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Expansive Cements

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MISCELLANEOUS PAPER C-70-21

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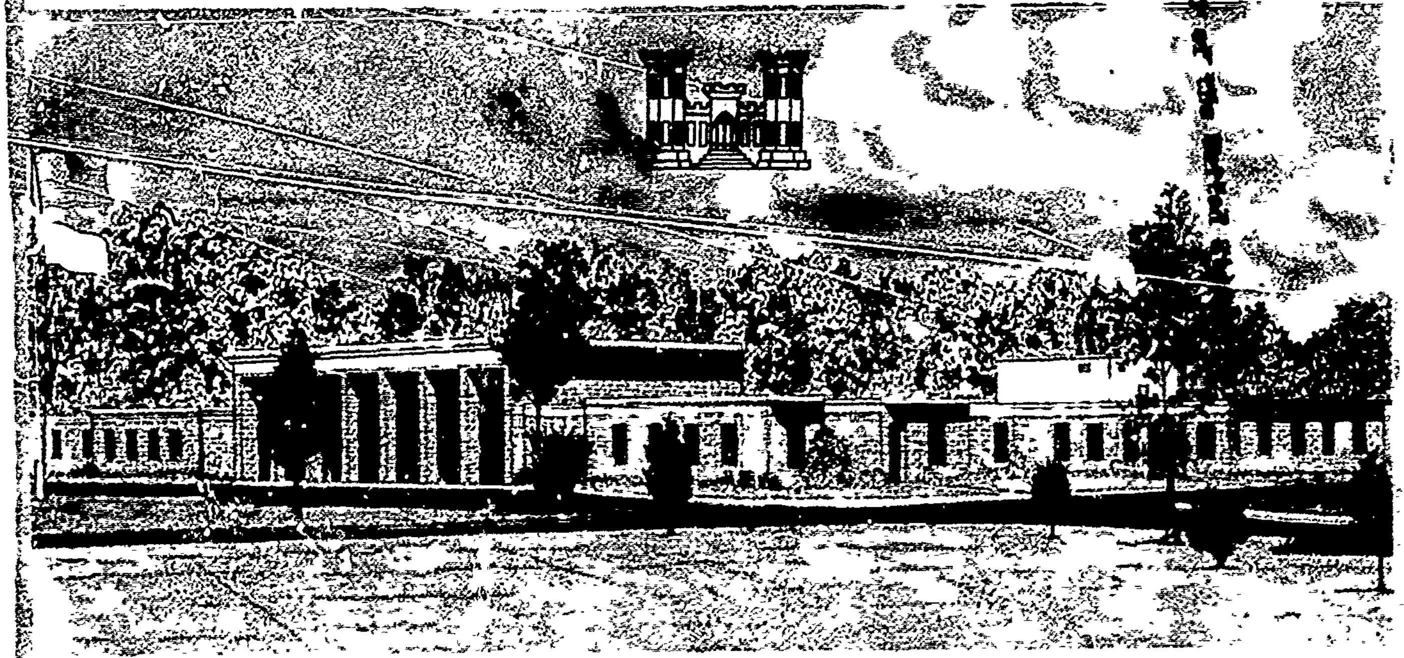
by

B. Mather



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ARMY-MRC VICKSBURG, MISS

FOREWORD

Señor Ignacio Soto, Executive President, Instituto Mexicano del Cemento y Concreto, invited Mr. Bryant Mather to attend and participate in the International Seminar on Control of Quality of Concrete and Construction Techniques in Mexico City in April 1971.

The paper "Expansive Cements" was prepared for that seminar, reviewed and approved for publication by the Office, Chief of Engineers, and has been forwarded to Señor Soto for Translation.

Directors of the Waterways Experiment Station during preparation and approval of this paper were COL Levi A. Brown, CE, and COL Ernest D. Peixotto, CE. Technical Director was Mr. F. R. Brown.

EXPANSIVE CEMENTS*

by

Bryant Mather**

Abstract

Products made with hydraulic cement are generally desirably possessed of the property of volume stability, i.e., after they have once been formed to the desired dimensions, they retain these dimensions. When the dimensions change significantly, the change is usually regarded as a deleterious effect. Cements are now being produced that take some of the same phenomena that are associated with harmful expansions and utilize these, under controlled conditions, to produce beneficial effects. Two kinds of such effects have been most studied. One is to provide a tendency to expand that may compensate for a tendency to shrink. Such cement is designated "shrinkage-compensating expansive cement." The other is to provide a tendency to expand that, when restrained by reinforcing, places that reinforcing in tension. Such cement is designated "self-stressing cement."

The American Concrete Institute glossary (SP-19) defines expansive cement of three types: Type K - one containing anhydrous calcium aluminum

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sulfate ($C_4A_3\bar{S}$)(1) either burned simultaneously with a portland cement or interground with portland cement clinker; Type M - a mixture of portland cement, calcium-aluminate cement, and calcium sulfate; and Type S - a portland cement containing a large computed C_3A content and an excess of calcium sulfate over the usual optimum amount. When hydrated, cements of any of these types contain ettringite, calcium aluminum sulfate hydrate, the same reaction product that is associated with deleterious expansion of concrete due to sulfate attack.

Background

The development of expansive cement concrete can be said to have originated from the investigation of ettringite in cement. Candlot reported in 1890 that this substance was formed from the reaction of tricalcium aluminate (C_3A) with calcium sulfate ($CaSO_4$). Michaelis in 1892 suggested that ettringite was responsible for the destructive expansion of portland-cement concretes in the presence of sulfates in solution.

One of the earliest investigators to recognize the potential of ettringite in the production of an intentionally expansive cement was Henri Lossier in France. His work extended more than 20 years, starting in the mid-1930's and resulted in an expansive cement consisting of portland cement, an expansive component, and blast-furnace slag. The expansive agent was obtained by grinding gypsum, bauxite, and chalk to a slurry and burning the mixture to a clinker. Slag was included to stop the expansion at the desired point. A later study of Lossier's expansive component by Lafuma, showed that it

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(1) See Table 1.

