VOLUME CHANGES IN SAND-GRAVEL CONCRETE

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The tests described in this progress report were made in an effort to determine the causes of the premature failure of certain concrete pavements in the Middle West in which a naturally occurring mixture of sand and fine gravel known locally as "sand-gravel" was used as total aggregate Determinations of volume change were made on numerous combinations of materials varying both in grading and mineral composition, using a weathering cycle similar to that proposed several years ago by W E Gibson, Engineer of Tests, Kansas State Highway Commission, and described by him in a paper before the Board at the 1938 annual meeting Aggregates included, in addition to Platte River gravel, a calcareous gravel from Chicago, Illinois, and a siliceous gravel from Long Island, New York Each of these materials was investigated in concrete in three gradations,—the normal sand-gravel grading as used in the pavements in question, a similar grading modified by the addition of fines passing the No 50 sieve, and a typical concrete grading with 1½-inch maximum size aggregate In the case of the Platte River material, crushed limestone was added to produce the normal concrete grading Four cements differing considerably in chemical composition and in physical properties were used in the tests

These tests revealed abnormal expansion in all combinations which involved the use of Platte River gravel as total aggregate That the character of the material rather than its fine grading is responsible for high expansion is indicated by the fact that no abnormal expansion was found with either of the other materials even when graded exactly the same as the Platte River aggregate

Adding crushed limestone to the Platte River gravel reduced the expansion to values comparable to those obtained with the other aggregates indicating that the practice of "sweetening" the aggregate by the addition of sufficient calcareous material to produce a normal concrete grading will eliminate this trouble

A complete and final report of this investigation will be made, if possible, at the 1943 annual meeting of the Board

HISTORY

The lack of suitable deposits of coarse concrete aggregate in many parts of Kansas and Nebraska and in certain sections of western Missouri and Iowa has led to the extensive use of a naturally occurring mixture of sand and fine gravel as total aggregate for concrete work in these regions. This material (substantially all of which passes a ⅜-inch sieve) is known locally as "mixed aggregate" or "sand-gravel" Concrete in which it is used is known as "sand-gravel" concrete to distinguish it from concrete containing normally graded coarse aggregate, which is called locally "fine-and-coarse-aggregate" concrete. These sand-gravels vary somewhat in mineral composition from place to place but, in general, are composed of quartz and granitic materials with varying amounts of feldspar and very little limestone or other calcareous material.

The local sand-gravel deposits, widely distributed along the beds of such streams as the Arkansas and Kaw Rivers in Kansas and the Platte River in Nebraska, furnish the only type of aggregate readily available in many parts of these States These aggregates are, in general, reasonably well graded from ⅜-in down, although the process of washing results in a deficiency in the finer sand sizes, particularly in the material passing the number 50 sieve. Since these deposits are usually worked by means of portable or semiportable plants set up close to the project, their availability makes them exceedingly attractive from the economic point of view, even though the fine grading has in some cases necessitated the use of cement contents as high as 7.5 to 8.0 sacks per cubic yard.

The belief that these materials are of excellent quality, coupled with the fact that they are so readily available, has resulted in their use in the construction of a substantial mileage of concrete pavements in Kansas and Nebraska. For example, most of the concrete pavement along U. S. Route No. 30 in Nebraska is of this type. This route follows the Platte River for many miles and the local sand-gravel is available at almost any point along the road with very little haul.

Unfortunately, the sand-gravel type of concrete pavement has not proved entirely satisfactory. Defects which usually take the form of multiple map-cracking of the surface frequently develop on sections of many projects within a few years. These defects lead sometimes to progressive failure of a type which eventually requires repair or replacement of the affected areas. A survey of Nebraska pavements conducted in 1939 by the Public Roads Administration in cooperation with the State Highway Department revealed that about one-third of the approximately 500 miles of sand-gravel concrete pavement surveyed, all of which was constructed between 1925 and 1935, had developed map-cracking of a type which appeared to be progressive. This was in 1939 so that the percentage is probably higher at the present time. In contrast, no evidence of map-cracking had developed up to that time on any of the pavements laid with fine-and-coarse-aggregate concrete.

Map-cracking as used in this report may be defined as the type of multiple cracking which forms a pattern of roughly square, rectangular or hexagonal blocks in the surface of the concrete. Map-cracking *per se* is not necessarily serious; nor does it lead necessarily to disintegration or complete failure. Severely map-cracked pavements have often proved durable under severe weathering conditions. However, when map-cracking is accompanied by evidence of abnormal expansion, deep scaling or unsoundness, as revealed by a lack of ring under the hammer, it can be generally assumed to be of the progressive type. An advanced stage of map-cracking of this type is shown in Figure 1. Such a condition is evidence of "disintegration" even though under favorable conditions it may be possible to maintain traffic over the road for many years

Figure 1. Advanced Map Cracking of "Sand-Gravel" Pavement

without the necessity of making extensive repairs or replacements.

The fact that map-cracking sometimes develops on roads carrying comparatively light traffic would indicate that the fundamental causes underlying the initial cracking are independent of this factor. The primary cause appears to be excessive and abnormal expansion of the concrete. Evidence of this is found in the closed expansion joints which usually accompany the appearance of map-cracking. Furthermore, this expansion seems to be confined to the sand-gravel mixes, being entirely absent, insofar as the Nebraska field survey indicates, on all concrete pavements containing normally graded coarse aggregate.

TESTING PROGRAM

It seemed desirable to investigate in the laboratory the factors which might contribute to this condition, particularly the effect on volume change of variations in the character and grading of the aggregates and the kind of cement. Accordingly, a series of tests was arranged with the idea of subjecting concrete specimens containing various combinations of aggregates and cements to a weathering cycle involving alternate heating, cooling, wetting and drying and observing the length changes which occurred from time to time

Materials

Twelve combinations of materials involving four cements and three aggregates were used in these tests. The cements were chosen to give a considerable range in composition The results of physical tests and chemical analyses are given in Table 1 All of the cements meet the A S T M and the A A S H O specifications, Nos. 1 and 2 conforming to the requirements of Type I and Nos 3 and 4 to the requirements of Type II In addition, Nos 3 and 4 conform to the requirements of the New York Board of Water Supply (the so-called "Merriman" specification), whereas Nos. 1 and 2 do not This difference is revealed principally by the sugar solubility test, cements 1 and 2 showing values greatly in excess of the value allowed by the Merriman specification. It will also be observed that cement No. 2 has a considerably higher

TABLE 1

PROPERTIES OF CEMENTS

	Cement number			
	1	2	3	4
	Per cent	Per cent	Per cent	Per cent
Silica	21 95	20 60	22 71	23 16
Alumina	5 57	7 74	4 72	5 11
Iron	3 20	2 65	4 60	3 67
Lime	62 70	62 70	62 54	64 28
Magnesia	2 99	2 77	2 77	1 15
Sulphuric Anhydride	1 70	1 79	1 51	1 32
Sodium Oxide	0 26	0 36	0 19	0 26
Potassium Oxide	0 67	0 56	0 43	0 47
C_3S	42	38	39	42
C_2S	32	31	36	35
C_3A	9	16	5	7
C_4AF	10	8	14	11
$CaSO_4$	2 8	3 0	2 5	2 1
Specific surface, cm^2 per gram	1850	1705	1965	1815
Sugar test, Merriman				
Neutral, ml	33 2	36 8	2 7	2 7
Clear, ml	48 1	57 5	2 7	2 7
Autoclave expansion, per cent	0 09	0 42	0 05	0.01
Normal consistency, per cent	24 5	25 5	23 5	24 0
Tensile strength, 1 3 mortar				
7 days, lb per sq in	305	340	315	360
28 days, lb per sq. in.	375	420	445	435
Water-soluble alkali calculated as Na_2O	0 52	0.38	0 18	0 21

autoclave expansion than the other three. It is also the coarsest in terms of specific surface. It is of interest to note that cements 2 and 3 were from the same mill, No. 2 being the regular commercial product and No. 3, a cement modified to meet the requirements of the Merriman specification.

In addition to the sand-gravel from the Platte River, sand and gravel from Long Island, New York (the so-called "Cowe Bay" aggregate), and sand and gravel from Rockdale, Illinois (near Chicago), were included. The physical characteristics are shown in Table 2. It will be seen that they differ widely as regards mineral composition, the Long Island material being almost pure quartz, whereas the Chicago gravel is almost entirely dolomitic in character. The Platte River material is a mixture consisting essentially of granite and quartz with some feldspar and practically no calcareous material. The Long Island and the Chicago gravels were chosen to give as wide a range in mineral composition as possible with materials of known satisfactory quality. As is well known, both of these ag-

TABLE 2

PROPERTIES OF AGGREGATES

Aggregate designation	Source	Essential characteristics	Bulk specific gravity	Weight per cubic foot dry-rodded	Voids dry-rodded	Absorption
		(A) TOTAL AGGREGATE AS USED IN GRADING NO. 1				
				Pounds	Per cent	Per cent
A	Platte River, Neb.	Granite, quartz, feldspar	2.61	116	29	0.32
B	Long Island, N. Y.	Quartz	2.65	112	32	0.29
C	Chicago, Ill.	Dolomite	2.62	110	33	2.34
		(B) TOTAL AGGREGATE AS USED IN GRADING NO. 2				
A	Platte River, Neb.	Granite, quartz, feldspar	2.61	122	25	0.32
B	Long Island, N. Y.	Quartz	2.65	117	29	0.23
C	Chicago, Ill.	Dolomite	2.62	117	29	1.98
		(C) FINE AGGREGATE USED IN GRADING NO. 3				
A	Platte River, Neb.	Granite, quartz, feldspar	2.61	118	28	0.27
B	Long Island, N. Y.	Quartz	2.66	109	34	0.31
C	Chicago, Ill.	Dolomite	2.62	110	33	1.69
		(D) COARSE AGGREGATE USED IN GRADING NO. 3				
A[a]	Bethany Falls, Kan. Platte River, Neb.	Limestone Granite, quartz, feldspar	2.60	104	36	1.17
B	Long Island, N. Y.	Quartz	2.63	111	32	0.30
C	Chicago, Ill.	Dolomite	2.65	108	35	1.79

[a] Coarse aggregate made up of 83 per cent limestone (55 per cent between 1½-in. and ¾-in. and 28 per cent between ¾-in. and ⅜-in.), and 17 per cent Platte River gravel between ⅜-in. and No. 4.

gregates have been used extensively in concrete for many years with good results.

Grading of Aggregates

Three different aggregate gradations were investigated. They are shown in Table 3 No. 1 corresponds to the approximate gradation of the sand-gravel aggregate as used in Nebraska and Kansas in 1934. It will be noted that only 5 per cent is retained on the ⅜-in. sieve and that only 20 per cent passes the No. 30 sieve No. 2 is the same as No. 1 except that it has been modified by the addition of sufficient material passing the No. 30 sieve to bring the total percentage passing that sieve up to 35. Grading No. 3 is a combined grading corresponding to a normally graded mixture of fine and coarse aggregate running up to 1½-in. in size. In the case of aggregates B and C, fine and coarse aggregate from the respective sources were combined so as to give grading No. 3. In the case of aggregate A, the combined grading was made up of a mixture of Platte River sand passing No. 4 sieve and coarse aggregate consisting of a mixture of Platte River gravel passing ⅜-in. and limestone from Bethany Falls, Kansas, graded from ⅜-in to 1½-in.

Two separate series of tests were run. In each series the four cements were combined with each of the three aggregate types and each of the three aggregate gradings to make 36 combinations. Test specimens were beams 6 by 6 by 20-in. in size. Two specimens of each combination were made in each series, making a total of 144 specimens in the entire program. The proportions and other mix data are given in Tables 4 to 8, inclusive The basis of proportioning was as follows·

In all of the mixes involving gradings 1 and 2 in both Series I and II the slump was maintained at approximately 1 in. This is the consistency used in pavement work with the sand-gravel aggregate mixes. In all of the mixtures involving grading 3 in both series, the slump was held at approximately 2½ in This corre-

TABLE 3

SIEVE ANALYSES OF AGGREGATES

Percentage retained on sieve	Grading No 1	Grading No 2	Grading No 3			
			Fine	Coarse	Combined	
					a	b
1½-in.	—	—	—	0	0	0
¾-in.	0	0	—	55	35	36
⅜-in.	5	5	—	83	53	54
No. 4	10	10	0	100	64	65
No. 8	30	30	20	100	71	72
No 16	55	50	40	100	78	79
No 30	80	65	60	100	85	86
No. 50	95	80	84	100	94	94
No 100	100	95	97	100	99	99
F. M.	3.75	3 35	3 01	7.38	5.79	5.85

[a] This combined grading is for a mixture of fine and coarse aggregate containing 36.1 per cent material passing the No 4 sieve by weight This is the grading used in the combination involving Platte River sand-gravel (aggregate A) and crushed limestone

[b] This combined grading is for a mixture of fine and coarse aggregate containing 35 1 per cent sand by weight This grading was used with aggregates B and C.

