Shrinkage of Concrete—Comparison of Laboratory and Field Performance

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In general, portland cement concrete, on drying, does not develop an amount of shrinkage detrimental to adequate service; however, there are cases where serviceability is known to have suffered due to an abnormal amount of shrinkage of the hardened concrete. Such distress has occurred in both structures and pavements. One reason for the poor performance was that the acceptability of the work in progress was based largely on strength tests that bore little relationship to shrinkage.

In this paper, factors producing shrinkage of laboratory specimens are reviewed from the literature 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. A combination of unfavorable conditions and materials can increase shrinkage fourfold, an amount conducive to poor performance.

The results of laboratory specimens dried under standard conditions are compared to those 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.

• 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 on 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 of attention that the subject warrants. One reason for this situation is due to the emphasis 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.

Because 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 per-

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Paper sponsored by Committee on Durability of Concrete—Physical Aspects.

formance 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 unsatisfactory performance in 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 recent articles in Engineering News-Record (6, 7) and by a British report (8) published in 1961.

Laboratory studies of shrinkage are fairly numerous and they point out the fact that shrinkage 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 have greater adverse effects and which are more readily susceptible to control in a practical manner. This report attempts to answer 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, as measured on one axis, which results mainly from loss of moisture due to drying. It is recognized that the measured shortening may also partly result from carbonation, but in the early stages of drying the effects of carbonation are believed to be relatively minor. Carbonation shrinkage, as such, is only incidentally discussed in this report.

The studies presented here of the field performance of concrete as affected by drying relate generally to exterior exposure and specifically to highway pavements and building structures. A distinction between pavements and buildings is made because certain members in heated or air-conditioned buildings may be expected to reach a more advanced state of dryness than concrete exposed entirely to outdoor weather does. Further, portions of buildings are subjected to an intermediate degree of exposure. Examples are exterior walls, floor slabs on grade, and the lower portions of interior walls and columns.

The first part of this report deals with the shrinkage of laboratory-made specimens dried under controlled and uniform conditions. The second part deals with the performance of pavements and structures subjected to drying under exterior exposure, and with 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.

Original data in this report are from tests made in the laboratory of the California Division of Highways referred to as "California." Unless otherwise noted, mortar shrinkage tests were made on 1:2 graded Ottawa sand mortar having a flow of 100 to 115 percent. Specimens were 1- by 1- by 11¼-in. prisms with gage studs giving a gage length of 10 in. Four specimens were made from each batch of mortar. They were removed from the molds at 24 hr, placed in water at 73.4 ± 3F to the age of 72 hr, and then measured for length. They were placed on racks in a drying room maintained at 73.4 ± 2F, with a relative humidity of 50 ± 4 percent and with air movement. This resulted in evaporation of water from an atmometer at 3 ± 0.5 ml per hr. At an age of 7 days, they were again measured for length. The average decrease in length during drying expressed as a percentage of 10 in. 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, concrete shrinkage tests were made of 7-sack, 3½-in. 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-in. maximum size. Specimens were 3- by 3- by 11¼-in. prisms with gage studs giving a gage length of 10 in. Three specimens were made from each batch of concrete. They were removed from the molds at 24 hr and stored in a fog room at 73.4 ± 3F to the age of 7 days when they were measured for length. They were then placed on racks in the drying room described for mortar specimens, to an age of 21 days (14 days of drying), when they were again measured for length. The decrease in length during drying, expressed as a percentage of 10 in. of at least 7 specimens of 9, is reported as "shrinkage." Further details of the method (specifically written for testing admixtures) are given in Test Method No. Calif. 530, a publication of the California Division of Highways.

LABORATORY PERFORMANCE

Concrete Composition

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, whereas other data do not show much change. Carlson (13) found that, when a mixed gravel aggregate was used, the cement factor had 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 the corresponding concretes of lower cement factor do.

Lyse (14) reported that shrinkage is proportional to the volume of paste:

$$S = bp \tag{1}$$

in which

b = a coefficient; and
p = absolute volume of water plus cement.

Further, he reported that the quality of paste has little, if any, effect on shrinkage per unit of paste. Pickett (15) found that shrinkage is related to a function of the absolute volume of aggregate:

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

in which

b = a coefficient; and
g = absolute volume of aggregate.

In the absence of air (or if air is calculated as part of the paste), $p = 1 - g$. Whereas Eq. 1 states that shrinkage is directly proportional to the volume of paste, Eq. 2 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 3- by 6-in. cylinders.

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

The data show that the volume of paste increased and the volume of aggregate decreased with increasing cement factor, and that shrinkage did not change (at least not in the direction indicated by the equations of Lyse and Pickett). 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

TABLE 1

EFFECT OF CEMENT FACTOR ON SHRINKAGE OF CONCRETE[1]

Cement Factor (sacks/cu yd)	Concrete Composition by Absolute Volume[2]						Water-Cement Ratio by Wt.	Slump (in.)	Shrinkage[3] (%)
	Cement	Water	Air	Total (paste)	Aggregate	Water + Air			
4.99	0.089	0.202	0.017	0.308	0.692	0.219	0.72	3.3	0.0330
5.99	0.107	0.207	0.016	0.330	0.670	0.223	0.62	3.6	0.0330
6.98	0.124	0.210	0.014	0.348	0.652	0.224	0.54	3.8	0.0289
8.02	0.143	0.207	0.015	0.365	0.635	0.223	0.46	3.8	0.0300
Summary of variances:									
Mean of values		0.2065				0.222			0.0312
Std. dev.		0.003				0.002			0.0021
Coeff. of variation (%)		1.5				0.9			6.7

[1] American River sand and gravel graded to 1-in. maximum.
[2] Average of 3 batches.
[3] Average of nine 3- by 3- by 10-in. prisms cured wet for 7 days, then dried for 14 days.

used, in the range of practical concrete mixes, the cement factor has little effect on shrinkage. Because 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, 1:2½, 1:2, and 1:1½ (Table 2). Corresponding cement factors were 8.0, 9.3, 11.2, and 13.5 sacks per cubic yard. The data show 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. Although the shrinkage of the 1:1½ 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:

Variable	Percent
Unit volume:	
Water	2.3
Water + air	1.7
Shrinkage:	
Dried 4 days	5.9
Dried 7 days	3.2

Although an analysis of variance shows the effect of the cement factor to be significant with respect to shrinkage, this finding is due to the relatively high shrinkage found in the 1:1½ 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.

TABLE 2

EFFECT OF CEMENT FACTOR AND DURATION OF PRELIMINARY WET CURING ON SHRINKAGE OF MORTAR[1]

Cement-Sand Ratio by Wt.	Mortar Composition by Absolute Volume[2]						Shrinkage[3] (%)							
							4-Day Drying				7-Day Drying			
	Cement	Water	Air	Total (paste)	Sand	Water + Air	2-Day Wet Curing	3-Day Wet Curing	7-Day Wet Curing	Average	2-Day Wet Curing	3-Day Wet Curing	7-Day Wet Curing	Average
1:3	0.155	0.242	0.057	0.453	0.547	0.299	0.0421	0.0410	0.0416	0.0416	0.0545	0.0544	0.0550	0.0546
1:2½	0.177	0.246	0.051	0.474	0.526	0.297	0.0420	0.0391	0.0388	0.0400	0.0547	0.0519	0.0528	0.0535
1:2	0.211	0.252	0.037	0.500	0.500	0.289	0.0428	0.0411	0.0407	0.0415	0.0560	0.0536	0.0533	0.0543
1:1½	0.256	0.255	0.033	0.544	0.456	0.288	0.0469	0.0458	0.0442	0.0458	0.0589	0.0572	0.0564	0.0575
Avg.							0.0435	0.0418	0.0413	0.0423	0.0560	0.0542	0.0544	0.0549

[1] Type II, low-alkali cement; graded Ottawa sand mortar, flow 100 to 115 percent.
[2] Average of 3 batches.
[3] Average of 12 specimens from 3 batches.

Carlson found that among the potential compounds in portland cement, their relative contribution to 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 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 investigated was 119 percent of that of Type II cement, the determination being made on 1- by 1- by 10-in. 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 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 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 rate of shrinkage of concrete. He concluded, however, that because many factors affect the rate of shrinkage, and alkalies have many other effects that may affect shrinkage indirectly, one should expect many real and apparent contradictions to his finding that an increase in alkalies retards shrinkage.

Pickett (22) also concluded that the addition of gypsum to the optimum reduces shrinkage by reducing the specific surface of the gel that is formed. He also found that cements 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 2- by 2- by 10-in. specimens of 1:2 concrete sand mortar. Such specimens normally shrink about 0.04 percent in 7 days; therefore, the permissible increase in shrinkage amounts to about 50 percent at this test age.

California has determined the effect of the processing 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 increments to increase the SO_3 contents progressively by 0.5 percent up to 3.0 percent. Test specimens were 1- by 1- by 10-in. prisms of 1:2 graded Ottawa sand mortar which were cured wet for 3 days and then dried for 4 and 11 days. The test results are shown in Figure 1. The increase in shrinkage produced by TDA was considerably less when the SO_3 content of the cement exceeded optimum.

