VOLUME CHANGES IN SAND-GRAVEL CONCRETE

Further discussion of data reported at the 22nd Annual Meeting with additional data covering exposure of test specimens up to 9 years.

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SYNOPSIS

In 1942 a report was presented giving the results of a laboratory investigation of the volume change characteristics of concrete containing the so-called "sand-gravel" type of aggregate which is so abundant in many parts of Kansas and Nebraska and which has been used extensively as a total aggregate for concrete in those areas. The study was made to determine whether the severe expansion with resulting map cracking which occurs in many concrete pavements constructed with this material as total aggregate could be reproduced in the laboratory and, if so, what particular materials or combinations of materials produced these effects and what corrective measures might be taken to eliminate the trouble The present paper reviews briefly the results of the earlier tests and presents additional data covering further tests up to 9 yr

Following the various cycles of heating and cooling and wetting and drying described in the 1942 report, the test specimens (beams 6- by 6- by 20-in in size) were stored in the moist room at 70 F for approximately 5 yr , after which they were stored outdoors on the ground for an additional 2 yr Measurements made at the conclusion of each of these storage periods revealed that practically all of the specimens which had developed excessive expansion as reported in 1942 had continued to expand during the subsequent storage periods. In other words, they were still growing when last measured at an age of approximately 9 yr On the other hand, the concrete specimens which had not expanded excessively up to 1942 showed only slight additional expansion during the subsequent moist curing period, followed, as would be expected, by contraction during the outdoors exposure. These data indicate that whatever influences were responsible for the excessive expansion of certain combinations involving the Platte River gravel, these influences were still at work during the exposure periods following the cycles of alternate wetting and drying and heating and cooling to which they had been originally subjected

The study of the behavior of the normally graded concrete as revealed by the more recent measurements indicates that, in the case of the two siliceous aggregates, the specimens containing the two so-called "Merriman cements" showed appreciably less expansion during exposure in moist air than concretes containing the two so-called "A S.T M." cements. These differences were not so marked in the case of the specimens containing the dolomitic aggregates.

In 1942 a report[1] was presented before the Board giving the results of a study to determine whether the severe expansion with resultant map cracking, which occurs on many concrete pavements constructed with sand-gravel as total aggregate, could be reproduced in the laboratory and, if so, what particular combinations of materials produced these effects and what corrective measures might be used to eliminate the trouble. At the time of presenting this report the statement was made that "a complete and final report of this investigation will be made, if possible, at the 1943 annual meeting of the Board." This statement was made because at that time no analysis of length change measurements along the upper and lower surfaces of the beam specimens had been made, the 1942 report having been based entirely on measurements along the central axis of the specimens. It was be-

[1] "Volume Changes in Sand-Gravel Concrete," by F. H. Jackson and W. F. Kellermann, *Proceedings*, Highway Research Board, Vol. 22, p 252 (1942)

lieved at that time that the indications from these measurements were so positive and the conclusions so important that publication of a progress report was justified, even though all of the test data had not been studied

Subsequent to the presentation of the 1942 report, the additional data furnished by measurements along the surfaces of the specimens were studied carefully. It was soon found that these measurements added nothing to the conclusions which had already been drawn and which had been published in the 1942 report It was accordingly decided that, instead of presenting the additional data in 1943 as a "final" report as originally planned, more information would be obtained by making additional measurements along the central axis at longtime intervals.

This procedure was followed with the result that measurements on these specimens are now available after approximately 9-years' exposure to various cycles of wetting and drying, heating and cooling, continuous moist storage and outdoor storage The present paper discusses the additional measurements and also summarizes again some of the original conclusions, none of which will have to be changed as the result of the additional data.

OBJECT OF THE INVESTIGATION

One of the objects of this investigation was to determine whether the characteristic map cracking which is frequently associated with the use of sand-gravel as total aggregate could be reproduced in the laboratory As early as 1938[2] Mr. W E Gibson, of the Kansas State Agricultural College, had shown that this type of failure could be developed by subjecting specimens of concrete to alternations of heating and cooling and wetting and drying without the introduction of a freezing cycle It was considered desirable to continue the line of attack suggested by Gibson by running a series of tests which would include, in addition to the Platte River aggregate, materials from two other sources differing widely from it and from each other in mineral composition It was considered desirable to study the behavior of concrete containing these other materials when graded exactly the same as the Platte River aggregate as well as to compare the behavior of concrete containing the Platte River material "sweetened" by the addition of crushed limestone to make a conventional total aggregate gradation, with that of concrete of the same proportions containing the other two ingredients. Complete descriptions of the materials used in the study, the mix data and the weathering cycles which were employed up to the end of the 660-day storage period are given in the 1942 report, and will not be repeated except to point out the principal variables which were studied

MATERIALS AND AGGREGATE GRADINGS

The following materials and aggregate gradations were used in the tests:

1 *Portland Cements* (4), as follows:

No. 1 A S T.M. Type I, with 9 per cent C_3A, low autoclave (0.09 per cent) expansion, high Merriman sugar test value, 0.70 per cent total alkali and 0 52 per cent water soluble alkali, both calculated as Na_2O.

No. 2 A.S.T.M. Type I, with 16 per cent C_3A, relatively high (0 42 per cent) autoclave expansion, high sugar test value, 0.73 per cent total alkali and 0 38 per cent water soluble alkali.

No. 3. A.S T.M. Type II from same mill as No. 2, with 5 per cent C_3A, low sugar test value, low autoclave expansion, 0.47 per cent total alkali and 0.18 per cent water soluble alkali. Cement No. 3, in addition to meeting the A.S.T.M requirements, also complied with the requirements of the New York Board of Water Supply. It could therefore be classified as a "Merriman" type cement.