TABLE 4

DATA ON MIXES, SERIES I, GRADING 1

NET WATER-CEMENT RATIO CONSTANT AT 0 67 BY VOLUME

Slump approximately 1-in

Aggregate	Cement	Proportions by Weight	Proportions by Absolute volume	Solids	Actual-cement factor	Paste voids ratio	Unit weight (wet)
				Per cent	Sacks per cu yd		Lb per cu ft
A	1	1 4 10	1 4 92	77 6	7 38	1.19	143
B	1	1 3 73	1 4 43	76 3	7.90	1 15	143
C	1	1 3 39	1 4 05	76 4	8 48	1 20	145
A	2	1.3 83	1 4 60	76 6	7 70	1 28	142
B	2	1 3 15	1 3 74	73 5	8 74	1 36	140
C	2	1 2 98	1 3 56	74 2	9 15	1 37	143
A	3	1 4 01	1 4 82	77 9	7.55	1 22	144
B	3	1 3 44	1 4 08	75 1	8 31	1 25	142
C	3	1 3 30	1 3 94	76 0	8 64	1 24	145
A	4	1 4 12	1 4 95	77 9	7 37	1 19	143
B	4	1 3 61	1 4 28	74 4	7 95	1 19	140
C	4	1 3 30	1 3.94	75 2	8 56	1 24	144

TABLE 5

DATA ON MIXES, SERIES I, GRADING 2

NET WATER-CEMENT RATIO CONSTANT AT 0 67 BY VOLUME

Slump approximately 1-in

Aggregate	Cement	Proportions by Weight	Proportions by Absolute volume	Solids	Actual cement factor	Paste voids ratio	Unit weight (wet)
				Per cent	Sacks per cu yd		Lb per cu ft
A	1	1 4 04	1 4 86	78 3	7 52	1.48	144
B	1	1.3 53	1 4 20	75 3	8 13	1 39	141
C	1	1 3 10	1 3 70	75 3	9 02	1 65	145
A	2	1 3 62	1 4 35	76 9	8 09	1.65	143
B	2	1:3 02	1 3 59	73 3	9 00	1 63	140
C	2	1 2 71	1 3 24	73 6	9 77	1 89	143
A	3	1 3 87	1 4 65	78.1	7.79	1 54	144
B	3	1 3 30	1.3 91	74 9	8 58	1 50	142
C	3	1 3 17	1 3.79	75 9	8 90	1.61	145
A	4	1.4 13	1 4 96	78 4	7 40	1 45	144
B	4	1·3 50	1 4 15	74 6	8.15	1 41	140
C	4	1 2 93	1.3 49	74.5	9.30	1 75	143

TABLE 6

DATA ON MIXES, SERIES II, GRADING 1

VARIABLE WATER-CEMENT RATIO [a]

Slump approximately 1-in.

Aggregate	Cement	Proportions by: Weight	Proportions by: Absolute volume	Solids	Water cement ratio	Actual cement factor	Paste voids ratio	Unit weight (wet)
				Per cent	By volume	Sacks per cu yd		Lb per cu ft
A		1 4 10	1 4 92	77 4	0 67	7 35	1 19	142
B	1	1 4 10	1 4 86	74 3	0 77	7 15	1 14	140
C		1 4 10	1 4 89	75 3	0 84	7 19	1 14	144
A		1 3.83	1 4 60	77 3	0 67	7 75	1 28	143
B	2	1 3 83	1 4 55	73 1	0 80	7 41	1 25	139
C		1 3 83	1 4 57	74 4	0 82	7 50	1 20	143
A		1 4 01	1 4 82	77 9	0 67	7 55	1 22	144
B	3	1 4 01	1 4 76	73 8	0 82	7 21	1 21	140
C		1 4 01	1 4 79	74 7	0 86	7 26	1 18	143
A		1 4 12	1 4 95	76 8	0 67	7.28	1 19	141
B	4	1 4 12	1 4 89	73 7	0 79	7 04	1 15	138
C		1 4 12	1 4 92	74 0	0 89	7 04	1 18	142

[a] In the case of aggregate A, the proportions for each cement and grading are the same as for the corresponding combinations in Series I In the case of aggregates B and C, the same proportions of cement to aggregate by weight were used as for the corresponding combinations involving aggregate A.

TABLE 7

DATA ON MIXES, SERIES II, GRADING 2

VARIABLE WATER-CEMENT RATIO [a]

Slump aproximately 1-in.

Aggregate	Cement	Proportions by: Weight	Proportions by: Absolute volume	Solids	Water cement ratio	Actual cement factor	Paste voids ratio	Unit weight (wet)
				Per cent	By volume	Sacks per cu yd		Lb per cu ft
A		1 4 04	1 4 86	78 1	0 67	7 51	1 48	144
B	1	1 4 04	1 4 80	73 9	0 80	7 19	1 36	140
C		1 4 04	1 4 83	74.9	0 86	7 22	1 47	143
A		1:3 62	1 4 35	76 9	0 67	8 09	1 65	143
B	2	1 3 62	1 4 29	73 2	0 77	7 79	1 48	139
C		1.3 62	1.4 32	73 7	0 82	7 80	1 60	142
A		1 3 87	1 4 65	77 9	0 67	7 76	1 54	144
B	3	1 3 87	1 4 60	74 3	0 79	7 45	1 41	140
C		1.3 87	1 4 62	75 0	0 82	7 50	1 49	143
A		1 4 13	1 4 96	78 1	0 67	7 38	1 45	143
B	4	1.4 13	1 4 90	73 3	0 81	6 99	1 34	138
C		1 4 13	1 4 93	74 6	0 86	7 07	1 44	142

[a] In the case of aggregate A, the proportions for each cement and grading are the same as for the corresponding combinations in Series I In the case of aggregates B and C, the same proportions of cement to aggregate by weight were used as for the corresponding combinations involving aggregate A.

sponds to the average slump used in concrete paving, with 1½-in maximum size coarse aggregate.

In Series I, all of the combinations involving gradings 1 and 2 were proportioned on the basis of a constant net water-cement ratio of 0.67 by volume (5 gal. per sack). In the case of the Platte River material (aggregate A), this gave a mix with a cement factor of about 7¾ sacks per cubic yard, which corresponds very closely to that used in the earlier roads. It will also be noted that, for both gradings 1 and 2, the use of a constant water-cement ratio (0.67) with the three aggregate types resulted in a considerable variation in cement content in spite of the fact that the gradings were identical. This can only be due to differences in aggregate characteristics other than grading, such as angularity, surface texture, etc., and illustrates the wide variations in cement content which are possible with various kinds of aggregate when a constant water-cement ratio is used as the sole basis of mix design.

In Series II, gradings 1 and 2, the proportions were changed in order to equalize somewhat the differences in cement content resulting from the use of the constant water-cement ratio in Series I. Accordingly, for each cement and each grading, the same weight proportions were used with aggregates B and C as with aggregate A, which in turn were the same as were used in Series I for this material. It will be noted, therefore, that for each cement the proportions used with aggregate A were the same in both series, whereas with the other two aggregates the cement contents in Series II were reduced to values more nearly comparable with those used with aggregate A.

The proportions used in Series I and II, grading 3, were adjusted in all cases to give a cement content of approximately

TABLE 8

DATA ON MIXES, SERIES I AND II, GRADING 3

CEMENT FACTOR CONSTANT AT 5.1 SACKS PER CUBIC YARD

Slump approximately 2½-in

Aggregate	Cement	Proportions by: Weight	Proportions by: Absolute volume	Solids	Water-cement ratio	Mortar voids ratio	Unit weight (wet)
				Per cent	By volume		Lb per cu ft
A	1	1 2.53 4.49	1 3.23 5.77	0.85	0.81	1.88	152
B	1	1 2.43 4.49	1 3.05 5.70	0.84	0.80	2.18	151
C	1	1 2.43 4.49	1 3.09 5.67	0.84	0.84	1.98	154
A	2	1 2.53 4.49	1 3.23 5.77	0.85	0.77	1.85	152
B	2	1 2.43 4.49	1 3.05 5.70	0.84	0.80	2.18	151
C	2	1 2.43 4.49	1 3.09 5.67	0.83	0.88	2.01	153
A	3	1 2.53 4.49	1 3.23 5.77	0.85	0.81	1.88	152
B	3	1 2.43 4.49	1 3.05 5.70	0.84	0.80	2.18	152
C	3	1 2.43 4.49	1 3.09 5.67	0.84	0.87	2.00	153
A	4	1 2.53 4.49	1 3.23 5.77	0.85	0.77	1.85	152
B	4	1 2.43 4.49	1 3.05 5.70	0.84	0.80	2.18	150
C	4	1 2.43 4.49	1 3.09 5.67	0.83	0.87	2.00	152

five sacks of cement per cubic yard The mix data are shown in Table 8. It will be seen that the same weight proportions were used throughout, except for a somewhat smaller amount of sand in the case of aggregates B and C as compared to aggregate A. However, the actual cement factors computed from yield tests were the same to within 0 1 sack in all cases. In the case of grading 3, the same proportions were used in Series II as in Series I However, the specimens were made on different days The values shown for unit weight of wet concrete are the average of determinations made in both series However, as will be noted later, the volume change readings are reported for each series separately.

MIXING, FABRICATING AND PRELIMINARY STORAGE

In the case of gradings 1 and 2 and the fine aggregate fraction of grading 3, the aggregates contained some free water at the time of mixing. The coarse aggregates used in grading 3 were saturated-surface dry at time of use. The necessary corrections for free water were made when computing the net water-cement ratios Mixing was done in an open pan type Lancaster mixer, sufficient concrete for one 6 by 6 by 20-in volume-change specimen being mixed at one time. Eight mixing days were required to make the 144 specimens One specimen for each of the three aggregates, the three gradings and two cements was made on each working day, making 18 specimens per day, or a total of 144 specimens for the eight working days. All specimens containing the ⅜-in. maximum size aggregate (gradings 1 and 2) were molded by thoroughly spading the concrete with a trowel, as it was found that the standard rodding procedure was not applicable to "sand-gravel" mixtures. Specimens of normal concrete (grading 3) were fabricated by rodding in the standard manner. The consistency was not controlled directly by the use of the slump test but was judged by means of the flow test. Flows were adjusted to give concrete with a consistency corresponding to approximately a 1-in. slump for gradings 1 and 2, and 2½-in slump for grading 3. All specimens were cured 1 day in the molds in the mixing room and 27 days in the moist room prior to test

DETERMINATIONS OF VOLUME CHANGE

The type of weathering cycle employed in this investigation was decided upon largely as the result of tests which have been under way for a number of years at the road materials laboratory of the Kansas State Highway Commission located at the Kansas State Agricultural College, Manhattan, Kansas The results of these tests were presented to the Board at the 1938 annual meeting in a paper by W E Gibson, Engineer of Tests [1]

The studies made by Mr. Gibson indicated that the characteristic map-cracking observed on these pavements could be reproduced in the laboratory by subjecting the specimens to alternate wetting and drying and that freezing and thawing alone would apparently not produce these effects In this connection he called attention to the fact that map-cracking has been observed on pavements located in sections of the country where freezing conditions are not encountered It was decided, therefore, to eliminate the element of freezing in the tests to be conducted by the Public Roads Administration and to study the behavior of the concrete when subjected to a cycle involving complete saturation at 70 deg. F., followed by drying at 130 deg F.

The investigation included a study of

[1] "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, p 227 (1938).

the effect of three modifications of the general procedure, as follows:

Cycle A.	24 hr. in moist room	at 70 deg. F.,	followed by	
	24 hr. in air	at 130 deg. F.,	followed by	
	48 hr. in air	at 70 deg. F.	Repeat.	
Cycle B.	24 hr. in water	at 70 deg. F.,	followed by	
	24 hr. in air	at 130 deg. F.,	followed by	
	48 hr. in air	at 70 deg. F.	Repeat.	
Cycle C.	24 hr. in water	at 70 deg. F.,	followed by	
	24 hr. in air	at 130 deg. F.	Repeat.	

Cycle A was used in the beginning of the tests. Measurements for length were made periodically on plugs cast in the center of the ends of the specimens, as well as on plugs set in the upper and lower surfaces of the beams. Reference in this progress report will be made only to end measurements, reserving for the final report a discussion of readings taken at the surface. End measurements were taken with a horizontal comparator reading directly to 0.0001-in. A view of the comparator is shown in Figure 2. All measurements were taken on specimens at 70 deg. F., immediately after the wet storage period, so as to eliminate, insofar as possible, variations due to differences in temperature and moisture content at time of measurement. At the end of 40 cycles (160 days) of cycle A, it was found that all of the specimens were showing small residual contraction. This indicated quite definitely that 24 hr. in the moist room was not long enough to insure complete resaturation after drying at 130 deg. F. The procedure was therefore changed to require immersion in water instead of storage in the moist room (cycle B). This resulted in general in a change in the trend from contraction to expansion, as will be noted by reference to the tabular data. However, at the expiration of 50 additional alternations of cycle B (360 days), the net expansions were found in all cases to be so small that it was decided again to change the cycle by omitting altogether the 48-hr. storage period in air at 70 deg. F. Under this procedure (cycle C), the specimens were immersed immediately in water upon removal from the drying oven at 130 deg. F., thus simulating the effect of a sudden cool shower upon a concrete pavement at the close of a hot, dry day. This treatment had the effect desired; that is, it differentiated quite definitely between the concretes in a manner similar to that observed in service (see Figs. 3 and 4). In this progress report the discussion will be con-

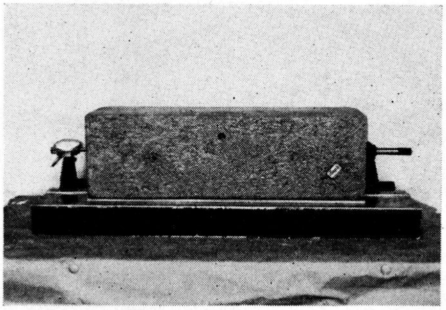

Figure 2. Horizontal Comparator With Test Specimen

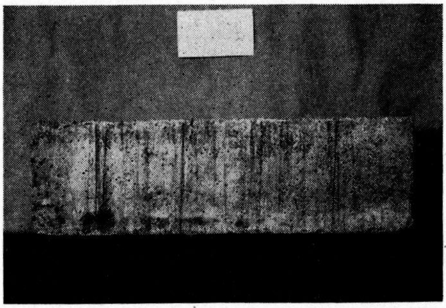

Figure 3. Appearance of Specimen After 150 Alternations of Cycle C. Aggregate C—Grading 1.

cerned principally with a comparison of the behavior of the concrete specimens at the conclusion of 150 alternations of cycle C (total storage period 660 days), with the idea of determining to what extent the three variables under study—namely, quality of aggregate, grading of aggregate and cement—may be responsible for the wide variations in expansion which have been observed.

