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**16. ABSTRACT**

Proposals involving tests for drying shrinkage of neat pastes and mortars as measures of the performance of Portland cement in concrete have been made recently. The author has made such tests of 40 cements that previously had been tested in concrete mixtures for drying shrinkage as developed by 3x3x10-inch specimens subjected to drying at 73*F and 50 per cent relative humidity.

The shrinkage of the concrete bars after one year of drying is considered to be close to the ultimate shrinkage. The shrinkage developed by mortar and neat paste specimens is compared to that of the concrete specimens that had been dried for one year.

"No sort of short-time tests on neat pastes or mortars at 3, 7 or even 28 days can hope to approximate the ultimate shrinkage of cement in concrete, which is what we are interested in from a structural standpoint."

Autogenous volume changes differentially affect the relationship between loss of water and drying shrinkage when test specimens contain different original water-cement ratios.

"It therefore seems inconsistent to rely on the behavior of either neat pastes or rich mortars to predict the ultimate shrinkage of concrete, especially if the tests are concluded at early ages. The comparative data here presented appear entirely too erratic for any such reliance.

"The general conclusion to be based on the outcome of the tests here presented is that if information is desired on the shrinkage of cement in concrete, the test specimens should be of concrete."

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STATE OF CALIFORNIA
DEPARTMENT OF PUBLIC WORKS
DIVISION OF HIGHWAYS

Discussion

of

"VOLUME CHANGES IN CONCRETE"

by
Myron A. Swayze

Presented at Meeting of ASTM Committee C-1
Denver, Colorado, December 6, 1960

9

by
Bailey Tremper
Supervising Materials and Research Engineer

60-18

January 1961

Abstract of

"Volume Changes in Concrete"

by
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Director of Research
Lone Star Cement Corporation

(Paper presented to ASTM Committee C-1 at its meeting in Denver, Colorado, December 6, 1960)

Proposals involving tests for drying shrinkage of neat pastes and mortars as measures of the performance of portland cement in concrete have been made recently. The author has made such tests of 40 cements that previously had been tested in concrete mixtures for drying shrinkage as developed by 3x3x10-inch specimens subjected to drying at 73°F and 50 per cent relative humidity.

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(The above abstract has been prepared by Bailey Tremper, Supervising Materials and Research Engineer, California Division of Highways.)

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"VOLUME CHANGES IN CONCRETE"

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The author has reached unfavorable conclusions with respect to the significance of drying shrinkage tests of small prisms of neat cement and 1:2 Ottawa sand mortar as indicators of the drying shrinkage of portland cement in concrete.

It is noteworthy that ASTM Committee C-1 recently has approved Tentative Specifications for Processing Additions for Use in Manufacture of Portland Cement. These specifications provide for the determination of the effect of additions on drying shrinkage by means of a test performed on mortar specimens. It appears therefore, that Committee C-1 as a whole does not share the view of the author.

The following discussion is devoted solely to the use of mortar specimens as a measure of the performance of portland cement in concrete that is subjected to drying in outside exposure. It is not intended to imply that neat paste specimens are necessarily inferior, but rather that the writer lacks extensive experience with such tests.

California Division of Highways has for several years, made tests of portland cements in 1:2 graded Ottawa sand mortar by a standardized procedure in accordance with Test Method No. Calif. 527-A, which is available to interested investigators. Both the repeatability and the reproducibility of the test when performed in accordance with this method, have been established by carefully controlled procedures.

The data presented by the author include test results by a method similar to Calif. 527-A but which departed therefrom in certain details. For the most part, the writer's investigations indicate that the author's modifications of the test method make no material difference in the observed results. On the other hand, the author's reported values are the average of three specimens only for each cement tested. Calif. 527-A requires that four specimens be tested and it provides for the rejection of specimens that do not meet specified criteria for uniformity. There is no evidence in the paper that the author has applied such criteria before computing average results. There is no evidence that the author has made replicate tests to establish the repeatability of his test procedure. This subject is discussed because of its important bearing on correlation data that the writer will develop later.

It is the primary purpose of this discussion to question the author's philosophy as to the drying period of mortar or concrete test specimens that best provides an index of the performance of cement in concrete that is subjected to exterior exposure. It will be shown that the author's use of his data is unrealistic and that when the data are properly evaluated, they show, in fact, a high degree of correlation between the drying shrinkage of mortar bars and concrete test specimens. It will be shown that concrete pavements and structures that are exposed out-of-doors in continental U.S. do not reach a state of dryness that is comparable to that of laboratory specimens that are dried at 73°F and 50 percent relative humidity for more than short periods of time.

"After concrete has dried to constant water content at one atmospheric condition, a drop in humidity will cause it to lose water or an increase will cause it to gain; hardened cement paste is hygroscopic. The paste and the concrete of which it is a part, shrink or swell with each such change in water content."[1] The rate at which hardened cement paste loses water is extremely slow.[2] The temperature and relative humidity of the atmosphere surrounding exterior concrete varies from hour to hour, from day to day and from season to season. Concrete exposed to such an environment is subjected to influences tending to cause it to lose or take on water continuously but since the paste responds slowly to short-time changes, it must reach an equilibrium condition which depends on the prevailing or average temperature and relative humidity of the atmosphere.