TABLE 3

EFFECT OF SO_3 CONTENT ON SHRINKAGE OF MORTAR AND CONCRETE[1]

SO_3 in Cement (%)	Shrinkage (%)	
	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
Est. optimum	2.2	2.7

[1] Pulverized gypsum added in progressive amounts to Type II, low-alkali cement containing 1.0 percent SO_3. Mortar tests were 1- by 1- by 10-in. prisms of 1:2 graded Ottawa sand mortar cured wet for 3 days, then dried for 4 days. Concrete tests were 3- by 3- by 10-in. prisms of 6-sack concrete, 1-in. maximum size aggregate, 3- to 4-in. slump, cured moist 7 days, then dried for 28 days.

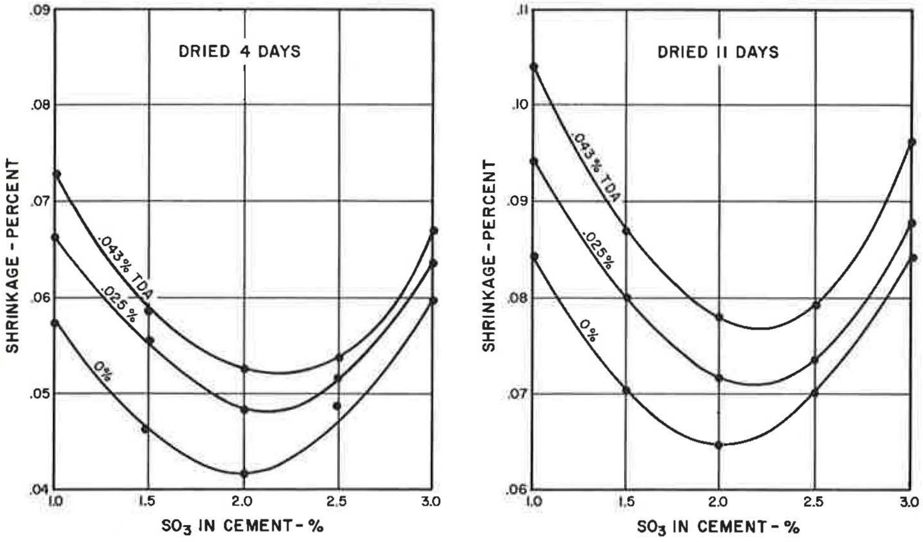

Figure 1. Influence of SO_3 in cement on shrinkage effect of TDA.

An analysis of variance applied to the data of Figure 1 indicates that a reaction occurred between the TDA and the SO_3. In a later discussion of admixtures, it is shown that the effect of variations in the amount of triethanolamine (a constituent of TDA) on the shrinkage of concrete is not proportional to the effect on mortar. It is 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 on mortar, 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 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 were of importance. He concluded that the particular properties of aggregates conducive to tight bond with cement paste remain to be determined.

Carlson (13) also found that among four aggregates studied 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 increases 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 gives the tested aggregates 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 but which have a large effect on concrete shrinkage.

Roper (26) investigated the volume changes of mortars and concretes containing certain South African aggregates which 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 noted 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 may be expected to increase shrinkage (23). As noted earlier, the air entrained by air-entraining admixtures has virtually no effect on shrinkage.

The effect on shrinkage of chemical admixtures is varied and cannot be correlated with a possible reduction in unit water content, which is often 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) (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 is discussed later.

Two compounds frequently used to destroy the set-retarding effect of chemical admixtures and to increase the rate of strength development are calcium chloride and triethanolamine. California test results for the effect of these admixtures are given in Tables 6 and 7, and Figures 2 and 3. The effect on shrinkage is disproportionately large with small amounts of these admixtures, thus 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 4 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.

TABLE 4

RELATIVE SHRINKAGE OF CONCRETE MADE WITH DIFFERENT AGGREGATES[1]

Aggregate (Ref. No.)	Drying Shrinkage[2] (% of control)
1	70
2	76
3	79
4	81
5	83
6	86
7	89
8	89
9	92
10	94
11	95
12	97
13	97
14	97
15	97
16	97
17	100
18	106
19	107
20	110
21	110
22	110
23	112
24	120
25	124
26	129
27	130
28	133
29	145
30	153

[1] Five-sack concrete, 2-in. slump, 1½-in. maximum size aggregate. Specimens were 4- by 5- by 18-in. prisms, moist cured for 7 days, then dried for 28 days. All aggregates were washed, then sieved and recombined to same grading.

[2] Average of 2 to 5 specimens expressed as percentage of control concrete containing aggregate from American River.

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 allowed to dry immediately. California (Table 8 and Fig. 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

TABLE 5

EFFECT OF CHEMICAL ADMIXTURES ON SHRINKAGE SUMMARY OF MISCELLANEOUS TESTS[1]

Type of Admixture	Quantity per Sack of Cement		Maximum Size Aggregate (in.)	Cement Factor (sacks/ cu yd)	Relative Shrinkage Control = 100
	Fl. Oz	Lb			
Hydroxylated carboxylate:					
a	2		1	7.0	100
	4		1	7.0	97
	3		1	7.0	93
	3		1	7.0	94
	2		1	7.0	104
	4		1	7.0	98
		0.5	1	7.0	104
		1.0	1	7.0	104
	2		1	7.0	104
	4		1	7.0	104
	2		1½	5.5	90
	1		1½	6.0	91
	2		1½	6.0	87
	3		1½	6.0	85
b	2.75		1	6.0	143
c	2.5		1	6.0	141
	4.5		1	6.0	161
Lignosulfonate:					
a		0.125	1	7.0	113
		0.25	1	7.0	113
		0.125	1	7.0	110
		0.25	1	7.0	114
		0.125	1	7.0	111
		0.25	1	7.0	114
		0.25	1½	5.5	106
b	4		1	7.0	106
	8		1	7.0	113
	4		1	7.0	106
	8		1	7.0	108
	3.75		1½	6.0	103
	7.5		1½	5.5	106
	7.5		1½	6.0	113
	11.25		1½	6.0	120
c		0.25	1	7.0	137
		0.25	1	7.0	138
		0.15	1	7.0	126
		0.30	1	7.0	144
		0.125	1	7.0	123
		0.25	1	7.0	144
		0.25	1½	6.0	133
		0.20	1	6.0	130
d	4.5		1	7.0	103
	9		1	7.0	106
	3		1½	5.5	97
e		0.125	1	7.0	141
		0.25	1	7.0	155
		0.125	1	7.0	141
		0.25	1	7.0	156
f		0.15	1	7.0	109
		0.30	1	7.0	119
		0.25	1	5.0	101
		0.25	1	6.0	98
		0.25	1	7.0	105
		0.25	1	8.0	99
		0.15	1	7.0	106
		0.30	1	7.0	114
		0.25	1½	5.5	102
		0.25	1	6.0	120
g		0.15	1	7.0	119
		0.30	1	7.0	133
h		0.15	1	7.0	107
		0.30	1	7.0	118
		0.20	1	6.0	106
i	4		1	7.0	111
	8		1	7.0	121
j		0.25	1½	5.5	113
k		0.125	1½	5.5	105
l	6		1½	5.5	131
Table sugar	0.3[2]		1½	5.5	100
unclassified					
a	0.5		1	7.0	94
	1.0		1	7.0	94
b	1.0		1	7.0	100
	2.0		1	7.0	100
c	0.375		1	7.0	100
	0.75		1	7.0	103
	0.375		1	7.0	106
	0.75		1	7.0	103

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[1] 5½- to 8-sack concrete, 3½- to 4-in. slump. Aggregate 1½-in. max. size (concrete wet sieved through ¾-in.) or 1-in. max. size; 3- by 3- by 10-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.

[2] Dry weight.

TABLE 6

EFFECT OF CALCIUM CHLORIDE ADMIXTURE ON SHRINKAGE[1]

Type	Chloride Radical (%)[2]	Slump (in.)	Air (%)	Unit Wt. (pcf)	Water-Cement Ratio (% by wt.)	Cement Factor (sacks /cu yd)	Flow (%)
Fresh concrete[3]	0	3.7	1.6	150.8	0.502	7.01	
	0.04	3.5	1.8	150.5	0.493	7.01	
	0.08	3.5	1.6	150.9	0.492	7.02	
	0.16	3.6	1.9	150.4	0.479	7.01	
	0.32	3.6	2.1	150.5	0.493	7.00	
	0.64	3.5	2.3	150.5	0.478	7.02	
	1.28	3.5	2.6	149.6	0.492	6.97	
Fresh mortar[4]	0				0.363		104
	0.04				0.363		107
	0.08				0.363		106
	0.16				0.363		109
	0.32				0.365		109
	0.64				0.367		108
	1.28				0.390		110

[1] Figure 2 shows shrinkage results.
[2] By weight of cement.
[3] Average of 3 batches; Test Method No. Calif. 530.
[4] Average of 3 batches; 1:2 graded Ottawa sand mortar; Test Method No. Calif. 527.