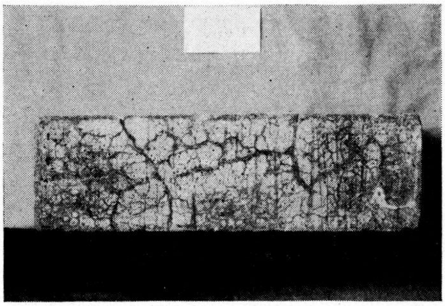

Figure 4. Appearance of Specimen After 150 Alternations of Cycle C. Aggregate A—Grading 1.

DISCUSSION OF RESULTS

The results of the length change measurements are given in Tables 9, 10 and 11; values for Series I, gradings 1 and 2, in Table 9; for Series II, gradings 1 and 2, in Table 10; and for Series I and II, grading 3, in Table 11. In studying these data, bear in mind that gradings 1 and 2 represent the so-called sand-gravel type, that grading 3 corresponds to a normal concrete grading with maximum size of $1\frac{1}{2}$-in., and that grading 2 differs from No. 1 only in the somewhat higher proportion of the finer sizes (see Table 3). It is important, also, to recall that in Series I, gradings 1 and 2, a constant water-cement ratio (0.67 by volume) was used for all cements and aggregate types, whereas in Series II, gradings 1 and 2, the proportions used with aggregates B and C were changed so as to obtain approximately the same cement content as was used with aggregate A. Note also that, in the case of the normal concrete specimens (grading 3), the proportions used in Series II were the same as in Series I, but the specimens were made on different days.

The length change measurements are shown graphically by means of a series of charts, which will be discussed in detail.

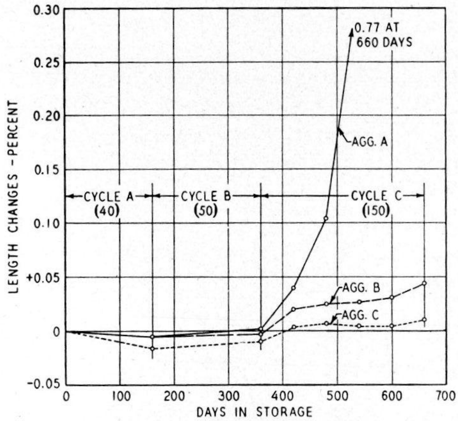

Figure 5. Effect of Aggregate Type Grading 1. Series I—Cement 1

Figure 5 shows the effect of the three types of cycle upon the amount of linear change for the three aggregate types in Series I, grading No. 1 and cement No. 1. It will be observed that, at the end of 40 alternations of cycle A, a small residual contraction had developed in specimens containing all three aggregate types, with aggregate C (from Chicago) showing the largest amount. As previously mentioned, this tendency to contract is due probably to the fact that 24 hr. in the moist room was not long enough to thoroughly resaturate the specimens. It was on this account that cycle B, providing for 24 hr. resaturation in water, was introduced. The figure shows that at the end of 50 alternations of this cycle all three combinations had expanded somewhat and that they were expanding very slowly and at about the same rate. These trends are typical of all combinations. Furthermore,

TABLE 9

CHANGES IN LENGTH IN PERCENTAGE—SERIES I, GRADINGS 1 AND 2

Aggregate	Cement	Days in storage						
		160	360	420	480	540	600	660
GRADING 1								
A		−0 0052	+0 0005	+0 0392	+0 1042	+0 3222	+0 5712	+0 7718
B	1	−0 0052	−0 0022	+0 0198	+0 0240	+0 0265	+0 0315	+0 0442
C		−0 0170	−0 0098	+0 0032	+0 0060	+0 0034	+0 0042	+0 0100
A		−0 0050	+0 0085	+0 0616	+0 0810	+0 0918	+0 1038	+0 1185
B	2	−0 0076	+0 0024	+0 0215	+0 0258	+0 0288	+0 0301	+0 0382
C		−0 0192	−0 0065	+0 0076	+0 0108	+0 0118	+0 0123	+0 0152
A		−0 0098	−0 0109	+0 0212	+0 0331	+0 0765	+0 1358	+0 2228
B	3	−0 0118	−0 0128	+0 0081	+0 0061	+0 0072	+0 0075	+0 0104
C		−0 0174	−0 0116	+0 0032	+0 0020	+0 0027	+0 0034	+0 0065
A		−0 0100	−0 0050	+0 0185	+0 0387	+0 0828	+0 1851	+0 3163
B	4	−0 0158	−0 0112	+0 0065	+0 0043	+0 0072	+0 0078	+0 0086
C		−0 0219	−0 0152	−0 0012	−0 0034	−0 0026	−0 0020	−0 0016
GRADING 2								
A		−0 0100	−0 0001	+0 0332	+0 0709	+0 1638	+0 3236	+0 4982
B	1	−0 0072	−0 0044	+0 0136	+0 0192	+0 0178	+0 0208	+0 0328
C		−0 0176	−0 0152	+0 0026	+0 0049	+0 0035	+0 0042	+0 0112
A		−0 0056	+0 0018	+0 0362	+0 0512	+0 0599	+0 0695	+0 0824
B	2	−0 0116	+0 0030	+0 0178	+0 0200	+0 0228	+0 0269	+0 0326
C		−0 0219	−0 0105	+0 0054	+0 0070	+0 0080	+0 0088	+0 0175
A		−0 0134	−0 0174	+0 0088	+0 0095	+0 0142	+0 0135	+0 0296
B	3	−0 0205	−0 0166	+0 0082	+0 0082	+0 0074	+0 0079	+0 0120
C		−0 0152	−0 0144	+0 0030	+0 0016	+0 0032	+0 0045	+0 0105
A		−0 0164	−0.0149	+0 0028	+0 0028	+0 0041	+0 0032	+0 0085
B	4	−0 0132	−0 0155	+0 0040	+0 0022	+0 0030	+0 0045	+0 0068
C		−0 0211	−0.0165	−0 0016	−0 0012	−0 0008	−0 0013	+0 0028

TABLE 10

CHANGES IN LENGTH IN PERCENTAGE—SERIES II, GRADINGS 1 AND 2

Aggregate	Cement	Days in storage						
		160	360	420	480	540	600	660
		GRADING 1						
A	1	−0 0090	−0 0020	+0 0276	+0 0644	+0 2034	+0 4479	+0 7524
B	1	−0 0098	−0.0012	+0 0155	+0 0206	+0 0309	+0 0490	+0 1015
C	1	−0 0186	−0 0026	+0 0042	+0 0068	+0 0100	+0 0116	+0 0156
A	2	−0 0095	+0 0066	+0 0501	+0 0723	+0 0895	+0 0994	+0 1241
B	2	−0 0108	+0 0062	+0.0164	+0 0185	+0 0202	+0 0175	+0 0219
C	2	−0 0270	−0 0074	+0 0004	+0 0027	+0 0041	+0 0017	+0 0108
A	3	−0 0088	−0 0046	+0.0222	+0 0451	+0.1090	+0 2605	+0 4452
B	3	−0 0171	−0 0054	+0 0040	+0 0058	+0 0084	+0 0066	+0 0192
C	3	−0 0231	−0 0033	+0 0037	+0 0045	+0 0043	+0 0038	+0 0158
A	4	−0 0154	−0 0096	+0 0082	+0 0140	+0 0284	+0.0640	+0 1058
B	4	−0 0126	−0 0044	+0.0075	+0 0099	+0.0110	+0 0064	+0 0172
C	4	−0 0275	−0 0134	−0 0110	−0 0088	−0 0077	−0 0102	−0 0052
		GRADING 2						
A	1	−0 0104	−0 0058	+0 0320	+0.0796	+0.2245	+0.4440	+0 6462
B	1	−0 0105	−0 0014	+0 0128	+0 0156	+0 0196	+0 0192	+0 0406
C	1	−0 0188	−0 0112	−0 0005	−0 0006	+0 0025	−0 0002	+0 0129
A	2	−0 0151	+0 0006	+0 0284	+0 0512	+0.0717	+0.0884	+0.1147
B	2	−0.0138	+0.0016	+0 0154	+0 0170	+0 0201	+0 0203	+0 0304
C	2	−0.0212	−0 0065	+0 0020	+0.0054	+0 0090	+0 0056	+0 0221
A	3	−0 0198	−0 0191	+0.0026	+0 0090	+0 0186	+0 0602	+0 1440
B	3	−0 0166	−0 0062	+0.0051	+0 0098	+0.0101	+0 0078	+0 0216
C	3	−0 0212	−0.0075	+0 0012	+0 0034	+0 0035	−0 0012	+0 0105
A	4	−0 0154	−0 0136	+0 0048	+0 0066	+0 0085	+0 0124	+0 0268
B	4	−0.0189	−0 0100	−0 0004	+0 0010	+0.0020	−0 0013	+0 0105
C	4	−0 0205	−0 0074	−0 0021	−0 0012	+0 0002	+0 0025	+0 0082

TABLE 11

Changes in Length in Percentage—Series I and II, Grading 3

Aggregate	Cement	Days in storage						
		160	360	420	480	540	600	660
SERIES I								
A	1	−0.0028	−0.0008	+0.0116	+0.0138	+0.0192	+0.0220	+0.0220
B		−0.0043	−0.0037	+0.0142	+0.0199	+0.0271	+0.0410	+0.0620
C		−0.0039	+0.0016	+0.0100	+0.0096	+0.0110	+0.0116	+0.0092
A	2	−0.0038	−0.0002	+0.0100	+0.0104	+0.0100	+0.0121	+0.0120
B		0.0000	+0.0045	+0.0225	+0.0236	+0.0240	+0.0259	+0.0245
C		−0.0069	−0.0050	+0.0054	+0.0055	+0.0067	+0.0076	+0.0068
A	3	−0.0085	−0.0064	+0.0008	+0.0017	+0.0035	+0.0030	+0.0050
B		−0.0096	−0.0034	+0.0098	+0.0090	+0.0114	+0.0132	+0.0155
C		−0.0134	−0.0011	+0.0062	+0.0038	+0.0055	+0.0062	+0.0078
A	4	−0.0090	−0.0032	+0.0032	+0.0012	+0.0028	+0.0029	+0.0035
B		−0.0065	+0.0014	−0.0028	+0.0152	+0.0220	+0.0270	+0.0390
C		−0.0090	−0.0012	+0.0050	+0.0024	+0.0032	+0.0048	+0.0016
SERIES II								
A	1	−0.0009	+0.0058	+0.0138	+0.0162	+0.0188	+0.0218	+0.0348
B		−0.0061	+0.0023	+0.0127	+0.0188	+0.0363	+0.0569	+0.1006
C		−0.0120	+0.0064	+0.0108	+0.0108	+0.0094	+0.0095	+0.0188
A	2	−0.0048	+0.0029	+0.0084	+0.0094	+0.0108	+0.0140	+0.0233
B		−0.0068	+0.0036	+0.0162	+0.0188	+0.0212	+0.0204	+0.0298
C		−0.0175	−0.0034	+0.0039	+0.0086	+0.0103	+0.0066	+0.0156
A	3	−0.0070	+0.0012	+0.0086	+0.0089	+0.0100	+0.0094	+0.0162
B		−0.0122	+0.0002	+0.0111	+0.0122	+0.0124	+0.0128	+0.0280
C		−0.0154	+0.0010	+0.0052	+0.0058	+0.0049	+0.0048	+0.0152
A	4	−0.0092	−0.0022	+0.0033	+0.0032	+0.0036	+0.0018	+0.0115
B		−0.0126	−0.0040	+0.0038	+0.0058	+0.0055	+0.0050	+0.0142
C		−0.0142	−0.0021	+0.0010	+0.0032	+0.0045	+0.0028	+0.0140

during these stages of the test, there was no visual indication of action on any of the specimens. It was decided, therefore, to change the cycle again by omitting the 48-hr. period in air at 70 deg F. and placing the specimens in water immediately following the 24-hr drying at 130 deg F.

Up to the time of temporarily discontinuing the test at the end of 660 days, the specimens had been subjected to 150 alternations of this new cycle (cycle C). The figure illustrates the marked effect of

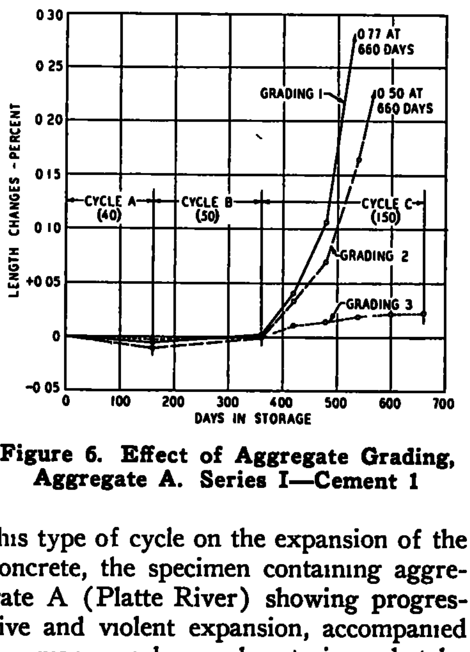

Figure 6. Effect of Aggregate Grading, Aggregate A. Series I—Cement 1

this type of cycle on the expansion of the concrete, the specimen containing aggregate A (Platte River) showing progressive and violent expansion, accompanied by map cracking almost immediately. Much greater expansion was shown in the specimens containing the material from Long Island, which consists almost entirely of quartz (aggregate B), than in those containing the gravel from Chicago (aggregate C), which is essentially dolomitic in character, but both show very low expansion as compared to the specimens containing the Platte River material (aggregate A).

