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The  
Thermal Expansion  
of Concrete



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Technical Paper No. 7

DEPARTMENT OF SCIENTIFIC AND  
INDUSTRIAL RESEARCH  
(BUILDING RESEARCH STATION)

# THE THERMAL EXPANSION OF CONCRETE

BY

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AND

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## PREFATORY NOTE

CONSIDERABLE divergence exists between the values reported of the thermal expansion of concrete. The present report describes an investigation made by the Building Research Station, with the collaboration and support of the Institution of Civil Engineers, in order to obtain further information on the thermal expansion of concretes made with various British aggregates and with different cements and conditions of curing. The results are discussed in conjunction with those found in the literature.

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September, 1950.

# CONTENTS

	PAGE
INTRODUCTION .. .. .	1
DESCRIPTION OF TESTS .. .. .	2
Preparation of Specimens .. .. .	2
Apparatus used for the Measurement of Thermal Expansion	2
Calibration of the Apparatus .. .. .	2
Measurements of Concrete Specimens .. .. .	4
COEFFICIENT OF THERMAL EXPANSION OF CONCRETE .. .. .	4
Effect of Aggregate used .. .. .	4
Measurement of the Thermal Expansion of the Aggregate .. .. .	4
Concretes with Different Aggregates .. .. .	6
Effect of Different Cements .. .. .	7
Measurement of Neat Cement Specimens .. .. .	7
Concretes with Different Cements .. .. .	9
Effect of Mix Proportions .. .. .	10
Effect of Age of Concrete .. .. .	12
Effect of Water Content on Thermal Expansion .. .. .	13
Concretes with Different Slump or Water/Cement ratio .. .. .	13
Different Curing Conditions .. .. .	14
Effect of Wetting Air-cured Specimens .. .. .	15
Effect of Drying Wet-cured Specimens .. .. .	16
Effect of Soaking Specimens in Liquids other than Water .. .. .	18
Discussion of the Effect of Water Content on the Thermal Expansion .. .. .	18
CONCLUSIONS .. .. .	20
REFERENCES .. .. .	22

## FIGURES

	PAGE
1. Grading of Aggregates for each Mix .. .. .	3
2. Thermal Expansion of Aggregate .. .. .	5
3. Relation between Thermal Coefficient of Aggregate and Concrete .. .. .	7
4. Coefficient of Thermal Expansion of Different Aggregates as Measured by Various Authors .. .. .	8
5. Effect of Mix Proportions on Thermal Expansion .. .. .	11

# THE THERMAL EXPANSION OF CONCRETE

## INTRODUCTION

CERTAIN values for the coefficient of linear thermal expansion of concrete appear to have become recognized as standards by different authorities for design calculations for concrete structures. In Germany the value of  $5.6 \times 10^{-6}/^{\circ}\text{F}$ . is incorporated in the Standard Specification DIN 1045: May 1937, whereas Busing and Schumann<sup>(1)</sup> in their book on the uses of Portland cement in building give the value of  $7.6 \times 10^{-6}/^{\circ}\text{F}$ ., and the *Taschenbuch für Eisenhüttenleute*<sup>(2)</sup> quotes  $7.8 \times 10^{-6}/^{\circ}\text{F}$ .

In America a commonly accepted value for all concretes is  $5.5 \times 10^{-6}/^{\circ}\text{F}$ .<sup>(3)</sup> which is also recognised as a standard in this country<sup>(4)</sup>.

These values vary considerably among themselves and are all based on the work of the early investigators in this field<sup>(5), (6), (7), (23)</sup>. Although a considerable amount of data is available on the thermal expansion of concrete, most of the work, until recent years, has been carried out without adequate control of the temperature conditions. Since 1930 numerous further measurements have been made by workers in Germany and America but only the more important results of this work will be quoted when discussing the results obtained in the present investigation, which was carried out as part of the general research programme of the Building Research Board with the collaboration and support of the Institution of Civil Engineers.

The aim of the present work was to obtain information on the coefficient of thermal expansion of concretes made with different aggregates commonly used in Great Britain and on the way these values vary with different cements and conditions.

The investigation includes measurements on:—

- (1) Samples of the following aggregates: Pink granite from Shap Fell, Cumberland; Quartzite from Charfield, Gloucestershire; Olivine dolerite from Clee Hill; Sandstone from Darley Dale; a carboniferous limestone from Clitheroe; an oolitic limestone (Portland Whitbed); and blastfurnace slag.
- (2) Concrete made with Portland cement and each of the aggregates mentioned in (1) as well as washed river gravel and foamed slag.
- (3) Concretes made with washed river gravel and Portland blastfurnace or high alumina cement.
- (4) Concretes made with different proportions of cement and aggregate. The mixes used were 1 part Portland cement to  $4\frac{1}{2}$ , 6 and  $7\frac{1}{2}$  parts of aggregate by weight.
- (5) Concretes, made of 1 : 6 mixes with different aggregates, at the ages of 2, 4, 8 and 12 weeks and at 1 year.
- (6) Concretes cured at  $65^{\circ}\text{F}$ . in atmospheres of different relative humidities and in water.

Wherever possible the natural aggregates were supplied from the same location in the quarry in the form of pieces about 1 cwt. This ensured that the aggregate was as uniform as could be obtained. Gravel and foamed slag were obtained as coarse loose aggregate.

## DESCRIPTION OF TESTS

## PREPARATION OF SPECIMENS

In order to standardize the concrete as much as possible the same grading was used for each concrete and is shown in Fig. 1. This type of grading represents the best compromise which will suit all the aggregates though it is probably not the best for any one aggregate. Three mixes were used, 1 : 4½, 1 : 6, and 1 : 7½ cement to aggregate by weight except for foamed slag where volume proportioning in these ratios was necessary to obtain a workable mix. For the 1 : 6 mix this is equivalent to 1 : 2.53 by weight.

