SOME FACTORS AFFECTING THE DURABILITY OF LIME-FLY ASH-AGGREGATE MIXTURES

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Lime-fly ash-aggregate (LFA) mixtures have proved to be effective and economical paving materials. In certain instances, however, these materials show a tendency to deteriorate slowly with time under severe service conditions. The objective of this study was to evaluate some of the important factors believed to influence the durability of LFA mixtures and to determine whether control of these variables can produce a more durable product. Specifically, the effect of the following parameters on the durability of LFA mixes was studied: aggregate gradation, lime plus fly ash content, ratio of lime plus fly ash to aggregate fines, curing time, fly ash content, and saturation. Strength and durability of the various mixes were evaluated by using standard procedures outlined in ASTM C 593-69. Durability was determined by the weight loss exhibited by the specimens during 12 standard freeze-thaw cycles. Results indicate that (a) for maximum durability the mix should have sufficient fines (material passing No. 4 sieve) to float the coarser aggregate particles, (b) the ratio of lime plus fly ash to fine aggregate is optimum in the range of 1:4 to 1:7, (c) durability generally increases with increased curing, (d) most mixes used in current practice have insufficient fly ash for optimum mix proportions, and (e) the effect of saturation is dependent on the freezing rate and freezing conditions. The results provide background information for design of LFA mixes to give optimum performance.

•LIME-fly ash-aggregate (LFA) mixtures have proved to be very effective and economical materials for use in base and subbase layers of pavement systems. Although LFA mixtures are relatively new, their use has increased significantly in the last several years, and with it, so has their record of field performance. From this record, it has been learned that perhaps the most significant property of this material in terms of pavement performance is durability. That is, when pavements with LFA mixtures have been exposed to the harmful effects of loading and environment, some of them have shown a typical time-related decrease in serviceability, which requires periodic maintenance to maintain the desired level of service. Through a better understanding of the problem of durability, it may be possible to build LFA pavements with a longer life expectancy and a lower maintenance requirement. This study was undertaken to investigate some of the factors that affect the durability of lime-fly ash-aggregate mixtures. More specifically, the effects of six major factors on durability were studied:

1. Aggregate gradation,
2. Lime plus fly ash content,
3. Ratio of lime plus fly ash to total fines,
4. Increased curing time,
5. Fly ash content, and
6. Saturation.

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Results from this study give insights into the LFA material durability characteristics that are influenced by parameters that can be controlled through proper mix design.

PREPARATION OF TEST SPECIMENS

All testing was done by using the standard $\frac{1}{30}$-ft^3 (940-cm^3) Proctor size specimens and was carried out in accordance with appropriate ASTM specifications.

Materials

The lime was monohydrated dolomitic lime. The fly ash was a conditioned fly ash obtained from a stockpile near Romeoville, Illinois, commonly referred to as the Will County plant. The coal burned at the time this fly ash was produced was mined in Illinois. Two aggregates were used in this study, a well-graded gravel and a well-graded crushed stone.

Mixture Design and Preparation

Three mixture proportions were chosen for use in this study. The percentages by weight of lime, fly ash, and aggregate were 2½-10-87½, 3-12-85, and 3½-14-82½. Except in one study, a lime to fly ash ratio of 1:4 was maintained. These proportions are representative of mix proportions currently in use in field applications using similar types and gradations of aggregates.

For each test a set of five specimens was prepared in two batches to minimize moisture loss. The dry materials were charged into a Lancaster mixer and thoroughly mixed before water was added to bring the mix to optimum moisture content.

Compaction

The specimens were compacted in accordance with ASTM C 593. Briefly, this specification requires that compaction be carried out at optimum moisture content by using a standard $\frac{1}{30}$-ft^3 (940-cm^3) mold and compacting the material in three layers with 25 blows per layer of a 10-lb (4.5-kg) hammer falling through an 18-in. (45-cm) drop.

Curing

All specimens were cured at 100 F (38 C) for 7 days before testing was initiated except for those specimens used to evaluate the effect of additional curing on freeze-thaw durability. All specimens were sealed in plastic bags to maintain the moisture at the mixing water content throughout the curing period.