No 4. A S T M Type II, with 7 per cent C_3A, low sugar test value, low autoclave expansion, 0 55 per cent total alkali and 0 21 per cent water soluble alkali. Cement No. 4 was also classified as a Merriman type cement.

Complete chemical and physical tests of the cements are given in Table 1 of the 1942 report

2 *Aggregates* (3), as follows.

Aggregate A. Sand-gravel from the Platte River at Schuyler, Nebraska, composed essentially of granite, quartz and feldspar, with about 0.3 per cent material classified as opal. The amount of feldspar, predominantly potash (orthoclase and microcline), varied widely in the different sizes from a high of 40 per cent in

[2] "A Study of Map-Cracking in Sand-Gravel Pavements" by W. E Gibson, Engineer of Tests, Kansas State Highway Commission. *Proceedings*, Highway Research Board, Vol. 18, Part I (1938).

the No. 4–8 size to a low of 3 per cent in the material passing No. 100. This material has, in general, a poor service record.

Aggregate B. Sand and gravel from Long Island, N. Y. (the so-called "Cowe Bay" material). Sand and gravel almost entirely siliceous in composition. About 90 per cent quartz and quartzite, with practically no feldspar. This aggregate has an excellent service record.

Aggregate C. Sand and gravel from Plainfield, Illinois (Chicago area). In contrast with Aggregate B, this aggregate was almost entirely dolomitic in composition, the sand carrying about 80 per cent and the gravel about 90 per cent dolomitic material The sand contained about 15 per cent quartz. This material also has an excellent service record

All three of the aggregates used in these tests met the conventional physical test requirements for aggregates for concrete (wear, silt content, organic impurities, etc) as shown in the table on page 289 of the 1942 report.

Complete mineral analyses of the aggregates are given on pages 287 and 288 of the 1942 report.

3. *Aggregate gradations* (3), as follows·

Grading No. 1: The Platte River sand-gravel gradation as normally used. This material is in reality a coarse sand, only 5 per cent being retained on the ⅜-in. sieve and only 5 per cent passing the No. 50 sieve.

Grading No. 2: The same as No. 1 except for the addition of sufficient fines (from the same source) to bring the total passing the No. 50 sieve up to 20 per cent. The maximum size was not increased.

Grading No. 3: For this gradation, sufficient coarse aggregate was added to produce a conventional total aggregate gradation from 1½ in. down, with about 65 per cent retained on the No. 4 sieve. In the case of Aggregate A, this was accomplished by adding crushed limestone (1½ to ⅜ in. in size) from Bethany Falls, Kansas to the Platte River material. This procedure is locally known as "sweetening." It resulted in a combined aggregate consisting of 53 per cent limestone and 47 per cent sand-gravel by weight. In the case of Aggregates B and C, the total aggregate was obtained by using gravel from the same source as the sand; the total aggregate gradings being practically identical with that used for Aggregate A sweetened with limestone.

Sieve analyses of the various aggregates and aggregate combinations are given in Table 3 on p. 256 of the 1942 report.

TESTING PROGRAM

The test specimens were beams 6- by 6- by 20-in. in size, with stainless steel plugs set in the center of the ends of the specimens as well as brass inserts provided with drilled gage seats in the upper and lower surfaces. Three sets of readings were taken, one on the end plugs and the others along the upper and lower surfaces. These latter measurements were made with a mechanical hand strain gage over a 10 in. gage length; the end measurements with a horizontal comparator. All measurements were taken with the concrete in a moist condition at 70 F. in order to eliminate insofar as possible differences due to variations in temperature and moisture conditions at time of test.

Each of the four cements and three aggregates were tested in each of the three gradations, making 36 combinations. Two series of tests were run and two specimens were cast for each combination in each series, making a total of 144 specimens in the entire program.

Series I. For gradings 1 and 2 of Series I the proportions were determined on the basis of using a constant water-cement ratio of 0.67 by volume (5.0 gal. per sack) for all combinations of cements and aggregates. This resulted in average cement contents of about 7.6 sacks per cubic yard for the Platte River material, or about the same as used in the roads which had given trouble. The corresponding cement factors for Aggregates B and C ran considerably higher, averaging about 8 4 for Aggregate B and 9 0 for Aggregate C. For gradings 1 and 2 a slump of approximately 1 in. was used, as this is the consistency normally employed in practice when using sand-gravel aggregate. For grading 3 of Series I (the normal concrete grading), all combinations were proportioned on the basis of securing an approximately constant cement factor of 5 sacks per cubic yard with the slump maintained at approximately 2½ in.

Series II. For gradings 1 and 2 of Series II the same proportions and consistency were used for all three aggregates and a given cement as were used in Series I with that cement and the Platte River material (Aggregate A). This was for the purpose of equalizing somewhat the variations in cement content which resulted from the use of a constant water-cement ratio. However, the resultant water-cement ratios varied considerably, running as high as 6.7 gal. per sack as compared to the 5.0 gal. per sack used in all mixes containing the Platte River material. For grading 3 of Series II, the same proportions, including water, were used as in Series I.

It will be seen from the foregoing that, for each variable involving Aggregate A, in gradings 1 and 2, we have results based on four specimens of a kind (two in Series I and two in Series II) as compared to two specimens of a kind in the case of Aggregates B and C. Thus, in the case of Aggregate A, Series II serves as a check on Series I. In the case of grading 3, all of the data from Series II serve as a check on Series I inasmuch as the same mixes were used throughout. Complete mix data are given in Tables 4 to 8, inclusive, of the 1942 report.

