Cracking in Cement-Treated Bases and Means for Minimizing It

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This report describes the causes and control of cracking of pavements, with specific reference to cement-treated bases. In order to study the variables influencing cracking of cement-treated bases, analytical expressions for both crack spacing and crack width were derived. The crack spacing (L) is influenced by the tensile strength, the coefficient of sliding friction (μ) and specific weight of the material (γ). The crack width (δ_T), primarily a function of the total maximum shrinkage, is to some degree influenced by μ, γ, L, and the modulus of elasticity in tension (E_t). A simple expedient to minimize cracking would be to control the shrinkage of the cement-treated soil.

A search for treatments to reduce shrinkage led to several promising additives; lime and fly ash proved to be the best and sulfates in appropriate concentrations, particularly those of magnesium and sodium, appear to be effective.

•MIXING cement and soils reduces shrinkage because the cement matrix tends to restrain the movement of the soil; nevertheless, the resulting product undergoes some shrinkage due to moisture loss. Results of a study on the shrinkage characteristics of cement-treated soil are reported elsewhere in this RECORD (1).

A cement-treated base that is trying to contract due to internal changes, if fully or partially prevented from doing so, will be stressed in tension and usually in shear. When the ultimate tensile strength of the material is exceeded, cracks begin to form. This study is concerned with the problem of building pavement bases with fewer cracks and minimizing the crack width.

A simplified theoretical analysis of the crack-spacing and crack-width problem is presented. It is possible that the intensity of cracking can be controlled by reducing the shrinkage of the soil-cement through treatment with trace additives.

SIMPLIFIED THEORETICAL ANALYSIS OF CRACKING

Cracks in cement-treated bases may be due to two factors: ambient temperature and changes in moisture content. Calculations indicate that the contraction and expansion due to changes in temperature are insignificant compared to shrinkage and swelling due to drying and wetting. For example, for a temperature differential of about 30 F, the strain is only about 0.02 percent whereas the shrinkage for a typical sand-clay topping due to drying out is 0.20 percent. For this reason, emphasis in this study is on the causes and control of transverse cracking caused by drying out.

The analytical discussion that follows will concentrate on crack spacing and crack width, which determine to an important degree the damage due to cracking in a cement-treated base.

Crack Spacing

As a result of linear shrinkage, tension stresses can be set up in cement-treated base slabs. If the slab is free to move (no friction between the slab and the subgrade),

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stresses will not result. However, if friction exists between the slab and subgrade, restraint results from the friction forces.

Figure 1a shows the forces acting on a contracting slab. The stress distribution due to subgrade friction is shown in Figure 1b. The movement of a contracting slab is increased from zero at the center to a maximum toward the free end, as is the frictional resistance. For equilibrium conditions, the summation of the friction forces from the center of the slab to the free end must be equal to the total tension in the slab.

Balancing total forces in Figure 1a,

$$\sigma_c \, bh = \mu \gamma b h \frac{L}{2} \tag{1a}$$

where

σ_c = tensile stress at center of slab, psf;
b = breadth of pavement, ft;
h = depth of pavement, ft;
μ = coefficient of sliding friction;
γ = unit weight of material, pcf; and
L = length of slab, ft.

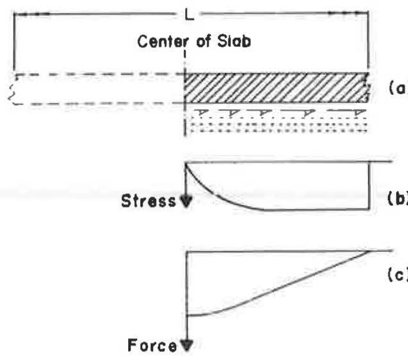

Figure 1. Stress resulting from shrinkage; (a) force acting on shrinking slab, (b) variation of stress with length, and (c) force diagram.

The slab length (L_{max}) at which tensile stress will become critical is as follows:

$$L_{max} = \frac{2\sigma_u}{\mu\gamma} \tag{1b}$$

where σ_u = ultimate tensile strength, psf.

In other words, for a specific slab placement the spacing of cracks is directly related to the tensile strength of the material.

Crack Width

Let us consider a slab with cracks at L-ft intervals, as in Figure 2a. The slab contracts from both ends while the center portion of the slab is assumed to remain stationary (Fig. 2b). The crack width is thus influenced by two opposing factors: the tendency of soil-cement to shrink, compensated to some extent by the extensibility of the material. Accordingly, the width of crack (δ'_{cr}) will be the difference between the contraction due to shrinkage of the slab (δ_1), assuming no friction, and the elongation of the same section of the slab (δ_2) due to frictional resistance. To make the derivation more general, it is assumed that at the time of cracking, the material has not attained its maximum shrinkage. Let δ'_{cr} denote the crack width immediately after cracking while δ''_{cr} refers to the subsequent widening of the crack. Then