TEST PROCEDURE

Strength and durability tests were conducted in accordance with ASTM C 593. Of each set of five specimens, three were tested for strength and two for durability. The standard durability test consisted of 12 freeze-thaw cycles ranging from -10 to 70 F (-23 to 21 C) with a 24-hour freeze cycle and a 23-hour thaw cycle. All specimens were brushed in the prescribed manner in accordance with ASTM C 593, and the weight loss for each cycle was determined.

In the study phase to determine the effect of saturation on durability, tests were performed by using the freeze-thaw durability testing unit developed by Dempsey (1).

This unit was designed to simulate freeze-thaw temperature conditions and mechanisms similar to those that exist in in-service pavement systems. This testing chamber is programmed to subject specimens to uniaxial temperature gradients similar to those measured in in-service pavements. The durability of stabilized materials was evaluated by determining the compressive strength loss after five freeze-thaw cycles in the test unit.

ANALYSIS AND DISCUSSION OF RESULTS

Aggregate Gradation

All aggregates were split on a No. 4 sieve, and the fine and coarse fractions were reblended in various ratios so that the fine (minus No. 4 sieve) component ranged from 25 to 100 percent of the total aggregate fraction. For each mix design, one set of five specimens was made at each fines content and evaluated for strength and durability.

The gradation of the aggregate was found to have a very significant effect on the density, strength, and durability of the mixes tested. For the gravel aggregate, there seemed to be a single optimum gradation for all three properties (Figure 1). The crushed stone showed a similar trend (Figures 2 and 3), but the optimum fines content for maximum durability was slightly higher than that for maximum density and strength. This is believed to be related to the density of the cementing matrix. For high strength and good durability of the mixes, it is essential to achieve high density in the matrix, i.e., in the fines portion of mixes. High overall mix density does not necessarily produce the highest matrix density, which is achieved only when the coarse aggregate is slightly less than that required for maximum overall density so that the coarse particles are floating in the matrix. This allows the compactive energy to be used in densifying the cementing matrix rather than being dissipated, overcoming shear resistance between the coarse particles. The coarse aggregate in well-bonded mixes serves only as a filler, and the integrity of the mix depends primarily on the cohesion supplied by the cemented matrix.

It is believed that, because of the increased angularity in the crushed stone aggregate, a greater dispersion of the coarse fraction is required than with the more rounded particles to eliminate the coarse aggregate interlock, and hence a slightly higher fines content was necessary to permit densification of the matrix. The large gravel particles, which are more rounded particles and have a smoother surface texture, provided less frictional resistance to densification and required a relatively lower fines content to permit densification of the matrix.

The mixes using the crushed stone aggregate, in particular, showed a very rapid decrease in durability when fines content was reduced below optimum. This also is believed to have been caused by the low cementing matrix density and the higher voids content, but may have been accentuated by the severity of the durability test method employed. Vigorous brushing of the specimen after each freeze-thaw cycle seemed to be more detrimental to specimens with a lower fines content. Regardless of why, the results clearly indicate that it is better to be on the fat side (excess fines) than on the lean side of the optimum fines content. This is an important point to consider in mix design. It might be advantageous to design a mix with a slightly higher than optimum fines content, which would reduce the probability of poor pavement performance caused by normal variations in gradation and possible segregation during placement. The excess fines would shift the mix into the less sensitive range (Figure 2) where field variability has a relatively smaller effect on the performance of the finished pavement.

Lime Plus Fly Ash Content

The effect of lime plus fly ash content on mix properties was also studied.

Figure 1. Effect of aggregate gradation for 2½-10-87½ gravel aggregate mix.