Each concrete was made to give a 2-in. slump which necessitated a different water-cement ratio for each.

The concretes were made into cylindrical specimens, 6 in. × 3 in., with three stainless steel balls in the base and a hardened-steel disc parallel to the plane of the steel balls, centrally in the top. From the top surface a hole extended to the centre of the specimen to allow the entry of a thermocouple.

At least six specimens were made from each mix and were cured for 24 hours under damp sacks, demoulded and then cured in one of the following ways:—

- (1) By storing under water maintained at 65°F. (referred to in the text as wet storage).
- (2) By storing on racks in circulating air in a room maintained at 64 per cent RH and 65°F. (referred to in the text as air storage).
- (3) By storing at various relative humidities over different salt hydrates in still air in sealed tins at 65°F.

## APPARATUS USED FOR THE MEASUREMENT OF THERMAL EXPANSION

The thermal movement of the concrete specimens was measured over the temperature range 32°F. to 104°F. by means of roller type extensometers of which four were used during the investigation. These were constructed of two units, each unit carrying two extensometers as described by Bonnell and Watson<sup>(20)</sup>.

The concrete cylinders were contained in cylindrical boxes which allowed 2 mm. clearance between the wall of the box and the specimen, thereby allowing rapid transfer of heat and also minimising the amount of water which might distil from the specimen during the heating cycle.

Movements of the specimen were transmitted to vertical rods which caused mirrors attached to rollers to rotate and so movements could be read on a vertical scale from the change in position of reflected slits of light.

The extensometer units were immersed in a paraffin bath so that the specimen boxes were completely covered with paraffin. The temperature of the bath was controlled to  $\pm 0.1^\circ\text{F}$ . by means of a contact thermometer which operated, through an electronic relay, a heater and a refrigeration coil.

## CALIBRATION OF THE APPARATUS

Since any measured movement is the resultant of the movement of the specimen and that of the apparatus, the instruments were calibrated directly by measuring the movements, over the range 32°F.-104°F. with specimens of invar, mild steel, brass and aluminium in the boxes. The coefficient of thermal expansion of each



of these specimens had previously been determined by the National Physical Laboratory. By repeat measurements with each metal in each box it is possible to find a relation between the thermal expansion of the specimen in the box and the scale deflection for each extensometer.

The values given in the paper are averages of measurements of two concrete specimens and analysis of the many measurements has indicated that, using the 5 per cent probability level, differences of more than  $0.4 \times 10^{-6}/^{\circ}\text{F}$ . are significant when comparing results.

#### MEASUREMENTS OF CONCRETE SPECIMENS

The routine adopted in the measurement of concrete specimens was as follows. The specimen was placed in the measuring box which was then immersed in the thermostat at  $68^{\circ}\text{F}$ . and, when the specimen had reached thermal equilibrium, the length was measured. After maintaining at  $68^{\circ}\text{F}$ . for a further 24 hours, the length was again measured; the amount of movement of the specimen when kept at constant temperature in the extensometer was, however, negligible. The length was then measured at temperatures of  $32^{\circ}$ ,  $50^{\circ}$ ,  $86^{\circ}$ ,  $104^{\circ}$ , and  $68^{\circ}\text{F}$ . in that order. A straight line relationship was found between temperature and movement of the specimen, and the final reading at  $68^{\circ}\text{F}$ . was always found to be very close to the initial reading, suggesting no loss of water by the specimen during the cycle.

#### COEFFICIENT OF THERMAL EXPANSION OF CONCRETE

The results obtained in this work will be discussed in conjunction with those found in the literature under the following headings :—

1. Effect of the aggregate used
2. Effect of the cement used
3. Effect of varying the mix proportions
4. Effect of age
5. Effect of curing conditions
6. Effect of varying the water content of matured specimens.

#### EFFECT OF THE AGGREGATE USED

##### *Measurement of the thermal expansion of the aggregate*

The values in this and the subsequent sections are reported as  $\times 10^{-6}/^{\circ}\text{F}$ .

Wherever possible a pair of specimens, 6 in.  $\times$  2 in.  $\times$  2 in. with the ends carefully ground parallel, was prepared for determining the thermal expansion of the aggregates themselves. Measurements were made on specimens dried *in vacuo* over anhydrous calcium chloride at  $122^{\circ}\text{F}$ . and on specimens saturated with water while *in vacuo*. The values obtained for individual specimens are shown in Table 1.

The values are given separately for each specimen because they were obtained from different blocks. The table shows that the two siliceous materials, quartzite and sandstone, have the highest values, the two limestones the lowest with the igneous materials intermediate.

The difference between dry and wet specimens does not appear to be of significance.

TABLE I. COEFFICIENT OF THERMAL EXPANSION OF AGGREGATES

AGGREGATE	THERMAL EXPANSION (per °F.)					
	Dry			Wet		
	1	2	Av.	1	2	Av.
Granite .. .. .	3.3	3.1	3.2	3.3	2.6	3.0
Quartzite .. .. .	6.4	6.5	6.5	6.2	6.0	6.1
Dolerite .. .. .	4.2	4.3	4.3	4.2	4.0	4.1
Sandstone .. .. .	5.6	5.6	5.6	5.8	5.2	5.5
Limestone .. .. .	2.4	2.5	2.5	2.2	2.1	2.2
Portland stone .. .. .	2.4	2.4	2.4	2.1	2.1	2.1
Blastfurnace slag .. .. .	4.3	4.4	4.4	4.4	4.3	4.4