Figure 6 shows a similar set of data in which the comparison is on the basis of aggregate grading rather than type. The same small contractions will be noted at the end of cycle A, followed by slight expansion in cycle B and relatively large expansion in cycle C. These two charts are presented primarily to show graphically the relatively small length changes which took place during cycles A and B as compared to the movements during cycle C. They are typical and similar charts for any combination may of course be prepared from the data in Tables 9, 10 and 11. The principal point of interest in connection with these initial movements is that, in general, the combinations which show the greatest contraction during cycle A are those which involve aggregate C, the dolomitic material, with the two aggregates composed essentially of siliceous materials showing somewhat smaller values for contraction. A study of the data will show also that, in general, the normal concrete, grading No. 3, showed less contraction during cycle A than combinations in which the maximum size of aggregate was ¾-in. A more complete discussion of these initial movements will be given in the final report

As previously stated, it is the purpose of this progress report to call particular attention to the relatively large expansions which have been observed with certain combinations after 150 alternations of cycle C.

In Figures 7 to 12, inclusive, length changes at the end of 660 days are shown for each of the various combinations in bar diagram form The values are taken from the last columns of Tables 9, 10 and 11, and represent the residual expansions resulting from 240 reversals of wetting and drying, 40 under cycle A, 50 under cycle B, and the remaining 150 under cycle C. To facilitate comparisons, the data have been arranged in three ways (1) by aggregate type, (2) by aggregate grading and (3) by cement.

In Figures 7 and 8 the effect of aggregate type for each of the three gradings

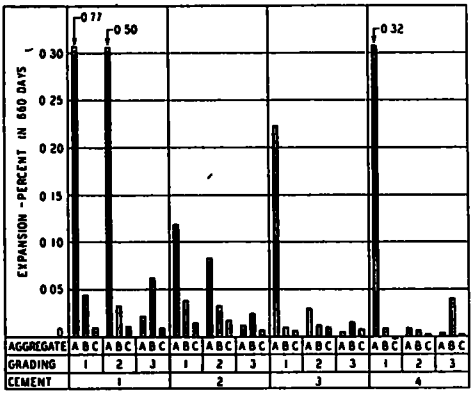

Figure 7. Effect of Aggregate Type, Series I

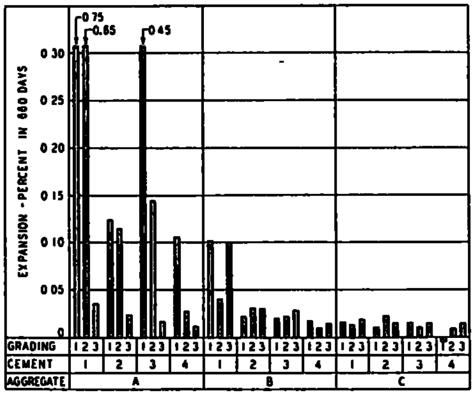

Figure 10. Effect of Aggregate Grading, Series II

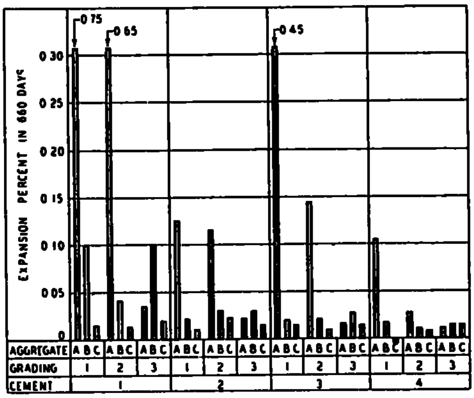

Figure 8. Effect of Aggregate Type, Series II

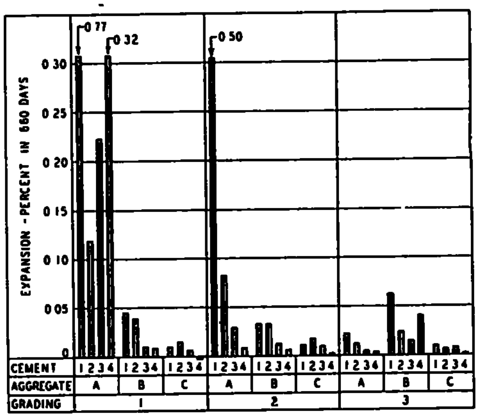

Figure 11. Effect of Cement, Series I

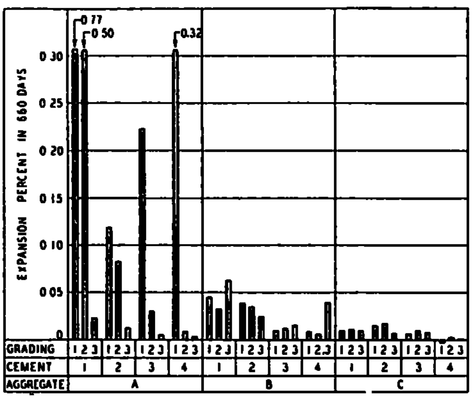

Figure 9. Effect of Aggregate Grading, Series I

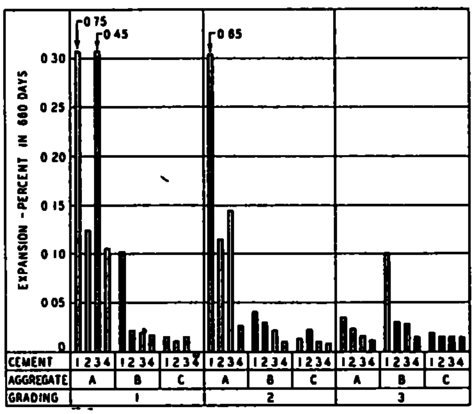

Figure 12. Effect of Cement, Series II

and for each of the four cements is shown. It will be seen at once that, in the case of both gradings 1 and 2, the greatest expansion by far occurs with aggregate A (the Platte River gravel), the next with aggregate B (Long Island) and the least with aggregate C (Chicago) This general relation is consistent for both series and with each cement, although the actual expansions vary considerably with the different combinations. However, in the case of grading No 3 (normal concrete), we find that aggregate B shows consistently higher expansions than either aggregate A or C This relation also holds for both series and for all cements, except that, in the case of cement No 4, Series II, aggregates B and C show about the same expansion.

Inspection of Figures 7 and 8 indicates that some characteristic or combination of characteristics other than gradation of aggregates or quality of cement is responsible for the marked differences in expansion which were obtained This must be true, since within each group the effect of these variables was entirely eliminated Furthermore, since in Series I the water-cement ratio was constant and in Series II the cement factor was reasonably constant, the differences in expansion appear to be independent of these variables also It is possible that they are associated in some way with the mineral composition of the aggregates. Quantitative determinations indicate that aggregate A contains about 20 per cent feldspar with the balance mostly quartz and granite, that aggregate B is almost pure quartz and that aggregate C is almost pure dolomite. This trend towards higher volume change in the case of the siliceous materials is further confirmed by an examination of the results obtained with grading 3 It will be recalled that, in making up the normally graded aggregate containing the Platte River material, a limestone graded from ⅜-in. to 1½-in. was blended with the sand-gravel. The addition of this limestone appears to have decreased the tendency of the Platte River concrete to expand to such an extent that the measured length changes were actually less than with the Long Island material, although, in general, somewhat greater than when the all-calcareous Chicago gravel was used When it is recalled that each result shown in these figures is the average of only two determinations, the relative behavior of these materials appears to be quite consistent

The same data, arranged to reveal readily the effect of aggregate gradations, are shown in Figures 9 and 10. Comparing first the results obtained with aggregate A, it will be noted that in each case the addition of fines (grading No 2) reduces the amount of expansion as compared to that obtained with grading No 1 However, the reduction is not nearly so marked as when grading 3 is used This is particularly noticeable in the case of cements 1 and 2 Here the abnormal expansion found in both series with grading 1 is only slightly reduced by the addition of fines (grading 2) but is virtually eliminated (less than 0 05 per cent) by the addition of crushed limestone to the Platte River material (grading 3) On the other hand, in the case of cements 3 and 4, the addition of fines reduces the expansion to a marked degree, although in neither case is the reduction as great as when grading 3 is used.

The foregoing relations do not hold for either aggregates B or C. There does not seem to be any consistent relation between grading and volume change for either of these materials. Length changes, in general, are well below those which reveal abnormal expansion such as is found with certain combinations involving aggregate A.

In Figures 11 and 12 the effect of varying the cement is shown. Study of these charts reveals some interesting trends Comparing first the six groups which involve aggregate A, it will be observed that concrete containing cement No 1 shows the greatest expansion in all cases, whereas concrete containing cement No 4 shows the lowest expansion in five out of the six groups. Cements 2 and 3 are not consistent, No. 3 showing higher expansion than No 2 in three of the six groups and lower expansion in the other three groups However, the outstanding indication is, of course, the very high expansion obtained with cement No 1 in both gradings 1 and 2 The average of the four values reported is 0 67 per cent as compared to an average of 0.21 for cement No. 3 and 0 11 for cements 2 and 4

A similar comparison of the six groups containing aggregate B shows in general the same relative expansions insofar as the effect of the cement is concerned. However, the actual values are very much lower Cement No 1 again shows the highest expansion in all cases, whereas cement No. 4 is the lowest in five of the six groups. It is also interesting to note that in all six groups involving aggregate B, cement No 2 shows higher expansion than No 3, although the differences in certain instances are not marked. In the case of aggregate C there seems little trend except that, in these groups also, there seems to be a definite tendency for cement No. 4 to show the lowest expansion In fact, in the two groups involving grading No. 1, the specimens still show slight contraction.

There seems to be no consistent relationship between either the chemical composition or physical properties of the cement and the amount of expansion which has developed. However, as noted above, there does seem to be a distinct tendency for cements 3 and 4 (the Merriman cements) to show lower expansions than Nos. 1 and 2 This is particularly true of all combinations involving aggregate B, as well as those which involve aggregate A in grading 3. In the case of aggregate A, gradings 1 and 2, cement No. 1 shows by far the greatest expansion. It is probable that this cement possesses some characteristic which causes exceptionally high expansion when the cement is used with the Platte River material The possibility of an alkali reaction should, of course, be considered Table 1 gives for each cement the total percentage of sodium oxide and potassium oxide, as well as the percentage of water-soluble alkali calculated as Na_2O All of the determinations were made strictly in accordance with the standard A.S.T.M. method without modification The relatively small differences in the percentages of the sodium and potassium oxide shown for the four cements would hardly seem sufficient to account for the wide variation in expansion when used in combination with the Platte River material. However, it will be observed that cement No 1 contains the highest percentage of water-soluble alkali (0 52) It is possible that this may be the clue to the very high volume changes observed in all combinations in which this cement was used On the other hand, cement No. 2, containing the next highest percentage of free alkali (0.38), shows, at least insofar as grading 1 is concerned, substantially lower expansion than cement No. 3 with 0 18 per cent water-soluble alkali. The relation, therefore, is not at all clear cut

A general discussion of the conditions under which a cement-aggregate reaction may take place is far beyond the scope of this paper. The many discussions which have appeared since Stanton first called attention in 1940 to the situation in California reveal the extreme complexity of the problem as a whole and point to the necessity for intensive research to determine the fundamental relations which are involved. So far as Platte River aggregate is concerned, there seem to be two possibilities; one that the trouble is caused by a reaction between opaline silica in the aggregate and the alkali in the cement, and the other that it is due to a reaction between the feldspathic materials in the aggregate and some constituent of the cement

The Platte River aggregate used in these tests contains about 20 per cent of materials which may be classed as feldspars These feldspars are predominantly potash in composition (orthoclase and microcline), with occasional pieces of the lime-soda type. The feldspathic materials are found both as separate fragments and as essential constituents of the granitic particles A small percentage of opal (approximately 0 3 per cent) has also been identified in the Platte River material, whereas no opal was found in either of the other aggregates The authors are not prepared at this time to advance any theory as to which, if either of these constituents, is responsible for the trouble. Further research will be needed to establish the facts.

SUMMARY

The outstanding indication of these tests up to the present time is, of course, the abnormal expansion which resulted from the use of Platte River gravel as total aggregate This suggests that the fundamental cause of the failure of concrete roads containing this aggregate is restrained expansion which, in turn, induces high concrete stress with consequent map-cracking and ultimate disintegration That the character of this aggregate rather than its grading is the primary cause of the trouble is indicated by the fact that no abnormal expansion was found in the case of either of the other aggregates even when graded exactly the same as the Platte River material. This applies equally to the siliceous material (Long Island) and to the calcareous material (Chicago), although there was a definite tendency for the siliceous gravel to show higher expansions than the calcareous material.

In the case of the Platte River material, adding fines to the normal grading appears to reduce the expansion although the amount of reduction varied greatly, depending upon the cement used.

Adding crushed limestone to the Platte River material reduced the expansion to values comparable to those obtained with the other materials. In fact the expansion of the Platte River material with added crushed limestone was actually less than was found for the siliceous Long Island material of comparable grading although not so low as was obtained with the calcareous Chicago gravel

Other things being equal, there appeared to be a tendency for concrete containing cement No 1 to show the highest, and cement No 4, the lowest expansion There seemed to be some characteristic present in the combination of aggregate A and cement No. 1 which caused very high expansion. This was true of all four groups involving this combination.

RECOMMENDATIONS

It is recommended that "sand-gravel" of the type represented in these tests be not used as concrete aggregate unless blended in the proper proportions with crushed limestone or with some other type of coarse aggregate which experience or test has demonstrated to be satisfactory for the purpose.