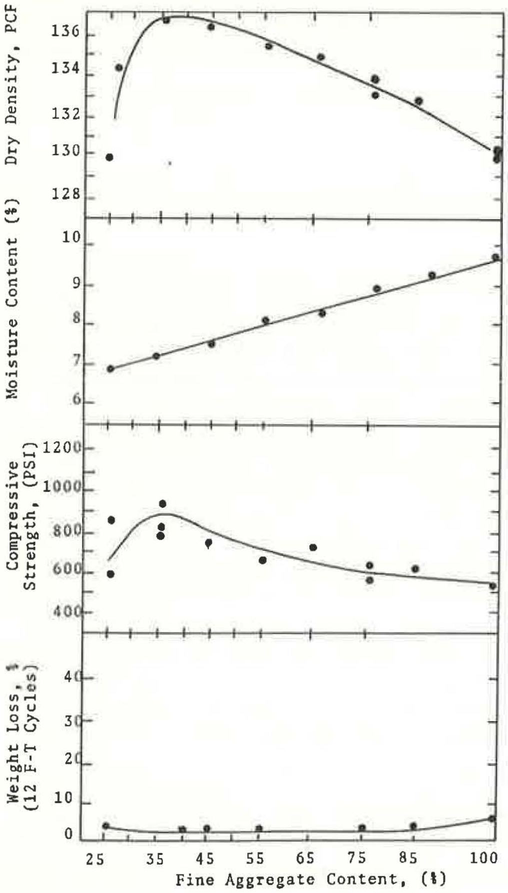
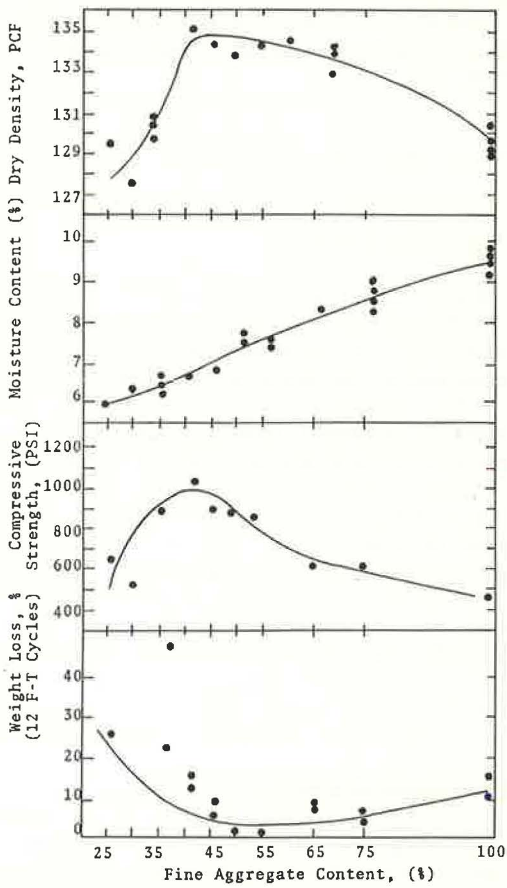


Figure 2. Effect of aggregate gradation for 2½-10-87½ crushed stone aggregate mix.



Basically, an increase in lime plus fly ash content serves to increase the percentage of cementing agents in the mix and therefore controls the quality of the cementing matrix. Its effect was most pronounced in mixes with low fines content, especially with the crushed stone aggregate (Figure 4). These mixes had a high voids content and low matrix density, which resulted in poor durability. Increasing the lime plus fly ash content helped to fill the voids and float the coarse particles and to increase the concentration of cementing products in the matrix. Small increases in the lime plus fly ash content in the mix resulted in marked improvements in durability.

The effect of the lime plus fly ash content was reduced with mixes having higher fines contents. Increased lime and fly ash provided only slight increases in durability. It is believed that these specimens already had low voids content and floating coarse particles and therefore adequate matrix density was achieved without the large lime plus fly ash contents. The effect of increasing the lime plus fly ash content diminishes as the fines content in the aggregate portion of the mix increases. These results show that the effect of the lime plus fly ash content is dependent on the aggregate gradation.

For the aggregates tested in this study, there seemed to be a range in which the mix was most sensitive to changes in the lime plus fly ash content. Decreasing the lime and fly ash content within this range resulted in large increases in weight loss, and increasing it beyond the critical range produced less dramatic results. At the higher lime plus fly ash contents, aggregate gradation had a decreasing effect on durability.

On a practical basis, this result is highly significant. Because of economical considerations, the practice has been to design mixes with the lowest lime plus fly ash content that produces adequate durability. The mix proportions used in this study ($2\frac{1}{2}$-10-$87\frac{1}{2}$, 3-12-85, and $3\frac{1}{2}$-14-$82\frac{1}{2}$) were chosen because they were representative of the proportions most often used in field applications. Mixes with these proportions can produce durable mixes. However, the results presented show that variations in such parameters as aggregate gradation, density, and lime plus fly ash content can significantly reduce the durability of these mixes to a level where the mix is no longer acceptable. Thus, these mixes have a low factor of safety against handling errors and are sensitive to the level of control that can be maintained during mixing, compaction, and curing. By increasing the lime plus fly ash content to a level outside the sensitive range, the mix becomes durable over a wider range of conditions and a factor of safety is provided to help withstand variations in construction.