TABLE 7

EFFECT OF TRIETHANOLAMINE ADMIXTURE ON SHRINKAGE[1]

Type	Triethanolamine (%)[2]	Slump (in.)	Air (%)	Unit Wt. (pcf)	Water-Cement Ratio (% by wt.)	Cement Factor (sacks /cu yd)	Flow (%)
Fresh concrete[3]	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	46.3	6.99	
Fresh mortar	0				0.371		101
	0.03				0.371		101
	0.06				0.371		103
	0.12				0.371		104
	0.24				0.371		104
	0.48				0.371		105

[1] Figure 3 shows shrinkage results.
[2] By weight of cement.
[3] Average of 3 batches; Test Method No. Calif. 530.
[4] Average of 3 batches; 1:3 graded Ottawa sand mortar; Test Method No. Calif. 527.

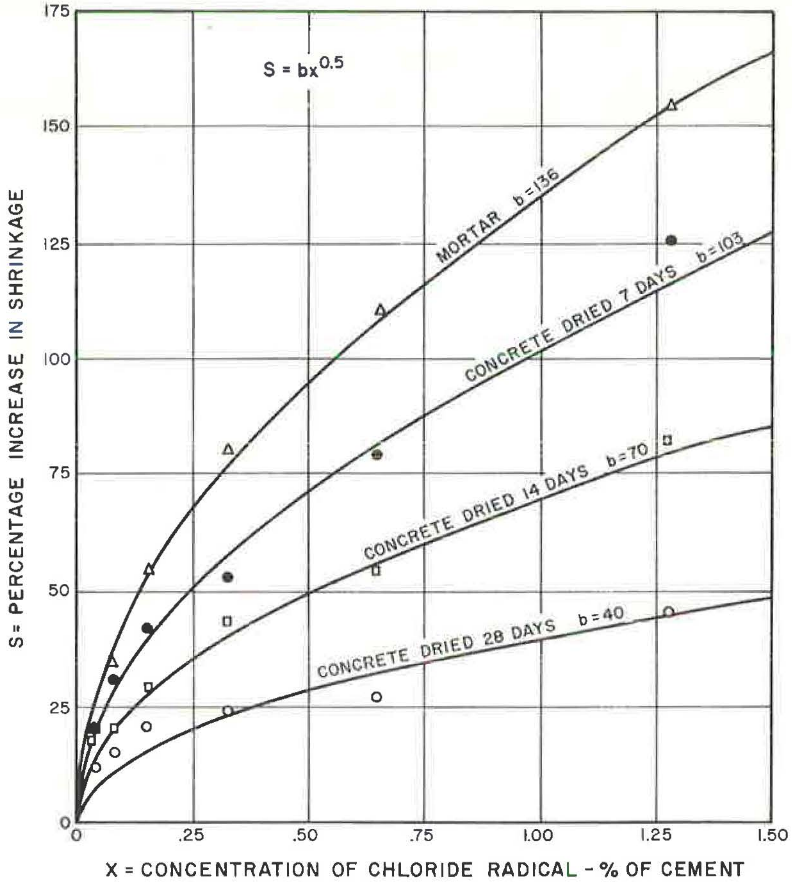

Figure 2. Effect of $CaCl_2$ admixture on shrinkage of mortar and concrete.

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, 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 and 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.

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 3 by 3 in. in section dried under California standard laboratory conditions (temperature, 73.4 ± 3F; relative humidity, 50 ± 4 percent; evaporation from atmometer, 3 ± 0.5 ml per hr), shrinkage due to drying appears to stop after about 32 weeks. Figures 6, 7, and 8 show 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 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 (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 (Table 17 gives additional data). 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

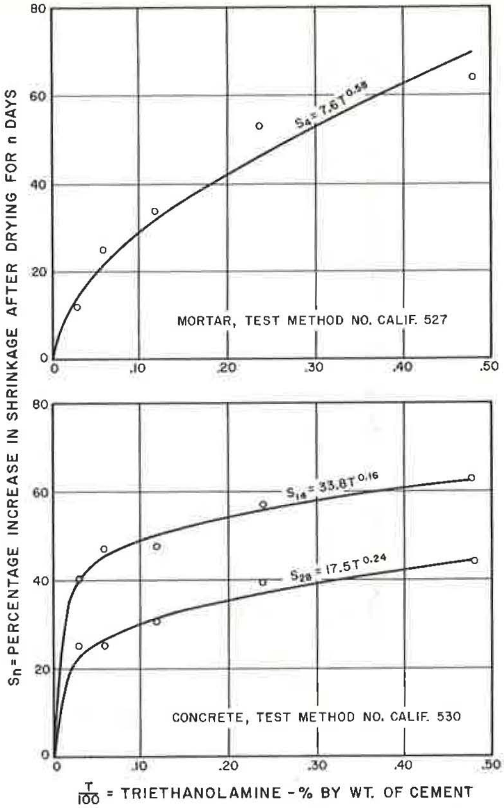

Figure 3. Effect of triethanolamine admixture on shrinkage of mortar and concrete.

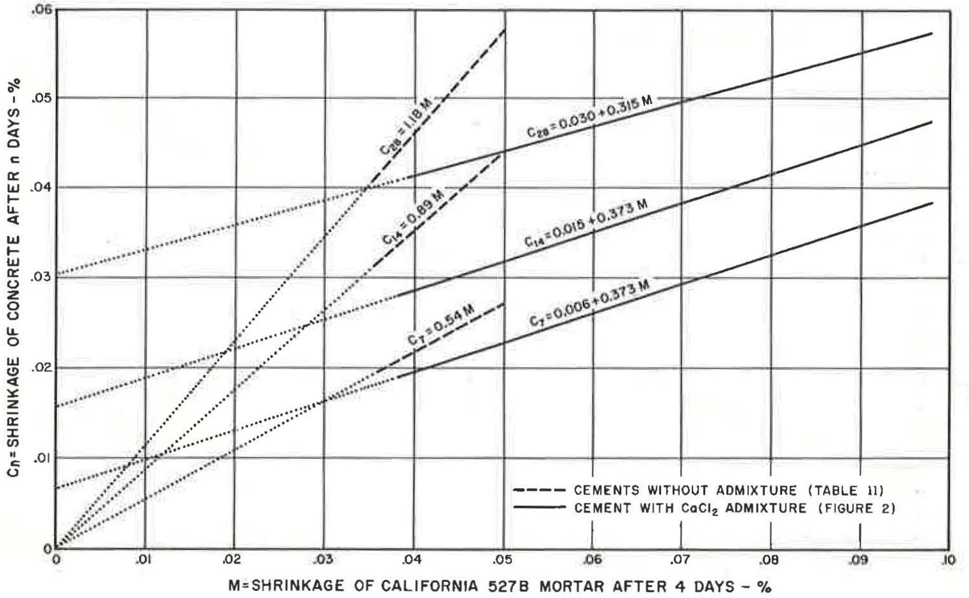

Figure 4. Effect of $CaCl_2$ on shrinkage relationship of mortar and concrete.

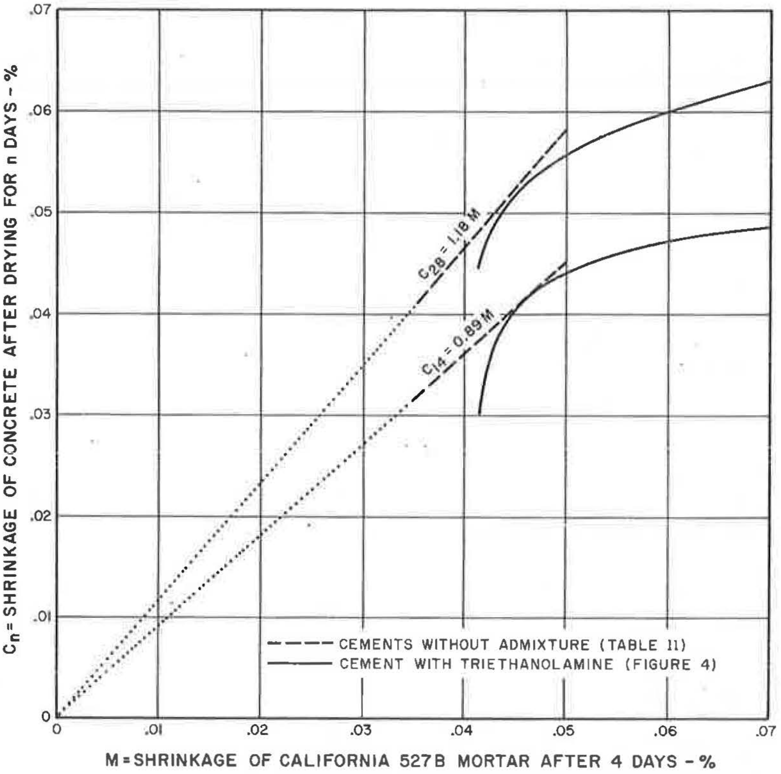

Figure 5. Effect of triethanolamine on shrinkage relationship of mortar and concrete.