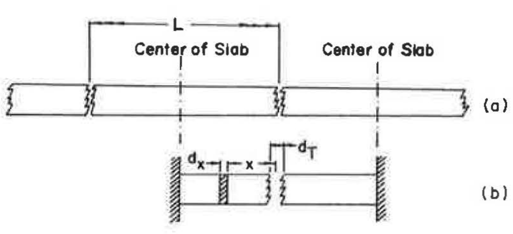

Figure 2. Transverse cracks in a pavement base; (a) cracked base, and (b) section considered for crack width calculation.

$$\delta_1 = \epsilon_{cr} L$$

$$\delta_2 = 2\int_0^{L/2} \frac{\sigma_x}{E_t}\,dx = 2\int_0^{L/2} \frac{\mu\gamma x}{E_t}\,dx$$

$$= \frac{\mu\gamma L^2}{4E_t}$$

And

$$\delta'_{cr} = \delta_1 - \delta_2$$
$$= \epsilon_{cr}L - \frac{\mu \gamma L^2}{4E_t} \qquad (2a)$$

where

ϵ_{cr} = shrinkage at cracking, in./in.;
E_t = modulus of elasticity of cement-treated soil in tension, psf; and

$$\delta''_{cr} = (\epsilon_c - \epsilon_{cr})L \qquad (2b)$$

where ϵ_c = total shrinkage, in./in.

In Eq. 2b, it is tacitly assumed that the coefficient of sliding friction remains unchanged from that before cracking; hence the narrowing of the crack due to the extensibility of the slab becomes zero.

Total width of crack, therefore, will be obtained by combining Eqs. 2a and 2b. Thus,

$$\delta_T = \epsilon_c L - \frac{\mu \gamma L^2}{4E_t} \qquad (2c)$$

where δ_T = total crack width, ft.

Factors Affecting Crack Width and Crack Spacing

Narrow cracks, at the widest spacing possible, is the objective in a soil-cement base. From Eq. 1b it is evident that crack spacing is influenced by μ, σ_u, and γ. Eq. 2c reveals that crack width is primarily a function of the total maximum shrinkage (ϵ_c) and is to some extent influenced by μ, γ, L and E_t.

The effect of sliding friction (μ) on crack spacing can be seen from Eq. 1b, which indicates that the crack spacing is inversely proportional to the friction coefficient. To evaluate its influence on crack width, however, the partial derivative of δ_T with respect to μ is determined. Substituting $L = \frac{2\sigma_c}{\mu \gamma}$ in Eq. 2c and performing the differentiation, we get

$$\frac{\partial \delta_T}{\partial \mu} = \frac{\sigma_c}{\mu^2 \gamma}\left(2\epsilon_c - \frac{\sigma_c}{2E_t}\right)$$

Since $2\epsilon_c >> \frac{\sigma_c}{2E_t}$, for normal values of σ_c and E_t, the slope of δ_T vs μ is always negative. It is therefore concluded that the crack width always decreases with increase in subgrade friction.

Similar reasoning may be advanced to interpret how other factors, i.e., tensile strength and specific weight, might influence crack spacing and crack width. Table 1 summarizes these results. The significance of these factors is emphasized by an index number such as 1 or >1. The use of this index number can best be illustrated by an example. From the results in Table 1, the change in sliding friction appears to have greater influence on crack spacing than on crack width. Also, the crack width increases with crack spacing, though not linearly.

TABLE 1

DEPENDENCE OF VARIOUS FACTORS ON CRACKING

Cracking	Coefficient of Sliding Friction (μ)	Tensile Strength (σ_u)	Specific Weight (γ)
Crack spacing increases with	Decrease >1	Increase >1	Decrease 1
Crack width decreases with	Increase 1	Decrease 1	Decrease 1

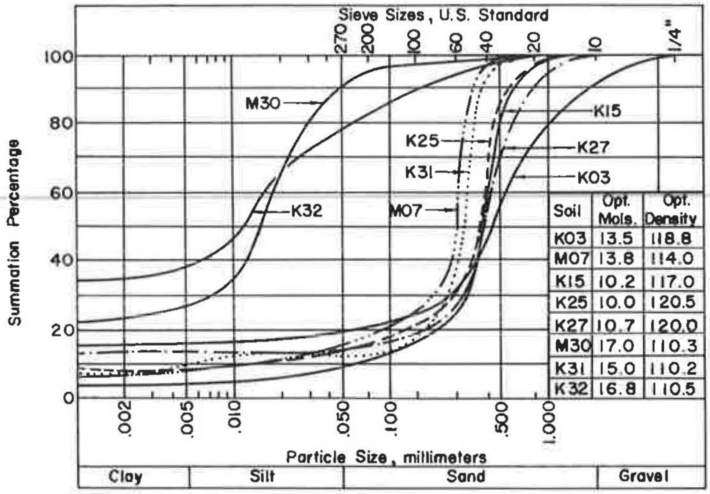

Figure 3. Particle size distributions of soils.