Ratio of Lime Plus Fly Ash to Total Fines

The previous discussion has shown that both the lime plus fly ash content and the aggregate gradation affect durability, and it has been suggested that some relationship exists between these parameters. An attempt was made to combine them into a single parameter, the ratio of lime plus fly ash to aggregate fines. This ratio, in effect, is a measure of the proportion of cementing agents present in the matrix. A plot of this ratio versus durability is shown in Figure 5 for all mixes tested. Each curve represents a mix with a constant lime plus fly ash content, and the percentage of aggregate fines is varied to alter the lime plus ash to aggregate fines ratio.

In Figure 5 there appears to be a relationship between this ratio and durability for a limited range. At the very low ratios, durability becomes very poor, probably because of the effect of the low fines content in the mix.

For practical purposes, then, this parameter is of limited use in the mix design process. It might serve as a guide for use in design of trial mixes by giving an indication of the range of ratios that would be expected to give good durability. The data shown suggest that mixes with a range of, say, 1:4 to 1:7 for the lime plus fly ash to aggregate fines ratio would perform well for the aggregates used in this study.

Curing Time

Studies were made to evaluate the effect of increased curing time on strength and dura-

Figure 3. Effect of aggregate gradation for 3½-14-82½ crushed stone aggregate mix.

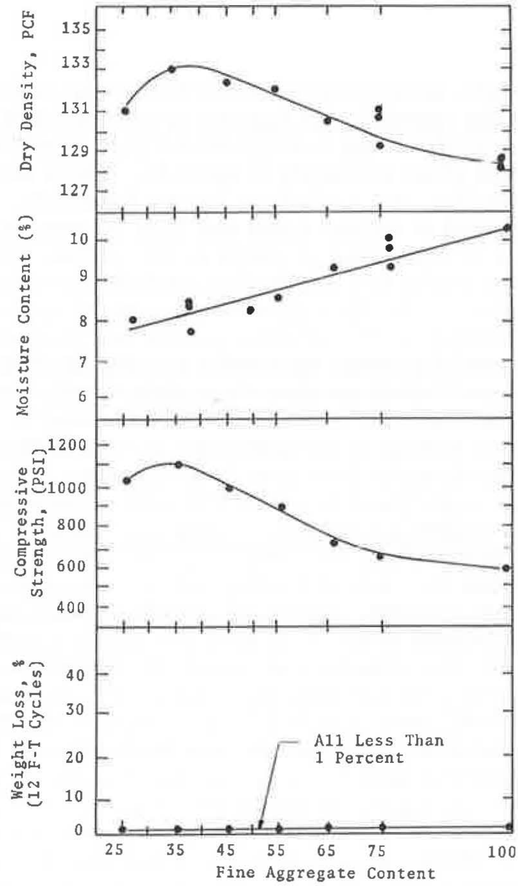
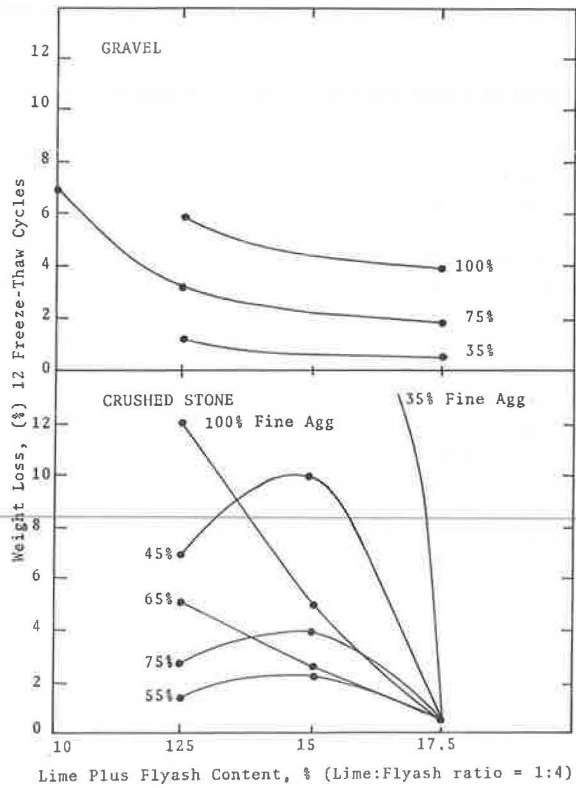


