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16. ABSTRACT

Although Portland cement concrete in general does not develop an amount of shrinkage on drying that is detrimental to adequate service, there are cases of record in which serviceability has suffered due to an abnormal amount of shrinkage of the hardened concrete. Such distress has occurred in both structures and pavements. One reason why poor performance has resulted is because the acceptability of the work in progress has been based largely on strength tests which bear little relationship to shrinkage.

Many of the factors producing shrinkage of laboratory specimens have been discussed in the literature. These are reviewed and supplemented by original test data. Of the many factors contributing to shrinkage, those that are controllable on the work under typical specifications are of less importance than the characteristics of the constituent materials for which the usual specification requirements provide inadequate protection.

It is shown that a combination of unfavorable conditions and materials can increase shrinkage by four fold, which amount is conducive to poor performance.

The results of laboratory specimens dried under standard conditions are compared to results of field exposure of full size or near full size structures and pavements. It is shown that by proper design of laboratory tests, the performance of job concrete can be predicted with assurance.

The need of specification requirements against high shrinkage produced by cements and aggregates and more restrictive requirements for admixtures is demonstrated.

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DEPARTMENT OF PUBLIC WORKS
DIVISION OF HIGHWAYS

SHRINKAGE OF CONCRETE
COMPARISON OF LABORATORY AND FIELD PERFORMANCE

By

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California Division of Highways

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DRYING SHRINKAGE OF CONCRETE

COMPARISON OF LABORATORY AND FIELD PERFORMANCE

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SYNOPSIS

Although portland cement concrete in general does not develop an amount of shrinkage on drying that is detrimental to adequate service, there are cases of record in which serviceability has suffered due to an abnormal amount of shrinkage of the hardened concrete. Such distress has occurred in both structures and pavements. One reason why poor performance has resulted is because the acceptability of the work in progress has been based largely on strength tests which bear little relationship to shrinkage.

Many of the factors producing shrinkage of laboratory specimens have been discussed in the literature. These are reviewed and supplemented by original test data. Of the many factors contributing to shrinkage, those that are

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controllable on the work under typical specifications are of less importance than the characteristics of the constituent materials for which the usual specification requirements provide inadequate protection.

It is shown that a combination of unfavorable conditions and materials can increase shrinkage by four fold, which amount is conducive to poor performance.

The results of laboratory specimens dried under standard conditions are compared to results of field exposure of full size or near full size structures and pavements. It is shown that by proper design of laboratory tests, the performance of job concrete can be predicted with assurance.

The need of specification requirements against high shrinkage produced by cements and aggregates and more restrictive requirements for admixtures is demonstrated.

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SHRINKAGE OF CONCRETE, COMPARISON OF LABORATORY AND FIELD PERFORMANCE

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Constancy of volume of concrete after it has hardened has long been recognized as essential to satisfactory performance. Early studies, however, have been concerned mainly with provisions to avoid long-time expansion in the presence of moisture rather than shrinkage upon drying. Requirements have been in effect to avoid excessive expansion due to excess amounts of free lime, magnesia, and SO_3 in portland cement, and to chemical reactions between alkalies and certain constituents of aggregates. The presence of sulfates in the surrounding environment has also been recognized as a potential cause of detrimental expansion as has the effect of frequent cycles of freezing and thawing.

On the other hand, the effect of shrinkage due to loss of moisture on drying has not received the amount

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of attention that the subject warrants. One reason for this situation is the emphasis that is placed on strength as a measure of the desirable properties of concrete. Too often the fact has been overlooked by designers and construction engineers that shrinkage bears little relationship to strength. This condition has prevailed despite a statement in the ACI Manual of Concrete Inspection[1] that a principal requirement of hardened concrete is that it should not shrink excessively on drying.

Since in most cases there is little easily recognized adverse effect of shrinkage, many engineers and architects have been prone to disregard it as a factor requiring special attention. Nevertheless, evidence in U.S. literature of unsatisfactory performance dates back as early as 1924[2]. The detrimental effects of shrinkage of concrete in pavements was emphasized by Hveem[3] in 1951. Tremper gave illustrations of unsatisfactry performance of pavements due to excessive shrinkage in a discussion of a paper by Jackson[4] in 1950 and in structures in the author's closure of a paper[5] in 1959.

The subject of shrinkage is now receiving greater attention as evidenced by two articles that have appeared recently in Engineering News-Record[6,7] and by a British report[8] published in 1961.

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Laboratory studies of shrinkage are fairly numerous and they point out the fact that it is influenced by many factors. What is lacking is a thorough investigation of the significance of laboratory test results with respect to performance of concrete in service. There is also a need of perspective as to which factors are of greater adverse affect and which are more readily susceptible of control in a practical manner. This report aims to bring out answers to such questions.

In accordance with the growing custom in the United States, the term "shrinkage" as used in this report, refers to the shortening of hardened concrete, measured on one axis, that results mainly from loss of moisture due to drying. It is recognized that the measured shortening may be the result in part of carbonation also, but in the early stages of drying, the effects of carbonation are believed to be relatively minor. Carbonation shrinkage, as such, is dealt with only incidentally in this report.

Studies of the field performance of concrete as affected by drying as presented herein, relate mainly to exterior exposure and specifically to highway pavements and structures. The distinction is made because certain members in heated or air-conditioned buildings may be expected to reach a more advanced state of dryness than

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does concrete that is exposed entirely to natural outdoor weather. Portions of buildings are subjected to an intermediate degree of exposure. Examples are exterior walls, floor slabs on grade, the lower portions of interior walls and columns, etc.

This report is in two parts. Part I deals with the shrinkage of laboratory made specimens dried under controlled and uniform conditions. Part II deals with the performance of pavements and structures that are subjected to drying under exterior exposure and the relationship between laboratory and field performance. Methods of making laboratory tests for shrinkage to obtain meaningful results in a minimum of elapsed time are discussed.

Test Methods

Original data given in this report are from tests made in the laboratory of the California Division of Highways. In the text, such tests are said to have been made by "California".

Unless otherwise noted, tests for shrinkage of mortar were made on 1:2 graded Ottawa sand mortar having a flow of 100% - 115%. Specimens were 1x1x11-1/4-inch prisms with gage studs giving a gage length of 10 inches.

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Four specimens were made from each batch of mortar. They were removed from the molds at 24 hours and were placed in water at 73.4 ± 3°F to the age of 72 hours, and then were measured for length. They were placed on racks in a drying room maintained at 73.4 ± 2°F, relative humidity 50 ± 4 percent, and air movement to result in evaporation of water from an atmometer at 3 ± 0.5 ml per hour, to the age of 7 days when they were again measured for length. The average change in length during drying expressed as a percentage of 10 inches, is reported as "shrinkage". Further details of the method are given in Test Method No. Calif. 527, a publication of the California Division of Highways.

Unless otherwise noted, tests for shrinkage of concrete were made of 7-sack, 3-1/2-inch slump concrete, using a blend of equal parts of Type II, low-alkali cements from five California mills, and washed aggregates of uncrushed sand and gravel from the American River near Sacramento, after sieving and recombining to a predetermined grading of 1 inch maximum size. Specimens were 3x3x11-1/4-inch prisms with gage studs giving a gage length of 10 inches. Three specimens were made from each batch of concrete. They were removed from the molds at 24 hours and stored in a fog room at 73.4 ± 3°F to the age of 7 days

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when they were measured for length. They were then placed on racks in the drying room described for mortar specimens, to the age of 21 days (14 days of drying), when they were again measured for length. The change in length during drying, expressed as a percentage of 10 inches of at least 7 specimens of 9, is reported as "shrinkage". Further details of the method (specifically written for testing admixtures) is given in Test Method No. Calif. 530, a publication of the California Division of Highways.

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PART I

LABORATORY PERFORMANCE

Composition of Concrete

Tests by the U. S. Bureau of Reclamation[9] show that shrinkage is related primarily to the unit water content of concrete. Variations in slump and in the grading of aggregates affect shrinkage by virtue of their effect on unit water content. Walker and Bloem[10] found that the water requirement increased with decreasing maximum size of aggregate and that shrinkage increased, a finding that was confirmed by Tremper[10], in his discussion of that paper.

Tests by the U. S. Bureau of Reclamation[9] show that an increase in entrained air (up to 5 percent) has virtually no effect on shrinkage if the slump of the concrete is held constant. Keene[11] also found this to be true as did California.

Davis[12] reported that some data show marked increase in shrinkage in richer mixes while other data do not show much change. Carlson[13] found that, when a mixed gravel aggregate was used, the cement factor had

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little effect on shrinkage. On the other hand, he found that rich concretes containing dolomite and granite aggregates (and by inference, possibly all aggregates of high rigidity) shrink more than do corresponding concretes of lower cement factor.

Lyse[14] reported that shrinkage is proportional to the volume of paste, that the quality of paste has little, if any, effect upon shrinkage per unit of paste. His equation states:

$$S = bp \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

Where S = shrinkage

b = a coefficient

p = absolute volume of water plus cement

Pickett[15] found that shrinkage is related to a function of the absolute volume of aggregate, viz:

$$S = b\,(1 - g)^{1.7} \quad \ldots\ldots\ldots\ldots \quad (2)$$

Where b = a coefficient

g = absolute volume of aggregate

In the absence of air (or if air is calculated as part of the paste), $p = 1 - g$. While Lyse's equation

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states that shrinkage is directly proportional to the volume of paste, that of Pickett states that shrinkage is proportional to the 1.7th power of the paste volume.

Lyse apparently took no account of air content, his values for paste evidently being the sums of the absolute volumes of cement and water. Pickett did not report air contents, but he concluded that high air contents due to poor compaction were responsible for those observed shrinkages that were greater than predicted by his equation.

Pickett worked entirely with mortar. Lyse worked with concrete of unreported maximum size of aggregate, but the size was not large because his test specimens were 3x6-inch cylinders.

Tests made by California for effect of cement factor (see Table 1), were made with concrete containing aggregate of 1-inch maximum size. The percentage of fine aggregate was reduced progressively with increasing cement factor in accordance with ACI Standard 613[16].

It is evident by inspection of the data that the volume of paste increased and the volume of aggregate decreased with increasing cement factor, and that shrinkage was not so affected (at least not in the direction indicated by the equations of Lyse and Pickett).

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It will be noted that the volume of water plus air varies but little, and the volume of water alone is nearly as constant. The coefficient of variation in shrinkage from the mean value, due to changes in cement factor, is 6.7 percent. The data, therefore, appear to indicate that with the aggregate used, in the range of practical concrete mixes, the cement factor has no effect on shrinkage. Since the unit water content is nearly constant, the data are in agreement with the statement made in the Concrete Manual of the U. S. Bureau of Reclamation that shrinkage is governed mainly by unit water content.

California made tests of graded Ottawa sand mortar in the proportions of 1:3, 1:2-1/2, 1:2, 1:1-1/2 (see Table 2). Corresponding cement factors were 8.0, 9.3, 11.2, and 13.5 sacks per cubic yard. It is evident by inspection of the data, that the trends are similar to those found for concrete mixtures. The volume of the paste increased, and the volume of the sand decreased with increasing cement factor. While the shrinkage of the 1:1-1/2 mortar is slightly higher, that of the remaining mortars is essentially constant.

Coefficients of variation from the mean of the four mixtures are as follows:

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Unit volume of water	2.3%
Unit volume of water plus air	1.7%
Shrinkage, dried 4 days	5.9%
Shrinkage, dried 7 days	3.2%

Although an analysis of variance shows the effect of cement factor to be significant with respect to shrinkage, this finding is due to the relatively high shrinkage found in the 1:1-1/2 mix. It seems more logical to conclude that shrinkage is related to the unit volume of water or water plus air within customary mortar mixtures, and that because these values are constant, the shrinkage is also constant. This conclusion agrees with that derived from the California tests of concrete.

Cement

Carlson[13] found difficulty in measuring the shrinkage of neat cement paste because cracking developed and obscured the over-all change in length. He estimated that cement paste, if unrestrained, would shrink from 5 to 15 times as much as does concrete.

Carlson found that among the potential compounds in portland cement, their relative contribution to

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shrinkage in increasing order is C_3S, C_2S, and C_3A.

Carlson[13] found that an increase in specific surface of the cement increases shrinkage, but that fineness has less effect on cements that are very low in C_3A.

Swayze[19] reported shrinkage tests of concrete specimens containing 40 cements. After drying for 25 days, the shrinkage of one cement exceeded that of another by 68 percent. The average shrinkage of the group of 10 cements having the highest shrinkage exceeded that of the group of 10 cements having the lowest shrinkage by 25 percent.

Lyse[14] found that Type III cements give higher shrinkage than Type I cements in lean concrete (W/C = 1.00), but that in a rich concrete (W/C = 0.50), the difference in shrinkage is small.

California found that the average shrinkage of the Type I cements that were investigated was 119 percent of that of Type II cement, the determination being made on 1x1x10-inch specimens of 1:2 graded Ottawa sand mortar that were dried for 4 days following 3 days of water curing. Among Type III cements from 7 mills, similarly tested, the range in shrinkage was from 0.045 percent to 0.083 percent, and the average value was 0.065 percent. Only one Type III cement gave a shrinkage lower than 0.048 percent, which is the maximum under California Division

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of Highways' specifications for Type II, low-alkali cement.

Lerch[17] demonstrated that the proportion of gypsum in the cement has a major effect on shrinkage and that when the SO_3 is in optimum amount for a particular cement, the shrinkage is the lowest.

A report by the Working Committee on SO_3 Content of ASTM Committee C-1[18] shows that of 8 cements, each containing SO_3 at approximate optimum, the shrinkage of one exceeded that of another by 67 percent. Higher shrinkage was found in cements of higher potential C_3A and alkalies.

Haskell[20] has shown by statistical analysis that the optimum percentage of SO_3 is closely related linearly to the specific surface and the percentages of alkalies and tricalcium aluminate.

Pickett[21] concluded that the percentage of SO_3 for minimum shrinkage in concrete may be greater than that in mortar. California found that for a Type II, low-alkali cement to which additions of pulverized gypsum were made, the percentage of SO_3 for minimum shrinkage of 6-sack concrete was about 0.5 percent greater than for minimum shrinkage of 1:2 graded Ottawa sand mortar (Table 3).

