# INVESTIGATION OF DURABILITY OF WYOMING AGGREGATES

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## SYNOPSIS

Laboratory studies of aggregates and concrete were initiated after field-performance surveys indicated significant concrete deterioration in certain areas of Wyoming, although the performance of concrete in most of the state was excellent. These laboratory studies were to determine causes for the deterioration through analysis of the aggregates and simulated-weathering tests on concrete made with these materials and to develop preventive measures against future deterioration. This paper represents a progress report of the investigation covering seven aggregates; tests of additional materials, and other tests of those materials covered here, are in progress.

The tests indicated three of the aggregates were potentially reactive with cement alkalies; use of cement with low alkali content or of pozzolanic admixtures is indicated. One aggregate also caused rapid concrete deterioration under freezing-and-thawing action, wetting and drying, or rapid temperature change. Resistance to these effects was also improved by pozzolanic admixtures. Two other aggregates, not alkali reactive, were also affected by rapid temperature-change tests. Further study of the effect of rate of temperature change on concrete deterioration indicated that too rapid a change in laboratory tests may introduce factors not present in natural weathering conditions. Some exploratory data on possible chemical factors entering into temperature-change tests are also presented.

● FIELD SURVEYS of the condition of concrete in Wyoming showed that the large preponderance of structures were in good to excellent condition, with many having 20 to 30 years of service. There were, however, significant occurrences of concrete deterioration which were consistent from structure to structure in certain regions. This performance indicated a need for study of the causes of the deterioration and of aggregates in those regions. Accordingly, laboratory studies were initiated with the primary objective of determining corrective measures for preventing abnormal deterioration in future construction. The laboratory studies included physical tests and petrographic analyses of the aggregates, and simulated weathering of concrete specimens, such as alternations of temperature, wetting and drying, freezing and thawing, and moist storage.

*Field Performance*—Concrete highway and railroad structures throughout Wyoming were examined and classified as to the extent of abnormal deterioration. In this classification, only the relative soundness of the concrete itself was described, eliminating the effect of factors such as settlements, structural-tension cracks, or pavement transverse cracking and faulting. Construction data on the structures were compiled and analyzed to determine whether the observed performance could be accounted for from this information. In certain cases abnormal deterioration appeared to be related to the aggregate used; in other cases the performance of different structures made with the same aggregate was inconsistent. Table 1 summarizes the performance data for the seven aggregates upon which the tests described in this report were conducted.

The type of deterioration associated with the use of Aggregates 299 and 312 is illustrated in Figure 1. Figure 2 shows the Shoshone-arch bridge in which the concrete is in excellent condition. This was constructed in 1925, with crushed limestone from a ledge near the bridge site.

*Description of Aggregates*—Aggregates from a number of sources were sampled and brought to the laboratory. Seven coarse aggregates and five fine aggregates are described in this report and represent a portion of the whole study of Wyoming aggregates. A lithological analysis of the heterogeneous coarse aggregates is given in Table 2. In this analysis, 300 pebbles of each

[1] A progress report of an investigation sponsored jointly by a Charles Boettcher Fellowship and the University.

TABLE 1
PERFORMANCE DATA

| Aggregate Source Designation | Geographical Location | Field Performance |
|---|---|---|
| 299 | Southeast Wyoming | Very bad deterioration with mapcracking in most concrete constructed prior to 1940 |
| 303 | Southeast Wyoming | Excellent |
| 307 | Southeast Wyoming | Excellent although limited in extent |
| 308 | South-Central Wyoming | Concrete in two structures, constructed in 1929, severely mapcracked—Other structures built in 1934 or later in good condition |
| 309 | Southwest Wyoming | One structure built in 1937 shows severe D-line cracking in thin exposed sections —Massive sections are unaffected |
| 310 | North-Central Wyoming | One structure, built in 1920, mapcracked severely — Others, built in 1936 and later, in good condition |
| 312 | East-Central Wyoming | Very bad deterioration similar to that shown by No. 299 |

of three sizes between the ¾-in. and No. 4 sieve were examined and classified as to rock type. Thin sections of questionable materials from these sources were made as an aid in identification. Thin sections were also made from samples 303 and 307 and both were found to be high-calcium limestones with 1 to 9 percent quartz.

Results of specific-gravity and absorption tests on the coarse aggregates are given in table 3. Standard methods were used in these determinations, except for the vacuum absorption, true specific gravity, porosity, and degree of saturation. The vacuum-absorption data were obtained by evacuating the aggregate at 2 cm. of mercury for one hour, followed by admitting water into the vacuum chamber. True specific gravity was determined by the procedure for specific gravity of soils (*4*), the test being conducted on material crushed from the coarse aggregate to pass the No. 50 sieve. Porosity, expressed as the ratio between the total-void volume and the volume of solids, was calculated (*24*) from relationships between absorption, apparent specific gravity, and true specific gravity. The degree of saturation was calculated as the proportion of the total-void volume filled with water.