A review of weather bureau records for continental U.S., including California, shows that only in a few southern states does the mean annual temperature exceed 70°F. Of approximately 300 weather bureau stations, only 21 show mean annual temperatures above 70°F. Of the latter, the prevailing relative humidity is well above 60 percent, except in Arizona. 7 AM relative humidities characteristically are above 70 percent.

Weather records, therefore, indicate that the probability of exterior concrete attaining a relative humidity as low as 50 percent, is exceedingly remote. Confirmation of this statement has been obtained by direct tests under a variety of exposure conditions in California. Tests are made by drilling or forming a hole about 1 inch in diameter to various depths. The hole is lined with metal tubing which extends to within about 1 inch of the bottom of the hole and which is cemented in place with epoxy adhesive. The outlet of the tubing is closed with a screw cap. After a period of time, the humidity of the air within the enclosure reaches equilibrium with the surrounding concrete. At appropriate intervals, the screw cap is removed and a humidity sensing element is inserted. The leads of the sensing element pass through a metal screw cap which replaces the original cap. Readings of relative humidity are made until a constant value is obtained. Usually this requires about one hour. The sensing elements are calibrated frequently against saturated salt solutions which produce known values of relative humidity in the confined space above them.

Relative humidities measured within pavement slabs generally have been well above 80 percent. A few observed values that were somewhat lower are not believed to be reliable. The high humidity within pavement slabs in contact with the ground may be explained by the transpiration of moisture from the subgrade.

Attempts have been made to explain the occurrence of transverse cracks that have developed in pavements after many years of service on the basis of long-time drying shrinkage. High measured relative humidities provide strong evidence that pavements do not continue to dry over long periods of time and hence do not continue to shrink.

Non-reinforced pavement slabs constructed in Missouri[3] in August, 1956, developed no greater total drying shrinkage when measured in the late summer of 1958 than was measured in September, 1956.

In Washington, D.C.,[4] a pavement slab placed in September, 1930, reached its minimum length, as a result of moisture changes only, two years later. At this time the length was only slightly less than the minimum reached in 1931. Measurements were continued to the age of five years. During this period, the minimum seasonal length was always greater than that in 1932. The greatest winter to summer drying shrinkage also occurred during the second year.

The delayed development of cracks, or their progressive widening, can be explained in a more rational manner on the basis of thermal changes. Compressible material in expansion joints provides relief for compressive stresses due to temperature rise causing the slabs to elongate. Upon cooling, subgrade friction induces tensile stresses which can exceed the strength of the slab and produce a crack. Intrusion of foreign material into cracks causes progressive opening as a result of thermal cycling. Recognition of this behavior has led to the majority of state highway departments to eliminate expansion joints in non-reinforced pavements.

The relative humidity within concrete bridge structures of varying age has been measured at eight locations within California at points carefully selected to represent the range in weather conditions and elevations within the State. Holes for this purpose were drilled to depths of 3 and 5 inches during July, 1960, in each of the selected structures. When measured during late August and early September of 1960, after a prolonged dry season, relative humidities were found to be as shown in Table 3. At only two of the eight locations were relative humidities less than 60 percent observed at a depth of 2 to 3 inches from the surface. Both locations were in desert areas. At a depth of 4 to 5 inches, the lowest measured relative humidity was 60 percent in a desert area at an elevation of 4000 feet.

Table 4 gives periodic measurements at a location near Sacramento. Gradual lowering of relative humidity occurred during late summer and fall, a period without rainfall. Since the beginning of the rainy season and higher atmospheric humidity on November 3, the trend has reversed and humidites within the concrete have risen. It would appear to be a reasonable expectation that similar cycles will be repeated annually with little change in the relative humidity reached at the end of the dry season.

The average relative humidity of the eight structures listed in Table 3, is 72 percent. A value of 70 percent appears to be a good estimate for the end of the dry season. A comparison of weather records indicates that California weather on a state-wide basis embraces the typical range of the greater part of continental United States. The use of 70 percent as an estimate of the lowest relative humidity in exterior structure therefore, appears to be realistic. Laboratory tests for drying shrinkage therefore, should be discontinued after specimens have lost an amount of water that reduces the relative humidity to this condition.

Humidity readings at the center of a 3x3x11-1/4-inch concrete bar exposed to drying at 73°F and 50 percent relative humidity, indicate that the concrete reaches a relative humidity of 70 percent after about 50 days. This indicates the appropriate maximum time of drying of such specimens under these conditions. It will be shown that a shorter drying period also yields similar relationships between different concretes.