TYPES OF STORAGE

After a preliminary moist storage period of 28 days, the concrete test beams were measured for length and then exposed successively to the following cycles of heating and cooling and wetting and drying for the durations indicated in each case.

Cycle A. One day in moisf room at 70 F., followed by one day in air at 130 F., followed by two days in air at 70 F. Forty cycles, requiring 160 days.

Cycle B. One day in water at 70 F., followed by one day in air at 130 F., followed by two days in air at 70 F. Fifty cycles, requiring 200 days.

Cycle C. One day in water at 70 F., followed by one day in air at 130 F. One hundred and fifty cycles requiring 300 days.

Cycle D. Continuous storage in moist air at 70 F. for 1790 days. (Approximately 5 yr.).

Cycle E Exposure outdoors near Washington, D. C. for 820 days (Approximately 2 yr. and 3 mo.).

As pointed out in the 1942 report, Cycle A was found to be ineffective in developing excessive expansion in any of the combinations within the periods indicated. This was due no doubt to the relatively short (24-hr.) resaturation period in the moist room following 48 hr. in the air of the laboratory, a treatment which resulted in small residual contraction. Cycle B tended to reverse this trend somewhat but certainly not to a degree that would indicate abnormal expansion. However, when the 48-hr. drying period at 70 F. was eliminated (Cycle C), excessive expansion in certain combinations became almost immediately evident. This cycle was continued for 300 days, at the conclusion of which the final readings shown in the 1942 report were made. The abnormal expansion (an increase in length of almost 1 percent in certain cases), which had developed in some of the combinations by that time, with resultant map-cracking and other evidences of deterioration, indicated the desirability of discontinuing the type of cycle which involved daily handling of the specimens. It was therefore decided to discontinue Cycle C at the end of 660 days and to store the specimens in the moist room. This storage condition was continued for approximately 5 yr. (Cycle D), after which the specimens were again measured for length and then stored outdoors on the ground in the vicinity of the laboratory (Cycle E). A set of readings taken after approximately 2 years' outdoor exposure, together with the readings taken at the conclusion of the 5-yr. moist storage period, form the additional data of the present report. These final readings were made after 96 hours' resaturation in water following the outdoor storage The balance of this paper will be devoted to a discussion of all of the available data up to the present time.

DISCUSSION OF RESULTS

As previously noted, a study was made of the length change data furnished by measurements along the upper and lower surfaces of the specimens. These measurements showed, in general, the same trends as those taken along the central axis. However, the surface measurements, which were made with a mechanical strain gage over a gage length of 10 in., were individually somewhat erratic. The end measurements were made with a horizontal comparator over the entire length of the beam—that is, 20 in and were quite consistent. The individual discrepancies noted in the case of the surface readings reveal the difficulty of securing consistent results with a mechanical strain gage which involves the personal equation. With the horizontal comparator, on the other hand, very consistent results are obtainable because the personal equation is absent

The surface measurements, though erratic, do indicate two definite trends, neither of which would have been revealed by end measurements. During Cycle D, continuous moist storage for 1790 days, the surface measurements revealed appreciable warping in many of the specimens, particularly those which had developed large residual expansions at the end of Cycle C (660 days) These were principally the combinations involving Aggregate A (the Platte River material) in gradings 1 and 2. In the case of these specimens, the overall expansion at the end of Cycle D (continuous moist storage) was also large. In other words, they continued to expand after the wetting and drying cycle had been discontinued Warping was revealed by substantially higher expansion along the top surface as molded than along the lower surface. This caused the ends to curl downward, as illustrated in Figure 1, which shows readings for one of the beams in the combination of Aggretate A with Cement No 1 and grading 1. These measurements no doubt reflected the tendency of the surface mortar to expand at a greater rate than the mass of the concrete, a tendency which probably exists in most concrete pavements, where, due to finishing operations, a layer of mortar of distinctly inferior quality is formed on the surface of the pavement These differentials between the upper and lower surfaces were revealed only in the case of combinations which had expanded excessively. In cases where the overall expansions were small (of the order of 0.1 per cent or less) which was the case with the majority of the combinations, the warping tendency was not indicated by the measurements This was due, it is believed, to the fact that the surface measurements were not sufficiently precise to reveal the very small length changes involved

The other interesting trend is the fact that at the end of Cycle E (outdoor storage on the ground for about 2 yr), most of the specimens showed evidence of upward warping at the ends, due, probably to differential drying out of the top surface with respect to the lower surface in contact with the ground. Here again, however, the individual results show many inconsistencies. All in all, it is believed that, although the general trends indicated by the surface measurements are probably bona fide, the individual measurements, for the reasons stated, are not sufficiently accurate to permit of detail comparisons between combinations where the total movements are small. These include most of the combinations involving Aggregates B and C as well as Aggregate A in grading 3. For this reason these data are omitted and the balance of the present report will be limited to a discussion of the results of the end measurements only.