A similar tendency is found in the results of Willis and de Reus<sup>(8)</sup>, Griffith<sup>(10)</sup> and Johnson and Parsons<sup>(24)</sup>. Fig. 2 gives a selection of rocks with the values

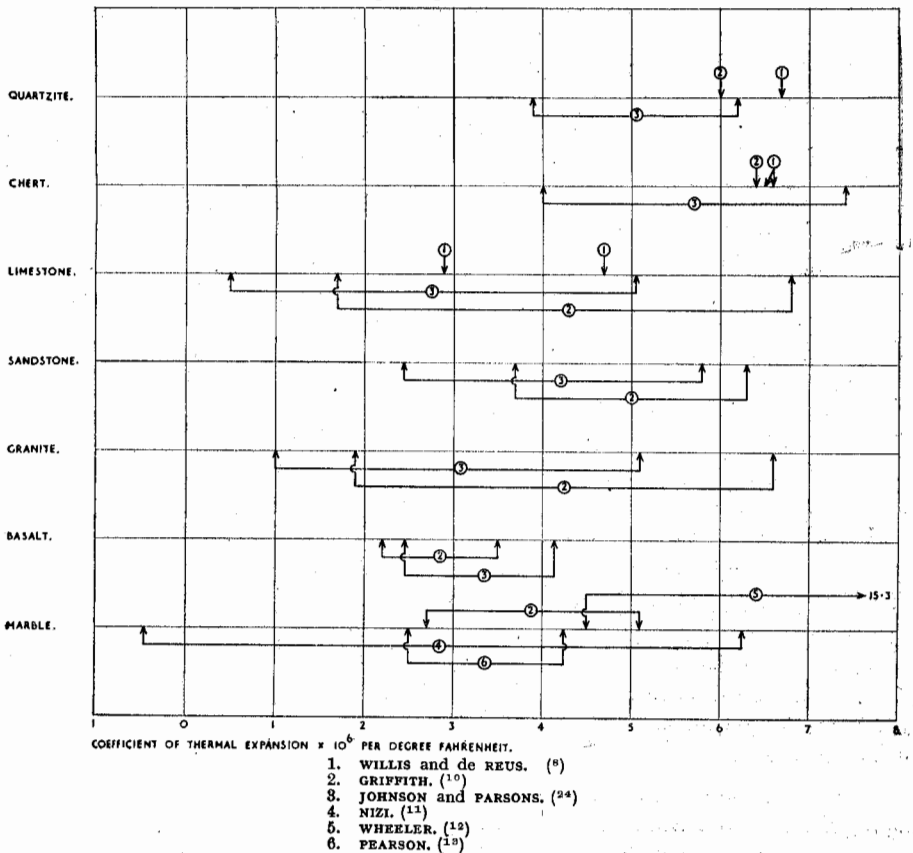


FIG. 2. THERMAL EXPANSION OF AGGREGATE

obtained by these and other authors. The results obtained by Griffith (temperature range room temperature–212°F.) and Johnson and Parsons (temperature range 32°–140°F.) show, however, that the values for a particular rock may vary considerably from one source to another. The amount of this variation is well illustrated by the values given for marble by different authors. Whether this variation can be related to differences in physical characteristics or to chemical composition is not known.

#### *Concretes with different aggregates*

Concrete specimens of mix proportions 1 : 6 were made from each of the nine aggregates and normal Portland cement and measurements were made after curing either in air or in water for three months. The results are given in Table 2.

TABLE 2. COEFFICIENT OF THERMAL EXPANSION OF CONCRETES WITH DIFFERENT AGGREGATES

AGGREGATE	THERMAL EXPANSION (per °F.)	
	Air Storage	Wet Storage
Gravel .. .. .	7·3	6·8
Granite .. .. .	5·3	4·8
Quartzite .. .. .	7·1	6·8
Dolerite .. .. .	5·3	4·7
Sandstone .. .. .	6·5	5·6
Limestone .. .. .	4·1	3·4
Portland stone .. .. .	4·1	3·4
Blastfurnace slag ..	5·9	5·1
Foamed slag .. .. .	6·7	5·1

These results show the same trend and are in conformity with those obtained with the rock specimens, namely the concretes made with siliceous aggregate having the highest expansion, the limestone concrete showing the lowest expansion while concretes with igneous aggregate form an intermediate group.

When, as shown in Fig. 3, the values for the aggregate are plotted against those for the concrete made with that aggregate the effect of the aggregate on the expansion of the concrete is clearly indicated by the approximate linear relationship. It will be observed, however, that the value for the concrete is always higher than that for the aggregate used. This is to be attributed to a higher thermal expansion of the set cement.

Various authors have reported values for concretes made with different aggregates but direct comparisons between the values obtained by different authors cannot be made because, firstly, there is no guarantee that aggregates which have been defined by the same name are identical and, secondly, the various authors have used different mixes, water-cement ratios, gradings of aggregates etc., all