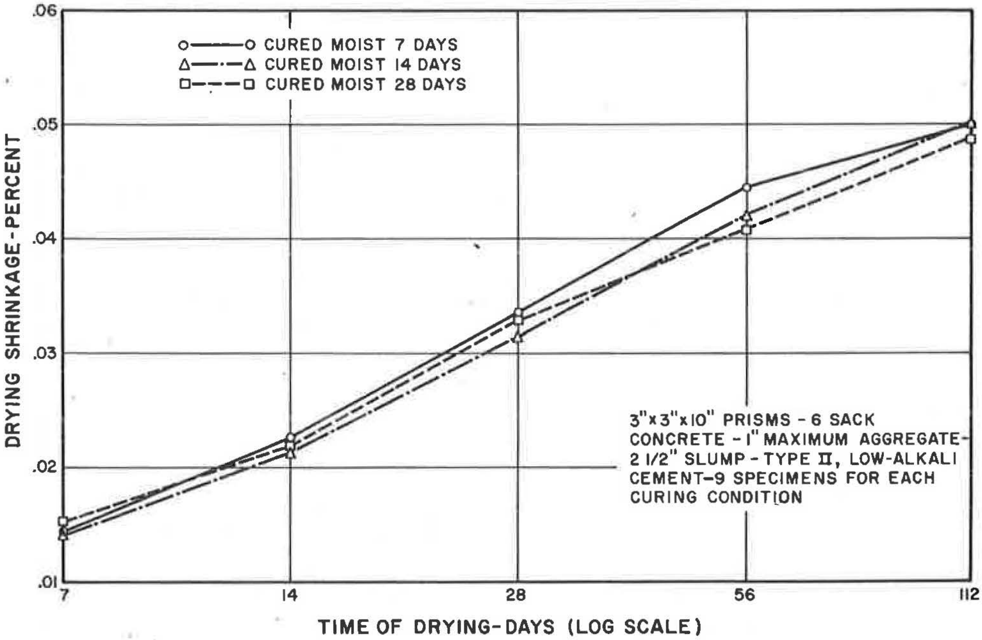

Figure 6. Effect of duration of preliminary moist curing on shrinkage.

TABLE 8

EFFECT OF DURATION OF PRELIMINARY MOIST CURING ON SHRINKAGE OF CONCRETE[1]

Fresh Concrete[2]				Period of Drying (days)	Shrinkage[3] (%)		
Slump (in.)	Air (%)	W/C by Wt.	Cement Factor (sacks)		7-Day Moist Curing	14-Day Moist Curing	28-Day Moist Curing
2.6	1.8	0.512	6.02	7	0.0144	0.0140	0.0153
				14	0.0226	0.0212	0.0218
				28	0.0337	0.0314	0.0328
				56	0.0447	0.0423	0.0412
				112	0.0498	0.0506	0.0492

[1] Type II, low-alkali cement; 1-in. maximum aggregates from American River; nine 3- by 3- by 10-in. prisms (3 selected from each curing period) molded from each batch.
[2] Average of three batches.
[3] Average of nine specimens.

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 lb of water per cubic yard increases shrinkage 160 millionths, or 30 percent. Using this basis the following possible increases in shrinkage result.

Temperature.--Figure 99 of the USBR Concrete Manual (9) shows that 13 pcy of additional mixing water are required for a 20F 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) shows that the use of a slump of 6 to 7 in. requires 17 pcy more water than does a slump of 3 to 4 in. The equivalent increase in shrinkage is 10 percent.

Maximum Size of Aggregate.--Table 3 of ACI Standard 613 (16) indicates that the use of ¾-in. aggregate requires 42 pcy more water than does 1½-in. 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 min in discharging from a transit mixer, a reasonable assumption is that the water demand may be increased by about 15 pcy, 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 previously discussed, and they are believed to be conservative. The table indicates that a fourfold increase in shrinkage is a distinct possibility in many projects. The first four factors listed are those subject to job control under most specifications. 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 which may result from a poor selection of the constituent materials of the concrete.

Analysis of Laboratory Studies

Although methods employed by different investigators varied considerably, in general, mortar specimens were prisms of 1 by 1 to 2 by 2 in. in section. Concrete specimens have ranged from 3 in. in diameter to 4 by 5 in. in section with occasional

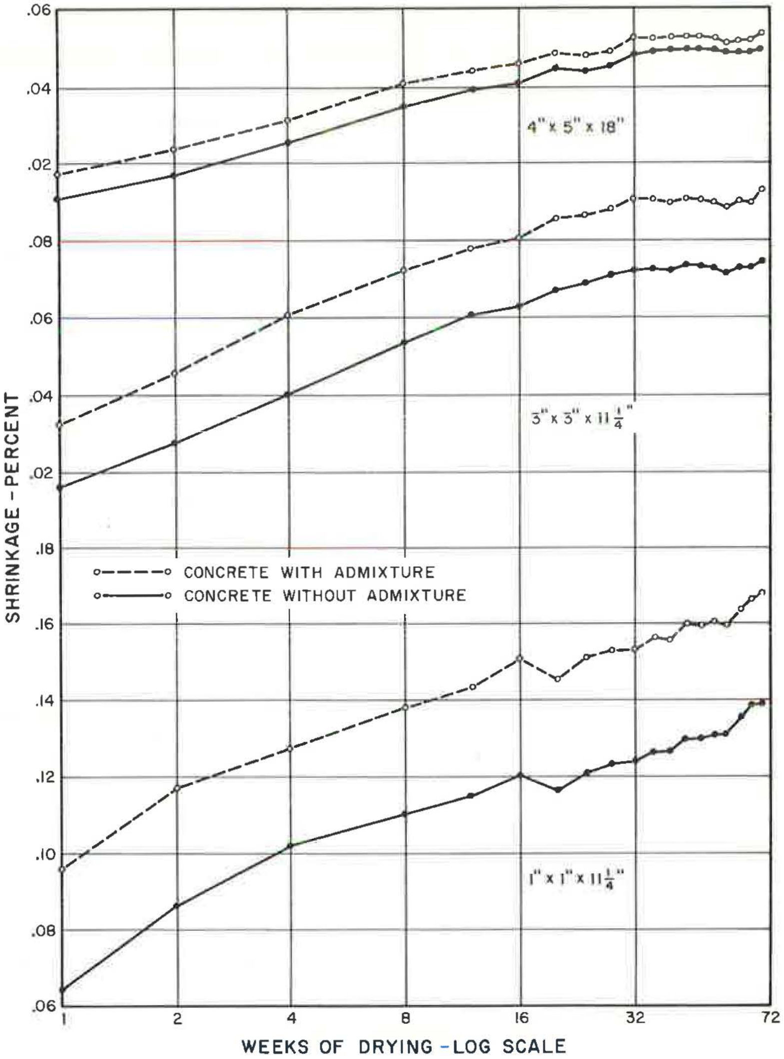

Figure 7. Increase in shrinkage with length of drying period.

tests on larger specimens. Drying has been accomplished at room temperature or in an atmosphere controlled at about 73F and 50 percent 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 in. square provides a significant index of shrinkage. A number have used specimens 3 in. square or 3 in. 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 (Table 16 gives additional data). Data available from two other laboratories, involving cements of other types as well, indicated similar precision of