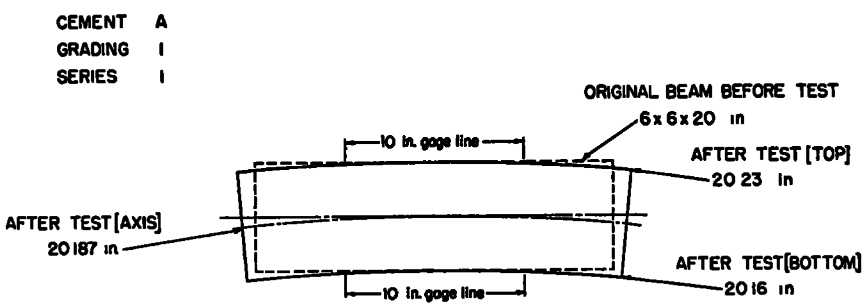

Figure 1. Exaggerated View of Test Beam after Various Exposure Cycles Showing Typical Expansions

The cumulative changes in length of the test specimens, in percents, at the expiration of the various exposure periods are given in Tables 1 and 2 Each value is the average of measurements on two specimens made on different days In the case of Aggregate A in gradings 1 and 2 and all three aggregates in grading 3, the same proportions and consistency were used in Series II as in Series I. In these cases, therefore, the results of Series I and II are directly comparable, a point which should be born in mind when studying the data. On the other hand, combinations involving Aggregates B and C in gradings 1 and 2 are not strictly comparable in the two series due to the fact that a constant water-cement ratio was used in Series I whereas in Series II the proportions were kept constant for each cement. However, even in these cases the data will show that the differences in cement content and water content, although quite large, were apparently not sufficiently great to affect the general trends to an appreciable extent. Figure 2 illustrates the appearance of the end of Cycle E of two of the specimens which had developed excessive expansion during Cycle C.

TABLE 1
CUMULATIVE CHANGES IN LENGTH AFTER VARIOUS STORAGE PERIODS
SERIES I

Aggregate	Cement	Percent Change in Length After Storage for				
		160 days	360 days	660 days	2,450 days	3,270 days
		Cycle A	Cycle B	Cycle C	Cycle D	Cycle E
Grading 1						
A	1	−0 005	0 001	0 772	0 940	0 968
B		− 005	−.002	.044	108	.095
C		− 017	−.010	010	038	.003
A	2	− 005	008	118	.156	143
B		− 008	.002	038	.047	.034
C		− 019	− 006	015	.052	013
A	3	− 010	−.011	223	.459	.508
B		−.012	− 013	.010	–	–
C		− 017	− 012	006	036	.004
A	4	− 010	− 005	316	529	.548
B		− 016	− 011	009	.043	.017
C		− 022	− 015	− 002	010	− 006
Grading 2						
A	1	−0 010	0	0 498	0 605	0 607
B		− 007	−0 004	.033	072	.059
C		− 018	− 015	.011	026	0
A	2	− 006	002	082	098	093
B		− 012	.003	.033	060	039
C		− 022	− 010	018	.041	.010
A	3	− 013	− 017	030	095	099
B		− 020	− 017	012	057	045
C		− 015	− 014	.010	026	.009
A	4	− 016	− 015	008	038	.011
B		−.013	−.016	007	019	008
C		− 021	−.016	003	014	− 001
Grading 3						
A	1	−0 003	−0 001	0 022	0 042	0 033
B		−.004	−.004	.062	.187	.163
C		− 004	002	009	024	.016
A	2	− 004	0	012	107	.081
B		0	004	.024	072	.078
C		− 007	− 005	007	.043	014
A	3	− 008	− 006	.005	.014	009
B		−.010	− 003	.016	030	023
C		−.013	−.001	008	027	.016
A	4	−.009	−.003	004	010	007
B		− 006	001	039	046	033
C		− 009	− 001	002	.013	007

Each value is the average of tests of two beams.

TABLE 2
CUMULATIVE CHANGES IN LENGTH AFTER VARIOUS STORAGE PERIODS
SERIES II

Aggregate	Cement	Percent Change in Length After Storage for				
		160 days	360 days	660 days	2,450 days	3.270 days
		Cycle A	Cycle B	Cycle C	Cycle D	Cycle E
Grading 1						
A	1	−0 009	−0 002	0 752	0 952	0 976
B		− 010	− 001	102	.172	169
C		− 019	− 003	.016	023	.001
A	2	− 010	.007	.124	.176	.147
B		− 011	006	022	028	.017
C		− 027	− 007	.011	016	−.002
A	3	− 009	− 005	445	648	686
B		− 017	− 005	019	.032	013
C		− 023	−.003	016	023	.004
A	4	− 015	− 010	106	–	–
B		− 013	− 004	017	.020	.004
C		− 028	− 013	− 005	0	−.001
Grading 2						
A	1	−0 010	−0 006	0.646	0 720	0 728
B		− 010	− 001	.041	.042	057
C		−.019	− 011	.013	.019	0
A	2	− 015	001	115	148	.138
B		−.014	002	030	.039	035
C		−.021	− 006	022	036	.012
A	3	−.020	− 019	144	.204	195
B		−.017	− 006	022	033	012
C		−.021	− 008	010	.013	.003
A	4	− 015	− 014	027	.041	020
B		− 019	− 010	010	019	005
C		− 020	− 007	008	013	001
Grading 3						
A	1	−0 001	0 006	0 035	0 047	0.044
B		− 006	002	.101	.169	.184
C		− 012	006	.019	.020	013
A	2	− 005	003	023	.108	.103
B		−.007	004	.030	.068	.075
C		−.018	− 003	016	.029	012
A	3	− 007	001	016	026	018
B		− 012	0	.028	.032	.032
C		− 015	001	.015	017	016
A	4	− 009	− 002	012	.015	.019
B		− 013	− 004	014	019	010
C		− 014	− 002	.014	014	.011

Each value is the average of tests of two beams.

The values shown in Tables 1 and 2 have been plotted to show graphically for the various combinations of cement and aggregates the cumulative effect of the five exposure cycles on the volume constancy of the concrete. The curves are shown in Figures 3 to 6, inclusive. The following comments on these graphs will include a brief discussion of the indications as they appeared in 1942 at the conclusion of Cycle C as well as additional comments bearing on the indications revealed by the further exposure of the specimens to Cycles D and E.

