THERMAL EXPANSION OF CONCRETE AGGREGATE MATERIALS

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ABSTRACT

As a part of a study of the properties of concrete aggregates, thermal-expansion determinations were made on 123 specimens of aggregate materials by the optical interferometer method over the temperature range $-20°$ to $+60°$ C. Additional measurements were made on crystals of calcite, quartz, and feldspar. The thermal expansivities of most aggregate materials are close to or within the range of expansivities of hardened portland cements. Certain exceptions are pointed out. Crystal orientation, rock texture, and composition are discussed with regard to their effects on the relation of the thermal expansion of aggregates to the durability of concrete.

CONTENTS

I. INTRODUCTION

In concrete structures, where resistance to frost action is one of the properties required of the concrete, the thermal expansivity of the aggregate may be an important factor. If, for instance, the thermal expansion of an aggregate differs considerably from that of the cementitious matrix, a potential incompatability exists, which may result in excessive internal stresses if the concrete is subjected to large temperature changes. Pearson [1][1] and also Hornibrook [2]

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[1] Figures in brackets indicate the literature references at the end of this paper.

have described concrete failures attributed to an initial weakening of the concrete because of differences between the thermal expansion of the aggregates (which had unusually low coefficients of thermal expansion) and that of the matrix. The weakened concrete then became susceptible to frost action, which caused the actual disruption. This sequence of disintegration has recently been demonstrated in the laboratory by Pearson [3].

Adequate information is lacking on the thermal expansion characteristics of commercial concrete aggregates. Accordingly, as a part of a general study at this Bureau of the properties of aggregate materials, commercial aggregates from a number of sources were obtained and separated into fractions representing the various rocks and minerals constituting the aggregates. Coefficients of linear thermal expansion were then determined for the rocks and minerals over the temperature range of $-20°$ to $+60°$ C ($-4°$ to $+140°$F). This paper gives a petrographic description of the various rock and mineral fractions of the aggregates, the respective thermal-expansion coefficients of these materials, and a discussion of the factors which may effect the thermal expansion in relation to concrete.

Some problems encountered during the present investigation warrant further study, and additional thermal-expansion measurements should be made on certain of the aggregate materials herein considered. Due to the pressure of the wartime emergency, however, these studies cannot be continued at this time.

II. PREVIOUS WORK

Griffith [4] has made thermal-expansion measurements on a considerable number of rocks from room temperature to 500° F; he also made some measurements between 32° F and room temperature. Willis and De Reus [5] measured the thermal expansion of wet and dry specimens of chert, quartzite, sandstone, basalt, granite, limestone, and dolomite between 37° and 140° F. Koenitzer [6] measured the expansion of marble and calcite between $-25°$ and $+212°$ F. Souder and Hidnert [7] have made thermal-expansion measurements on marble and have shown that permanent changes occur with succeeding temperature cycles. (A comparison of some of these results with those of the present investigation will be given later.) Davis [8] and others [5, 6, and 9] have measured the thermal expansion of hardened portland cements, mortars, and concretes under various conditions. They have shown the effects of such factors as water saturation, extreme drying, steaming, richness of mix, and age on the thermal expansion.

An examination of the available data shows that there is very little information regarding the thermal dilation of the aggregate materials within the temperature range of natural weather conditions. The majority of investigators, furthermore, have assumed a more or less straight-line relationship between temperature and thermal expansion, without regard to possible irregularities during the large intervals between readings. Although the expansion of various materials, when plotted against temperature, usually yield smooth curves, it will be shown that there are some glaring exceptions. In this investigation, therefore, the length changes of the aggregate materials have been followed continuously from $-25°$ to $+65°$ C and from $+65°$ to $-5°$ C.

III. TEST METHOD

1. APPARATUS AND CALIBRATION

(a) GENERAL DESCRIPTION

The interferometer method described by Merritt [10] and modified by Saunders [11] was used in conjunction with a thermal chamber that could be varied continuously between −25° and +65° C. This permitted the use of small specimens, the measurement of low expansivities, and the taking of frequent observations separated by small temperature intervals. The thermal chamber (fig. 1) consisted essentially of a closed brass cylinder, about 9 in. high and 3 in. in diameter, inserted through the top of a remodeled household refrigerator into a tank of kerosine which surrounded the freezing coils. A hard-rubber tube wound with 30 ft. of No. 24 Nichrome resistance wire served as
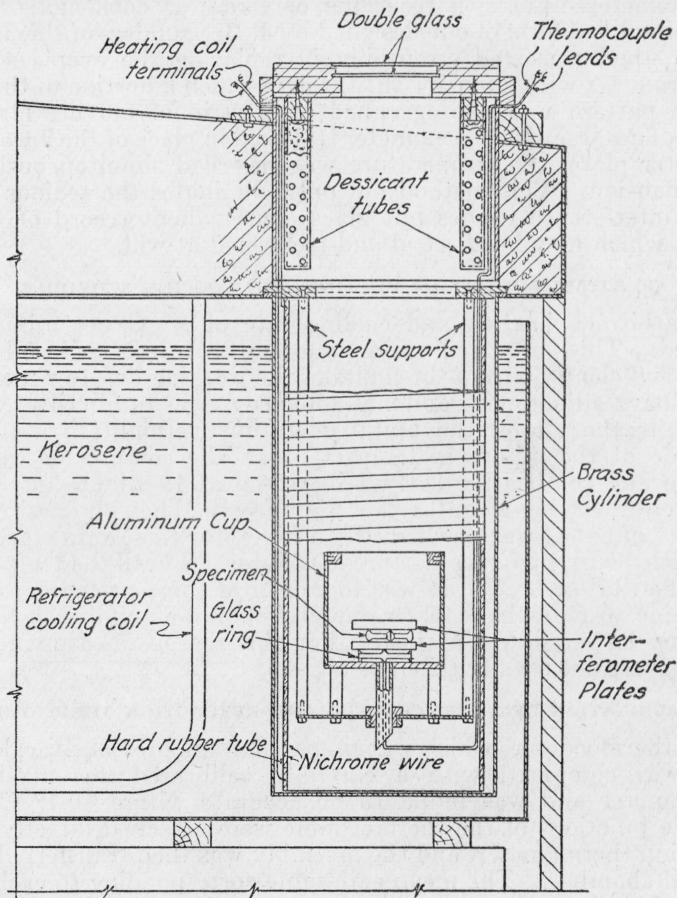
Vertical Section

FIGURE 1.—*Schematic diagram of thermal chamber.*

the heating element. The specimen and interferometer plates were supported from the top of the cylinder by ¼-in. steel rods. The top was closed by means of a plastic lid fitted with a double glass window. Perforated brass tubes were filled with absorbent cotton, which served as a desiccant. These tubes were removable and were dried at 105° to 110° C before each test. The lower interferometer plate was separated from the bottom of the aluminum specimen cup by means of a glass ring cut from a piece of tubing and ground in such a way that there were three equidistant bearing surfaces on the top and three on the bottom.

About half of the expansion measurements were made by the visual method. The temperatures were measured by means of a three-junction copper-constantan thermocouple [12], the variable junctions of which were situated just beneath the lower interferometer plate. The emf of the thermocouple was measured by means of a portable potentiometer. Later, a recording camera was constructed, which was a simplified form of one designed by J. B. Saunders of this Bureau. This method consisted essentially in replacing the eyepiece of the interferometer with a narrow slit through which a portion of the interference pattern was photographed on a strip of moving film. By means of a refraction thermometer [13] used in place of the lower interferometer plate, the temperature was recorded simultaneously with the expansion. This method not only eliminates the tedious counting of interference fringes but gives a permanent record of the behavior, which may be checked and rechecked at will.

(b) ESTABLISHMENT OF HEATING AND COOLING SCHEDULE

An arbitrary heating and cooling rate of ½° C per minute was adopted. This permitted a complete temperature cycle in 6 hours, a period sufficiently within the limits of the working day to permit such preliminary adjustments and maintenance as was ordinarily required. By leaving the refrigerating unit in operation overnight, the start could be made at the minimum temperature. The compressor was then stopped and the heating current increased at 15-minute intervals in increments varying from 0.1 to 0.2 ampere. When the desired temperature of 65° C was reached, the refrigerator was again started and the heating current decreased at regular intervals until the temperature had fallen below 0° C. It was found, after some preliminary trials, that below 0° C further cooling was so slow that a uniform cooling rate could no longer be maintained. For this reason, measurements on cooling were not usually taken below −5° C.

(c) CALIBRATION OF THERMOCOUPLE AND REFRACTION THERMOMETER

The thermocouple, which was prepared from previously calibrated wire, was compared with a carefully calibrated mercury-in-glass thermometer and was found to be accurate within ±0.1° C. The variable junctions of the thermocouple were attached directly to the refraction thermometer, and the assembly was then transferred to the thermal chamber. The mean emf value corresponding to each interference fringe was determined by heating and cooling through several temperature cycles, according to schedule, and recording the emf for the passage of each fringe across the reference mark of the thermometer. The accuracy of the temperatures, as measured by this refraction thermometer, was found to be within ±0.2° C.

(d) DETERMINATION OF TEMPERATURE LAG IN TEST SPECIMEN

The actual temperature of the specimen, for a given thermocouple reading, was determined by means of a small quartz refraction thermometer placed between the interferometer plates and separated from them by small grains of sand. The temperature reading of the thermometer was found to lag several degrees behind that of the thermocouple when heating or cooling. As this thermometer had about the same mass as that of the specimens to be measured, the assumption was made that the temperature lag would be about the same in each case. Several temperature cycles were made according to the current-time schedule previously adopted, and emf-temperature curves were drawn from the data obtained. These curves were used to determine the temperatures under actual operating conditions. When measurements were made with the recording apparatus the temperature of the specimen was assumed to be the same as that of the refraction thermometer.