Figure 4. Effect of lime plus fly ash content.



bility. Two mixes at three fines contents (35, 75, and 100 percent fines) were chosen for this study. Specimens were cured at 100 F (38 C) for 7, 10, and 14 days before standard strength and durability were tested. The two mixes used in this study were a $2\frac{1}{2}$-10-$87\frac{1}{2}$ mix, which showed marginal durability after a standard 7-day cure, and a $3\frac{1}{2}$-14-$82\frac{1}{2}$ mix, which showed excellent durability after a similar curing period.

The results from both mixes showed that the increased curing had a substantial effect on the unconfined compressive strength. The mixes with $2\frac{1}{2}$ percent lime showed an average increase in strength of 38 percent as the curing time was increased from 7 to 14 days at 100 F (38 C), and the mixes with $3\frac{1}{2}$ percent lime showed an average increase in strength of 66 percent with the same increase in curing.

Increased curing had an important effect on the durability of the $2\frac{1}{2}$-10-$87\frac{1}{2}$ mix: Mix durability increased from marginal to excellent for all three aggregate gradations. The $3\frac{1}{2}$-14-$82\frac{1}{2}$ mix, which showed excellent durability after only 7 days of curing, showed little reduction in weight loss when subjected to the standard durability test after the additional curing.

These results suggest that increasing the strength of the lime-fly ash-aggregate mixture through additional curing beyond 7 days at 100 F (38 C) appears to be beneficial to mixes, especially those with low lime plus fly ash contents. For mixes with high durability (low weight loss) after 7 days, the additional curing does not substantially decrease the weight loss due to brushing. These results suggest that mixes with higher lime plus fly ash contents can be used to develop mixes with high performance for pavements built and used under unfavorable curing conditions. For late-season construction, for example, it would be possible to obtain adequate durability to withstand the critical first winter by increasing the lime plus fly ash content of many of the mixes currently used.

Increased Fly Ash Content

Evaluation of the mixes with $2\frac{1}{2}$ and 3 percent lime indicated that some of both mix formulations exhibited marginal durability characteristics. One possible cause was insufficiency of fine fly ash in the mix to react totally and quickly with the available lime. This would retard potential strength and durability development of the mix. A separate investigation was conducted in which the lime content was held constant at 3 percent and the flyash content varied from 9 to 18 percent. Specimens made by using the crushed stone aggregate at four fly ash contents were evaluated for strength and durability. The aggregate gradation was a 50-50 blend of fines and coarse aggregate, which corresponded to the optimum fines content determined in the mix design durability evaluation. It was felt that at optimum this gradation, the effect of an increased pozzolanic reaction, would not be masked by beneficial effects produced by the additional fly ash merely filling voids and increasing matrix density.

The results showed that the increased fly ash content had a significant effect on both strength and durability (Figure 6). Increasing the fly ash content from 9 to 18 percent increased the 7-day unconfined compressive strength from approximately 900 to 1,300 psi (6200 to 8900 kPa), an increase of approximately 50 percent. With the same change in fly ash content, weight loss during freeze-thaw decreased from 10 to 5 percent, a 50 percent reduction.

These results tend to confirm other results by the authors that show that many mixes currently used in practice could be improved substantially by increasing the fly ash content by 2 to 6 percent. Such an increase would allow for some minor segregation, which logically occurs during construction and provides a margin of safety for the material.

Saturation

Tests were conducted to determine the effect of saturation on the mix durability by using two radically different test procedures. First, standard durability tests were

Figure 5. Effect on durability of ratio of lime plus fly as to aggregate fines.