The relative humidity within model beams, 14x20x48-in. in size, exposed outside at Sacramento, is shown in Table 5. It is evident that rainfall and fog accompanied by higher atmospheric humidity is causing the concrete to take on, rather than lose, moisture after 84 days of exposure. These measurements were made in connection with a study of drying shrinkage of specimens of varying size that were exposed outside and also in the laboratory at 73°F and 50 percent relative humidity. The specimens were cast late in July, 1960. The concrete contains 6 sacks of cement per cubic yard, 1-1/2-inch maximum size aggregate and water to give a slump of 3-1/2 inches. Concrete was mixed in the laboratory. Two types of concrete were used. One contains a lignin base water-reducing admixture at the rate of 1/4-pound per sack of cement. The other concrete contains no admixture. The number of specimens cast from each of these concretes were:

| | | |
|---|---|---|
| 14x20x48-inch | 1 | Contains concrete as mixed |
| 4x5x18-inch | 6 | Contain concrete as mixed |
| 3x3x11-1/4-inch | 10 | Concrete wet-sieved through 3/4-inch |
| 1x1x11-1/4-inch | 10 | Concrete wet-sieved through No. 4 |

The largest specimens, or model beams, are intended to represent near job size structural members. The ends were painted to retard moisture loss from these surfaces and thus more nearly represent a long beam. After moist curing in the laboratory for 7 days, the large model beams and one-half of the smaller bars were exposed out of doors. The remainder of the small specimens was exposed to controlled drying in the laboratory at 73°F and 50 percent relative humidity. The large beams are supported at the quarter points on pedestals above a concrete slab. Roller and ball bearings prevent restraint to free movement. Smaller specimens are supported on bars. All outside specimens are covered with removable gable roofs to prevent direct access of rain,

The results of measurement of shrinkage are shown in Figure 5.

During the first 56 days of exposure, there was no rainfall and shrinkage has been proportional to the logarithm of time. Subsequently there has been considerable rainfall, fog and rising atmospheric humidity. The effect has been to cause a lengthening of the specimens. A comparison of drying shrinkage between the smaller specimens exposed outside and in the laboratory, is shown in Figure 6.

Length measurements of the smaller specimens are between gage studs at the ends. Length changes of the large beams are indicated by Carlson strain gages at the center of the section and between points in gage studs in four rows at 10-inch centers of each side face. Thirty-two measurements are used to determine length changes near the surface.

The effect of temperature changes on observed measurements for shrinkage are eliminated for exposure periods greater than 28 days by bringing all specimens to the laboratory for 24 hours or until embedded thermocouples show that the temperature is at 72-73°F which is the temperature at which original measurements were made.

The curves of Figure 5 display a number of points of interest. The relationship between surface-volume ratio and shrinkage is approximately linear with a small break caused by wet sieving the concrete used in the two smaller sizes of specimens. The admixture consistently increased drying shrinkage. Drying shrinkage increases in proportion to the logarithm of time.

A study of the test data indicates that equal amounts of shrinkage are developed among laboratory test specimens when dried for the periods indicated below.

| | |
|---|---|
| 1 x 1-inch section | 4 days |
| 3 x 3-inch section | 14 days |
| 4 x 5-inch section | 28 days |

It is also indicated that test drying for these periods will develop an amount of shrinkage that is fully as great as that normally to be expected in exterior concrete.

The data show that the relative increase in drying shrinkage caused by the use of the water-reducing agent is as follows:

| | |
|---|---|
| 14x20-x48-inch beam, dried 56 days ...... | 38 percent |
| 4x5x18-inch prisms, dried 28 days ....... | 32 percent |
| 3x3x11-1/4-inch prisms, dried 14 days ... | 41 percent |
| 1x1x11-1/4-inch prisms, dried 7 days .... | 45 percent |

It is reasonable to expect therefore, that different cements will show proportionate values of drying shrinkage in 1-inch mortar bars and 3-inch concrete bars if the times of drying are suitably selected.

The advantages of using relatively short drying periods are the greater utility for control purposes and avoidance of the complicating and possibly unequal effects of carbonation of specimens of different sizes.

The above unavoidably long preamble has been necessary to establish the basis that the writer believes to be proper for evaluating Mr. Swayze's data on mortars in terms of his concrete tests. The comparison is best expressed as the shrinkage of one cement in terms of another. An example is afforded by the data of Tables 1A and 1B for cements 2738 and 2767 representing high and low shrinkage in the concrete specimens. The data referred to the length at the end of the 3-day moist curing period are given in Table 6.

It will be noted the difference in magnitude of drying shrinkage of the two cements in concrete specimens is greatest after 25 days of drying and decreases considerably at later periods. On a relative basis, the increase in shrinkage produced by cement 2738 is about the same in mortar dried for 4 days as in concrete dried for about 14 days.

Since the data for these two cements indicate that significant values of drying shrinkage are obtained from mortar dried for 4 days, the data have been examined to determine how closely the relationship holds for the group of 40 cements as a whole.