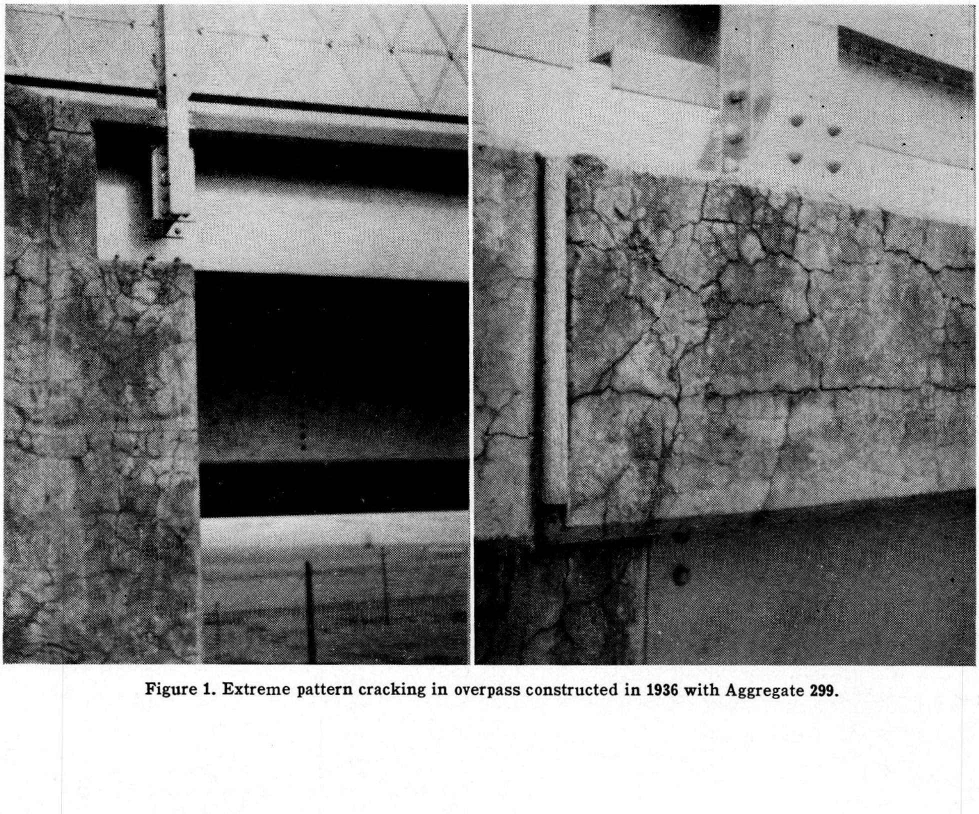

**Figure 1. Extreme pattern cracking in overpass constructed in 1936 with Aggregate 299.**

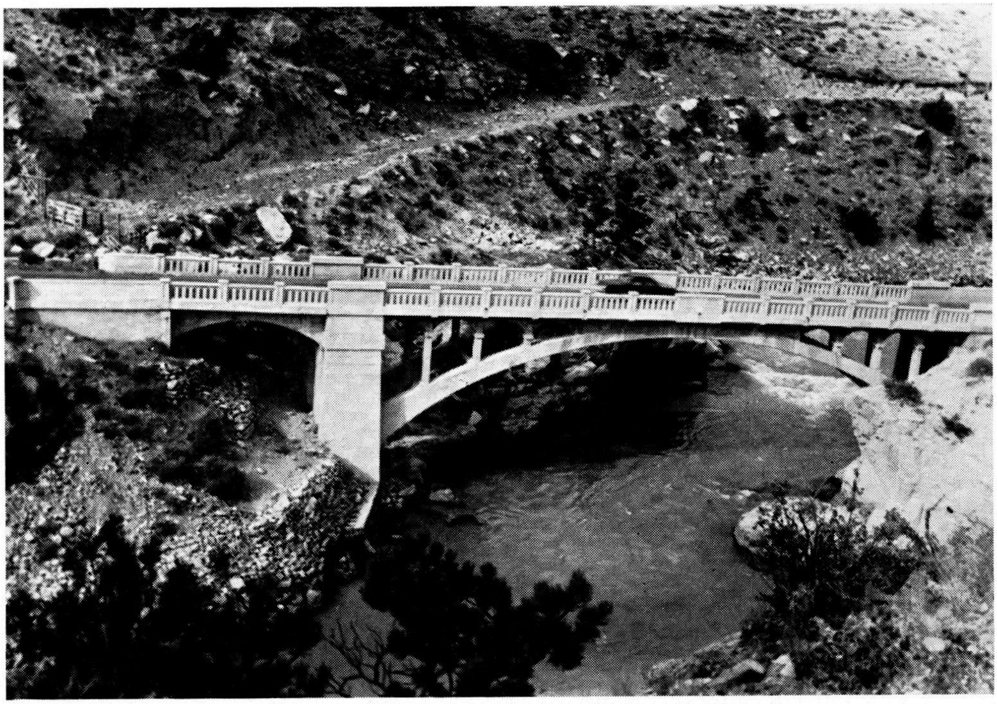

**Figure 2. Shoshone arch bridge in excellent condition (Constructed in 1925).**

TABLE 2
LITHOLOGICAL ANALYSIS OF COARSE AGGREGATE

| Rock Type | Percentage Composition of Coarse Aggregate | | | | |
|---|---|---|---|---|---|
| | No. 299 | No. 308 | No. 309 | No. 310 | No. 312 |
| Quartz | 8 | 15 | 3 | 3 | 21 |
| Quartzite | 1 | 17 | 15 | 17 | 5 |
| Granite | 76 | 14 | | 7 | 18 |
| Feldspar | | 22 | 11 | 14 | 25 |
| Basalt | | 10 | 6 | 14 | 11 |
| Gabbro | | | 2 | 5 | 6 |
| Diorite | | | | 11 | 8 |
| Gneiss | 2 | | | 1 | 2 |
| Pyroxene | | 3 | | | |
| Limestone | | Tr. | 2 | 3 | 3 |
| Sandstone, hard | 2 | 8 | 36 | 13 | 1 |
| Sandstone, friable | | 9 | 20 | 9 | |
| Chert | 2 | 1 | 5 | 1 | |
| Rhyolite | 9 | 1 | | 1 | |
| Travertine | | | | 1 | |
| Trachyte | | Tr. | | | |
| Phyllite | | Tr. | | Tr. | |
| Arkose | | Tr. | | Tr. | |
| Tuff | | | | Tr. | |
| Breccia | | | | Tr. | |

The absorption, specific gravity, and fineness modulus of the fine aggregates are shown in Table 4. A limited petrographic analysis of the fine aggregate was conducted with particular emphasis on determination of optical character and refractive index. The procedure followed was the immersion of fine-aggregate particles in a liquid having the same refractive index as the lower index of quartz (1.544). Quartz and feldspar cystals were readily identified, and the remaining particles were classified as to color, opacity, cleavage, refractive index (above or below 1.544) and isotropy or non-isotropy (Table 5).

This limited analysis was undertaken to determine the degree of correlation between the alkali reaction and expansion of the aggregate and the amount of isotropic material with a refractive index below 1.544, since most recognized alkali-reactive materials fall in this category. Unfortunately, some reactive minerals, such as tridymite, cristobalite, and chalcedony may exhibit uniaxial tendencies and some innocuous materials are isotropic with a refractive index below 1.544.

*Concrete-Test Procedures*—Concrete specimens were made and subjected to accelerated-

weathering tests in an attempt to identify the particular elements of weathering which caused the deterioration observed in the field. Each aggregate was used in four or more air-entrained concrete batches with the same cement. In addition, some mixes were made with different cements and with pozzolanic admixtures Specimen dimensions were 3- by ⅜- by 11⅜-in. and 2- by 2⅛- by 11⅜-in. These were subjected to cycles of alternate heating and cooling, wetting and drying, freezing and thawing, or to moist storage at constant temperature. Mortar bars were also made with high-alkali cement and stored in a humid atmosphere at a constant temperature of 100 F.

Data on the concrete mixes are shown in Table 6. Cement No. 200 was used in these mixes, with the following exceptions: Mixes 38 and 39 contained fly ash as a 20 percent replacement of the cement. Mix 56 contained gypsum as a 4 percent replacement. Mix 59 contained calcined Mowry shale as a 20 percent replacement. Mix 60 was made with No. 204 cement. Mix 61 was made with No. 205 cement. Mix 62 was made with No. 201 cement. The chemical analyses of these cements are given in Table 7.

Gradation of the coarse aggregate was maintained constant by sieving and recombining to the following proportions:

¾ to ½ in., 25 percent by weight

TABLE 3
PHYSICAL PROPERTIES OF COARSE AGGREGATES

| Aggregate No. | Trial | Percent Absorption | | Bulk Specific Gravity (dry) | Bulk Specific Gravity (SSD) | Apparent Specific Gravity | True Specific Gravity | Porosity | Degree of Saturation | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 24-hr. | Vacuum | | | | | | 24 hr. | Vacuum |
| 303 | 1 | 1 26 | 2 69 | 2.49 | 2 55 | 2.62 | | | | |
| | 2 | 1 25 | 2 68 | 2 48 | 2.55 | 2 61 | | | | |
| | 3 | 1.27 | 2 69 | 2.50 | 2 56 | 2 61 | | | | |
| | 4 | 1 25 | 2.69 | 2 48 | 2.55 | 2.63 | | | | |
| | Avg | 1 26 | 2 69 | 2 49 | 2.55 | 2 62 | 2.73 | .0766 | 0.43 | 0.92 |
| 299 | 1 | 0 57 | 0.73 | 2.55 | 2.58 | 2.60 | | | | |
| | 2 | 0 60 | 0.74 | 2.57 | 2.60 | 2.62 | | | | |
| | 3 | 0 61 | 0.74 | 2.59 | 2 60 | 2.62 | | | | |
| | 4 | 0 61 | 0.74 | 2.60 | 2.62 | 2 63 | | | | |
| | Avg. | 0 60 | 0.74 | 2.58 | 2.60 | 2.62 | 2.66 | 0313 | 0.51 | 0.63 |
| 307 | 1 | 0.76 | 0.80 | 2 64 | 2.67 | 2.70 | | | | |
| | 2 | 0.76 | 0.79 | 2 63 | 2.65 | 2.69 | | | | |
| | 3 | 0.76 | 0.77 | 2.63 | 2.65 | 2.69 | | | | |
| | 4 | 0.77 | 0.78 | 2.63 | 2.64 | 2 68 | | | | |
| | Avg | 0.76 | 0.78 | 2.63 | 2 65 | 2.69 | 2.74 | .0394 | 0.53 | 0.54 |
| 308 | 1 | 0.59 | 0 76 | 2.61 | 2.63 | 2.65 | | | | |
| | 2 | 0.55 | 0.71 | 2.62 | 2.64 | 2.67 | | | | |
| | 3 | 0.57 | 0.73 | 2.62 | 2.63 | 2.67 | | | | |
| | 4 | 0.56 | 0.74 | 2.63 | 2.65 | 2.67 | | | | |
| | Avg. | 0.57 | 0 74 | 2.62 | 2.64 | 2.67 | 2.71 | .0305 | 0.51 | 0.66 |
| 309 | 1 | 1.00 | 1.25 | 2.55 | 2.58 | 2 63 | | | | |
| | 2 | 1.10 | 1.25 | 2.55 | 2.58 | 2.62 | | | | |
| | 3 | 0.87 | 1.25 | 2.55 | 2.58 | 2.62 | | | | |
| | 4 | 1.04 | 1.25 | 2.55 | 2.58 | 2.64 | | | | |
| | Avg | 1.00 | 1.25 | 2.55 | 2.58 | 2.63 | 2.70 | .0576 | 0.47 | 0.57 |
| 310 | 1 | 1.30 | 1.50 | 2.58 | 2 61 | 2.67 | | | | |
| | 2 | 1.26 | 1.30 | 2.58 | 2.61 | 2 67 | | | | |
| | 3 | 1.10 | 1 40 | 2.58 | 2.61 | 2.67 | | | | |
| | 4 | 1.21 | 1.40 | 2.58 | 2.61 | 2.67 | | | | |
| | Avg | 1 22 | 1 40 | 2.58 | 2.61 | 2.67 | 2.75 | .0674 | 0 50 | 0 57 |
| 312 | 1 | 0.63 | 0.71 | 2.66 | 2.68 | 2.72 | | | | |
| | 2 | 0 60 | 0 75 | 2 66 | 2 68 | 2.71 | | | | |
| | 3 | 0.58 | 0.69 | 2.67 | 2.69 | 2.71 | | | | |
| | 4 | 0.59 | 0.66 | 2.67 | 2.68 | 2.71 | | | | |
| | Avg. | 0.60 | 0.70 | 2.67 | 2.68 | 2.71 | 2.77 | .0387 | 0.43 | 0.50 |