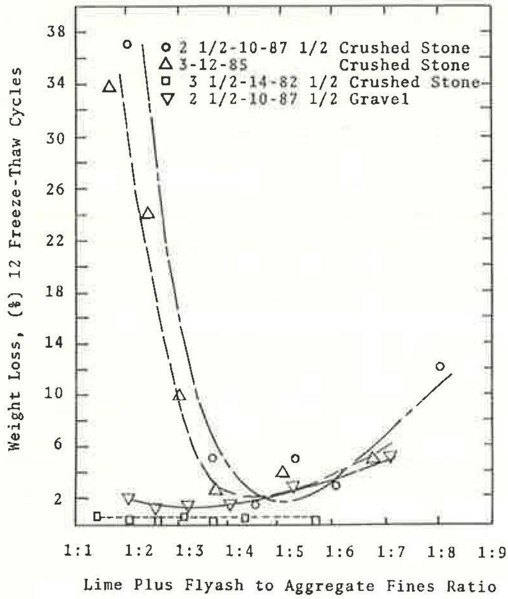


Figure 6. Effect of fly ash content.

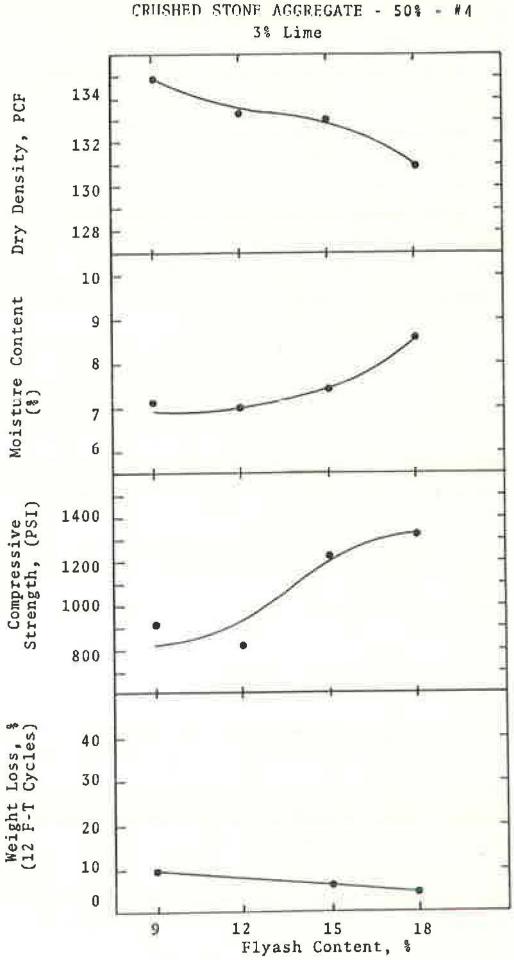


Table 1. Effect of saturation on the durability of 2½-10-87½ LFA mixtures.

Aggregate Fines (percent)	Initial Compressive Strength (psi)	Durability Weight Loss (percent) Standard F-T	Saturated F-T
100	571	5.2	8.7[a]
85	634	3.2	6.0
75	649	3.0	6.2
65	717	2.0	4.4
55	674	1.8	6.8[a]
45	750	1.6	6.7[a]
35	919	1.3	9.9[a]
25	890	2.1	6.1[b]

Note: 1 psi = 6.9 kPa.

[a]Cycles during which specimens failed.
[b]Specimen failed after seven freeze-thaw cycles.

Table 2. Durability strength loss data for specimens subjected to five field-simulated freeze-thaw cycles.

Aggregate Fines (percent)	Initial Compressive Strength (psi)	Compressive Strength After Five Freeze-Thaw Cycles (psi) Standard	Saturated
100	552	526	562
75	603	556	592
75	597	485	483
35	857	759	753

Note: 1 psi = 6.9 kPa.

performed on vacuum-saturated specimens and on specimens that were provided only with capillary water throughout the test. The results of this evaluation are given in Table 1. Second, durability tests were conducted on both saturated and unsaturated specimens by using the test method described by Dempsey (1), which closely simulates conditions that exist in actual pavement systems. The results of this evaluation are given in Table 2.

Comparing the results from these two tests shows conflicting data. The results given in Table 1 indicate that saturation during freeze-thaw is extremely detrimental to durability. In Table 2, the loss of strength of the saturated specimens is not significantly different from that of the unsaturated specimens, which suggests that saturation is not an important parameter. Reasons for this discrepancy become apparent when differences in the freezing mechanism of both procedures are studied.