Pickett[22] found that under the conditions of test, the addition of alkali hydroxide to cement decreased the

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rate of shrinkage of concrete. He concluded however, that since many factors affect the rate of shrinkage, and alkalies have many other effects which may affect shrinkage indirectly, one should expect many real and apparent contradictions to his finding that an increase in alkalies retards shrinkage.

Pickett[22] concluded that the addition of gypsum up to the optimum reduces shrinkage by reducing the specific surface of the gel that is formed.

Pickett[22] found that cements that are high in alkali have a lower coefficient of shrinkage diffusivity, and that the lower coefficient produces higher shrinkage stresses and hence, a greater tendency to crack.

The effect on shrinkage of processing additions used in the manufacture of portland cement is controlled under ASTM Designation: C 465-62 T by a requirement that the shrinkage (expressed as a percentage), of mortar made with the cement containing the addition shall not be more than 0.020 greater than that developed by the cement without the addition after drying for 7 days, 28 days and 3 months. Length change measurements are made on 2x2x10-in. specimens of 1:2 concrete sand mortar. Such specimens normally shrink about 0.04 percent in 7 days and therefore, the permissible increase in shrinkage amounts to about 50

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percent at this test age.

California has determined the effect of the addition TDA, used as an admixture, on the shrinkage of a Type II, low-alkali cement as influenced by its content of SO_3. The cement as received contained 1.0 percent SO_3. Pulverized gypsum was added in amounts to increase the SO_3 contents progressively in increments of 0.5 percent up to 3.0 percent. Test specimens consisted of 1x1x10-in. prisms of 1:2 graded Ottawa sand mortar that were cured wet for 3 days and then dried for 4 and 11 days. The test results are shown in Figure 1. It will be noted that the increase in shrinkage produced by TDA was considerably less when the SO_3 content of the cement exceeded optimum.

An analysis of variance applied to the data of Figure 1 indicates that a reaction occurred between the TDA and the SO_3. Triethanolamine is a constituent of TDA. In the discussion of admixtures to be presented later, it will be shown that the effect of variations in the amount of triethanolamine on the shrinkage of concrete is not proportional to the effect on mortar. It will be shown that a similar situation holds with calcium chloride, which is known to react chemically with constituents of cement. These results indicate that tests for the effect of processing additions that react with cement when made upon mortar,

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as provided in ASTM Designation: C 465-62 T, are likely to be misleading as a measure of the shrinkage produced in concrete.

Aggregates

Carlson[13] studied the effect of different aggregate types on their contribution to shrinkage of concrete. He found that sandstone and slate produce high shrinkage. Among the pure mineral aggregates that were tested, hornblende and pyroxene produced the highest shrinkage. Quartz, feldspar, dolomite and calcite produced low shrinkage.

Carlson[13] concluded that the relative compressibility of aggregate particles appears to be the most important factor causing different aggregates to produce concrete of different shrinkage although in a previous paper[24], he discounted the effect of aggregate compressibility. He believed that surface characteristics of aggregates and their ability to entrain air voids at the surface of the particles was of importance. He concluded that there remains to be determined, the particular properties of aggregates that are conducive to tight bond with cement paste.

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Carlson[13] found that among four aggregates, there was a close correlation between absorption of the aggregate and shrinkage of the concrete.

Hveem and Tremper[25] found in tests of sands that higher absorption produced higher shrinkage of mortar, and that the correlation was exceptionally high. Exceptions consisted of expanded shale aggregates and sands consisting mainly of vesicular basalt.

Hveem and Tremper[25] found that the content of clay-like particles in sands, as determined by the sand equivalent test, is an important factor contributing to shrinkage. Mortar containing sand of 70 sand equivalent was found to shrink twice as much as one made with sand of 95 sand equivalent. When the effects of sand equivalent and absorption were considered together, the correlation was found to be significant at the 0.1 percent level. They also found that the presence of clay-like particles in coarse aggregate increase the drying shrinkage of concrete. The contribution of clay-like particles to shrinkage was found to be in excess of that expected purely by an increase in unit water content.

California has determined the shrinkage of concrete containing a variety of sand and gravel aggregates produced in the State. Table 4 lists the tested aggregates

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in ascending order of shrinkage. The tests were made on aggregates of the same grading that were comparably free from clay-like particles. Differences in shrinkage cannot be accounted for solely by differences in absorption or percentage of wear in the Los Angeles Abrasion machine. Expanded shale aggregates (produced in California), not included in Table 4, produced relatively low shrinkage. It thus appears that there are properties of aggregates that are not measured in the commonly made tests that have a large effect on concrete shrinkage.

Roper[26] investigated the volume changes of mortars and concretes containing certain aggregates from southern Africa that had a poor service record. He found that the aggregates that produced high shrinkage in mortar or concrete were themselves dimensionally unstable when dried and subsequently wetted. He notes that many rocks being used as concrete aggregate in the United States evidence dimensional instability, a few of serious degree.

Admixtures

Many powdered admixtures require an increase in the unit water content of concrete and for this reason,

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may be expected to increase shrinkage.[23]

As noted under "Composition of Concrete", the air entrained by air-entraining admixtures has virtually no effect on shrinkage.

The effect on shrinkage of members of the class known as chemical admixtures is varied and cannot be correlated with a possible reduction in unit water content, which often is substantial in amount. Many, but not all, chemical admixtures of the set-retarding type reduce shrinkage or increase it only slightly (not more than about 10 to 20 percent). See Table 5. On the other hand, some set-retarding admixtures and most lignin base admixtures that have been treated to destroy set-retarding properties, when used at the manufacturer's recommended dosage, produce substantial increases in shrinkage, up to 60 percent when measured in concrete specimens dried for 14 days. (The relative effect after longer periods of drying will be discussed later.)

Two compounds frequently used to destroy the set-retarding effect of chemical admixtures and increase the rate of strength development, are calcium chloride and triethanolamine. California test results for the effect of these admixtures are shown in Tables 6 and 7, and Figures 2 and 4. The effect on shrinkage is disproportionately large with small amounts of these admixtures, thus

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demonstrating that their inclusion in other types of admixtures can seriously increase drying shrinkage even though used in relatively small amounts as a percentage of the cement.

Figures 3 and 5 show that the effect of calcium chloride and triethanolamine on the shrinkage of concrete is not directly proportional to the effect on the shrinkage of mortar.

There is evidence that many chemical admixtures react with the cement, thus forming compounds that are not otherwise present. This is a probable reason that many of them increase shrinkage while also reducing the unit water content.

Duration of Moist Curing

Carlson[13] reported that the duration of preliminary moist curing does not have much effect on shrinkage. Lyse[14] found that increasing periods of moist curing up to 7 days increased shrinkage, but that further curing up to 28 days had no additional effect. Keene[11] reported that the shrinkage of concrete cured in moist air for 7 days is greater than that of concrete that is allowed to

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dry immediately. California (Table 8 and Figure 6) found substantially constant shrinkage in concrete that was moist cured for 7, 14 and 28 days before drying was started. In graded Ottawa sand mortars of varying richness (Table 2), specimens cured wet for 3 and 7 days developed equal amounts of shrinkage but shrank slightly less than those cured wet for only 2 days. An analysis of variance shows the difference between 2 and 3 days of curing to be highly significant.

Powers[27] states that from fundamental considerations there is reason to believe that prolonging the curing period should increase the amount of shrinkage of cement paste. He states that the effect of curing of concrete may be expected to be more complicated, that prolonged curing makes paste more prone to crack when severely restrained. If cracking of paste relieves stresses around aggregate particles, the over-all shrinkage may thereby be diminished.

It appears that, given a period of moist curing adequate to develop reasonable strength, additional moist curing is relatively unimportant in the control of shrinkage.

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Length of Drying Period

All tests made by California show that under uniform drying conditions, shrinkage is proportional to the logarithm of time of drying up to the age at which the concrete approaches moisture equilibrium with the environment. Further shrinkage at later ages is believed to be due to carbonation.

For specimens 3x3-in. in section dried under California standard laboratory conditions*, shrinkage due to drying appears to stop after about 32 weeks. Figures 6, 7 and 8 illustrate the relationship of shrinkage to period of drying.

Combined Effect of Unfavorable Factors

Powers[27] pointed out that the cumulative effect of individual factors that increase drying shrinkage can be very large. His calculations were made on the assumption that the combined effect is the product of

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*Temperature 73.4 ± 3°F, relative humidity 50 ± 4 percent, evaporation from atmometer 3 ± 0.5 ml per hour.

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the individual effects and is, therefore, much greater than if they were simply additive. Although the assumption is logical, Powers offered no data to support it.

California has obtained data that support the theory that the cumulative effect is the product, not the sum, of individual effects. See Table 9. The data show the shrinkage produced by two aggregates each used with and without a chemical admixture. The data are used to compute the shrinkage for aggregate B with the admixture, first on the assumption that the effects are additive (Item 4) and second, that they are factors to be multiplied together (Item 7). Item 8 shows the results as measured. It will be noted that simple addition consistently underestimates the shrinkage, whereas multiplication yields a close estimate of the observed shrinkage.

The effect of characteristics of materials has been discussed in preceding sections. In addition, there are several construction practices that can increase shrinkage by reason of an increase in water demand. From Figure 7 of USBR Concrete Manual[9], assuming a cement factor of 6 sacks per cubic yard, it is estimated that an increase of 50 pounds of water per cubic yard increases shrinkage 160 millionths, or 30 percent. Using this basis

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the following possible increases in shrinkage are indicated.

Temperature. Figure 99 of the USBR Concrete Manual[9] shows that 13 pounds per cubic yard of additional mixing water are required for a 20°F increase in temperature of concrete as it is mixed. The equivalent increase in shrinkage is 8 percent.

Slump. Table 3 of ACI Standard 613[16] indicates that the use of a slump of 6-7 inches requires 17 pounds per cubic yard more water than does a slump of 3-4 inches. The equivalent increase in shrinkage is 10 percent.

Maximum Size of Aggregate. Table 3 of ACI Standard 613[16] indicates that the use of 3/4-inch aggregate requires 42 pounds per cubic yard more water than does 1-1/2-inch aggregate. The equivalent increase in shrinkage is 25 percent.

Time of Mixing or Agitation. After satisfactory mixing has been achieved, additional mixing, or prolonged agitation produces additional aggregate fines and increases temperature of the concrete. Both effects tend to increase the water demand for a given slump. The specific increase is a variable depending on characteristics of the aggregates and other factors. For an unnecessary delay of 30 minutes in discharging from a

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transit mixer, a reasonable assumption is that the water demand may be increased by about 15 pounds per cubic yard which is equivalent to a 10 percent increase in shrinkage.

In Table 10, the cumulative effect on shrinkage of eight individual factors is computed as the product of the individual effects. Justification for the use of the values assigned to each factor has been discussed above, and they are believed to be conservative. The table indicates that a four-fold increase in shrinkage is a distinct possibility in many projects. The first four listed factors are those that are subject to job control under most specifications. It is to be noted that the combined effect of the four departures from the best practice is an increase of 64 percent in shrinkage. Although important in many types of work, this increase in shrinkage is but a small part of that that may result from a poor selection of the constituent materials of the concrete.

Discussion of Laboratory Studies

Although methods employed by different investigators varied considerably, in general, mortar specimens were prisms of 1x1-in. to 2x2-in. in section. Concrete

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specimens have ranged from 3 inches in diameter to 4x5-in. in section with occasional tests on larger specimens. Drying has been accomplished at room temperature or in an atmosphere controlled at about 73°F and 50% relative humidity. Except for California, no laboratory appears to have given consideration to the effect of air movement on the rate of evaporation of water from concrete.

Few, if any, have questioned that a prism of concrete 4 inches square provides a significant index of shrinkage. A number have used specimens 3 inches square or 3 inches in diameter. Some have questioned the significance of specimens containing mortar only in evaluating shrinkage of concrete even though the variables under study do not include coarse aggregate.

California compared the shrinkage of eight Type II, low-alkali cements in mortar and concrete with results as summarized in Table 11. It was found that the shrinkage of the concrete could be predicted from the mortar test result, using a linear equation represented by a curve passing through the origin, with a standard error of estimate of less than 10 percent. Data that were available from two other laboratories, involving cements of other types also, indicated similar precision of prediction. The equations were of the form of:

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$$Y = bX \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

Where b varies with the time of drying concrete

On the other hand, California found that the concrete to mortar relationship cannot be expressed satisfactorily by equation (3) if additions or admixtures that react chemically with the cement are used. For calcium chloride, the equation although linear, is of the form:

$$Y = bX + a \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

in which the value of a is of considerable magnitude. (See Figure 3.) For triethanolamine, a curvilinear relationship was found between the shrinkage of concrete and that of mortar. (See Figure 5.) It appears therefore, that mortar tests are satisfactory for comparing the shrinkage of cements unless they have been interground with reactive additions. When cements contain reactive additions or when admixtures are used, shrinkage should be determined by means of tests of concrete rather than mortar unless the concrete to mortar relationship has been established by prior tests for each addition or admixture.

Objections have been raised to the use by California of Test Method No. Calif. 530 for determining the effect

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of admixtures on shrinkage (see section on Test Methods for description of the method). One objection is that the expression of the effect on shrinkage in terms of a percentage of the control concrete (without the admixture) is not realistic because of the small base values involved and that the use of absolute numerical differences in shrinkage is preferable.

The following test data are presented in answer to this objection.

Table 9 shows that the numerical difference in shrinkage for a given admixture can vary widely depending on the characteristics of the aggregates used in the test concrete. On the other hand, if the performance of the admixture is expressed as a percentage relative to the control concrete, the rating is essentially constant regardless of the aggregate used in the test concrete.

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PART II

FIELD PERFORMANCE

Carlson[28] and later Pickett[29] calculated the effect of size of member or test specimen on the rate of shrinkage by means of a coefficient of shrinkage diffusivity in a manner analogous to that used in studies of heat flow. Carlson concluded that in large masses moisture is fed toward the surface from the underlying concrete so as to prevent or delay substantial shrinkage except near the exposed surface, and that under ordinary climatic conditions, the average shrinkage of structural members one foot or more in thickness probably never would approach that of small bars.

Keeton[30] found a curvilinear relationship between the surface to volume ratio of specimens of varying size and the amount of shrinkage at any time. California (Figure 7) found that the relationship presumably is linear. It thus appears that size of test specimen *per se* is of little practical importance, and that equal values of shrinkage can be obtained from different sizes of specimen if drying times are suitably varied.