TABLE 4
FINE-AGGREGATE PHYSICAL PROPERTIES

| Agg. No | Percent Absorption at 24 hr. | Bulk Sp. Gr (Dry) | Bulk Sp Gr (SSD) | Apparent Sp Gr. | Fineness Modulus |
|---|---|---|---|---|---|
| 299 | 0.88 | 2 65 | 2 67 | 2.77 | 2 66 |
| 308 | 0 94 | 2 60 | 2.62 | 2.66 | 3.10 |
| 309 | 1 27 | 2.59 | 2.62 | 2.68 | 2.82 |
| 310 | 1.61 | 2.68 | 2.72 | 2 80 | 2.96 |
| 312 | 1.27 | 2.72 | 2.75 | 2.81 | 2.82 |

TABLE 5
PETROGRAPHIC ANALYSIS OF FINE-AGGREGATE PARTICLES IN PERCENTAGE OF TOTAL PARTICLES

| Particle Types | | Cleavage | Fine Aggregate Number | | | | |
|---|---|---|---|---|---|---|---|
| | | | 308 | 299 | 312 | 310 | 309 |
| | | *deg.* | | | | | |
| Isotropic | *n* above 1.544 | 90 | | | | | |
| | | 60–120 | tr. | | | | |
| | | None | | 1 | tr. | | tr. |
| | *n* below 1 544 | 90 | | | tr. | tr. | |
| | | 60–120 | | | | | |
| | | None | | 2 | 6 | | |
| Non-Isotropic | *n* above 1.544 | 90 | tr. | 8 | | 6 | 1 |
| | | 60–120 | 1 | 1 | | 3 | tr. |
| | | None | 16 | 16 | | 9 | 10 |
| | *n* above & below 1.544 | 90 | tr. | 4 | 4 | tr. | tr. |
| | | 60–120 | | | | | 1 |
| | | None | 5 | 7 | 14 | tr. | 4 |
| | *n* below 1 544 | 90 | 4 | | 7 | 3 | 1 |
| | | 60–120 | tr. | 6 | | 2 | 2 |
| | | None | 9 | 18 | 32 | 12 | 9 |
| Quartz | | | 56 | 21 | 24 | 47 | 58 |
| Feldspar | | | 4 | 10 | 4 | 14 | 13 |
| Hornblende | | | tr. | 2 | | 2 | |
| Opaque | | | 5 | 4 | 9 | 2 | 1 |

TABLE 6
CONCRETE MIX DATA

| Batch No. | Aggregate | | Cement Factor | Air Content | Water Cement Ratio | Slump | Unit Weight |
|---|---|---|---|---|---|---|---|
| | Coarse | Fine | | | | | |
| | | | *Sk. per cu. yd.* | % | | *in.* | *pcf.* |
| 21 | 303 | 303 | 4.88 | 2.3 | 0.71 | 3 | 142.3 |
| 22 | 299 | 299 | 5 00 | 5.1 | 0 55 | ¼ | 142.0 |
| 23 | 299 | 299 | 5.00 | 3 3 | 0.60 | 2 | 142.4 |
| 24 | 303[a] | 303 | 4.91 | 1 6 | 0 65 | ¼ | 144.1 |
| 25 | 303[a] | 303 | 4.54 | 3 0 | 0.75 | 7 | 140.9 |
| 26 | 299[a] | 299 | 4.92 | 3.9 | 0.63 | 3 | 140.9 |
| 27 | 299[a] | 299 | 4.89 | 4.3 | 0.63 | 3 | 140.1 |
| 28 | 299 | 299 | 4.96 | 3.6 | 0.63 | 2 | 142 1 |
| 29 | 303[a] | 303 | 4.92 | 2 6 | 0.70 | 2¼ | 141.5 |
| 30 | 307 | 299 | 5.00 | 4 0 | 0.68 | 3½ | 141.9 |
| 31 | 307[a] | 299 | 4.96 | 4.3 | 0.68 | 4 | 141.3 |
| 32 | 307[a] | 299 | 4.98 | 3.5 | 0.68 | 5 | 141.8 |
| 33 | 307 | 299 | 4.99 | 4.1 | 0 68 | 4 | 142.0 |
| 34 | 308 | 308 | 5.00 | 3.7 | 0.65 | 6 | 142.2 |
| 35 | 308 | 308 | 5.00 | 3.9 | 0.63 | 3 | 142.8 |
| 36 | 308[a] | 308 | 4.98 | 3.9 | 0.63 | 3 | 142.2 |
| 37 | 308[a] | 308 | 4.96 | 4.0 | 0.63 | 3 | 141 8 |
| 38 | 299 | 299 | 4.96 | 3.5 | 0 60 | 1½ | 141.8 |
| 39 | 299 | 299 | 4 97 | 3.7 | 0.63 | 6 | 140.7 |
| 40 | 309 | 309 | 4 96 | 3 9 | 0 63 | 2¾ | 140 2 |
| 41 | 309 | 309 | 4 97 | 3.7 | 0 63 | 1 | 142.2 |
| 42 | 309[a] | 309 | 4 96 | 4 0 | 0 63 | 1½ | 142.2 |
| 43 | 309[a] | 309 | 4 87 | 4 0 | 0.65 | 2 | 139.6 |
| 44 | 310 | 310 | 4.74 | 3.7 | 0.64 | 2¾ | 141.4 |
| 45 | 303[a] | 303 | 4.84 | 3.8 | 0.70 | 7 | 139.4 |
| 46 | 303 | 299 | 4.88 | 3.9 | 0.68 | 2½ | 139 3 |
| 47 | 303 | 299 | 4.89 | 3.7 | 0.68 | 5 | 139 3 |
| 48 | 310 | 310 | 4 85 | 4.9 | 0.65 | 7 | 138.3 |
| 49 | 310[a] | 310 | 4 89 | 3.9 | 0.63 | 3 | 140.6 |
| 50 | 310[a] | 310 | 4 97 | 2.9 | 0.63 | 1½ | 142.8 |
| 51 | 310[a] | 310 | 4 92 | 3 9 | 0.65 | 3½ | 140 3 |
| 52 | 312 | 312 | 4 87 | 4 4 | 0.70 | 4 | 140.8 |
| 53 | 312[a] | 312 | 4 88 | 4.0 | 0.70 | 6 | 141.4 |
| 54 | 312[a] | 312 | 4 87 | 3.9 | 0.70 | 7 | 141.1 |
| 55 | 312 | 312 | 4 88 | 3.5 | 0.70 | 4 | 141 3 |
| 56 | 299 | 299 | 4.91 | 4.0 | 0.64 | 3 | 140 4 |
| 57 | 299 | 299 | 3 89 | 3.9 | 0 79 | 2 | 139.3 |
| 58 | 299 | 299 | 3.95 | 4.4 | 0 80 | 3¼ | 138 8 |
| 59 | 299 | 299 | 5 00 | 3.9 | 0 64 | 2½ | 140.0 |
| 60 | 299 | 299 | 4 85 | 3.2 | 0.68 | ½ | 141.9 |
| 61 | 299 | 299 | 4 96 | 2.8 | 0.70 | 2½ | 141.6 |
| 62 | 299 | 299 | 4.96 | 2.8 | 0.70 | 5 | 141.6 |

[a] Vacuum saturated aggregate

½ to ⅜ in., 26 percent by weight
⅜ in. to No. 4, 49 percent by weight

The fine aggregates were used in their natural gradation (Table 8). It may be noted in Table 6 that each coarse aggregate was used in two mixes in a vacuum-saturated condition. This variable was incorporated in order to represent a possible "stream-wet" condition, a condition which has been shown to be critical from the standpoint of freezing-and-thawing resistance. Except where this was noted in the table, the aggregates were immersed for 24 hr. before the concrete was mixed. Appropriate corrections for free water in the aggregate were made. In every case equal parts by weight of coarse and fine aggregate were used.