One of the limitations of Eqs. 1b and 2c is the fact that they are applicable only to elastic materials. Since cement-treated soil exhibits creep, it is only partly elastic. It may be asserted that the higher the creep, the greater the crack spacing, and the smaller the crack width.

INFLUENCE OF ADDITIVES ON SHRINKAGE

A positive appraoch to minimize cracking in cement-treated pavements would be to control the shrinkage of the treated material. Some of the factors that regulate the shrinkage of the soil-cement mix are discussed elsewhere in this RECORD (1). This report evaluates the competence of various additives in reducing shrinkage of cement-treated soil.

Materials and Procedures

Eight soils with particle-size distributions (Fig. 3) were used. The preceding paper (1, Table 1) lists compositional data, physical properties, and classification of these soils. Each soil is identified by a 1-letter, 2-digit system; for example, K03 means No. 3 soil, with kaolinite as predominant clay mineral. Various additives tested are listed in Table 2.

A description of the procedure for preparation and testing of beam specimens is given elsewhere in this RECORD (1). Harvard miniature samples were used for unconfined compression testing. The shrinkage result reported for a specific variable is the average of two specimens and the strength results is the average of three specimens.

TABLE 2

ADDITIVES TESTED

Material	Source
Lime	United States Gypsum Company, New Orleans
Calcium chloride	Reagent grade
Fly ash	Detroit Edison Co., Detroit
Pozzolith	The Master Builders Co., Cleveland
Expansive cement	Penn-Dixie Cement Corp., Nazareth
Gypsum	United States Gypsum Co.
Sodium sulfate	Reagent grade
Magnesium sulfate	Reagent grade
Sodium hydroxide	Reagent grade
Cationic emulsion SS-K	Chevron Asphalt Co., Tucson

Effect of Additives

The additives investigated and found beneficial are broadly grouped according to the principal mechanism responsible for their effectiveness. They are lime and calcium chloride, widely known for the cation exchange

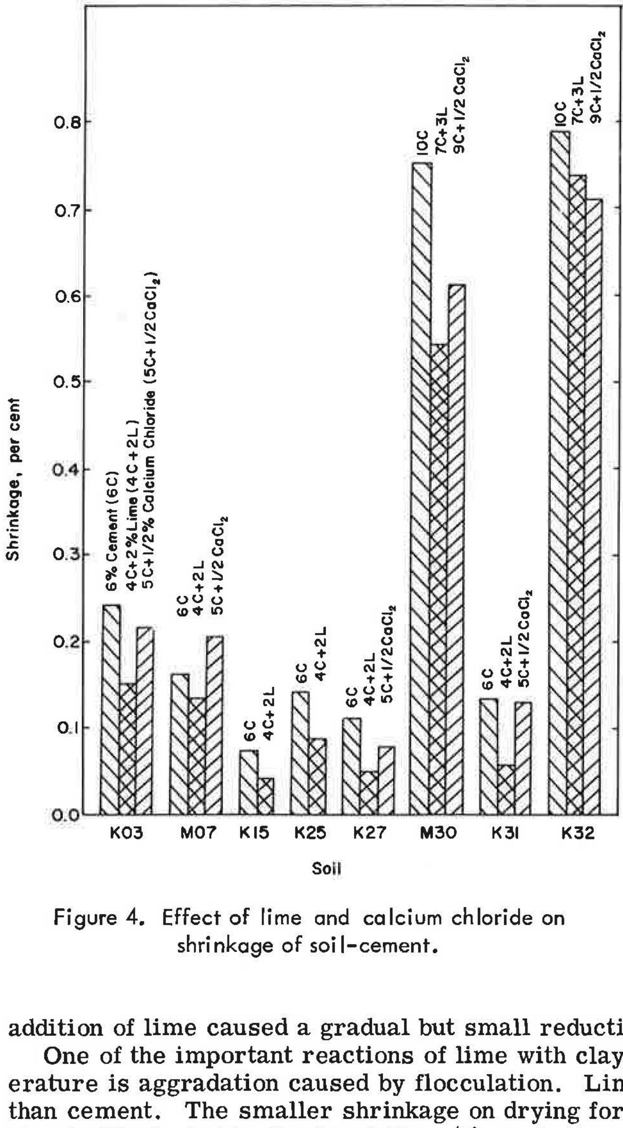

Figure 4. Effect of lime and calcium chloride on shrinkage of soil-cement.

properties; fly ash; pozzolith 8; and, to some extent, calcium chloride. These improve the workability of the mix and thereby increase the density and/or decrease the optimum moisture. Expansive cement and sulfates of calcium, sodium, and magnesium expand and partly compensate for the shrinkage.

Lime—Depending on the clay content (2-μ) lime proportions were varied from 2 to 3 percent. In the soil-cement blends, lime replaced an equal amount of cement.