2. PREPARATION OF SPECIMENS

The majority of the specimens were taken from gravel ranging from ¾ in to 1½ in. in diameter. A few were taken from larger pieces of stone, and in some cases specimens were cut from material less than ½ in. in diameter. Figure 2 (a, b, c, d, e, and f) shows, schematically, the successive steps in the preparation of a test specimen. Slabs (a), ranging in thickness from 0.2 in. to 0.4 in., were cut from each specimen, and triangular pieces (b), having sides of about ¾ in., were cut

(a)   (b)

(c)   (d)
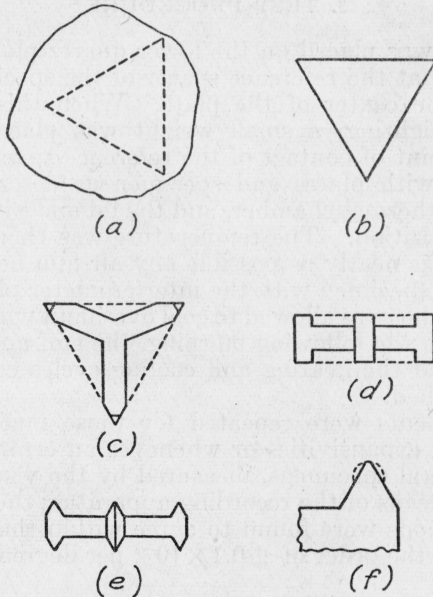
(e)   (f)

FIGURE 2.—*Schematic diagrams to show successive steps in the preparation of a test specimen.*

(a) Original flat slab marked for further cutting; (b) triangular slab; (c) arms cut from triangular slab leaving a Y-shaped specimen; (d) side view of (c) after grinding it to form the spacers; (e) points cut on spacers; (f) enlarged part of one spacer, showing rounding of its point.

from the slabs. The sides of the triangular-shaped pieces were prepared by grinding on a small silicon carbide wheel to leave a Y-shaped specimen (c) having one arm slightly longer than the others. Portions of the top and bottom of each arm were then ground to form two small projections (d), these two projections forming a spacer. The spacers were pointed as shown (e), care being taken that the top point of each spacer was vertically above lower contact point. By means of a micrometer gage and an emery stone, the heights of the spacers were equalized to within 0.001 in. The projections were slightly rounded (f) by rubbing on a very fine emery stone. The spacers of the finished specimens were about 0.25 in. in height.

The nearly completed specimen was placed between interferometer plates and examined through a viewing instrument. The interference pattern observed usually consisted of very narrow fringes, and a slight pressure on the upper plate caused these fringes to move toward the tallest spacer of the specimen [10]. The heights of the spacers were adjusted by grinding them carefully until the fringes were of the desired width and the tallest spacer was on the longest arm [11]. The tips of the spacers were usually polished sufficiently in the process to show the points of contact with the upper interferometer plate as tiny spots surrounded by Newton rings, and the point on the longest arm was used as a reference point for counting the fringes. When this point could not be seen, a small grain of sand or a piece of fine wire was placed directly over the estimated point of contact for reference. The finished specimen was placed in a desiccator containing calcium chloride for several days before testing.

3. TEST PROCEDURE

The specimen was placed on the lower quartz plate and the upper plate placed so that the reference spacer of the specimen was as near as possible to the center of the plate. When this did not permit sufficient overweighting, a small weight was placed on the upper plate near the point of contact of the reference spacer with the plate [11]. The cup, with plates and specimen as described above, was lowered into the thermal chamber, and the lid and viewing instrument were placed in position. The temperature was then raised to about 65° C to remove as nearly as possible any air film between the points of contact of the specimen with the interferometer plates, after which the thermal chamber was allowed to cool overnight with the refrigerator in operation. On the following morning, the emf and fringe readings were recorded and the heating and cooling cycles carried through as previously described.

The measurements were repeated for those materials which displayed abnormal expansivities or whenever an error in the data was suspected. Several specimens, measured by the visual method, were remeasured by means of the recording apparatus; the results obtained for the two methods were found to agree within the limits of experimental error (on the order of $\pm 0.1 \times 10^{-6}$ per degree centigrade).

4. RELIABILITY OF RESULTS

In order to test the performance of the apparatus and the accuracy of the calibrations, samples of known thermal expansion were obtained from the Thermal Expansion Section of this Bureau and were tested in the manner described. A comparison of the results obtained is as follows:

Sample	Temperature interval	Coefficient of linear thermal expansion per degree centigrade	
		Hidnert [a]	Johnson
P	°C 20 to 60	29.0×10^{-6}	29.1×10^{-6}
Q	−20 to 0	11.0×10^{-6}	11.0×10^{-6}
Q	0 to 20	11.3×10^{-6}	11.3×10^{-6}
Q	20 to 60	12.1×10^{-6}	12.1×10^{-6}
R	20 to 60	0.38×10^{-6}	0.4×10^{-6}

[a] Peter Hidnert, Thermal Expansion Section, National Bureau of Standards

IV. DESCRIPTION OF MATERIALS TESTED

Commercial aggregates from 26 different sources were divided into various rock and mineral fractions (table 1). Specimens of these rocks and minerals and of some related materials, whose thermal expansion behaviors are reported in the present study, were examined with a petrographic microscope. The results of these examinations, together with designations of source, classification, and texture, are shown in table 2. The mineral compositions were determined by microscopic study of thin sections and the relative amounts or percentages of each mineral were estimated without a quantitative microscopic count. The percentage values given in table 2 are, therefore, approximations. The naming, or classification, of the rocks has followed common geologic and petrographic usage.

Under the heading of texture (table 2), noncrystalline materials are described as amorphous or glassy; specimens cut from single crystals are so indicated; and the grain size is given for minerals or rocks composed of many particles or crystals. The grain-size terminology refers to actual sizes in millimeters as follows:

Very fine-grained_____ Less than 0.02.
Fine-grained_____ 0.02 to 0.2.
Medium-grained_____ 0.2 to 2.0.
Coarse-grained_____ 2.0 to 10.0.
Very coarse-grained_____ Over 10.0.

For rocks of porphyritic texture (most of the rocks between specimens 75 and 94), the grain size in the groundmass is given first and is followed by the grain size of the larger crystals, or so-called phenocrysts. Similarly, with breccias (some of the rocks between specimens 95 and 104), the grain sizes of both the groundmass and of the larger fragments are given.

TABLE 1.—*Approximate percentages of rock and mineral fractions in various commercial concrete aggregates*

Designations	Source of aggregate	Chert	Quartz pebbles	Unclassified sandstones	Limonitic and hematitic sandstones	Clayey, chloritic, and micaceous sandstones	Arkosic and feldspathic sandstones	Limestone	Dolomite	Quartzites [a]	Granite	Other granitic rocks [b]	Felsites: dacite, andesite, trachyte	Basalt	Volcanic breccia	Argillite	Phyllite	Schists and gneisses	Greenstone	Miscellaneous rock types
A	Buck Dam, Va.																100			
B	Potomac River, Md.-Va.	11	30	15	8	7				[h]39	2							3		
C	Silver Hill, Md.	17	50	15	1					17										
D	Pt. Jefferson, N. Y.		80							7	5							8		
E	Lyon Mt., N. Y.											60		35						5
F	Norwood, N. Y.								100											
G	Jordanville, N. Y.							100												
H	N. LeRoy, N. Y.	[c]20						80												
I	Mille Roche, Canada							100												
J	North Central Ohio	[c]95						5												
K	Camden, Tenn.	100																		
L	Cumberland River, Tenn.	100																		
M	Estill Springs, Tenn.	100																		
N-1	Kentucky Dam area, Tenn, bank gravel	99		1																
N-2	Kentucky Dam area, Tenn. river gravel	99		1																
O	Tishomingo, Miss.	100																		
P	Winn Parish, La.							100												
Q	Elgin, Ill.	4								[g]92								4		
R	Bethany Falls, Mo.							100												
S	St. Louis Co., Mo.							100												
T	Reading, Mo.	95								5										
U	Kimball, Nebr.							[e]4		[j]90		2						4		
V	Bill Williams, Ariz.		7				2			2	41	10		17				19		2
W	Paso Robles, Calif.							[f]100												
X	Kutras, Calif.	[d]6				25	17					8	7	4	5			4	18	[k]6
Y	Cowlitz River, Wash.						13					3	59		21			4		
Z	Spokane, Wash.									[i]49		19			32			4		

ᵃ Includes ferruginous, chloritic, feldspathic, micaceous, and calcareous quartzites.
ᵇ Includes syenite (Lyon Mt.), monzonite, granodiorite, diorite, and gabbro.
ᶜ Calcareous chert.
ᵈ Micaceous chert.
ᵉ Soft, sandy limestone.
ᶠ Opaline dolomitic limestone.
ᵍ Includes 6% of sandy limonitic dolomite.
ʰ Includes 18% of pure siliceous quartzites.
ⁱ Includes some siliceous limestone.
ʲ Occurs as gravel; about half of the pebbles are separate quartz or feldspar fragments.
ᵏ Includes 5% of serpentine.