TABLE 1

Formulae for Compounds in Expansive Cements and Concretes

1. Standard Abbreviations

$C = CaO$

$\bar{S} = SO_3$

$S = SiO_2$

$A = Al_2O_3$

$H = H_2O$

$F = Fe_2O_3$

2. Compounds

Calcium Oxide: $CaO = C$

Calcium Hydroxide: $Ca(OH)_2 = CH$

Gypsum: $CaSO_4.2H_2O = C\bar{S}H_2$

Anhydrite: $CaSO_4 = C\bar{S}$

Anhydrous Calcium Sulfoaluminate:

$4CaO.3Al_2O_3.SO_3 = Ca_4Al_6O_{12}SO_4 = C_4A_3\bar{S}$

Calcium Aluminate Trisulfate Hydrate (Ettringite):

$3CaO.Al_2O_3.3CaSO_4.32H_2O = C_3A.3C\bar{S}.32H = C_6A\bar{S}_3H_{32}$

Calcium Aluminate Monosulfate Hydrate:

$3CaO.Al_2O_3.CaSO_4.12H_2O = C_3A.C\bar{S}.12H = C_4A\bar{S}H_{12}$

Tricalcium Aluminate:

$3CaO.Al_2O_3 = C_3A$

Tricalcium Aluminate Hexahydrate:

$3CaO.Al_2O_3.6H_2O = C_3AH_6$

Tetracalcium Aluminate Hydrate:

$4CaO.Al_2O_3.13H_2O = C_4AH_{13}$

consisted of a mixture of calcium sulfate ($C\bar{S}$), a calcium aluminate (C_5A_3), and gamma dicalcium silicate (C_2S). Lafuma concluded that it was not necessary to make an expansive component since ettringite could develop during hydration of a mixture of portland cement and anhydrite or gypsum.

Russian work in the field of expansive cements involved developing both an expansive cement for repairs and waterproofing and a self-stressing cement. Mikhailov's cement for repairs was made by intergrinding high alumina cement, gypsum, and tetracalcium aluminate hydrate. The latter material prepared by hydrating, drying, and grinding a mixture of high alumina cement with lime, accelerated the formation of ettringite. The self-stressing cement was an interground mixture of selected proportions of portland cement, high alumina cement, and gypsum. Expansion of the desired quantity was obtained by control of the gypsum and a rather involved curing process.

Studies by the late Alexander Klein and his associates at the University of California were based on the formation of a stable anhydrous calcium sulfoaluminate compound by heat treating a mixture of bauxite, chalk, and gypsum at about 2400°F. While the ingredients were quite similar to those used by Lossier, the material selection and clinkering conditions contributed to the formation of a distinct compound the nature of which was established by X-ray diffraction. Combined with portland cement, the expansive component consisting of anhydrous calcium sulfoaluminate, calcium sulfate, and lime, produced a cement that could be handled much in the same manner as regular portland cement and adjusted to produce a tendency to expansion of any of a number of different degrees.

Much is yet to be learned about the mechanism and chemistry of expansive cement, but rapid progress is being made. Reviews have been published by Li, Mather, and Aroni-Polivka-Bresler. These documents also include extensive lists of references.

Nomenclature Pertaining to Expansive Cement Concretes
(From ACI SP-19)

1. Expansive cement is a cement which when mixed with water forms a paste that, during and after setting and hardening, increases significantly in volume.
2. Expansive cement, Type K is a mixture of portland cement compounds, anhydrous calcium sulfoaluminate ($C_4A_3\bar{S}$), calcium sulfate($C\bar{S}$) or ($C\bar{S}H_2$) or both, and lime (C). The anhydrous calcium sulfoaluminate is a component of a separately burned clinker that is interground with portland clinker or blended with portland cement or, alternately, it may be formed simultaneously with the portland clinker compounds during the burning process.
3. Expansive cement, Type M is either a mixture of portland cement, calcium aluminate cement, and calcium sulfate; or an interground product made with portland cement clinker, calcium aluminate clinker, and calcium sulfate.
4. Expansive cement, Type S is a portland cement containing a large C_3A content and modified by an excess of calcium sulfate above usual amount found in other portland cements.
5. Expansive cement concrete is a concrete made with Type K, Type M or Type S expansive cement.
6. Shrinkage-compensating concrete is an expansive cement concrete in which expansion, if restrained, induces compressive stresses which approximately offset tensile stresses in the concrete induced by drying shrinkage.

7. Self-stressing concrete is an expansive cement concrete in which expansion, if restrained, induces compressive stresses of a high enough magnitude to result in significant compression in the concrete after drying shrinkage has occurred.

8. Expansive component is the material interground with portland cement clinker to obtain Type K expansive cement. It is made up of the anhydrous calcium sulfoaluminate ($C_4A_3\bar{S}$), calcium sulfate ($C\bar{S}$), and free lime (C) as well as other known portland cement compounds.

9. Ettringite ($C_6A\bar{S}_3H_{32}$) is the phase formed during the hydration of expansive cements which is the source of the expansive force. It is comparable to the natural mineral of the same name. This high sulfate calcium sulfoaluminate is also formed by sulfate attack on mortar and concrete and was designated as "cement bacillus" in older literature.

Current Status of Expansive Cements in U. S. A.

Comprehensive laboratory research programs have been conducted on concrete, mortar, and paste specimens made of expansive cements. Both self-stressing and shrinkage-compensating cements have been investigated and many results have been published. All three types, K, M, and S are now commercially available in the United States. Application has been largely restricted to production of shrinkage-compensating concrete. The reduction in drying shrinkage cracking is due to the tendency of the concrete to expand during the early stages of hydration. This expansion, when restrained, allows stress to develop that compensate for later drying shrinkage stresses.