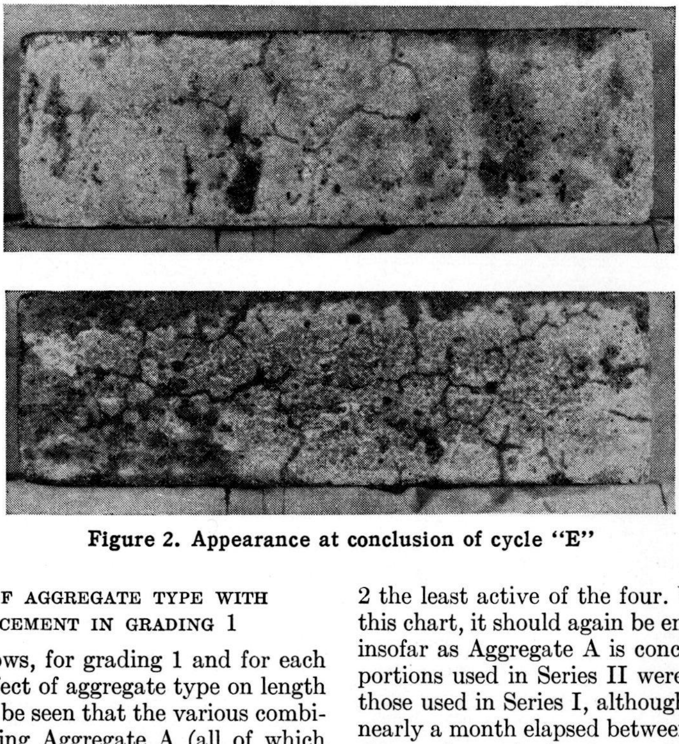

Figure 2. Appearance at conclusion of cycle "E"

EFFECT OF AGGREGATE TYPE WITH EACH CEMENT IN GRADING 1

Figure 3 shows, for grading 1 and for each cement, the effect of aggregate type on length change. It will be seen that the various combinations involving Aggregate A (all of which showed high expansion at the end of Cycle C, as noted in the 1942 report) all continued to expand through Cycle D and, in most cases, through Cycle E. The concrete containing Cement 2 is the only exception to this tendency. On the other hand, the concretes containing Aggregates B and C, although showing small expansions as the result of Cycle D, all show some contraction as the result of the outdoor exposure of Cycle E. The fact that these concretes all showed contraction at the end of Cycle E, whereas the specimens containing Aggregate A continued to expand, would indicate that whatever the nature of the internal reactions which caused the excessive expansion with Aggregate A, the same reactions were continuing through Cycle E. Otherwise, we would expect contractions during Cycle E similar to those shown in the case of Aggregates B and C. It should also be noted that the amount of the expansion occurring in the concrete containing Aggregate A is influenced appreciably by the cement, Cement 1 being by far the most active and Cement 2 the least active of the four. When studying this chart, it should again be emphasized that, insofar as Aggregate A is concerned, the proportions used in Series II were identical with those used in Series I, although an interval of nearly a month elapsed between the casting of the specimens in the two series. It should be noted also that the influence of aggregate grading has been entirely eliminated by this grouping of the data, all of the specimens regardless of aggregate type containing material of identical grading; in this case grading 1, the normal grading of the Platte River material. The data confirm the conclusion stated in the 1942 report to the effect that aggregate grading alone is not responsible for the excessive expansions which have taken place.

As noted above, all of the concretes containing Aggregates B and C expanded somewhat during Cycle D and then showed contraction at the end of Cycle E. Furthermore, Aggregate B, the siliceous material from Long Island, generally shows higher expansions than Aggregate C, the dolomitic material from Chicago. There is a strong possibility that these differences, although small as compared to the expansions found in the case of Aggregate A, may be related to differences in the thermal characteristics of the two aggregates. However, there is no evidence of abnormal growth in the case of either of these materials