The data for concrete are given at test ages of 7 and 28 days, representing 4 and 25 days respectively of drying. It would be desirable to interpolate between these values to estimate shrinkage after 14 days of drying. But since the values, although reported to the third decimal, contain only two significant places, such interpolation if carried only to two significant places, would not be of great value. In lieu of this procedure, the mean of shrinkage after 4 and 25 days of drying has been computed. In view of the relationship of shrinkage to the logarithm of time, the computed value represents the shrinkage developed at approximately 10 days. The amount of shrinkage has been computed with respect to the length at the end of the moist curing period, 3 days, rather than at 1 day as reported by the author. This value, in the opinion of the writer, has more merit in determining performance in service. Mean values have been computed to the nearest 0.0005 percentage point to give some measure of approach to three significant figures. Values of shrinkage of the mortar bars as reported at the age of 7 days, or 4 days of drying, are used. They are also referenced to the length after 3 days of moist curing. These values are reported to two significant places also, but the fact that the range of reported values is quite large makes them reasonably comparable to concrete tests computed to the nearest 0.0005 percentage point.

Coefficients of correlation between mortar specimens dried 4 days and concrete specimens dried for various periods are given in Table 7. It will be noted that the highest correlation is shown with concrete specimens dried for 10 and 25 days.

A plot of 4-day drying shrinkage of mortar bars against 10-day shrinkage of concrete bars is shown in Figure 7. The solid curve in this figure represents the linear relationship as determined by the method of least squares. The equation of this curve is:

$$M = 2.333\ C + 0.0015$$

Where M = shrinkage of mortar bars after 4 days of drying

C = shrinkage of concrete bars after 10 days of drying.

The equation indicates that the curve intersects the ordinate at a point very near the origin.

The coefficient of correlation, r, is 0.502. This value according to statistical tables, indicates that the probability of the observed relationship being due purely to chance is less than one in one-thousand.

The analyses therefore, establishes beyond reasonable doubt that the mortar test does in fact furnish a useful index of the performance of cement in service.

The standard error of estimate, shown by broken lines in Figure 7, is 0.0118 and is relatively large. Reasons that it is large include the use of values for the concrete specimens that are reported to two significant figures only and possible lack of reliability in reported values for the mortar specimens. Aside from failure of the author to make replicate tests of the mortars, there is evidence that the quantity of water used in these tests may not have been adjusted as precisely as desirable for correlation purposes. In 31 of the 40 mortar tests made, the water was added in multiples of 5 ml or to the nearest 1 percent by weight of the cement. It is highly improbable that more than three-fourths of the cements would require an exact multiple of 5 ml of water.

The coefficients of correlation between mortar dried 4 days and neat paste dried 2 days and 6 days, are 0.63 and 0.70 respectively. This indicates that the two types of specimen respond to drying in a highly similar manner.

The mortar tests of three of the cements, Nos. 2778, 2788 and 3073, are among those for which exceptionally high values of shrinkage were found. Mortar tests of these three cements when compared to the neat cement test results, are also high. The inference is strong therefore, that had the tests been repeated, the mortar results for these three cements would have been lower and better in line with the least squares curve of Figure 7.

All of the Type II, low-alkali cements gave concrete shrinkage values of less than 0.022 percent. In the mortar tests, values of drying shrinkage are 0.041 percent or less for all cements except No. 2767. The mortar test result for this cement is also high when compared with that for neat paste suggesting possible inaccuracy of the mortar test.

Mr. Swayze's comments on autogenous volume change imply that this factor differentially affects the relative rate of water loss during drying of mortar and concrete specimens because of differences in original water-cement ratio. Apparently he considers that autogenous volume change of itself constitutes a valid reason for rejecting pastes and mortars as test specimens for drying shrinkage.

The data of autogenous volume change as given in the paper, have been plotted and from the derived curves, values for ages other than those reported have been interpolated.

The estimated values are shown in Table 8. The increase in autogenous shrinkage beyond three days amounts to 0.8 percent at 7 days and 1.1 percent at 14 days. It is doubtful that autogenous volume changes take place at the indicated rate while the concrete is drying, but if they do, the amount is hardly sufficient to exert significant differences in the mortar and concrete tests.

Although the effect of autogenous action is to decrease volume, the author's data show that, with one exception, all mortar and concrete specimens either remained constant or increased in length during moist curing. The conclusion is inescapable that other factors are acting on the paste in a direction opposite to that of autogenous volume change and that either they nulify or exceed it in over-all effect.

In summary, the writer offers the conclusion that the author has not presented a good case against the use of mortar specimens to evaluate differences in shrinkage characteristics of cements. On the contrary, the data show a very high degree of correlation when evaluated in terms of concrete pavements and structures subjected to exposure out-of-doors.

