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SHRINKAGE OF CONCRETE

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SYNOPSIS

This paper presents the results of an investigation of the use of ordinary 3 by 6-in. concrete cylinders for volume change observations and of observing these changes by a simple apparatus consisting of an Ames dial attached to a metal base, and of a study of some of the factors which contribute to volume change in concrete. The factors investigated were quality and quantity of the cement paste used, length of moist curing, and different cements and aggregates.

The 3 by 6-in. cylinders were found to serve well for shrinkage observations and the measuring apparatus used gave satisfactory results. The quality of the paste showed little effect upon the shrinkage, while the quantity of the paste contributed approximately in proportion to its percentage of the volume of the concrete. The length of moist curing had practically no effect upon the shrinkage. The high-early-strength portland cement produced more shrinkage than did the standard portland cement, particularly in lean mixes, but in terms of shrinkage per unit of strength, the high-early-strength cement proved superior. Fine aggregate showed more effect upon shrinkage than did coarse aggregate.

INTRODUCTION

The problem of volume changes in concrete caused by variation in its moisture content has been given much experimental study by numerous investigators. An excellent review of present knowledge of these volume changes was recently presented in a paper by Davis.[2] This paper contains such a complete bibliography of the more important publications in this field, that it is unnecessary to present but later references here. One of the most important recent publications is by the late Professor Slater,[3] in which is presented a summary of the results of the elaborate investigation carried out by the Portland Cement Association over a number of years.

The investigation undertaken at the Fritz Engineering Laboratory of Lehigh University had as its aims the study of a simplification in volume change experiments, and of some of the fundamental causes of shrinkage of concrete. For the purpose of simplifying the experimental work, ordinary 3 by 6-in. concrete cylinders were used as test specimens, both for shrinkage

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[2] R. E. Davis, "A Summary of the Results of Investigations Having to do with Volumetric Changes in Cements, Mortars and Concretes, Due to Causes Other than Stress," *Proceedings*, Am. Concrete Inst., Vol. 26, p. 407 (1930).

[3] W. A. Slater, "Designing Concrete for High Strength, Low Permeability and Low Shrinkage," *Proceedings*, Internat. Assn. Testing Mats., Vol. 1, p. 1000 (1931).

measurements and for compression tests. The particular shrinkage factors investigated were quality of cement paste, quantity of cement paste, length of moist curing, and a few different types of cement and aggregate. Certain of these factors have received but scant observations in the past, and since they were considered to be some of the most significant factors in the quality-giving elements of concrete, they were selected for this study.

OUTLINE OF TESTS

The test program was divided into five groups, each group devoted to one certain factor. Group 1 dealt with the effect of the quality of the cement paste of the concrete. This quality was varied from a cement-water ratio by weight of 1.0 which represents a very lean concrete mix, to a ratio of 2.5 which represents a very rich mix. Four cement-water ratios by weight were used (1.0, 1.5, 2.0, and 2.5) and two consistencies, one having slumps between 1 and 3 in., and one between 6 and 9 in. Thus the range included all concrete mixes used in ordinary construction. Two sets of specimens were made, one for compression test at the age of 7 days, that is, at the time the other set of specimens was removed from the moist room and placed in dry storage for observation of change in length. Each set of specimens consisted of three 3 by 6-in. cylinders, which were made, capped, cured, and tested for strength in accordance with standard practice. All specimens of each group were made on the same day (a deviation from the usual practice) so that they would receive identical treatment throughout the investigation. All mixes of relatively dry consistency had a water content of 38 gal. per cu. yd. of concrete, regardless of cement-water ratio, and all the mixes of wet consistency had a water content of 45 gal. per cu. yd. The information regarding the concrete in group 1 is given in Table I. The cement used was a standard portland, cement A of Table IV.

Group 2 was designed for the study of the effect of the quantity of paste. Two mixes were used, in one of which the cement-water ratio was 1.0, and in the other 2.0. The quantity of paste was so controlled that concrete varying from a very dry to a relatively wet consistency was secured. The percentages of paste for the lean mix (cement-water ratio of 1.0) were 24, 26, 28, and 30. The corresponding percentages for the rich mix were 30, 32, 34, and 36. The information on these mixes is given in Table II. As in group 1, two sets of specimens were made, one for compression test at the time of removing the specimens from the moist room, which was at the age of 7 days, and one set for shrinkage observation. The cement used was cement A of Table IV.

Group 3 was made for the study of the effect of the length of moist curing on the shrinkage of concrete. Two mixes had standard portland cement (cement A of Table IV) and two had high-early-strength portland cement (cement B of Table IV). The cement-water ratios of the two mixes

TABLE I.—CONCRETE USED IN GROUP 1.