# COEFFICIENT OF THERMAL EXPANSION

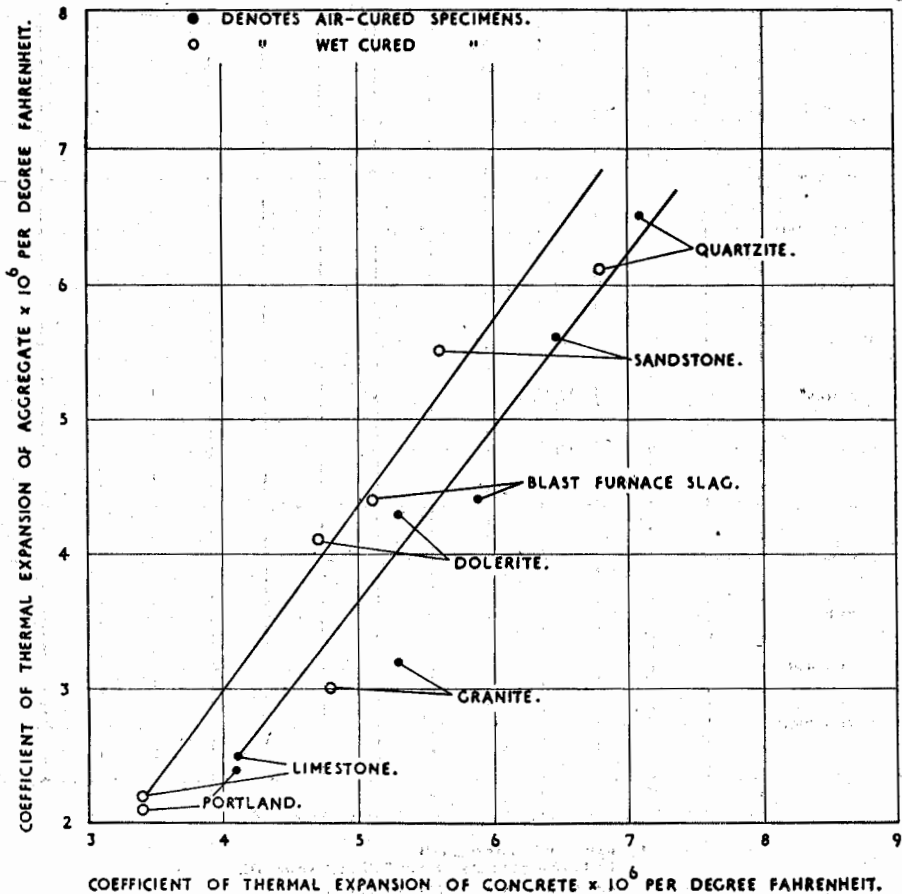


FIG. 3. RELATION BETWEEN THERMAL COEFFICIENT OF AGGREGATE AND CONCRETE (1 : 6 MIX, PORTLAND CEMENT)

of which may affect the value of the thermal expansion. It is better, therefore, to confine any discussion to the results obtained by any one author.

The values obtained by various authors are shown diagrammatically in Fig. 4. All these values agree with the previous conclusion that a predominating influence on the coefficient of thermal expansion is the type of aggregate and that siliceous aggregates give concretes of high expansion, limestones those of low expansion and igneous rocks those with expansions between these two extremes.

## EFFECT OF DIFFERENT CEMENTS

### Measurement of neat cement specimens

Cylindrical specimens, similar to those used for the measurements of concrete, were prepared of neat normal Portland, high alumina and Portland blastfurnace cements. They were cured in a similar manner to the concretes but it was found that the graph of scale deflection against temperature was not linear. Any value of thermal expansion which can be derived from these graphs can be only very approximate and of a different order of accuracy to the values quoted for the other

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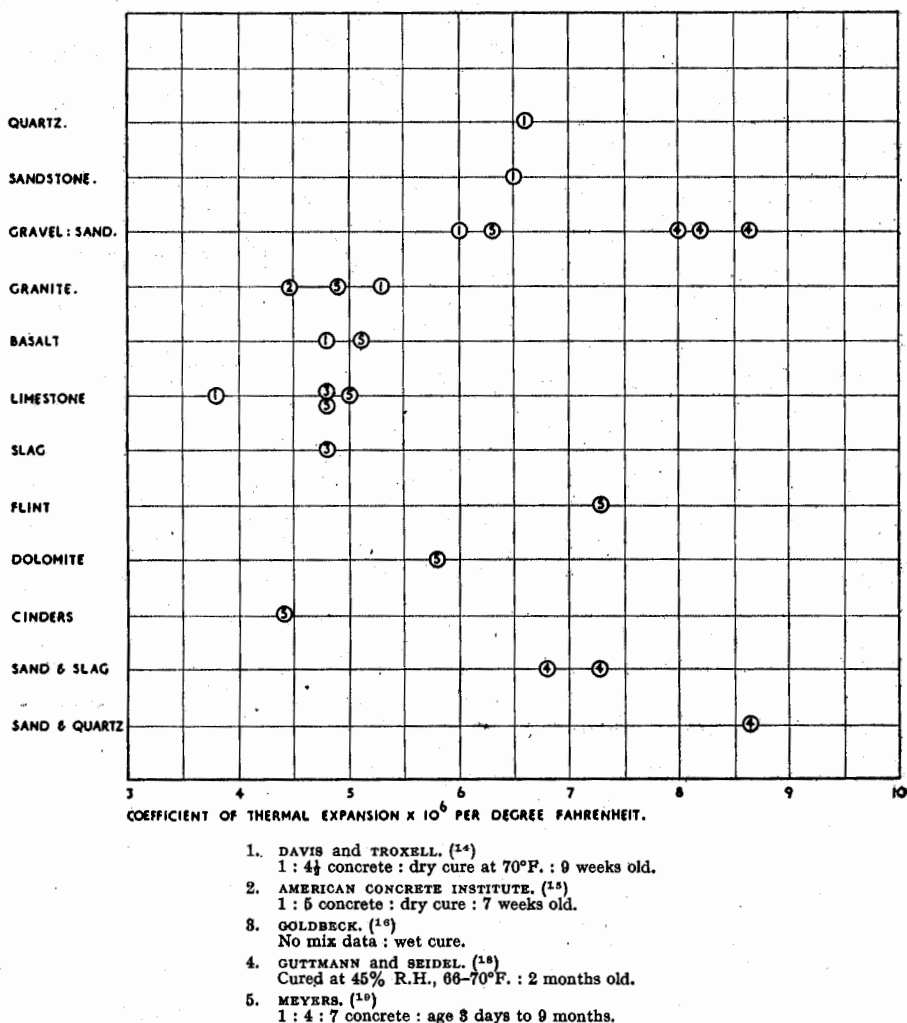


FIG. 4. COEFFICIENT OF THERMAL EXPANSION OF DIFFERENT AGGREGATES AS MEASURED BY VARIOUS AUTHORS

specimens. It is suspected that moisture changes due to the rise in temperature were masking purely thermal effects.

