6.85	11.50	9.65	0.85	- .05

*Exposed to 14 freeze-thaw (F/T) cycles after curing 14 days in moist room.

**Data from Table 3.

Freeze-Thaw Resistance

Eight of the twelve mixes investigated for shrinkage characteristics were used to study the freeze-thaw durability. Mixes containing LCFA were eliminated for freeze-thaw studies.

CFA Mixtures

The residual strengths, index of resistance (ratio of average compressive strength of freeze-thaw specimens tp that of control specimens), and weight loss following 14 cycles of freezing and thawing are given in Table 4. The compressive strengths of control specimens are also given in Table 4. The comparison of strength gain during freeze-thaw cycles and standard moist curing for various CFA mixes is shown in Figure 6.

An examination of data in Figure 6 indicates that the rate of strength gain during freeze-thaw cycles was significantly lower than the rate of strength in standard or normal moist cure. But the gain of strength of the CFA mixes continued even during freezing and thawing. The data in Table 4 indicate that the index of resistance for CFA mixes ranged from 0.72 to 0.85 except the CIi mix (2.22 cement:17.78 Forestburg fly ash:40 sand:40 gravel). The index of resistance of 0.54 for CIi mix is quite low compared to 80 percent recommended (14). However, residual strength of 8.3 MPa for this mix is significantly higher than the recommended residual strength. The residual strength values of CFA mixes ranging from 7 MPa to 10 MPa (Table 4) are well above the suggested minimum residual strength by George and Davidson (14). Their results indicate that the residual strength criteria are more reliable than the index of resistance. In general, compressive strengths of materials after freeze-thaw cycles should not drop below the recommended strengths of 3 to 5 MPa for pavements.

A visual examination of specimens after freeze-thaw cycles showed no deterioration of specimens. An insignificant amount of weight loss of the specimens was observed after the freeze-thaw cycles. Little or no difference was observed in the moisture content of samples after the freezing and thawing.

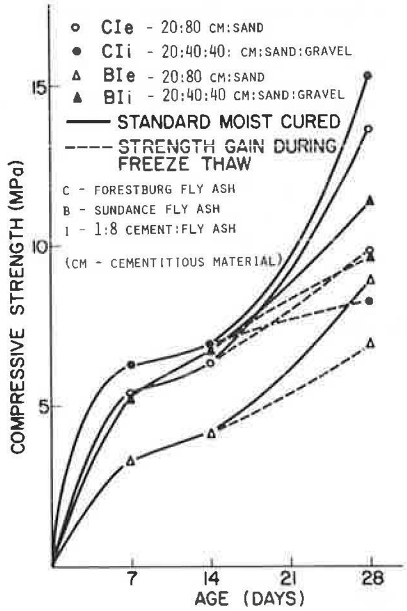

FIGURE 6 Comparison of strength gain during freeze-thaw cycles and under standard curing of CFA mixtures.

LFA Mixtures

The comparisons of strength gain during freeze-thaw cycles and moist curing after 28 days initial cure are shown in Figure 7. Strength recovery of freeze-thaw specimens between 42 and 56 days (after 14 freeze-thaw cycles) is also shown in Figure 7. Table 5 lists compressive strengths of freeze-thaw and control specimens, index of resistance, and regained strengths of freeze-thaw specimens.

The data in Table 5 indicate residual strength to be approximately 11.2 to 13.8 MPa and the index of resistance ranges from 0.91 to 0.96. This falls well above the suggested values for durable material in base and sub-base construction. The weight loss of LFA mixes during freeze-thaw cycles as given in Table 5 was insignificant. No deterioration of freeze-thaw specimens could be observed by visual examination. Like CFA mixes, the LFA mixes also maintained the same moisture content after as before the freeze-thaw cycles.

The rate of strength gain during alternate freezing and thawing was found to be lower than the standard moist curing as indicated in Figure 5. In order to observe the strength recovery of freeze-thaw specimens, some of these specimens were cured in a moist room subsequent to 14 freeze-thaw cycles. A close examination of Figure 7 reveals that freeze-

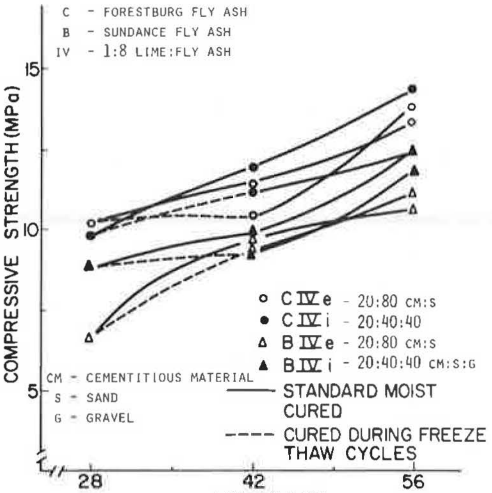

FIGURE 7 Comparison of strength gain during freeze-thaw cycles and standard moist curing and recovery of strength of freeze-thaw specimens for LFA mixtures.

thaw specimens after moist curing attained compressive strengths close to those of the control. This finding indicates that even those LFA materials placed late in the construction season will develop their ultimate specified strength when the temperature rises the following spring, provided that the lime used in the mix is not subjected to significant leaching or carbonation.