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Long periods of drying introduce the hazard of variations in test conditions. This suggests that the specimen should be of the smallest cross-section that is suitable for the maximum size of aggregate involved in the concrete.

An objection has been raised to the use by California of Test Method No. Calif. 530 for determining the effect of admixtures on shrinkage on the ground that a drying period of only 14 days is too short to establish relationships that are significant in terms of long-time field performance. Answers to the objection are provided by the following experiment and by results to be described later under "Pavement Performance Related to Shrinkage."

California investigated the effect of a chemical admixture on shrinkage of 14x20x48-in. beams that were exposed out-of-doors at Sacramento. The admixture under study was the same as that of Table 9. It was tested with a third aggregate also in accordance with Test Method No. Calif. 530, and was found to produce a relative shrinkage of 144 percent. The average increase in shrinkage at 14 days as determined by the use of three aggregates is 40 percent. Outside exposure of the beams was started in August 1960. Shrinkage took place for 2

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months after which the beams began to lengthen. Shrinkage resumed in the early spring and continued until November of that year. Table 12 gives the relative increase in drying shrinkage due to the admixture at intervals of 4 weeks. During the last half year of exposure, the admixture caused an average increase of 32 percent. The increase is somewhat less than 40 percent as found by the laboratory tests on bars. It should not be inferred however, that a test drying period of 14 days does not afford a realistic measure of the effect of admixtures. It is to be expected that the performance of admixtures in service will vary, depending on weather conditions and size of member. No single laboratory test can be expected to predict service performance exactly under all conditions. For specifications purposes, the test is as significant as would be a longer period. Furthermore, early shrinkage may be of greater importance than final shrinkage. The test has the very great advantage that the elapsed time in conducting it is less than 28 days. It is feasible to use it, therefore, for control testing of deliveries to the work. The results demonstrate that Test Method No. Calif. 530 provides a reliable measure of the performance of concrete subjected to exterior exposure.

Figure 10 has been drawn using the data of Figure 8

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to illustrate the change in ratio of shrinkage produced by admixtures to that of control concrete that takes place with time of drying. Ratios at 7 days are shown to be much higher than those after longer periods of drying. For admixtures 2, 3 and 4, (Figure 10), representing the set-retarding, water-reducing type, ratios determined at 14 days are not changed greatly by longer drying. For the straight accelerators, calcium chloride and triethanolamine, 28 days of drying are required to obtain reasonably stable ratios. The order of rating the admixtures is essentially the same at all drying periods. Since water-reducing admixtures, if they contain accelerators, contain relatively small amounts of them, it is not seriously unrealistic to evaluate their performance with respect to shrinkage after 14 days of drying.

The data presented thus far indicates that the effect of the cement on shrinkage can be measured satisfactorily in 1x1x10-in. bars of graded Ottawa sand mortar if it contains no addition. Tests of admixtures should be made in concrete with aggregates graded up to 3/4-inch or larger. The test specimen may be as small as 3x3x10-in. and the period of drying may be as short as 14 days.

Comparisons of aggregates should be made with specimens large enough for concrete of the largest maximum

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size under consideration. When specimens larger than 3x3-in. in section are required, the period of drying should be extended to yield numerical results of comparable magnitude. Test specimens 4x5-in. in cross-section have been used with 1-1/2-inch maximum size aggregate. Six-inch diameter cylinders have also been used. In either case, a drying period of 28 days has been found to produce shrinkage comparable in magnitude to that obtained by drying 3x3-in. specimens for 14 days.

Pavement Performance Related to Shrinkage

California has investigated the surface contour of pavements by means of an instrument known as a "Profilograph". The results show a pronounced tendency for slabs to curl upward at the ends. Curling is due to unequal moisture and temperature distribution from top to bottom. The upper portion of a pavement is nearly always drier than the bottom. Upward curling due to moisture differential may be offset wholly or partially in the afternoon by a higher temperature at the top than at the bottom. The temperature effect seldom produces a downward curvature. At night, a reversal in temperature

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distribution adds to the curling due to uneven moisture distribution. During the greater part of the time, pavement slabs are curled upward. Figure 11 is a view of pavement slabs as they appeared shortly after dawn. Surface water has drained from the slab ends which have dried sufficiently to afford a visual contrast.

Hveem[3] found that deflections under a heavy axle load were equal at the end and middle of slabs when they were essentially flat, that is, in contact with the subgrade at all points. When the slabs were curled upward, deflections at the ends were four times as great as at the middle.

Although it appears to be axiomatic that concrete of greater shrinkage should produce greater curling, California has obtained direct evidence that this is true. Also, it has obtained evidence that if curling is sufficiently severe, deflections under traffic result in a high incidence of slab cracking.

As a part of the Long Time Study of the Performance of Portland Cement in Concrete, the Kansas Highway Department constructed a 4-lane divided highway 4-1/2 miles in length near Topeka. Among the variables studied were three cements, LTS Nos. 19A, 19B, and 19C, representing "old fashioned", "modern coarse ground", and "modern" cements

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respectively. Each cement was used in one-third of the experimental sections which were 1000 feet in length. Shrinkage tests of 2x2x11-in. prisms of concrete containing the cements after drying for 1 month were as follows:

Cement	Shrinkage, Percent
19A	0.022
19B	0.027
19C	0.029

In 1956 when the pavement was 7 years old, California obtained profilograms of the pavement using a 25-foot manual Profilograph. The average amount of permanent curling of slabs containing each cement, was measured from the profilograms with results as follows:

Cement	Curling, Ins. per Slab
19A	0.139
19B	0.147
19C	0.182

The order of the cements with respect to slab curling is the same as the order in the shrinkage tests. To this extent, the laboratory tests for cement are found to be significant with respect to pavement performance.

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One of the most productive comparisons of pavement performance with laboratory shrinkage data is found in the results obtained when calcium chloride was used as an admixture. Laboratory tests of calcium chloride by Calif. 530-A are shown in Figures 2, 8, and 10.

Depending on the cement used, calcium chloride at the rate of 2 pounds per sack of cement, may be expected to increase the shrinkage of concrete by from 40 to 70 percent as measured by Test Method No. Calif. 530. The effect of using 1 pound per sack is about three-fourths as great. Short sections of pavement have been constructed frequently with calcium chloride in California for purposes of accelerating strength gain. Although many of such sections were less than 100 feet in length, records of a few were found that were at least several hundred feet in length, that were constructed concurrently with other pavement, and that were of an age suitable for comparative purposes.

Table 13 summarizes data of four such projects with respect to slab curling, as measured from profilograms, and the development of cracking.

In the Merced County project, 77 percent of the slabs containing calcium chloride have cracked transversely at about the midpoint. The amount of curling in

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these half slabs averages 0.10-in. It is assumed that before the slabs cracked, the curling was 0.20-in. which is the value shown in the table. This section is noticeably "rough riding". Figure 12 shows profilograms of portions of the Merced County pavement, and Figure 13 is a view of the section with calcium chloride. Figure 12 indicates the method used in measuring slab curling.

Profilograph data as summarized in Table 13, show that the use of calcium chloride has increased the amount of curling in pavement slabs by 50 percent as an average of the four projects. As a consequence of the increased curling, the riding qualities of the pavements have been impaired. In the lanes receiving heavy traffic, a substantial increase in cracking has occurred. The results therefore, provide striking evidence that Test Method No. Calif. 530 rates the effect of admixtures on shrinkage in a highly significant manner.

Highway Structure Performance Related to Shrinkage

In a preceding section, reference was made to the shrinkage of two model beams that were exposed out-of-doors

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at Sacramento. Weather locations at other sites may be expected to result in different rates and degrees of drying. In order to evaluate conditions at other locations, humidity measurements have been made periodically in the concrete of eight existing structures in California. The locations were selected to represent elevations from 200 feet below sea level to 6000 feet above sea level, and from moist coastal to arid desert climates.

During July 1960, two 1-1/2-in. holes were drilled in the side of an interior girder of each of six of the selected structures. One structure was of box girder design and the holes were drilled in an exterior side facing north. In the remaining structure, of flat slab design, the holes were drilled in the east face. Holes were drilled to depths of 3 inches and 5 inches. Brass tubes 1 inch shorter than the depth of the hole were cemented in place with epoxy adhesive, the tube ends being flush with the surface of the member. The outer end of the tube was threaded and the opening was closed with a screw cap. When tests for relative humidity within the concrete were made, the cap was removed and a humidity sensing element connected to an electric hygrometer was inserted. The leads of the sensing element passed through

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a metal cap which replaced the one that was removed and were sealed against leakage. Several readings were made until equilibrium was established which required about one hour. The sensing elements were calibrated from time to time at 70°F against saturated salt solutions which produce known relative humidities in the enclosed space above them. Measurements have been made five times at 3-month intervals with results as detailed in Table 14. This table shows the temperature within the test hole at the time of humidity measurement. There was considerable variation in temperature, but the observed humidity is corrected for temperature by means of a chart that is supplied with the instrument. Independent tests that were made confirmed the accuracy of the manufacturer's charts.

The average of minimum relative humidities measured at the eight locations, is 67 percent at the 3-inch depth and 70 percent at the 5-inch depth. Thus, it appears that the typical expectation in California is that concrete in structures will reach an average relative humidity of 70 percent. The only area where markedly greater drying was found was in the high desert area near Bishop. A review of weather records for the continental United States indicates that the test locations in California

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provides a fair representation of exposure conditions on a nationwide basis. Only in parts of Arizona is it indicated that drying conditions as severe as those at Bishop are encountered.

Exposure at Sacramento as indicated for Location 5 of Table 14, produces internal humidity that is close to the average expectation of 70 percent. The data of the model beams, presented in a preceding section, therefore, are of particular significance with respect to performance of structures subjected to exterior exposure. It was shown that laboratory shrinkage results after 14 days of drying provided significant data with respect to shrinkage of the model beams, and therefore, of exterior concrete in general. Although the minimum humidity reached in the model beams up to the age of 26 months was 72 percent and somewhat further drying in succeeding years may be expected, there is no reason to doubt that earlier shrinkage relationships will hold.

Outward indications of the effects of excessive shrinkage of concrete in highway structures would be expected to be most evident in a bridge deck. Some cracking in the deck is to be expected with all concrete because of the relatively high percentage of steel. The evaluation of performance as affected by shrinkage in

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laboratory tests therefore, must be by qualitative rather than strictly quantitative methods. Calcium chloride has been used in the decks of a number of California bridges. Abnormal amounts of cracking have been reported for the majority of structures containing calcium chloride. Figures 8 and 10 show that calcium chloride increases shrinkage when tested in the laboratory.

A California highway contract provides for the construction of twin, parallel bridges over Webber Creek in El Dorado County, in which concrete of different shrinkage characteristics is specified for use in the composite concrete and structural steel roadways. The bridges are approximately 540 feet in length and are divided by expansion joints to provide four approximately equal test sections in each bridge. Differences in shrinkage are provided by combinations of high-alkali, high C_3A cement and low-alkali Type II cement with aggregates from two sources which give much different results in laboratory shrinkage tests. Each of the four combinations is to be used twice in the bridge decks and once in auxiliary non-reinforced slabs cast on grade to represent pavement slabs. Construction of the decks was complete in October, 1962. Final evaluation of performance must await analysis of strain test data and visual observations

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over a period of several years, but preliminary data indicate that the shrinkage of the four types of concrete are in the ratio of 1:1.2:2.4:3.2. Thus, it will be possible to observe the effect of wide differences in shrinkage in the bridge deck and the slabs cast on the ground. Up to the first of November, 1962, however, there has not been any evidence of shrinkage to any great degree because of damp, rainy weather.

Warehouse Floor Performance

In 1924, Chapman[2] reported serious warping and cracking of a relatively new warehouse floor constructed above grade in two courses. The upper course was a 1:2 mortar of conglomerate screenings. Cracks divided the floor into rectangles 4 to 6 feet on a side which curled upward about 5/16-in. In general, the cracks were not visible on the underside of the floor; however, curling could be detected at junctions with brick supporting walls. The author made laboratory shrinkage tests of 1:2 mortar using the job and other sands, and also of concrete of job proportions. Shrinkage of the job mortar after 40 weeks of drying was about twice that of Ottawa sand mortar

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and about four times that of the job concrete. Approximately the same relationship resulted after short periods of drying. The evidence therefore, is quite conclusive that job performance was in accordance with laboratory shrinkage results.

Effect of Reinforcement

Miller[31] attributes the dishing of thin slab floors, the sagging of shallow beams, and the drooping of marquees to warping deformations caused by non-symmetrical position of the reinforcement. He found experimentally, that in non-symmetrical sections, warping (curling) on drying is a function of the free shrinkage of the concrete. One means of reducing warping is to use concrete of low shrinkage.

Miller's findings may be extended to show a benefit from distributed reinforcement in concrete pavements. If the steel is placed near the upper surface, as is the usual practice, it can prevent or reduce the tendency of individual slabs to curl upward due to unequal drying. Profilograms obtained by California of the reinforced pavement of the Missouri Test Road[32], do not show the

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upward curling that is typical of non-reinforced pavements. This single illustration however, may not constitute complete proof of the effectiveness of reinforcement in this respect because of unknown conditions at this site that may have greatly minimized curling. Even though it has been indicated that steel is effective in reducing moisture curling, it does not appear that it assists in reducing warping due to thermal differentials. The latter behavior may account for failure of reinforcement to improve performance in the AASHO National Road Test[33].

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DISCUSSION AND SUMMARY

There is substantial evidence that suitably designed laboratory tests can be used to predict the effect of the characteristics of the constituents of concrete and the conditions of its manufacture on its shrinkage in service. The elapsed time to complete the tests need not be long. For most purposes, they can yield significant results in from 7 to 21 days.

Shrinkage is dependent on the unit water content of concrete; however, the effect of materials having different characteristics cannot be foretold by a knowledge of their effect on water demand.

Factors such as aggregate size and gradation, slump, temperature of the concrete upon discharge from the mixer, and the time of mixing or agitation have an effect on water requirement. These factors are subject to control within limits under the provisions of most specifications. Their combined effect, if adverse, is not likely to result in an increase in shrinkage of more than about 60 percent. The reduction in shrinkage that can be achieved by stringent control of these factors, while important, is much less than is possible through control of materials under specification requirements

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that are not presently in widespread use.