## References

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2. Powers, T. C. and Brownyard, T. L., "Studies of the Physical Properties of Hardened Cement Paste", Proc. Amer. Conc. Inst., Vol. 43 (1947), also Bulletin 22, Research and Development Laboratories, Portland Cement Association, Skokie, Illinois

3. Best, J. L., Stites, W. D., Alch, W. F. and Carlton, E. W. "Length Changes in Prestressed Concrete Slabs" Published by Missouri State Highway Commission, August, 1960

4. Teller, L. W., and Sutherland, Earl C. "The Structural Design of Concrete Pavements, Part 2" Public Roads, Col. 16, No. 9, Nov. 1935

Table 3

Relative Humidity in Concrete of Existing Bridges in California as Measured in August and September, 1960

| Location | Elevation | Date Built | Relative Humidity at Depth Shown | |
|---|---|---|---|---|
| | | | 2"-3" | 4"-5" |
| 1. Mojave Desert near Victorville | 3000 | 1958 | 66 | 74 |
| 2. Southern Coast near San Diego | 10 | 1956 | 80 | 80 |
| 3. Central Coast near Santa Cruz | 10 | 1947 | 78 | 79 |
| 4. Northern Coast near Eureka | 10 | 1929 | 84 | 85 |
| 5. Central Valley near Sacramento | 25 | 1959 | 74 | 78 |
| 6. Sierra Nevada Range near Kingvale | 6000 | 1959 | 70 | 77 |
| 7. East of Sierra Nevada Range near Bishop | 4400 | 1949 | <50 | 60 |
| 8. Imperial Valley near Salton Sea | -200 | 1950 | 58 | 67 |

Table 4

Relative Humidity in Concrete of
Existing Bridge near Sacramento

(Location No. 5)

| Date of Measurement | Relative Humidity at Depth Shown | |
|---|---|---|
| | 2"-3" | 4"-5" |
| July 22, 1960 | 77 | 81 |
| Sept. 12, 1960 | 74 | 78 |
| Sept. 26, 1960 | 73 | 76 |
| Oct. 21, 1960 | 68 | 72 |
| Nov. 4, 1960 | 68 | 73 |
| Jan. 3, 1961 | 78 | 75 |

Remarks: No rainfall between May 24 and Nov. 2. 0.4" rain on Nov. 3. Total rain May 24, 1960 to Jan. 3, 1961, is 5 inches.

Table 5

Relative Humidity in 14x20x48-inch
Concrete Beams Exposed Outside
at Sacramento since early August, 1960

| Period of Exposure, Days | Percent Relative Humidity at Depths Shown | | | | | |
|---|---|---|---|---|---|---|
| | Concrete Without Admixture | | | Concrete Containing Water-Reducing Agent | | |
| | 3" | 5" | 7" | 3" | 5" | 7" |
| 0 | 98 | 98 | 94 | 95 | 95 | 88 |
| 28 | 92 | 93 | 82 | 91 | 92 | 84 |
| 56 | 89 | 91 | 81 | 86 | 90 | 82 |
| 84 | 88 | 90 | 80 | 85 | 88 | 81 |
| 112 | 86 | 89 | 78 | 84 | 88 | 79 |
| 140 | 89 | 95 | 79 | 87 | 92 | 82 |

Note: No rainfall during first 84 days of exposure. Rainfall since then, up to 140 days, has been 5 inches.

Table 6

Relative Drying Shrinkage of Two Cements

| Type of Specimen | Cement Number | Period of Drying | | | | |
|---|---|---|---|---|---|---|
| | | 4 da. | 10 da.* | 25 da. | 3 mo. | 1 yr. |
| Concrete | 2738 | .018 | .031 | .044 | .055 | .068 |
| | 2767 | .008 | .020 | .032 | .048 | .061 |
| | Difference | .010 | .011 | .012 | .007 | .007 |
| Mortar | 2738 | .075 | | .124 | | |
| | 2767 | .050 | | .084 | | |
| | Difference | .025 | | .040 | | |
| Relative Shrinkage of Cement 2738 in Terms of Cement 2767 | | | | | | |
| Concrete | | 225 | 155 | 137 | 114 | 111 |
| Mortar | | 150 | | 148 | | |

*Values interpolated.

Table 7

Coefficients of Correlation between the Author's values of shrinkage of 1:2 mortar specimens at the age of 7 days representing 4 days of drying and shrinkage of 3x3x10-in. specimens of concrete after drying for various periods.

| Time of Drying Concrete Specimens | Coefficient of Correlation 1:2 mortar dried 4 days | Significance Index |
|---|---|---|
| 10 days (interpolated) | 0.502 | 0.001 |
| 25 days | 0.504 | 0.001 |
| 3 Months | 0.346 | 0.05 |
| 1 Year | 0.332 | 0.05 |