Shrinkage-compensating concrete is believed by many to hold promise as a more general and practical corrective for shrinkage cracking than heretofore obtained by other means. The production of self-stressing cement has been limited, and field performance of the experimental structures in which it has been used, has not yet been conclusively evaluated. Expansive cements, having greater expansive potential than is characteristic of shrinkage-compensating expansive cements, have been used to provide gas-tight tunnel fillings in connection with underground tests of nuclear devices.

Chemical Reactions

While all the details of the hydration chemistry of expansive cements are not yet fully understood, it is generally recognized that the formation of ettringite, $C_6A\bar{S}_3H_{32}$, is the source of the expansive force common to all three types of expansive cements.

In a sense it may be considered that there are four components, CaO, Al_2O_3, SO_3, and H_2O, that constitute ettringite. The three components other than water may originate from a large variety of reactants. The materials must be either soluble or at least slightly soluble, or form soluble to slightly soluble hydration products. A second requirement is that the solution formed when the mixing water reacts initially with the materials contain concentrations of CaO, SO_3, and Al_2O_3 in sufficient amount for stabilization of ettringite. This second condition is provided as long as SO_3 is available to the solution in amounts equal to, or exceeding, the solubility of ettringite.

Lime, as calcium hydroxide (CH), required for chemical combination originates by hydration of alite (C_3S), belite (C_2S), and hydration of free lime in both the expansive component and portland cement. Calcium sulfate, when present, supplies the CaO associated with the SO_3. The Al_2O_3 is obtained from CA and $C_{12}A_7$ of the calcium aluminate cement, C_3A and C_4AF of the portland cement, and $C_4A_3\bar{S}$ of the type K cement. The SO_3 in practice is supplied either as gypsum or anhydrite, or partially by $C_4A_3\bar{S}$ when the latter is present.

Proportioning of Expansive Constituents

The proportioning of the expansive constituents in the different cements is not based on the amounts represented by the theoretical ratio of $C_6A\bar{S}_3$. The important requirement to be fulfilled in the choice of proportioning the materials is that the CaO, SO_3, and especially the Al_2O_3. become avilable for ettringite formation at the right time. Ettringite starts to form during the mixing and continues to form during subsequent water curing until the SO_3 or Al_2O_3 is exhausted. A major part of ettringite must form after attainment of a certain degree of strength, otherwise the expansive force will dissipate in deformation of a still plastic or semi-plastic concrete and place no stress on the restraint provided. If, on the other hand, the ettringite continues to form rapidly for too long a period of time after the major part of strength has developed through cement hydration, disruptive expansion of the hardened concrete might occur. Most of the expansive reaction of formation of ettringite must therefore cease before development of high strength through hydration has occurred. Experience has shown that some expansive forces may continue to develop over the ettringite formation period without major deleterious effect on strength. This period includes the time of continuing hydration of the cement with substantial strength development. Continuing expansion may cause microcracking in the paste, but such microcracks are being continually sealed with new hydration products, provided sufficient moisture is available.

Some of the SO_3 and some of the Al_2O_3 present combines with the hydrating silicates. The distribution of SO_3 and Al_2O_3 between ettringite and the hydrated calcium silicate requires special care in proportioning. Control is based on securing expansion of desired amounts and at predetermined time by careful control of the proportions of the cement mixture established in laboratory tests.

Mechanism of Expansion

The mechanism of expansion of cement pastes containing $C_4A_3\bar{S}$, CA, or a higher than usual C_3A content is usually attributed to ettringite formation, however, some have attributed it, at least in part, to the formation of calcium aluminate monosulfate. Some workers have proposed that the ettringite crystals form directly on the surfaces of the C_3A grains without the latter entering solution. In normal process of hydration, the residual C_3A grains would be completely surrounded by hydration products and growth of the ettringite crystals formed in such sites would develop expansion stresses. Similar reaction mechanisms could apply to $C_4A_3\bar{S}$ and CA as well.

Chatterji and Jeffery proposed that C_4AH_{13} was an initial product of reaction of C_3A and in subsequent reaction, with $C\bar{S}$ through a solid-liquid reaction, the crystals grew in size and produced expansive stresses. Mikhailov observed presence of calcium aluminate monosulfate ($C_4A\bar{S}H_{12}$) in aqueous mixtures of calcium aluminate cement, gypsum, and lime. He stated that the monosulfate formed initially and its later transformation to ettringite caused expansion in portland cement-calcium aluminate-gypsum pastes.

Heat of Hydration

All types of expansive cement may be expected to have significantly higher heats of hydration at early ages, and slightly higher heats of hydration at later ages, compared to portland cements.

Expansion

The attainment of a predetermined rate and subsequent amount of expansive force is the objective of expansive concretes and is influenced by many factors. A clear distinction should be made between laboratory measured expansion, which depends mainly on the particular expansive cement, and the actual expansion realized, which depends on the conditions of use. The factors which influence expansion are generally the same with expansive cement concretes of the same cement type, regardless of the expansion level.

Expansion characteristics have been shown to be a function of the chemical composition of the particular cement. The oxide compositions of the Type K, M, and S cements are similar to portland cement except for higher Al_2O_3 and SO_3 contents. The rate of expansion appears to be dependent upon the amount of readily hydratable aluminates and proportional to the amount present as long as $CaSO_4$ is still available. For a given aluminate content the length of time that the expansion takes place appears dependent upon the amount of calcium sulfate present. Normal portland cements have different active sulfate-to-aluminate ratios and the blending of different portland cements with expansive ingredients can cause the concrete to have different expansion rates and levels.

The fineness of an expansive cement has a major influence on the expansion characteristics. As the fineness increases with a given sulfate content, the amount of expansion decreases. The increase in fineness accelerates very early formation of ettringite.