The amount of shrinkage that is tolerable depends on the design of each member and the function it is intended to perform. In many cases, there is considerable leeway in the amount of shrinkage that can develop before adverse effects are evident visually. On the other hand, it is reasonable to expect something less than the best in performance if shrinkage is allowed to increase too far beyond a practical limit. Combinations of unfavorable factors can result in an increase of several fold in shrinkage. The probability of such an occurrence is augmented by the emphasis that is too frequently placed on high strength without proper consideration of other properties.

When the factor of safety against excessive shrinkage has been exhausted, experience shows that the cost of maintenance or repair is substantially greater than the cost of initial prevention.

The California Division of Highways has adopted the following requirements for the quality of materials as insurance against excessive shrinkage.

1. Portland cement is required to be Type II, low-alkali cement and the shrinkage developed in mortar shall not exceed 0.048 percent when

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tested by Test Method No. Calif. 527.

2. Aggregates are required to be sufficiently free from clay-like coatings or inclusions to meet test requirements for sand equivalent and cleanness value.

3. The maximum permissible dosage of chemical admixtures is limited to an amount that does not increase the shrinkage of concrete by more than 20 percent when tested by Test Method No. Calif. 530.

Although the restrictions were opposed at first by a few manufacturers, they are now accepted as a matter of course. In general, the manufacturers of portland cement and concrete aggregates have co-operated fully, once the reasons for the added requirements were fully understood. As far as known, there has been no increase in the price of cement due to the added requirements. There may have been a nominal increase in the cost of producing cleaner aggregates, but such added costs if any, have not been discernible in the bid prices for construction items involving portland cement concrete. There is some evidence that the cost of the completed work has been reduced.

In certain areas of the state, the only aggregates

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that are available locally are those having inherent characteristics that increase the shrinkage of concrete. To date, the California Division of Highways has not specified against their use. It would be desirable to eliminate aggregates of the higher inherent shrinkage producing characteristics, particularly for use in non-reinforced pavements where curling is a major adverse factor affecting service. Nevertheless, the haul distances involved in importing other aggregates make it necessary to compare costs with benefits. Studies of possible economical means of improving aggregates with respect to their inherent contribution to shrinkage have not been encouraging to date. The adopted measures, 1, 2, and 3 described above, together with previously adopted requirements for quality of materials and good construction procedures provide a significant margin of safety against excessive shrinkage. Further steps to effect a greater reduction in shrinkage logically should await additional studies as to costs involved and the benefits to be gained.

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TABLE 1

EFFECT OF CEMENT FACTOR ON SHRINKAGE OF CONCRETE

American River sand and gravel graded to 1" max.

Composition of Concrete by Absolute Volume
(Average of 3 Batches)

	Cement Factor Sacks per Cubic Yard			
	4.99	5.99	6.98	8.02
Cement	0.089	0.107	0.124	0.143
Water	0.202	0.207	0.210	0.207
Air	0.017	0.016	0.014	0.015
Paste	0.308	0.330	0.348	0.365
Aggregate	0.692	0.670	0.652	0.635
Water + Air	0.219	0.223	0.224	0.223
Shrinkage, %*	0.0330	0.0330	0.0289	0.0300

*Average of nine 3x3x10-in. prisms cured wet for 7 days, then dried for 14 days)

	Summary of Variances		
	Mean of Values	Std. Dev.	Coeff. of Variation
Water	0.2065	0.003	1.5%
Water + Air	0.222	0.002	0.9%
Shrinkage	0.0312	0.0021	6.7%

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TABLE 2

EFFECT OF (1) CEMENT FACTOR, AND (2) DURATION OF PRELIMINARY WET CURING ON SHRINKAGE OF MORTAR

Type II, low-alkali cement. Graded Ottawa sand mortar flow 100 - 115 percent.

Composition of Mortar by Absolute Volume
(Average of 3 batches)

Cement:Sand by Wt.	1:3	1:2-1/2	1:2	1:1-1/2
Cement	.155	.177	.211	.256
Water	.242	.246	.252	.255
Air	.057	.051	.037	.033
Paste	.453	.474	.500	.544
Sand	.547	.526	.500	.456
Water + Air	.299	.297	.289	.288

Shrinkage, Percent
(Average of 12 Specimens from 3 Batches)

Days of Wet Cure	Days of Drying	Cement:Sand by Weight 1:3	1:2-1/2	1:2	1:1-1/2	Avg.
2	4	.0421	.0420	.0428	.0469	.0435
3	4	.0410	.0391	.0411	.0458	.0418
7	4	.0416	.0388	.0407	.0442	.0413
Avg.	4	.0416	.0400	.0415	.0458	.0423
2	7	.0545	.0547	.0560	.0589	.0560
3	7	.0544	.0519	.0536	.0572	.0542
7	7	.0550	.0528	.0533	.0564	.0544
Avg.	7	.0546	.0535	.0543	.0575	.0549

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TABLE 3

EFFECT OF SO_3 CONTENT ON SHRINKAGE OF MORTAR AND CONCRETE

Pulverized gypsum was added in progressive amounts to a Type II, low-alkali cement containing 1.0 percent SO_3.

Mortar tests are 1x1x10-inch prisms of 1:2 graded Ottawa sand mortar cured wet for 3 days, then dried for 4 days.

Concrete tests are 3x3x10-inch prisms of 6-sack concrete, 1-inch maximum size aggregate, 3-inch to 4-inch slump, cured moist 7 days, then dried for 28 days.

SO_3 in Cement Percent	Shrinkage, Percent	
	Mortar	Concrete
1.0	0.071	0.044
1.5	0.048	0.041
2.0	0.039	0.036
2.5	0.040	0.031
3.0	0.051	0.031
3.5	0.060	
4.0		0.045
4.5		0.048

Estimated Optimum SO_3:

Mortar	2.2 percent
Concrete	2.7 percent

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TABLE 4

RELATIVE SHRINKAGE OF CONCRETE MADE WITH DIFFERENT AGGREGATES

5-sack concrete, 2-inch slump, 1-1/2-inch maximum size aggregate. Specimens are 4x5x18-inch prisms, moist cured for 7 days, then dried for 28 days. All aggregates were washed, then sieved and recombined to same grading. Values are average of 2 to 5 specimens expressed as a percentage of control concrete containing aggregate from the American River near Sacramento.

Aggregate Reference Number	Drying Shrinkage, % of Control	Aggregate Reference Number	Drying Shrinkage % of Control
1	70	16	97
2	76	17	100
3	79	18	106
4	81	19	107
5	83	20	110
6	86	21	110
7	89	22	110
8	89	23	112
9	92	24	120
10	94	25	124
11	95	26	129
12	97	27	130
13	97	28	133
14	97	29	145
15	97	30	153

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TABLE 5

EFFECT OF CHEMICAL ADMIXTURES ON SHRINKAGE
SUMMARY OF MISCELLANEOUS TESTS

5-1/2 to 8-sack concrete, 3-1/2 to 4-in. slump. Aggregate 1-1/2-in. max. size (concrete wet sieved through 3/4-in.) or 1-in. max. size. 3x3x10-in. prisms cured moist for 7 days, then dried for 14 days. Values are averages of 6 or more specimens from 2 or more batches mixed on different days. Values are relative to shrinkage of control concrete containing no admixture.

Type of Admixture		Quantity per Sack of Cement	Max. Size Aggr.	Cement Factor Sks/CY	Relative Shrinkage Control=100
Hydroxylated Carboxylate	(a)	2 fl.oz.	1"	7.0	100
	(a)	4 " "	1"	7.0	97
	(a)	3 " "	1"	7.0	93
	(a)	3 " "	1"	7.0	94
	(a)	2 " "	1"	7.0	104
	(a)	4 " "	1"	7.0	98
	(a)	0.5 lb.	1"	7.0	104
	(a)	1.0 "	1"	7.0	104
	(a)	2 fl.oz.	1"	7.0	104
	(a)	4 " "	1"	7.0	104
	(a)	2 " "	1-1/2"	5.5	90
	(a)	1 fl. oz.	1-1/2"	6.0	91
	(a)	2 " "	1-1/2"	6.0	87
	(a)	3 " "	1-1/2"	6.0	85
	(b)	2.75 fl. oz.	1"	6.0	143
	(c)	2.5 fl. oz.	1"	6.0	141
	(c)	4.5 " "	1"	6.0	161
Lignosulfonate	(a)	.125 lb.	1"	7.0	113
	(a)	.25 lb.	1"	7.0	113
	(a)	.125 lb.	1"	7.0	110
	(a)	.25 "	1"	7.0	114
	(a)	.125 "	1"	7.0	111
	(a)	.25 "	1"	7.0	114
	(a)	.25 "	1-1/2"	5.5	106
	(b)	4 fl.oz.	1"	7.0	106
	(b)	8 " "	1"	7.0	113
	(b)	4 " "	1"	7.0	106

Continued

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Table 5 (Continued)

Type of Admixture		Quantity per Sack Cement	Max. Size Aggr.	Cement Factor Sks/CY	Relative Shrinkage Control=100
Lignosulfonate	(b)	8 fl.oz.	1"	7.0	108
	(b)	3.75	1-1/2"	6.0	103
	(b)	fl.oz.			
	(b)	7.5 fl.oz.	1-1/2"	5.5	106
	(b)	7.5 " "	1-1/2"	6.0	113
	(b)	11.25" "	1-1/2"	6.0	120
	(c)	.25 lb.	1"	7.0	137
	(c)	.25 lb.	1"	7.0	138
	(c)	.15 lb.	1"	7.0	126
	(c)	.30 lb.	1"	7.0	144
	(c)	.125 "	1"	7.0	123
	(c)	.25 "	1"	7.0	144
	(c)	.25 "	1-1/2"	6.0	133
	(c)	.20 "	1"	6.0	130
	(d)	4.5 fl.oz.	1"	7.0	103
	(d)	9 fl.oz.	1"	7.0	106
	(d)	3 " "	1-1/2"	5.5	97
	(e)	.125 lb.	1"	7.0	141
	(e)	.25 lb.	1"	7.0	155
	(e)	.125 lb.	1"	7.0	141
	(e)	.25 lb.	1"	7.0	156
	(f)	.15 lb.	1"	7.0	109
	(f)	.30 lb.	1"	7.0	119
	(f)	.25 lb.	1"	5.0	101
	(f)	.25 lb.	1"	6.0	98
	(f)	.25 lb.	1"	7.0	105
	(f)	.25 lb.	1"	8.0	99
	(f)	.15 lb.	1"	7.0	106
	(f)	.30 lb.	1"	7.0	114
	(f)	.25 lb.	1-1/2"	5.5	102
	(f)	.25 lb.	1"	6.0	120
	(g)	.15 lb.	1"	7.0	119
	(g)	.30 lb.	1"	7.0	133
	(h)	.15 lb.	1"	7.0	107
	(h)	.30 lb.	1"	7.0	118
	(h)	.20	1"	6.0	106
	(i)	4 fl.oz.	1"	7.0	111
	(i)	8 " "	1"	7.0	121
	(j)	.25 lb.	1-1/2"	5.5	113
	(k)	.125 lb.	1-1/2"	5.5	105
	(l)	6 fl.oz.	1-1/2"	5.5	131
Table Sugar		0.3 oz.	1-1/2"	5.5	100
Unclassified	(a)	0.5 fl.oz.	1"	7.0	94
	(a)	1.0 " "	1"	7.0	94
	(b)	1.0 " "	1"	7.0	100
	(b)	2.0 " "	1"	7.0	100
	(c)	.375 " "	1"	7.0	100
	(c)	.75 " "	1"	7.0	103
	(c)	.375 " "	1"	7.0	106
	(c)	.75 " "	1"	7.0	103

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TABLE 6

EFFECT OF CALCIUM CHLORIDE ADMIXTURE ON SHRINKAGE

Properties of Fresh Concrete
(Average of 3 batches)
Test Method No. Calif. 530

Chloride Radical, % by Wt. of Cement	Slump, Inches	Air %	Unit Weight Lbs./Cu.Ft.	W/C, by Wt.	Cement Factor Sks./CY
0	3.7	1.6	150.8	.502	7.01
0.04	3.5	1.8	150.5	.493	7.01
0.08	3.5	1.6	150.9	.492	7.02
0.16	3.6	1.9	150.4	.479	7.01
0.32	3.6	2.1	150.5	.493	7.00
0.64	3.5	2.3	150.5	.478	7.02
1.28	3.5	2.6	149.6	.492	6.97

See Figure 2 for shrinkage results.

Properties of Fresh Mortar
(Average of 3 batches)
1:2 Graded Ottawa Sand Mortar
Test Method No. Calif. 527

Chloride Radical % by Wt. of Cement	Flow, Percent	W/C, by Wt.
0	104	.363
0.04	107	.363
0.08	106	.363
0.16	109	.363
0.32	109	.365
0.64	108	.367
1.28	110	.390

See Figure 2 for shrinkage results.

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TABLE 7

EFFECT OF TRIETHANOLAMINE ADMIXTURE ON SHRINKAGE

Properties of Fresh Concrete
(Average of 3 Batches)
Test Method No. Calif. 530

Triethanol-amine, % by Weight of Cement	Slump, Inches	Air %	Unit Wt. Lbs./Cu.Ft.	W/C, % By Wt.	Cement Factor Sks/CY
0	3.5	1.4	151.2	48.5	7.01
0.03	3.5	2.0	150.6	48.0	7.03
0.06	3.5	2.2	150.4	48.7	6.98
0.12	3.3	2.4	150.0	48.1	6.99
0.24	3.4	2.6	149.8	48.4	7.01
0.48	3.4	2.9	149.4	46.8	6.99
See Figure 4 for shrinkage results					

Properties of Fresh Mortar
(Average of 3 Batches)
1:2 Graded Ottawa Sand Mortar
Test Method No. Calif. 527

Triethanol-amine, % by Weight of Cement	Flow Percent	W/C, % By Wt.
0	101	0.371
0.03	101	0.371
0.06	103	0.371
0.12	104	0.371
0.24	104	0.371
0.48	105	0.371
See Figure 4 for shrinkage results		

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TABLE 8

EFFECT OF DURATION OF PRELIMINARY MOIST CURING ON SHRINKAGE OF CONCRETE

Type II, low-alkali cement. 1-in. max. aggregates from American River. Nine 3x3x10-in. prisms molded from each batch. (3 selected for each curing period.)