The values quoted in Table 3 below are calculated from the expansion obtained over the whole temperature interval 32°-104°F. and expansions obtained at intermediate temperatures are ignored. The values are given solely to indicate the relative order of the thermal expansion and are not intended for direct comparison with the values obtained for concrete or aggregate specimens.

The relationship shown in Fig. 3 suggests that an approximate value for the thermal expansion of hydrated normal Portland cement may be calculated by assuming that the expansion of the concrete is the sum of the expansion of the aggregate and the hydrated cement, and that none of the movement of the individual materials is taken up by compression of the other.

TABLE 3. COEFFICIENT OF THERMAL EXPANSION OF DIFFERENT CEMENTS

CEMENT	THERMAL EXPANSION (per °F.)	
	Air Storage	Wet Storage
Portland .. ..	12.6	8.2
High alumina .. ..	7.9	6.7
Portland blastfurnace ..	12.9	10.1

From the air storage data on the seven concretes and aggregates measured in this investigation a value of 12.2 is calculated for hydrated Portland cement. A similar value cannot be obtained for the other types of cement since concretes were made only with gravel aggregate, the thermal expansion of which was not measured.

Little other work has been done on the measurement of neat cement. Meyers<sup>(19)</sup> has measured various cements of widely different compound content and has obtained values varying between 5.4 and 11.8. The only other values reported for Portland cement are by Wolters<sup>(17)</sup> as 7.9 and Mills<sup>(22)</sup> as 7.8.

#### *Concretes with different cements*

A 1 : 6 gravel concrete was used to investigate the effect of varying the cement on the thermal expansion of the concrete. Normal Portland, high alumina, and Portland blastfurnace cements were used and both wet and air cured specimens were measured in the investigation. The results obtained are shown in Table 4.

TABLE 4. EFFECT OF DIFFERENT CEMENTS ON THE COEFFICIENT OF THERMAL EXPANSION OF CONCRETE

CEMENT	THERMAL EXPANSION (per °F.)	
	Air Storage	Wet Storage
Portland .. ..	7.3	6.8
High alumina .. ..	7.5	5.9
Portland blastfurnace ..	7.9	6.9

The values for the different air-stored concretes are not significantly different. The wet concretes, however, show high alumina cement to give a lower expansion than the other two. The effect of curing conditions is dealt with later in this paper.

Some work on this subject has been published by Guttmann<sup>(20)</sup> and by Wolters<sup>(17)</sup>, the former working with concretes and the latter with mortars. Guttmann first investigated 5 different types of cement (3 normal Portland with high  $Al_2O_3$  and low  $Fe_2O_3$  content and 1 high alumina cement) using a 1 : 6 concrete with Rhine-sand and curing the specimens for two years at 45 per cent RH and 66–70°F. The values for the different concretes are fairly close, the high alumina cement concrete

being highest at 7.5, the normal Portland cements close together around 6.7 and the Portland cement with high  $Al_2O_3$  and low  $Fe_2O_3$  being lowest at 6.5. In a further series of experiments Guttmann measured concretes at 3 months old and these gave values for concretes with Portland cement of 8.1, Eisen Portland cement also 8.1, and Hochofen cement 7.9.

Wolters conducted a very comprehensive study of mortars using various mixes. For the purpose of discussing the effect of cement on the thermal expansion the 1:1 mix will be considered since this is the most likely to emphasise the effect of the cement constituent. The values shown in Table 5 were obtained.

TABLE 5. EFFECT OF CEMENT ON THERMAL EXPANSION OF MORTARS  
(WOLTERS)

CEMENT	THERMAL EXPANSION (per °F.)
Portland (Saxonia) .. .. .	6.4
Hochwertiger (Alemannia) (rapid hardening Portland) ..	6.2
Hochofen A .. .. .	6.1
Hochofen B .. .. .	6.7
Eizencement .. .. .	5.9
Portland (Alemannia) .. .. .	7.5
Dyckerhoff Weiss (White Portland) ..	7.5
Dry slaked lime .. .. .	4.8
Hydraulic lime I .. .. .	4.8
Hydraulic lime II .. .. .	4.9
Lime I .. .. .	4.1
Lime II .. .. .	4.6
Eminently hydraulic lime .. .. .	5.1

These values from the literature along with those of the present investigation show that the different cements have only a minor effect on the thermal expansion of concrete.

It is interesting to note from Wolters' work that lime mortars have a much lower thermal movement than cement mixes and this is in agreement with the low values obtained with limestone aggregate.

#### EFFECT OF MIX PROPORTIONS

The foregoing sections suggest that the cement has a higher thermal expansion than any of the aggregates used in the tests. If this be true then lean mixes should have values of thermal expansion near to that of the aggregate and as the proportion of cement is increased the value should tend to become higher.