Amount of Expansive Material

The amount of expansion is closely related to the amount of expansive material as well as the chemical composition of the cement. With all the cements, the expansion rates and levels are influenced by the proportioning of the ingredients.

The essential expansive ingredients can be proportioned into all types of expansive cements in such a manner that the expansion levels can cover the entire range of expansions.

In Type K and Type S cements, the expansive ingredients are generally preproportioned and the expansion levels are predetermined. The commercially available Type K and Type S shrinkage-compensating cements are proportioned to produce relatively low expansions. The Type K cements contain approximately 10 to 15 percent expansive complexes having from 25 to 50 percent calculated $C_4A_3\overline{S}$. Within the normal range of cement usage in concrete, an increase in expansion can be obtained by increasing the total cement content of the mixture.

Type K self-stressing cements may also be based on a preproportioned ratio of expansive component to portland cement. Laboratory studies have utilized Type K self-stressing cements which contained from 10 to 50 percent expansive complexes. Expansion characteristics of unrestrained specimens are related to the amount of expansive component but not proportionately. The influence of the amount of expansive component on the expansion characteristics of restrained self-stressing concretes is more complex. The amount and direction of the restraint and the amount of expansive component all influence the expansion characteristics. The influence of the amount of expansive component used in self-stressing concretes should be evaluated on the specific type of concrete and specimen to be used.

Water-Cement Ratio

The data generally indicate that the expansion level is increased by decreasing the w/c ratio, however, w/c-ratio manipulations have an influence on the relative proportions of the ingredients in the concrete. Concretes with low w/c ratios contain more expansive ingredients than concretes of equal slump having higher w/c ratios, since they contain approximately the same water content. On the other hand, concretes containing the same cement content may be made with a range of w/c ratios. In this case, the concretes have the same potential for expansion (cement content) except that the more pervious, higher slump, concretes (high w/c ratio) will take up external curing water more readily.

Curing

The necessity of proper curing of portland cement concrete is well established. The requirements for proper curing of expansive cement concretes are even more stringent. With expansive concretes two hydration reactions should be considered. The formation of strength-producing calcium silicate hydrate and expansion-curing ettringite are affected differently by curing temperature and availability of water. Inadequate curing can substantially reduce the expansion level.

Curing procedures may have different effects with the various types of expansive cements. All expansive cement concretes expand significantly more when cured in water or in a moist room than when cured in an environment which cannot supply water to the concrete. The presence of free water is required for development of expansion. Polyethylene-cured Type K and M cement concretes can expand additionally when subsequently water-cured. Reinforced normal weight concretes made with Type K shrinkage-compensating cement and cured in steam at 150 F (66 C) for 15 hours, expand about 80 percent as much as companion water-cured reinforced concrete. Corresponding data show polyethylene-cured reinforced concretes to typically expand about 65 percent as much as companion water-cured reinforced concrete. Data on shrinkage-compensating reinforced lightweight concretes indicate a similar curing-expansion behavior although the response of polyethylene-cured and water-cured lightweight concretes was not too dissimilar.

The improved expansion characteristics of moist-cured and polyethylene-cured lightweight concretes have been attributed to the additional internal curing as provided by the water in the lightweight aggregate. This internal water supply reduces moisture gradients and the resulting differential expansion with its potentially detrimental effects, and has other benefits.

Temperature

For unrestrained self-stressing Type K cement concretes increased expansion was noted with increased temperature of the curing environment; however, restrained self-stressing Type K cement concretes in one case expanded slightly less as the temperature was raised. The concretes required different lengths of moist curing ranging from 12 to 200 days to reach the maximum expansions. For unrestrained shrinkage-compensating Type K cement concrete increased expansion with increased temperature was noted, and a very significant decrease of expansion with low relative humidity. However, the expansion level of some expansive cement concretes is reduced with increased curing temperature. These data are conflicting and limited in scope and future studies are needed.

Size and Shape of Specimen

Measured expansion decreases as the specimen size increases; the exterior can expand at a different rate than the interior of large moist-cured specimens. Limited tests, of uniaxially restrained self-stressing cement concrete specimens, have shown that the larger the size, the greater the gradient and magnitude of local transverse strains, with deterioration of mechanical properties. Internal curing, provided by a porous lightweight aggregate, and triaxial restraint could mitigate these detrimental effects.

Restraint

Restraint of expansion can be applied by external means or by internal reinforcement, and laboratory studies have used both techniques. Most laboratory investigations used uniaxial or biaxial restraint. Only a limited number of tests have been reported with triaxial restraint.

The degree of restraint has a significant influence on measured expansion. Unrestrained expansion of concretes can be many times that of restrained concrete. Self-stressing concretes may require biaxial or triaxial restraint, although some data from uniaxially restrained specimens have shown that the detrimental lateral expansions of self-stressing concretes are lower for lightweight aggregate concretes.

With self-stressing concrete, excessive differential expansion and subsequent warpage can occur with unsymmetrical restraint. Further studies are required.

To induce compressive stresses, shrinkage-compensating concretes must be restrained. Restraint may be provided by internal steel reinforcement, indeterminate forces such as subgrade friction, forms, or adjacent structures. The restraint offered by frictional forces and forms has not yet been determined quantitatively. When internal steel reinforcement is used, the steel is stressed to levels of about 5,000 to 15,000 psi, (nom. 3.5 to 11 kg/mm^2) and the induced compressive stresses in concrete are about 25 to 100 psi (nom. 2 to 7 kg/cm^2). The objective of this type of concrete is the minimization of cracks caused by drying-shrinkage. Laboratory and field studies have attempted to define the type and amount of restraint that is required. Most field installations with shrinkage-compensating concretes have been designed as though conventional concrete were to be used. The usual amount, kind, and position of reinforcement has apparently been sufficient to provide adequate restraint to expansion with shrinkage-compensating concretes.