Kennedy (2) summarized the mechanisms believed to be important in concrete scaling, and, because of similarities in matrix structure, many of the mechanisms for concrete scaling may be applicable to the breakdown of stabilized materials during freezing and thawing. One of the primary mechanisms generally believed to be responsible for freeze-thaw damage is the hydraulic pressure mechanism. Briefly, this mechanism is caused by the initiation of freezing in the pore water. As the water freezes, its expansion creates a hydraulic pressure in the remaining unfrozen pore water. This increase in pressure creates a gradient that causes a flow of pore water away from the freezing front. If this pressure is allowed to dissipate freely and quickly, the excess water will flow out of the pores and the pore will fill completely with ice without causing undue tensile stresses in the matrix surrounding the pore. This is often not the case, however, for the magnitude of the hydraulic pressure depends on several factors including (a) rate of freezing, (b) pore water flow distance, (c) matrix porosity, and (d) matrix permeability. If these factors all combine to create resistance to the flow of excess pore water, significant hydraulic pressures can build up that tend to dilate the pore structure. When the stresses induced by this hydraulic pressure exceed the tensile strength of the matrix material, freeze-thaw damage occurs, resulting in a loss of strength and durability. Such damage has apparently taken place in the saturated specimens of Table 1, which were frozen very rapidly, but not in those of Table 2 in which the freezing rate was much slower.

Specimens tested in accordance with standard durability procedures are subject to three-dimensional freezing. Freezing of the specimen begins at the outer surface and progresses inward toward the center. By the very nature of this freezing mechanism, flow of excess pore water is almost immediately cut off, causing the buildup of significant hydraulic pressures in the unfrozen pore water. These pressures can exceed the tensile strength of the matrix material and may cause significant damage of the matrix structure.

On the other hand, specimens tested in the freeze-thaw cabinet are subject to a uniaxial temperature gradient, and freezing progresses uniformly from top to bottom. This freezing mechanism does not inherently retard the flow of pore water. This water is, instead, allowed to flow dependent mainly on the rate of freezing, the length of the flow path, and the porosity and permeability of the matrix.

These results suggest that saturation is not in itself detrimental to freeze-thaw durability. The amount of damage that occurs depends on the combination of several factors, of which the degree of saturation is only one; saturated specimens can perform equally as well as unsaturated ones for a given combination of these factors. However, it must be kept in mind that the potential for freeze-thaw damage is greatly increased when high saturation prevails. The hydraulic pressure mechanism theory is valid only under nearly saturated conditions, and, if the degree of saturation is kept below a critical level, the potential for damage by this mechanism is greatly reduced. Therefore, steps should be taken to minimize the potential for saturation of LFA pavement layers in design, construction, and maintenance.

CONCLUSIONS

The following conclusions are indicated by the findings from this study. They are also supported by the authors' experience with these materials, which spans nearly 14 years of research, testing, and quality control on LFA mixes.

1. Aggregate gradation is an important factor in the durability of LFA mixes. For good durability, it is important that a high relative density be achieved in the cementitious matrix of the mix. This can be achieved only if the coarse aggregate particles are floating in the matrix. A lack of fines in coarse aggregates can be compensated for by an increase in fly ash content. It is better to have an excess of fines in the mix than to have a deficiency.
2. To achieve durability in a mix requires that the mix have adequate quantities of lime plus fly ash. The amount of lime plus fly ash required varies with aggregate gradation, but generally mixes with well-graded aggregates will require from 12 to 16 percent lime plus fly ash on a dry weight basis. Mixes with a high percentage of minus No. 4 aggregate may require a higher lime plus fly ash content to prevent diluting the matrix. Mixes with a shortage of fines may require a higher lime plus fly ash to fill the voids and float the coarse particles.
3. The ratio of lime plus fly ash to total fines appears to go through an optimum value. Ratios of lime plus fly ash to fine aggregates of from 1:4 to 1:7 appear valid for a range of mixes.
4. Increased curing time at a given temperature will result in a more durable and stronger product, particularly if the product had marginal durability under standard curing [7 days at 100 F (38 C)]. This factor is critical when LFA mix designs for late-season construction are considered.
5. Increased fly ash content has a significant effect on the strength and durability of LFA mixes. In general, even with aggregates with adequate fines, an increase in the the fly ash content results in increased strength and durability in the mix.
6. Excess water in LFA materials is detrimental to performance. The ultimate effect of saturation on the durability of LFA mixes is also influenced by other factors such as method of test, rate of freezing, and permeability. In general, however, mixes that are saturated do not perform so well as mixes that are well drained.

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