The concrete was mixed by hand in batches of approximately 0.3 cu. ft. Air content was measured in a "Washington-type" air-meter. The concrete was compacted into oiled steel molds, having the dimensions noted above.

TABLE 7
CHEMICAL ANALYSES OF CEMENTS

| Cement Constituents | Percentage by Weight | | | |
|---|---|---|---|---|
| | No. 200 | No. 201 | No. 204 1265 Sp. Surf. | No 205 1375 Sp. Surf. |
| Oxide Composition | | | | |
| $SiO_2$ | 22.18 | 21 54 | 22.74 | 22 74 |
| $Al_2O_3$ | 4.37 | 5.33 | 4.61 | 4 61 |
| $Fe_2O_3$ | 4.91 | 2 53 | 3.74 | 3 74 |
| CaO | 60 80 | 63.23 | 62 57 | 62 57 |
| MgO | 0.92 | 2 97 | 2 22 | 2 22 |
| $SO_3$ | 1.69 | 1.67 | 1.56 | 1 56 |
| Ig. Loss and Insol. Res. | 3.57 | 1 37 | 2.26 | 1 37 |
| $Na_2O$ | 0.14 | 0.19 | | |
| $K_2O$ | 0.40 | 0.95 | | |
| Tot. Alk | 0.40 | 0.82 | | |
| Compound Composition | | | | |
| $C_3S$ | 37.6 | 49 33 | 41 0 | 41.0 |
| $C_2S$ | 35.3 | 24 61 | 34 3 | 34.3 |
| $C_3A$ | 3.3 | 9.83 | 5.9 | 5.9 |
| $C_4AF$ | 14.9 | 7.69 | 11.4 | 11.4 |
| $CaSO_4$ | 2 9 | 2.84 | | |

TABLE 8
SIEVE ANALYSES OF FINE AGGREGATES
Cumulative Percents Retained on Each Sieve

| Sieve Size | Fine Aggregate Number | | | | |
|---|---|---|---|---|---|
| | 299 | 308 | 309 | 310 | 312 |
| 4 | 0 | 0 | 0 | 0 | 0 |
| 8 | 8.1 | 21.0 | 15.6 | 22 2 | 15.7 |
| 16 | 22.4 | 41.0 | 27 1 | 37.7 | 35 9 |
| 30 | 49.7 | 71.6 | 52 5 | 60 1 | 59 0 |
| 50 | 88.9 | 80.1 | 88 1 | 84.5 | 80 9 |
| 100 | 96 8 | 96.0 | 98 4 | 92.0 | 90 2 |

Reference plugs for length-change determinations were molded into the ends of the specimens. After 24 hr. in a fog room, the molds were removed and measurements of length, weight in air, and weight in water were obtained. One 2- by 2⅛- by 11⅜-in. specimen was cured under water for 27 days and then tested in freezing-and-thawing. The remaining specimens were cured in the fog room for 27 days before being subjected to heating-and-cooling or wetting-and-drying.

One 3- by 2⅜- by 11⅜-in. specimen from each mix was subjected to alternating cycles of heating in an oven at 130 F. for 8 hr., followed by cooling in water at 70 F. for 16 hr. Since the temperature in the small oven used for this test varied at different levels from 110 to 150 F., care was taken to alternate the beams at different positions. Measurements of weight,

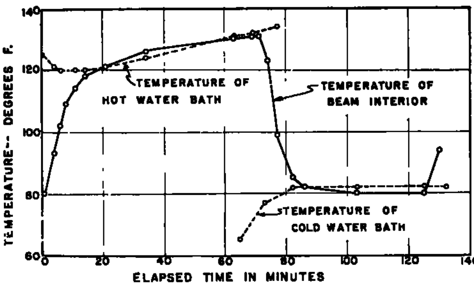


**Figure 3. Temperature curves for a typical thermal shock cycle.**

length, and dynamic modulus of elasticity were made at intervals during the cycling.

Rapid heating-and-cooling tests, designated as thermal-shock tests, were also conducted on the larger-size specimen This test consisted of repeated cycles of immersion of the specimens in a tank of hot water at 130 F. ± 10 F. for 1 hr. followed by cooling in water at 65 F. ± 10 F. The changes in temperature that occurred are indicated in Figure 3. Determinations of weight, length, and dynamic modulus of elasticity were made periodically, always after a 12- to 14-hr. period in the cooling tank.

A thermal cycle parallel to the thermal shock test was set up with automatic controls for slowly varying the temperature of a water bath from 65 F. ± 5 F. to 135 F. ± 5 F. over a period of approximately 2 hr., followed by gradual cooling to 65 F. in a period of 45 min. to 1 hr. The bath was heated by an electric

heater combined with a small flow of hot water from the building system. For the cooling cycle, the water was slowly replaced by cold tap water. Time-temperature curves for this test are shown in Figure 4. The cycles were interrupted for 8-hr. periods at intervals for determinations of length, weight, and dynamic modulus of elasticity.

For the freezing and thawing tests, the equipment and procedures were the same as those described in reference (*28*).

Other specimens were placed in outdoor storage for eventual comparison with natural weathering, and still others were stored continuously in water at 100 F.

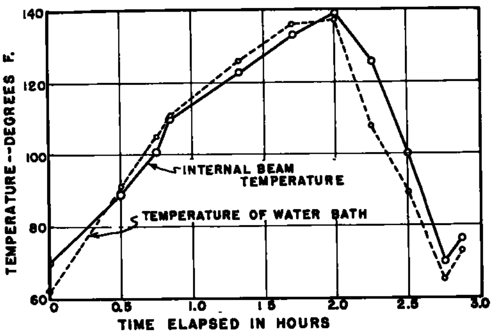


**Figure 4. Temperature curves for a typical slow-heating-and-cooling cycle.**

To evaluate reactivity with cement alkalies, 1- by 1- by 11⅝-in. mortar bars were made with the fine aggregates and cements 200 and 201. Cement and fine aggregate were combined in the ratio of 1 to 2.125 by weight. The water was varied to maintain a flow of 100 to 115 percent. The aggregates were used in the grading shown in Table 8, except for No. 310; the fine aggregate was crushed from No. 310 coarse aggregate and recombined to a grading consisting of 20 percent of material between each of the following sieves: No. 4, 8, 16, 30, 50, and 100. Two separate mixes of four mortar bars each were made for each aggregate. They were cured for one day in the fog room at 70 F., followed by removal from the molds and determination of specimen lengths. Two bars from each mix were placed in covered metal containers, in which they were supported vertically above approximately one inch of water. The cans were stored in a high-humidity cabinet maintained at 100 F. ± 1 F. Length measurements were made on all bars at intervals of 1, 7, and 28 days after fabrication and at monthly intervals thereafter. Before each measurement the specimens were stored at 70 F. for 24 hr.

