

USE OF ADDITIVES AND EXPANSIVE CEMENTS FOR SHRINKAGE CRACK CONTROL IN SOIL-CEMENT: A REVIEW

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The mechanisms and factors affecting shrinkage and cracking in soil-cements are reviewed. Secondary additives that have been found to be effective in reducing shrinkage and/or decreasing cracking are reported, with emphasis on the mechanisms involved. The use of expansive cements in concretes and in soils is presented, and other promising additives and approaches are also suggested. Although drying shrinkage is primarily responsible for inducing cracking in soil-cement, shrinkage and cracking nonetheless do not go hand-in-hand with each other. Factors such as geometric and restraint characteristics of the soil-cement layer, tensile properties of the soil-cement, and environmental factors such as mixing, curing, and temperature also control the development of the shrinkage stresses and cracking behavior of the soil-cement. Most of the results reviewed are based on laboratory studies. Because of the diversity of factors present in the field, more field experiments and data are needed before secondary additives and expansive cements can be used with confidence in shrinkage crack control in soil-cement.

•SOIL-CEMENT commonly contracts following construction, and under normal field conditions this shrinkage results in cracks. The extent and effect of such shrinkage cracking have caused increasing concern in recent years. The purpose of this report is to present the state of the art of using secondary additives and expansive cements for reducing shrinkage and cracking in soil-cement.

A review of existing pertinent literature shows that the available information is largely limited to laboratory investigations. Very little information on controlled field experiments concerning the use of secondary additives and expansive cements for reducing shrinkage is available.

Within the limitations of available information, this report describes the factors influencing soil-cement shrinkage and cracking. Effects and mechanisms of secondary additives and properties of expansive cements used in concrete and in soil-cement are presented, with emphasis on the relationships of each treatment method to one or more specific factors affecting shrinkage and cracking in soil-cement.

FACTORS AFFECTING SHRINKAGE AND CRACKING

Major causes of shrinkage in soil-cement are understood to be the loss of water from evaporation, self-desiccation during the hydration of cement, and temperature changes. When contractions resulting from all these shrinkages are partially or fully restrained in the field due to friction and/or material weight, tensile stresses are developed. Cracking is usually a direct result of failure when the developed tensile stresses exceed the tensile strength of the soil-cement material. Cracks due to fatigue and creep under

externally applied stresses such as traffic are different in both the mechanisms and the pattern from cracks resulting from shrinkage and will not be discussed in this paper.

The mechanisms involved in drying shrinkage were first proposed by George (3) to be of three different hypotheses: the capillary tension effects, the surface sorption phenomenon, and lattice shrinkage in clay. Each perhaps operates more prominently within a certain range of humidities. When evaporation first occurs in a fresh soil-cement (high humidity), contraction is mostly due to compressive stresses resulting from surface tension in the capillaries. As evaporation continues (medium humidities), decreases in the thickness of adsorbed water film around the colloidal particles of clay and hydrated cement gels begin to affect contraction. As humidities become fairly low, it was proposed that water in the crystal lattice starts to decrease, which results in lattice shrinkage in clay. [A later study (24), however, showed that lattice shrinkage in clay occurs as soon as evaporation begins.] The rate of evaporation decreases with time, mainly because of increasing bonding energy of the remaining water with decreasing water content and decreasing size of water-filled capillaries. Nevertheless, evaporation of held water is believed to cause much greater shrinkage per gram evaporated, because it results in increased internal tensions in the remaining water.

These hypotheses for drying shrinkage are obviously only partly valid for cohesionless soils that contain very little or no clay content. Nevertheless, evaporation is generally believed to be the major source of shrinkage in both cohesionless and cohesive soils. The changing of free water to crystalline water when cement hydrates, known as intrinsic shrinkage or autogenous volume changes in concrete technology (22), also results in self-desiccation and shrinkage. It was estimated that perhaps 15 to 20 percent of the maximum shrinkage was the result of self-desiccation (3, 7). Finally, thermal shrinkage in soil-cement is believed to be insignificant compared to shrinkage due to drying (4); for example, for a temperature differential of about 30 F, thermal strain is only one-tenth that from the drying-out of a sand-clay.