Batch	Cement-Water Ratio by Weight	Water Content, gal. per cu. yd.	Concrete Mix by Weight	Paste, per cent	Slump, in.	7-day Compressive Strength, lb. per sq. in.
No. 1	1.0 (1.22)	38	1:4.16:6.24	24.8 (21.4)	¼	470
No. 2	1.0 (1.22)	45	1:3.31:4.96	29.4 (25.4)	6	480
No. 3	1.5	38	1:2.65:3.98	27.8	2½	1510
No. 4	1.5	45	1:2.08:3.12	33.0	8	1240
No. 5	2.0	38	1:1.91:2.86	30.8	3¼	3030
No. 6	2.0	45	1:1.48:2.22	36.6	9	2770
No. 7	2.5	38	1:1.47:2.20	34.0	2	4320
No. 8	2.5	45	1:1.12:1.68	40.2	7	4680

TABLE II.—CONCRETE USED IN GROUP 2.

Batch	Cement-Water Ratio by Weight	Paste, per cent	Water Content, gal. per cu. yd.	Concrete Mix by Weight	Slump, in.	7-day Compressive Strength, lb. per sq. in.
No. 9	1.0	24	36.7	1:4.35:6.53	¼	590
No. 10	1.0	26	39.8	1:3.92:5.88	2	570
No. 11	1.0	28	42.8	1:3.52:5.28	4	490
No. 12	1.0	30	45.9	1:3.20:4.80	6¾	490
No. 13	2.0	30	37.0	1:1.99:2.98	1¼	3240
No. 14	2.0	32	39.4	1:1.82:2.73	4¾	3050
No. 15	2.0	34	41.8	1:1.67:2.51	6	3410
No. 16	2.0	36	44.3	1:1.53:2.30	8¾	3490

TABLE III.—CONCRETE USED IN GROUP 3.

Batch	Type of Portland Cement	Cement-Water Ratio by Weight	Concrete Mix by Weight	Slump, in.	Age at Removal to Dry Storage, days	Compressive Strength at Removal to Storage, lb. per sq. in.
No. 25	Standard	1.0	1:3.92:5.88	4	1 3 7 28	64 226 640 1000
No. 26	Standard	2.0	1:1.82:2.73	5½	1 3 7 28	530 1520 2770 5170
No. 27	High-early-strength	1.0	1:3.92:5.88	4½	1 3 7 28	178 575 940 1500
No. 28	High-early-strength	2.0	1:1.82:2.73	4½	1 3 7 28	1480 2930 4600 5600

TABLE IV.—CONCRETE USED IN GROUP 4.

Batch	Brand of Cement	Cement-Water Ratio by Weight	Paste, per cent	Concrete Mix by Weight	Slump, in.	7-day Compressive Strength, lb. per sq. in.	Fineness, per cent Passing No. 200 Sieve
No. 17	A	1.0	26	1:3.92:5.88	2	550	90.90
No. 18	B				4	810	97.30
No. 19	C				3¼	430	95.74
No. 20	D				4	860	99.86
No. 21	A	2.0	32	1:1.82:2.73	6½	3030	
No. 22	B				3½	4230	
No. 23	C				6½	2080	
No. 24	D				3¼	4100	

	Cement A	Cement B	Cement C	Cement D
SiO_2, per cent	19.96	19.52	22.44	20.92
Fe_2O_3, per cent	2.39	2.23	1.92	2.04
Al_2O_3, per cent	6.81	6.15	5.40	5.12
CaO, per cent	62.78	62.95	63.46	63.93
MgO, per cent	3.89	3.68	3.29	3.65
SO_3, per cent	1.84	2.48	1.66	2.29
Loss, per cent	1.83	2.53	1.35	1.52
Total, per cent	99.50	99.54	99.52	99.47

TABLE V.—CONCRETE USED IN GROUP 5.

Batch	Aggregate	Type of Aggregates: Fine	Type of Aggregates: Coarse	Cement-Water Ratio by Weight	Concrete Mix by Weight	Slump, in.	7-day Compressive Strength, lb. per sq. in.
No. 29	No. 1	Bank 1	Gravel	1.0	1:3.20:4.80	7½	540
No. 30	No. 2	Bank 2	Gravel	1.0	1:3.20:4.80	6	510
No. 31	No. 3	Crushed Limestone 1	Gravel	1.0	1:3.20:4.80	4½	490
No. 32	No. 4	Crushed limestone 2[a]	Gravel	1.0	1:3.20:4.80	5	630
No. 33	No. 5	Bank 1	Crushed limestone	1.0	1:3.20:4.80	6	560
No. 34	No. 1	Bank 1	Gravel	2.0	1:1.52:2.28	8	2710
No. 35	No. 2	Bank 2	Gravel	2.0	1:1.52:2.28	7	2790
No. 36	No. 3	Crushed limestone 1	Gravel	2.0	1:1.52:2.28	6½	2810
No. 37	No. 4	Crushed limestone 2[a]	Gravel	2.0	1:1.52:2.28	4	2990
No. 38	No. 5	Bank 1	Crushed limestone	2.0	1:1.52:2.28	8½	3360

[a] Contained clay.

were 1.0 and 2.0. The ages at which shrinkage observations were first made and compression tests were made, were 1, 3, 7, and 28 days. As for all the other groups, the first day of curing consisted in leaving the concrete in the steel molds for this length of time. Subsequently curing was in a moist room of 100 per cent humidity and at 70 F. The information on the mixes used in group 3 is given in Table III.