TABLE 2.—*Description, source, thermal-expansion coefficients, texture, and mineral composition of all materials tested*

Specimen number	Description	Source	Designation in table 1	Mean coefficient of linear thermal expansion per degree $C \times 10^6$			Texture [a]	Mineral constituents [b] (in decreasing order of abundance; percentages approximate only)	
				−20° to +60°	0° to +60°	+60° to 0°		Major, more than 3 percent	Minor, less than 3 percent
1	Quartz (measured perpendicular to c-axis).	Minas Geraes, Brazil		13.5	14.0	13.5	Single crystal	Quartz	
2	Quartz (measured parallel to c-axis).	___do___		7.4	7.7	7.7	___do___	Same crystal as specimen 1	
3	Quartz, pale yellow	Potomac River gravel, Md-. Va.	B	12.9	13.1	13.5	Coarse and fine	Quartz	Trace of limonite.
4	___do___	___do___	B	12.7	12.8	13.5	___do___	___do___	Do.
5	Quartz, milky	Port Jefferson gravel, Long Island, N. Y.	D	13.5	13.8	13.8	Coarse	___do___	
6	Quartz, pale yellow	___do___	D	11.8	11.8	12.0	___do___	___do___	Do.
7	Quartz, colorless	___do___	D	11.7	12.8	12.4	___do___	___do___	Traces of kaolin, limonite.
8	Quartzite, light-colored	Potomac River gravel, Md.-Va.	B	11.3	12.0	12.9	Medium	Quartz 99%	Traces of kaolin, limonite.
9	Quartzite, brown	___do___	B	10.3	10.4	10.9	___do___	___do___	Limonite; trace of kaolin.
10	Quartzite, tan-gray	___do___	B	11.9	12.1	12.7	___do___	Quartz 95%, goethite 4%	Limonite.
11	Quartzite, greenish-gray	___do___	B	10.7	11.1	11.1	Fine	Quartz 94%, chlorite 5%	Chalc.; trace mica, limo.
12	Quartzite, feldspathic	Port Jefferson gravel, Long Island, N. Y.	D	7.0	7.5	7.5	Medium	Quartz 90%, feldspar, biotite.	
13	___do___	___do___	D	12.2	12.5	12.8		Quartz, feldspar, biotite	
14	Quartzite, light-colored	Spokane gravel, Irvin, Wash	Z	7.6	7.9	8.4	Fine	Quartz 93%, sericite 3%	Musc. 2%, calcite 2%, plagioclase.
15	Quartzite, micaceous	___do___	Z	9.0	8.7	9.8	___do___	Quartz 65%, sericite 25%, biotite 10%.	Trace of titanite, leucoxene.
16	Quartzite, calcareous micaceous.	___do___	Z	9.5	9.3	9.8	___do___	Quartz 55%, cal. 25%, groundmass of microq. and sericite 20%.	Musc. 2%, pc.; traces of titanite and leucoxene.
17	Sandstone, hematitic	Potomac River gravel, Md.-Va.	B	7.5	1.5	9.4	___do___	Quartz 94%, hematite 3%	Mica 3%; traces pc., limo., py.
18	Sandstone, limonitic	___do___	B	9.4	8.7	10.4	___do___	Quartz 94%, limo. and goethite 5%.	Chalc.; traces of mica, feldspar titanite.
19	___do___	___do___	B	8.5	7.0	10.2	___do___	Quartz 96%, limo. and goethite 3%.	Chalc.; traces of mica, feldspar, zircon.
20	___do___	___do___	B	10.1	9.5	10.9	___do___	Quartz 92%, limo. and goethite (clayey and carb.) 8%.	Mica; traces chalc., feldspar, titanite, zircon.
21	Sandstone, chloritic	___do___	B	10.4	10.3	11.0	___do___	Quartz 80%, sericite 10%, chlorite 6%.	Limo., musc. 2%, bio.; traces of chalc., feldspar, titanite.

See footnotes at end of table.

TABLE 2.—*Description, source, thermal-expansion coefficients, texture, and mineral composition of all materials tested*—Continued.

Specimen number	Description	Source	Designation in table 1	Mean coefficient of linear thermal expansion per degree C x 10⁶			Texture [a]	Mineral constituents [b] (in decreasing order of abundance; percentages approximate only)	
				−20° to +60°	0° to +60°	+60° to 0°		Major, more than 3 percent	Minor, less than 3 percent
22	Sandstone, calcareous feldspathic.	Bill Williams gravel (Parker Dam), Ariz.	V	5.1	5.0	5.7	Medium	Feldspar and quartz cemented by cal.; sericite, hema.	Microcline, limo., mt.
23	Sandstone, cherty micaceous	Kutras gravel (Shasta Dam), Calif.	X	6.4	5.0	9.7	Fine	Microq., sericite, quartz, kaolin.	Graphitic matter, limo., mica, chlorite.
24	Sandstone, feldspathic	do	X	4.4	2.4	6.3	do	Microq., feldspar (or., ab.), titanite.	Chlorite; traces leucoxene, limo., hema.
25	do	Cowlitz River gravel, Wash.	Y	4.8	3.5	6.7	Medium	Feldspar 60%, quartz 35%	Mica 3%, chlorite 2%, sericite.
26	do	do	Y	6.8	6.5	8.1	Fine	Microq., feldspar, quartz, sericite, chlorite or antigorite, graphite.	Altered mica; trace of iron oxides.
27	do	Kutras gravel (Shasta Dam), Calif.	X	7.9	7.4	9.1	Medium	Quartz, feldspar, microq	Mica, chlorite, epidote.
28	Chalcedony	Serra do Mar, Brazil		13.8	13.8	14.2	Fine	Fibrous quartz	
29	Flint chat	Lead-zinc mine area, Mo		11.4	11.4	12.0	Very fine	Microq., chalcedony	Trace of limonite.
30	Chert, brown	Potomac River gravel, Md.-Va.	B	11.2	11.4	11.4	Very fine to fine	Microq. 65%, chalc. 35%	Limonite 1%, trace of quartz.
31	Chert, white	do	B	10.7	10.7	11.0	Very fine	Microq., chalcedony	(Rhombic holes.)
32	Chert, gray	Silver Hill gravel, Md	C	11.3	11.6	11.6	Very fine to fine	Microq. 65%, quartz 35%	
33	Chert, tan	do	C	11.2	11.4	11.6	Very fine	Microcrystalline quartz	Chalcedony, (rhombic holes).
34	Chert, brown	Reading gravel, Mo	T	11.4	11.6	11.6	Very fine to fine	Microq., quartz	Limonite, (porous).
35	do	do	T	10.9	10.8	11.4	Very fine	do	Limonite.
36	Chert, light gray	Reading gravel, Mo	T	11.5	11.7	11.9	Very fine	Microq., chalcedony	
37	Chert, brown	do	T	11.8	12.1	12.0	do	Microq., quartz	Limonite, (porous).
38	Chert, white	Tishomingo gravel, Miss	O	11.0	11.2	11.4	do	Microq., (various shaped holes).	Quartz.
39	Chert, light gray	do	O	11.0	10.9	11.4	do	Microq., chalc., (rhombic holes).	Quartz veinlets.
40	Chert, brown	do	O	11.0	11.0	11.4	Very fine, variable	Microq., (rhombic holes), quartz	Limo., goethite; trace chalc.
41	Chert, light-colored	Bank gravel, Kentucky Dam area, Tenn.	N-1	11.4	11.4	11.9	do	Microcrystalline quartz	(Rhombic holes), quartz.
42	Chert, oolitic	River gravel, Kentucky Dam area, Tenn.	N-2	11.4	11.7	11.8	Very fine to fine, oolitic.	Microq., quartz	Calcite, limonite.
43	Chert, dark gray	Cumberland River gravel, Tenn.	L	11.9	12.4	12.4	Very fine and medium.	Chalc. 65%, microq. 35%	Cal., (rhombic holes): trace limo.
44	Chert, brown	do	L	11.7	11.9	11.9	Very fine	Chalc. 50%, microq. 50%	Limo., (rhombic holes), quartz.
45	do	Estill Springs gravel, Tenn	M	11.8	12.0	12.3	do	Microcrystalline quartz	(Rhombic holes), limo., quartz.
46	Chert, brown fossiliferous	do	M	11.4	11.8	11.5	Very fine to fine, irregular.	Quartz, microq	Calcite, limonite.