Mixing Time

Increasing the time of mixing decreases the expansion of all expansive cements. Mixing accelerates formation of ettringite and thereby depletes availability of this hydrate for later expansion. Prolonged mixing also increases the water requirement to maintain constant slump.

Admixtures

The effects of admixtures on expansion have been studied to a limited extent. In one study admixtures reduced the amount of expansion; in another admixtures had little or no effect.

Type and Size of Aggregate

The type and size of the aggregate can influence the rate and amount of the expansion. Structural lightweight aggregate concrete may expand significantly more than equally proportioned and sized normal weight aggregate concrete.

The availability of water contained within certain lightweight aggregates may cause the early-age expansion to be higher than for normal weight aggregates. Concrete with lightweight aggregate has been observed to continue to expand during the early drying stages, resulting in significantly lower drying-shrinkage and losses of self-stress due to drying-shrinkage. Lower drying-shrinkage was also observed when the specimens were moist cured to full expansion for a period of 33 days.

The data regarding the effect of aggregate size on expansions are limited. Indeed the proportioning changes involved to maintain workability and yield with different aggregate sizes, may have more influence than merely changing aggregate size. For example, a decrease in cement content accompanies an increase in aggregate size for a given workability, yield, and water-cement ratio. Such a change in cement content may cause a greater change in expansion characteristics than the change in aggregate size. Future studies dealing with aggregate size are necessary.

Aging of Expansive Cement

The length of storage of all expansive cements after manufacture has an influence on expansion. Aging tends to reduce the unrestrained expansion while restrained expansion characteristics are not reduced to the same extent. The aging is apparently connected with carbonation as well as hydration effects, and in the case of Type K cements to particle disintegration due to hydration of CaO which produces expansive component with a higher surface area. The aging effect is greatly reduced when little or no free CaO is present in the Type K expansive component.

Cements of all three types may be affected by exposure to normal levels of CO_2 and water present in the atmosphere, and the expansion levels may be reduced when exposure to air is allowed.

Shrinkage Compensating Concretes

Workability. The workability of expansive cement concretes is the same as that of portland-cement concrete of equal slump. In general, Type K cement concrete has shown a greater slump loss with time after mixing or during an extended mixing period than has portland-cement concrete. Thus, a higher water-cement ratio is required with Type K cement concrete for a given slump after extended mixing. This additional water does not appear to adversely affect the other properties of Type K cement concrete to the degree that would be expected from experience with similar portland-cement concretes. The reason for this result is thought to be that a substantial portion of the added water becomes associated very early with the expansive compound rather than with the silicate phases. Slump loss of Type M cement concrete appears to be related to the calcium aluminate cement - gypsum ratio employed in a given cement; the lower the ratio the less the slump loss. As a general rule, ratios greater than unity are to be avoided to prevent excessive slump loss. Addition of calcium chloride to Type M cement concrete reduces slump loss by retarding the hydration of aluminate phases, but it also reduces the amount of expansion. Slump loss of Type S cement concrete is similar to portland-cement concrete.

Bleeding. Expansive cement concretes have shown a consistent decrease in, and in some cases a complete absence of, bleed water. In the case of slabs, this allows earlier finishing of the concrete, but it also requires that care be taken to avoid too rapid drying of the surface.

Time of Setting. The time of initial setting of Type K and Type S cement concretes is essentially the same as for Type I portland-cement concrete. Time of initial and final set of Type K and Type S cement concretes can be modified by using admixtures which are effective with portland-cement concrete. Tests of a Type M cement have shown results comparable to Type I portland cement.

Unit Weight and Yield. The specific gravity of portland cement is usually taken at 3.15; this value can be used for Type K and Type S cements with no effect on the unit weight and yield of shrinkage-compensating concrete since tests for the specific gravity of Type K and Type S cements have shown a value of about 3.10.

Strength. Shrinkage-compensating concretes develop compressive, tensile, and flexural strength equivalent in rate and magnitude to Type I or II portland-cement concretes.

Expansion and Shrinkage. Shrinkage of shrinkage-compensating concrete is not a function of expansion; a more expansive concrete may or may not show more shrinkage depending upon the usual parameters such as richness of mixture, water-cement ratio, etc.

Modulus of Elasticity. Static and dynamic determinations of the modulus of elasticity of Type K, Type S, and Type M cement concretes have been made using both natural and lightweight aggregates, and the results were comparable to portland-cement concretes.

Bond Strength. Tests have been made comparing the bond strengths of Type K cement concrete and Type I portland-cement concrete. In one series, 1/4-in. (6.35 mm) smooth rod was pulled out of two-way reinforced test slabs, and in another deformed reinforcing steel was used. In each case the Type K cement concrete developed equal or greater bond strength than the companion portland-cement concrete.

Coefficient of Thermal Expansion. Type K cement concrete has been tested between 40 F and 158 F (4 C and 70 C) and at four intermediate points using 517 lbs of cement/cu yd of concrete (307 kg/m^3). The coefficient determined in this experiment was 5 x 10^{-6} in./in./^{o}F (9 x 10^{-6} cm/cm/^{o}C). This is consistent with the coefficient of a corresponding portland-cement concrete.

Resistance to Freezing and Thawing. Tests with Type K, Type S, and Type M cement concretes in two-way reinforced slab specimens (p = 0.007, 0.009, and 0.018) show their freeze-thaw resistance to be a function of the presence of entrained air. Air contents recommended for expansive cement concretes are the same as are recommended for portland-cement concrete in the same exposure.

Resistance to Sulfate Attack. The resistance of concrete to sulfate attack is generally considered to be influenced by the aluminate content of the cement used. Expansive cements achieve their early age expansions by the reaction of sulfates with various aluminates; the source being different for each type of expansive cement. The rate at which these aluminates react with sulfates in the concrete environment, and the amount of sulfate provided in the cement, determine whether an expansive cement produces sulfate resistant concrete. If the reaction is rapid enough to be complete in a few days, and if sufficient sulfate is provided to convert substantially all of the aluminate source to ettringite, then a sulfate resistant concrete will result.