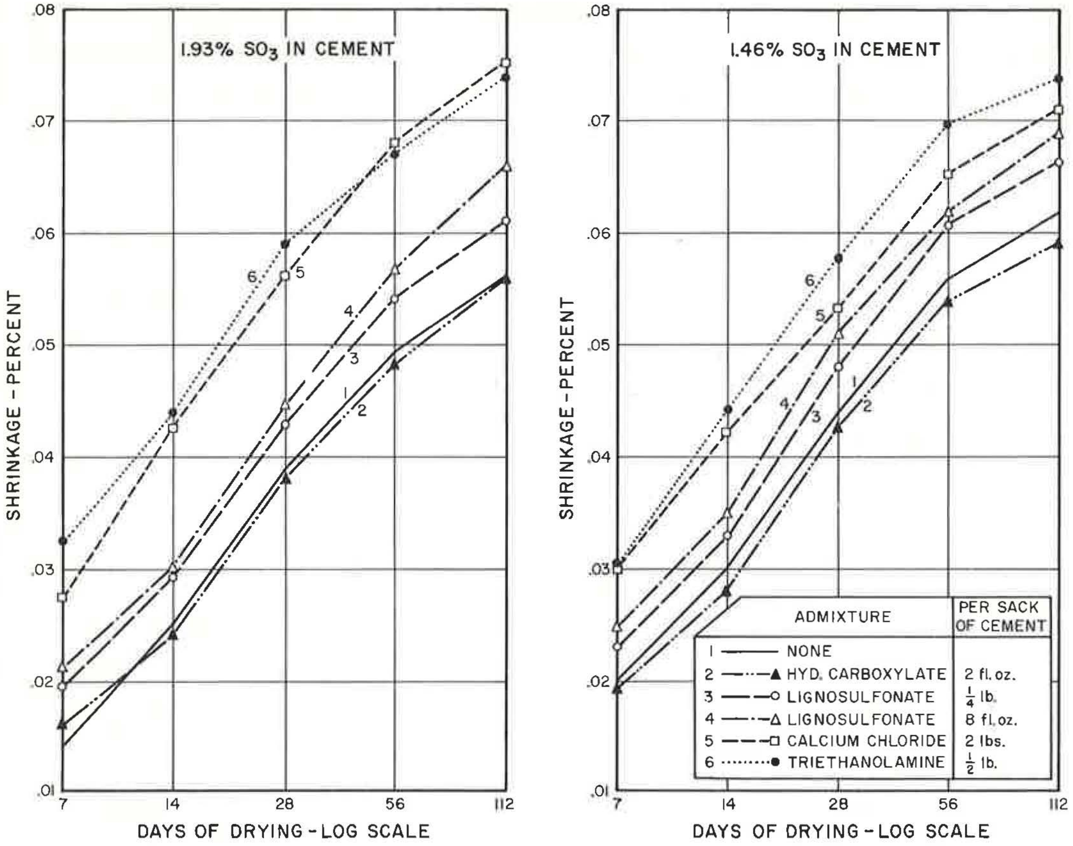

Figure 8. Increase in shrinkage with time of drying.

prediction. The equations were of the form

$$Y = bX \qquad (3)$$

in which 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 Eq. 3 if additions or admixtures that react chemically with the cement are used. For calcium chloride, the equation, although linear, is

$$Y = bX + a \qquad (4)$$

in which the value of a is of considerable magnitude (Fig. 4).

For triethanolamine, a curvilinear relationship was found between the shrinkage of concrete and that of mortar (Fig. 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 of admixtures on shrinkage. 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

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

TABLE 10

CUMULATIVE EFFECT OF ADVERSE FACTORS ON SHRINKAGE[1]

Factor	Equivalent Increase in Shrinkage (%)	Cumulative Effect
Temperature of concrete at discharge allowed to reach 80F, whereas with reasonable precautions, temperature of 60F could have been maintained	8	1.00 × 1.08 = 1.08
Used 6- to 7-in. slump where 3- to 4-in. slump could have been used	10	1.08 × 1.10 = 1.19
Use of ¾-in. max size of aggregate under conditions where 1½-in. size could have been used	25	1.19 × 1.25 = 1.49
Excessive haul in transit mixer, too long a waiting period at job site, or too many revolutions at mixing speed	10	1.49 × 1.10 = 1.64
Use of cement having relatively high shrinkage characteristics	25	1.64 × 1.25 = 2.05
Excessive "dirt" in aggregate due to insufficient washing or contamination during handling	25	2.05 × 1.25 = 2.56
Use of aggregates of poor inherent quality with respect to shrinkage	50	2.56 × 1.50 = 3.84
Use of admixture that produces high shrinkage	30	3.84 × 1.30 = 5.00

[1] Based on effect of departing from use of best materials and workmanship.

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.

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 would never 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 (Fig. 9) found that the relationship is presumably 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. Long periods of drying introduce the hazard of variations in test conditions. This suggests that the specimen should be of the smallest cross-section suitable for the maximum size of aggregate involved in the concrete.

TABLE 11

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

Property	Mortar[1] 4 Days	Concrete[2] 7 Days	14 Days	28 Days
Cement No.				
1	0.0374	0.0219	0.0365	0.0488
2	0.0448	0.0233	0.0365	0.0487
3	0.0386	0.0221	0.0363	0.0598
4	0.0384	0.0226	0.0354	0.0586
5	0.0462	0.0273	0.0470	0.0600
6	0.0394	0.0186	0.0308	0.0544
7	0.0462	0.0228	0.0371	0.0599
8	0.0471	0.0252	0.0388	0.0636
Value of b[3]				
Std. error of est.				
(S_{yx}):		0.54	0.89	1.18
Numerical		0.0021	0.0038	0.0041
Percent		9	9	8

---

[1] Mortar tests by Test Method No. Calif. 527; each value is average of 12 specimens from 3 batches.

[2] 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 average of 12 specimens from 4 batches.

[3] In equation Y = bX.

[4] $\frac{S_{yx}}{\text{Avg. obs. concrete shrinkage}} \times 100.$

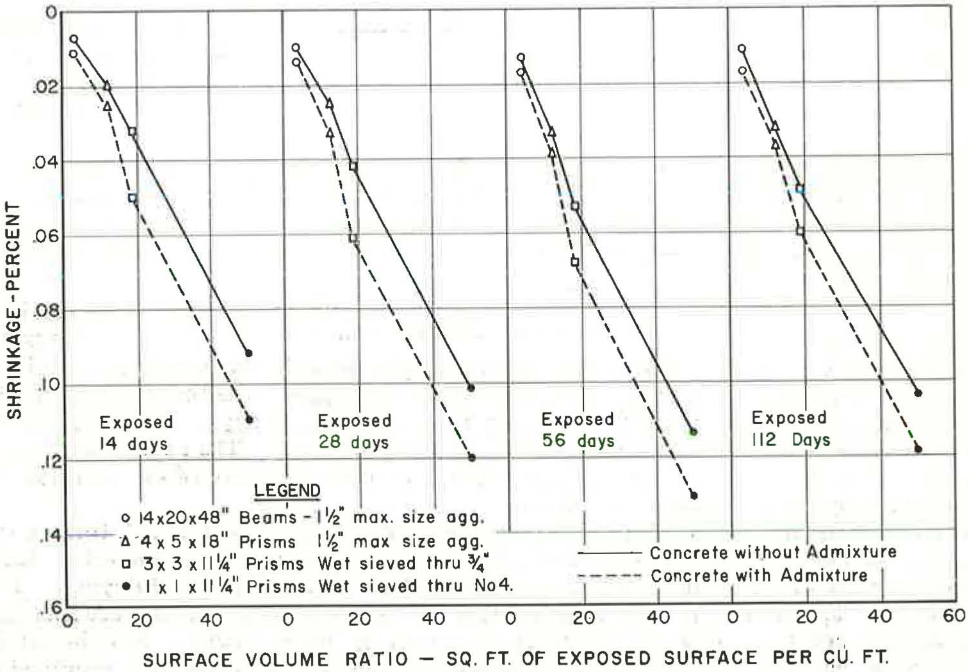

Figure 9. Relationship between shrinkage and surface-volume ratio; specimens exposed outdoors.

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 presented later.

California investigated the effect of a chemical admixture on shrinkage of 14- by 20- by 48-in. beams that were exposed out of doors at Sacramento. The admixture under study was the same as that in 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 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 through three drying seasons. During the last half-year of the second drying season the admixture caused an average increase of 32 percent in shrinkage. At the end of the third drying season, the increase was reduced to 23 percent. The increase is less than 40 percent as found by the laboratory tests of prisms. 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 under all conditions. For specification purposes, the test is as significant as for one of a longer period. Furthermore, early shrinkage may be of greater importance than final shrinkage. The test has the great advantage that the time elapsed 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.

TABLE 12

EFFECT OF A CHEMICAL ADMIXTURE[1] ON SHRINKAGE OF A 14- BY 20- BY 48-IN. BEAM EXPOSED OUTDOORS

Date	Length of Exposure (No. of weeks)	Increase in Shrinkage[2] (% of control concrete[3])[4]
Oct. 1960	8	36
Nov.	12	37
Dec.	16	44
Dec.	20	50
Jan. 1961	24	59
Feb.	28	39
Mar.	32	48
Apr.	36	35
May	40	36
June	44	31
July	48	33
Aug.	52	32
Sept.	56	31
Oct.	61	31
Nov.	65	32
Dec.	69	33
Feb. 1962	78	36
May	93	33
Sept.	111	22
Dec.	123	23

[1] 6-sack concrete, 3- to 4-in. slump, 1½-in. max. size aggregate; moist-cured 7 days, then exposed outdoors at Sacramento, Aug. 1960.

[2] Due to admixture.

[3] Without admixture.

[4] Average of measurements at center and surface.