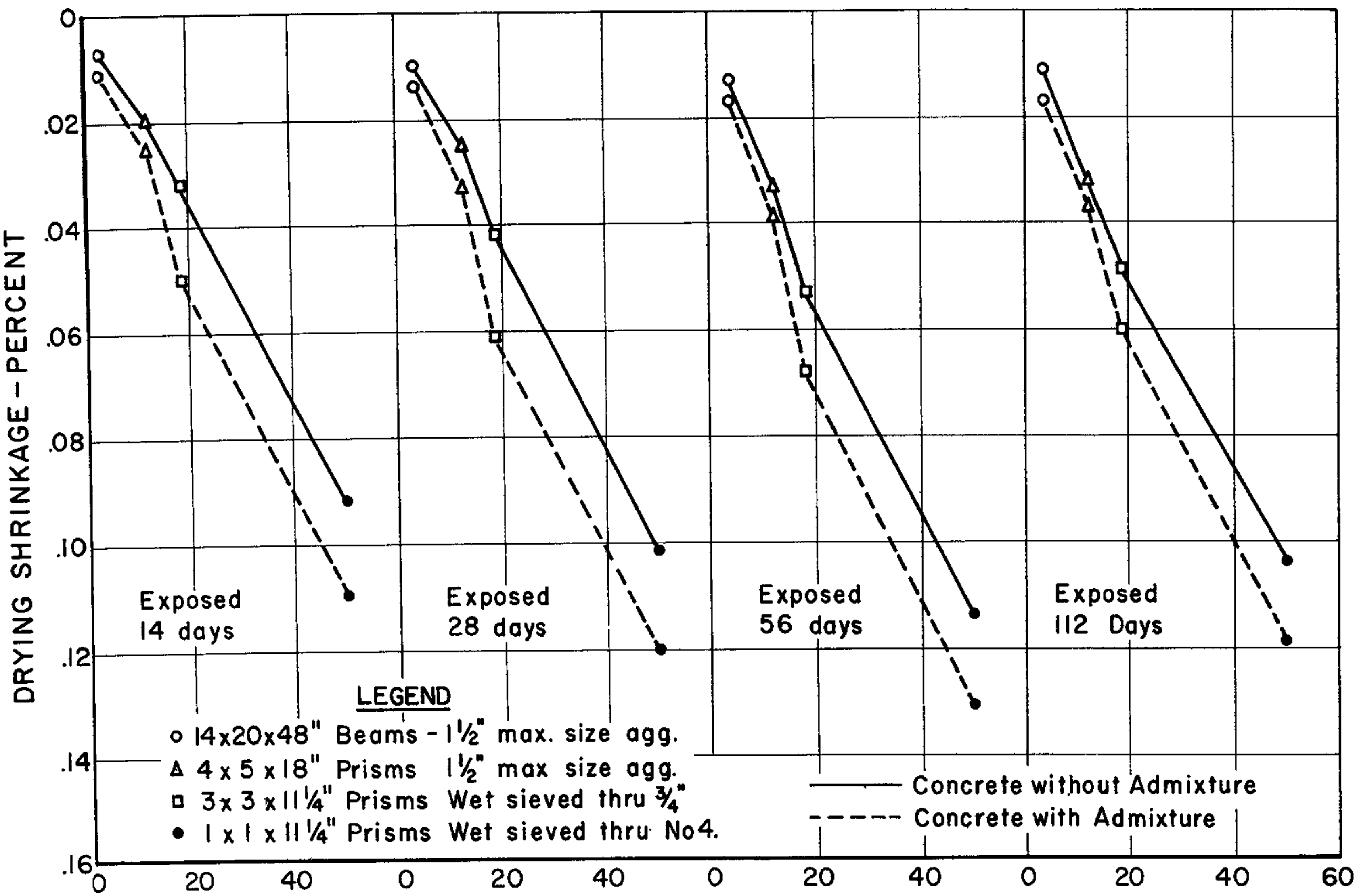
Table 8

Autogenous Shrinkage

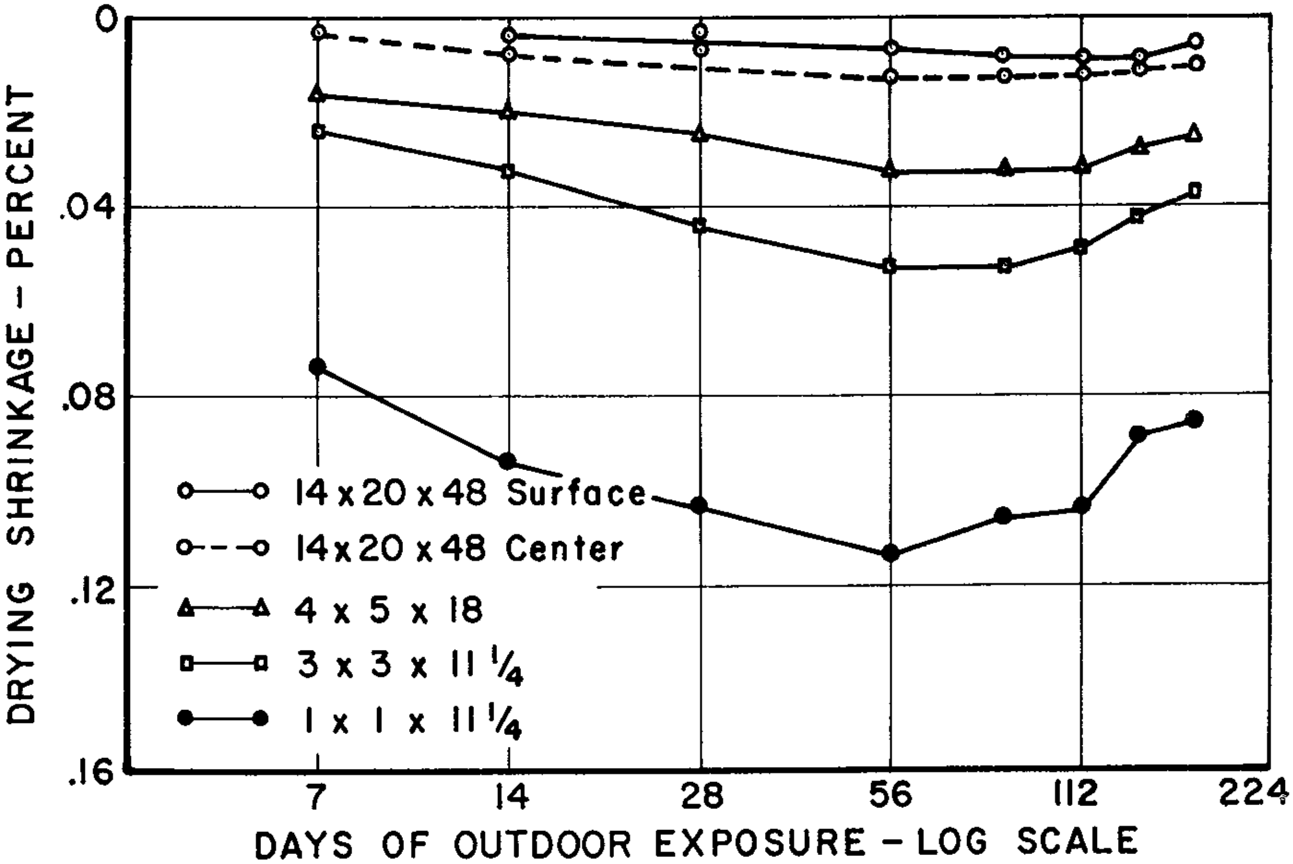
Values are interpolated from the author's data and are shown as equivalent percent water by weight.

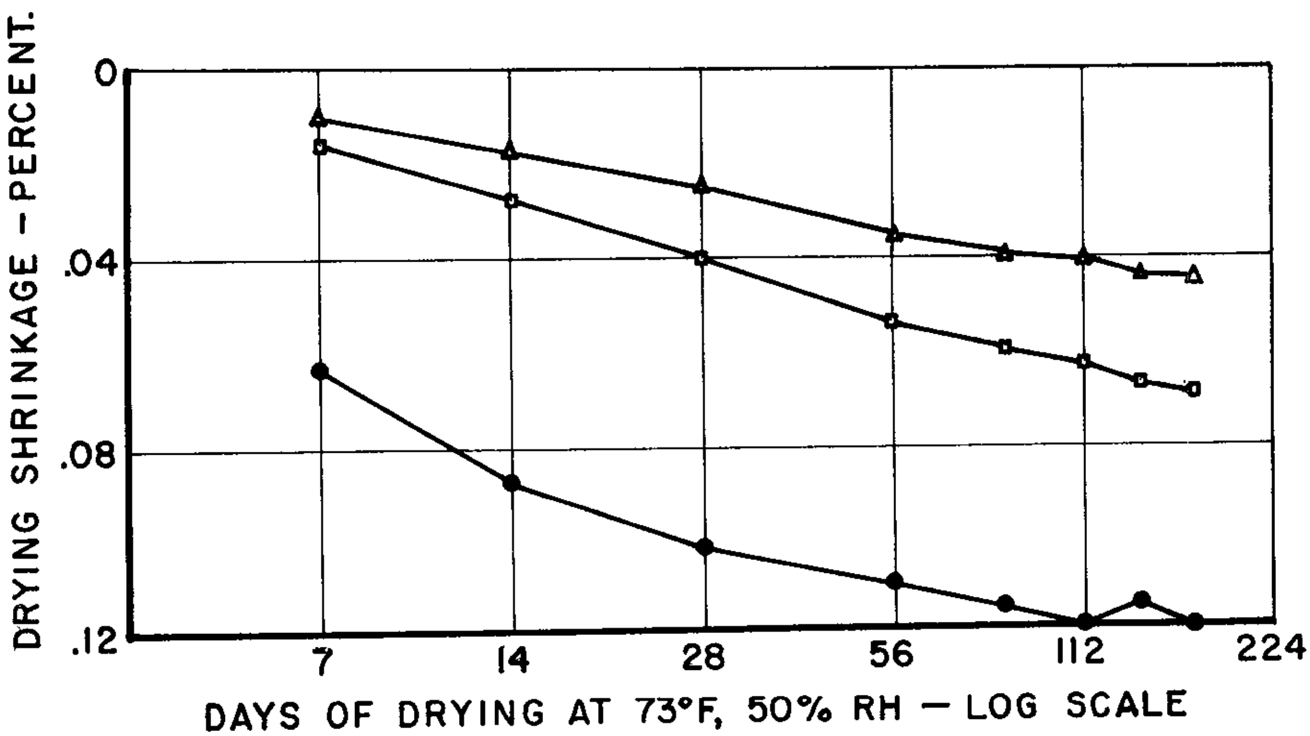
| Age in Days | Cement Type | | | |
|---|---|---|---|---|
| | I and II | | III | |
| | Total | Increase from 3 days | Total | Increase from 3 days |
| 3 | 2.8 | | 3.6 | |
| 7 | 3.7 | 0.9 | 4.3 | 0.7 |
| 14 | 4.0 | 1.2 | 4.6 | 1.0 |