Properties of Fresh Concrete
(Average of 3 batches)

Slump	2.6
Air, Percent	1.8
W/C, by Weight	0.512
Cement Factor, Sacks	6.02

Shrinkage, Percent
(Average of 9 specimens)

Period of Drying, Days	Period of Moist Curing, Days		
	7	14	28
7	.0144	.0140	.0153
14	.0226	.0212	.0218
28	.0337	.0314	.0328
56	.0447	.0423	.0412
112	.0498	.0506	.0492

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TABLE 9

EFFECT OF INDIVIDUAL SHRINKAGE FACTORS ON CUMULATIVE SHRINKAGE

Tests by Test Method No. Calif.530 except aggregates were from different sources. Lignosulfonate water-reducing admixture at 0.25-lb. per sack of cement.

Properties of Fresh Concrete
(Average of 4 batches)

	Slump, Inches	Air %	W/C By Wt.	Unit Wt. Lbs./CF	Cement Factor Sks/CY
Aggregate A					
Control	3.5	1.8	.445	148.0	7.06
With Admixture	3.4	5.0	.388	144.4	7.02
Aggregate B					
Control	3.8	1.5	.468	150.5	7.05
With Admixture	3.6	4.4	.406	148.0	6.99

Shrinkage, Percent, After Number of Days Shown
(Average of 12 specimens from 4 batches)

	Aggregate A					
	Control			Admixture		
	7	14	28	7	14	28
Shrinkage	.0170	.0230	.0293	.0240	.0319	.0397
Numerical increase				.0070	.0089	.0104
% of Control	100	100	100	141	137	135
	Aggregate B					
Shrinkage	.0305	.0443	.0594	.0455	.0611	.0760
Numerical increase				.0150	.0168	.0166
% of Control	100	100	100	149	138	128

	Days of Drying			
	7	14	28	Avg.
(1) Shrinkage, Aggregate A	.0170	.0230	.0293	
(2) Increased shrinkage due to admixture, Aggregate A	.0070	.0089	.0104	
(3) Shrinkage, Aggregate B	.0305	.0443	.0594	
(4) Computed shrinkage of Aggregate B with admixture, (2) + (3)	.0375	.0532	.0698	
Average of Drying Periods				.0535
(5) Relative Shrinkage, admixture to Control, Aggr. A	1.41	1.37	1.35	
(6) Relative Shrinkage, Aggregate B to Aggregate A	1.80	1.92	2.03	
(7) Computed Shrinkage of Aggregate B with admixture, (5) x (6) x (1)	.0430	.0609	.0800	
Average of Drying Periods				.0613
(8) Measured Shrinkage of Aggr. B with admixture	.0455	.0611	.0760	
Average of Drying Periods				.0609

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TABLE 10

CUMULATIVE EFFECT OF ADVERSE FACTORS ON SHRINKAGE

Based on effect of departing from the use of the best materials and workmanship

Individual Factor	Cumulative Effect
Temperature of concrete at discharge allowed to reach 80°F, whereas with reasonable precautions, a temperature of 60° could have been maintained (8%)	1.00 x 1.08 = 1.08
Used 6"-7" slump where 3"-4" slump could have been used (10%)	1.08 x 1.10 = 1.19
Use of 3/4" max. size of aggregate under conditions where 1-1/2" size could have been used (25%)	1.19 x 1.25 = 1.49
Excessive haul in transit mixer or too long a waiting period at job site or too many revolutions at mixing speed (10%)	1.49 x 1.10 = 1.64
Use of cement having relatively high shrinkage characteristics (25%)	1.65 x 1.25 = 2.05
Excessive "dirt" in aggregate due to insufficient washing or contamination during handling (25%)	2.05 x 1.25 = 2.56
Use of aggregates of poor inherent quality with respect to shrinkage, (50%)	2.56 x 1.50 = 3.84
Use of an admixture that produces high shrinkage (30%)	3.84 x 1.30 = 5.00

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TABLE 11

CONCRETE AND MORTAR SHRINKAGE TESTS OF EIGHT TYPE II, LOW-ALKALI CEMENTS

Mortar tests by Test Method No. Calif. 527. Each value is the average of 12 specimens from 3 batches. Concrete tests by Test Method No. Calif. 530 except cement factor is 6 sacks per cu. yd., and no admixtures were included. Each value is the average of 12 specimens from 4 batches.

Shrinkage in Percent After Drying for Period Indicates

Cement Number	Mortar 4 days	Concrete 7 days	Concrete 14 days	Concrete 28 days
1	.0374	.0219	.0365	.0488
2	.0448	.0233	.0365	.0487
3	.0386	.0221	.0363	.0598
4	.0384	.0226	.0354	.0586
5	.0462	.0273	.0470	.0600
6	.0394	.0186	.0308	.0544
7	.0462	.0228	.0371	.0599
8	.0471	.0252	.0388	.0636

Precision of Prediction of Concrete Shrinkage From Mortar Shrinkage by Equations of Form, $Y = bX$

Days Concrete Dried	Value of "b" in Equation	Standard Error of Estimate, S_{yx} Numerical	Standard Error of Estimate, S_{yx} Percent*
7	0.54	0.0021	9
14	0.89	.0038	9
28	1.18	.0041	8

$$*\frac{\text{Numerical value of } S_{yx}}{\text{Avg. Observed Concrete Shrinkage}} \times 100$$

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TABLE 12

EFFECT OF A CHEMICAL ADMIXTURE ON SHRINKAGE OF A 14x20x48-inch BEAM EXPOSED OUTDOORS

6-sack concrete, 3-in. to 4-in. slump, 1-1/2 in. max. size aggregate. Moist cured 7 days, then exposed outdoors at Sacramento, August, 1960.

Length of Exposure, Weeks	Increase in Shrinkage Due to Admixture in Percent of Control Concrete (Without Admixture)*
8	36
12	37
16	44
20	50
24	59
28	39
32	48
36	35
40	36
44	31
48	33
52	32
56	31
61	31
65	32
69	33

*Average of measurements at center and surface.

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TABLE 13

EFFECT OF CALCIUM CHLORIDE ADMIXTURE ON PERFORMANCE OF PAVEMENTS IN CALIFORNIA

Reference No.	1		2		3		4	
Contains Calcium Chloride?	Yes	No	Yes	No	Yes	No	Yes	No
Avg. curl per slab, ins. (from profilograms)	0.20	0.11	0.09	0.06	0.13	0.09	0.16	0.14
Slabs with transverse cracks, %	77	13	14	8	19	7	0	0
Slabs with longitudinal cracks, %	29	0	0	0	0	0	0	0
Slabs with partial cracks, %	29	20	0	0	13	0	0	0
Slabs with corner breaks, %	2.0	2.0	1.8	0.1	0	0	0	0

Project Data

Ref. No.	Location, County	Date Const.	Age at Survey, Years	Length of Sections, Feet	Lbs. of $CaCl_2$ per sack of Cement
1	Merced	1955	6	840	1
2	(Sacramento (San Joaquin	1957	4	9800	2
3	Santa Barbara	1956	5	650	2
4	San Diego	1955	6	1050	2

All slabs are 15' between weakened plane joints. Surveys were made in outer, traveled lane of divided highways, except in Ref. 4 which is an inner, passing lane. Comparison sections are in same lane and adjacent to sections with calcium chloride, except in Ref. 2 in which comparison section is opposite the section with calcium chloride. The length of each comparison section is approximately equal to that with calcium chloride.

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TABLE 14

TEMPERATURE AND RELATIVE HUMIDITY IN CONCRETE OF EXISTING BRIDGES IN CALIFORNIA

Location	Elev. Above Sea Level, Feet	Year Built	Date of Test, Mo.-Yr.	Temp. and Rel. Hum. at depth shown 2"-3" T	2"-3" H	4"-5" T	4"-5" H
1. Br. No. 54-500R Mojave Desert near Victorville	3000	1958	8-60	78	66	79	74
			1-61	53	67	55	74
			4-61	56	67	60	75
			8-61	87	67	88	76
			11-61	59	59*	58	72*
2. Br.No. 57-332L Southern Coast near San Diego	10	1956	8-60	74	80	71	81
			1-61	58	76*	54	79
			4-61	64	77	61	77*
			8-61	71	79	68	80
			11-61	68	77	68	79
3. Br. No. 36-65 Central Coast near Santa Cruz	10	1947	9-60	59	77	57	80
			1-61	49	76	46	77*
			4-61	54	78	50	79
			8-61	64	79	61	82
			11-61	54	75*	54	78
4. Br.No. 4-84R Northern Coast near Eureka	10	1929	9-60	54	84*	54	86
			1-61	48	86	48	86
			4-61	53	84*	53	84*
			8-61	57	86	60	87
			11-61	53	86	53	87
5. Br.No. 24-134 Central Valley near Sacramento	25	1959	9-60	87	74	82	77
			1-61	36	78	36	75
			4-61	57	77	55	76
			9-61	64	72*	61	75
			12-61	57	80	53	68*
6. Br.No. 19-106L Sierra Nevada Range near Kingvale	6000	1959	8-60	57	70	57	77
			1-61	32	72	32	72
			4-61	45	72	47	69*
			8-61	68	70	67	75
			10-61	39	66*	38	69*
7. Br.No. 48-22 East of Sierras near Bishop	4400	1949	8-60	83	50	80	60
			1-61	53	47*	52	51
			4-61	74	49	74	57
			8-61	85	48	85	57
			11-61	50	47*	52	50*
8. Br.No. 58-277 Imperial Valley near Salton Sea	-200	1950	8-60	88	58	88	67
			1-61	64	71	61	63*
			4-61	99	72	95	73
			8-61	101	67	103	71
			11-61	68	56*	68	63*

*Minimum observed relative humidity at location

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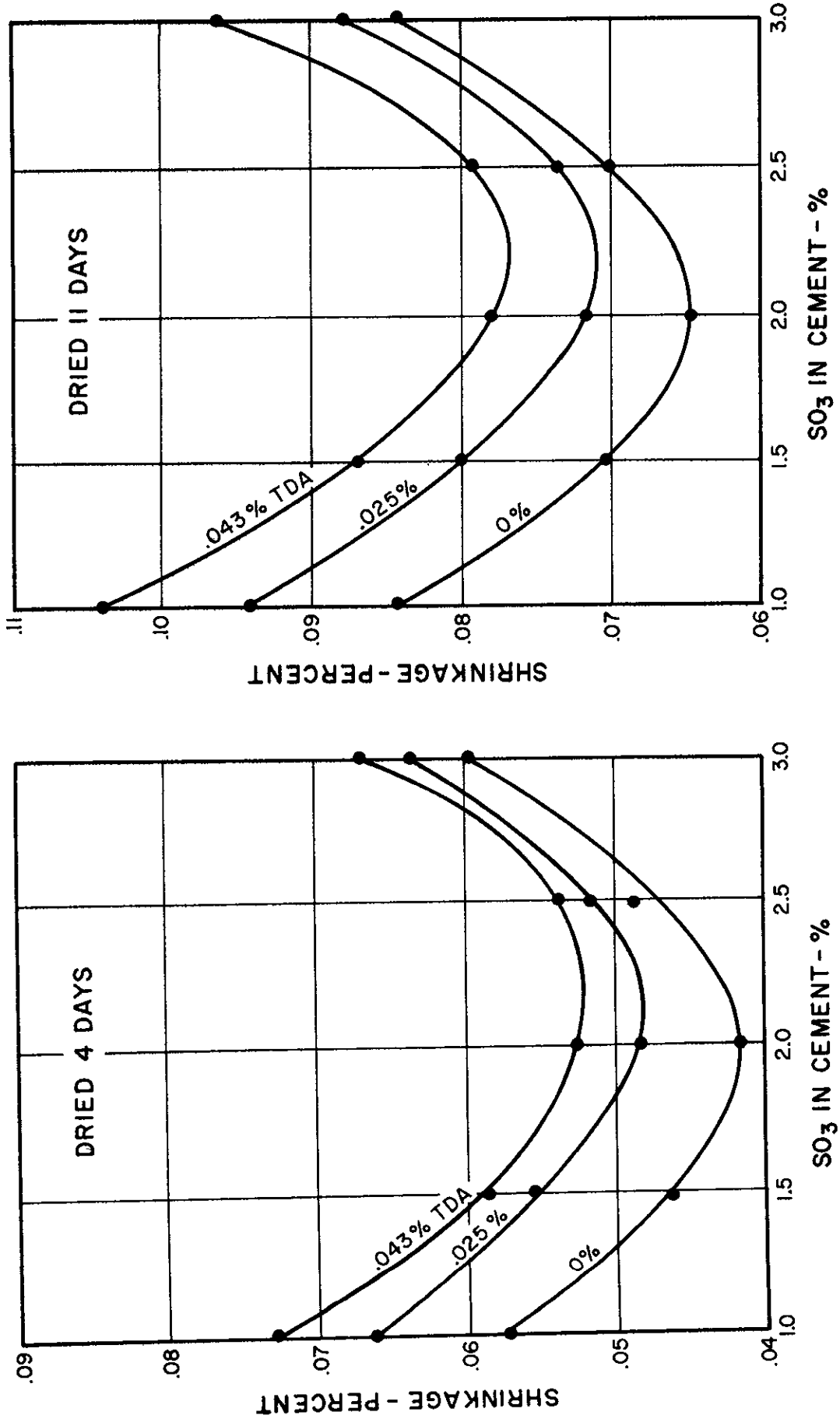
Figure 1