Figure 10 uses the data of Figure 8 to show the change taking place with time of drying in the ratio of shrinkage produced by admixtures to that of control concrete. Ratios at 7 days are shown to be much higher than those after longer periods of drying. For admixtures 2, 3, and 4 (Fig. 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. Because water-reducing admixtures, if they contain ac-

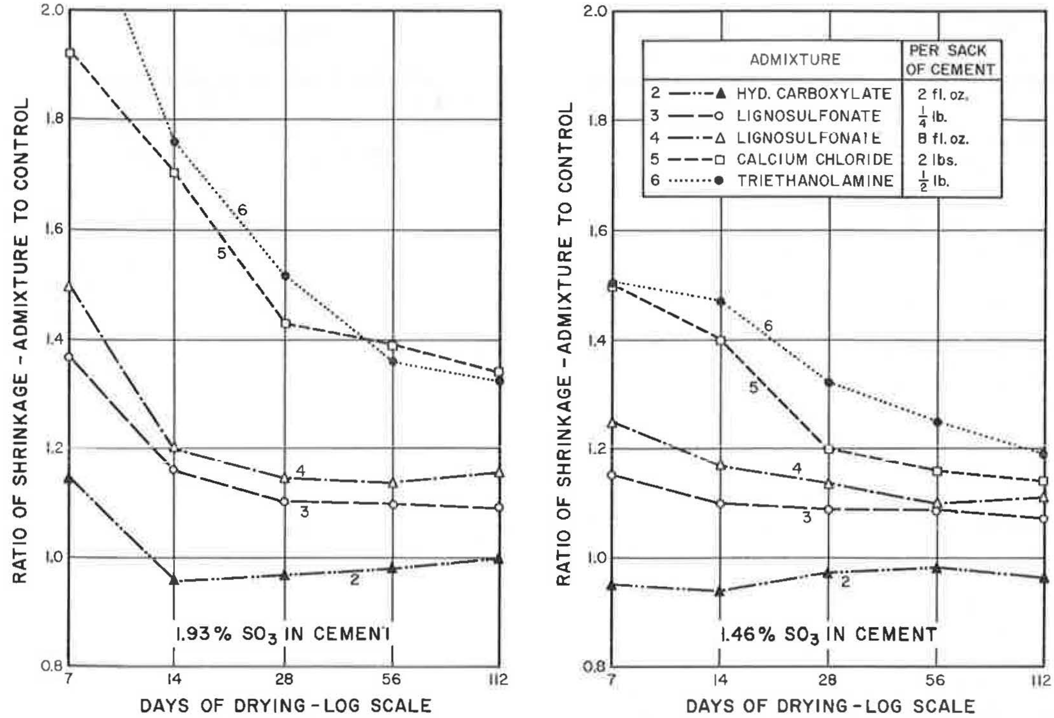

Figure 10. Change in relative shrinkage with drying time.

celerators, 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 indicate that the effect of the cement on shrinkage can be measured satisfactorily in 1- by 1- by 10-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 ¾ in. or larger. The test specimen may be as small as 3 by 3 by 10 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 size under consideration. When specimens larger than 3 by 3 in. in section are required, the period of drying should be extended to yield numerical results of comparable magnitude. Test specimens 4 by 5 in. in cross-section have been used with 1½-in. 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 3- by 3-in. specimens for 14 days.

Pavement Performance Related to Shrinkage

California has investigated the surface contour of pavements by means of 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 a 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 distribution adds to the curling due to uneven moisture distribution. During the greater part of the time, pavement slabs are curled upward. Figure 11 shows pavement slabs as they appeared shortly after dawn. Surface water has drained from the slab ends which have dried sufficiently to show a visible contrast.

Figure 11. Curled pavement slabs.

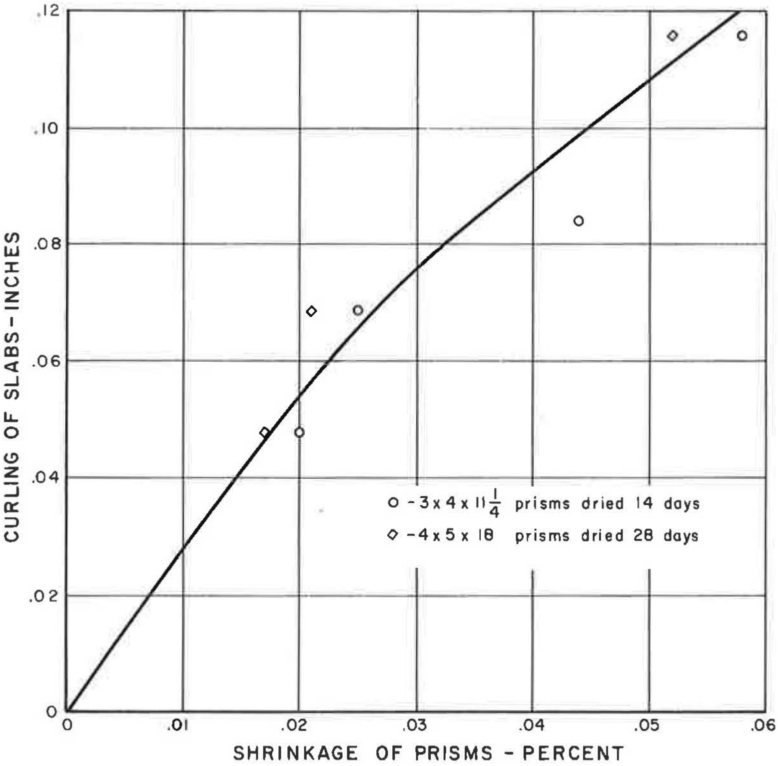

Figure 12. Slab curling related to concrete shrinkage.

TABLE 13

SHRINKAGE AND CURLING IN KANSAS TEST CEMENTS

Cement	Shrinkage (%)	Curling (in./slab)
19A	0.022	0.139
19B	0.027	0.147
19C	0.029	0.182

Hveem (3) found that deflections under a heavy axle load were equal at the end and the 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 (Fig. 12). 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 four-lane divided highway 4½ miles long near Topeka. Among the variables studied were three cements, LTS 19A, 19B, and 19C, representing "old-fashioned," "modern coarse ground," and "modern" cements, respectively. Each cement was used in one-third of the experimental sections which were 1,000 ft in length. Results of shrinkage tests for 2- by 2- by 11-in. prisms of concrete containing the cements after drying for 1 month are given in Table 13.

In 1956, when the pavement was 7 years old, California obtained profilograms of the pavement using a 25-ft manual profilograph. The average amount of permanent curling of slabs containing each cement was measured from the profilograms (Table 13).

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.

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 lb per sack of cement may be expected to increase the shrinkage of concrete by 40 to 70 percent as measured by Test Method No. Calif. 530. The effect of using 1 lb 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 ft 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 14 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 in the outer, or driving, lane containing calcium chloride have cracked transversely at about the midpoint. The amount of curling in 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 13 shows profilograms of the Merced County pavement. This figure also shows the method of measuring slab curling. Figure 14 shows the section containing calcium chloride. Although both lanes contain calcium chloride, cracking has developed only in the outer lane which receives heavy truck traffic on this 4-lane divided highway.

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.

TABLE 14

EFFECT OF CALCIUM CHLORIDE ADMIXTURE ON PERFORMANCE OF PAVEMENTS[1] IN CALIFORNIA

Location (county)	Date Constr.	Age at Survey (yr)	Length of Sections (ft)	Section[2] Contains $CaCl_2$	$CaCl_2$ per Sack of Cement (lb)	Avg. Curl per Slab[3] (in.)	Slabs (%)			
							With Transverse Cracks	With Longitudinal Cracks	With Partial Cracks	With Corner Breaks
Merced	1955	6	840	Yes	1	0.20	77	29	29	2.0
				No[4]	-	0.11	13	0	20	2.0
Sacramento-San Joaquin	1957	4	9,800	Yes	2	0.09	14	0	0	1.8
				No[5]	-	0.06	8	0	0	0.1
Santa Barbara	1956	5	650	Yes	2	0.13	19	0	13	0
				No[4]	-	0.09	7	0	0	0
San Diego	1955	6	1,050	Yes	2	0.16	0	0	0	0
				No[4]	-	0.14	0	0	0	0

[1] All slabs 15 ft between weakened plane joints. Surveys made in outer, traveled lane of divided highways, except in San Diego which is an inner, passing lane.

[2] Length of section not containing $CaCl_2$ approximately equal to that with $CaCl_2$.

[3] From profilograms.

[4] In same lane and adjacent to section with $CaCl_2$.

[5] Opposite section with $CaCl_2$.

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 at Sacramento. Weather locations at other sites may be expected to result in different rates and degrees of drying. 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 ft below to 6,000 ft above sea level, and from moist coastal to arid desert climates.