In one experiment continued for one year, 6-inch biaxially restrained concrete cube specimens were tested. At the end of the test period, all specimens showed only slight attack with minor deterioration of the edges and corners. There were some surface pocks on all cubes. All specimens showed a continuing weight gain during the test. The concrete with a higher cement factor performed slightly better than the leaner concrete, but there were no significant differences between the three cement types. In another test, unrestrained specimens place in an artificial sulfate soil and periodically saturated with sulfate solution, exhibited inferior sulfate resistance. This was probably due to their unrestrained condition, and perhaps to an undersulfated condition in the cement. In a third series of tests, the sulfate resistance of uniaxial restrained expansive cement concretes was significantly less than that of concretes made with Type II and Type V portland cements.

Resistance to Cracking. Shrinkage-compensating concrete is designed to give improved resistance to cracking caused by restrained drying shrinkage. Other mechanisms which cause concrete to crack are still operative in shrinkage-compensating concrete, and standard methods of prevention and control of these cracks still should be incorporated into the design of structures using this concrete.

Poisson's Ratio. Limited and preliminary data indicate little, if any, difference in Poisson's Ratio between portland-cement concrete and shrinkage-compensating concrete.

Abrasion Resistance. Type K cement concrete has been reported to be more resistant to abrasion than is comparison Type I cement concrete.

Effect of Alternate Wetting and Drying. Unrestrained expansive cement concretes have shown excellent stability to alternate cycles of wetting and drying after initially being properly moist or steam cured.

Self-Stressing Concretes

Workability. Most reports of experiments utilizing self-stressing concretes have noted a rapid stiffening of the mixtures, regardless of the type of cement. Anyone working with these cements, particularly at low water-cement ratios, should anticipate a more rapid loss of workability than with portland-cement concrete.

Bleeding. Type K and Type M self-stressing concretes exhibit no bleeding.

Time of Setting. Type K self-stressing concrete mixes exhibit more rapid setting characteristics than those of corresponding portland-cement concrete mixes. The results of one series of tests indicate setting in about 70 percent of the time required by the control. Use of either of three commercial retarding admixtures compensated for this acceleration. The use of the retarders was reported to have had no significant influence on the expansive characteristics of these concretes. Others have reported a slight loss in expansion when set retarders were used.

In manufacturing self-stressed pipe, the Russian literature mentions that shotcreting techniques are used due to the quick setting character of the cement. Tests have shown that set retarders effective with portland cement and Type K cement have no effect on Type M cement. Calcium chloride retards Type M cement, but should not be used in prestressed work.

Tests made with Type M cements containing smaller calcium aluminate cement additions than the Russian cements have shown more normal setting characteristics. It also has been reported that set retarders effective with portland cement are effective with this Type M cement.

Unit Weight and Yield. The specific gravity of Type K self-stressing cement is about 3.0. The difference between this value and 3.15, the usually assumed value for portland cement, is enough that it should be taken into account when calculating weight and yield of a specific concrete mix design.

Compressive Strength. Many investigations have shown that the compressive strength of self-stressing concretes is inversely related to the amount of expansion; the amount of expansion is inversely related to the amount of restraint. Thus, within practical limits and with everything else held constant, the greater the restraint, the higher the strength.

The strength of any self-stressing concrete specimens is a function of its stress history, and this is influenced by the amount and rate of expansion, the amount of restraint, the direction of the restraint, whether it is uniaxial, biaxial, or triaxial, and the direction relative to the restraint in which the strength is determined. In one series of tests, self-stressing concrete subjected to triaxial restraint was shown to have compressive strength up to 25 percent higher than corresponding uniaxially restrained specimens.

Tests were made of 6 by 18-3/4 in. triaxially restrained specimens of Type K cement, and different types of aggregates. With the restraint removed before testing, 28-day strengths of 4020, 4590, and 5600 psi (282, 323, and 394 kg/cm^2) were obtained with expanded shale, river gravel, and crushed granite, respectively. Similar size specimens, made with portland-cement concrete of the same total cement content, and using the same aggregates, has 28-day strengths of 4600, 7480, and 8360 psi (324, 526, and 588 kg/cm^2), respectively. The relative strength (Type K cement/portland cement) of the specimens made with expanded shale, which absorbed greater amounts of water, was significantly higher than that of the other two aggregates. This was attributed partly to the beneficial effects of more uniform internal curing and higher early-age expansion.

High strength, self-stressing concrete can be made when due consideration is given to the many variables involved. Conversely, if due consideration is not given, low strength concrete can result.

Expansion. The expansion potential of an expansive cement concrete depends on the composition of the cement and the particular concrete mix used. The actual expansion achieved with a given mix is a function of the many factors previously discussed. One of the major factors in the performance of self-stressing concretes is the amount of restraint provided.

Tests have shown that stiffness, size, shape, and surface texture of aggregate influence expansion, and in the case of lightweight aggregate, provides an internal source of curing water.

An optimum uniaxial restraint may exist for a given cement and concrete mix design. An optimum may exist for biaxial and triaxial restraint also, but it has not been investigated.

Shrinkage and Creep. Loss of prestress force due to shrinkage and creep must be taken into consideration as in mechanically prestressed applications. Reports on structural elements made with self-stressing Type K cement concrete indicated that the magnitude of stress losses in steel and concrete due to drying shrinkage and creep were about equal to or less than those observed for conventional prestressed concrete. Tests on Type K cement concrete with lightweight aggregate capable of storing water in its pores and thus providing internal curing, showed significant reduction in shrinkage upon drying for 28 days, after periods of both 7-day and 33-day curing.