The remaining mortar bars from each mix were subjected to the same storage for the first 28 days, followed by a soaking, drying, soaking procedure, designated the Conrow procedure (*7*). In more detail, this procedure consisted of the following:

1. At 28 days of age, length measurements were made. The bars were then immersed in distilled water in covered metal containers, which were placed in the 130 F. oven for 7 days.
2. At 35 days, the containers were placed in the moist room for a 1-day period of cooling to 70 F.
3. Lengths were measured at 36 days, whereupon the bars were returned to the 130 F. oven and allowed to dry for 7 days.
4. The specimens were measured at 43 days, while still as near 130 F. as possible. Immediately the bars were placed in 70 F. dry storage (in a container desiccated by calcium chloride).
5. At the end of a 1-day storage period, lengths were measured and the bars were submerged in water for 12 days at 70 F.
6. On the fifty-sixth day, the bars were again measured and returned to the 100 F. high-humidity storage. Thereafter they were measured at one-month intervals.

*Results and Discussion*—The results of the accelerated weathering tests on the concrete specimens are described and compared to the characteristics of the aggregates. These results, because of a lack of repeated check tests, must be considered as tentative in nature and exploratory, in that they may best be used as guides to further research However, the data furnish insight into the significance of test methods, and corrective procedures are indicated by which the aggregates in question can be used successfully with the expectation of good field durability.

### FREEZING-AND-THAWING TESTS

The results of the freezing-and-thawing tests are summarized in Table 9. In this summary, only those specimens are reported in which the degree of saturation of the mortar was less than 0.91, in accordance with the de-

velopments described by Whiteside and Sweet (*28*). The relative resistance to freezing and thawing is represented by the durability factor, defined as:

$$DF = \frac{PN}{200}$$

where $P$ = relative dynamic modulus of elasticity in percentage of the dynamic modulus at zero cycles

$N$ = number of cycles at which $P$ reaches 70 percent, or 200 if $P$ does not reach 70 percent prior to the end of the test.

The test results for all aggregates except 299 and 312 showed excellent consistency. The specimens made with aggregate No. 299 showed severe surface scaling and deep popouts from rhyolite and porous chert particles. Durability factors averaged 56 and ranged from 38 to 85 for the specimens made with No. 200 cement. The beams with vacuum-saturated aggregate are included in this average since no apparent difference in performance was caused by this procedure. The generally lower durability of this concrete may be related to the minor amounts of these deleterious materials or to thermal compatibility factors similar to those affecting the thermal-shock tests. In connection with the latter possibility, it is pertinent that marked improvement to excellent durability was shown by the specimens in which 20 percent of the cement was replaced by fly ash. The implications of this phenomenon are discussed in some detail in the later section on the thermal shock tests. The variation in durability factor shown by different specimens made with this aggregate should be investigated further; it is possible that accidental variations in the amount of deleterious material from sample to sample could account for these variations.

Aggregate No. 303 showed excellent, consistent, performance when immersed 24 hrs. prior to incorporation in concrete; when vacuum saturated, its durability was low. These results are in accordance with the degree of saturation data for the aggregate, shown in Table 3. Since the quarry is in an elevated location, and dry, the tests with vacuum-saturated material may be interpreted as being unduly severe and not in accordance with field conditions. Performance of this material was good when used with No. 299 fine aggregate.

Concretes made with aggregate No. 307 (combined with No. 299 fine aggregate), 308, and 310, all showed excellent resistance to freezing and thawing. The specimens in which No. 309 was incorporated in a vacuum-saturated condition gave the lowest durability factors, 25 and 20, while those with immersed aggregate were durable. The sandstone and chert in this material, when saturated, were probably the major factors contributing to this performance. The concrete with No. 312 aggregate showed inconsistent performance in that one out of four specimens showed a 29 percent loss in dynamic modulus in only 135 cycles while the remainder resisted 200 cycles with 19 percent loss or less. The extreme alkali reactivity of this material (discussed later) may be related to this result although a low-

TABLE 9
SUMMARY OF FREEZING-AND-THAWING TEST RESULTS

| Aggregate | | Specimen | No of Cycles | Percentage Loss in E | Durability Factor |
|---|---|---|---|---|---|
| Coarse | Fine | | | | |
| 299 | 299 | 22 D | 107 | 29 | 38 |
| 299 | 299 | 23 G | 110 | 27 | 40 |
| 299 | 299 | 28 G | 200 | 20 | 80 |
| 299[a] | 299 | 26 J | 119 | 34 | 39 |
| 299[a] | 299 | 27 D | 200 | 15 | 85 |
| 299 | 299 | 38 I[b] | 200 | 0 | 100 |
| 299 | 299 | 39 H[b] | 200 | 0 | 100 |
| 303 | 303 | 1 A3[c] | 291 | 8 | 97 |
| 303 | 303 | 2 A3[c] | 204 | 8 | 92 |
| 303 | 303 | 1 A4[c] | 203 | 5 | 95 |
| 303 | 303 | 1 A5[c] | 327 | 0 | 100 |
| 303[a] | 303 | 25 F | 97 | 34 | 32 |
| 303[a] | 303 | 45 F | 170 | 30 | 60 |
| 303 | 299 | 46 C | 200 | 4 | 96 |
| 303 | 299 | 47 F | 200 | 1 | 99 |
| 307 | 299 | 30 H | 200 | 1 | 99 |
| 307 | 299 | 33 H | 200 | 2 | 98 |
| 307[a] | 299 | 31 F | 200 | 4 | 96 |
| 307[a] | 299 | 32 H | 200 | 7 | 93 |
| 308 | 308 | 34 D | 200 | 0 | 100 |
| 308 | 308 | 35 F | 200 | 5 | 95 |
| 308[a] | 308 | 37 D | 200 | 0 | 100 |
| 309 | 309 | 40 F | 200 | 0 | 100 |
| 309 | 309 | 41 G | 200 | 17 | 83 |
| 309[a] | 309 | 42 F | 75 | 33 | 25 |
| 309[a] | 309 | 43 F | 60 | 33 | 20 |
| 310 | 310 | 44 H | 200 | 0 | 100 |
| 310 | 310 | 48 F | 200 | 0 | 100 |
| 310 | 310 | 48 F | 200 | 0 | 100 |
| 310[a] | 310 | 49 F | 200 | 0 | 100 |
| 310[a] | 310 | 50 F | 200 | 5 | 95 |
| 310[a] | 310 | 51 E | 200 | 3 | 97 |
| 312 | 312 | 52 H | 200 | 7 | 93 |
| 312 | 312 | 55 D | 135 | 29 | 48 |
| 312[a] | 312 | 53 G | 200 | 6 | 94 |
| 312[a] | 312 | 54 H | 200 | 19 | 81 |

[a] Vacuum saturated aggregate.
[b] Contains 20 percent fly ash as cement replacement
[c] From reference (*28*).

alkali cement was used in the freezing-and-thawing-test specimens.

WETTING-AND-DRYING TESTS

Resistance of the concrete to alternate drying in air at 130 F. and wetting in water at 70 F. is compared in terms of the expansion resulting from this treatment. Average expansions for concrete made with different aggregates are shown in Figure 5. Although the number of cycles is not sufficient to compare these data with criteria established by others (*20*), well-established trends can be observed from the graphs and definite separation of the performance of different aggregates has occurred. The specimens made with No. 299 ag-

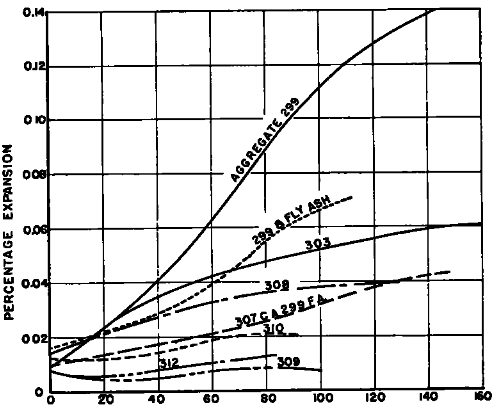


**Figure 5. Effect of wetting and drying on concrete made with different aggregates.**

gregate were consistently and markedly affected by this test in comparison with all other materials. Replacement of the low-alkali cement with fly ash (20 percent) was partially effective in reducing expansion, especially in the early part of the test. However, this improvement is indicated as being inadequate, in comparison with the other materials' performance.

Slight cracking occurred in all of the specimens made with No. 299 aggregate. The cracks were delineated by thin, dark-colored stains in a pattern closely resembling that shown by the less durable specimens in the thermal-shock tests (illustrated in a later section). However, exuded material was lacking, or so slight that no further analysis was undertaken.