No.	Material	Source	Code				Texture	Composition	Other minerals
47	....do...........	....do....	M	11.2	11.3	11.6	....do....	....do....	Cal., limo., (rhombic holes).
48	Chert (novaculite)...........	Camden, Tenn........	K	11.4	11.6	11.8	Very fine, even..	Microq., (rhombic holes)......	Quartz.
49	Chert, calcareous...........	Quarries in North Central Ohio.	J	10.6	10.8	10.9	Very fine to fine..	Microq. 85%, calcite 15%......	Trace of iron oxide.
50	....do...........	....do....	J	11.2	11.5	11.3	....do....	Microq. 90%, calcite 10%......	Quartz; trace of limonite.
51	Chert, calcareous buff........	....do....	J	9.3	9.3	9.4	....do....	....do....	Limonite, quartz.
52	Chert, calcareous...........	Quarry, North, Le Roy, N.Y.	H	11.9	12.6	12.3	....do....	....do....	Traces of quartz, graphitic matter.
53	Chert, micaceous...........	Kutras gravel (Shasta Dam), Calif.	X	7.3	7.2	8.1	Very fine........	Microq., sericite........	Traces of epidote, actinolite.
54	Opaline chert........	San Luis Obispo, Calif......		13.4	14.1	14.2	Amorphous........	Opal 90%, chalcedony 10%......	
55	....do...........	Paso Robles, Calif......		13.3	14.6	14.6	....do....	....do....	Trace of iron oxide.
56	Opal........	Virgin Valley, Nev......		6.3	5.8	7.9	....do....	Opal (relic diatom structures)..	
57	Microcline feldspar........	Bathurst, Ontario......		0.7	0.8	0.9	Single twinned crystal.	Perthite (microcline 90%, ab. 10%).	Quartz less than ½%.
58	Microcline feldspar (measured perpendicular to 010 cleavage face and parallel to *b*-axis).	....do....		1.1	1.4	1.3	....do....	Similar to No. 57........	
59	Microcline feldspar (measured perpendicular to No. 58).	....do....		3.5	3.3	3.2	....do....	Same crystal as No. 58........	
60	Microcline feldspar (measured perpendicular to Nos. 58 and 59 and parallel to *a*-axis).	....do....		17.1	17.3	17.3	....do....	....do....	
61	Microcline feldspar........	....do....		2.0	2.5	2.7	....do....	Similar to Nos. 57 and 58......	
62	Oligoclase feldspar........	Mitchell Co., N.C......		3.1	3.1	3.7	Single crystal........	Oligoclase feldspar 99%........	Muscovite, quartz.
63	Bytownite feldspar........	Unknown........		4.2	4.2	4.5	Coarse........	Bytownite feldspar 97%........	Chlorite, calcite, zeolites.
64	Granite........	Potomac River gravel, Md.-Va.	B	9.2	9.3	9.8	Medium........	Or., perthite, microcline, quartz, ab.	Garnet, chlorite, limo.
65	....do...........	Port Jefferson gravel, Long Island, N.Y.	D	6.0	5.8	6.8	....do....	Microcline, quartz, perthite, ab.	Sericite, biotite.
66	....do...........	Bill Williams gravel (Parker Dam), Ariz.	V	1.8	−1.7	4.6	....do....	Or., microcline, quartz, perthite, ab.	Biotite, sericite.
67	....do...........	Gravel, Kimball, Nebr.	U	7.2	6.4	8.4	Medium to coarse.	Or., oligoclase, quartz........	Musc., zoisite, sericite.
68	Quartz syenite........	Lyon Mountain, N.Y......	E	7.0	7.3	7.7	Medium........	Microcline 45%, perthite 20%, ab. 20%, quartz 10%.	Chlorite, cal., mt., augite, titanite.
69	Augite syenite........	....do....	E	5.3	5.8	6.1	....do....	Or. and perthite 65%, augite 25%, ab. 5%, mt. 5%.	Quartz, titanite.
70	Granodiorite........	Spokane gravel, Irvin, Wash.	Z	3.6	3.7	4.3	....do....	Pc. 50%, quartz 25%, or. 10%, bio. 5%, hb. 3%.	Titanite, zoisite, chlorite, and sericite, each 2%; traces of mt., apatite, cal.
71	Diorite........	....do....	Z	6.7	6.7	6.7	....do....	Amphibole (hb. and/or actinolite), pc.	Cal., zoisite, sericite, quartz, mt., titanite.
72	....do...........	Kutras gravel (Shasta Dam), Calif.	X	6.2	5.6	6.9	Medium to coarse.	Sericite, oligoclase, hb., chlorite.	Mt., zoisite, epidote, limo.
73	Diorite (altered)........	....do....	X	6.4	6.2	7.4	Medium........	Zoisite, hb. and/or actinolite..	Quartz, titanite.
74	Diorite (altered)........	Kutras gravel (Shasta Dam), Calif.	X	6.6	6.3	7.1	Medium........	Zoisite, hornblende, quartz..	

See footnotes at end of table.

TABLE 2.—*Description, source, thermal-expansion coefficients, texture, and mineral composition of all materials tested*—Continued.

Specimen number	Description	Source	Designation in table 1	Mean coefficient of linear thermal expansion per degree C×10⁶			Texture [a]	Mineral constituents [b] (in decreasing order of abundance; percentages approximate only)	
				−20° to +60°	0° to +60°	+60° to 0°		Major, more than 3 percent	Minor, less than 3 percent
75	Monzonite porphyry	Cowlitz River gravel, Wash.	Y	6.7	6.6	7.2	Medium, porphyritic.	Pc., chorite, epidote, sericite	Titanite, calcite.
76	Obsidian	Lake Co., Oreg		4.5	4.5	4.8	Glassy	Volcanic glass 99%	Feldspar laths.
77	Pitchstone	Magdalena Mts., N. M		6.8	7.0	7.3	Glassy and fine	Vol. glass 70%, feldspar, quartz 5%.	
78	Trachyte	Cowlitz River gravel, Wash.	Y	5.2	5.0	6.5	Fine, porphyritic.	Oligoclase, hb., vol. glass	Magnetite.
79	Trachyte porphyry	Kutras gravel (Shasta Dam), Calif.	X	6.5	6.7	6.4	Fine and medium, porphyritic.	Andesine, chlorite, sericite	Quartz, magnetite.
80	Dacite porphyry	Bill Williams gravel (Parker Dam), Ariz.	V	6.3	6.0	6.7	___do	Plagioclase, orthoclase, quartz	Chlorite, hematite, mt.
81	Andesite	___do	V	5.8	5.4	6.8	___do	Feldspar, sericite, hematite	Volcanic glass (much altered).
82	Andesite porphyry	___do	V	7.4	7.4	7.8	___do	Lab., vol. glass 25%, bio., augite.	Magnetite.
83	Andesite	Cowlitz River gravel, Wash.	Y	6.2	6.1	6.5	___do	Lab., hypersthene (¾ altered to uralite).	
84	___do	___do	Y	6.4	6.3	6.6	___do	Lab., uralite, epidote, augite	Do.
85	Andesite (altered)	___do	Y	6.7	6.4	7.5	___do	Pc. (much altered), chlorite, sericite, epidote, cal.	Trace of iron oxide.
86	Andesite porphyry	___do	Y	3.8	4.1	4.2	Very fine and medium, porphyritic.	Lab., hypersthene, vol. glass	Magnetite.
87	Basalt	Bill Williams gravel (Parker Dam), Ariz.	V	5.7	5.3	6.0	Fine porphyritic.	Lab., olivine (¾ altered to iddingsite), augite.	Magnetite, a zeolite.
88	Basalt, vesicular	___do	V	4.4	3.7	5.7	___do	Lab., olivine (¾ altered to iddingsite.)	Magnetite; trace of calcite.
89	Basalt porphyry	Kutras gravel (Shasta Dam), Calif.	X	6.2	5.9	6.5	Fine and medium, porphyritic.	Labradorite, augite	Magnetite, analcite (?).
90	___do	___do	X	6.2	6.0	6.6	___do	Lab., augite, zoisite	Mt., chlorite, sericite, microq.
91	Basalt	Lyon Mountain, N. Y	E	6.8	6.9	6.9	Very fine	Plagioclase laths, augite	Chlorite, magnetite.
92	___do	___do	E	7.0	7.1		___do	Same as No. 91	
93	Basalt (diabase)	___do	E	7.4	7.3	7.9	Medium	Pc. laths (⅔ altered to sericite), bio., augite, chlorite.	Antigorite (after olivine), mt., apatite, cal., limo.
94	Felsite (altered)	Gravel, Kimball, Nebr	U	6.1	5.7	6.8	Fine and medium, porphyritic.	Quartz or chalcedonic silica, feldspar.	Biotite, iron oxides.
95	Volcanic breccia	Kutras gravel (Shasta Dam), Calif.	X	6.6	5.6	7.4	Fine and medium.	(Small vol. rock fragments); feldspar, vol. glass, quartz, hema., sericite.	Calcite, chlorite.