Group 4 represents a study of the effect of the cement used in the concrete. Two brands of standard portland cements, cement A and C, and two brands of high-early-strength portland cements, cements B and D, were studied. Each brand of cement was used in two concrete mixes, one with a cement-water ratio of 1.0, the other with a cement-water ratio of 2.0. Moist curing was applied for 7 days. The information for this group is given in Table IV.

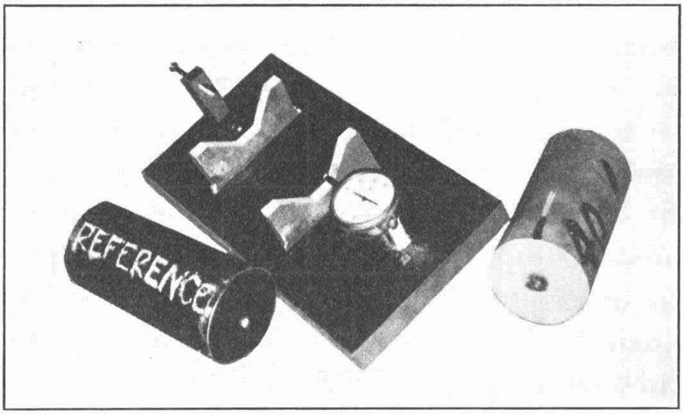

FIG. 1.—Measuring Apparatus and Weighing Balance.

Group 5 included five combinations of aggregates, containing four fine and two coarse aggregates. Two of the fine aggregates were natural bank sands, the other two were crushed limestone, one of which was relatively clean, while the other contained an appreciable amount of fine clay. The two coarse aggregates were natural siliceous gravel and crushed limestone. Mixes having cement-water ratios of 1.0 and 2.0 by weight were selected for the tests. The specimens were cured moist until tested at the age of 7 days. The information for this group is given in Table V.

The study presented in this paper was based on the shrinkage that took place during approximately ½-yr. storage in dry air.

APPARATUS FOR SHRINKAGE OBSERVATION

The apparatus used for observing changes in length of the 3 by 6-in. concrete cylinders consisted simply of a steel base to which were welded two uprights; one of them held the screw which served as the fixed end and the other had a 0.0001-in. Ames dial attached for recording the length. Two V-shaped sections, welded to the base, served as guides for the cylinders. A black line, painted at one end of the cylinder, served to secure the same position during each observation. With this instrument the length of the cylinder could readily be determined to the nearest 0.0001 in. In order to secure the same method of observation the same operator took all readings. Immediately after the observation of length the specimen was weighed to the nearest gram for loss of water. A photograph of the measuring apparatus is presented in Fig. 1.

The 3 by 6-in. shrinkage specimens had stainless steel plugs in the center at each end. The specimen was so placed in the measuring apparatus that the plug at one end was resting against the screw which served as the fixed point, and the plunger of the Ames dial bore against the other plug.

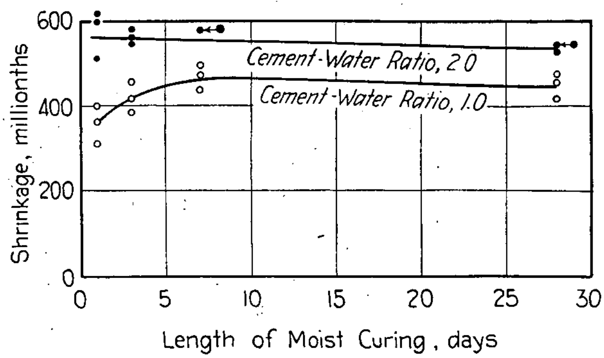

FIG. 2.—Variation Between Individual Specimens of Group 3.

These specimens proved very convenient for the shrinkage observation as well as for weighing. Since the plugs were set in ½-in. steel cubes cast in the concrete, the gage line was considered to be 5½ in. in working up the data.

An indication of the suitability of this apparatus and the 3 by 6-in. cylinders for volume-change observations is obtained from the study of variation in results between the individual specimens in a set. Figure 2 shows the individual results for the standard portland-cement specimens in group 3, which was a study of the effect of length of moist curing. It is noted that the individual variation is relatively small, particularly so when it is remembered that it is practically impossible to insure the identical amount of each constituent of the concrete in each of the companion specimens. The variation shown is therefore probably due more to the variation in the constituents of the concrete than to the method of observation. The results indicated that the very simple apparatus and the small specimens used in this investigation served well for observations of volume changes in concrete.