During July 1960, two 1½-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

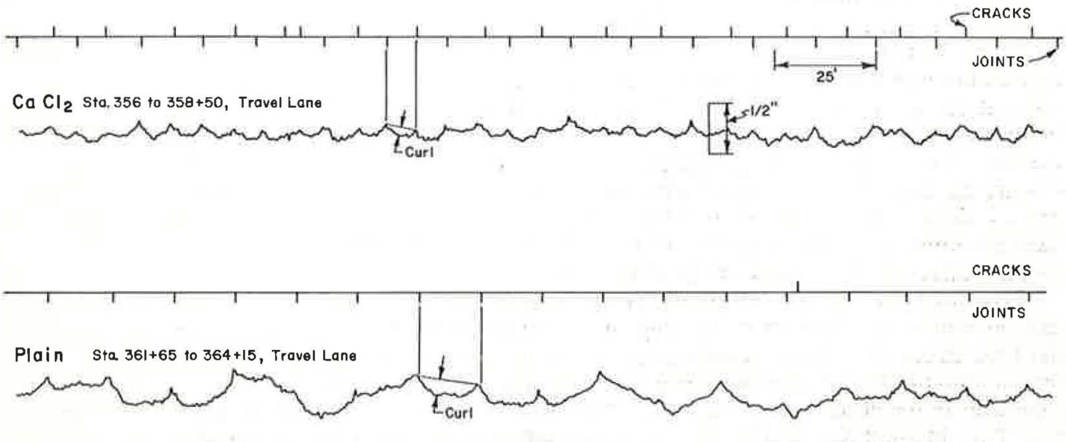

Figure 13. Profiles of pavement, plain and with 1 percent $CaCl_2$.

Figure 14. Pavement containing $CaCl_2$, Merced County.

3 and 5 in. Brass tubes 1 in. 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 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 70F 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 given in Table 15. 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 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-in. depth and 70 percent at the 5-in. depth. Thus, the typical expectation in California is that concrete in structures will reach an average relative humid-

TABLE 15

TEMPERATURE AND RELATIVE HUMIDITY IN CONCRETE OF EXISTING BRIDGES IN CALIFORNIA

Location	Elevation Above Sea Level (ft)	Year Built	Date of Test (mo-yr)	At 2- to 3-In. Depth		At 4- to 5-In. Depth	
				Temp. (°F)	Rel. Hum. (%)	Temp. (°F)	Rel Hum. (%)
Br. No. 54-500R Mojave Desert near Victorville	3,000	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[1]	58	72[1]
Br. No. 57-332L Southern Coast near San Diego	10	1956	8-60	74	80	71	81
			1-61	58	76[1]	54	79
			4-61	64	77	61	77[1]
			8-61	71	79	68	80
			11-61	68	77	68	79
Br. No. 36-65 Central Coast near Santa Cruz	10	1947	9-60	59	77	57	80
			1-61	49	76	46	77[1]
			4-61	54	78	50	79
			8-61	64	79	61	82
			11-61	54	75[1]	54	78
Br. No. 4-84R Northern Coast near Eureka	10	1929	9-60	54	84[1]	54	86
			1-61	48	86	48	86
			4-61	53	84[1]	53	84[1]
			8-61	57	86	60	87
			11-61	53	86	53	87
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[1]	61	75
			12-61	57	80	53	68[1]
Br. No. 19-106L Sierra Nevada Range near Kingvale	6,000	1959	8-60	57	70	57	77
			1-61	32	72	32	72
			4-61	45	72	47	69[1]
			8-61	68	70	67	75
			10-61	39	66[1]	38	69[1]
Br. No. 48-22 East of Sierras near Bishop	4,400	1949	8-60	83	50	80	60
			1-61	53	47[1]	52	51
			4-61	74	49	74	57
			8-61	85	48	85	57
			11-61	50	47[1]	52	50[1]
Br. No. 58-277 Imperial Valley near Salton Sea	-200	1950	8-60	88	58	88	67
			1-61	64	71	61	63[1]
			4-61	99	72	95	73
			8-61	101	67	103	71
			11-61	68	56[1]	68	63[1]

[1] Minimum observed at location.

ity 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 provide 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.

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 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.

The decks of twin, parallel bridges over Webber Creek in El Dorado County were completed under contract in October 1962. The bridges are of composite reinforced concrete and steel girder design. Each is approximately 540 ft in length and is divided by expansion joints into four sections of approximately equal length. Four combinations of two cements and two aggregates were used in replicate in the eight-deck sections. One of the cements (No. 1) is high in C_3A and alkalies. Cement No. 2 is a Type II, low-alkali cement. The two aggregates produce concrete of greatly different shrinkage as measured by laboratory tests. Thus, concrete of four degrees of shrinkage was produced. The decks are instrumented to provide data of strain and deflection, which, together with visual observations over a period of years, will give information on the effect of concrete shrinkage of the performance of bridge decks of this design. Other data secured during the progress of the work now afford useful comparisons with the results of shrinkage tests described previously in this report.

TABLE 16

TESTS OF JOB-MIXED CONCRETE FOR WEBBER CREEK BRIDGES[1]

Aggregate	Cement[2]	Shrinkage (%)								Curl[5] (in.)
		3- by 3- by 11¼-In. Prisms[3]				4- by 5- by 18-In. Prisms[4]				
		7-Day Drying	14-Day Drying	28-Day Drying	56-Day Drying	7-Day Drying	14-Day Drying	28-Day Drying	56-Day Drying	
A	1	0.041	0.058	0.076	0.092	0.025	0.037	0.052	0.071	0.116
	2	0.030	0.044	0.061	0.077	0.021	0.030	0.043	0.060	0.083
B	1	0.018	0.025	0.033	0.040	0.010	0.016	0.021	0.028	0.069
	2	0.015	0.020	0.026	0.034	0.008	0.012	0.017	0.023	0.048

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[1] Cement content, 6 sacks per cu yd; maximum size of aggregate, 1½ in.; specified slump, 4 in. maximum.

[2] Contraction of cement in mortar (Calif. 527-B): cement 1 (average of 4 job samples), 0.0547 percent; cement 2 (average of 4 job samples), 0.0373 percent.

[3] Concrete wet sieved through 1-in. sieve; average of 18.

[4] Average of 12.

[5] Curling of slabs on grade; measurements at time of maximum curling for season (40 days).

As the concrete was being placed in the decks, one 12-ft by 12-ft by 8-in. slab was cast on a cement-treated base and twelve 4- by 5- by 18-in. prisms and eighteen 3- by 3- by 11¼-in. prisms were molded from each aggregate-cement combination. Concrete placed in the smaller molds was wet sieved through a 1-in. sieve.

The prisms were moved to the laboratory at Sacramento on the day after molding. They were cured in fog at 73.4F to the age of 7 days. They were then measured for initial length and were placed in storage at 73.4F and 50 percent relative humidity. Changes in length were measured after 7, 14, 28, and 56 days of drying.

A small hole surrounded by a metal ring was cast near each corner and at the center of the slabs on grade. Metal rods were driven through the holes 4 ft into the subgrade, the upper half of the rod being protected from contact with the soil by a metal sleeve. Measurements of relative elevation were made with a dial gage supported on

TABLE 17

PREDICTION OF CONCRETE[1] SHRINKAGE[2] FROM MORTAR SHRINKAGE

Prism (in.)	Days of Drying	Aggt.	Cement	b[2]	Shrinkage (%)		Difference	
					Predicted[3]	Observed	Numerical	%
3 × 3 × 11¼	7	A	1	0.78	0.043	0.041	0.002	5
			2		0.029	0.030	0.001	3
		B	1	0.37	0.019	0.018	0.001	6
			2		0.014	0.015	0.001	7
	14	A	1	1.12	0.061	0.058	0.003	5
			2		0.042	0.044	0.002	5
		B	1	0.50	0.027	0.025	0.002	8
			2		0.019	0.020	0.001	5
	28	A	1	1.51	0.083	0.076	0.007	9
			2		0.056	0.061	0.005	8
		B	1	0.65	0.036	0.033	0.003	9
			2		0.024	0.026	0.002	8
	56	A	1	1.86	0.100	0.092	0.008	9
			2		0.070	0.077	0.007	9
		B	1	0.80	0.044	0.040	0.004	10
			2		0.030	0.034	0.004	12
4 × 5 × 18	7	A	1	0.51	0.028	0.025	0.003	12
			2		0.019	0.021	0.002	10
		B	1	0.20	0.011	0.010	0.001	10
			2		0.007	0.008	0.001	12
	14	A	1	0.74	0.040	0.037	0.003	8
			2		0.028	0.030	0.002	7
		B	1	0.30	0.016	0.016	0.000	0
			2		0.011	0.012	0.001	8
	28	A	1	1.04	0.057	0.052	0.005	10
			2		0.039	0.043	0.004	9
		B	1	0.42	0.023	0.021	0.002	10
			2		0.016	0.017	0.001	6
	56	A	1	1.43	0.078	0.071	0.007	10
			2		0.054	0.060	0.006	10
		B	1	0.56	0.030	0.028	0.002	7
			2		0.021	0.023	0.002	9

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[1] From Webber Creek bridges.

[2] In equation $Y = bX$.

[3] From mortar shrinkage X (Calif. 527B) using equation $Y = bX$.

the metal ring and with the stem in contact with the upper end of the rod. The difference between the average elevation of the four corners and the center of the slab was reported as "curl." Measurements were not corrected for warping due to temperature differential because it was not large and because each of the slabs was subjected to the same conditions.