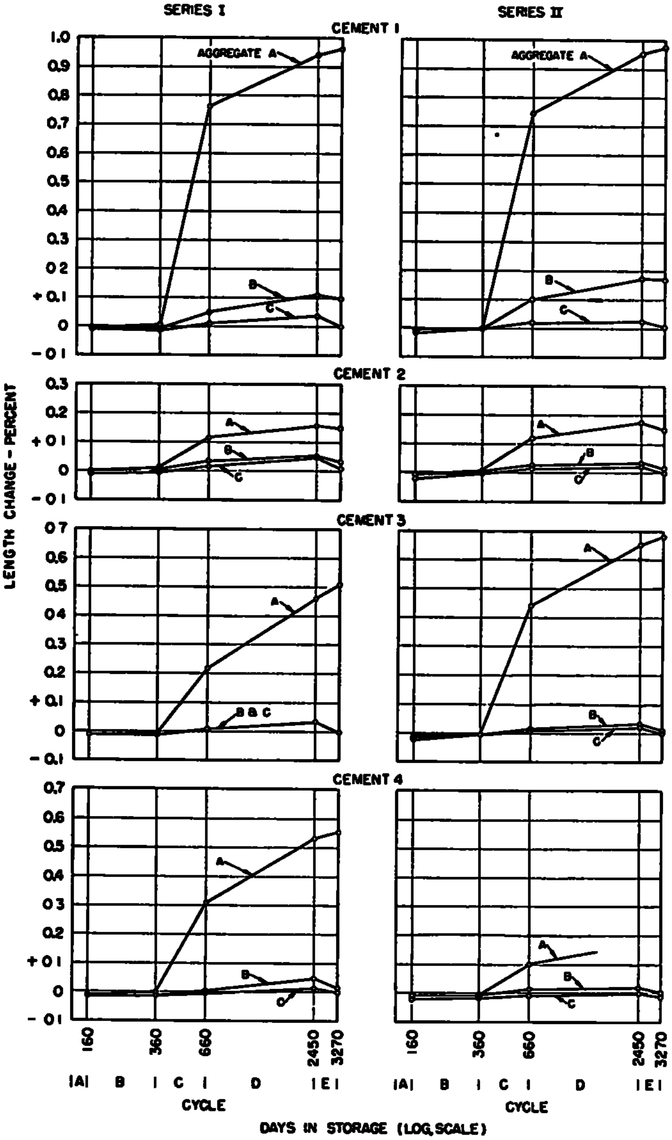

Figure 3. Effect of Aggregate Type
Grading 1

when used in this grading, the maximum expansions with all but one cement being less than the 0.1 percent which is frequently indicated as the dividing line between normal and abnormal behavior in this regard

The reason for the abnormal expansions found with the Platte River material remains unanswered. In the 1942 report the possibility of an alkali-aggregate reaction was mentioned. However, the fact that the Platte River aggregate used in these tests contained only 0.3 percent opal coupled with the lack of relation between the alkali contents of the four cements and the resultant volume change would tend to eliminate this possibility. Neither can these abnormal expansions be due to the rich mix that was used, because in Series I the cement contents of the combinations involving Aggregates B and C were actually higher than those which involved Aggregate A. There remains the possibility that these abnormal effects are due to differential thermal characteristics of the aggregates. Blanks[3] calls attention to the fact that aggregate of the same general nature as the Platte River material contains substantial amounts of the orthoclase and microcline feldspars and that these minerals have a very low thermal coefficient of expansion. The Platte River gravel used in these tests contained varying amounts of these minerals ranging up to as much as 40 percent in the No. 4–No. 8 size and it is possible that the deterioration of concrete containing this material may be due in part, at least, to stress developed within the concrete as the result of thermal incompatibility. This fact alone, however, would not account for the wide differences in expansion noted with the different cements. These differences must be related to some characteristic or characteristics of the combination which are influenced by both the aggregate and the cement Whether these effects are physical or chemical, or a combination of the two, has not been determined.

EFFECT OF AGGREGATE TYPE WITH EACH CEMENT IN GRADING 2

Figure 4 shows, for each cement, the effect of aggregate type when used in grading 2. This grading was the same as grading 1 except that sufficient fine material from the same source was added to increase the total amount passing the No. 50 sieve from 5 percent to 20 percent, with no increase in the amount retained on the ¾-in sieve.

Comparison of Figures 3 and 4 indicates, for Cements 1 and 2, trends almost identical with those found with grading 1 In the case of Cement No. 1, the addition of fines, while causing some reduction, did not appreciably reduce the excessive expansion shown by Aggregate A in grading 1. In the case of Cement No. 2, about the same expansions were noted for both gradings, the values being comparatively low in both cases. In the case of Cement 3 in Series I, and Cement 4 in both series, the abnormal expansion shown for Aggregate A in grading 1 was largely eliminated. In fact, so far as Cement 4 is concerned, the expansions found for all three aggregates were all well within the 0.1 percent limit previously mentioned In other words, for this cement, as well as for Cement 3 in Series I, concrete containing the Platte River material in grading 2 behaved normally.

In general, it may be said that the addition of fines to the Platte River material (Aggregate A) reduced the expansions somewhat, the amount of the reduction varying with the cement. Moreover, we do not find the same tendency for continued expansion with Cements 1, 3 and 4 during Cycle E as was noted in the case of grading 1 (Fig. 3).

Attention has been directed to the fact that, in Series I, the cement contents of the concretes containing Aggregates B and C were substantially higher than those used with Aggregate A For example, in the case of Aggregate C in grading 2, Cement 2 (Fig 3), the cement factor was 9.77 sacks per cubic yard as compared to 9 00 for Aggregate B and 8.09 for Aggregate A. These values as well as the corresponding cement factors for the other combinations used in Series I, gradings 1 or 2, are shown in Tables 4 and 5 of the 1942 report. The variations were necessary in order to maintain the same water-cement ratio throughout the series. The data show definitely that, contrary to the thought expressed in a discussion of the 1942 report, there is no relation whatever between cement content and expansion. In fact, as will be seen later, the actual expansions of certain combinations in

[3] "Modern Concepts Applied to Concrete Aggregate," by R. F. Blanks, *Proceedings*, ASCE, Vol. 75, No 4, April 1949.

gradings 1 and 2, all of which involved the use of very rich mixes in Series I, were no higher at any time than the expansions developed with grading 3 (the normal concrete), where the cement content was reduced to 5 sacks per cubic yard.