INFLUENCE OF SO_3 IN CEMENT ON SHRINKAGE EFFECT OF TDA

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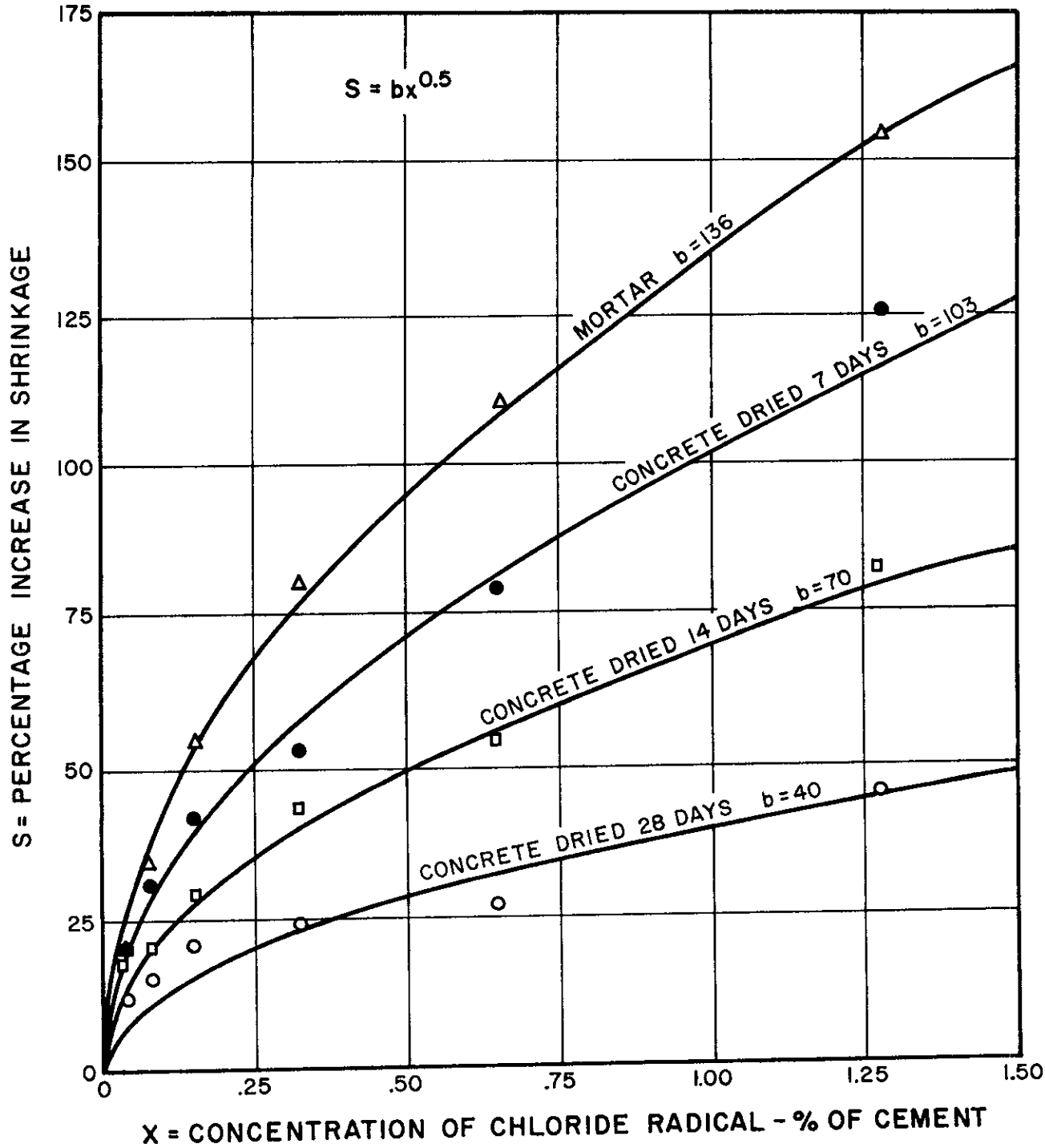

EFFECT OF CALCIUM CHLORIDE ADMIXTURE ON SHRINKAGE OF MORTAR AND CONCRETE

(SEE TABLE 6 FOR MIX DATA)

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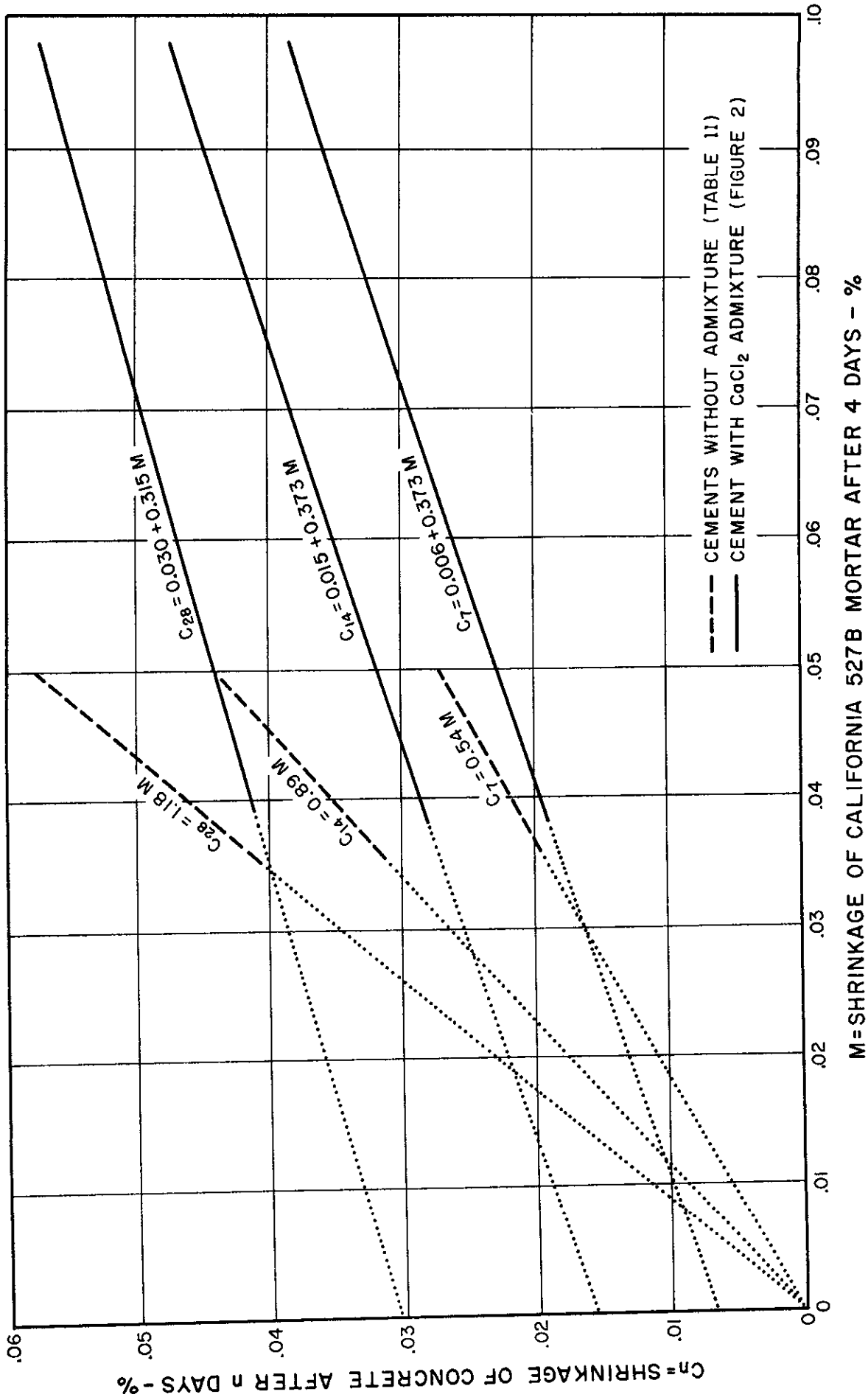
Figure 3



EFFECT OF CALCIUM CHLORIDE ON SHRINKAGE RELATIONSHIP OF MORTAR AND CONCRETE

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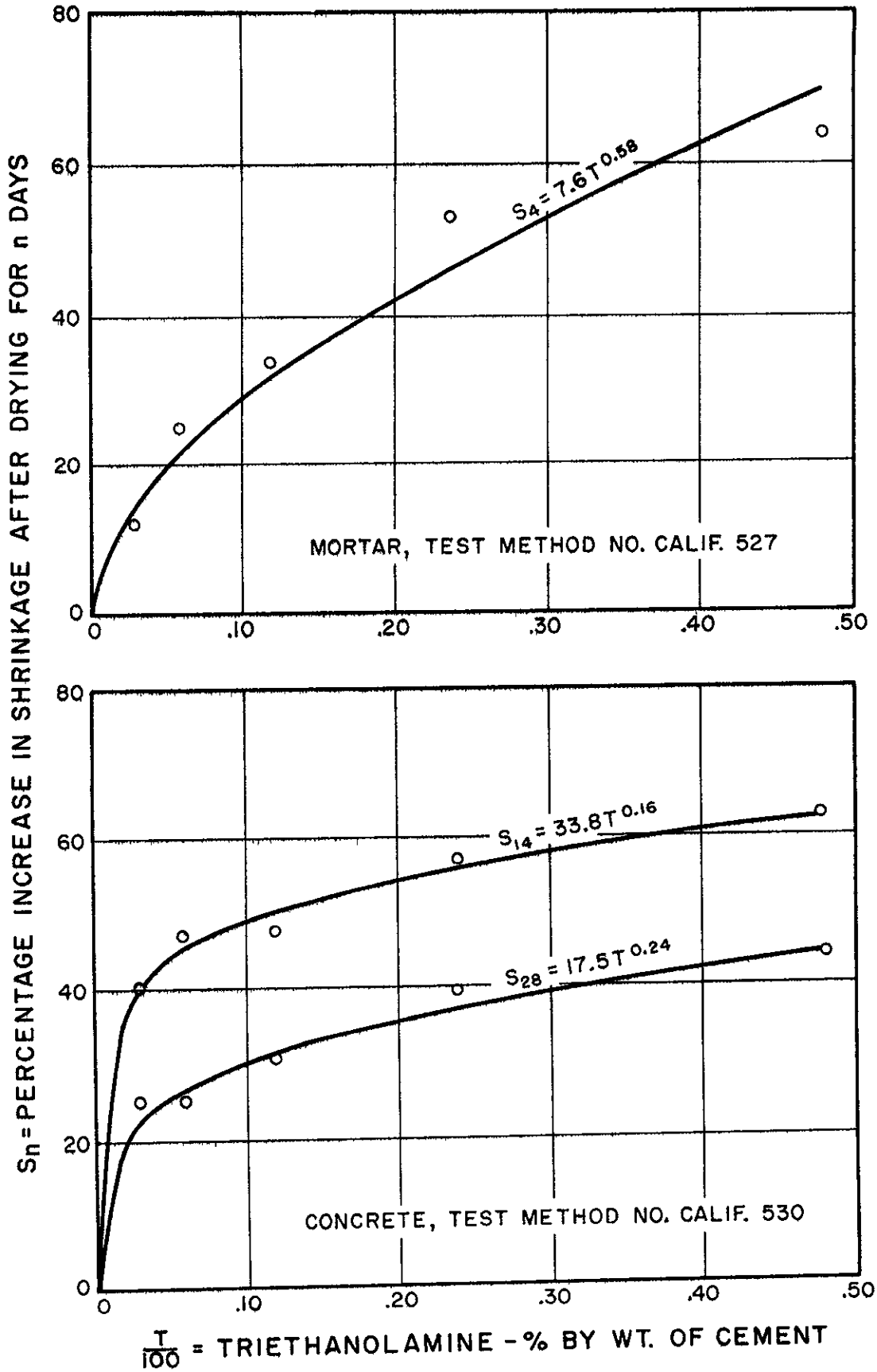
Figure 4



EFFECT OF TRIETHANOLAMINE ADMIXTURE ON SHRINKAGE OF MORTAR AND CONCRETE

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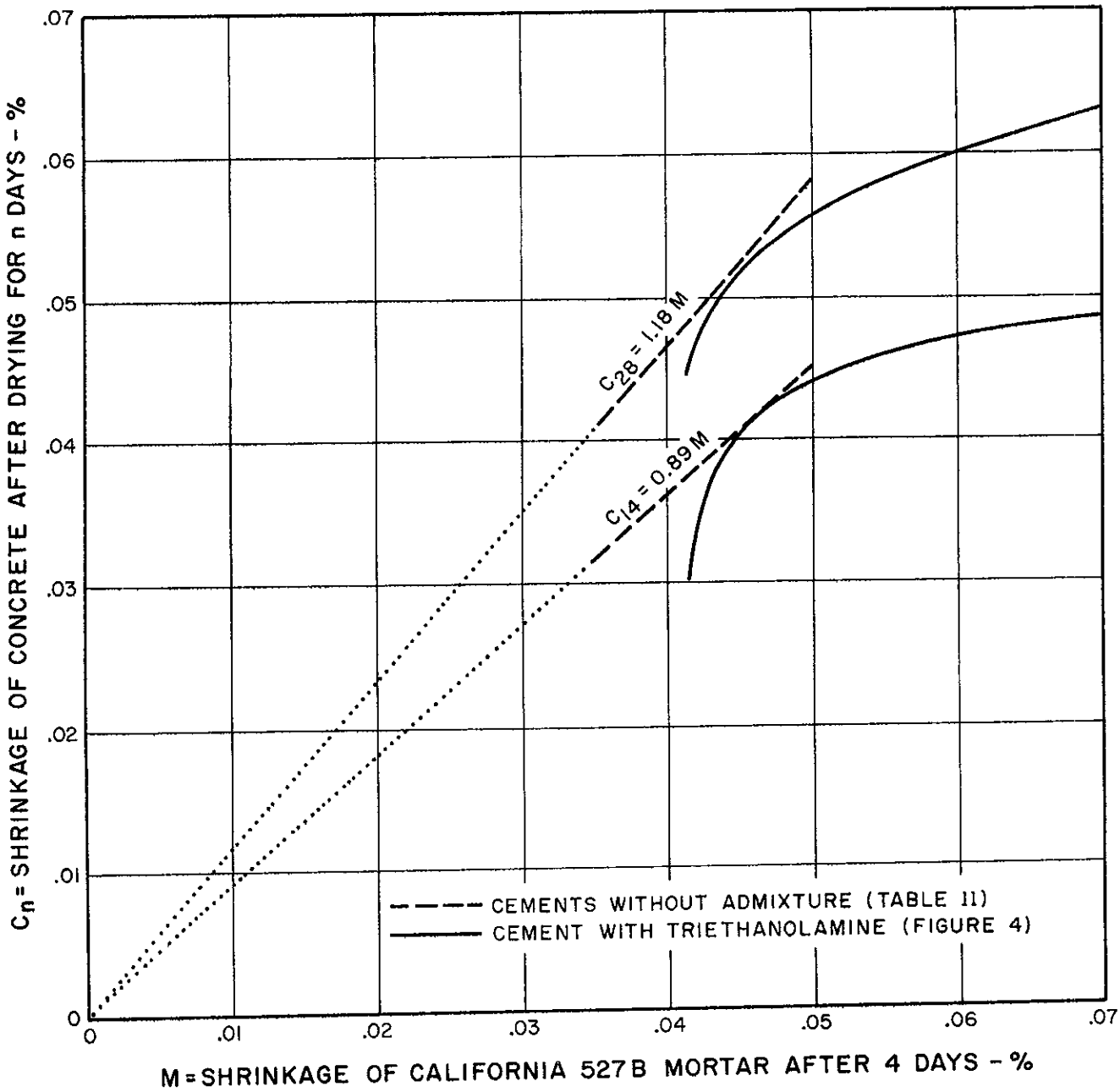