No.	Rock	Source	Code				Texture	Composition	Accessory
96	_____do_____	Cowlitz River gravel, Wash.	Y	6.9	6.8	7.4	Very fine to fine and very coarse.	(Large vol. rock fragments); pc., epidote, actinolite, chlorite, microq.	Mt.; traces sericite, calcite.
97	_____do_____	_____do_____	Y	6.1	6.2	8.0	Very fine to medium and coarse.	Pc., quartz, chlorite, microq.	Sericite; traces mt., limo.
98	Phyllite	Buck Dam, Va.	A	6.1	0.6	10.7	Very fine	Quartz, microq. and chalc., sericite, calcite.	Micas, limo., feldspar; trace chlorite.
99	_____do_____	_____do_____	A	6.7	.1	10.7	_____do_____	Similar to No. 98.	
100	Biotite argillite	Spokane gravel, Irvin, Wash.	Z	9.5	9.6	10.5	Fine	Quartz 45%, sericite 35%, bio. 20%.	Titanite, leucoxene.
101	Sericite argillite	_____do_____	Z	9.8	9.8	10.1	_____do_____	Quartz 45%, sericite 45%, bio. (part altered to chlorite) 10%.	Musc.; traces py, graphitic matter.
102	Greenstone breccia	Cowlitz River gravel, Wash.	Y	5.1	5.4	5.8	Very fine to fine and coarse.	Actinolite, microq., feldspar (altered).	Titanite, sericite, chlorite, mt.
103	_____do_____	Kutras gravel (Shasta Dam), Calif.	X	6.6	6.6	7.5	Fine	Oligoclase, epidote, chlorite, sericite.	Magnetite.
104	_____do_____	_____do_____	X	8.2	7.3	8.9	Very fine and medium.	Feldspar, chlorite, epidote, sericite.	Quartz.
105	Greenstone	_____do_____	X	6.2	6.2	7.0	Fine to medium	Actinolite, quartz, epidote, feldspar.	Titanite, magnetite.
106	Serpentine	_____do_____	X	6.0	6.3	6.9	Fine	Antigorite (intersecting lamellas).	Hb. and/or olivine, py., titanite.
107	Chloritic schist	Port Jefferson gravel, Long Island, N. Y.	D	6.7	6.6	7.5	_____do_____	Quartz 75%, chlorite 15%, sericite 10%.	Magnetite, feldspar.
108	Calcite (measured parallel to c-axis).	Texas, Md		22.5	22.9	23.5	Single crystal	Calcite	
109	Calcite (measured perpendicular to c-axis).	_____do_____		−4.0	−4.8	−4.2	_____do_____	Same crystal as No. 108	
110	Calcite (measured parallel to c-axis).	Taos, N. M		25.7	26.3	26.0	Single crystal	Calcite	
111	Calcite (measured perpendicular to c-axis).	_____do_____		−5.0	−4.8	−4.8	_____do_____	Same crystal as No. 110	
112	Limestone	Mille Roche, Canada	I	3.8	4.0	4.1	Fine, variable	Calcite 95%, quartz 4%	Carbonaceous matter, pyrite.
113	_____do_____	_____do_____	I	4.1	4.3	4.0	Fine to medium, variable.	Similar to No. 112	
114	_____do_____	St. Louis Co., Mo	S	3.8	3.9	4.4	Fine to medium, variable.	Calcite, microcrystalline quartz.	Kaolin, quartz; trace py.
115	_____do_____	_____do_____	S	6.4	5.4	7.4	Fine, variable	Similar to No. 114	
116	Limestone, nodular	Bethany Falls, Mo	R	3.0	3.3	4.3	Very fine	Calcite 98%	Quartz, kaolin, mica.
117	Limestone	Winn Parish, La	P	1.0	0.8	-0.5	Fine to medium	_____do_____	Barite.
118	Limestone, banded	_____do_____	P	0.9	−.4	−.4		Calcite	Traces quartz, limo., carb.
119	Limestone	_____do_____	P	6.9	7.7	9.0	Medium to coarse	_____do_____	Trace limonite.
120	_____do_____	Jordanville, N. Y	G	4.0	4.2	4.4	Medium, variable	_____do_____	Quartz; trace carb.
121	_____do_____	_____do_____	G	4.8	5.0	5.2	_____do_____	Similar to No. 120	
122	_____do_____	_____do_____	G	9.1	9.7	9.9	_____do_____	_____do_____	
123	_____do_____	North Le Roy, N. Y	H	5.6	5.7	5.8	Fine	Calcite 99%	Traces carb., kaolin, quartz.
124	_____do_____	_____do_____	H	4.4	4.9	4.9	_____do_____	Similar to No. 123	
125	Limestone, sandy	Gravel, Kimball, Nebr	U	3.6	3.5	4.6	Fine to medium	Calcite 50%, quartz, feldspar	Opal, mica.
126	Limestone, siliceous	Spokane gravel, Irvin, Wash.	Z	9.8	10.1	10.2	Very fine	Calcite, quartz	Musc., limo., pyrite.

See footnotes at end of table.

TABLE 2.—*Description, source, thermal-expansion coefficients, texture, and mineral composition of all materials tested*—Continued

Specimen number	Description	Source	Designation in table 1	Mean coefficient of linear thermal expansion per degree Cx10^6			Texture [a]	Mineral constituents [b] (in decreasing order of abundance; percentages approximate only)	
				−20° to +60°	0° to +60°	+60° to 0°		Major, more than 3 percent	Minor, less than 3 percent
127	Limestone, siliceous dolomitic (measured parallel to bedding planes).	Paso Robles, Calif	W	8.6	9.1	9.4	.....do............	Dolomite and cal., opal 10%, chalc. 10%.	
128	Limestone, siliceous dolomitic (measured perpendicular to bedding planes).	......do............	W	9.4	9.7	10.0	.....do............	Same as No. 127............	
129	Limestone, siliceous dolomitic (measured parallel to bedding planes).	......do............	W	8.9	9.2	9.3	.....do............	Similar to No. 127............	
130	Limestone, siliceous dolomitic (measured perpendicular to bedding planes).	......do............	W	9.5	9.8	9.8	.....do............	Same as No. 129............	
131	Dolomite............	Norwood, N. Y.	F	6.6	5.9	8.1	Fine............	Dolomite 95%, quartz 5%.	Carbonaceous matter.
132	......do............		F	7.6	7.7	8.3	.....do............	Similar to No. 131............	
133	......do............	Elgin gravel, Ill	Q	8.2	8.6	8.7	.....do............	Dolomite............	Quartz.
134	......do............	......do............	Q	7.3	7.1	8.4	.....do............		Limonite.
135	......do............	......do............	Q	7.2	7.6	8.9	.....do............	Dolomite, quartz 5%............	
136	Dolomite, limonitic sandy....	......do............	Q	8.7	8.5	9.3	.....do............	Dolomite 50%, quartz 50%....	Musc., limo., feldspar.
137	Magnesite............	Muntodi, Greece		8.1	7.5	9.2	Very fine............	Magnesite, kaolin 5%............	Trace limonite.

[a] Grain size terminology designates the following approximations in millimeters:

Very fine-grained........ Less than 0.02.
Fine-grained............ 0.02 to 0.2.
Medium-grained........ 0.2 to 2.0.
Coarse-grained............ 2.0 to 10.0.
Very coarse-grained...... Over 10.0.

[b] Abbreviations used:

ab.......... albite.
bio.......... biotite.
cal.......... calcite.
carb.......... carbonaceous matter.
chalc.......... chalcedony.
hb.......... hornblende.
hema.......... hematite.
lab.......... labradorite.
limo.......... limonite.
microq......... microcrystalline quartz.
musc.......... muscovite.
mt.......... magnetite.
or.......... orthoclase feldspar.
pc.......... plagioclase feldspar.
py.......... pyrite.
vol.......... volcanic.

V. RESULTS AND DISCUSSION

The coefficients of linear thermal expansion of all materials tested are given for three different temperature ranges in table 2. Typical expansion curves of some of the materials are shown in figures 3 to 10, inclusive. Variations in these coefficients for similar rocks or minerals may be attributed to three main factors, namely, crystal orientation, composition difference, and texture.

1. EFFECT OF CRYSTAL ORIENTATION

Measurements were made on oriented crystals of calcite (fig. 3), quartz (fig. 4), and microcline feldspar (fig. 5) to illustrate the differences in thermal expansivity that occur in minerals along different crystallographic axes. These values are given in table 3, together with values reported by other investigators. It can be seen, therefore, that with such minerals the thermal-expansion measurements on individual crystals of unknown orientation are of limited value.
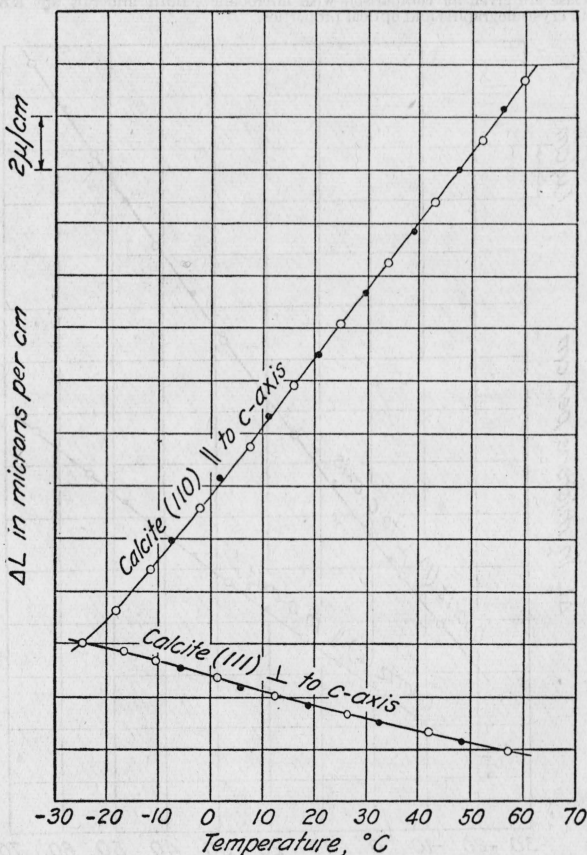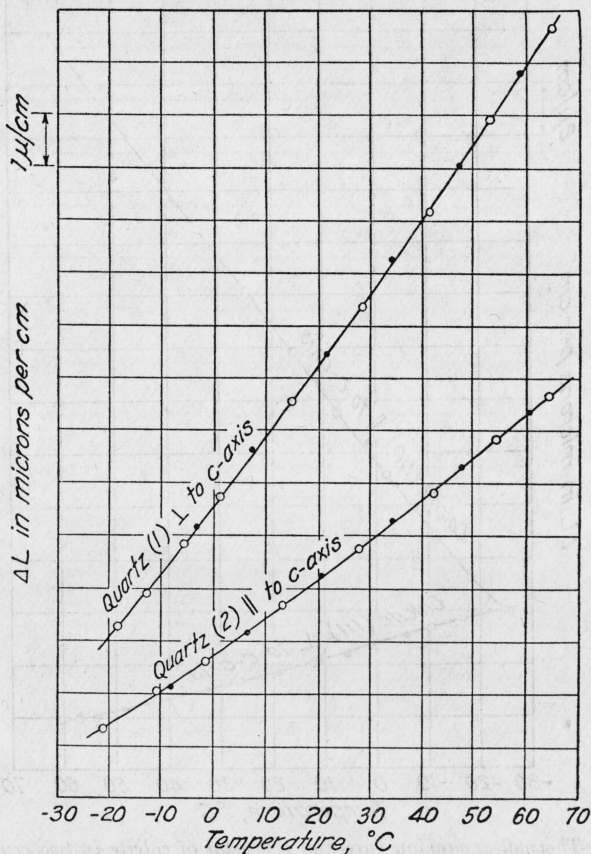

FIGURE 3.—*Thermal-expansion curves of a crystal of calcite in two crystallographic directions.*

○ Are heating points; ● are cooling points. Figures in parentheses refer to the specimen numbers in table 2.