DISCUSSION ON VOLUME CHANGES IN SAND-GRAVEL CONCRETE

MR DUFF A ABRAMS, *Consulting Engineer*. In reviewing the attempts of the authors to account for the nondurable concrete made from Platte River aggregate, one is struck by the limited data on the fundamental properties of this material, by the meager information on the characteristics of the concrete made from it, and by the absence of data on the cements used or the exposure of the pavements that "developed surface defects," which "lead usually to progressive failure and ultimately to complete disintegration." That these premature failures represent a serious loss is shown by the statement that "about ⅓ of the total mileage of sand-gravel concrete laid in that state (Nebraska) since 1927 has disintegrated." That was in 1939; conditions are probably much worse in 1943

In a paper before this Board in 1938, W. E Gibson (1)[1] showed similar results in concrete roads in Kansas made of aggregates from the Arkansas and the Kaw Rivers

My discussion will point out some factors that were neglected in this study, comment on the extremely wide variations in duplicate tests, question the significance of the tests and the validity of the conclusions, and offer some suggestions on the disintegration of the Nebraska roads.

SOME NEGLECTED FACTORS

In attempting to account for the disintegration of Nebraska pavements, information on the following would have been helpful:

Platte aggregates used in laboratory tests

- *Petrographic or mineralogical analysis
- *Organic impurities
- Silt content
- *Soft and deleterious materials (chert, coal, lignite, slate)
- *Soundness by freezing and thawing
- *Soundness by use of sodium sulfate
- Abrasion tests
- Strength using constant-water-ratio mortar
- *Thermal expansion of different rocks
- Sp gr and absorption of different rock types

Laboratory concrete

- *Free lime in portland cements
- *Compressive strength, 28-day, 3-month, 1 and 2-year
- *Freezing and thawing tests
- Elastic properties after freezing and thawing
- Permeability
- Water absorption of dry concrete

Nebraska concrete pavements

- *Free lime in portland cements
- *Alkalies in portland cements
- *Alkalies in mixing and curing waters
- Water-ratio and cement factor
- Slump
- Method of curing
- Concrete strength
- Type of subgrade and moisture content
- Elevation of ground water with respect to slabs
- *Alkali content of subgrade soil
- *Weather conditions
  - Temperature
  - Humidity
  - Rainfall
  - Evaporation
  - Number of freezing and thawing cycles
- Traffic loads with reference to slab strength
- *Properties of aggregates that were successfully used

* Items that the writer considers most significant.

Considerable information was available to the authors on many of these topics; data on others could easily have been obtained; all are necessary to an understanding of the laboratory tests and of the disintegration of Nebraska concrete pavements Many of the 34 topics cover tests that have been widely used for determining in advance the suitability of concrete sands, or as measures of concrete quality, some of them are covered by recognized standards It is probable that these well-recognized tests would throw light on the poor performance of the Platte aggregate.

No convincing evidence was presented to show that the high expansion of certain laboratory specimens had any bearing on the failure of the pavements The failure of Nebraska pavements can readily be accounted for on the basis of factors that were long ago recognized elsewhere.

[1] Numbers in parentheses refer to the list of references at the end of this discussion.

THE PLATTE RIVER

The principal branches of the Platte River rise in the Rocky Mountains in Colorado, after a wide swing into Wyoming, the North Platte, after being joined by the Laramie and the South Platte, forms the Platte River which practically bisects the State of Nebraska from West to East. Under normal conditions the Platte, particularly during spring floods, is a swift-flowing stream At Ft Laramie, Wyoming, a few miles west of the Nebraska line, the river elevation is 4250 ft. above sea level, at Plattsmouth where it joins the Missouri, the elevation is 950 For its length of about 550 miles in Nebraska the average drop is 6 ft per mile.

Practically all the sand and gravel carried by the Platte originate in the upper reaches. Boulders and gravel are left behind in Colorado and Wyoming; the aggregate in Nebraska may be classed as a coarse sand

TESTS OF PLATTE AGGREGATES BY U. S. BUREAU OF RECLAMATION

In preparation for the construction of Seminoe Dam across the North Platte, in Wyoming (elevation 6300 ft), the U S.B R made a study of Platte aggregates near the dam (2). Seven of the eight deposits investigated were rejected because of lack of large gravel, friable or carbonaceous material, poor grading, organic impurities or excessive silt. This is the same material, except for water erosion, that was used in Nebraska pavements

The U S B.R report noted that the Platte sand from the deposit finally selected for Seminoe Dam aggregates

Contained coal and oil-impregnated shale, a great deal of feldspar, poor sandstone, and friable granite,
The silt content varied from 1 4 to 8.5 per cent,
Unwashed sand gave color values of Plate 2 to Plate 5 in the A.S.T M. Colorimetric Test for Organic Impurities,
Durability tests showed a rather high loss for both freezing and thawing and sodium sulfate, (7 7 and 7 9 per cent)

A petrographic analysis was made of the deposit that was selected for use. Data for the sand are given in Table 1 Applying the U.S.B.R. figures to the two gradings of the paper we secure the values in columns 3 and 4

The U S.B.R. also carried out freezing-and-thawing tests of concrete made of the Platte sand and gravel, and other aggregates The principal indications may be summarized:

Concrete of Platte sand (unwashed) and gravel, stored 90 days in fog room, disintegrated after 31 cycles
Similar concrete made on washed sand failed at 35 cycles
Little improvement was found when Grand Coulee Dam gravel was substituted for Platte gravel
Platte sand and local crushed granite showed a loss in compressive strength of 30 per cent at end of 40 cycles

The U.S.B R. concrete studies of Platte aggregate were made with a blend of six normal portland cements that contained 1.5 per cent of free lime. This cement high in free lime may have contributed to the early failures in these tests.

The Platte sand failed in practically every test carried out by the U.S.B.R ; but in spite of these results, they decided to use it in Seminoe Dam These tests were available before the studies of the paper were begun.

ALKALIES-AGGREGATE REACTIONS

The authors attempt to account for the poor results obtained with the Platte aggregate in this way:

. . . . there seem to be two possibilities one that the trouble is caused by a reaction between opaline silica in the aggregate and the alkali in the cement, and the other that it is due to a reaction between the feldspathic materials in the aggregate and some constituent in the cement.

No information was given as to the alkali content of the cements used in the

TABLE 1

PETROGRAPHIC ANALYSIS OF PLATTE RIVER AGGREGATE

Columns 1 and 2 from U S Bureau of Reclamation Technical Memo 576 1938

USBR Rock type	Seminoe Dam sand, per cent	Platte aggregate based on Seminoe sand analysis, per cent	
		Grading 1	Grading 2
Chert	1 2	1 1	1 1
Chlorite	0 8	0 5	0 5
Dolorite[a]	1 5	2 4	2 1
Feldspar	12 5	14 0	13 0
Gneiss	b		
Granite	1 0	3 7	3 7
Graywacke	3 7	5 4	4 8
Hornblende	1 7	1 3	1 4
Limestone	b		
Magnetite	0 7		0 1
Quartz	66 0	52 9	55 0
Quartzite	3 0	6 3	6 3
Sandstone (good)	4 3	7 2	6 8
Sandstone (poor)	1 7	2 7	2 3
Shale	b		
Slate	2 5	2 6	2 7
Total	100 6	100 1	99 8

[a] The report reads "dolorite", it is impossible to determine whether *dolerite* or *dolomite* was intended, it was assumed to be *dolerite*

[b] Trace

TABLE 2

ALKALIES IN AMERICAN CEMENTS

Approximate Date	Cements		$Na_2O + K_2O$			Authority	Ref No
	Type	No	Low	High	Av		
1837[a]	Natural	17	0 50	9 00	5 00	U Cummings	28
1904[a]	Natural	13	0 50	7 96	4 18	L C Sabin	12
1877	Portland	2	1 39	1 75	1 57	W W Maclay	29
1900	Portland	4	0 98	1 34	1 10	U S Geol Survey	30
1904[a]	Portland	20	0 40	2 25	1 14	E C Eckel	31
1904[a]	Portland	10	0 40	2 00	1 15	L C Sabin	12
1909	Portland	17	0 23	1 26	0 80	P H Bates	32
1936	Portland	106	0 12	1 58	0 75	Miller and Manson	14
1939	Portland	10	0 21	1 68	0 80	G W Ward	33
1939	Portland	4	0 62	0 92	0 80	Jackson and Kellermann	

[a] Some of these early analyses are undoubtedly many years older than the dates shown

Nebraska pavements, or on any other of their properties

The authors apparently meant to disarm critics by calling the paper a progress report and these conclusions "possibilities" In spite of these qualifications we must accept the above as the conclusions of the paper, they are the only conclusions that had any bearing on "Volume Changes in 'Sand-Gravel' Concrete" If they had not seemed highly probable, such conclusions should not have been presented in any form However, they must be dismissed as pure speculations for these reasons:

- To attribute failure to "some constituent in the cement," without indicating what constituent is under consideration, is a meaningless use of words
- Rating cements on the basis of "water-soluble alkalies calculated as Na_2O" is largely fictitious, since it is probable that with sufficient time all the alkalies would be soluble
- The narrow range in alkali content of the four cements used and the small percentage of opaline silica (0.30 per cent) in the aggregate do not justify such speculations
- Apparently no complete analysis was made of either the portland cements or the Platte aggregate used in the laboratory tests
- No consideration was given to the alkalies in the water absorbed by the Platte aggregate, or of water used for mixing and curing the Nebraska pavement concrete
- No account was taken of any of the 34 factors listed at the beginning of this discussion.
- No account was taken of the explanations previously given by other investigators of similar concrete road failures

ALKALIES IN CEMENT

It has been known for nearly a century that portland cements contain alkalies. The first complete analysis of a portland cement ever reported, made in 1849 by an Austrian chemist (3) on an English cement, showed 2.7 per cent of alkalies Alkalies in cements arise from the fact that practically all raw materials and many fuels contain them. It is doubtful if a commercial cement has ever been made without alkalies.

Table 2 was compiled to determine how the alkali contents of the four cements in the paper compared with past and present practice. Our information is incomplete in that no single item includes all American cements. It is notable that the most exhaustive investigation of portland cements ever reported, carried out by the National Bureau of Standards in 1931 on 138 samples of cement gave no consideration to alkalies and did not report them in any cement (13). Table 2 brings out several facts:

- The alkali content of recent portland cements ranges from about 0.1 to 1.7 per cent
- Alkalies in the four cements used in the paper are about the average; they cover too narrow a range to form the basis of speculations on concrete durability
- Up to 1909 the alkali content of portland cements decreased rapidly, probably as a result of gradually increasing kiln temperatures
- Average alkali content of portland cements has not changed much in the past 30 years
- Alkalies in 19th century natural cements were about 6 times that in recent portlands.

CAUSES OF CONCRETE FAILURES

The disappointing lack of durability of concrete has attracted widespread attention during the past 20 years. Prior to January 1940 practically all concrete failures were attributed to incorrect proportions or to poor workmanship. This was the view expressed by the Portland Cement Association, after 4 or 5 years of intensive work on a continent-wide survey of existing structures begun in 1928 (4). After about 700 structures had been studied by experts who visited every corner of the United States and Canada, F. R. McMillan gave the following conclusions in an illustrated paper before the International Congress on Large Dams, Stockholm, 1933 (5):

> As the examination of the hundreds of structures, of which those illustrated are typical, progressed, it became increasingly more evident that the major factors in producing durable concrete were those items included under the

general term, good workmanship, or more explicitly, the use of proper mixtures and consistencies and the exercise of care in placing the concrete Such factors as the size and grading of the aggregate are quite unimportant except as they affect the proportions and consistency necessary to obtain proper placing Even the quality of the aggregate did not stand out as an isolated factor causing deterioration in dams In almost every case where aggregate of low durability was found, its presence was disclosed by faulty concrete resulting from workmanship defects Portions of the structure free from these workmanship defects were still in good condition, indicating that the aggregate alone was not the major factor in deterioration

So far as quality of the cement itself is concerned, in only 3 out of the 700 structures examined could suspicion be cast on the performance of the cement, and in only one of these cases is the evidence entirely convincing

A detailed report on these structures would be invaluable to engineers. The writer is not familiar with any statements on this survey since 1933.

After January 1940 it became fashionable to attribute concrete failures to defects in the cement, particularly to reactions between the cement alkalies and certain materials in the aggregates. Since September 1941 many writers have been specific and attributed these reactions to opaline silica in the aggregate We can fix the dates exactly. T. E Stanton, of the California Division of Highways, was the first to attribute concrete failures to a reaction between cement alkalies and aggregates, in a paper before the American Society of Civil Engineers, January, 1940. His views as published from time to time may be shown thus:

Date	Reacting aggregates
1940 February	"Sands . that have a relatively high shale and chert content" (6)
	"Siliceous shale or impure limestone containing a comparatively high percentage of magnesia" (6)
1940 December	"Siliceous magnesian lime rocks found in the aggregates from the Upper Miocene sedimentary deposits of the State and frequently in the presence of some of the low-magnesian, low-lime shales and cherts" (7)
1941 September	"Any type of aggregate that contains opal may be reactive" (8)
1942 January	"Opaline silica in the chert portion of the aggregate" (9)

An examination of the extensive literature on this subject, of the past 3 years, shows a strong tendency to "follow the leader." This may be illustrated by the frequent editions of a "Concrete Manual" by the U. S Bureau of Reclamation

Edition	Reacting aggregates
1936	Not Mentioned.
1938	Not Mentioned.
1939	Not Mentioned
1941	"Certain siliceous limestones and shales"
1942	"Opaline silica . . many other siliceous minerals and rocks."