In virtually all soils studied, shrinkage was reduced by blending trace amounts of lime (Fig. 4). Typically, 30 to 40 percent reduction in shrinkage was observed; in a few sand soils it was as much as 60 percent. This finding is in general agreement with the reported results (2, 3). Some other advantages in using lime with cement-treated soil are the improved workability and increased compressive strength (4). The compressive strength was slightly increased in two soils, and decreased in two others (Fig. 4). The slight reduction in strength of M30, a friable loess, is in agreement with the reported findings. Pinto et al (4) observed that for a friable loess-cement, addition of lime caused a gradual but small reduction of strength.

One of the important reactions of lime with clay, repeatedly documented in the literature is aggradation caused by flocculation. Lime flocculates clay more effectively than cement. The smaller shrinkage on drying for flocculated clay than for dispersed clay is illustrated by Seed and Chan (5), and others. In two cement-treated soils quicklime was substituted for hydrated lime. Results indicate that the former was nearly as effective as the latter.

Calcium Chloride—As little as 0.5 percent calcium chloride, substituted for 1 percent of cement, reduced the shrinkage in four out of six soils tested (Fig. 4). A comparison shows that lime reduced shrinkage somewhat more than calcium chloride. The theory that calcium chloride assumes the role of an accelerator for cement hydration and, in so doing, becomes less effective is in keeping with the results reported by the author (1) that shrinkage increased with the rate of cement hydration.

Repeatedly cited in the literature (6, 7) (but not considered in this study) is the hypothesis that under the same compactive effort the dry density of a chloride-treated soil is often increased with a corresponding decrease in optimum moisture. This hypothesis is substantiated in two soils, K03-06 and M30-10, where it is observed that with 0.5 percent calcium chloride, the increase in dry density is 1.2 and 1.1 pcf and the decrease in optimum moisture is 0.9 and 0.8 percentage points, respectively. So far as shrinkage is concerned this result is significiant, since the writer's study (1)

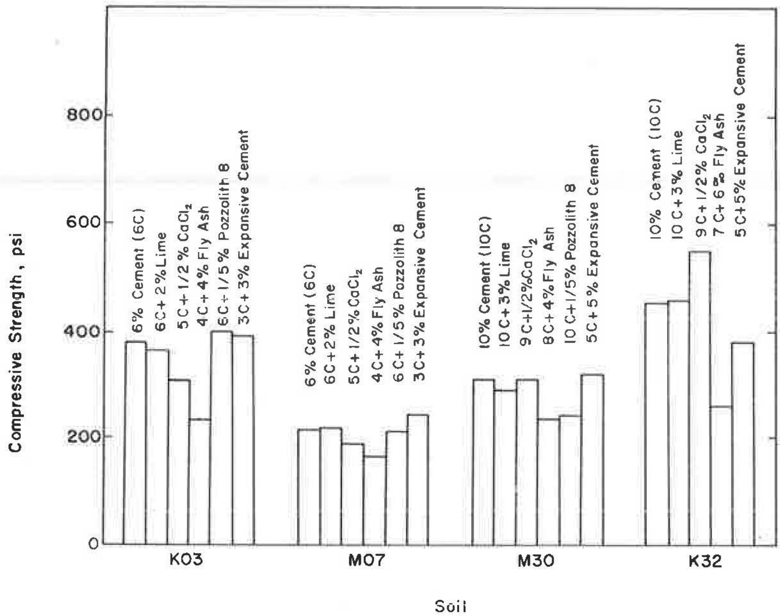

Figure 5. Unconfined compressive strengths of soil-cement with various additives. Specimens 7-day cured, 1-day immersed.

points out that increasing the dry density and/or decreasing the molding moisture tends to reduce shrinkage. Direct experimental evidence to this effect can be found in Wood (8), who reports that in field test sections the calcium chloride treated sections were found to be free of cracks and showed no failure.

From the strength results (Fig. 5), it appears that calcium chloride does not improve the strength on replacing cement in soil-cement. Clare and Pollard (9), however, report that in soils containing active organic matter, calcium chloride results in marked improvement in strength.

In conclusion, it is postulated that either a poorly reacting sand or a soil that presents compaction problems could be benefited from calcium chloride; a typical example is soil K31. Of the seven admixtures tested in this soil only three were effective; of the three, calcium chloride proved to be the best.

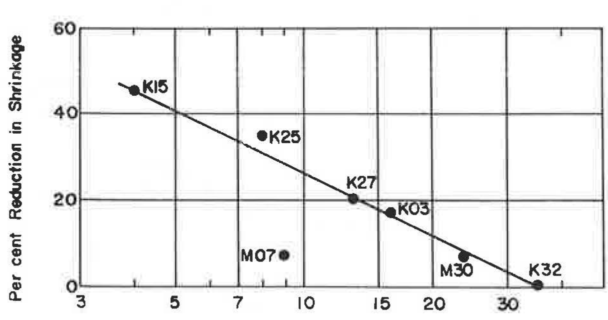

Figure 6. Reduction in shrinkage of fly ash-treated soil-cement as percent of untreated mix. Four percent cement and 4 percent fly ash in soils K03, K15, K25, and K27. Seven percent cement and 6 percent fly ash in soils M30 and K32.