Although the performance of LFA mixes and CFA mixes cannot be compared directly because of their different initial curing times, the LFA mixes showed a better overall performance than the CFA mixes under cyclic freezing and thawing. A possible explanation for this appears to be that the LFA mixes were subjected to freezing and thawing after 28 days of initial curing when their compressive strengths ranged from 6.6 to 10.2 MPa. Whereas the CFA mixes were subjected to freeze-thaw cycles after 14 days when their strength ranged from 4.15 to 6.9 MPa. This supports the fact that the higher the strength of stabilized materials, the better their durability characteristics during freezing and thawing.

Another observation made was that mixes containing the Sundance fly ash were less susceptible to freeze-thaw attack than the mixes of Forestburg fly ash, although the initial strengths of the Forestburg fly ash mixes were higher than the Sundance fly ash mixes. The better behavior of the Sundance fly ash mixes may be attributed to the coarseness of the Sundance fly ash particles. Gray et al. (16) have reported that according to the U.K. Transport and Road Research Laboratory results, the coarser fly ashes are less susceptible to the frost than the finer fly ashes. The coarser Sundance fly ash has a specific surface area of 3140 cm^2/g, whereas the finer Forestburg has a specific surface area of 3690 cm^2/g (6).

The freeze-thaw study for this report was conducted on a preliminary basis. The residual strength criteria were used as suggested by some researchers (12-14). The freeze-thaw test, ASTM D 560, was not chosen because this test is basically for soil-cement mixtures. The stabilized aggregate studied in this report was considered comparable to dry lean concrete or roller-compacted concrete. A detailed freeze-thaw study for these materials using a test between ASTM C 666 (for concrete) and ASTM D 560 is under way at the University of Calgary. However, on the basis of mixes studied in this report, it may be concluded that the CFA and LFA mixes should perform reasonably well under moderate freeze-thaw conditions. The stabilized material is proposed to be used in the base course in pavements and is not likely to be subjected to similar environmental conditions as the surface course of the pavement structure.

CONCLUSIONS

1. CFA, LFA, and LCFA mixtures have great potential in pavement construction.
2. CFA, LFA, and LCFA mixes do shrink, but significantly less than the soil cements.
3. The majority of the shrinkage in stabilized aggregate occurred during the first 28 days of drying.
4. Greater shrinkage was observed for lime-fly ash mixes than for those of cement-fly ash mixes.
5. The shrinkage of the mixes studied is related to the weight loss (moisture loss) of the mixes. No definite correlation could be established between shrinkage and weight loss up to the first 3 days of drying. However, linear relationships were found between weight loss and shrinkage from 3 to 28 days and then 28 to 150 days.

TABLE 5 Residual Strengths, Recovered Strengths, Index of Resistance, and Strength of Control Specimens of the Various LFA Mixes

Mix	Compressive Strength (MPa)					F/T Resistance Ratio $\frac{(3)}{(2)}$	Weight Loss during F/T cycles %
	28 days† cured in Fog room (1)	42 days cured in Fog room (2)	42 days* after 14 F/T cycles (3)	56 days† cured in Fog room (4)	56 days** cured in Fog room after 14 F/T cycles (5)		
CIVe	10.20	11.40	10.35	13.30	13.80	0.91	0.2
CIVi	9.80	11.95	11.10	14.35	12.45	0.93	0.2
BIVe	6.60	9.75	9.40	10.55	11.20	0.96	0.17
BIVi	8.85	9.85	9.25	12.5	11.95	0.94	0.16

*Exposed to 14 freeze-thaw (F/T) cycles after curing 28 days in moist room.
**Specimens cured in Fog room for 14 days after freeze-thaw cycles.
†Data from Table 3.

6. Cement-fly ash and lime-fly ash stabilized mixes have the ability to retain and regain compressive strengths under repeated cycles of freezing and thawing and subsequent curing.

7. No deterioration or weight loss was observed in cement-fly ash or lime-fly ash stabilized aggregate samples after 14 freeze-thaw cycles.

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