Factors Affecting Shrinkage

Examination of the factors that influence the behavior of shrinkage in soil-cement yields the following (3, 17):

1. Shrinkage of soil-cement is a function of the cement content, and when plotted it exhibits a minimum at an optimum cement content. Increasing shrinkage of soil-cement with increasing cement content above optimum is presumed to be due to the greater water requirement of the cement to complete hydration. Thus cement hydration results in desiccation and shrinkage, and this shrinkage increases with cement content.
2. The clay content has also been known to increase shrinkage in soil-cement. This is due to the fineness of the particles smaller than 2 microns, which have a large quantity of adsorbed water and hence result in large shrinkage as the water evaporates. It is also possible that the clay content constitutes a matrix that is restrained less by the proportionally fewer particles larger than 2 microns that act as rigid inclusions.
3. The kind of clay present in the soil-cement influences the amount of shrinkage; montmorillonite contributes the most, being the finest of all clay minerals. In addition, evaporation of the inter-layer water in montmorillonite results in decreasing lattice spacing of the clay mineral.
4. Shrinkage increases with molding moisture greater than the Proctor optimum moisture content. The reason is that the high moisture contents make the particles smaller than 2 microns more apt to change from a cardhouse, flocculated structure to an oriented, dispersed one during compaction. When evaporation occurs, the latter structure allows more shrinkage because of its weakly restrained particles. High compactive effort also favors a more dispersed clay structure. Therefore, increasing the compacted density of clayey soils would not necessarily decrease the shrinkage unless the compaction moisture content is reduced.
5. Prolonged moist curing before drying generally slightly decreases the total shrinkage in clayey soils and increases the total shrinkage in soils with less than 12 percent clay. This prolonged curing usually causes a late start in shrinkage but a faster rate after shrinkage has started.

6. Kaolinitic soil-cement shrinks faster than montmorillonitic soil-cement because of large clay particles and hence less adsorbed water.

7. Shrinkage increases with increasing mixing temperature, mainly because of large thermo-contraction when curing takes place at lower ambient temperatures. But it has been known that for untreated soils the strength and stiffness, including density, of soils tested at one temperature but compacted at different temperatures increase with increasing compaction temperature (10). For cement-treated soils, nevertheless, mixing and compacting at high temperatures may cause abnormal early set of cement prior to the completion of compaction and force rapid evaporation of water for compaction and cement hydration. As a result, poor compaction and loss in strength may enhance the susceptibility of the soil-cement to volume change and cracking.

Factors Affecting Cracking

Mechanisms of shrinkage cracking in soil-cement have been subjected to intensive studies by George and others (4, 5, 6, 7, 13, 14, 19). Theories of elasticity, viscoelasticity, and brittle fracture have been applied to predict shrinkage stresses and cracking patterns. Factors such as the amount and rate of shrinkage, geometric characteristics and restraint, development of shrinkage stresses, and tensile strength and viscoelastic properties combine to govern the cracking process in soil-cement; they are summarized in the following paragraphs.

Amount and Rate of Shrinkage—Although total shrinkage generally exerts most influence on cracking of soil-cement, cracking is not necessarily always directly related to total shrinkage because the combined effects of many other factors affect cracking. As was discussed previously, an increase in cement content in a soil above a certain optimum results in increased shrinkage. Model test results, however, show decreased crack intensity due to higher tensile resistance in the soil-cement (5, 7). (The decreased crack intensity implies longer crack spacing and narrower crack width.) Furthermore, prolonged moist curing before drying was said to increase the rate and sometimes the amount of shrinkage, but adequately extended curing has been found to reduce cracking (5, 7). Above all, however, molding moisture and clay content, known to increase shrinkage, still exert more influence on cracking than does any other factor (7).

Crack intensity increases with the shrinkage rate because a high shrinkage rate favors large stresses and low failure strain (5). Evidence is not conclusive enough to relate cracking with early setting (or high rate of hydration) of cement, but early setting and fast strength gains of cement have often been said to be detrimental to cracking (7). It may be true that an abnormal early set, such as "flash" set of cement or improper mixing and curing under high temperatures, results in structurally poor quality soil-cement and enhances cracking. In addition, a high rate of cement hydration may increase the rate of shrinkage due to higher intrinsic shrinkage, but a corresponding gain in the early strength of soil-cement, on the other hand, should offer more resistance to shrinkage stress and cracking.

Shrinkage Stress—Shrinkage stress in a soil-cement slab is not uniform due to the difference in shrinkage strain at different locations and depths. The tensile shrinkage stress is highly localized on the exposed surface and decreases sharply with depth (7, 13). Irrespective of the condition of restraint, this stress attains maximum value during the early stages of drying and is much greater than the tensile strength of soil-cement in normal use; consequently the exposed surface will usually crack first. The inclusion of large aggregates tends to create stress concentrations at the soil-aggregate boundaries and enhances cracking (7).