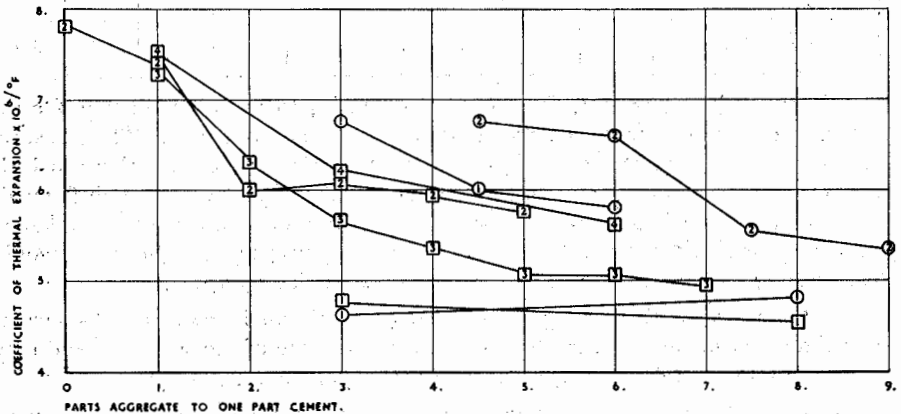
The effect of mix proportions has been investigated for each of the aggregates using 1:4½, 1:6, 1:7½ mixes by weight (foamed slag mixes by volume). The specimens were measured at 3 months old for both wet and air storage and the results are shown in Table 6.

TABLE 6. EFFECT OF MIX PROPORTIONS ON THE COEFFICIENT OF THERMAL EXPANSION OF CONCRETE

AGGREGATE	THERMAL EXPANSION (per °F.)					
	Air Storage			Wet Storage		
	1 : 4½	1 : 6	1 : 7½	1 : 4½	1 : 6	1 : 7½
Gravel .. .. .	7.6	7.3	7.4	6.9	6.8	6.8
Granite .. .. .	5.4	5.3	5.3	4.7	4.8	4.5
Quartzite .. .. .	8.1	7.1	7.1	6.5	6.8	6.6
Dolerite .. .. .	5.8	5.3	5.1	4.2	4.7	4.3
Sandstone .. .. .	6.9	6.5	6.1	5.7	5.6	5.8
Limestone .. .. .	4.3	4.1	3.4	3.5	3.4	3.2
Portland stone .. .. .	4.2	4.1	3.8	3.8	3.4	3.5
Blastfurnace slag .. .. .	6.2	5.9	5.7	5.3	5.1	4.8
Foamed slag .. .. .	7.2	6.7	5.6	5.2	5.1	5.9

These results show that for air-stored concrete the rich mixes tend to have a higher coefficient of thermal expansion than lean mixes but that for wet-stored concretes the differences are not significant.

Values obtained by other authors on the effect of mix proportions are plotted in Fig. 5. The data show that the thermal expansion increases with increase in cement content, the order of variation within the same range of mixes being similar to that obtained in the present work with air-stored specimens. The



- 1. DAVIS and TROXELL. (14)
- 2. MILLS. (22)
- 3. WOLTERS. (17)
- 4. MEYERS. (10, 21)
- Mortar.
- Concrete.

FIG. 5. EFFECT OF MIX PROPORTIONS ON THERMAL EXPANSION

evidence, therefore, is that, outside the range of very rich mixes, the effect of cement content appears to be of less importance than that of the aggregate used.

#### EFFECT OF AGE OF CONCRETE

The effect of age of the concrete on the thermal expansion has been measured on 1 : 6 concretes made from all the aggregates but only three aggregates were used for the investigation at early ages. The results are given in Table 7 for both wet- and air-curing.

TABLE 7. EFFECT OF AGE ON THE COEFFICIENT OF THERMAL EXPANSION OF CONCRETE

AGGREGATE	THERMAL EXPANSION (per °F.)									
	Air storage tested at age of					Wet storage tested at age of				
	2 weeks	4 weeks	8 weeks	12 weeks	1 year	2 weeks	4 weeks	8 weeks	12 weeks	1 year
Gravel ..	7.1	7.5	7.5	7.3	7.4	7.1	6.7	6.8	6.8	6.6
Granite ..				5.3	4.9				4.8	4.7
Quartzite ..				7.1	6.8				6.8	6.6
Dolerite ..	5.1	5.4	5.4	5.3	5.1	4.6	4.2	4.5	4.7	4.3
Sandstone ..				6.5	5.8				5.6	5.9
Limestone ..				4.1	3.5				3.4	3.4
Portland stone	3.9	4.2	4.1	4.1	3.7	3.5	3.7	3.7	3.4	3.5
Blastfurnace slag				5.9	5.4				5.1	5.6
Foamed slag				6.7	5.9				5.1	3.9

These results show that, for air-cured concrete, there is a tendency for the thermal expansion to decrease between three months and one year. The measurements at earlier ages show no significant trend. For wet curing there is little change to be noted even between three months and one year except with foamed-slag concrete. The large movement with foamed-slag concrete cannot be explained but it may be significant that this is a light-weight aggregate. Further work would be necessary to show whether this is typical of all such aggregates.

It seems reasonable to suggest that changes in thermal expansion of concrete with time are functions of the cement matrix rather than of the aggregate and may be caused by physical changes in the gel structure of the cement paste.

Meyers<sup>(21)</sup> found that neat cement bars, enclosed in air sealed jackets to prevent drying, increase in thermal expansion with age and then begin to decrease. A cement high in tricalcium silicate reached its maximum at 5 months whereas one with low tricalcium silicate reached its maximum only after 18 months. With concretes, however, Meyers' results do not show very much alteration with age except for a rich limestone mix (1 : 3 : 1) which follows the same trend as the cements.

Davis and Troxell<sup>(14)</sup> suggest on very slight evidence that there is no change with age.

Rudeloff and Sieglerschmidt<sup>(23)</sup> using large (20×20×75 cm.) specimens of a peculiar shape, have measured the effect of age. Though the aggregate was not specified the mix was 1 : 3 and measurements were made at 3, 7, 28, and 90 days between 77° and 122°F. They found that the thermal expansion of air-cured specimens rose from 5.7 to 7.5 and wet cured ones rose from 6.1 to 6.9.