Curling increased with time but leveled off at about 40 days, after which weather conditions caused a reduction in curling. There were no further increases up to the age of 100 days, the time of the most recent measurement.

Table 16 gives shrinkage results of the cements in mortar (Test Method No. Calif. 527B) and of the concrete prisms. Curl in the slabs on grade at the age of 40 days is also given in the table. The data of these tests may be used to determine agreement with certain findings presented earlier in the report.

Shrinkage of Cement in Concrete Related to That in Mortar. —For each of the cements there are two sizes of concrete test specimen, two aggregates, and four drying periods, making a total of 16 values for comparison with the cement mortar values. Predictions of concrete shrinkage Y from the mortar shrinkage X using Eq. 3, in which the value of b was selected for best fit, with differences from observed values given in Table 17. In most instances the predicted shrinkage differs from that observed by not more than 10 percent of the observed value. Two of the three cases in which the difference exceeds 10 percent are for 4- by 5- by 18-in. specimens dried for 7 days, in which the numerical values are very low and differences expressed as percentages are magnified. The results confirm those reported in Table 11 and discussed under "Analysis of Laboratory Studies."

Effect of Individual Factors on Cumulative Shrinkage. --The data of Table 16 have been used to calculate the shrinkage of the aggregate-cement combination A-1 from the remaining data. Table 18 gives the results of these calculations and compares them to the observed results. Separate calculations have been made under two assumptions:

1. The cumulative shrinkage is the sum of the individual factors; i.e.,

$$\text{A-1} = (\text{A-2} - \text{B-2}) + (\text{B-1} - \text{B-2}) + \text{B-2} \tag{5}$$

2. The cumulative shrinkage is the product of the ratios of the individual factors; i.e.,

$$\text{A-1} = \frac{\text{A-2}}{\text{B-2}} \times \frac{\text{B-1}}{\text{B-2}} \times \text{B-2} \tag{6}$$

TABLE 18

EFFECT OF INDIVIDUAL FACTORS ON CUMULATIVE SHRINKAGE[1]

Prism (in.)	Age (days)	Shrinkage[2] (%) Observed	Assumption 1	Assumption 2
3 × 3 × 11¼	7	0.041	0.033	0.036
	14	0.058	0.049	0.055
	28	0.076	0.068	0.075
	56	0.092	0.083	0.091
4 × 5 × 18	7	0.025	0.023	0.026
	14	0.037	0.034	0.040
	28	0.052	0.047	0.053
	56	0.071	0.065	0.073

[1] Concrete from Webber Creek bridges.

[2] Of aggregate-cement combination A-1 as observed and as calculated under two assumptions.

The data show that the shrinkage of combination A-1 is consistently underestimated when calculated under the first assumption, but is closely approximated under the second. This result confirms the finding that was developed from the data of Table 9 and discussed under "Combined Effect of Unfavorable Factors."

Slab Curling Related to Concrete Shrinkage. —It is obvious from Table 16 that the order of increasing slab curling is the same as that of shrinkage of the test specimens. Figure 12 shows the relationship of slab curling to shrinkage of 3- by 3- by 11¼-in. prisms after drying for 14 days and of 4- by 5- by 18-in. prisms after drying for 28 days. Considering that job-mixed concrete was used, the results are impressive in indicating that, under similar exposure, the amount of curling developed in pavement slabs is approximately proportional to the shrinkage of laboratory test specimens, also discussed in relation to the Topeka test road under "Pavement Performance Related to Shrinkage."

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 ft 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 job and other sands, and also tests of concrete of job proportions. Shrinkage of the job mortar after 40 weeks of drying was about twice that of Ottawa sand mortar 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 nonsymmetrical position of the reinforcement. He found experimentally that, in nonsymmetrical 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 upward curling typical of nonreinforced 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 which 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 ASSHO Road Test (33).

ANALYSIS 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 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 on 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, though important, is much less than is possible through control of materials under specification requirements that are not presently in widespread use.

The amount of tolerable shrinkage 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 visually evident. 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 severalfold 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 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 cooperated 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 locally available 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 nonreinforced 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 just described, 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.

REFERENCES

1. "ACI Manual of Concrete Inspection." American Concrete Institute, 3rd ed. (1955).
2. Chapman, C. M., "Influence of Aggregates Upon Shrinkage of Mortar and Concrete." Proc., ASTM, 23: pt. II, pp. 767-777 (1924).
3. Hveem, F. N., "Slab Warping Affects Pavement Performance." Proc., ACI, 47: 797-808 (1951).
4. Jackson, F. H., "Why Type II Cement?" Discussion by B. Tremper, Proc., ASTM, 50:1225-1227 (1950).

5. Tremper, B., "Control of Gypsum in Portland Cement." Author's Closure, Proc., ASTM, 59:1109-1110 (1959).
6. "Shrinkage Control Cuts Deck Cost." Eng. New-Record, p. 35 (May 10, 1962).
7. "TWA's Concrete Wing-Roofed Terminal Now Ready for Flight." Eng. News-Record, pp. 48-50 (May 31, 1962).
8. Fulton, F. S., "A Co-Ordinated Approach to the Shrinkage Testing of Concretes and Mortars." Mag. Concrete Research (London), 13: No. 39, pp. 133-140 (1961).
9. "Concrete Manual." U. S. Bureau of Reclamation, 6th ed. (1955).
10. Walker, S., and Bloem, D. L., "Effects of Aggregate Size on Properties of Concrete." Proc., ACI, 27:283-298 (1960).
11. Keene, P. W., "The Effect of Air-Entrainment on the Shrinkage of Concrete Stored in Laboratory Air." Mag. Concrete Research (London), 13: No. 38, pp. 55-60 (1961).
12. Davis, R. E., "A Summary of the Results of Investigations Having to Do with Volumetric Changes in Cements, Mortars and Concretes Due to Causes Other Than Stress." Proc., ACI, 26:407-443 (1930).
13. Carlson, R. W., "Drying Shrinkage of Concrete as Affected by Many Factors." Proc., ASTM, 38: pt. II, pp. 419-440 (1938).
14. Lyse, I., "Shrinkage of Concrete." Proc., ASTM, 35:383-395 (1935).
15. Pickett, G., "Effect of Aggregate on Shrinkage and a Hypothesis Concerning Shrinkage." Proc., ACI, 52:581-590 (1956).
16. American Concrete Institute, "Recommended Practice for Selecting Proportions for Concrete." Proc., ACI, 51:49-64 (1954).
17. Lerch, W., "Influence of Gypsum on Hydration and Properties of Portland Cement Pastes." Proc., ASTM, 46:1252-1297 (1946).
18. ASTM Committee C-1, "The Optimum Gypsum Content of Portland Cement." ASTM Bull. 169, 39-45 (Oct. 1950).
19. Swayze, M. A., "Volume Changes in Concrete." Materials, Research and Standards, 1:700-704 (Sept. 1961).
20. Haskell, W. E., "Three Factors Govern Optimum Gypsum Content of Cement." Rock Products, 62:108 (April 1959).
21. Pickett, G., "Effect of Gypsum Content and Other Factors on Shrinkage of Concrete Prisms." Proc., ACI, 44:149-175 (1947).
22. Pickett, G., "Shrinkage Stresses in Concrete, Part 2." Proc., ACI, 42:361-398 (1946).
23. Davis, R. E., Hanna, W. C., and Brown, E. H., "Strength, Volume Changes and Sulfate Resistance of Mortars Containing Portland-Pozzolan Cements." ASTM Special Tech. Publ. 99, 131-155 (1949).
24. Carlson, R.W., "The Chemistry and Physics of Concrete Shrinkage." Proc., ASTM, 35: pt. II, pp. 370-379 (1935).
25. Hveem, F. N., and Tremper, B., "Some Factors Influencing Shrinkage of Concrete Pavements." Proc., ACI, 53:781-789 (1957).
26. Roper, H., "Volume Changes of Concrete Affected by Aggregate Type." Jour. PCA Research and Development Lab., 2:13-19 (Sept. 1960).
27. Powers, T. C., "Causes and Control of Volume Change." Jour. PCA Research and Development Lab., 1:29-39 (Jan. 1959).
28. Carlson, R. W., "Drying Shrinkage of Large Concrete Members." Proc., ACI, 33:327-336 (1927).
29. Pickett, G., "Shrinkage Stresses in Concrete, Part I." Proc., ACI, 42:165-204 (1946).
30. Keeton, J. R., "Time Dependent Deformations of Plain Concrete." HRB Proc., 39:310-335 (1960).
31. Miller, A. L., "Warping of Reinforced Concrete Due to Shrinkage." Proc., ACI, 54:939-950 (1958).
32. McMillan, F. R., and Tyler, I. L., "Long-Time Study of Cement Performance in Concrete, Chapter 1, History and Scope." Proc., ACI, 44:441-453 (1948).
33. "The AASHO Road Test, Report 5, Pavement Research." HRB Special Report 61E (1962).