A complete analysis of the views expressed by other writers on the reactions between cement alkalies and aggregates would lead us too far afield, however, I call attention to certain facts

- Portland cements have always contained alkalies
- English portland cements, of excellent service records in many parts of the world for three-fourths of a century, contained up to 2½ per cent of alkalies, they were considered so superior that it was common practice for competitors to add alkalies, if their cements contained less than 1 per cent of alkalies (10)
- Nobody has explained why natural cements that contained six times as much alkalies as the recent portlands did not show this reaction
- An exhaustive survey of 700 structures did not reveal evidences of cement-alkali attacks on aggregates
- No conclusive scientific evidence has been presented to show that opaline silica or any other rock minerals enter into a destructive reaction with cement alkalies, under the conditions that prevail in concrete pavements

PROBABLE CAUSES OF FAILURE OF PLATTE-AGGREGATE CONCRETE

I present a number of factors that seem much more "probable" as causes of the failures of Nebraska concrete roads made of Platte aggregates than the two "possibilities" listed by the authors The following "probable" causes will be considered.

Free lime in portland cement,
Alkalies in water and aggregate,
Chert and other deleterious materials in aggregate,
Too much cement in concrete

In addition to the above three other topics will be discussed:

Variation of tests,
What is the significance of the tests?
Recommendation of paper

FREE LIME IN PORTLAND CEMENT

More than 100 years ago General Totten (11) recorded the effect of free lime as causing "false set" of a natural cement Most of the writers on cement during the past 100 years have discussed free lime In 1905, L C Sabin (12) wrote

> It may then require weeks or months of exposure to the atmosphere to correct tendencies to expand due to the presence of free lime or magnesia
> It has been said that as small an amount as 1 per cent free lime is dangerous

Sabin's conclusions are as sound today as when they were written nearly 40 years ago Recent specifications of the U S Bureau of Reclamation restricted free lime to 0.5 per cent

The authors gave no data on free lime in the laboratory cements or in those used in Nebraska concrete roads, but there are some evidences that have a bearing on the question We saw above that the blend of six normal cements used in the U S B R. tests of Platte aggregates for Seminoe Dam (2), averaged 1.5 per cent free lime, some may have contained as much as 2 to 3 per cent. It is probable that some of these high-free-lime cements were used in Nebraska roads Carlson and Bates (13) reported analyses of 87 cements, showed free lime up to 4 8 per cent, 20 per cent of these cements gave free lime 1 5 per cent or over. Miller and Manson's (14) analyses of 106 portland cements, about 1936, showed free lime up to 3 per cent, average over 1 per cent, and that 18 per cent of the 106 cements contained 1 5 per cent or more free lime In their tests of durability of mortars exposed to alkali waters, the 16 least durable cements contained nearly twice as much free lime as the 20 most durable.

Tests on 32 cements in 1937 by ASTM Committee on Cement (34) gave free lime up to 5 33 per cent, average 1 46 per cent, 41 per cent of the cements had 1 50 per cent or more free lime.

A cubic foot of the concrete used in the Nebraska pavements made from Platte aggregate contains

	lb
Water	12
Cement	26
Aggregate	105
	143

Assuming 1 5 per cent free lime, a cubic foot of concrete will contain 0 39 lb of free lime; and using the value in the paper, 0 32 lb. of opaline silica. In view of the known behavior of free lime, it is gratuitous to look at a "possibility" in a lesser quantity of opaline silica

The case of high-free-lime cements in concrete roads was adequately stated in 1938 by V. L. Glover (15) ·

> Entirely distinct from disintegration due to frost action is a type of failure which takes the form of abnormal expansion of the concrete and which sometimes does not develop until after several years of service When this expansion is restrained, multiple cracking followed by ravelling and ultimate disintegration results There is evidence indicative that this type of failure is due to so-called "delayed" unsoundness, probably caused by hard-burned free lime or magnesia in the cement, the effect of which is not revealed in the standard soundness test

The authors cite the low autoclave expansion of the four cements used, probably to meet the free-lime argument, however we have a recent statement from Mr. Jackson (16) that reflects accepted opinion:

> The autoclave high-pressure steam test is favored by many even though we may not have absolute evidence that it will ensure against delayed unsoundness

All the evidence on high-free-lime cements indicate the same type of expansion that was noted for concrete containing Platte aggregate The chances are very high that free lime in the cements contributed to the failure of Nebraska pavements.

ALKALIES IN WATER AND AGGREGATE

As pointed out above, the Platte River, especially during the spring floods, was originally a swift-flowing stream During the past 20 years this condition has been greatly changed Several large storage reservoirs were constructed on the headwater streams and spring floods have been much reduced in volume During the road-construction season the river is practically dry, the small sub-surface flow is largely spent irrigation water Samples of Platte River water in 1906 and 1907, before the days of irrigation reservoirs, contained over 400 parts per million of soluble solids (17), about 50 per cent of which consisted of alkalies that are injurious to portland cement The percentages of these alkalies in the spent irrigation water is probably several times that of the original water

Due to the general practice of irrigation in Western Nebraska, there has been a decided rise in the water-table These waters contain alkalies that are known to be injurious to concrete The general downward slope of a road paralleling the Platte River (Route 30 mentioned in the paper) would cause the ground water in many places to collect under the slabs. High evaporation would draw this water through the pavement leaving the alkalies in the porous concrete High evaporation is shown by the experiments of the Department of Agriculture at North Platte, Neb. During May, June, July and August the evaporation from a free water surface averaged 0 25 in per day (18)

Alkalies in river waters originate in the native rocks of the region A chemical analysis of Platte aggregate would no doubt show appreciable quantities of the same alkalies that are found in cement. The work of A S Cushman (19) on rock powders, 1905, carried out by the same organization as the work of the paper under discussion, showed the mechanics of the occurrence of alkalies in river waters. Erosion grinds rocks to fine powders and the alkalies are quickly extracted.

Aggregates dredged from the Platte during the road-building season would be saturated with water high in alkalies Concrete was probably mixed with the same water, which no doubt was used also for curing. Other aggregates used in Nebraska probably were not saturated with alkalies; it is likely that mixing and curing waters were obtained from sources lower in alkalies

CHERT AND OTHER DELETERIOUS MATERIALS IN PLATTE AGGREGATE

The only petrographic data in the paper may be shown thus.

Granite and quartz	"Essentially", "mostly"
Feldspar	"Some", "about 20 per cent"
Calcareous material	"Practically none"
Opaline silica . .	"0 3 per cent"

Opaline silica was reported in precise figures, other constituents were dismissed with such generalities as "some" and "practically none" Other studies of the same aggregate had shown chert and soft and deleterious materials in amounts exceeding the usual specification limits

Table 1 gives a petrographic analysis made by the U S Bureau of Reclamation (2) on Platte sand for Seminoe Dam, and the corresponding values for Platte aggregate of the paper. The U S B R analysis did not reveal opaline silica, but it shows questionable materials (when computed to the grading of the paper):

	Per cent
Chert	. 1 1
Chlorite	. 0 5
Dolerite	2 3
Poor sandstone	2 5
Slate	2 6
	9 0

This does not include silt, organic impurities or friable granite

Observation and tests extending over 20 years have shown chert (20) (21) (22) to be an extremely questionable aggregate. Platte aggregate contained four times as much chert as opaline silica.

F. V. Reagel (20) of the Missouri Highway Department, pointed out nearly 20 years ago that many of their crushed limestones contained large percentages of chert that was unsatisfactory in concrete roads, and specified a limit of 5 per cent on this impurity.

Freezing and thawing tests of concrete reported in 1931 by the Portland Cement Association showed (21):

> Materials which appear to be least resistant in these durability tests are shale, absorbent chert, argillaceous limestone (water-lime variety) and argillaceous sandstone Of these shale and chert particles are the most detrimental to mortar and concrete and hence for severe exposure should be avoided or at least restricted to relatively small amount .

H F Gonnerman (23) of the Portland Cement Association reported tests in 1932 in which concrete cylinders made with Missouri chert showed numerous surface "pop-outs" at 25 cycles of freezing and thawing.

Chlorite (17) is a monoclinic mineral, similar to mica, and is obviously inferior The U S B R analysis shows nearly twice as much chlorite as the 0 3 per cent opaline silica of the paper. Lea and Desch (24) in 1935 discussed a failure of concrete products made of dolerite that showed destructive expansion several months after manufacture. Platte aggregate contained eight times as much dolerite as opaline silica. It is unnecessary to elaborate on the inferior concrete-making qualities of poor sandstone and slate.

In placing the finger of suspicion on 8 lb of opaline silica in a cubic yard of concrete, the authors neglected 30 times as much other materials, all of which have long been known to be either injurious to concrete or of doubtful quality

Potassa and soda in river waters are usually considered to exist as sulfates (17) W. C. Hanna, of the California Portland Cement Co, is authority for the statement (25):

> There is evidence that potassium in cement often occurs as K_2SO_4 The possibility of complex calcium-sodium silicates should not be overlooked, nor should the alkalies in the aggregates be forgotten

Why was the opaline silica in the Platte aggregate not long ago corroded and destroyed by hundreds of years of contact with the same alkalies in the water that are found in cements?

The early failure of Platte sands in the Bureau of Reclamation freezing and thawing tests of concrete (2), cannot be accounted for by a reaction between cement alkalies and opaline silica, that is said to require many months or years. They can be explained by 1 1 per cent chert and 8 per cent of other soft, deleterious materials in the aggregate and by 1 5 per cent of free lime in the cement

TOO MUCH CEMENT IN CONCRETE

There is a saying that "dense concrete is good concrete, denser concrete is better concrete." That Platte-aggregate concrete is extremely porous is shown by its weight of 143 lb. per cu ft ; water and air voids are about 2½ times that of a road concrete with aggregates graded to 2½ or 3 in, which weighs about 154 lb

The case of the deterioration of porous concrete subjected to percolating water and high evaporation was stated in 1935 by J. A. Kelley, of the Public Roads Administration (26):

> The theory also serves to explain the deterioration of pavement slabs that begins at the top and works downward

Tests of drying shrinkage of concrete by the Portland Cement Association (27) throw considerable light on the behavior of Nebraska roads made of Platte aggregate The shrinkage of concrete of constant water-ratio 0 67 by volume (0 45 by weight), after the specimens were moist cured for 7 days then dried in air at 70 deg. F. and 50 per cent relative humidity for 6 months, was:

Portland cement, sacks per cu yd	Shrinkage of concrete	
	In per 100 ft	Per cent
5	0 28	0 023
8	0 85	0 071

For the same W/C the rich mix showed three times the shrinkage of the lean one The rich mix corresponds to Platte-aggregate concrete; the lean one to the usual road mix. These tests gave drying shrinkage, but a corresponding expansion would occur when the concrete was wet after having been thoroughly dried. This undoubtedly points to the hazard of too much cement.

An extremely rich mix would be particularly vulnerable if the different rocks that make up the aggregate had widely varying thermal coefficients. Thermal data on the various rocks in Platte aggregate, would have furnished conclusive evidence.

In comparing the behavior of Platte aggregate when used alone with normal concrete made of sand and a coarse aggregate the authors state

> In contrast, no disintegration had developed up to that time on any of the pavements laid with fine-and-coarse-aggregate concrete

The principal differences in these mixes was overlooked. Instead of attributing the difficulties of Nebraska concrete roads to differences in aggregate grading, it should have been charged largely to differences in cement factor and the consequent excessive shrinkage of the too-rich mixes.

VARIATION OF TESTS

The authors point to such factors as 0 3 per cent of opaline silica and small variations in alkalies in the four cements used as "possibilities," in attempting to account for the excessive expansion of certain specimens made of Platte aggregate, but they do not even comment on the vast differences in the expansion of parallel specimens made of Gradings 1 and 2, of the same material, with only insignificant differences in grading, voids, etc In Table 3 we have assembled the expansions at 660 days to show a direct comparison between the two gradings and between the cements highest and lowest in alkalies We conclude that duplicate tests show:

> In each instance, in both series of tests, Grading 1 gave greater expansions than Grading 2.
>
> In specific instances Grading 1 expanded 4, 7½, 37 times as much as Grading 2, average of 8 trials, 7 1 times as much.
>
> The difference between the two gradings was greater than that between the highest and the lowest alkali cements, using combined alkalies as the basis of comparison

Table 1, based on the analysis of the U. S. Bureau of Reclamation, makes it apparent that these differences cannot be attributed to petrographic composition The only conclusion we can reach is that these differences must be charged to *variations in duplicate tests on the same* *material.* This study throws much doubt on any deductions based on the measurements in the paper.

WHAT IS THE SIGNIFICANCE OF THE TESTS?

We saw above that variations in duplicate tests were so great that little confidence can be placed in the measurements.

The authors state that they were interested primarily in producing "the characteristic map-cracking" which was not produced by repeated freezing in the laboratory. While the procedure used produced map-cracking in certain specimens, it appears that this is the beginning and the end of its resemblance to the behavior of Nebraska Roads. The test blocks were subjected to none of the warping and reversals of stress that are met in a road slab.

TABLE 3

VARIATION OF TESTS WITH PLATTE AGGREGATE

Data from tests by Jackson and Kellermann

Series		Grading	Cement	Length change, per cent at 660 days		
				Grad 1	Grad 2	Ratio 1/2
Comparison of two gradings	I		1	0 7718	0 4962	1 6
			2	0 1185	0 0824	1 4
			3	0 2228	0 0296	7 5
			4	0 3163	0 0085	37 3
	II		1	0 7524	0 6462	1 2
			2	0 1241	0 1147	1 1
			3	0 4452	0 1440	3 1
			4	0 1058	0 0268	4 0
						7 1
				High alkali cement 1	Low alkali cement 3	Ratio 1/3
Comparison of two cements	I	1		0 7718	0 2228	3 5
		2		0 4962	0 0296	16 7
	II	1		0 7524	0 4452	1 7
		2		0 6462	0 1440	4 5
						6 6

It appears extremely doubtful whether immersion-wetting followed by drying have any significant relation to the case of Nebraska roads which are subjected to a much more destructive regimen. Some of these differences may be noted:

- Temperature range in the tests was 60 F, whereas the range of the road slabs may reach 160 F,
- Slabs may be wet on bottom and dry on top, and vice versa,
- Roads subjected to frequent freezing,
- Road concrete may be exposed to alkali waters

RECOMMENDATION OF PAPER

The closing paragraph of the paper reads:

> It is recommended that sand-gravel of the type represented in these tests be not used as concrete aggregate unless blended in the proper proportions with crushed limestone or with some other type of coarse aggregate which experi-

ence or test has demonstrated to be satisfactory for this purpose.