Geometric Characteristics and Restraint—Theoretically, when drying begins on the exposed surface, tensile stresses due to warping are significantly lower in thick slabs on weak subgrades than in thin slabs on strong subgrades. Model testing has also shown the decrease in crack intensity with increasing slab thickness (7).

Laboratory evidences are not strong in supporting the conclusion that increasing the subgrade friction reduces crack intensity. Nevertheless, it has been observed that mixed-in-place jobs exhibit less cracking than do central-plant jobs (7). The high

subgrade friction in the mixed-in-place jobs is believed to redistribute more uniformly the stress concentrations caused by localized shrinkage and thereby reduces the incidence of cracking.

Tensile Strength and Viscoelastic Properties—The effects of increased tensile strengths in soil-cement have been known to increase crack spacing and decrease crack width, i. e., decrease crack intensity (5, 7). Factors influencing the tensile strength of a soil-cement mixture are in general similar to those influencing the compressive strength, because tensile strengths and strains of soil-cements have been directly related to compressive strengths and strains (15, 16, 26).

Crack intensity has also been known to decrease with decreasing modulus of viscosity (7). Inasmuch as viscosity can be regarded as the property of a solid to resist deformation before stress, low viscosity under tension would imply a material with low tensile modulus of elasticity. Therefore, an ideal soil-cement, as far as resistance to cracking is concerned, should possess high tensile strength and low tensile modulus of elasticity, something like plastics or rubber.

EFFECTS OF SECONDARY ADDITIVES

Investigations into the use of secondary additives for increasing the strength and durability of cement-treated soils have been numerous. The use of secondary additives for reducing shrinkage, however, has been slight, and most of the investigations are limited to laboratory studies only. The following sections summarize the effects and mechanisms of the different secondary additives that have been shown to be effective in reducing shrinkage and/or cracking in soil-cement.

Hygroscopic Additives

Sodium Chloride—Sodium chloride, when used in granular forms and up to 3 percent content, has been found to be effective in reducing shrinkage in montmorillonitic soil-cement mixtures cured under high relative humidity (24). The effectiveness increases with increasing NaCl content and is independent of the gradation of the salt. The addition of 0.5 percent NaCl in solution form was not effective in reducing shrinkage. Strength reductions associated with the addition of NaCl are due only to the coarseness of the additive and not to the amount used. Soil-cement with fine salt added was found to give strength comparable to that of soil-cement specimens without salt.

The reduction of shrinkage in soil-cement with the addition of NaCl was found to be primarily due to the ability of salt to reduce moisture loss in the mixture and to provide a non-shrinking and non-swelling lattice spacing of the montmorillonite clay in the soil-cement. Particle reorientation of the clays during curing was also believed to be responsible for some of the shrinkage and expansion observed.

Calcium Chloride—As little as 0.5 percent calcium chloride, substituted for 1 percent of cement, has been found to reduce the shrinkage in 4 out of 6 soil-cement mixtures tested (4). Although it was stated that the slight increase in dry density and the decrease in optimum moisture content in 2 of the CaCl_2 -treated soil-cements were also responsible for the reduction of shrinkage, it is now believed that, similar to sodium chloride, the hygroscopic properties of the salt in reducing moisture loss were primarily responsible and that the results obtained would have been more significant had slightly more salt been used.

Calcium chloride has been known to accelerate setting of cement in cold weather, although calcium chloride did not improve the soil-cement strength in the aforementioned study, perhaps because of the reduced cement content. Nevertheless, the use of calcium chloride as strength accelerator as well as hygroscopic agent should promise reduced shrinkage and cracking in soil-cement.

Sugar—Sugar has been known to retard the setting of cement in concrete. A recent experiment (7) showed that the addition of 0.375 percent sugar in a soil-cement-lime mixture was slightly more effective in reducing the crack intensity than in the same mixture without sugar but at the expense of great loss in strength; the effect was attributed to the retardation of hydration of the cement and, hence, the reduction of intrinsic shrinkage and shrinkage rate. Nevertheless, it is believed that the hygro-

scopic properties of sugar in preventing rapid moisture loss may have been mostly responsible.

Water-Reducing Additives

The name "water-reducing admixtures" comes from the ability of these additives to reduce the mixing water required in concrete. In their basic formulation, these materials usually retard the set of the concrete, but manufacturers usually modify the basic formulation with accelerators and other additives to change the setting time and other properties, resulting generally in an increase in the strength of the concrete (20).