EFFECT OF TRIETHANOLAMINE ON SHRINKAGE RELATIONSHIP OF MORTAR AND CONCRETE

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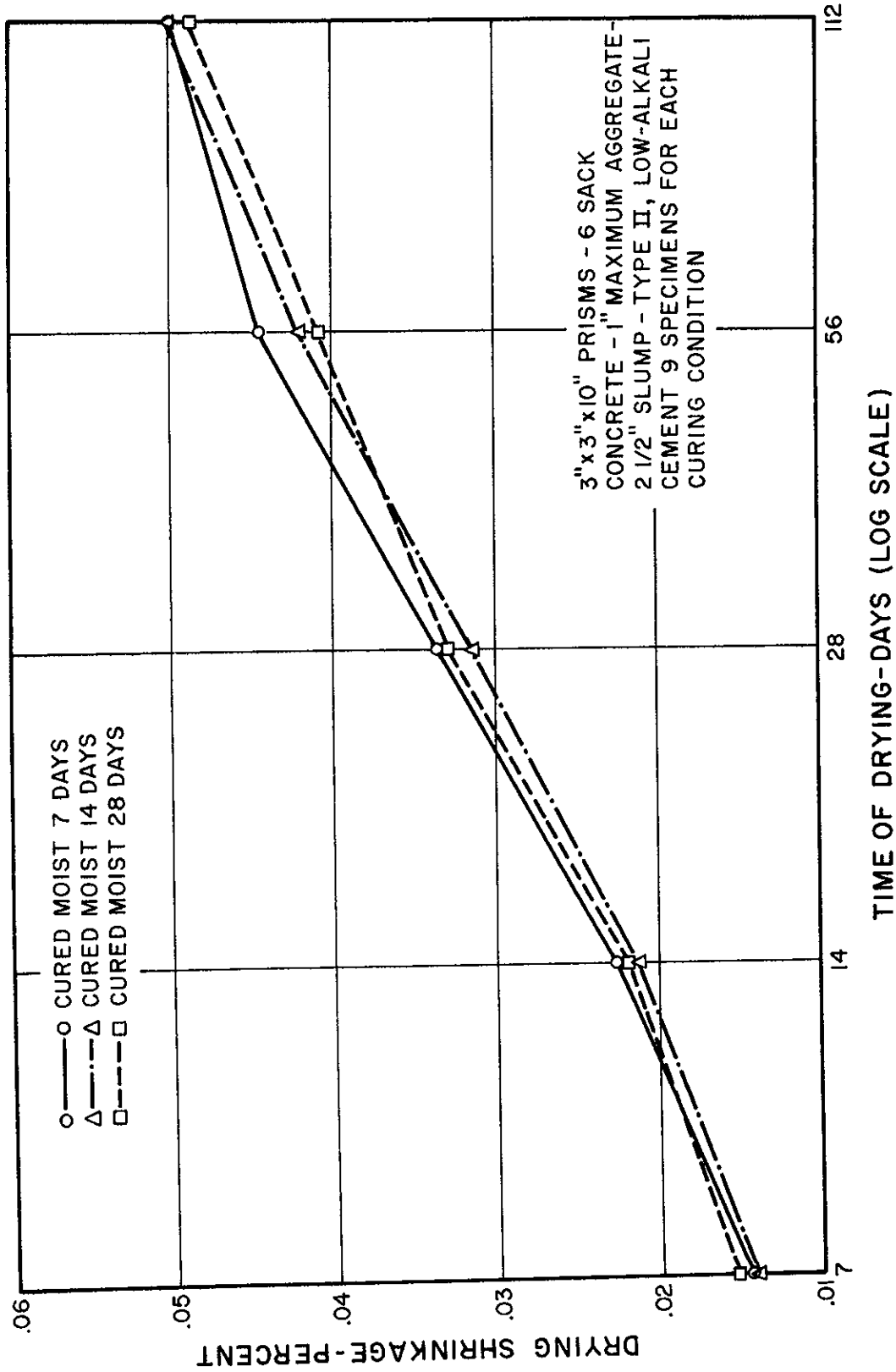
Figure 6



EFFECT OF DURATION OF PRELIMINARY MOIST CURING ON SHRINKAGE

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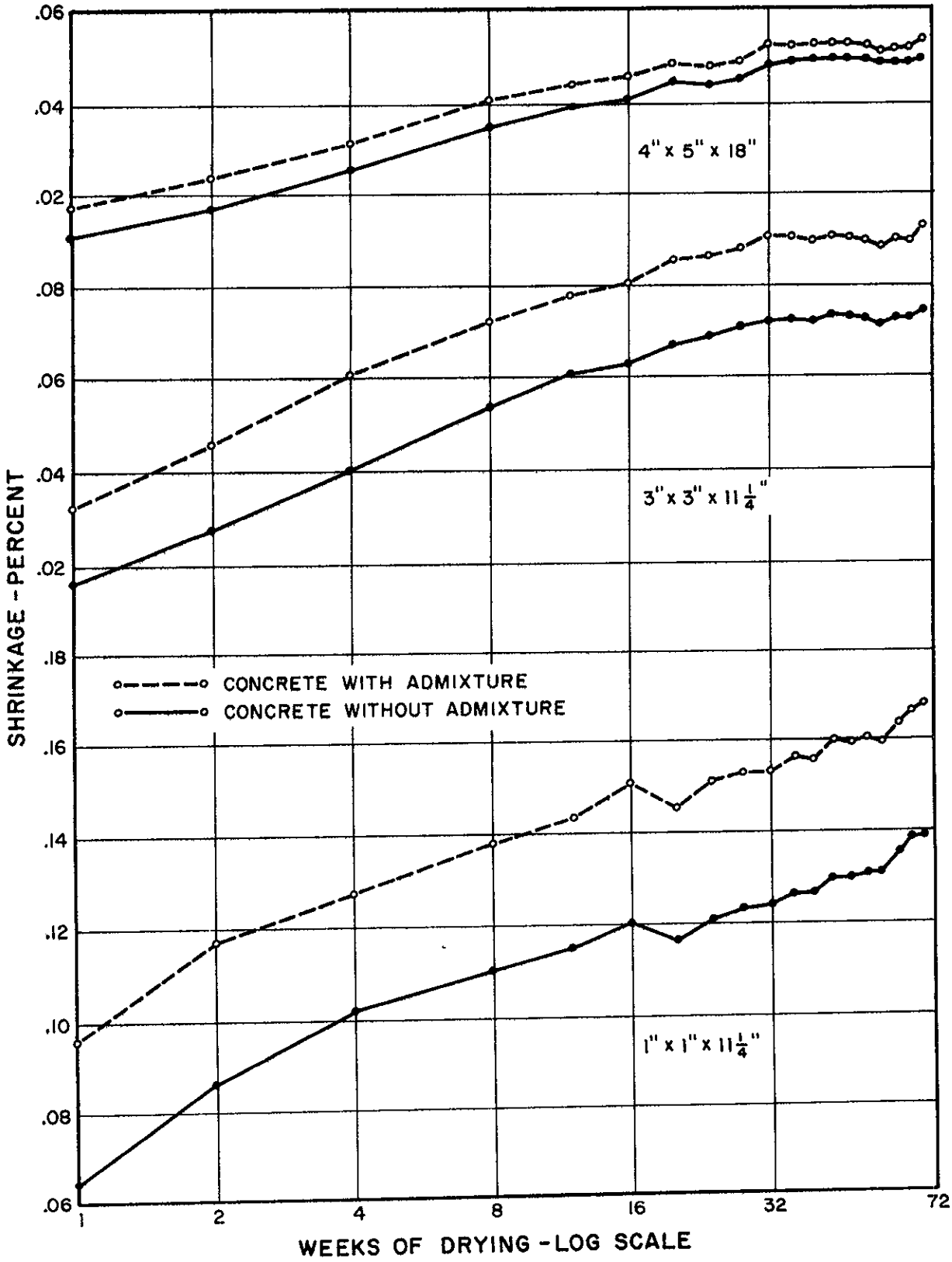
Figure 7



INCREASE IN SHRINKAGE WITH LENGTH OF DRYING PERIOD

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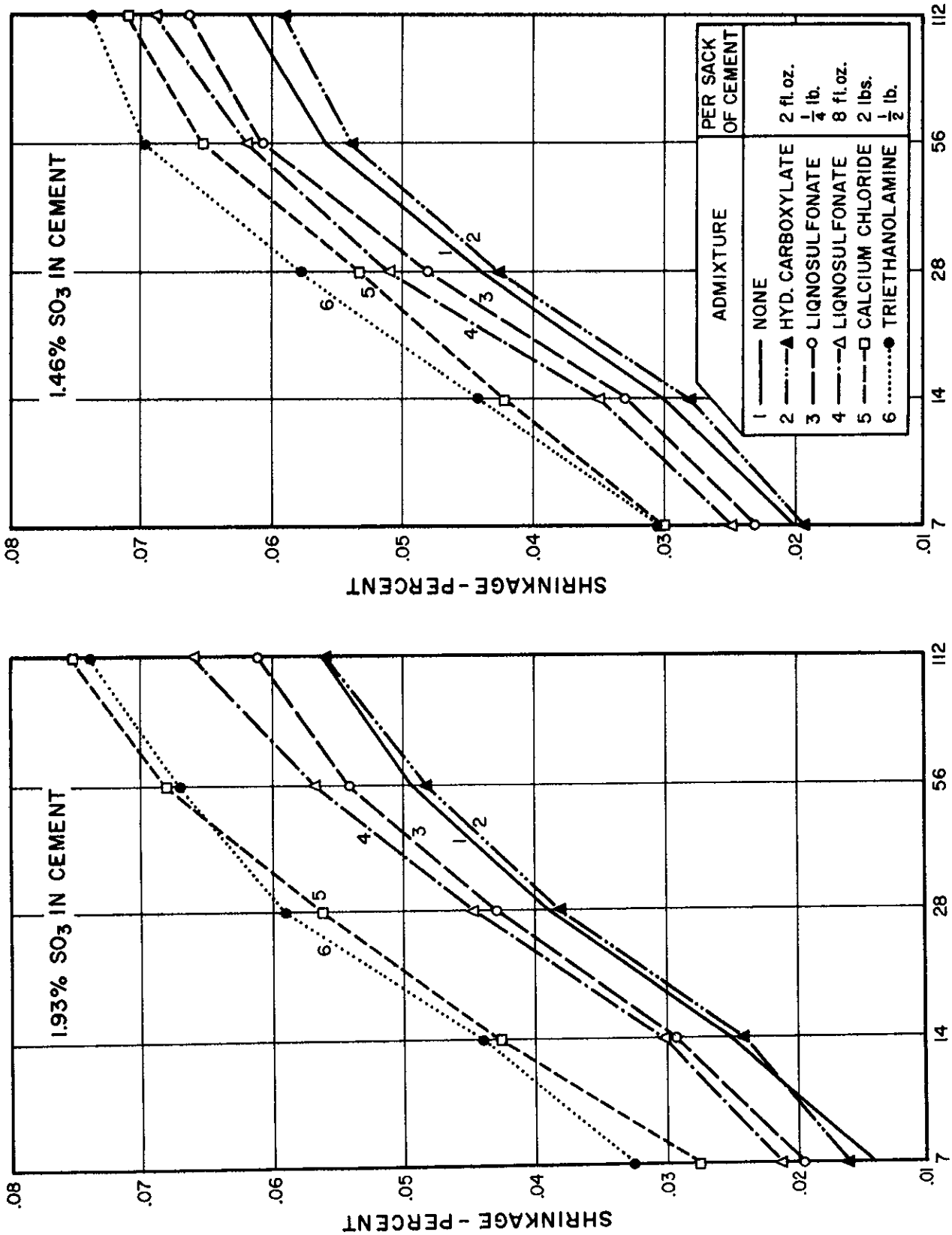
Figure 8