Fly Ash—Although the use of fly ash in mass concrete has been extensively studied, there have been only a few reports on its use in soil-cement. The strength results of soil-cement on adding fly ash conflict (10, 11, 12, 13). Some of the benefits in concrete, repeatedly documented, are decreased shrinkage, improved workability, and permeability. This investigation, therefore, evaluates fly ash as an additive to soil-cement, with particular reference to shrinkage.

Specimens of soil-cement for shrinkage study were prepared in which one part of the cement was replaced by 2 parts of fly ash. The results show that fly ash reduces shrinkage of soil-cement. Figure 6 shows the reduction in shrinkage of fly ash-treated soil-cement, expressed as a percentage of the untreated soil-cement, in relation to the -2μ clay content in the soil. The data indicate that the effectiveness of fly ash in reducing shrinkage decreases with the clay content. The beneficial effect of fly ash in reducing shrinkage can be due to the fact that fly ash retards the setting-up of the soil-cement. The observed variation of shrinkage with clay content may be expected since sand soils, being coarse, will not react well with cement alone, and a pozzolan such as fly ash is nearly always highly desired. The 7-day compressive strength is reduced by replacing cement with fly ash (Fig. 5). However, the 28-day strength of fly ash-treated soil-cement, with the exception of a few, equals that of the untreated mixtures.

In summary, so far as shrinkage is concerned, fly ash is beneficial in sand and friable soils. Concerning the proportion of fly ash, a good rule of thumb would be to replace one-fourth of the cement by fly ash (1: 2 ratio).

Pozzolith—Pozzolith 8 (sulfonated lignin), one of several basic formulations available, was used in this investigation. It is known to be a water-reducing agent for concrete, which, when added at the normal rate, has a retarding effect on the setting of concrete mixes.

The hypothesis that pozzolith can improve workability of cement-treated soil was substantiated in four soils; K03-06, M07-00, M30-10, and K31-03, where it was observed that with 0.5 percent pozzolith the increase in dry density was 2.0, 2.2, 6.3, and 2.7 pcf and the decrease in optimum moisture was 1.2, 0.6, 0.3, and 2.0 percentage points, respectively. This result is particularly significant in soil-cement in that the shrinkage was found to decrease with a decrease in optimum moisture and an increase in dry density (1).

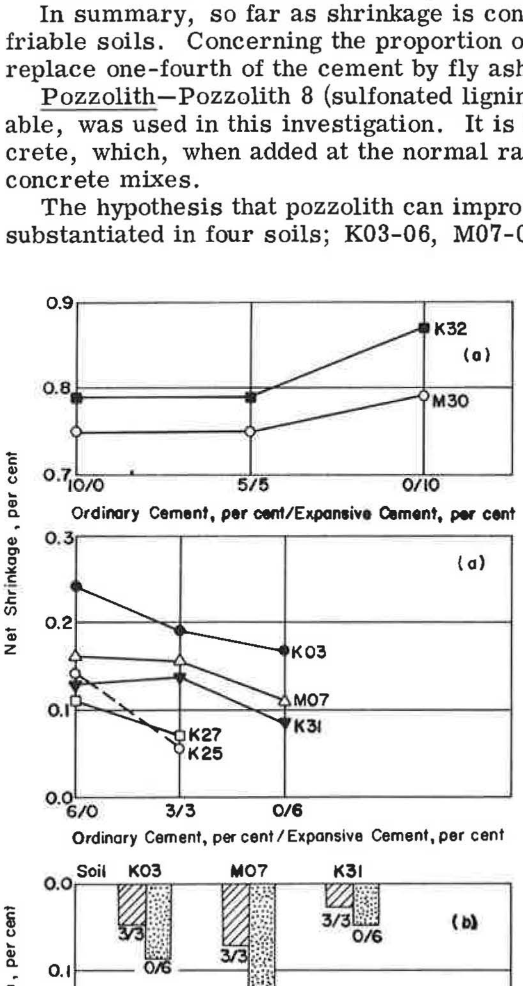

Figure 7. Effect of expansive cement on shrinkage; expansive cement replaced ordinary cement in 1 to 1 ratio. (Net shrinkage denotes that allowance has been made for expansion.) (a) Shrinkage related to content of expansive cement, and (b) expansion during moist curing.

The second phase of the study examined the effect of pozzolith on shrinkage. Making use of the improved moisture-density results, specimens were molded with varying amounts of pozzolith. The results (Table 3) indicate that the net shrinkage was reduced with small percentages of pozzolith. For the four soils studied here, a pozzolith content of 0.20 percent appeared to be optimum. In greater proportions, although the attainable density increased, the overall shrinkage tended to remain the same, except in a few cases where it increased slightly.