The leading types of water-reducers in concrete are the lignosulfonates, which are derived from spent sulfite liquor obtained in the acid process of wood pulping. In addition to their water-reducing ability in concrete, the lignosulfonates are excellent dispersing agents, and thus they keep the cement grains from clustering together, thereby promoting more effective hydration. Some wood sugars are known to retard setting of concrete, but most of the sugars are usually removed from the lignin before it is sold as a concrete admixture (20).

George (4) used a sulfonated lignin, commercially known as Pozzolith 8, and found that at an optimum content of 0.2 percent the Pozzolith was effective in reducing shrinkage in 4 soils studied. The reason given was mainly the ability of the lignosulfonates to reduce optimum moisture contents for compaction and to increase the compacted dry density. However, the hygroscopic properties of the sugar content in the sulfonated lignin are believed to have been partly responsible for the results, as evidenced by the tendency of some soil-cements to expand during the first few days of moist curing in 100 percent relative humidity when the pozzolith content was increased. No strength data were given in the study.

Flocculation Agent

Lime has been known to be the best stabilizer for high-clay-content soil by flocculating the clay particles and reducing the adsorbed water on the clay surface. The result is a reduced plasticity and improved workability of the soil. Hence lime has been used in small amounts (2 to 3 percent) in clayey soil-cement to improve the workability of the soil with the same or slightly reduced strength (18). Furthermore, lime, whether in hydrated or quick form, significantly reduced shrinkage and crack intensity in soil-cements when up to 4 percent of the cement was replaced by lime (4, 7). Apparently the flocculation of clay particles and the reduction of adsorbed water on the clay surfaces both are responsible for the reduced shrinkage. Earlier studies (21, 25) have shown that lime is indeed more effective than cement in raising the shrinkage limit of raw clays. A higher shrinkage limit implies that, upon drying, volume contraction of a soil ceases at a higher moisture content.

Reducing Heat of Hydration

Fly ash, a waste product from the burning of coal at power plants, is a very poorly crystalline, amorphous siliceous and aluminous pozzolan, which, when combined with lime liberated from the normal hydration of cement and in the presence of water, forms cementitious compounds. It has often been used in heavy concrete sections, where it may offer economies by saving cement and where it may lower the heat of hydration of cement and help to combat the problem of cracking due to large temperature changes in mass concrete (20).

Fly ash has also been found effective in reducing shrinkage in sandy soil-cement; its effectiveness decreases with increasing clay content (4). The reduced shrinkage is due to the low heat of hydration associated with the slow gain in strength, which decreases the amount of volume contractions from temperature change and intrinsic shrinkage. The fact that type II portland cement has been known to result in less block-cracking in cement-treated bases in California than the type I (28) is probably due to the same effects.

A recommended proportion of fly ash in soil-cement is to replace one-fourth of the cement by fly ash (at 1 part of cement by 2 parts of fly ash). The 28-day strength of the fly ash-treated soil-cement is usually comparable to that of the untreated soil-cement (4).

Surface Sealing and Hardening

Several investigations have been made in the past to study the use of sodium salts as secondary additives to soil-cement. Most of the studies are mainly concerned with the strength characteristics of soil-cement treated with sodium silicates and sodium hydroxide. A recent publication by Hurley and Thornburn (11) reviewed the mechanisms involved in strength production when sodium silicates and hydroxide are used in soil-cement. This article also reviewed the use of sodium silicates as dustproofing and waterproofing agents.

Briefly, various forms of sodium silicates and sodium hydroxide have different strength effects on soil-cements of different textures. The mechanisms are related to the availability of reactive silica in the soil and the rate of generation of the sodium hydroxide. NaOH is more effective in clays, and sodium silicates, especially meta-silicates, are more effective in sands; it is of relatively little importance which sodium compound is employed in silt, insofar as ultimate strength development is concerned. Sodium silicates, on the other hand, were found only moderately effective as a dust-proofer and totally ineffective as a waterproofing protector for untreated base course when the silicate was incorporated with a loess by off-site mixing and placed and compacted to a 3-in. depth. The moderate dustproof characteristics of the sodium silicate-treated surface is believed to be due to the hygroscopic effect of the NaOH generated from the silicate-clay reaction and to the increase in strength of the treated soil. The failure of the silicate-treated surface to waterproof the base might have been due to the sealing action of the silicate, which reduces the rate of evaporation from the base (4).

One other study, as reviewed by Hurley and Thornburn (11), resulted in satisfactory performance of a clayey silt road surface treated to a depth of 1½ in. by penetration with 30 percent solution of sodium silicate. Handy et al. (9) studied sodium silicate treatments for surface hardening of soil-cement. George (7) reported significant reductions in crack intensity for a surface-hardening treatment of soil-cement with 5 percent sodium metasilicate solution sprayed in 2 installments at the rate of 0.3 gal per sq yd. Inasmuch as critical shrinkage stress normally occurs at the exposed surface, the surface-hardening treatment increases the resistance of soil-cement to cracking and, at the same time, provides sealing and hygroscopic effects to minimize drying from evaporation.