There are tests on Type K and M cement concretes which indicate that there may be a so-called "pre-creep" mechanism at work in self-stressing concrete which reduces the ultimate creep strain to values considerably less than those of conventional concrete subjected to the same ratio of sustained stress to ultimate stress at the same ages of loading. The reason for this characteristic is postulated to be the application of load to the concrete at early age through the self-stressing mechanism when its ultimate strength is low.

Compressive Modulus of Elasticity. Most properties of self-stressing concretes are found to be related to the amount of restrained expansion and the degree of restraint.

The modulus has been found to increase with age and richness of mixture and to descrease with expansion. This relation is similar to that for compressive strength. A comparison has been made of modulus values for triaxially and uniaxially restrained specimens made with Type K cement and three aggregate types (expanded shale, crushed granite, and river gravel), with the restraint removed just prior to testing. The secant moduli of elasticity, to 0.45 f'_c, were 2.17, 3.29, and 3.46 x 10^6 psi (1.52, 2.32, and 2.43 x 10^5 kg/cm^2) with uniaxial restraint. and 2.59, 4.02, and 4.66 x 10^6 psi (1.82, 2.82, and 3.28 x 10^5 kg/cm^2) for triaxially restrained specimens, made with expanded shale, crushed granite, and river gravel,

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respectively. Thus, triaxial restraint resulted in an increase of modulus between 19 and 35 percent. Corresponding portland cement specimens had still higher moduli of 2.75, 4.90, and 5.47 x 10^6 psi (1.93, 3.44, and 3.85 x 10^5 kg/cm^2), respectively, showing increases of 6 to 22 percent over the triaxial restraint values.

In one set of tests using biaxially restrained specimens containing 1.77 percent steel in each direction, Type K and portland-cement concretes using river gravel as aggregate were compared. At age 31 days the portland-cement concrete had a dynamic modulus of 5.76 x 10^6 psi (4.05 x 10^5 kg/cm^2), and the corresponding Type K cement concrete showed a value of 5.56 x 10^6 psi (3.91 x 10^5 kg/cm^2).

In the same experiment the dynamic modulus of an unrestrained Type K specimen showed a reduction of 56.0 percent when compared to an unrestrained portland cement specimen, which demonstrates the need for restraint to develop the mechanical properties of self-stressing concretes.

Limited tests with Type M and Type S cement concretes show a similar reduction in modulus when compared to portland-cement concrete.

Bond Strength. High bond strength has been reported where adequate lateral restraint was present. This is to be expected, particularly in circumstances where frictional phenomena predominate. Loss of bond has been reported in tests with specimens containing only uniaxial restraint. This was probably due to large, unrestrained transverse expansions.

Resistance to Freezing and Thawing. This is another property related to expansion and amount of restraint. In one series of tests specimens made with air-entrained Type K and Type M cement concretes were tested and compared to Type V portland-cement concrete. The more heavily restrained specimens exhibited greater resistance to freezing and thawing than did specimens with less restraint, but in all cases the Type V portland-cement concrete was superior. The superiority was particularly notable when the internal restraint was low.

Behavior of Expansive Cement Concretes in Structures and Pavements

General. Type K cement has been available commercially since 1963 and the vast majority of structures built utilizing expansive cement concrete have incorporated this type. Type S cement was first made available in 1968 and has since been used in various types of construction. Type M cement became commercially available in the U.S.A. in 1970.

Because of the diversity of factors present in the field it has been difficult to predict actual magnitudes of field expansions and compare the data to previous laboratory results. Several field installations have been instrumented with electrical resistance and mechanical strain gauges, but results have been difficult to correlate. Early installations were evaluated strictly by performance observations. The primary interest was crack reduction compared to that of portland-cement concrete.

Restraint. Reduction in drying shrinkage cracking is based upon the ability of the concrete to compensate by expanding during the early stages of hydration. Storage of the expansive energy by restraint is required to induce compressive forces which will increase the cracking resistance of the structure. Reinforcing steel, forms, or external abutments such as existing floor slabs or footings can provide this restraint during the expansion period. Since a fairly gradual change in slope of curves for expansion vs percent of steel starts at approximately 0.15 percent steel, this has been recommended as minimum, except where structural and temperature requirements are greater.

Aggregates. Lightweight and normal weight aggregates, in both crushed and natural state, have been used in shrinkage-compensating concrete installations. Expanded shale coarse aggregate with a combination of lightweight and normal weight fine aggregate has also been used in many instances. It is known that various aggregates have different shrinkage characteristics in concrete and these affect the final performance of shrinkage-compensating concrete the same as in portland-cement concrete.

Admixtures. Many types of commercial admixtures have been included in various concrete mixtures. The majority of these admixtures have been of the water-reducing retarder type, and have generally been used in normal recommended dosages. During warm weather relatively large dosages have been added to delay initial concrete setting times and continued use in the winter did not create any difficulties with the concrete.

Several structures and highway installations observed after three years of exposure showed no damage due to freezing and thawing except in a few isolated cases where laboratory testing confirmed low air content or where deicing salts were applied before the concrete had cured and aged for one month.

Temperatures. Ambient temperatures at time of concrete placement have ranged from approximately 0°F to 95°F. Few problems other than those expected with ordinary concrete have occurred. Shrinkage-compensating concrete bleeds less than portland-cement concrete, and in warmer weather the tendency toward plastic shrinkage is increased. During the winter months most structural concrete installations have had adequate heating and no problems have been encountered. Where slabs on grade have been placed during the winter months, there have been some problems due to a drop in concrete temperatures. It has been common practice to use 1-2 percent calcium chloride by weight of the cement in mixtures for winter concreting especially on an unheated subgrade.

Range of Application. Expansive cement, Type K, designed to provide adequate expansion to reduce drying shrinkage cracking, has been incorporated in various concrete applications, including reinforced and post-tensioned prestressed structural slabs, slabs on grade, retaining walls, columns, highway pavements, grouting applications, and oil well cementing. A minimum cement content on 517 lb per cu yd (306 kg/m^3) is generally recommended and will provide 0.03 to 0.1 percent uniaxial restrained expansion with 0.16 percent steel in moist-cured specimens. Lower cement factors reduce the expansion below the desired level for successful results.