With increasing pozzolith content the specimens tended to expand during the first few days of moist curing in 100 percent RH. Similar but even more pronounced expansion was observed with soil-cement treated with expansive cement or sulfates of calcium, sodium, and magnesium.

Expansive Cement—Expansive cement and concretes are relatively new engineering materials. The primary use of expansive cement in concrete is to expand and compensate for the shrinkage that occurs in conventional portland cement concrete as it hardens (14). This cement, known as the "shrinkage-compensated cement," is used as an admixture to soil-cement.

In earlier experiments, a mixture of 25 percent expansive cement and 75 percent portland cement was selected to fabricate soil-cement specimens. The results were not striking, and expansive cement was increased to 50 percent. The results (Fig. 7a) indicate that due to the controlled expansion made possible by the use of expansive cement, the shrinkage was reduced in five out of seven soils (all five were sandy soils).

Furthermore, five of the soils were treated entirely by expansive cement. In sandy soils shrinkage can further be reduced by controlled expansion (Fig. 7a). A higher proportion of expansive cement will cause a larger expansion of the treated soil.

Besides being able to compensate for shrinkage, the mechanical behavior of a continuous base can be significantly modified by the expansion. It is hypothesized that if the ends of a pavement base are restrained, as in a continuous base, while the expansive soil-cement is curing and tending to expand, a compressive stress would be built up within the soil-cement. When allowed to dry, the soil-cement, which would shrink without the prior restraint, would be relieved first of the compressive stress developed during the curing period. In other words, by prestressing the base material, ultimate tensile capacity is increased by the same order of magnitude. According to Eq. 1b for an elastic material, the crack spacing (L) is directly proportional to the tensile strength. Therefore, crack spacing can either be increased, or by increasing the proportion of expansive cement, the shrinkage stress (tensile stress) can be limited to well below the ultimate tensile strength, thereby eliminating most of the shrinkage cracks.

There are two possible drawbacks in using expansive cement in soil-cement construction. First, the cost of treating the soil entirely by expansive cement may be prohibitive. Second, the expansion of the compacted mix takes place immediately after mixing with water, perhaps due to the rapid set of expansive cement; for example, while the specimen from soil K03 expanded 0.0809 percent in 2 hours, approximately 80 percent of this total expansion took place in 1 hour. The expansion shown by the laboratory specimens cannot be realized in the field where there is a time lag of two to three hours between mixing and compacting. What is required, therefore, is an

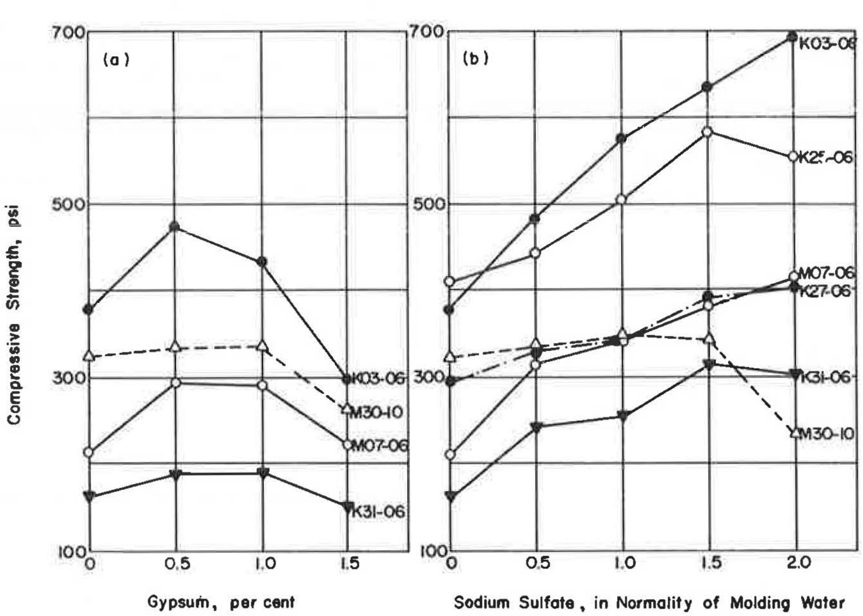

Figure 8. Effect of (a) gypsum and (b) sodium sulfate on compressive strength of soil-cement mixtures.

additive that will react slowly and cause gradual expansion of the base. Sulfates of calcium, sodium, and magnesium were investigated for this purpose.

Sulfates—Effects of sulfates of calcium, sodium, and magnesium in soil-cement have been studied, with conflicting results (15, 16, 17, 18, 19). The objective of this study is to elucidate the effect of sulfates on strength and shrinkage in soil-cement.

Gypsum—Small amounts of gypsum, in proportions up to 1 percent, increased the 7-day soaked strength of cement-stabilized soils (Fig. 8a). In concentrations greater than about 1 percent, however, the strength tended to decrease with gypsum.