DRY STORAGE

The concrete cylinders which were observed for shrinkage were stored in a room with the temperature controlled fairly well to 80 F. No attempt was made to control the humidity, but a humidigraph gave the record of

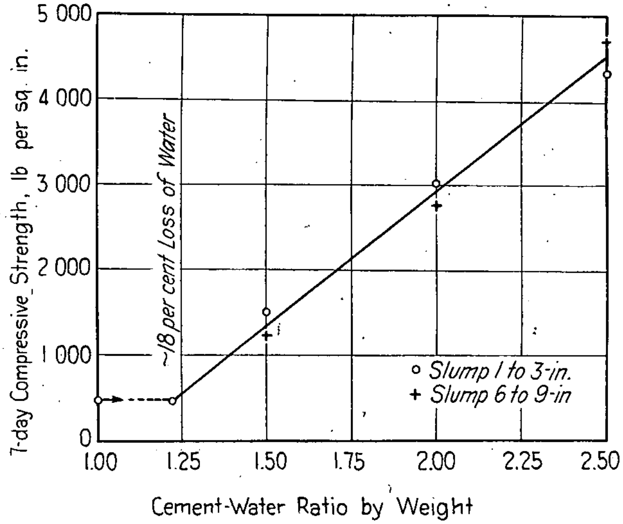

FIG. 3.—Relation Between Strength and Cement-Water Ratio of the Concrete in Group 1.

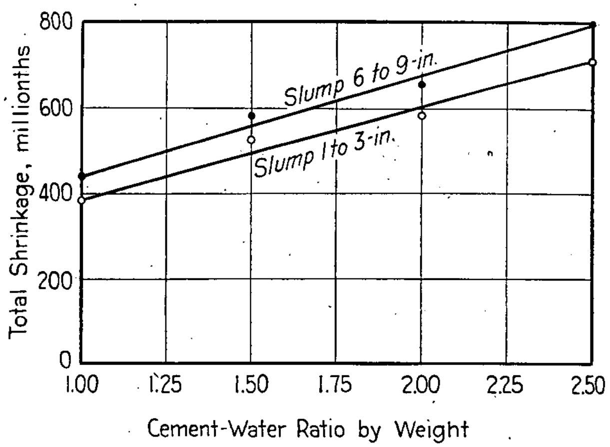

FIG. 4.—Relation Between ½-yr. Shrinkage in Air at 80 F. and 40 to 60 per cent Relative Humidity and Cement-Water Ratio of Concrete.

the relative humidity throughout the storage period. In general, the humidity varied between 40 and 60 per cent. Since all specimens of each group were made on the same day and for all groups, except group 3 on curing, were removed from the moist room at the same time, the variation in humidity did not have any effect upon the relative shrinkage results. The specimens in group 3 were not subjected to identical humidity conditions because of the difference in length of moist curing, but the results indicated that this possible variation in humidity probably did not affect the shrinkage appreciably.

EFFECT OF CEMENT-WATER RATIO—GROUP 1

The results of the specimens included in group 1 are presented in Figs. 3, 4 and 5. Figure 3 shows the relationship between the strength of the concrete at the age of 7 days, that is, at the time the volume change observations were started. It is noted that the relation between strength and cement-water ratio followed a straight line except for the very lean

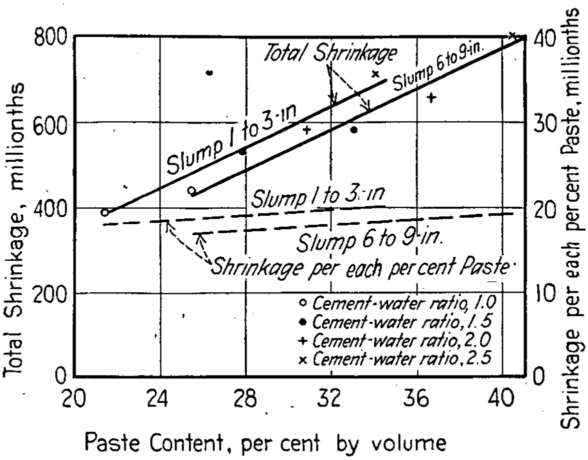

FIG. 5.—Effect of Paste Content on Shrinkage at 80 F. and 40 to 60 per cent Relative Humidity of Concrete in Group 1.

mix which had a cement-water ratio of 1.0. In this lean mix a part of the mixing water segregated from the concrete so that the actual water content became somewhat less than the total mixing water used in the batch. The strength relation in Fig. 3 indicates that the amount of segregated water was about 18 per cent of the total mixing water used.