NaOH alone was also studied for reducing shrinkage in soil-cement (4). With 0.5 percent addition mixed in soil-cements, the shrinkage of the sandy, kaolinitic soil-cement was reduced, whereas the shrinkage of 2 montmorillonitic soil-cements was increased. The hygroscopic properties of the NaOH are believed to be responsible for the reduction in shrinkage, while the increase in shrinkage was attributed to the conversion of the clay mineral into the highly swelling sodium form.

Expansive Additives

It has long been recognized that concrete made with regular (type I) portland cement will become unsound in a saltwater environment. The unsoundness is attributed to the expansion of the reaction product between the sulfate salts in the seawater and the tricalcium aluminate constituent in the cement. Insofar as shrinkage is concerned, sulfates (gypsum, magnesium, or sodium sulfate), when used in small quantity (less than 1 percent), generally increase the strength of soil-cement and decrease the overall shrinkage in laboratory studies (4).

The expansion of the reaction products between the sulfate and the aluminates, if unrestrained, partially compensates for the shrinkage of soil-cement. When the expansion is restrained, a compressive stress is built up in the soil-cement, which has been found to benefit the strength gain of soil-cement (4). In addition, shrinkage stress developed from drying must first overcome the compressive stress built up by the

restrained expansion before mobilizing the tensile strength of the soil-cement. In other words, cracking resistance is increased due to the restrained expansion; theoretically, it should reduce the cracking intensity of soil-cement, as was noted previously.

Soil-cement test pavements in Rhode Island (27), however, showed that an addition of 1 percent sodium sulfate seems to increase the rate of crack development in predominantly A-4 soil, possibly due to greater early strength gains.

Expansive cements utilizing the expansion of the sulfate-aluminate reactions, different from normal types of portland cements, have been synthesized and marketed commercially. The following section reviews the use of expansive cements for making shrinkage-compensating and self-stressing concretes and for reducing shrinkage in soil-cements.

SOIL-EXPANSIVE CEMENTS

The term "expansive cements" has been customarily used to describe hydraulic cements, similar in character to portland cement, that can be used to make concrete that if unrestrained will increase in apparent volume during hardening but will not become unsound and will develop a strength comparable to that attained by normal types of concrete. This expansive property can be employed to make concrete in which expansion, if restrained, induces compressive stresses. These induced compressive stresses can either approximately offset tensile stresses in the concrete induced by drying shrinkage or are great enough to result in a significant compression in the concrete after drying shrinkage has occurred. The former is usually called shrinkage-compensating concrete and the latter, self-stressing concrete.

Basically, there are two different reactions that have been used to synthesize expansive cements: the sulfoaluminate reaction and the periclase (magnesia) reaction (8). The following sections summarize the properties of each expansive cement and their effects on concrete and soil-cement.

Sulfoaluminate Expansive Cements

Much of the research work in synthesizing expansive cements has been on the basis of sulfoaluminate reaction. The basic principle is to use a mixture of portland cement with a constituent rich in aluminates and gypsum (calcium sulfate). When in contact with water, the aluminates from portland cement react with gypsum to form calcium sulfoaluminate hydrates, which is the compound responsible for expansion. This reaction is basically the same as the uncontrolled reaction that occurs when concrete is in contact with seawater that causes unsoundness of concrete.

Numerous articles and reviews have been published on the properties and uses of different expansive cements and concretes. The most recent and authoritative one is published by Committee 223 of the American Concrete Institute (1), in which three types of the sulfoaluminate expansive cements are named: Type K, developed at the University of California by Klein and commercially produced as ChemComp, is a mixture of portland cement compounds and anhydrous calcium sulfoaluminate plus SO_3 and lime; Type M, developed by Mikhailov in Russia, is a mixture of portland cement, calcium aluminate cement, and gypsum; Type S, developed by the Portland Cement Association, is a portland cement high in tricalcium aluminate and sulfate content. Currently only Type K and Type S are used commercially in the United States, and they are largely restricted to the production of shrinkage-compensating concrete.