THERMAL-SHOCK TESTS

A summary of the changes in length caused by the rapid heating-and-cooling cycles or thermal-shock tests is shown in Figure 6. Four of the aggregates expanded 0.08 percent or more in 350 cycles, with No. 299 being markedly less resistant to this treatment. Even those specimens with low expansion showed evidence of pattern cracking in 350 cycles, although the appearance of this cracking was usually a function of the expansion. The outlines of the cracks were accentuated by exudations of a white solid substance, generally either $CaCO_3$ or a high-sulfate calcium sulfoaluminate. Pattern cracking in a specimen containing No. 299 aggregate is shown in Figures 7 and 8. This is the typical crack pattern found in all beams having poor durability in the thermal shock test. This illustration also shows the interconnection of major cracks on the various faces and suggests that the cracking is not just a surface condition but must extend for a relatively great distance into the beams. The following observations were made regarding this condition:

1. The finished face was the one surface least affected by the extensive pattern cracking, while the plane formed by the bottom of the mold was the location of the first evident pattern cracks. This same surface was also the plane having the most dense crack systems when pattern exudation was taking place on the other surfaces. In beams not appreciably affected by the test, the finished surface was generally the only one exhibiting exudation of the white compound. The form of this type of deposition was unique in that, instead of forming pattern lines, the exudations appeared as small blobs of white matter scattered at random on the finished face. Only in the cases of the poorest performing beams in the thermal shock test did major pattern cracking appear on the finished faces.

2. Cracks seemed to form at the corners of the beams and progress into the various faces.

3. On all beams, exudations appeared at the points of weakness of the beams, at superficial cracks formed while making the beams, at the intersection of length plugs and the cement paste, and at small air-void depressions at the formed faces.

4. When the beams which were badly cracked were broken in the modulus of rupture

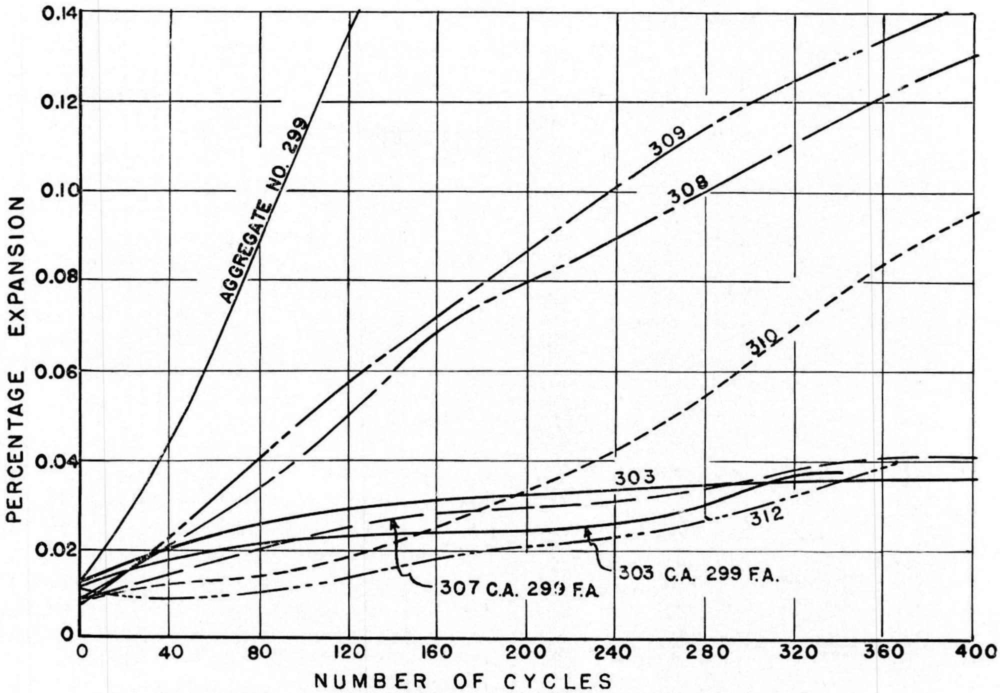


Figure 6. Effect of thermal shock cycles on concrete made with different aggregates.

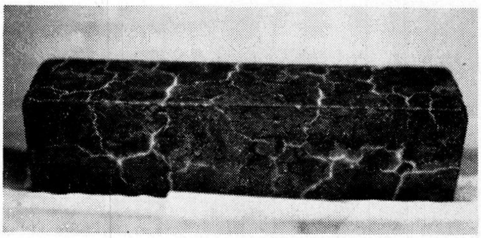

Figure 7. Pattern cracking of Beam 23B after 120 thermal shock cycles.

Figure 8. End view of Beam 23B showing length plug exudation and radial cracking after 120 thermal shock cycles.

test, the rupture produced in the tension face followed the lines of exudation. After the broken beams were dried, the silicic materials around which a break occurred were frosted with small crystals which were generally found to be either $CaCO_3$ or the high-sulfate calcium sulfoaluminate. If the break line in the compression face happened to depart from the exudation line, there was decidedly less frosting of the aggregate particles. Examination showed that the cracking caused by the calcite or calcium sulfoaluminate "wedges" extended almost completely through the smaller direction of the $11\frac{3}{8}$- by $2\frac{3}{8}$- by 3-in. beams.

5. The extreme amount of crystalline coating, after testing, present on the aggregates which were relatively free of any such contamination before being placed in the concrete indicated that crystalline formation occurred while thermal shock procedures were being

conducted. Heavy deposits of exudate on length plugs never before used in concrete, and a study of the aggregate and length plug casts similar to that described by Terzaghi (*25*) bear out this contention.

TABLE 10
MICROSCOPIC ANALYSIS OF THERMAL-SHOCK EXUDATE

| Beam Series | Aggregate | Cement | Exudate Description |
|---|---|---|---|
| 23 | No 299 | No. 200 | $CaCO_3$ in slight amounts Calcium-sulfoaluminate of the high-sulfate type (CSA) in majority. |
| 22 | No 299 | No. 200 | Slight amounts of $CaCO_3$ and mostly CSA |
| 60 | No. 299 | No 204 | Slight amounts of $CaCO_3$ and mostly CSA. |
| 61 | No. 299 | No. 205 | Slight amounts of $CaCO_3$ and mostly CSA. |
| 62 | No. 299 | No 201 | CSA with some indication of the low-sulfate type of calcium sulfoaluminate. |
| 32 | No 307 No 299 | No. 200 | CSA with equal amounts of calcite. |
| 29 | No. 303 | No. 200 | Calcite |
| 37 | No. 308 | No. 200 | CSA with some calcite and small amounts of unidentified material |
| 40 | No. 309 | No. 200 | CSA with unidentified isotropic material. |
| 46 | No. 303 No. 299 | No. 200 | Calcite with small amounts of CSA. |
| 50 | No. 310 | No. 200 | Principally CSA with little calcite. |
| 54 | No. 312 | No. 200 | $CaCO_3$ with some material, possibly sodium aluminosilicate. |
| 39 | No. 299 | No. 200 | $CaCO_3$ and CSA in small amounts with some isotropic sodium aluminosilicate. |

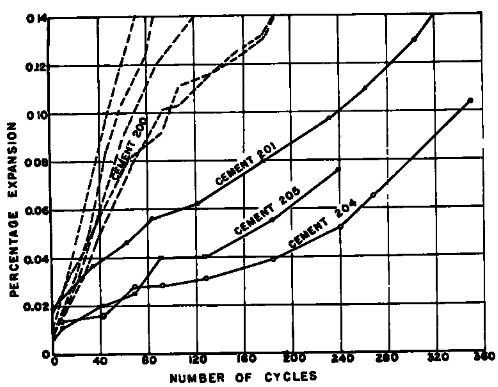


**Figure 9. Thermal shock expansion of concrete made with Aggregate 299 and different cements.**

6. The exuded and crystallized materials were analyzed microscopically with the results shown in Table 10. No precise evaluation was made of the amount of each material present but the table shows the relative quantities of calcite, calcium sulfoaluminate, or isotropic material (possibly sodium aluminosilicate).