Figure 4 shows the relationship between shrinkage and cement-water ratio of the concrete. The shrinkage increased regularly with the increase in the cement-water ratio. The relatively dry mix of slumps from 1 to 3 in. showed less shrinkage than did the relatively wet mix of slumps from 6 to 9 in. Thus the paste content as well as the cement-water ratio seemed to affect the shrinkage.

In Fig. 5 the shrinkage of these mixes has been plotted against the percentage of cement paste in the fresh concrete. The percentage of paste for the mix having a cement-water ratio equal to only 1.0 has been corrected for the indicated loss in mixing water. No correction was applied to any of the other mixes. The shrinkage increased regularly with the increase in the paste content of the concrete. Thus the question arises: Is the shrinkage caused primarily by the quality of the paste as given by the cement-water ratio, or by the quantity of paste as given by the percentage

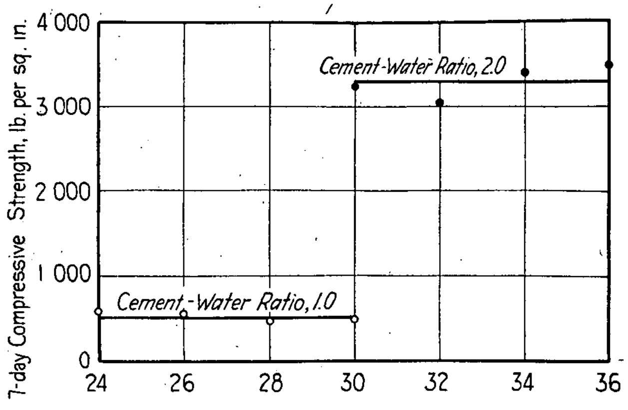

FIG. 6.—Effect of Paste Content on Strength of Concrete in Group 2.

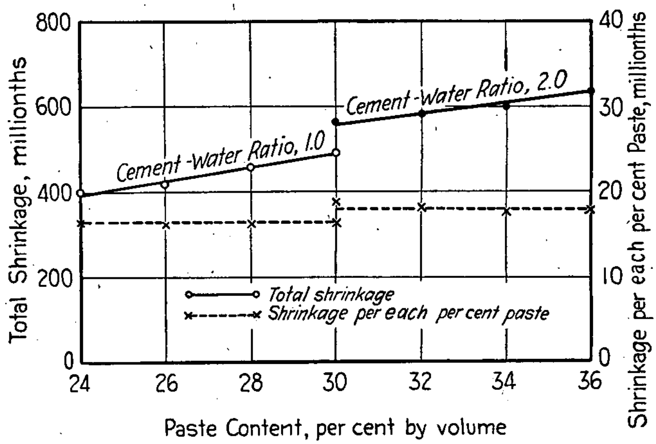

FIG. 7.—Effect of Paste Content on Shrinkage at 80 F. and 40 to 60 per cent Relative Humidity of Concrete in Group 2.

of paste used? In order to obtain some information on this question, the shrinkage was studied in terms of unit of paste. The broken lines in Fig. 5 give the shrinkage values obtained when the shrinkage as given by the solid lines is divided by the amount of paste. The shrinkage per 1 per cent of paste is thus found to vary from approximately 16½ millionths for a cement-water ratio of 1.0 to 18 millionths for a cement-water ratio of 2.5.

Although the cement content was increased $2\frac{1}{2}$ times, the shrinkage per unit of paste increased only about 10 per cent. This indicates that for the standard portland cement used in this group, the shrinkage of the concrete was caused primarily by the amount of paste used in the mix. The quality of the paste had very little effect upon the shrinkage of the concrete. The slightly lower shrinkage for concrete containing paste of low cement content as compared to that for the higher cement content may also partially be due to the segregation of mixing water which took place more readily in the lean than in the richer mixes.

The information obtained in group 1 may therefore be summarized as follows: The shrinkage of the concrete was nearly proportional to the amount of paste used, the quality of the paste having little, if any, effect upon the shrinkage per unit of paste. The increase in shrinkage with increased richness of the mix was principally caused by the increase in the paste content.

EFFECT OF QUANTITY OF PASTE—GROUP 2

In group 2 two mixes were selected (cement-water ratios of 1.0 and 2.0) using standard portland cement. The quantity of paste was varied from 24 to 30 per cent for the lean mix and from 30 to 36 per cent for the rich mix. The results of the compression tests on companion cylinders at the age of 7 days are given in Fig. 6. The compressive strength remained practically constant, regardless of the quantity of the paste, as long as the quality of the paste remained constant. This is in agreement with the cement-water ratio strength law which states that the strength varies directly with the concentration of cement in the paste regardless of amount of paste.