Factors Affecting Expansion—Based on the ACI review (1), the factors affecting the rate and amount of expansion may be listed as follows, with minimum explanation:

1. Chemical composition, fineness, amount of expansive material, and aging of the expansive cement are important.
2. At constant cement content and variable slump, expansion increases with increasing water-cement ratio. At variable cement content and constant slump, the expansion level is decreased by increasing water-cement ratio.
3. All expansive cement concrete expands significantly more when cured in water or in a moist room than in an environment that cannot supply water to the concrete; the presence of free water is essential for the development of expansion.

4. Generally, for unrestrained concrete, expansion increases with increasing temperature of the curing environment. For restrained concrete, however, the temperature effects appear to be minimum.

5. Rate of expansion at different parts of a specimen may be different, depending on the size and shape of the specimens. As an average, expansion decreases as size increases.

6. Degree of restraint has a significant influence on measured expansion; expansion of unrestrained concrete can be many times that of restrained concrete. Restraint can be applied by external means or by internal reinforcement.

7. Increasing the time of mixing decreases the expansion of all expansive cements.

8. Lightweight-aggregate concretes, which are usually porous and can store up more water for curing, expand significantly more than equally proportioned and sized normal-weight-aggregate concrete. The effects of aggregate size on expansion are limited but are believed to be insignificant, considering the effects of changing aggregate size on other properties such as workability and strength.

Usually a high expansion rate (60 to 80 percent of the total) in the the first 24 to 36 hours is desirable. For self-stressing concrete, the compressive strength is inversely proportional to the amount of expansion, and the amount of expansion is inversely proportional to the amount of restraint. Thus, within practical limits and everything else being held constant, the greater the restraint, the higher the strength.

Soil-Expansive Cements—Investigations into the use of sulfoaluminate expansive cement in soils have been few and brief (2, 4, 7). All published investigations have been using the Type K (ChemComp) expansive cement. Generally, expansive cement was found more effective in reducing shrinkage and cracking in sandy soils than in clays, and its effectiveness increases with the increasing proportion of expansive cement to normal portland cement in soils. Soil-expansive cement molded 3 percent below the optimum moisture content showed insignificant improvement over the regular soil-cement. Most improvements in preventing shrinkage cracking were observed on specimens molded 3 percent above the optimum moisture.

Very limited experimental results (2) showed no significant effects on cracking by varying the specimen dimensions, methods of curing, and types of restraints of soil-expansive cement. Nevertheless, as reviewed earlier on the use of sulfate salts as secondary additives to induce expansion, George (4) did find increased compressive strength of the soil-cement with restraint, similar to that found in expansive-cement concrete.

Although available data have been rather limited in scope, it is believed that factors affecting rate and amount of shrinkage in soil-expansive cements are rather similar to those of the expansive-cement concretes. More studies are needed.

Magnesia Expansive Cement

Magnesium oxide or magnesia is the ultimate product in the thermal decomposition of numerous magnesium compounds and minerals. It occurs infrequently in nature as the mineral periclase, MgO. The hydration of all grades of magnesium oxide leads to the formation of magnesium hydroxide, and the rate of hydration may vary from a few hours in the case of reactive oxides obtained at low-temperature decomposition of the hydroxide or basic carbonate to months or years for the "dead-burned" grades.

Magnesium oxide is present in small quantities in almost all portland cements because it is often found in nature as magnesium carbonate in association with calcium carbonate. This magnesia does not combine with the acidic oxides present in cement and remains as "free magnesia" in the finished product. The detrimental effects of "free magnesia" in ordinary portland cement have long been recognized. They are derived from the fact that the magnesia is "dead-burned" with cement clinker at 1,900 C during the process of manufacturing the cement. This causes the magnesia to hydrate very slowly, accompanied by an increase in volume. The first sign of this hydration may not show for many years, until it causes the cement to crack and become unsound. For this reason, the specifications for portland cements limit the percentage of magnesia to 5 percent.

The first type of investigation into the development of expanding cements utilizing the conversion of magnesium oxide into magnesium hydroxide, or periclase reaction, was done around 1952 in the U.S.S.R. by Budnikov and Kosyeva. The first account of this mix was presented in 1961 by Slatanoff and Dhabaroff (8). The expansive component was made by calcining dolomite at 800-900 C.

Wang (23) recently attempted to synthesize expansive cement by simply adding magnesia in controlled amounts and reactivities to normal portland cement in order to obtain desired expansions. The expansive component was made by decomposing magnesium hydroxide at different temperatures. Expansion produced by the periclase reaction in concrete was comparable to that produced by the sulfoaluminate expansive cement. As in the sulfoaluminate expansive concrete, presence of free water is also essential to the development of expansion of magnesia. At present, the magnesia expansive cement is still in the development stage.