INCREASE IN SHRINKAGE WITH TIME OF DRYING

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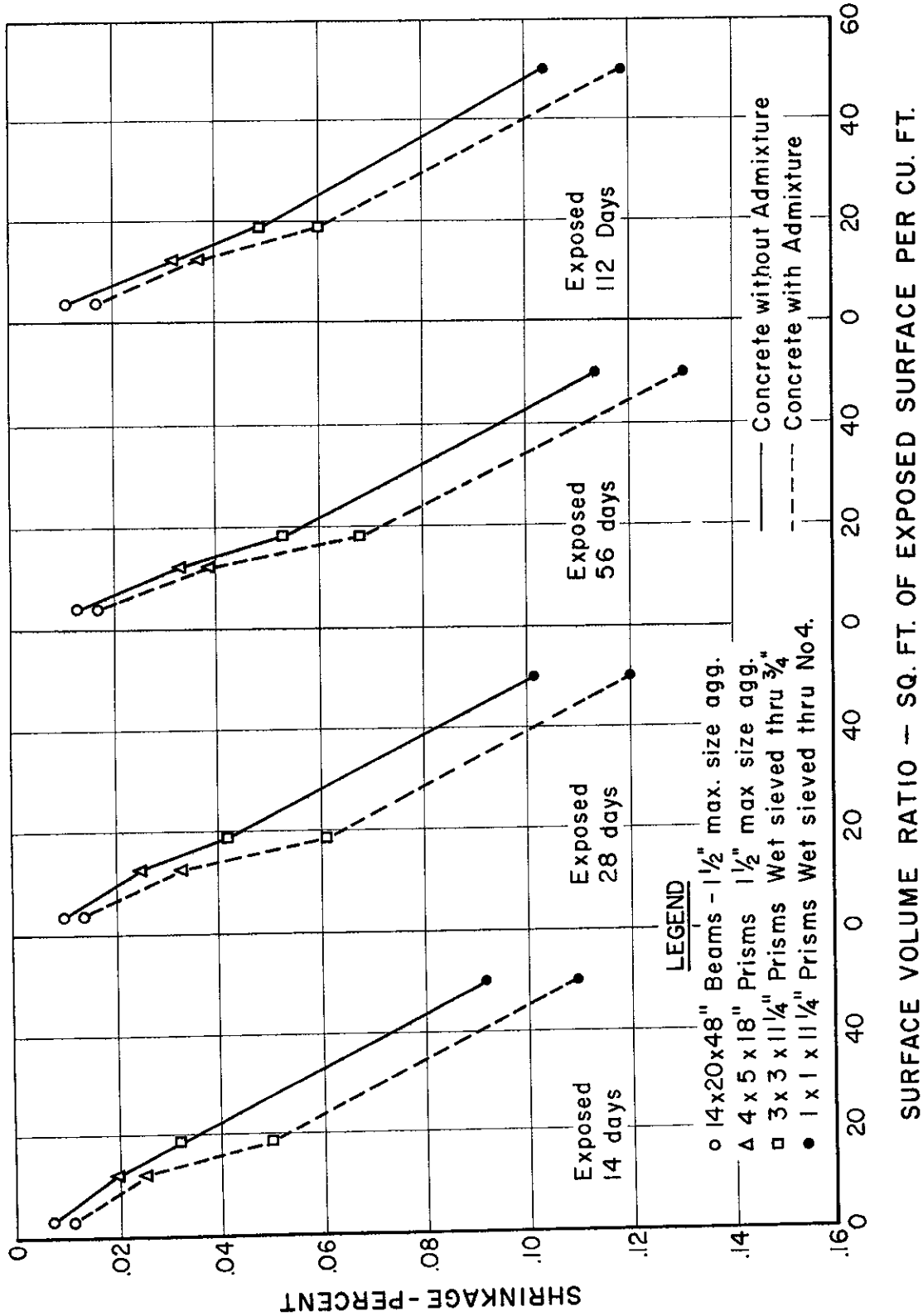
FIGURE 9



Relationship between shrinkage and surface - volume ratio
Specimens exposed outdoors

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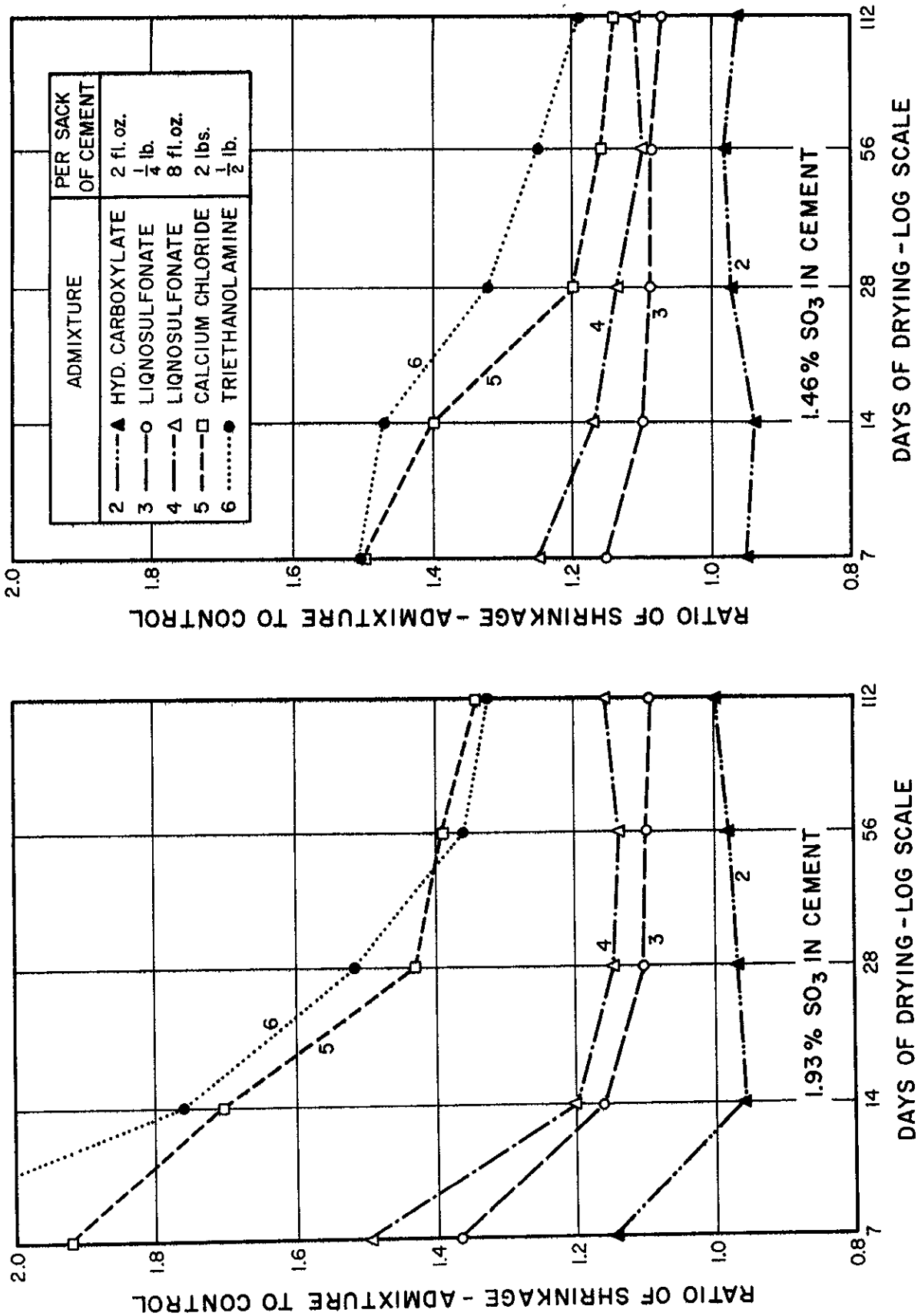
B. Tremper
D. L. Spellman

Figure 10



CHANGE IN RELATIVE SHRINKAGE WITH DRYING TIME

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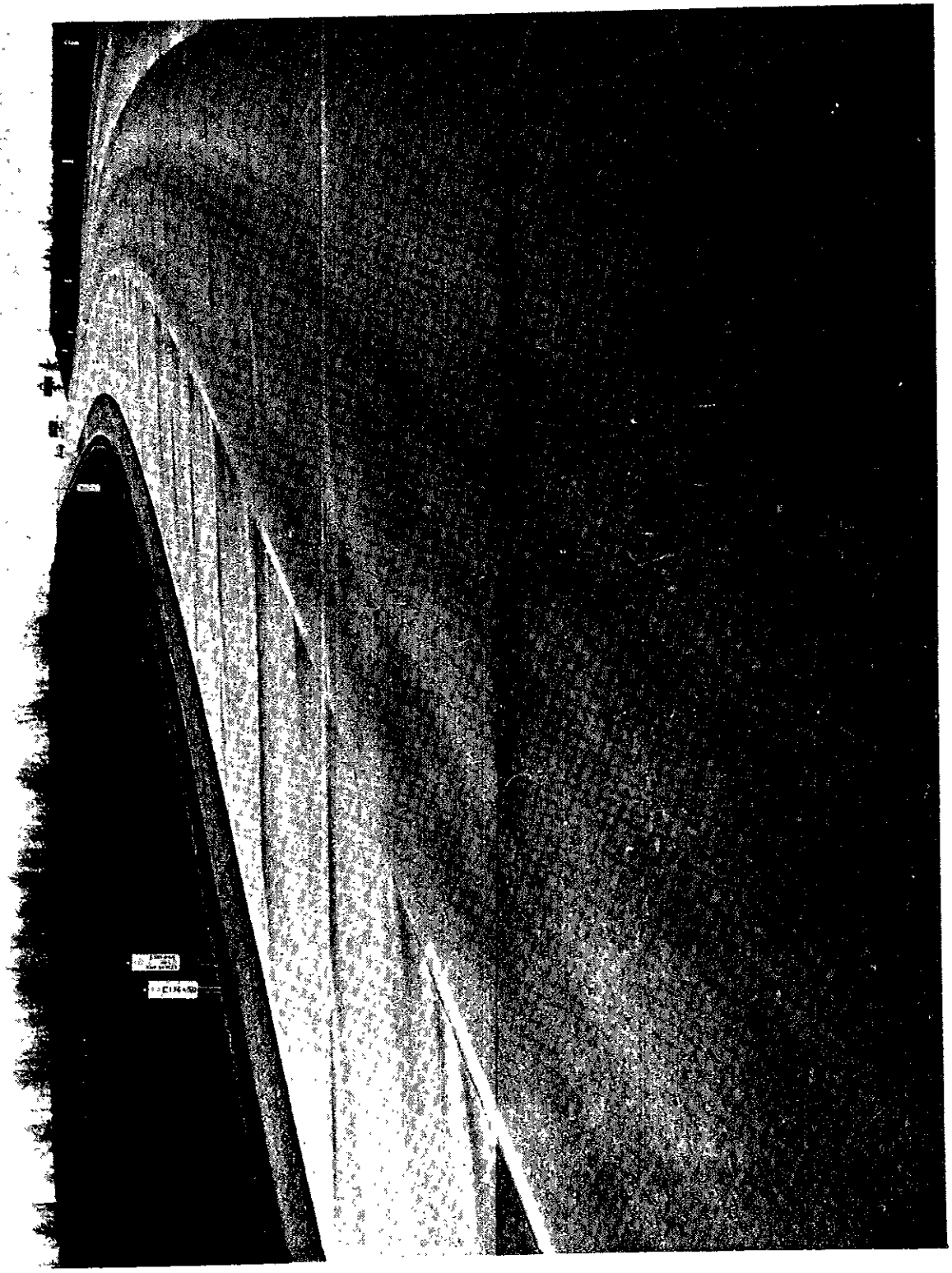
B. Tremper
D. L. Spellman

Fig. 11



View of Curled Pavement Slabs

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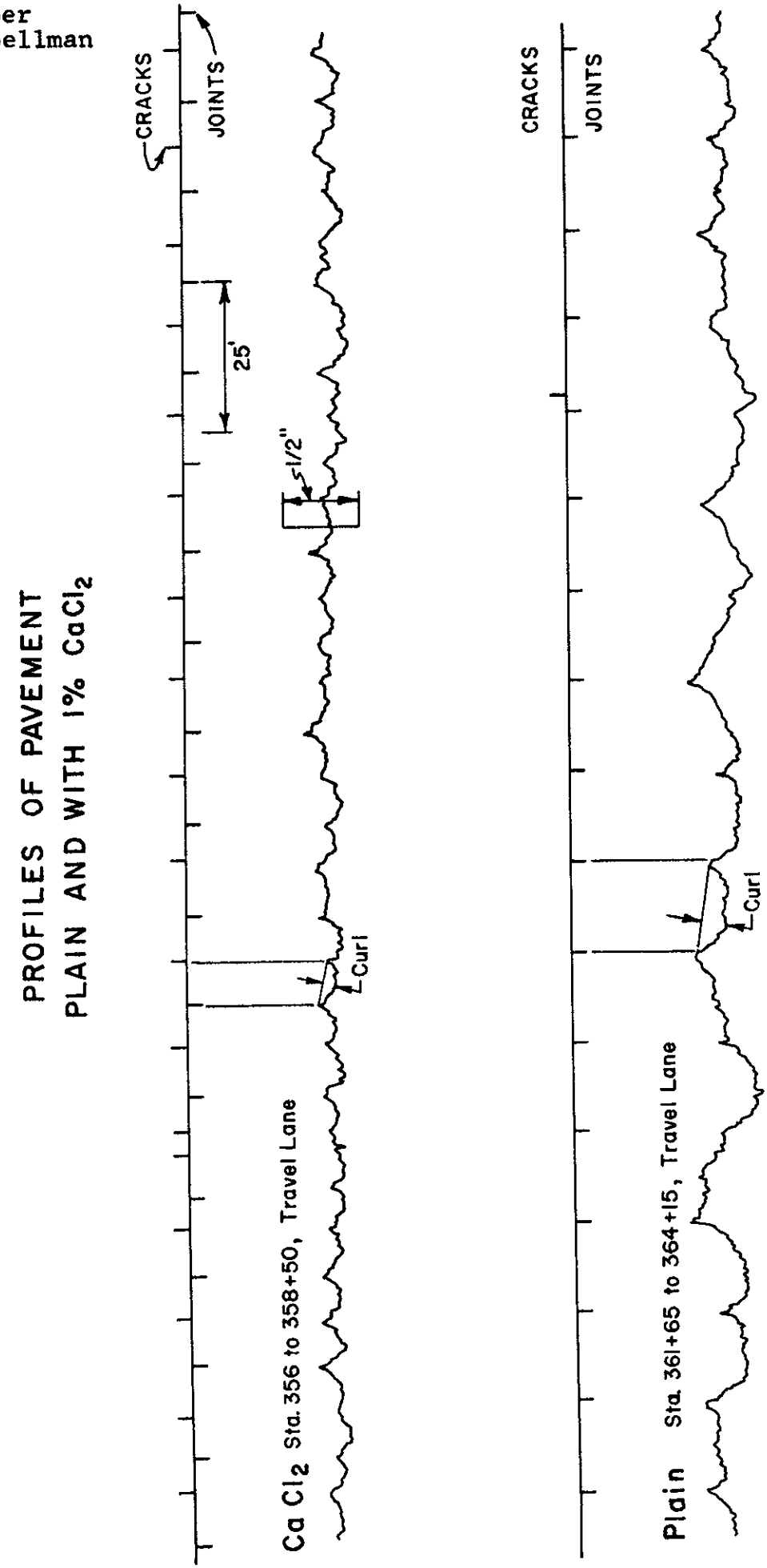
B. Tremper
D. L. Spellman

Figure 12



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View of Pavement Containing Calcium Chloride (Merced County)

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