Curing. Many types of curing procedures have been used with Type K and type S shrinkage-compensating concretes such as water pounding, spray membrane compounds, and polysheets. Spray membrane compounds have proved to be satisfactory and the majority of installations have been cured in this manner.

In cold weather insulating blankets have been used to maintain concrete temperatures for proper strength development.

Consistency and Finishing. The expansive component of Type K cement is water demanding, and ordinarily a higher slump will be required at the ready mix plant to achieve the desired field consistency. About two inches more slump than regular concrete is necessary to provide an equivalent slump when a thirty-minute haul is required. Generally, expansive cement provides finishing qualities superior to regular portland cement. Type S expansive cement concretes have demonstrated similar finishing characteristics.

Concrete made with expansive cement appears to bleed less than ordinary portland-cement concrete, which has been attributed to greater water demand of the expansive component. As a result, the initial stiffening or loss of slump may be greater, but the initial and final Proctor setting times are no more than thirty to sixty minutes less than those of an average Type I portland-cement concrete.

Forms. No additional strength has been provided in form construction for structural shrinkage-compensating concrete. Field experience has indicated that the increase in form pressure due to expansions has not required redesigning of the forms. This observation has been made on the fact that there have been no form collapses in hundreds of field installations.

General Performance. Three items which are as important to the performance of shrinkage-compensating concrete as to regular portland-cement concrete are proper consolidation, finishing, and curing. Improperly consolidated concrete or cold joints formed during placement are weak points where cracking may develop at a later age. Proper finishing and curing of the concrete is extremely important. The concrete should not be allowed to dry rapidly. If maximum expansion is to occur, carefully controlled moist curing is required. All known quality concrete practices should be maintained in placing if results in line with the capability of the product are to be obtained.

Field Performance Summary

Wide variations in performance have been noted where Type K cement has been used on several topping installations, with single and double tees. Cracks in the topping where flanges meet have not been uncommon; however, results in general have been better than those obtained with Type I portland cement.

No specific recommendations have been made as to maximum size of a single placement. With regular concrete a 10,000 sq ft slab on grade or 4000 sq ft of structural slab is average for a day's installation. With Type K expansive cement, however, the smaller the placement the better the chance for a crack-free area. Since sawed joints, construction joints, and shrinkage cracks are all detrimental to long-term performance, no limit on size of placement has been made. For example, two 5000 sq ft areas with a construction joint might be no better than one 10,000 sq ft area even if it cracks in the middle. But, with shrinkage-compensating concrete an excellent possibility exists that no cracks will occur. Some early Type K installations have placements up to 20,000 sq ft and are still crack-free.

It has been observed that slabs with close to a 1:1 ratio of length to width perform better than long, narrow slabs. Very few slabs have been placed at this ratio, however, and ratios of around 1:2 or 1:3 are more common. With a 1:1 ratio, expansion stresses and shrinkage stresses are uniform, assuming equal restraint in both directions.

Laboratory Investigations of Self-Stressing Concretes

General. A number of tests on laboratory-made structural elements of self-stressing concrete were performed at the University of California and have been reported in the literature. These include tests on four pipes, four slabs (two one-way, two two-way), five beams, two frames, two colums, and one hyperbolic paraboloid.

Laboratory and Field Performance of Expansive Cements Outside the United States

Although the original concept of expansive cements was established over 75 years ago, the investigations outside the United States undertaken in the last 30 years have provided significant data for improved concepts and further progress. There have been approximately 100 published papers originating from England, France, Germany, Italy, Japan, Poland, Russia, and Sweden. The works of Lossier in France in the 1930's and 1940's were of particular significance and his cement was perhaps the most widely known expansive cement in foreign usage. During and after World War II, research began simultaneously in numerous other countries. In general the findings of these studies are:

a. Restraint of expansion is important and the physical properties of restrained expansive concretes are better than those of unrestrained expansive concretes.

b. Temperature effects are significant with respect to the expansion characteristics.

c. Water curing was observed to be the most desirable curing technique.

d. Expansive cement concretes can be made impermeable to water.

e. Corrosion of steel reinforcement may be a problem.

f. Front resistance of self-stressing concretes may be poor.

Needed Research and Development

Introduction. There is still a general need for more data on almost every aspect of properties and behavior. In particular, the interactions of the numerous factors affecting the material characteristics need investigation. Though field applications in the United States have been restricted generally so far to Type K and Type S cements, research and development should proceed on all three types, as well as on new improved expansive cements that might be developed in the future.

To this time the commercial use of Type K and Type S cements has been primarily for shrinkage-compensating concrete. In the research work, however, greater emphasis has been placed on self-stressing concrete. Since the success of shrinkage-compensating concrete is judged on its reduction of shrinkage cracks in the field environment, greater emphasis is needed on field related problems. These include problems of placement and early hardening. Also there is a need for a systematic accumulation of data on field variables and performance data, for a better understanding and control of the important factors.

The use of self-stressing concrete presents some special problems. A variety of chemically prestressed elements have been successfully tested in the laboratory. More research and development is needed on some aspects of material properties, the development of suitable design methods, and the selection of best applications for self-stressing concrete. There is a need for full-scale tests and the accumulation of field data.

Another important field of activity is the development of specifications and recommended practices. A multitude of different types and sizes of specimens have been used in the various material investigations, and standard specimens should be developed. This is particularly important for triaxial restraint.

Applications. The research and development needs for applications differ for the two types of concretes, shrinkage-compensating and self-stressing. The required emphasis with shrinkage-compensating concrete is for work related to field performance in the prevention or reduction of cracking. On the other hand, the main needs for self-stressing concrete applications are the development of design techniques, evaluation of the most appropriate structural applications, and full-scale field testing.