Figure 7 shows the shrinkage of the concrete plotted against the percentage of paste used. The shrinkage increased quite uniformly with the increase in paste content. However, the rich mix with a cement-water ratio of 2.0 showed more shrinkage for 30 per cent nominal paste content than did the very lean mix with a cement-water ratio of 1.0. When the shrinkage is given per unit of paste, or per 1 per cent paste, each of the mixes showed a constant shrinkage. The lean mix showed a shrinkage of about $16\frac{1}{2}$ millionths per 1 per cent paste, while the rich mix showed about 18 millionths. These values correspond very well with those obtained in Group 1 and indicate that within the range of ordinary mixes, that is, from cement-water ratios of 1.25 to 2.25, the shrinkage of concrete per unit of paste is practically constant, regardless of the quality of the paste. In order that the shrinkage for 1 per cent of paste be equal for the two mixes used, about 15 per cent of the mixing water in the lean mix would have to segregate. The results in group 1 showed that a segregation of this amount of mixing water might well have taken place. Thus both these groups indicate that the shrinkage of the concrete was rather independent of the cement-water ratio of the paste, or in other words, the shrinkage was

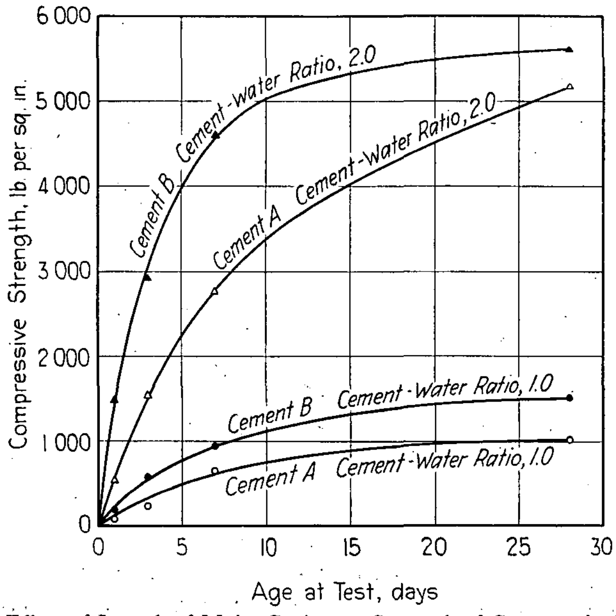

FIG. 8.—Effect of Length of Moist Curing on Strength of Concrete in Group 3.

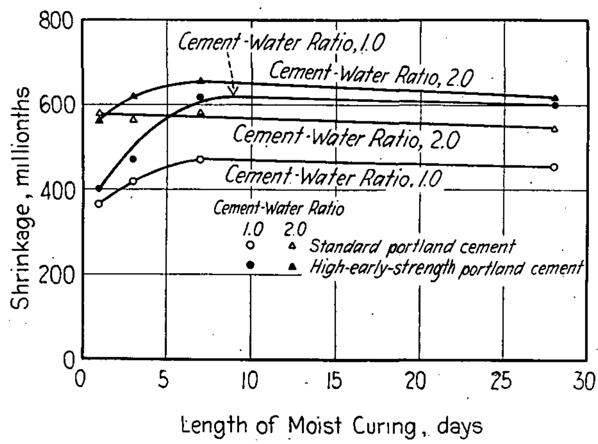

FIG. 9.—Effect of Length of Moist Curing on Shrinkage at 80 F. and 40 to 60 per cent Relative Humidity of Concrete in Group 3.

independent of the cement content in the paste. The shrinkage of the concrete may thus be expressed approximately by the formula:

$$s = k \cdot p$$

where s is shrinkage, k is a constant indicating shrinkage per 1 per cent of paste which depends upon the cement and aggregate used and upon the conditions of the tests, and p is percentage of cement paste in the concrete.

EFFECT OF LENGTH OF MOIST CURING—GROUP 3

The results of the strength tests are given in Fig. 8, and of the shrinkage tests in Fig. 9. It is noted that both the standard cement A and the high-

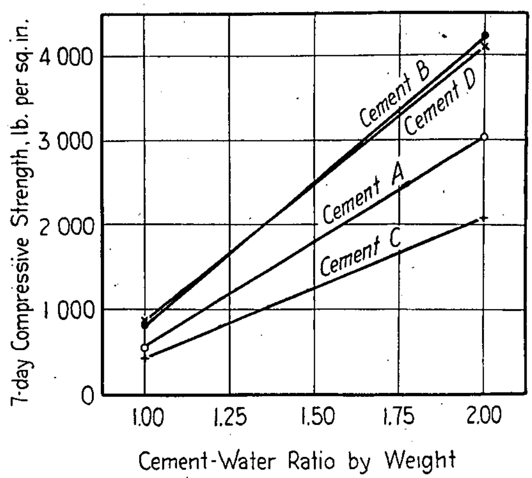

FIG. 10.—Effect of Cement on Strength of Concrete in Group 4.