Limited data from the author's research have shown that magnesium oxides of selected reactivity resulted in net expansion when used as a secondary additive to sand-cement and cement paste specimens cured under water.

SUMMARY AND SUGGESTIONS

The mechanisms and factors affecting shrinkage and cracking in soil-cements were reviewed. Secondary additives that have been found to be effective in reducing shrinkage and/or decreasing cracking were reported, with emphasis on the mechanisms involved. The use of expansive cements in concretes and in soils was also presented.

Although soil-cements are not exactly the same as concrete, this review as well as many other reports have repeatedly pointed out that many factors affecting the behavior of concrete also influence the properties of soil-cement, especially when the use of admixtures and expansive cements is involved. Soil-cement in fact is a more complex material than concrete, but, when an admixture is to be used in soil-cement, a study in the beginning of the effects of the admixture in concrete has, in general, proved to be beneficial.

It should also be remembered that, although drying shrinkage is primarily responsible for inducing cracking in soil-cement, shrinkage and cracking nonetheless do not go hand-in-hand with each other. Factors such as geometric and restraint characteristics of the soil-cement layer, tensile properties of the soil-cement, and environmental factors such as mixing, curing, and temperatures also control the development of the shrinkage stresses and cracking behavior of the soil-cement. An additive that reduces shrinkage and strength of the soil-cement at the same time is not necessarily effective in preventing cracking, just as an additive that increases shrinkage and strength simultaneously is not necessarily undesirable.

Although liquid asphalt has been shown to be ineffective in reducing shrinkage when mixed with soil-cement (4), it is an effective dustproofer and waterproofer (11). It is believed that liquid asphalt, if sprayed on the soil-cement surface, should provide a good seal and reduce evaporation and shrinkage. Many concrete installations have been cured by spray membrane compounds, or even by ponding water in expansive cement concrete. Such curing methods may show promise also in soil-cement; a good curing is just as essential in soil-cement as in concrete.

Insofar as preventing cracking is concerned, an ideal soil-cement should possess high tensile strength and low tensile modulus of elasticity, and the soil-cement should be subjected to a more uniform restraining force (uniform shrinkage stress). Roughing up the subgrade and the use of internal reinforcing such as short fiberglass intermixed with soil-cement, or even steel-wire meshes or straws, should improve the cracking resistance of soil-cement. The use of rubber in soil-cement may be worth trying in view of the beneficial effects the addition of rubber has on asphaltic concrete.

The remarkable improvements in the strength and durability properties of concrete by impregnating the concrete with polymer may have opened a new way of improving soil-cement. Although only one study (12) has been made of the effects of impregnating soil-cement with polymer and the results are inconclusive, additional research in this area should be pursued.

hydroxylated carboxylic acids (usually not sugar) have been used successfully in concrete as water reducers; their use in reducing shrinkage in soil-cement deserves study. Molasses, a waste by-product from the sugar industry, has been successfully used as a dust palliative for soil roads because of its sugar content. Its value in treating soil-cement shrinkage may be investigated. The difficulties in using molasses in soil-cement may lie in the quality control of the additive and the retarding effect of sugar on cement hardening.

There is much to look forward to in soil-cement construction with expansive additives and expansive cements. Generally, the effectiveness of each additive may only be applicable to a specific type of soil under given conditions, and there is an optimum amount for maximum effectiveness. Care should be taken to choose the right amount and type of additive for treatment. Well-graded soils usually appear to be more responsive to improvements by secondary additives.

Most of the results reviewed in this report were based on laboratory studies. Because of the diversity of factors present in the field, laboratory results may or may not be representative of constructed performance. Factors such as methods of application of the secondary additives, accuracy of proportioning, and uniformity of mixing, in addition to other previously mentioned factors, may all be significant in controlling field performance of the treated soil-cement. More field experiments and data are needed before secondary additives and expansive cements can be used with confidence in shrinkage crack control in soil-cement.