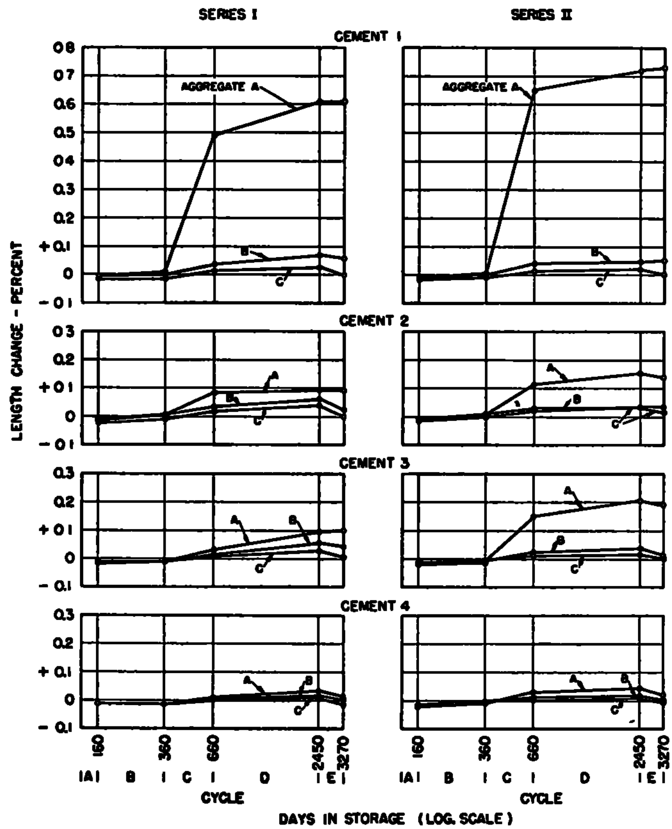

Figure 4. Effect of Aggregate Type
Grading 2

EFFECT OF AGGREGATE TYPE WITH EACH CEMENT IN GRADING 3

The effect of aggregate type with each cement in grading 3 is shown in Figure 5 It will be noted that in practically all cases the abnormal expansions which occurred when using Aggregate A in gradings 1 and 2 were eliminated by the use of a normal concrete grading obtained by "sweetening" the Platte River material with crushed limestone. In fact the maximum expansions with this combination were actually less in all cases except with Cement 2 than were those for the corresponding combinations involving Aggregate B. This exception from the general trend shown with gradings 1 and 2 is so outstanding as to indicate that it might be accidental were it not for the fact that almost exactly the same expansions were noted for this combination in Series I as in Series II which was made almost a month later. In the case of Cement No 2, both series show higher expansions for Aggregate A than for either B or C. Here again the reversal might be considered accidental except for the fact that the results of the two series check each other almost exactly.

EFFECT OF CEMENT IN GRADING 3

Except for the combination involving Cement No. 1 and Aggregate B virtually all of the expansions observed in the normally graded concrete were within the range of 0 to 0.1 percent. It was decided, therefore, to plot the length changes for this grading on a very much larger vertical scale than shown in Figures 3 to 5, inclusive. The data are shown in Figure 6. In this chart differences in expansion of the order of 0.01 percent or less are clearly indicated and may be of some interest. The results are for the average of Series I and II. In other words, each point used in plotting the curves was the average of four determinations, two in Series I and two in Series II.

concrete containing Aggregate C showed somewhat greater contraction than the concretes in which Aggregates A and B were used. At the conclusion of Cycle A the moist storage condition was changed to 24 hr. in water instead of in moist air, the period of drying remaining the same. At the expiration of 50 cycles of this treatment (Cycle B), all of the specimens had expanded although in most cases they still showed some residual contraction. With the elimination of the 48-hr. drying period at 70 F. (Cycle C), the specimens continued to ex-

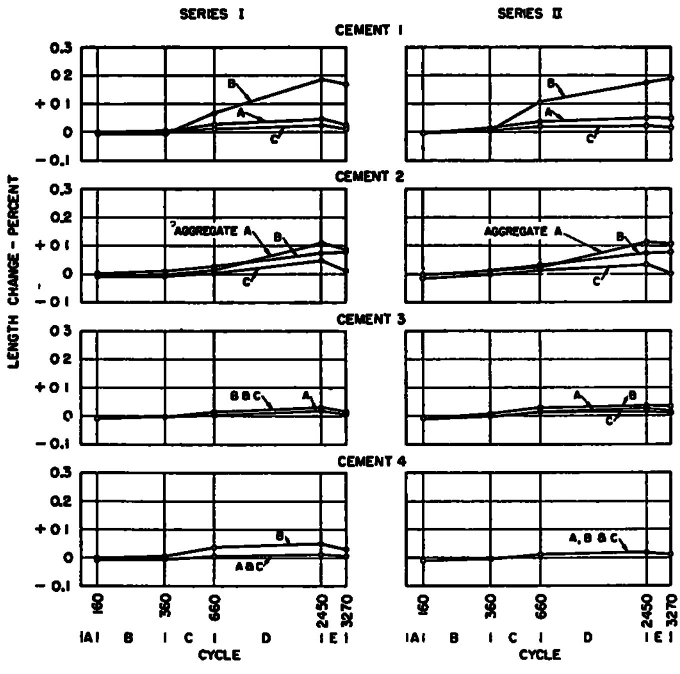

Figure 5. Effect of Aggregate Type Grading 3

In studying this figure, the nature of the various exposure cycles should be kept clearly in mind. It will be recalled that Cycle A involved a 72-hr. drying period followed by 24 hr. in moist air. The figure shows clearly that 24 hours' resaturation in moist air was not sufficient to prevent residual contraction. Furthermore, there seemed to be a definite tendency for Cements 3 and 4 to show greater contractions than Cements 1 and 2, this trend being evident in the case of all three aggregates and in both series. Also, for a given cement,

pand, this trend continuing through Cycle D. It will be noted that at the expiration of this cycle all combinations showed residual expansion, the amounts varying with both the cement and the aggregate. In general, Cements 1 and 2 had expanded more than Cements 3 and 4, the difference being much more marked in the case of Aggregates A and B than in the case of Aggregate C.