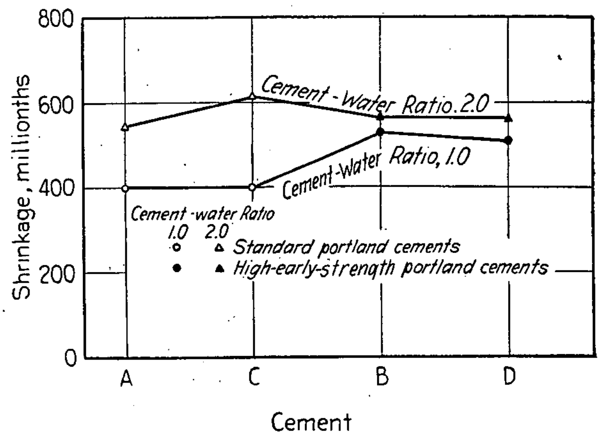

FIG. 11.—Effect of Cement on Shrinkage at 80 F. and 40 to 60 per cent Relative Humidity of Concrete in Group 4.

early-strength portland cement B showed consistent increase in strength with increase in length of moist curing up to 28 days which was the maximum used in this investigation. The high-early-strength cement gave concrete strength considerably above that for the standard portland cement for both cement-water ratios used. For the lean mix the high-early-strength cement gave approximately 50 per cent greater strength than did the standard cement at all ages of test. For the rich mix the high-early-strength cement gave concrete strength about 200 per cent greater than standard portland cement at the age of 1 day, 100 per cent greater at 3 days, 70 per cent greater at 7 days and less than 10 per cent greater at 28 days.

The shrinkage of the concrete as presented in Fig. 9 indicated that the length of moist curing did not have any marked effect. The results showed a tendency of an increase in shrinkage with increased length of moist curing up to 7 days and then practically no change in the shrinkage with the increase in moist curing up to 28 days. The high-early-strength cement gave considerably greater shrinkage for the lean concrete than did the standard portland cement. However, the effect of the type of cement on the shrinkage of the rich concrete mix was relatively small.

EFFECT OF BRAND AND TYPE OF CEMENT—GROUP 4

In this group four cements were used, two of which were standard portland cements (of which one was cement A of the previous tests) and the remaining two were high-early-strength portland cements (of which one was cement B of the previous tests). The compressive strength at the age of 7 days is given in Fig. 10. The strength qualities of the two standard portland cements differed considerably, while the two high-early-strength cements were nearly equal.

Figure 11 shows the shrinkage of the concrete containing these four cements for the two concrete mixes used. The two standard portland cements showed approximately the same shrinkage both for the lean and rich mix. So also did the two high-early-strength cements. However, for the lean mix the shrinkage of the concrete containing high-early-strength cements was considerably greater than that of the concrete containing the standard portland cements, while for the rich mix the difference was not marked.

Comparing the shrinkage with the strength, it is noted that the high-early-strength portland cements produced higher strength for a given shrinkage than did the standard portland cements. Furthermore, the results indicated that for the high-early-strength cements, the shrinkage per unit of paste decreased with the increase in the cement-water ratio of the concrete—that is, the lean mix showed greater shrinkage per each per cent of paste than did the rich mix.

EFFECT OF TYPE OF AGGREGATE—GROUP 5

Numerous investigators have pointed out that the aggregate in the concrete has an important effect upon the volume change. This action of the aggregate may be due to the volume change of the aggregate itself, to effect of the aggregate on the volume change of the cement paste, or to a combination of the two. Observations by Schumann[1] on volume changes on various building stones showed a considerable variation between different materials. Although certain stones such as special types of limestone showed a shrinkage of only 80 millionths, finely grained sandstone showed as much as 1780 millionths, when dried in air for two weeks. Different types of rock material may thus shrink more than ordinary concrete.

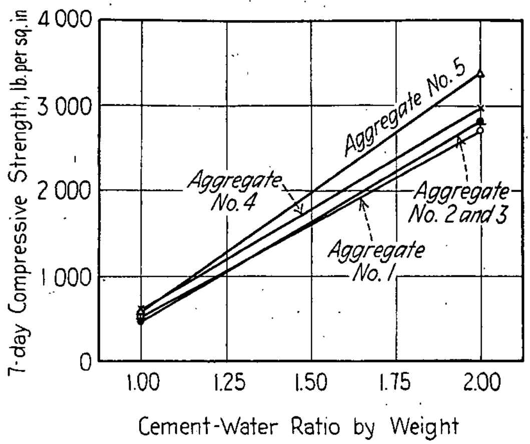

FIG.—12. Effect of Aggregate on Strength of Concrete in Group 5.