The results of shrinkage study appear in Figure 9 and Table 3. The plots below and above the abscissa (Fig. 9) represent the expansion during moist curing and shrinkage on air-drying. Due to the controlled expansion, however, the net shrinkage of soil-cement is slightly decreased with gypsum (Table 3). Far more significant is the fact that the sulfate-treated soil expanded during the 7-day moist curing (Fig. 9), and the expansion increased with the content of gypsum. It can be asserted that gypsum, like expansive cement, would inhibit shrinkage cracking.

Sodium Sulfate—The strength results with sodium sulfate were even more significant, since in the soils tested (with one exception—M30, silty clay) the strengths were substantially improved (about twofold) when the normality of the molding water was increased from 0 to 1.5 (Fig 8b). Stated differently, for the sand soil M07 (optimum moisture = 13.8 percent), 1 normal solution is equivalent to 0.98 percent of salt by dry weight of soil.

The expansions and shrinkages were similar to those observed with gypsum. Again, it was observed that there is an optimum concentration for maximum strength and minimum shrinkage.

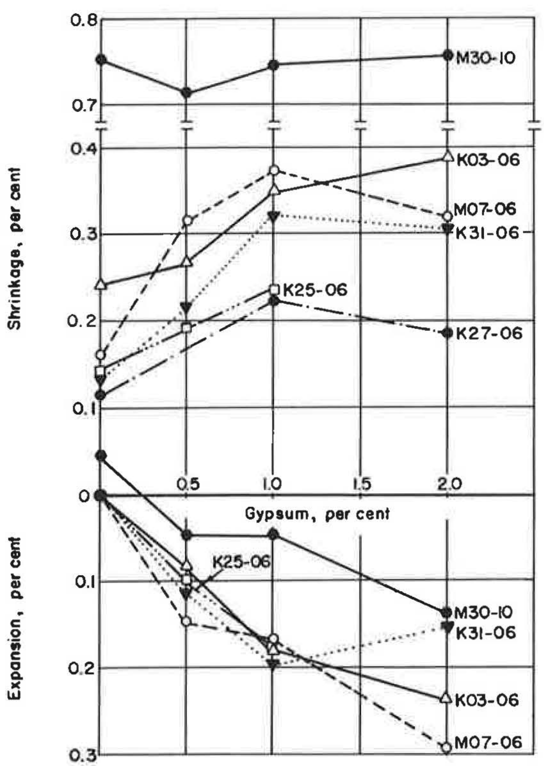

Figure 9. Expansion and shrinkage observed with gypsum.

Magnesium Sulfate—Magnesium sulfate was at least as effective as the other two sulfate salts. For example, when the normality of the molding water was increased from 0 to 2, the initial expansion was slightly increased, and the net shrinkages were significantly reduced (Table 2). This result is in keeping with the finding of Uppal and Kapur (20), who reported that shrinkage decreased with increasing quantities of magnesium sulfate.

Unlike the other two sulfates, magnesium sulfate did not improve the compressive strength. Up to concentration about 1 normal solution, the strengths remain unchanged, and from there onward they gradually decrease with the sulfate content.

Besides being able to reduce the overall shrinkage of the cement base, the expansion has other implications in the performance of the base.

Another benefit is that the cement-treated soil could become much stronger if cementation took place under a compressive force. To substantiate this point, the soaked compressive strength of sodium sulfate-treated (1 normal concentration) cement mixtures of two soils were determined. Respectively, the compressive strengths of soils K03-06 and M07-06, when confined in their respective aluminum molds during

TABLE 3

EFFECT OF ADDITIVES ON SHRINKAGE (%)

Additive Concentration (%)	Soil							
	K03	M07 (2)	K15	K25	K27	K31	M30	K32
Cement, 6	0.2407	0.1614	0.0742	0.1431	0.1124	0.1349		
Cement, 4; lime, 2	0.1520[a]	0.1347	0.0427	0.0889	0.0484	0.0551		
Cement, 5; calcium chloride, 0.5	0.2186	0.2053		0.1724	0.0875	0.1297		
Cement, 4; fly ash, 4	0.1995	0.1502	0.0409	0.0933	0.0898	0.1339		
Cement, 6; pozzolith, 0.2	0.1422	0.1493				0.1129		
Cement, 3; expansive cement, 3	0.1986	0.1609		0.0578	0.0702	0.1435		
Cement, 6; gypsum, 1	0.1725	0.1521		0.0693	0.0712	0.1298		
Cement, 6; normal sodium sulfate, 1	0.1529	0.1675		0.0978	0.0498	0.1590		
Cement, 6; normal magnesium sulfate, 1	0.1529	0.1342				0.1662		
Cement, 6; sodium hydroxide, ½	0.1690	0.1983			0.0631	0.0969		
Cement, 6; SS-K emulsion, 1	0.2710	0.1671				0.1635		
Cement, 10							0.7506	0.7899
Cement, 7; lime, 3							0.5413	0.7359
Cement, 9; calcium chloride, 0.5							0.6132	0.7097
Cement, 8; fly ash, 4							0.6969	0.7902
Cement, 10; pozzolith, 0.2							0.6657	
Cement, 5; expansive cement, 5							0.7581	0.7852
Cement, 10; gypsum, 1							0.7392	
Cement, 10; normal sodium sulfate, 1							0.6897	
Cement, 10; normal magnesium sulfate, 1							0.5893	
Cement, 10; sodium hydroxide, 1							0.9847	
Cement, 10; SS-K emulsion							0.6826	

[a]Shrinkage reduced to 70 percent or less of the control.

the 7-day moist curing, were increased from 380 to 450 psi and from 215 to 305 psi.