The cracking and expansion which occurred in the thermal-shock test has been found by a number of investigators (*8*, *9*, *12*, *18*). It is usually considered to be a function of the thermal properties of the materials, resulting in differential expansions which tend to disrupt the surrounding mortar or paste. However, it has not been established that the rapid rate of temperature change represents a duplication or even an acceleration of natural-weathering conditions. This point is discussed in connection with the slow-heating-and-cooling-test results in the next section. It is also not established as to whether the deposits on the aggregates and cracks are significant in contributing to the growth and disintegration or are merely incidental to the effects caused by other factors.

Exploratory tests toward answering this question included use of different cements, Figure 9, and of admixtures, Figure 10, all combined with No. 299 aggregate. In Figure 9, curves are shown for the expansion resulting in specimens from five different mixes made with No. 299 aggregate and No. 200 cement. These are consistently greater than the expansion occurring in specimens made with the same aggregate but with three other cements. Causes for these differences can only be speculated on at present, but the following possibilities might be listed:

1. The apparent differences may be only chance variations and not significant.

2. The thermal properties of the paste, due to the different cements, may have been sufficiently different to cause the performance shown.

3. The coarseness of cements 204 and 205 may have delayed release of calcium and magnesium compounds.

4. The high-alkali cement, No. 201, might retard the formation of calcium compounds by keeping them out of solution since, according to Mellor (*15*), "The solubility of calcium hydroxide is greatly reduced in the presence of alkali hydroxides, so much so . . . that calcium hydroxide is not soluble in alkaline lye, and is precipitated from solution by the alkali hydroxides."

Similar possibilities might be suggested as causes for the differences in expansion resulting

when admixtures were combined with No. 200 cement. Further investigation is required for evaluation of these possibilities.

The effect of extended curing before subjection to the thermal shock test is shown in Figure 11. The specimens with No. 299 aggregate which were cured for 147 and 182 instead of 28 days showed a lower initial expansion but a high rate later; the net effect was not markedly different. The mixes made with a cement factor of 4 sacks per cu. yd. also showed low initial expansion as indicated in Figure 11.

Typical dynamic modulus of elasticity curves are given in Figure 12. The curves for beams 27A and 34A show the tendencies of the specimens least durable in the test. Almost no decrease in dynamic modulus was evident until the beams were damaged to an extreme extent by pattern cracking. The gain in modulus of the specimen containing fly ash is noteworthy, indicating the pozzolanic reaction occurring after 28 days of curing.

In an attempt to determine the interrelation of thermal-shock action with the effects of freezing-and-thawing testing, Beam 23H was cycled in the thermal-shock test until signs of distress were evident and then placed in the freezing-and-thawing test. The dynamic modulus of elasticity curve is shown in Figure 13, along with the curve for the companion specimen, No. 23B, which was tested in freezing and thawing only (*21*). It is considered that the actual quality of the concrete had deteriorated in the thermal shock test although not indicated by the dynamic modulus. However, ice crystallization in the cracks immediately affected the modulus.

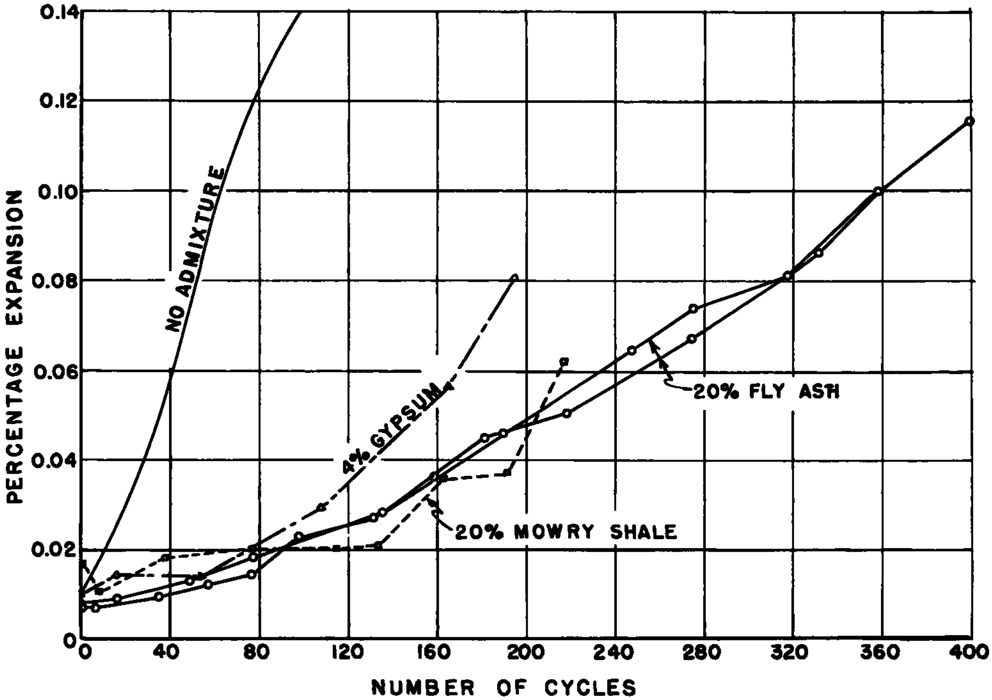

**Figure 10. Effect of admixtures on thermal shock expansion of concrete made with No. 299 aggregate.**

The major results of the thermal-shock tests may be summarized as follows:

1. Marked differences in expansion occurred with the different aggregates tested, high expansions being accompanied by severe pattern cracking and deposition of calcium carbonate and calcium sulphoaluminate.

2. In the case of the least-resistant aggregate, different expansion rates appeared to result when different cements or lower cement factors were used.

3. The four aggregates which were most

affected by the test also showed distress in field performance; however, this is considered inadequate as evidence of correlation of the test with field conditions. The content of siliceous material (quartz, quartzite, granite, feldspar, sandstone, and chert) for the three aggregates most severely affected was 86 to 90 percent; the fourth aggregate contained 68 percent.

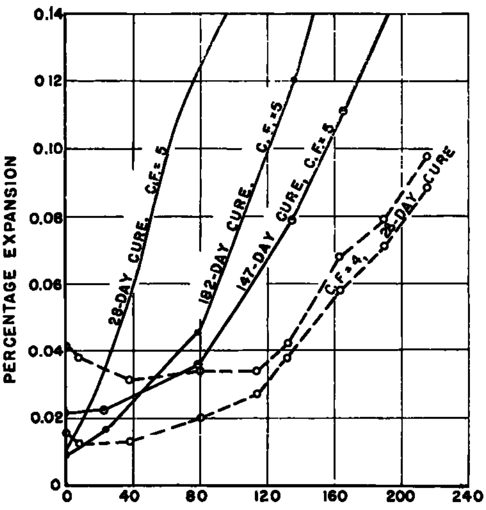


Figure 11. Thermal shock expansion of concrete with No. 299 aggregate with different cement factors and different curing periods.

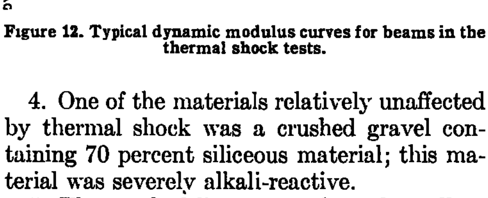


Figure 12. Typical dynamic modulus curves for beams in the thermal shock tests.

4. One of the materials relatively unaffected by thermal shock was a crushed gravel containing 70 percent siliceous material; this material was severely alkali-reactive.

5. The crushed limestones showed excellent resistance to thermal shock, either with natural sand or with crushed limestone fines.

6. The causes for these differences in performance are unestablished. Stresses and fractures due to differential thermal properties of the coarse aggregate appear to be the most probable cause for the cracking and expansion; possible related factors would include deposition of calcium compounds combined with the density and permeability of the aggregate and the physical and chemical properties of the aggregate surfaces as influencing the precipitation of migrating solutions.

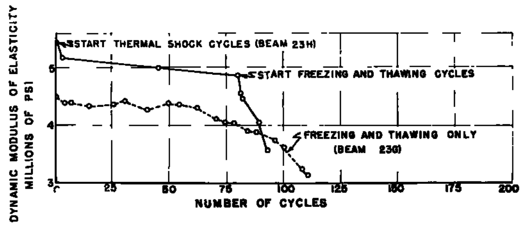


Figure 13. Effect of freezing and thawing on concrete initially subjected to thermal shock (Aggregate 299).