It seems from the evidence that the ageing process may influence the thermal expansion of concrete to a small extent. It must be borne in mind that, as will be discussed later, part at least of the change in the thermal movement may be due to changes in water content of the specimen.

#### EFFECT OF WATER CONTENT ON THERMAL EXPANSION

In this section must be included many different methods of reaching the final water content of the specimen and these will be treated separately.

##### *Concretes with different slump or water/cement ratio*

In the present investigation no work has been done on the effect of water/cement ratio as all the concretes were made to the same 2 in. slump and, while the water/cement ratios were different for each aggregate, no variation was investigated with any one aggregate.

Some investigators have, however, studied this effect. Davis and Troxell<sup>(14)</sup> measured concretes with different slump for the same aggregate and mix. Their results show that the thermal expansion decreases gradually as the water content is increased.

Meyers<sup>(19)</sup> quotes the following results, Table 8, showing the effect of water/cement ratio on thermal expansion.

TABLE 8. COEFFICIENT OF THERMAL EXPANSION OF NEAT CEMENT MIXES WITH DIFFERENT WATER/CEMENT RATIOS (MEYERS)

WATER/CEMENT RATIO	THERMAL EXPANSION (per °F.)
0.30	9.5
0.37	9.3
0.60	10.3
0.75	8.3

The mix with 0.75 water/cement ratio segregated. These results show no definite trend of any influence of water/cement ratio on thermal expansion though the results may be obscured by the specimens containing different amounts of cement.

There seems to be insufficient evidence to determine whether the water/cement ratio has an appreciable influence on the thermal expansion.

*Different curing conditions*

In the present work concretes have been cured under various conditions to find the influence of these on the thermal expansion. The conditions were

(a) at 65°F. and 64 per cent RH in free air circulation

(b) at 65°F. immersed in water

(c) in sealed tins over salt hydrates to give various relative humidities.

The results for conditions (a) and (b) have already been given on page 16 but are partly repeated here along with those for condition (c). Two aggregates, gravel and Portland stone, were used in condition (c) and the specimens were stored over calcium chloride ( $\text{CaCl}_2, 2\text{H}_2\text{O}$ ), calcium nitrate ( $\text{Ca}(\text{NO}_3)_2, 4\text{H}_2\text{O}$ ), oxalic acid ( $(\text{COOH})_2, 2\text{H}_2\text{O}$ ) and sodium sulphate ( $\text{Na}_2\text{SO}_4, 10\text{H}_2\text{O}$ ). These salts are in equilibrium with relative humidities of approximately 32.3, 52, 76 and 93 per cent respectively. All the specimens in Table 9 below were of 1:6 concrete and were measured when three months old.

TABLE 9. EFFECT OF STORAGE CONDITIONS ON THE COEFFICIENT OF THERMAL EXPANSION OF CONCRETE

AGGREGATE	THERMAL EXPANSION (per °F.)					
	Conditions of storage					
	32% (c)	52% (c)	65% (a)	76% (c)	93% (c)	100% (b)
Gravel .. ..	7.8	8.1	7.3	6.9	7.5	6.8
Portland stone ..	4.5	4.2	4.1	3.9	4.0	3.4

From these results and those shown in Table 2 it appears that dry curing results in a slightly higher thermal expansion than does wet curing.

Other workers have also investigated the effect of curing conditions. Meyers<sup>(10)</sup> quotes the following result, (Table 10), the concrete being stored in airtight copper containers and the results are the average of measurements at ages from 3 to 9 months.

TABLE 10. EFFECT OF STORAGE CONDITIONS ON THE COEFFICIENT OF THERMAL EXPANSION OF CONCRETE (MEYERS)

SPECIMEN	THERMAL EXPANSION (per °F.)
1. Limestone concrete, sealed with no addition of water after making ..	3.7
2. Limestone concrete with free water in the seal .. ..	2.8
3. Dolomite concrete sealed as 1 ..	5.3
4. Dolomite concrete sealed as 2 ..	5.0

This suggests that wet conditions favour a lower thermal expansion.

Rudloff and Sieglerschmidt<sup>(23)</sup> found that, at all ages (3-90 days) the thermal expansion of dry specimens is greater than that of water-cured specimens.

In direct contrast to these results are those of Davis and Troxell<sup>(14)</sup> who quote for 1 : 4 granite concrete the values given in Table 11.

TABLE 11. EFFECT OF CURING CONDITIONS ON THE COEFFICIENT OF THERMAL EXPANSION OF CONCRETE (DAVIS AND TROXELL)

CURING	THERMAL EXPANSION (per °F.)	
	at age of	
	7 weeks	4 months
In water .. ..	4.5	4.1
In dry air .. ..	3.8	3.9

The weight of the evidence, however, seems to support the present data that curing under drying conditions results in concretes with higher thermal expansion than those cured under water.

#### *Effect of wetting air-cured specimens*

Specimens prepared from 1 : 6 concrete were kept in air storage for three months. The thermal expansion of two specimens was measured at this age while a similar pair were saturated with water and then measured. The method of saturation involved evacuating the vessel containing the specimen, then running in sufficient water to cover the specimen while the vacuum was maintained and finally releasing the vacuum after 24 hours. The specimens were then stored in water for 2 weeks before measurement. The results are shown in Table 12.