In summary, sulfates in small quantities increased the strength of soil-cement and decreased the overall shrinkage. The prestressing of soil-cement bases, as caused by the initial expansion, resulted in increased crack spacing and much higher compressive strength. However, large amounts of sulfates had a detrimental effect on strength and durability of soil-cement mixtures. Tentatively, the sulfate content should not exceed 1 percent, based on the dry weight of soil solids.

Sodium Hydroxide—Shrinkage results with sodium hydroxide indicate that stabilized sand soils (those with kaolinite as the predominant clay mineral) were benefited from approximately 0.5 percent of the alkali compound (Table 3). The shrinkages of both the montmorillonite soil-cements (M07-06, M30-10) were increased with the addition of the sodium compound. It is believed that the relatively high shrinkage of these specimens was primarily from partial conversion of the montmorillonoid component of the soil into the highly swelling sodium form. The strength results reported by Lambe et al (16) and Norling and Packard (18) are somewhat in agreement with this finding. For example, Lambe reported that 1 percent sodium hydroxide significantly increased the strength of a silty loam (7 percent -2μ illite clay), whereas the same concentration was detrimental in a clay (36 percent -2μ montmorillonite clay).

Emulsion—The SS-K grade cationic emulsion was investigated in cement-stabilized soils. Emulsion (1 percent based on the dry weight of soil solids) was dissolved in water before mixing with the dry-mixed soil and cement. Four soils (K03, M07, M30, and K31) were investigated for shrinkage and compressive strength. In three sand soils neither the shrinkage nor the soaked compressive strength was influenced. In silty clay (M30), however, the indication was that shrinkage could be slightly reduced. Another beneficial effect of emulsion may be in the control of the crack width. That is to say, because of the excessive extensibility of emulsion-treated soil, the cracks could be narrower.

In summary, 9 of the 10 additives tested appeared to be beneficial in reducing the shrinkage (Table 3). Emulsion did not appear useful. With those 9 additives, the 7-day soaked compressive strength in some cases was increased and in others it was unchanged or slightly decreased. Insofar as the concentration of materials is concerned, a word of caution is in order, since a few of the additives (specifically, sulfates and pozzolith) were beneficial only at a critical optimum amount. Other levels of concentration, especially those above the critical optimum, may impair effectiveness.

Influence of Soil Texture on Response to Additives—In general, well-graded soils were responsive to practically all the additives. Typical examples were K03, K25, and K27, with very high uniformity coefficient values. M07 and K31, in this order, were less responsive. As expected, the uniformity coefficient values of these soils are the lowest. Interestingly enough, two samples of M07 with different uniformity coefficient values shrank differently, in that shrinkage decreased with increase in uniformity coefficient.

Concerning the texture of the soil, the writer has reported (1) that the shrinkage of sands and sandy soils was probably due to the shrinkage of cement. The results of this study reinforce this hypothesis. For instance, lime, especially fly ash and expansive cement, when added as replacements to cement significantly reduced the shrinkage in sand soils, but not in clay soils.

In conclusion, well-graded soils shrink less and are more susceptible to improvement by trace additives than uniformly graded soils.

CONCLUSIONS

Analytical expressions for both crack spacing and crack width were presented and discussed. Such refinements as creep and theory of failure applicable to cement-stabilized soil have been omitted, because much basic research information on these subjects in not available or is incomplete.

Results show that crack spacing is primarily a function of tensile strength of treated soil. In simple terms, crack width is the subject of two opposing influences. The tendency of the crack width to increase is to some extent compensated by the extensibility of the treated soil. Of all factors, total shrinkage exerts the most influence on cracking of pavements.

A search for treatments to reduce shrinkage, therefore, led to several promising additives. Lime and fly ash proved to be the best. Sulfates of magnesium, sodium, and calcium; and expansive cement (in this order), by virtue of their ability to expand and compensate for the shrinkage, are the second best additives. Pozzolith 8, although less effective than fly ash, improves the workability and thereby enables better compaction, which, in turn, reduces shrinkage. Calcium chloride provides improvement in poorly reacting uniformly graded sands, sodium hydroxide only in kaolinite soils, and emulsion none at all.

So far as the soils in relation to the response to additives are concerned, well-graded soils shrink less and are more susceptible to improvement by trace additives than uniformly graded soils.

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