FIGURE 5

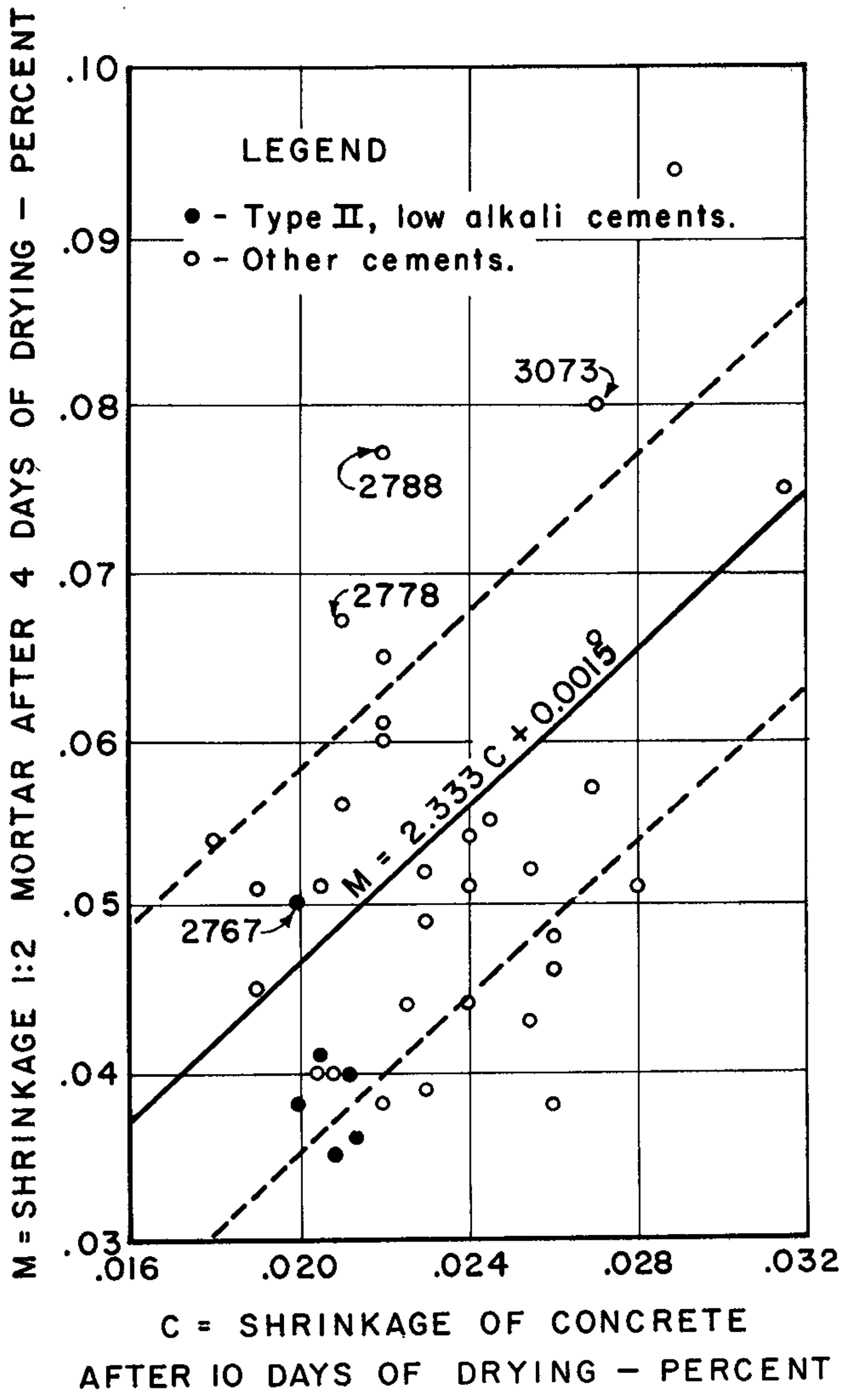



**Relationship between drying shrinkage and surface - volume ratio. Specimens exposed outdoors.**




Drying shrinkage related to size of specimen and condition of exposure. Concrete without Admixture.




Relationship between drying shrinkage of 1:2 graded Ottawa sand mortar in 1" x 1" x 10" prisms dried 4 days and concrete in 3" x 3" x 10" prisms dried 10 days.