It will be noted that in most cases the measurements taken at the end of Cycle E show some contraction. This is no doubt due to the fact that, after 2 years' outdoor exposure, the 96 hr. in water which was provided before the measurements were taken was not sufficient to resaturate the specimens. In the case of Cement 2 with Aggregate B, readings at the end of Cycle E showed further expansion, which is a definite exception to the general trend. However, it should be noted again that the same tendency was found in both series.

The point of chief interest regarding this figure is the relatively high expansion which took place in the combinations involving Cements 1 and 2 with Aggregates A and B. Aggregate A in this grading was composed of a mixture of the Platte River material and crushed limestone in about equal parts. Aggregate B was almost 100 percent quartz or quartzite. Aggregate C averaged about 95 percent dolomite. The chief difference in the cements is the fact that Cements 3 and 4, in addition to meeting the standard A.S.T.M. requirements, also met the specification requirements of the New York Board of Water Supply. These are the specifications originally sponsored by the late Thaddeus Merriman. Cement meeting these requirements would be classified as A.S.T.M. Type II, principally because of the limitation on alumina. However, they are much more restrictive than Type II in that they include also limitations on sugar solubility (a test devised by Mr. Merriman to detect underburning) as well as a requirement on maximum allowable water soluble alkali. The requirements are shown in detail in the specifications of the Board of Water Supply of the City of New York, edition of 1937. The authors are not prepared to advance

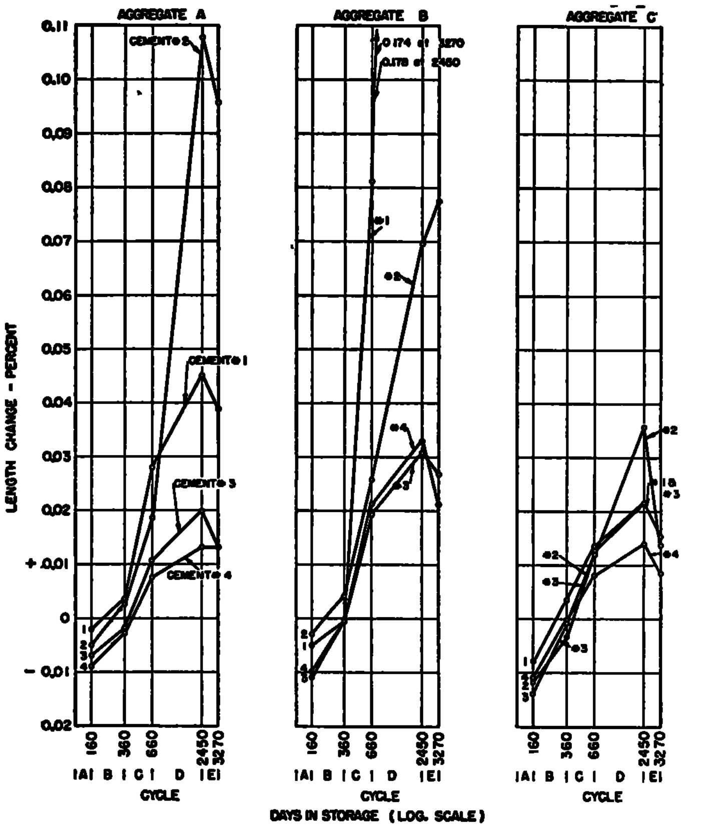

Figure 6. Effect of Cement; Grading 3. Average Series I & II

an explanation for the increase in expansion noted in the case of Cements 1 and 2 in combination with Aggregates A and B as compared to the expansion noted for other combinations However, the trends are so definite and are repeated so consistently in the two series of tests as to make it extremely unlikely that they are accidental. The data are presented as an interesting example of the possible variations in the volume change characteristics of different combinations of cements and aggregate They illustrate a principle which we are recognizing more and more, and that is that the volume constancy of concrete is influenced to a marked degree by the particular combination of cement and aggregates used in the mix and that these materials must be studied in combination with each other in concrete rather than individually.

CONCLUDING STATEMENT

It is realized that the foregoing discussions raise many questions for which answers have not been supplied. This is just as true now as it was in 1942 when the original report was prepared. For example, no one has yet, as far as the authors are aware, advanced an entirely satisfactory explanation for the abnormal expansion which takes place when Platte River or similar aggregate is used in concrete with certain cements. Nor has an adequate explanation been forthcoming as to why this expansion can be stopped by "sweetening" the mix with crushed limestone. These tests as well as tests made by other investigators have proved that conventional explanations such a aggregate grading, aggregate quality as measured by conventional tests, cement content, free lime in cement, etc., are not sufficient to explain the facts The probability that the aggregate is mildly alkali-reactive combined with the fact that from one-fourth to one-third of the aggregate consists of feldspar of a type having a low thermal coefficient of expansion may supply the answer. The data of these tests indicate quite definitely that neither of these factors taken separately is the answer. Moreover, the fact that the Platte River aggregate used in these tests contained only 0.3 per cent opal would indicate that the alkali-aggregate reaction, as we generally consider it, was not an important factor. It is also difficult to visualize the mechanics of an action which results in expansion due to the use of aggregate having a low thermal coefficient of expansion. However, there is also the possibility that the feldspar may be a factor, due to some other reason, such as possible alteration of the mineral with time, thus contributing to expansion

ADDENDA

Subsequent to the publication of the 1942 report it was discovered that the values shown in the column headed "Absolute Volume" in Table 8 (p. 259 *Proceedings* H. R B., Vol 22, 1942) were incorrect The correct values computed from the corresponding weight proportions are as follows:

Aggregate	Absolute Volume
A	1 3 04 5 43
B	1 2 86 5 37
C	1 2 92 5 31

The above values should be substituted for the values shown in Table 8 for each of the four cements.