If there is a "test (that) has demonstrated (aggregates) to be satisfactory for this purpose," two questions may be asked

What is the test?
Why was it not applied to the aggregates under study?

If we consider that in the recommended mix 40 per cent of Platte aggregate is used as sand, the opaline silica content of total aggregates will be·

Mix	Opaline silica, per cent	Result
Nebraska road ..	0 30	Disintegration
Recommended	0 12	Permanence

This leaves an extremely thin margin of 0 18 per cent of opaline silica between disintegration and permanence. We give no consideration to the changed cement factor, since the authors imposed no restriction on alkalies in the cements.

Besides the Platte material the only coarse aggregates tested were quartz gravel from New York, a dolomite gravel from Chicago and a limestone from Kansas It is obvious that New York and Chicago gravels are not available for roads in Nebraska, hence the applicability of the recommendation hinges on a favorable test on one limestone Even on this point the terminology of the paper is much confused; the first part refers to Chicago gravel as "dolomite"; later it is called "calcareous", this makes it impossible to be sure what the authors mean by "limestone."

The favorable evidence of the tests on dolomite and quartz gravels and on crushed limestone is offset by tests by the Bureau of Reclamation already cited, that showed early failure in freezing and thawing of concretes made of Platte sand mixed with Grand Coulee Dam gravel, and a local crushed granite.

The *Recommendation* was obviously based on the acceptance of the conclusions that were called "possibilities," or on field observations; it has no recognizable foundation on the data of the paper

CONCLUDING REMARKS

The most obvious omission of the paper was the failure to comment on the significance of variations of 710 per cent in parallel tests of concrete made of the same aggregate This makes it impossible to place confidence in the volume change measurements reported. Questions are raised as to whether the wetting-and-drying cycles used have any significant relation to the much more severe conditions to which Nebraska concrete roads are exposed.

Neither the conclusions nor the recommendation of the paper have any recognizable foundation on the data reported There is evidence that the premature failure of concrete roads built of Platte River aggregate resulted from causes that were not touched on in the paper, such as chert and soft and deleterious materials in the aggregate, free lime in the cements, alkalies in water or subgrade soil, and concrete mixes too rich in cement.

The assumptions made in this discussion would have been unnecessary had the authors given the values for the materials and conditions encountered in their tests and surveys

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MR HAROLD ALLEN,[1] *Public Roads Administration.* In the work described in this paper, the authors have made a large contribution to the solution of one of the difficult problems facing the highway engineer in Nebraska, and parts of Kansas, Iowa, and Missouri.

The writer's experience with sand-gravel or mixed-aggregate concrete started about 1925 and covers both laboratory test work and use of the materials in the field Before the mixed aggregate described in the paper was used extensively in pavement construction, laboratory investigations were made in the laboratories of Kansas State College to determine the strength and durability characteristics of concrete in which it was used. The durability was tested by alternate freezing and thawing of laboratory samples and later of cores drilled from finished pavements All of these tests indicated that the durability, as measured by freezing and thawing, was satisfactory but not as great as that shown by normal coarse and fine-aggregate concrete

The strength was found to be satisfactory and to follow the water-cement ratio law, being slightly lower for the same cement content than that of the normal coarse and fine-aggregate concrete To compensate for these slight differences in strength and durability, a lower water

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content per sack of cement was specified for mixed aggregate concrete The laboratory tests and the experience on the early projects led the engineers of the Kansas Highway Commission to the conclusion that for sections of the State where coarse aggregate was not available, the use of sand-gravel or mixed aggregate was justified.

The type of disintegration which Messrs Jackson and Kellermann describe in their paper, and which was also produced experimentally in the laboratory by Mr. Gibson of the Kansas Highway Commission, started to appear in mixed aggregate concrete pavements from 6 to 10 years after they were built

When the map cracking first appeared, an explanation of the cause could not be found. As stated above, the aggregates and concrete mixtures had been tested in the laboratory Special emphasis had been placed on concrete control during construction and adequate engineering inspection had been used on each project to insure strict adherence to the following basic requirements:

1. The gradation of the aggregate on each project was kept within specified limits by testing samples taken from each 50 tons. The materials were entirely free from organic matter, clay, or silt

2 All proportioning was on a weight basis.

3 Moisture determinations were made at frequent intervals (5 minutes to one hour) on the aggregate to insure adequate control of water added at the mixer.

4 The water-measuring device on the mixer on each project was calibrated by the Highway Commission project engineer's staff, and the water added, including that in the aggregate, was never permitted to exceed the maximum amount specified The specifications for the early projects placed the maximum at 5 gal. per sack of cement. Later this was increased to 5 75 gal because this quantity resulted in concrete of adequate strength.

5. All construction procedures such as placing, finishing and curing the concrete were in accord with the best accepted practices

Complete records and close supervision indicated that the procedures followed in producing the concrete were the best available and that the map cracking could not be attributed to any lack of field control

When the surface cracking first appeared, it was suggested that it might be due to alkali in the soil. Early investigations of alkalies in Kansas soils made by this writer indicated concentrations so low that their effect would be negligible This conclusion was substantiated by the fact that map cracking and subsequent disintegration appeared in concrete culvert and bridge guard rails and in bridge decks in which this type of aggregate was used

The possibility that some characteristic of the cement was a contributing factor to the disintegration was eliminated by the facts that cracking occurred in concrete pavements containing all of the brands marketed in the Kansas area, and did not occur in coarse and fine-aggregate concrete containing cements from the same sources A definite relationship between the cement content of the mixed aggregate concretes and the occurrence of map cracking was not apparent The disintegration did not appear in concretes composed of coarse and fine aggregates and in which fine aggregates came from the same source as mixed aggregates Since map cracking did not occur in coarse and fine aggregate concrete, it was assumed that an increase in the coarse aggregate content would be beneficial in the control of the disintegration.

Since it was necessary to take some steps to correct the condition without waiting to do the research work necessary to provide an answer, specifications were prepared and used requiring an increase in the percentages of the mixed aggregates retained on the ¾-in. and No. 4 sieves. This resulted in the "sweetening" or addition of coarse aggregate in the form of crushed limestone or gravel to the normal mixed aggregates Several of the projects on which sweetened aggregates were used have been in service more than 6 years and, to the best of my knowledge, signs of map cracking have not appeared in any of these pavements.

It is gratifying to this writer that the research in this paper justified the assumption made in an attempt to solve a difficult problem. The procedure described in the paper should be a useful tool to the laboratory technician in future investigations of aggregates of this type.

MR. W H CAMPEN, *Omaha Testing Laboratories* The authors certainly deserve a great deal of credit for discovering the cause of so called map cracking in Nebraska sand-gravel concrete The results prove rather conclusively that the cracking is due to a volume increase caused by some chemical reaction between the cement and some ingredients of the aggregate It is hoped that eventually the active aggregate ingredients will be identified.

In order to contribute to this paper, I invited Mr. Guy P. Dorsey, Assistant County Engineer, Douglas County, and Mr. E. W. Woodbridge, City Engineer of Omaha, to examine with me about 48 miles of concrete pavement laid in Douglas County between 1922 and 1931. We made the survey on March 13, 1943; this pavement was laid under my supervision and Mr. Dorsey did the engineering work under Mr. L. E. Adams, County Engineer.

Forty-one miles of this pavement is composed of sand gravel plus cement in amounts of from 7 5 to 8.2 sacks per cubic yard. There are 20 projects averaging about 2 miles each and they were laid as follows: 1922 to 1925, 26 miles; 1926 to 1931, 15 miles. The concrete was tamped and finished by one of four methods: (1) Mechanical tamper plus hand finisher; (2) mechanical tamper plus mechanical finisher; (3) hand roller plus hand finisher, (4) vibratory tamper plus hand finisher Curing was accomplished by water, through earth or canvasses One project was cured with calcium chloride and one with emulsified asphalt The traffic on these projects varies from very light to very heavy. The grading of the aggregate was similar to what the authors reported except that the percentage passing the No 50 sieve averaged 8.

After inspecting all the projects we decided to report our findings in respect to occurrence of cracks, and appearance of the surface in cracked areas. Map cracking occurs either in isolated areas or is generally distributed over the entire project. The former will be reported as "spotty" and the latter as "general." Insofar as appearance is concerned, we have three conditions (1) No disintegration, in which cracking is well defined, and no wear, grooving, chipping or scaling is apparent, (2) slight disintegration, in which cracking has caused occasional wearing or grooving to about $\frac{1}{8}$ in in depth, (3) severe disintegration, in which cracking has caused occasional grooving, chipping or scaling to a depth of $\frac{1}{8}$ in. to 1 in.

SUMMARY OF THE OBSERVATIONS

1. All projects show map cracking except one which was laid in 1931.

2 About half of the projects show spotty map cracking, whereas the other half show it generally.

3. The surface shows no disintegration in 16 of the projects.

4. The surface shows slight disintegration in two of the projects

5. The surface shows severe disintegration in two of the projects.

6. As a whole all the pavements are in good condition for their ages, and repairs are not excessive except on the two projects showing severe disintegration.

CRUSHED ROCK PAVEMENTS

During the same period four crushed rock projects, approximately 7 miles, were constructed using the usual 1·2·4 mixture. Quartzite was used on one project in 1925 This shows no map cracking In 1926 two projects were constructed with limestone They are generally map cracked and show severe scaling in places The fourth project, also limestone, was laid in 1931 and shows no map cracking

CONCLUSIONS

We draw the following conclusions from the survey.

1 While it is true that concretes containing Nebraska sand gravel as the entire aggregate generally show map cracking, the effects on the surface are not serious as evidenced by the facts that projects 18 to 21 years old are still in serviceable condition and do not require excessive maintenance
2 Two of the three projects containing limestone and Nebraska sand show severe disintegration in places as a result of map cracking, indicating that map cracking is not limited to sand gravel surfaces.

Mr R E Bollen, *Nebraska Department of Roads and Irrigation* The authors have reproduced a distinct type of concrete failure in the laboratory which is similar to failures observed in many concrete structures and concrete pavements in Nebraska The appearance of the concrete beam shown in Figure 4 of the paper is practically identical with the appearance of numerous headwalls and wing walls of concrete drainage structures which are exposed to the elements but which are not in direct contact with soil The appearance of the concrete pavement in Figure 1 of the paper is identical with that of some areas of pavement in Nebraska which have reached an advanced stage of map cracking The difference in appearance of the concretes in Figure 1 and in Figure 4 is primarily due to restrained expansion and to difference in size of the mass involved

The authors' summary indicates that the character of the sand-gravel aggregate rather than its grading is the primary cause of the trouble Experience in Nebraska confirms this where concrete was produced from aggregate varying between 35 per cent retained on a No 10 sieve and 65 per cent retained on a No. 10 sieve Our field observations indicate that the primary cause of the abnormal expansion is the combined character of the aggregate and the cement. Numerous structures which were constructed from 1926 to 1930 show practically no map cracking Structures and pavements which were constructed since 1930 in which aggregates from the same pits and cement from the same mills were used now show a considerable degree of map cracking

The description in the paper of the stages in the formation of the map cracking covers this occurrence in Nebraska quite well The stages in the development of the map cracking in structures, handrails, wheel guards on bridges, etc., are practically identical with that which can be reproduced by alternate wetting and drying in the laboratory Standard 6-in by 12-in concrete test cylinders which have been half buried in soil with the longitudinal axis of the cylinder parallel to the ground surface have shown map cracking similar to that of the beam in Figure 4 in less than three years The map cracking was severe on the exposed surface of the cylinder and very faint on the surface which was below ground level Other cylinders which were exposed in the same manner and which contained sand gravel from different pits and cement from different mills show very slight or no indications of map cracking after eleven years exposure.

A number of theories have been suggested to explain the map cracking and abnormal expansion which occurs in concrete pavements in Nebraska On many projects areas of pavements have been observed which show no indication of map cracking. Adjacent to these areas are areas which show a considerable degree of map cracking The aggregate and cement in one area was apparently identical with the aggregate and cement which was used in another area An explanation of the cause of this difference would be welcome

MESSRS JACKSON AND KELLERMANN In addition to charging the authors with numerous sins of omission and commission in connection with the report, Mr. Abrams discusses the general problem of concrete pavement failures in Nebraska, listing many factors which in his opinion are more "probable" causes of failure than the two possibilities indicated in the paper Before commenting it will be desirable to restate briefly, first, the primary object of this investigation and, second, the principal conclusions which were reached

As indicated in the paper, the characteristic map cracking which develops early in the life of pavements containing Platte River aggregate indicates quite definitely that excessive expansion of the concrete is the root of the trouble. The tests were made to determine whether effects similar to those observed in the field could be reproduced in the laboratory and, if so, what particular combinations of materials produced these effects and what methods might be employed to eliminate the trouble. The authors found that by using the type of weathering cycle described by Mr Gibson in 1938 (see reference 1 of the report) excessive expansion was induced in certain combinations containing Platte River sand-gravel (aggregate A in the report) which did not occur in concrete containing either the Long Island or Chicago materials, even when these aggregates were graded exactly the same as the Platte River material In view of the clear service records of both the Chicago and Long Island aggregates (aggregates B and C in the report) the authors cannot agree with Mr. Abrams that "no convincing evidence has been presented to show that the high expansion of certain laboratory specimens had any bearing on the failure of the pavements "

Mr Abrams lists 34 factors which he says were neglected in making this study All of them are in his opinion necessary "to an understanding of the laboratory tests and the disintegration of Nebraska concrete pavements." He includes in his list numerous physical characteristics of the aggregates, free lime in the cements, and various physical properties of the concrete. He also questions the omission of data on the characteristics of Nebraska pavement concrete in general, as well as information regarding weather, traffic, soils conditions, etc.