TABLE 3.—*Mean coefficients of linear thermal expansion for oriented mineral specimens*

Specimen number	Mineral	Orientation	Temperature interval	Mean coefficient of linear thermal expansion per °C×10⁶	Investigator
			°C		
1	Quartz	Perpendicular to c-axis	0 to 60	14.0	Johnson and Parsons.
2	do	Parallel to c-axis	0 to 60	7.7	Do.
	do	Parallel to c-axis	0 to 100	8.0	Sosman [14].
	do	Perpendicular to c-axis	0 to 100	14.4	Do.
58	Microcline	Perpendicular to 010 cleavage; parallel to b-axis.	0 to 60	1.4	Johnson and Parsons.
59	do	Perpendicular to specimen 58	0 to 60	3.3	Do.
60	do	Perpendicular to specimens 58 and 59; parallel to a-axis.	0 to 60	17.3	Do.
	Orthoclase a	Parallel to b-axis	20 to 100	0.0	Kozu and Saiki [15].
	do a	Parallel to a-axis	20 to 100	15.0	Do.
110	Calcite	Parallel to c-axis	18 to 50	26.3	Johnson and Parsons.
111	do	Perpendicular to c-axis	18 to 50	−4.8	Do.
	do	Parallel to c-axis	18 to 50	25.1	Austin and coworkers [16]
	do	Perpendicular to c-axis	18 to 50	−4.9	Do.

a As no data regarding the thermal expansion of microcline are found in the literature, published coefficients for orthoclase are given for comparison with microcline. Both minerals are $KAlSi_3O_8$, but vary slightly in certain crystallographic and optical properties.

FIGURE 4.—*Thermal-expansion curves of a crystal of quartz in two crystallographic directions.*

○ Are heating points; ● are cooling points. Figures in parentheses refer to the specimen numbers in table 2.

This is illustrated by specimen 62 (table 2), oligoclase feldspar, which shows a coefficient of 3.1×10^{-6} per degree centigrade but whose orientation is unknown.

A monomineralic rock composed of many crystals with haphazard crystallographic orientations should have, in all directions, a thermal-expansion coefficient representing an average of all possible orientations of the mineral concerned. The 19 cherts, for example, which are composed almost entirely of very fine-grained quartz (specimens 30 to 48, table 2) all have nearly equal thermal-expansion coefficients, averaging 11.3×10^{-6} per degree centigrade. This value is very close to the arithmetic average of the thermal expansion of quartz in all crystallographic directions, and, therefore, is representative of the coefficient of thermal expansion of rocks composed almost entirely of quartz grains with random orientations. If, on the other hand, a rock has more of its component crystal grains oriented in one direction than in any other, the coefficient of expansion in that direction will be different from those in other directions. An example of this is the siliceous dolomitic limestone from Paso Robles, Calif. (specimens 127 to 130,
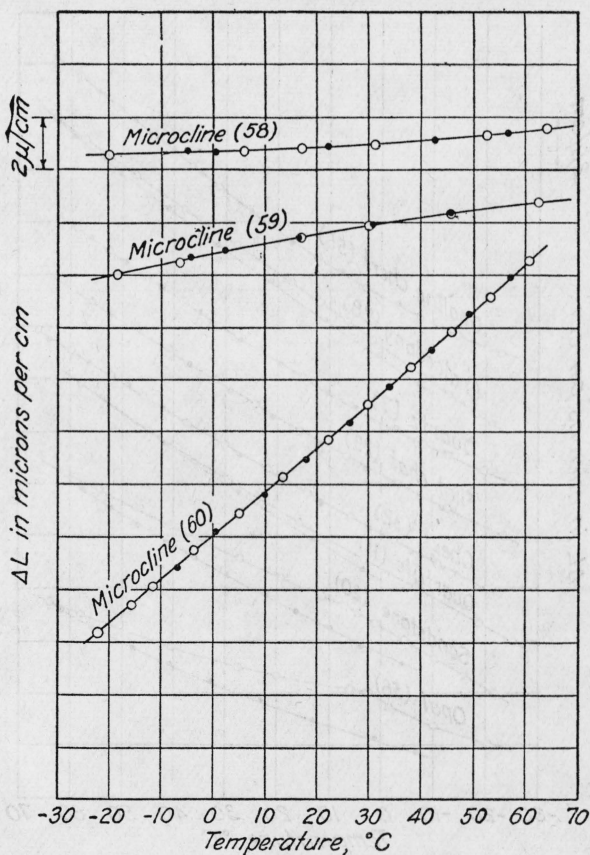
FIGURE 5.—*Thermal-expansion curves of a crystal of microcline feldspar.*

No. 58 perpendicular to 010 cleavage face and parallel to *b*-axis; No. 59, perpendicular to No. 58; No. 60, perpendicular to Nos. 58 and 59 and parallel to *a*-axis. ○ Are heating points; ● are cooling points; figures in parentheses refer to specimen numbers in table 2.

table 2), which has a coefficient of 8.7×10^{-6} parallel to its bedding planes and 9.4×10^{-6} perpendicular to its bedding planes. Another suspected example is the limestone from Jordanville, N. Y. Three specimens of this limestone taken in random directions gave coefficients of 4.0, 4.8, and 9.1×10^{-6} (Nos. 120, 121, and 122).

2. EFFECT OF COMPOSITION DIFFERENCE

Rocks from various sources but of similar composition have approximately the same expansivities, if orientation differences are disregarded. This is true for the siliceous rocks (fig. 6), the calcitic limestones (fig. 7), and the dolomites (fig. 7). As a specific example, cherts 30 to 48 (table 2), which were composed of little but silica, had notably similar coefficients ranging from 10.7 to 11.9×10^{-6}. When other minerals were present, however, as in Nos. 49 to 53, which contained varying amounts of calcite and mica (sericite), the coefficients ranged from 7.3 to 11.9×10^{-6}. Compare also sandstones 16 and 22 (fig. 8) and limestones 112 and 129 (fig. 8).
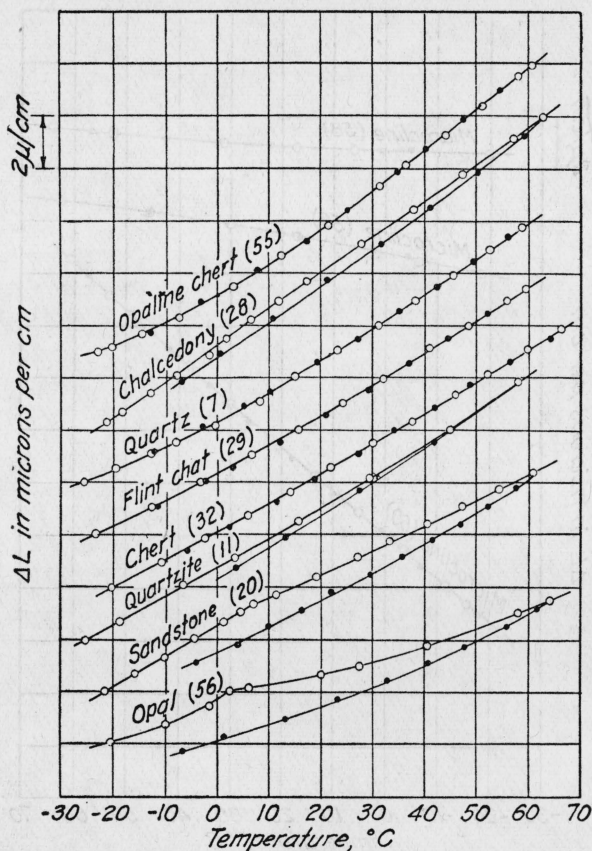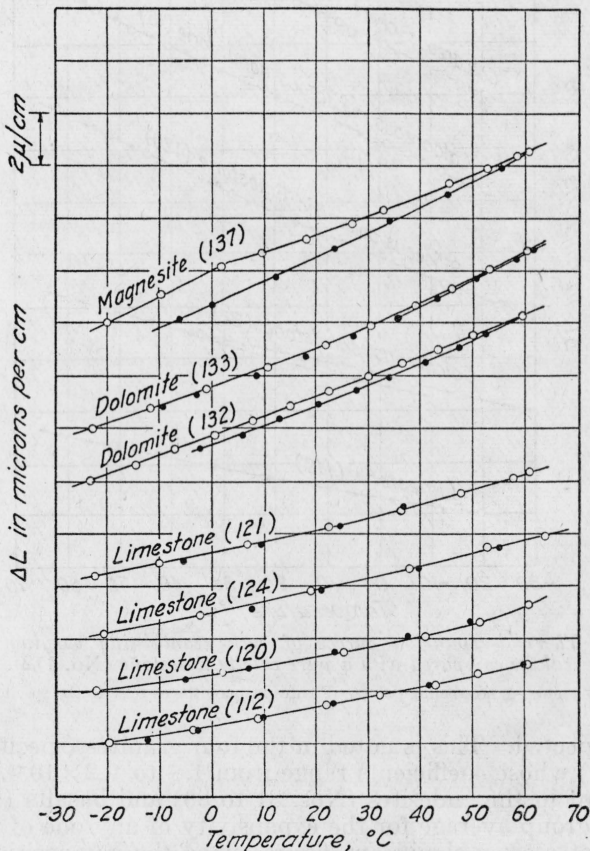

FIGURE 6.—*Thermal-expansion curves of various siliceous rocks.*

○ are heating points; ● are cooling points. Figures in parentheses refer to the specimen numbers in table 2.