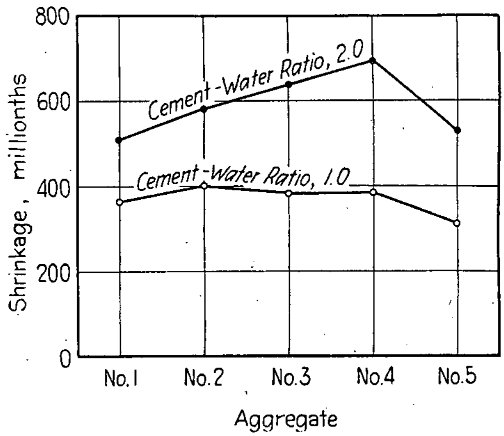

FIG. 13.—Effect of Aggregate on Shrinkage of Concrete in Group 5.

The results of the compressive strengths of the concrete containing the five different aggregate combinations in group 5, at 7 days are shown in Fig. 12. The compressive strength was affected very little by the different aggregates.

[1] Schumann, "Report of Commission on Constancy of Volume of Portland Cement," Assn. German Portland Cement Mfrs. (1889), *Tonindustrie Zeitung*, Vol. 5, p. 184 (1881), and Vol. 13, p. 435 (1889). A summary of Schumann's results is given in the paper by R. E. Davis, "A Summary of the Results of Investigations Having to Do with Volumetric Changes in Cements, Mortars and Concretes, Due to Causes Other than Stress," *Proceedings*, Am. Concrete Inst., Vol. 26, p. 407 (1930).

The results of the shrinkage observations are presented in Fig. 13. The variation in shrinkage is relatively small for the lean mix with a cement-water ratio of 1.0. However, aggregates Nos. 1 and 5 which had the coarser bank sand showed less shrinkage than did the concrete containing the three other fine aggregates. For the rich mix with a cement-water ratio of 2.0, the effect of the aggregates was more marked. Again, aggregates Nos. 1 and 5 show about the same shrinkage, indicating that the two coarse materials used—siliceous gravel and limestone—did not produce appreciable difference in the volume change. Aggregates Nos. 2, 3, and 4 showed a considerably greater shrinkage.

For the aggregates included in this study, the results indicated that practically no difference occurred due to the two coarse materials used, while a considerable variation in shrinkage was caused by the different fine aggregates.

GENERAL DISCUSSION

The results of this investigation help to account for most of the apparent independent factors which have been found to affect the volume change of mortars and concrete. For standard portland cement the shrinkage of the concrete was found to be practically proportional to the paste content. Thus every factor which tends to decrease the paste content of the concrete will also tend to reduce the shrinkage. This accounts for the fact that, as previous investigators have found, lean mixes will shrink less than rich mixes, concrete will shrink less than mortars, and dry mixes less than wet mixes; also that concrete of low sand content will shrink less than concrete of high sand content and concrete with coarse sand will show less shrinkage than concrete with fine sand. Concrete having well-graded aggregate will shrink less than concrete having poorly graded aggregate and the addition of powdered admixtures would in general be expected to increase the shrinkage. Thus the paste content explains the reason for the effect of practically all factors which have been found to influence the volume change of concrete.

Since the shrinkage of concrete is due to the evaporation of its mixing water, the prevention of evaporation will prevent shrinkage. However, the amount of loss of mixing water did not give direct information of the amount of shrinkage of the concrete. For lack of space the data on loss in weight have been omitted from this paper.

SUMMARY

The most important shrinkage results of this investigation based on ½ yr. dry storage of the concrete, may be summarized as follows:

1. The simple measuring apparatus used served well for volume change observations.

2. The 3 by 6-in. concrete cylinders proved easy to handle and gave dependable results both for compression tests and for shrinkage observations.

3. The quality of the cement paste, that is, the richness of the paste as given by the cement-water ratio, had practically no effect upon the shrinkage of concrete per 1 per cent of paste.

4. The shrinkage of concrete containing standard portland cement was practically proportional to the percentage of paste in the mix, regardless of the composition of the paste.

5. The length of moist curing up to 28 days had only small effect upon the shrinkage.

6. For lean mixes the high-early-strength portland cement produced considerably greater shrinkage than did standard portland cement, while for rich mixes the difference was inappreciable.

7. The shrinkage per unit of strength was less for high-early-strength than for standard portland cement.

8. For high-early-strength portland cement the shrinkage of the concrete per unit of paste was less for the rich mix than for the lean mix.

9. The fine aggregates showed greater effect upon the shrinkage than did the coarse aggregate.

10. For the standard portland cement used in this investigation (cement A), the shrinkage of the concrete may be expressed approximately by the formula:

$$s = k \cdot p$$

11. The results of this investigation are in agreement with previous investigations and the paste content theory explains many factors that have been found to contribute to the shrinkage of concrete.