As regards the lack of pavement data, the authors need only state that the paper covers a laboratory investigation and not a field study of pavement failures in Nebraska However, it may be well to point out that many of the characteristics listed by Mr. Abrams as contributing to pavement failure have been shown by Mr Gibson to have no bearing on the problem. (See *Proceedings* Highway Research Board, Vol 18, p 229.) In reporting the characteristics of the aggregates used in the laboratory study it was assumed that a general statement of mineral composition would be sufficient. However, complete mineral analyses were made and these are given in Table 12 In his Table 1, Mr. Abrams quotes from an unpublished report of the U S. Bureau of Reclamation (his reference 2) giving the petrographic analysis of aggregate taken from the North Platte River in Wyoming. This work was done in connection with an

TABLE 12

MINERAL ANALYSES OF AGGREGATES

Rock or mineral	Percentage composition for each size indicated									Ave composition for[c]	
	1½ in — ¾ in	¾ in — ⅜ in	⅜ in — No 4	No 4— No 8	No 8— No 16	No 16— No 30	No 30— No 50	No 50— No 100	Pass No 100	Gravel	Sand
A—PLATTE RIVER AGGREGATE											
Granite[a]	[b]	59	51	32	8	3	Tr			55	7.1
Feldspar		19	25	40	34	21	11	4	3	22	18.8
Quartz		8	19	25	55	74	89	96	94	13.5	72.1
Chert		3	Tr	Tr	Tr	1	Tr	Tr	3	1.5	0.6
Quartzite		4	3	1	3					3.5	0.6
Sandstone		3	1	1	Tr	1				2	0.3
Ferruginous sandstone		2								1	
Rhyolite		Tr	Tr	Tr	Tr					Tr	Tr
Epidosite		Tr								Tr	
Hornblende schist			Tr							Tr	
Andesite(?)				Tr							Tr
Hornblendite					Tr						Tr
Biotite							Tr				Tr

[a] Consists of quartz and feldspar with occasional biotite
[b] This size of Platte River aggregate not used
[c] Gravel size considered as material retained on No 4 sieve, sand as that material passing No. 4 sieve
NOTE Tr indicates trace

TABLE 12– Continued

Rock or mineral	Percentage composition for each size indicated									Ave composition for c	
	1½ in — ¾ in	¾ in — ⅜ in	⅜ in — No 4	No 4— No 8	No 8— No 16	No 16— No 30	No 30— No 50	No 50 — No 100	Pass No 100	Gravel	Sand
B—LONG ISLAND AGGREGATE											
Quartz	87	71	74	83	92	93	95	96	98	77 3	92 8
Quartzite	13	16	9	5	4	3	Tr	1		12 6	2 2
Schistose quartzite		1	3	2						1 3	0 3
Hornblende schist		1								0 3	
Feldspar		3								1	
Ferruginous sandstone		4	3							2 3	
Mica schist		4	3	4	1					2 3	0 8
Granite			6	4	1	3	Tr			2	1 3
Gneiss			2	2	1	1				0 6	0 7
Sandstone			Tr							Tr	
Garnet schist				Tr							Tr
Biotite							Tr	1	1		0 3
Muscovite							Tr				Tr
Hornblende							Tr	1	1		0 3
Sericite								Tr			Tr
C—CHICAGO AGGREGATE											
Dolomite	82	98	89	95	92	91	72	61	78	89 6	81 5
Quartzite	11		3				3	4		4 6	1 1
Trap	7		4	2	2	3	1	1	Tr	3 6	1 5
Limestone		2								0 6	
Chert			4	2	4	2				1 3	1 3
Quartz				1	2	4	24	34	22		14 5

investigation of materials for use in the construction of the Seminoe Dam

It will be noted that the mineral analyses of Platte River aggregate shown in Table 12 do not indicate the same percentages of the so-called deleterious materials which are shown by Mr. Abrams in his Table 1 Whereas he shows a total of 9 0 per cent chert, chlorite, dolerite, poor sandstone and slate in the Platte River sand, based on the Bureau of Reclamation analysis of the Seminoe Dam material, a complete analysis of the material actually used in the tests reveals less than 1 per cent of these constituents When one realizes that the aggregate analyzed by the Bureau of Reclamation was taken some 500 miles up stream from the source of the aggregate used in these tests, it is easy to account for the difference. As a matter of fact, Mr. Abrams himself recognizes it when he says that "This (the Seminoe Dam material) is the same material, *except for water erosion,* that was used in Nebraska pavements " The italics are the authors'.

Mr. Abrams complains that the report contains no information on silt content, organic impurities and other characteristics of the Platte River material. He discusses in some detail the tests made by the Bureau of Reclamation on materials taken from the North Platte in Wyoming and states that "the Platte sand failed in practically every test carried out by the U S B R." The authors question Mr Abrams' right to use the results of tests made on these materials as being indicative of what might be expected of Platte River aggregate in Nebraska As a matter of fact, had Mr Abrams been familiar with this material as normally produced for use as aggregate for concrete pavements and other structures in Nebraska he would know that silt and organic impurities are no problem in this case He would know also that when subjected to the various generally recognized tests for quality such as soundness, resistance to abrasion, etc, this material compares favorably with aggregates from many other sources known to be satisfactory, including the Chicago and Long Island materials, which were used for comparison in these tests The authors had assumed that these facts were generally known However, inasmuch as Mr Abrams has questioned the omission of these data in the report, they are given in full insofar as they are available in Table 13.

TABLE 13

PHYSICAL PROPERTIES OF AGGREGATES

Test	Aggregate		
	A (Platte)	B (Long Island)	C (Chicago)
Soundness (sodium sulphate) per cent loss, 5 cycles	3 2[a]	4 4[a]	10 2[a]
Resistance to abrasion (Los Angeles) per cent loss, grading D	29 0[b]	26 8[b]	24.7[b]
Organic matter, color test	OK	OK	
Mortar strength ratio, 7 days	94[c]	105[c]	90[c]

[a] Weighted average loss based on grading 1, Table 3 of report
[b] A S T M Standard C131-39, tentative revision 1942
[c] A S T M Standard C87-42

Mr Abrams criticizes the authors for calling attention to the possibility that the excessive expansions which were observed with certain combinations containing the Platte River aggregate might have been due to a reaction between the alkali in the cement and opaline silica in the aggregate or to a reaction between some constituent of the cement and the feldspar in the aggregate These statements definitely were not conclusions, and his statement that they should be so considered is in error In fact they were, as he says, "pure speculations" and, as such, were justified by the fact that the high volume changes noted in connection with combinations of the Platte River material and one of the cements were not observed in the case of specimens made with the same cement and the Long Island and Chicago materials The fact that the four combinations of the Platte River aggregate and cement 1, that is gradings 1 and 2 and series I and II, all showed expansions greater than any of the other combinations indicated, as the authors stated in the summary, that "there seemed to be some characteristic present in the combination . . . which caused very high expansion" The facts are beyond dispute The causes are not too clear.

Mr Abrams questions the omission of data on free lime in the laboratory cements, as well as in the cements used in the Nebraska roads So far as the roads are concerned, the authors need only point out again that they were discussing the results of a series of tests and not a survey of pavement failures. No free lime determinations were made on the laboratory cements. It was felt that such determinations would be of doubtful value unless made on the fresh clinkers which were not available. However, expansion of concrete resulting from the hydration of free lime in the cement would take place regardless of the nature of the aggregate used in the mix Therefore, the fact that excessive expansions were not observed when these same cements were used with the Long Island and Chicago materials would seem to indicate quite definitely that free lime in the cement was not the cause of the expansion For example, concrete containing cement No. 1, when used with Platte River material in gradings 1 and 2, series I and II, showed an average expansion of 0 67 per cent as compared to only 0 05 and 0 01 per cent expansion for similar combinations containing the Long Island and Chicago materials, respectively

According to Mr. Abrams, the alkalies in the soil and in the aggregates, as well as the alkalies present in the mixing and curing water, are more likely to be contributory factors than the alkalies contained in the cements. Potomac River water was used in mixing and curing the test specimens The only other source of alkali, insofar as the tests are concerned, would then be the aggregates themselves

A water extraction of the three aggregates used in the tests showed alkalies calculated at Na_2O as follows·

	Per cent
Platte River	0 002
Long Island	0 040
Chicago	0 004

The Platte River aggregate apparently contained a negligible amount of water soluble alkali

Mr. Abrams next comments on the high cement content and the relatively high porosity of the Platte River concrete. He intimates that these factors also contributed to the failures observed in Nebraska One of the major objects of the laboratory investigation was to investigate this possibility. It was on this account that the tests were designed so as to provide comparisons between identically graded aggregates on the basis of both a constant water-cement ratio (series I) and a reasonably constant cement factor (series II)

The data on mixes are given in Tables 4 to 7, inclusive, and the volume change data in Tables 9 and 10 of the paper Reference to these data will show that the cement factors used in gradings 1 and 2 with Long Island and Chicago aggregates were as high or higher than the comparable mixes containing the Platte River material. The unit weights were also as low or lower. The data show conclusively that the high volume changes observed in the Platte River concrete were not due to high cement content or low unit weight.

When Mr Abrams says that the authors "do not even comment on the vast differences in the expansion of parallel specimens of gradings 1 and 2 of the same material with only insignificant differences in grading" he is guilty of three specific misstatements. First, the effect of grading was discussed fully in the report; second, specimens involving gradings 1 and 2 can in no sense be considered as "parallel specimens", and third, the differences in grading were not "insignificant." One of the objects of this investigation was to study the effect of adding fines to grading 1 and the authors commented particularly on the fact that the reduction in expansion was much more marked in the case of *both* cements 3 and 4 than with cements 1 and 2 These trends are shown clearly in Mr. Abrams' Table 3. Of the eight ratios which he has computed to show the effect of grading, the only one markedly out of line is the one involving cement No. 4 in series I. This is, of course, due to the combination of an unusually low value for grading 2 and a comparatively high value for grading 1. The authors grant that there were individual discrepancies in their volume change measurements which are hard to explain. It should be evident, however, that in spite of them several marked trends are indicated. A few minutes study of Figures 7 and 8 of the paper should convince the unbiased reader of the fact. For this reason, the authors believe that they were justified in publishing the data in spite of certain obvious discrepancies in results After all, when one considers that in addition to all the other variables inherent in this type of testing, these measurements extended over a period of three years and that during this period the specimens were handled literally hundreds of times in moving them from one storage condition to another, it is not surprising that individual discrepancies should appear. It would be more surprising if they had not

It is obvious from the whole trend of Mr. Abrams' discussion that his chief purpose was to discredit the report because of its reference to the possibility of an alkali-aggregate reaction as explaining the excessive expansions which were observed in certain cases. To this end he not only questions the significance of the tests and the validity of the conclusions but also cites numerous factors which he says were more probably causes of failure.

The authors have shown that many of these factors, such as soil, climatic and traffic conditions in Nebraska are entirely irrelevant insofar as the laboratory investigation is concerned and further that many of the "probabilities" cited by Mr. Abrams, such as poor quality of aggregate, free lime in cement, high cement content, etc., cannot possibly explain the results which were obtained. The authors have gone to considerable trouble in answering Mr. Abrams, not because they feel that the answers will satisfy him but rather because of questions which may arise in the minds of other readers of his comments. His long and enviable career as an outstanding authority on concrete makes it imperative that his criticisms be answered. It is unfortunate that so many of them involve interpretations of the test data which are so obviously in error as to be quite inexcusable The authors hope that this discussion will serve to clarify any doubt which may have arisen as the result of Mr. Abrams' criticisms.

In connection with Mr. Campen's discussion, attention should be called to the fact that, when making the 1939 surveys, only those concrete pavements in Nebraska were included for which reasonably complete information regarding the materials used and the methods employed could be obtained. A number of projects, both in good and poor condition, were excluded from consideration because the desired information regarding constructional features was not available Only two projects in Douglas County were included Both were built with sand-gravel. One project 12.7 miles long which was built in 1925 was classified as "disintegrated" The other, 4 6 miles in length, was built in 1935, using essentially the same aggregate as the first. This project was reported as being in good condition but having considerable transverse cracking In addition, one other project in Douglas County was noted as showing disintegration This is a county project, for which no construction data were obtained For this reason it was not included in the formal survey

The results of Mr Campen's survey indicate either that his basis of classification differed considerably from that used at the time of the 1939 survey or that the percentage of sand-gravel concrete pavements showing progressive map-cracking or disintegration is much lower in Douglas County than in the State as a whole Direct comparisons are of course impossible due to the fact that Mr. Campen's survey was confined to Douglas County, whereas, with the exception of the projects above noted, the 1939 survey was conducted entirely outside of that county.

The existence in Douglas County of concrete pavement built with fine-and-coarse-aggregate apparently was not disclosed to our representatives at the time of the 1939 inspection. Pavements built with this type of concrete in other portions of the State were inspected closely but no disintegration was observed. It should be noted that the two fine-and-coarse-aggregate projects which Mr. Campen reports as showing map-cracking were built in 1926. The earliest projects of this type covered in our inspection were built in 1929. Whether some difference in construction methods which may account for the difference in behavior of the concrete occurred during this period is open to conjecture.