3. EFFECT OF TEXTURE

The kind of texture here considered is grain size, although other textures, such as crystallinity or noncrystallinity, may have important effects on rock expansivities. The grain size is particularly important in the present method of test because of the small size of the test specimen. The average height of the latter was only about 0.25 in., and the expansion of only one spacer was measured. The total number of grains through which measurement was made is strictly a function of the grain size of the rock and, based on the terminology given in section IV, was estimated to be as follows:

For very fine-grained rocks_____ More than 300.
For fine-grained rocks_____ 30 to 300.
For medium-grained rocks_____ 3 to 30.
For coarse-grained rocks_____ 1 to 3.
For very coarse-grained rocks_____ Less than 1.

The thermal-expansion coefficient of a specimen of very fine-grained, randomly oriented rock is, therefore, an average of all possible crystal

FIGURE 7.—*Thermal-expansion curves of various carbonate rocks.*

○ Are heating points; ● are cooling points. Figures in parentheses refer to specimen numbers in table 2.

orientations of all minerals in that rock and represents the actual expansivity of the rock. The coefficient given for a coarse-grained rock, however, may actually represent the expansivity of only one crystal orientation of one mineral and accordingly, cannot be considered as a true representation of the expansivity of that entire rock.

In the igneous and volcanic rocks, which have several minerals as part of their essential compositions and a large number of possible accessory and alteration minerals, considerable variation in expansivity
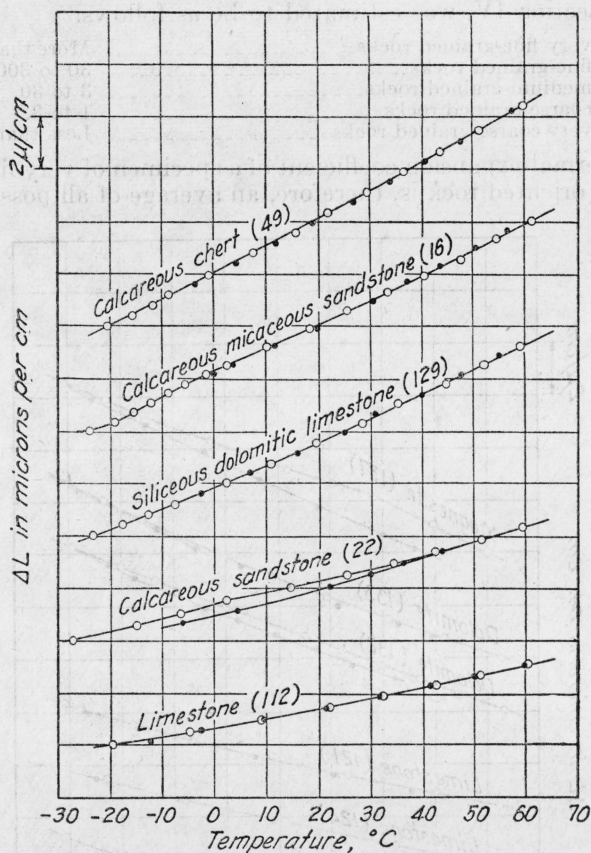
FIGURE 8.—*Thermal-expansion curves of rocks containing varying amounts of calcite compared with a pure calcite limestone* (No. 112).

○ Are heating points; ● are cooling points. Figures in parentheses refer to the specimen numbers in table 2.

is to be expected. This is noted in the four granites (specimens 64 to 67, table 2) whose coefficients range from 1.8 to 9.2×10^{-6}, and to a lesser extent in the andesites (Nos. 81 to 86) and basalts (Nos. 87 to 93). The group average for the expansivity of any one of these rock types is not a very significant figure, since the composition of such rocks is not necessarily as constant as the name suggests.

Also, different specimens of a particular mineral may differ in composition; for example, the combined water in opal varies in diff-

erent opal specimens. This may help to explain the expansivity differences (table 2 and fig. 6) between Nevada opal (No. 56, coefficient 6.3×10^{-6}) and California opaline chert (specimens 54 to 55, coefficients 13.4 and 13.3×10^{-6}).[2]

4. MATERIALS WITH IRREGULAR EXPANSION

Some materials do not expand uniformly on heating and the resulting expansion curves show more or less definite breaks in their con-
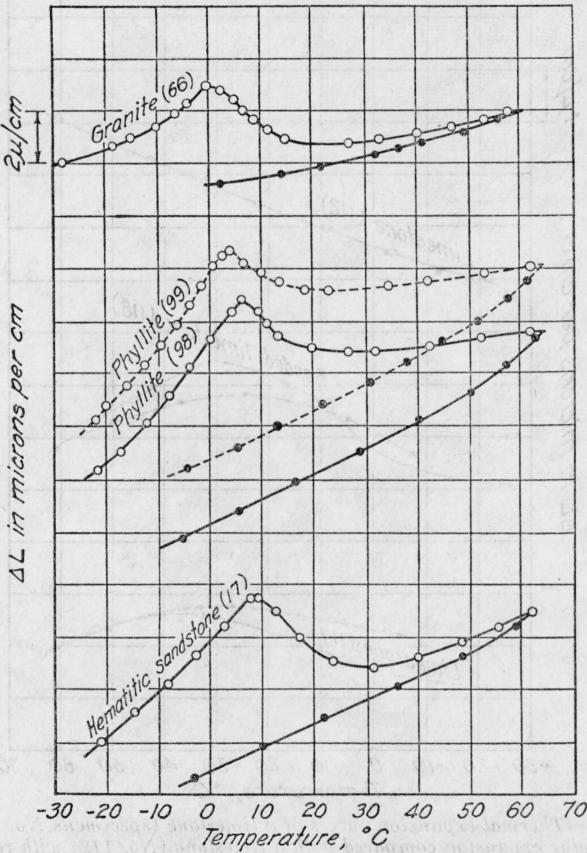

FIGURE 9.—*Thermal-expansion curves of rocks with irregular expansion.*

Nos. 98 and 99 are different specimens of the same rock sample; No. 66 was measured twice and No. 17 four times, and identical curves, respectively, were obtained each time: ○ are heating points; ● are cooling points. Figures in parentheses identify specimens in table 2.

tinuity because of a change in the rate or a change in the direction of expansion. In most of these cases the materials expand on heating until temperatures between 0° and 10° C have been reached. With further heating they either expand at a lesser rate (opal, No. 56, and sandstone 20, fig. 6) or contract (fig. 9) until temperatures between 15° and 30° C have been reached, when expansion is resumed. As a

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[2] Nevada opal showed an ignition loss at 1,300° C of 5.4 percent and the opal of the California opaline chert an ignition loss of 7.3 percent.

general rule, these irregularities are not evident on cooling. Two
specimens of a Louisiana limestone, however, were found that ex-
hibited reversals both on heating and on cooling (fig. 10). The
specimens exhibiting irregular expansion were retested with similar
results; for example, specimen 66 (fig. 9) was measured by both the
visual and the photographic methods, and specimen 17 (fig. 9) was
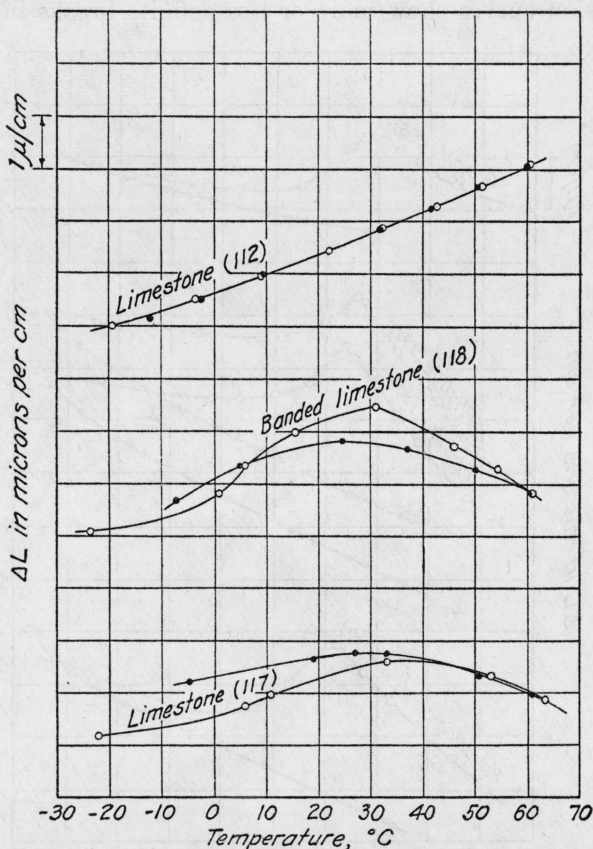tested twice by both methods. Identical curves were obtained, respec-

FIGURE 10.—*Thermal-expansion curves of a limestone (specimens No. 117 and 118)
with irregular expansion compared with a limestone (No. 112) with regular expan-
sion.*

○ are heating points; ● are cooling points. Figures in parentheses identify the specimens in table 2.

tively, for both specimens when retested. The coefficients given in
table 2 inadequately describe the thermal-expansion behavior of these
materials. For this reason, table 4 has been prepared to give the
average thermal coefficients between those points where sudden
changes in rates of expansion occurred.