REFERENCES

1. American Concrete Institute, Committee 223. Expansive Cement Concretes: Present State of Knowledge. *ACI Jour., Proc.* Vol. 67, 1970, pp. 583-610.
2. Barksdale, R. D., and Vergnolle, R. R. Expansive Cement Stabilization of Bases. *Highway Research Record* 255, 1968, pp. 30-41.
3. George, K. P. Shrinkage Characteristics of Soil-Cement Mixtures. *Highway Research Record* 255, 1968, pp. 42-58.
4. George, K. P. Cracking in Cement-Treated Bases and Means for Minimizing It. *Highway Research Record* 255, 1968, pp. 59-71.
5. George, K. P. Cracking in Pavements Influenced by Viscoelastic Properties of Soil-Cement. *Highway Research Record* 263, 1969, pp. 47-59.
6. George, K. P. Theory of Brittle Fracture Applied to Soil-Cement. *Jour. Soil Mech. and Found. Div., Proc. ASCE*, Vol. 96, May 1970, pp. 991-1010.
7. George, K. P. Shrinkage Cracking of Soil-Cement Base: Theoretical and Model Studies. *Highway Research Record* 351, 1971, pp. 115-133.
8. Halstead, P. E. Expanding and Stressing Cements. In *The Chemistry of Cements* (Taylor, H. F. W., ed.), Vol. 2, Academic Press, New York, 1964.
9. Handy, R. L., Jordan, J. L., Manfre, L. L., and Davidson, D. T. Chemical Treatments for Surface Hardening of Soil-Cement and Soil-Lime-Flyash. *HRB Bull.* 241, 1960, pp. 49-66.
10. Hightler, W. H., Altschaeffl, A. G., and Lovell, C. W., Jr. Low-Temperature Effects on the Compaction and Strength of a Sandy Clay. *Highway Research Record* 304, 1970, pp. 45-51.
11. Hurley, C. H., and Thornburn, T. H. Sodium Silicate Stabilization of Soils: A Review of the Literature. *Highway Research Record* 381, 1972, pp. 46-79.
12. Jones, C. W. Effect of a Polymer on the Properties of Soil-Cement. *Tech. Rept. REC-OCE-70-18*, Bureau of Reclamation, Denver, May 1970.
13. Kawamura, M. Shrinkage Stresses in Concrete as a Viscoelastic Material. *ACI Jour., Proc.* Vol. 66, 1969, pp. 968-971.
14. Kawamura, M. Fundamental Studies on the Fabric of Soil-Cement Mixture and Its Mechanical Properties. D. Eng. dissertation, Kyoto University, Japan, 1970.
15. Kennedy, T. W., Moore, R. K., and Anagnos, J. N. Estimations of Indirect Tensile Strengths for Cement-Treated Materials. *Highway Research Record* 351, 1971, pp. 112-114.

16. Moore, R. K., Kennedy, T. W., and Hudson, W. R. Factors Affecting the Tensile Strength of Cement-Treated Materials. Highway Research Record 315, 1970, pp. 64-80.
17. Nakayama, H., and Handy, R. L. Factors Influencing Shrinkage of Soil-Cement. Highway Research Record 86, 1965, pp. 15-27.
18. Pinto, C. deS., Davidson, D. T., and Laguros, J. G. Effect of Lime on Cement Stabilization of Montmorillonitic Soils. HRB Bull. 353, 1962, pp. 64-83.
19. Pretorius, P. C., and Monismith, C. L. Prediction of Shrinkage Stresses in Pavements Containing Soil-Cement Bases. Highway Research Record 362, 1971, pp. 63-86.
20. Reading, T. J. Admixtures for Concrete. Civil Engineering, March 1966, pp. 52-55.
21. Spangler, M. G., and Patel, O. H. Modification of a Gumbotil by Lime and Portland Cement Admixtures. HRB Proc., Vol. 29, 1949, pp. 561-566.
22. Troxell, G. E., Davis, H. E., and Kelly, J. W. Composition and Properties of Concrete, 2nd Ed. McGraw-Hill, New York, 1968.
23. Wang, J. W. H. Synthesis of Expansive Cements With MgO. To be offered to ASTM for publication, 1973.
24. Wang, J. W. H., and Kremmydas, A. H. Use of Sodium Chloride in Reducing Shrinkage in Montmorillonitic Soil-Cement. Highway Research Record 315, 1970, pp. 81-90.
25. Wang, J. W. H., Mateos, M., and Davidson, D. T. Comparative Effects of Hydraulic, Calclitic and Dolomitic Limes and Cement in Soil Stabilization. Highway Research Record 29, 1963, pp. 42-54.
26. Wang, M. C., and Huston, M. T. Direct-Tensile Stress and Strain of a Cement-Stabilized Soil. Highway Research Record 379, 1972, pp. 19-24.
27. Wang, M. C., Moulthrop, K., and Nacci, V. A. Performance of Soil-Cement Test Pavement in Rhode Island. Highway Research Record 379, 1972, pp. 52-61.
28. Zube, E., Gates, C. G., Shirley, E. C., and Munday, H. A., Jr. Service Performance of Cement-Treated Bases as Used in Composite Pavements. Highway Research Record 291, 1969, pp. 57-69.