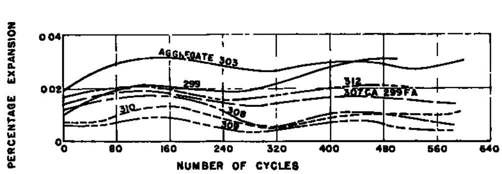


Figure 14. Expansion of concrete subjected to slow heating and cooling tests.

## SLOW HEATING-AND-COOLING TESTS

Length changes occurring when concrete specimens were subjected to slow temperature change are shown in Figure 14. Expansions and differences between different concretes appear to be negligible up to 600 cycles (approximately twice the number of cycles at which severe deterioration occurred in the thermal-shock tests). Slight exudations occurred around the length reference plugs and on the formed faces in nodular form, but no cracking appeared.

The major difference between this test and the thermal-shock procedure was a rate of temperature change of 38 F. per hr. compared to an initial rate of 200 F. per hr. in the thermal shock test. It is therefore most probable that the differences in reactions to the treatments are based on characteristics relating to these rates. Such characteristics would include the factors of thermal diffusivity and plastic adjustment of the paste. There is another possibility that the constantly changing water in the automatic heating-and-cooling equipment would cause more leaching of soluble compounds than occurred in the thermal shock apparatus, where the water was changed only once a week. This possibility is being investi-

gated although it seems unlikely in view of the results reported by Mullen (*18*) who observed the same effects arising from difference in rate of temperature change.

MORTAR-BAR ALKALI-REACTION TESTS

The expansions of mortar bars made with the various fine aggregates and with No. 201 high-alkali cement are plotted in Figure 15. The data indicate extreme alkali reactivity for

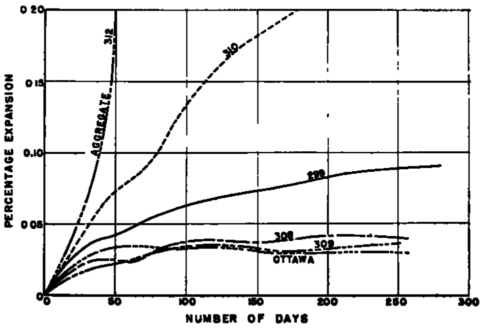


**Figure 15. Expansion of mortar bars made with different aggregates and high-alkali cement (100 F. storage).**

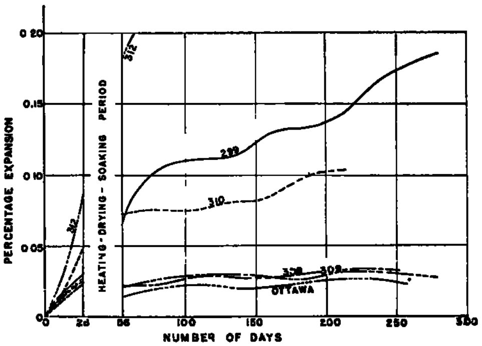


**Figure 16. Expansion of mortar bars made with different aggregates and subjected to Conrow procedure (high-alkali cement).**

aggregates 312 and 310 and sufficient reactivity in aggregate No. 299 to classify it as deleterious. Materials No. 308 and 309 appear to be nonreactive. The expansion of bars subjected to the Conrow procedure of heating-drying-soaking is shown in Figure 16. Because of the extreme length changes occurring during the heating and drying periods, only the changes during the first 28 days of moist storage and during the moist storage following the 56 days are shown. The same three aggregates are indicated as being reactive, although this procedure relatively accelerated the expansion of No. 299 and decreased the expansion of No. 310. This might be interpreted as reflecting the combination of alkali reactivity with the susceptibility of aggregate No. 299 to the thermal-shock and wetting-and-drying tests.

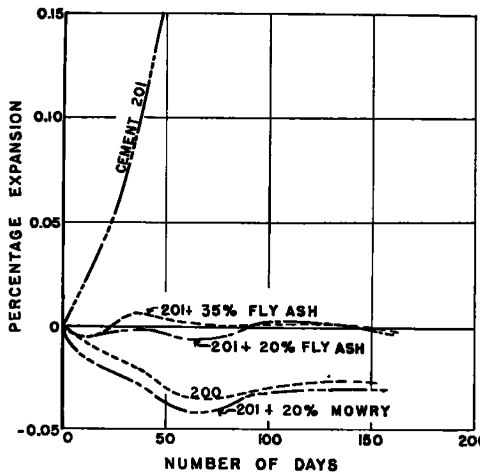


**Figure 17. Expansion of mortar bars made with Aggregate 312 and different cements and admixtures (100 F. storage).**

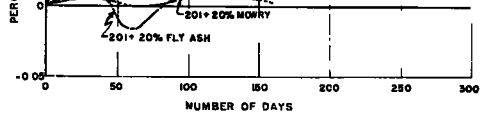


**Figure 18. Expansion of mortar bars made with Aggregate 299 and different cements and admixtures (100 F. storage.)**

Mortar-bar tests of materials No. 299 and No. 312 were also conducted with low-alkali cement (No. 200) and with combinations of high-alkali cement and pozzolanic materials. Expansions of these bars are shown in Figures 17 and 18. Either the use of low-alkali cement (less than 0.60 percent $Na_2O$ equivalent) or the fly ash or Mowry shale pozzolans is indicated as being a corrective for the alkali reactivity of these two aggregates.

CONCLUSIONS

1. Materials No. 303 and 307 with excellent service records showed excellent performance in the freezing-and-thawing, wetting-and-drying, thermal-shock, and slow-heating-and-cooling tests. Their use with No. 299 fine aggregate and a low-alkali cement is indicated as being durable for future construction.

2. Aggregate No. 312 was extremely reactive with a high-alkali cement although highly resistant to the other weathering tests in which low-alkali cement was used. Its resistance, in concrete, to freezing and thawing was inconsistent although generally good. Since its very bad service record is indicated as being caused by reaction with cement alkalies, future construction specifications with this material should require cement with less than 0.60 percent total alkali or pozzolanic admixtures.

3. Aggregate No. 299, with a consistently bad service record, was indicated to be alkali reactive and nondurable in freezing-and-thawing, wetting-and-drying, and thermal-shock tests. Considerable improvement was evidenced in concrete containing a pozzolanic replacement for the cement, but utilization of the coarse aggregate from this source is questionable even with low-alkali cement and pozzolan until the significance of wetting-and-drying tests and of thermal-shock is better understood.

4. Aggregate No. 310 was also reactive with high-alkali cement, somewhat susceptible to thermal shock but highly resistant to freezing and thawing and wetting and drying. Precautions against alkali-reaction should be taken in future construction with this material.

5. Aggregate No. 309 showed low resistance to freezing and thawing when the aggregate was vacuum saturated. Its performance was also poor in the thermal-shock test but good in wetting-and-drying and alkali-reaction tests. These data, together with the type of cracking observed in the field, indicate freezing and thawing of concrete containing saturated aggregate as being the cause of poor field performance. The use of stream-wet aggregate should be avoided in future construction.

6. Aggregate No. 308 showed excellent performance in all tests except the thermal-shock test. Its inconsistent field performance may be said to be unaccounted for except for the possible significance of the thermal-shock test.

7. In concrete made with four of the aggregates, alternations in temperature between 70 F. and 130 F. caused rapid expansion and cracking, accompanied by deposition of calcium carbonate and calcium sulphoaluminate in the cracks, when the rate of temperature change was 200 F. per hr. but had no effect when the rate was approximately 40 F. per hr. This difference in performance casts doubt on the validity of such tests, where temperature change rates are high, as being representative of accelerated natural weathering.

ACKNOWLEDGMENTS

The assistance of the Ideal Cement Company through a grant of a Charles Boettcher Fellowship is gratefully acknowledged. G. C. Wilsnack of that organization helped in formulating the working plan and reviewed the manuscript. The authors also wish to express their appreciation to Dr. H. G. Fisk, director of the Wyoming Natural Resources Research Institute, for his assistance in the microscopic analyses. The freezing-and-thawing tests of concrete were conducted by R. J. Schulke as a part of a thesis program, and R. V. Gomme assisted in the petrographic analyses. The Wyoming Highway Department, through I. E. Russell, chief materials engineer, supplied the aggregate samples.

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