It is possible that these irregularities are caused by capillary water
in the specimens. The specimens were dried for several days over
$CaCl_2$, but all water was not necessarily removed. The specimens
were held overnight at temperatures well below freezing, so that some

of the capillary water present was undoubtedly frozen. As the ice melted, two complicating factors affected the rate of expansion of the specimens, namely (1) the volume change occurring as ice melts into the corresponding smaller volume of water, and (2) the change in heating rate of the specimen as the heat of crystallization of the water is absorbed. The latter factor may help to explain the occurrence of the breaks in continuity a few degrees above 0°C. Additional

TABLE 4.—*Mean coefficients of linear thermal expansion, between points of inflection, of materials having irregular expansions*

Specimen number	Material	Temperature interval	Mean coefficient of linear thermal expansion per ° C×10⁶	Specimen number	Material	Temperature interval	Mean coefficient of linear thermal expansion per ° C×10⁶
		° C				° C	
17	Hematitic sandstone	−20 to 8	18.8	98	Phyllite	−20 to 7	23.4
17	do	8 to 30	−12.9	98	do	7 to 30	−8.4
17	do	30 to 60	6.4	98	do	30 to 60	2.4
19	Limonitic sandstone	−20 to 6	13.6	99	do	−20 to 4	24.8
19	do	6 to 17	−4.0	99	do	4 to 23	−8.0
19	do	17 to 60	9.2	99	do	23 to 60	3.3
23	Argillaceous sandstone	−20 to 15	10.5	115	Limestone	−20 to 4	9.2
23	do	15 to 60	3.2	115	do	4 to 20	2.1
				115	do	20 to 60	6.4
24	Feldspathic sandstone	−20 to 6	9.7				
24	do	6 to 26	−3.4	117	do	−20 to 35	2.3
24	do	26 to 60	4.9	117	do	35 to 60	−2.3
				117		60 to 30	−2.7
25	do	−20 to 6	9.5	117	do	30 to 0	1.6
25	do	6 to 18	−2.2				
25	do	18 to 60	3.9	118	do	−20 to 31	4.5
				118		31 to 60	−5.4
56	Opal	−20 to 2	8.5	118	do	60 to 25	−2.8
56	do	2 to 60	5.4	118	do	25 to 0	3.0
66	Granite	−20 to −1	12.5	119	do	−20 to 25	3.9
66	do	−1 to 22	−10.6	119	do	25 to 60	10.7
66	do	22 to 60	3.2				
				131	Dolomite	−20 to 4	8.2
67	do	−20 to 4	10.5	131	do	4 to 7	−1.1
67	do	4 to 15	−1.5	131	do	7 to 60	6.7
67	do	15 to 60	8.0				
				134	do	−20 to 6	7.5
95	Volcanic breccia	−20 to 7	10.1	134	do	6 to 11	−1.8
95	do	7 to 60	4.7	134	do	11 to 60	8.2
97	do	−20 to 13	5.7				
97	do	13 to 15	−4.0				
97	do	15 to 60	7.0				

study is needed on the effects of capillary water in the various materials. The irregular expansion of the limestone from Winn Parish, La., (specimens 117 and 118, table 4 and fig. 10) does not seem explainable as a water phenomenon, but no other explanation for these curves has yet been suggested.

5. COMPARISON OF PRESENT RESULTS WITH PREVIOUS WORK

The average coefficients for groups of similar rocks, as determined in the present study, are compared in table 5 with the results of other recent investigations. Not only are there variations in the average coefficients reported by the several investigators, but there are also considerable differences in values for individual specimens of the same

rock type as determined in the present investigation (see range of coefficients, table 5). Although most of the average values obtained by other investigators differ from the averages given in the present paper, they do fall within or close to the range of values obtained for individual specimens in this study. The lack of agreement may be due to differences in methods of investigations, in temperature ranges, in crystal orientations, and in mineral composition and textures of the rocks used by the various investigators.

TABLE 5.—*Mean coefficients of linear thermal expansion of similar materials determined by other investigators and compared with the results of the present study*

Material	Number of of specimens	Temperature range	Mean coefficients of linear thermal expansion per °C × 10⁶		Investigator
			Average	Range	
		°C			
Quartzite	9	−20 to +60	9.9	7.0 to 12.2	Johnson and Parsons.
Do	3	20 to 100	10.6		Griffith [4].
Do	5	0 to 60	11.7		Willis and De Reus [5].
Sandstone	11	−20 to +60	7.4	4.4 to 10.4	Johnson and Parsons.
Do	10	20 to 100	9.8		Griffith [4].
Do	ª 5	0 to 60	11.7		Willis and De Reus [5].
Chert	24	−20 to +60	11.1	7.3 to 11.9	Johnson and Parsons.
Do	1	20 to 100	11.5		Griffith [4].
Do	22	0 to 60	12.2		Willis and De Reus [5].
Granite	4	−20 to +60	6.1	1.8 to 9.2	Johnson and Parsons.
Do	17	20 to 100	7.9		Griffith [4].
Do	2	0 to 60	5.5		Willis and De Reus [5].
Other granitic rocks: syenite, diorite, monzonite.	8	−20 to +60	6.1	3.6 to 7.0	Johnson and Parsons.
Basalt	7	−20 to +60	6.2	4.4 to 7.4	Do.
Do	4	20 to 100	4.8		Griffith [4].
Do	2	0 to 60	9.4		Willis and De Reus [5].
Other felsitic rocks: andesite, dacite, trachyte.	10	−20 to +60	6.0	3.8 to 7.4	Johnson and Parsons.
Limestone	13	−20 to +60	4.4	0.9 to 9.1	Do.
Do	22	20 to 100	7.9		Griffith [4].
Do	5	0 to 20	4.6		Do.
Do	16	0 to 60	4.6		Willis and De Reus [5].
Do	5	−7 to +88	7.6		Koenitzer [6].
Marble ᵇ	2	−32 to +24	1.2		Pearson [1].
Do. ᵇ	2	24 to 100	7.8		Do.
Do	9	24 to 100	11.3		Souder and Hidnert [7].
Siliceous limestone	6	−20 to +60	8.3	3.6 to 9.8	Johnson and Parsons.
Dolomite	6	−20 to +60	7.6	6.6 to 8.7	Do.
Dolomitic marble	1	−17 to +49	3.6		Pearson [1].

ª Measurements made on water-saturated specimens.
ᵇ Same specimens.

6. AGGREGATE EXPANSIVITY IN RELATION TO CONCRETE

The coefficient of linear thermal expansion of hardened portland cement varies considerably with such factors as the kind and composition of the cement, the water-cement ratio, and the age [8]. This coefficient varies within the normal range of atmospheric temperatures between limits of approximately 11×10^{-6} and 16×10^{-6} per degree centigrade (6 and 9×10^{-6} per degree Fahrenheit), according to Davis [8], Pearson [1], and others [9]. As pointed out in the introduction, large differences in coefficients between the cementitious

material and the aggregate may lead to concrete failure where severe weather conditions are encountered.

The discussion in section V, 1 to 4, indicates four types of materials, classified according to expansivity characteristics, which might manifest themselves unfavorably in concrete. These are (a) materials having a uniform coefficient of thermal expansion markedly different from the normal value for concrete; (b) an aggregate composed of single crystal fragments with different expansivity in various crystallographic directions; (c) an aggregate (a gravel or a crushed coarse-grained rock) composed of two or more fractions which are present in considerable amounts and have widely different expansivities; and (d) a material with irregular expansion of the type illustrated in figures 9 and 10. At least two instances of disintegration of concrete have been ascribed recently to type (a), namely: a dolomitic marble aggregate with a thermal coefficient of 3.6×10^{-6} per degree centigrade studied by Pearson [1] and a fine-grained limestone aggregate with a coefficient of 4.0×10^{-6} per degree centigrade mentioned by Hornibrook [2]. These aggregates were used in concretes that disintegrated after exposure to one northern United States winter. An example of (b) has been pointed out in Central New York by Swayze [17], where a coarse aggregate consisting of single calcite crystals was used in a cast stone. This stone was in very bad condition after exposure to one winter. The Kimball, Nebr. gravel is a possible example of (c). This gravel contains about 90 percent of granite with a thermal-expansion coefficient of 7.2×10^{-6} (specimen 67, table 2). About half of the granite, however, is broken into fragments of quartz and orthoclase feldspar, minerals whose thermal-expansion coefficients vary with crystallographic directions between limits of 8.0 and 14.4×10^{-6} [14] and of 0.0 and 15.0×10^{-6} [15], respectively.

Most of the aggregate materials listed in table 2, excluding single crystals, have thermal expansions close to or within the range of expansions for hardened portland cement. A few, however, have sufficiently different expansivities to warrant some question as to their satisfactory use under severe weather conditions. Where aggregates containing such materials in large amounts are to be used in severe exposures, an examination should be made of the service record in structures having similar exposures. Lacking service background, they should be subjected to laboratory tests of the type described by Pearson [3].

VI. SUMMARY

Descriptions are given of an apparatus and test procedure used to measure the linear thermal expansion of 137 specimens of rocks and minerals found in concrete aggregates. The mineral constituents and textures of these specimens were determined petrographically. The common aggregate materials, excluding single crystals, were found to have thermal-expansion coefficients ranging from 0.9 to 13.8×10^{-6} per degree centigrade within the range of $-20°$ to $+60°$ C ($-4°$ to $+140°$ F). The majority of the coefficients are close to the coefficients of hardened portland cement. Crystal orientation, composition differences, and texture are factors which cause variations in the thermal expansions of aggregate materials. Some rocks do not expand uniformly on heating. Under severe weather conditions, the

expansivity of an aggregate might manifest itself unfavorably in concrete containing one of the following aggregate types: An aggregate having a uniform thermal expansion markedly different from the normal expansion of concrete; an aggregate composed of large crystal fragments having different thermal expansion in different crystallographic directions; an aggregate composed of two or more fractions with widely different expansivities; or an aggregate with irregular expansion.

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