ABSTRACT OF
"SHRINKAGE OF CONCRETE*
by Inge Lyse**

The investigation which is reported herewith was undertaken at the Fritz Engineering Laboratory of Lehigh University for the purpose of studying some of the fundamental causes of shrinkage of concrete. For the purpose of simplifying the experimental work, ordinary 3 by 6-inch concrete cylinders were used as test specimens, both for shrinkage measurements and for compression tests. The particular shrinkage factors investigated were: quality of cement paste, quantity of cement paste, and length of moist curing. Certain of these factors have only received scant observations in the past, and since they were considered some of the most significant factors in the quality-giving elements of concrete, they were selected for this study.

The portion of the test program discussed here was divided into three groups, each group devoted to one certain factor. The first group dealt with the effect of the quality of the cement paste of the concrete. Four cement-water ratios were used, that is, cement-water ratio by weight equal to 1.0, 1.5, 2.0 and 2.5, and two consistencies, one having slumps between one and three inches, and one between six and nine inches. Two sets of specimens were made, one for compression test at the age seven days, that is, at the time the other set of specimens were

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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-inch 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 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 second group was designed for the study of the effect of the quantity of paste. Two mixes were used, one in which the cement-water ratio was 1.0 and one with a cement-water ratio of 2.00. 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 of c/w = 1.0 were 24, 26, 28, and 30. The corresponding percentages for the rich mix were 30, 32, 34, and 36. As in Group I, 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 seven days, and one set for shrinkage observation.

The third group 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 and two had high-early-strength portland cement. The cement-water ratios of the two mixes were
1.0 and 2.0. The ages at which shrinkage observations began and compressive 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 one hundred per cent humidity and seventy degrees Fahrenheit temperature.

The study presented in this article is based on the shrinkage which took place during approximately one-half year storage in dry air.

The concrete cylinders which were observed for shrinkage were stored in a room with the temperature maintained at 80°F. No attempt was made to control the humidity, but a humidigraph gave the record of the relative humidity throughout the storage period. In general the humidity varied between forty and sixty per cent. Since all specimens of each group were made on the same day and for all groups, except Group III, 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. However, the specimens in Group III 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.

The results of the specimens included in Group I are presented in Fig. 1 and 2. Fig. 1 shows the relationship between shrinkage and cement-water ratio of the concrete. The shrinkage
increased regularly with the increase in the cement content in the paste. The relatively dry mix of slumps from one to three inches showed less shrinkage than did the relatively wet mix of slumps from six to nine inches. Thus the paste content as well as the cement-water ratio seemed to affect the shrinkage.

In Fig. 2 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 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 per cent 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. 2 give the shrinkage values obtained when divided by the amount of paste. The shrinkage per each per cent of paste is thus found to vary from approximately 16-1/2 millionths for cement-water ratio of 1.0 to 18 millionths for cement-water ratio of 2.5. Although the cement content was increased two and one-half times, the shrinkage per unit of paste increased only about ten 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.

In Group II, two concrete mixes were selected, c/w = 1.0 and c/w = 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.

Fig. 3 shows the shrinkage of the concrete plotted against the per cent 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 thirty per cent nominal paste content than did the very lean mix with c/w = 1.0. When the shrinkage is given per unit of paste, or per one per cent paste, each mix showed a constant shrinkage. The lean mix showed a shrinkage of about 16-1/2 millionths per one per cent paste, while the rich mix showed about 18 millionths. These values correspond very well with those obtained in Group I and indicate that within the range of ordinary mixes, that is, from c/w = 1.25 to c/w = 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 each per cent of paste be equal for the two mixes used, about fifteen per cent of the mixing water in the lean mix
would have to segregate. The results in Group I showed that a segregation of this amount of mixing water might well have taken place. Thus both 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 independent of the cement content in the paste. The shrinkage of the concrete in this investigation may thus be expressed approximately by the formula:

\[ s = k \cdot p \]

where \( s \) is shrinkage, \( k \) is a constant indicating shrinkage per unit 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 hardened concrete.

The results of the shrinkage tests for Group III are given in Fig. 4, which indicates 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 seven days with practically no change with the further increase in moist curing up to twenty-eight days. For the lean concrete mix the high-early-strength cement gave considerably greater shrinkage 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.

The fact that the amount of paste was found to determine the amount of shrinkage helps to account for most of the apparent independent factors which are known to affect the volume change
of mortars and concrete. For standard portland cement the shrinkage of the concrete was practically proportional to its paste content. Thus every factor which tends to decrease the paste content of the concrete may be expected to reduce the shrinkage. Lean mixes will shrink less than rich mixes, concrete will shrink less than mortars and dry mixes less than wet mixes. 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 theory 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 on the amount of shrinkage of the concrete.

The most important results of this investigation based on one-half year experimentation, may be summarized as follows:

1. The 3 by 6-inch concrete cylinders proved easy to handle and gave dependable results both for compression tests and for shrinkage observations.
2. 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 each per cent of paste.

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

4. The length of moist curing up to 28 days had little or no effect upon the shrinkage.

5. For standard portland cement the shrinkage of the concrete in this investigation may be expressed approximately by the formula:

   \[ s = k \cdot p \]

   where \( s \) is shrinkage of concrete, \( k \) is a constant indicating the shrinkage per each per cent paste, which depends upon the cement and the aggregates used, and upon the conditions of tests, and \( p \) is percentage of paste in the hardened concrete.

6. The results of this investigation are in agreement with previous investigations and the paste content theory explains practically all factors which have been found to contribute to the shrinkage of concrete made with standard portland cements.
Fig. 1 - Measuring Apparatus and Weighing Balance.
Fig. 2 - Variation between Individual Specimens
Fig. 3 - Relation between Strength and Cement-Water Ratio of the Concrete in Group I.
Fig. 6—Effect of Paste Content on Strength of Concrete in Group II
Fig. 8 - Effect of Length of Moist Curing on Strength of Concrete in Group III.
Fig 10: Effect of Cement on Strength of Concrete in Group IV.
Fig 11 - Effect of Cement on Shrinkage of Concrete in Group IV.
Fig. 12 - Effect of Aggregate on Strength of Concrete in Group I.
Fig. 13—Effect of Aggregate on Shrinkage of Concrete in Group V.