TABLE 12. EFFECT OF THE COEFFICIENT OF THERMAL EXPANSION OF CONCRETE OF WETTING AIR-CURED SPECIMENS

AGGREGATE	THERMAL EXPANSION (per °F.)	
	Air-cured	After wetting
Gravel .. ..	7.3	6.5
Granite .. ..	5.3	4.3
Quartzite .. ..	7.1	6.5
Dolerite .. ..	5.3	4.4
Sandstone .. ..	6.5	4.8
Limestone .. ..	4.1	3.3
Portland stone .. ..	4.1	3.6
Blastfurnace slag .. ..	5.9	4.9
Foamed slag .. ..	6.7	4.7

It is evident that the saturation of an air-cured specimen produces a significant reduction in the thermal expansion. The value of the thermal expansion of the wetted specimen is, for each specimen except Portland stone, slightly less than for a specimen which has been cured in water for three months (see Table 2).

As far as is known the only other worker to carry out an experiment on these lines is Meyers<sup>(19)</sup>, who investigated the effect of wetting specimens which had previously been cured for 9 months in sealed containers. Wetting was carried out by immersing the specimens in water and the results are shown in Table 13.

TABLE 13. EFFECT ON THE COEFFICIENT OF THERMAL EXPANSION OF WETTING SEALED-STORED SPECIMENS (MEYERS)

SPECIMEN	THERMAL EXPANSION (per °F.)	
	Sealed Storage	After wetting
Lime masonry concrete .. ..	10.4	5.3
High w/c limestone concrete .. ..	5.3	5.3
Flint concrete .. .. .	8.1	4.9
1 : 1 cement sand mortar .. ..	9.2	6.3
High tricalcium aluminate cement—neat	11.4	5.6

In this paper Meyers also quotes another table (14) with values for specimens 9 months old.

TABLE 14. EFFECT ON THE COEFFICIENT OF THERMAL EXPANSION OF WETTING SEALED-STORED SPECIMENS (MEYERS)

SPECIMEN	THERMAL EXPANSION (per °F.)	
	Before wetting	After wetting
Neat cement .. ..	12.5	6.9
Concrete .. ..	5.6	4.3

The figures in Tables 13 and 14 show a much greater fall in thermal movement with neat cement than with concrete, possibly because the difference is a function of the cement rather than of the aggregate.

#### *Effect of drying wet-cured specimens*

For investigating the effect of drying wet-cured specimens, specimens of 1 : 6 concrete were kept in wet storage for 3 months when the thermal movements of two specimens were measured while two others were dried *in vacuo* at 104°F. over anhydrous calcium chloride for two weeks and then measured. These dried specimens were then returned to the drying chambers and the drying continued for 6 months. The results are shown in Table 15.

TABLE 15. EFFECT ON THE COEFFICIENT OF THERMAL EXPANSION OF DRYING WET-CURED SPECIMENS

AGGREGATE	THERMAL EXPANSION (per °F.)			
	Wet	Dried for 2 weeks	Dried for 6 months	Wetted after 6 months
Gravel .. .. .	6.8	6.9	6.8	6.7
Granite .. .. .	4.8	4.4	4.3	4.2
Quartzite .. .. .	6.8	6.5	6.4	6.4
Dolerite .. .. .	4.7	4.4	4.5	4.1
Sandstone .. .. .	5.6	5.7	5.7	5.6
Limestone .. .. .	3.4	3.2	3.0	3.1
Portland stone .. .. .	3.4	3.5	3.4	3.4
Blastfurnace slag .. .. .	5.1	5.3	5.1	5.1
Foamed slag .. .. .	5.1	5.2	5.2	4.8

These results show that the thorough drying has no effect on the thermal expansion of wet-cured specimens.

Rudeloff and Sieglerschmidt<sup>(23)</sup> investigated the following cycle. Specimens were cured at 45 per cent RH and 66°-70°F. and measured between 68° and 122°F., heated to 212°F. for 3 hours and then remeasured between 68° and 122°F. Each specimen showed an increase in length and a fall in thermal expansion after this treatment. The increase in length was found not to be permanent and in the course of three months the specimen had returned to its original length.

Meyers<sup>(19)</sup> made measurements on cement and concrete specimens which had been stored in sealed copper foil for 9 months, then immersed in water for one week and finally dried over calcium chloride for one week. The results which are given in Table 16 show an increase in thermal expansion on drying but in a later paper<sup>(21)</sup> Meyers gives data (Table 17) indicating that drying for one week at 212°F. of specimens previously cured in sealed containers reduces the thermal expansion.

TABLE 16. EFFECT ON THERMAL EXPANSION OF DRYING WET CONCRETE SPECIMENS (MEYERS)

SPECIMEN	THERMAL EXPANSION (per °F.)		
	Sealed Storage	Water 1 w.	CaCl <sub>2</sub> 1 w.
Neat cement .. .. .	12.5	6.9	10.9
Concrete .. .. .	5.6	4.3	4.4

TABLE 17. EFFECT ON THERMAL EXPANSION OF DRYING CONCRETE SPECIMENS  
(MEYERS)

SPECIMEN	THERMAL EXPANSION (per °F.)	
	Before drying	1 w at 212°F.
High early strength cement ..	9.1	6.0
White cement .. .. .	10.4	6.5
Normal Portland cement ..	9.4	6.0
Portland-lime masonry cement ..	8.0	3.7
Limestone concrete .. ..	4.1	2.1
Plastic Portland cement .. ..	10.0	5.9

While the results in Table 17 appear not to agree with the previous results of the same author or with the results of the present investigation it should be noted that the conditions are different for each experiment. In the present work the specimen is taken from wet storage to desiccation, in Table 16 a wet specimen is allowed to dry slowly over calcium chloride and is presumably not desiccated whereas in Table 17 a dry-cured specimen is desiccated. This will be discussed more fully at the end of the section.

The specimens (Table 15) which had been desiccated for 6 months were re-wetted *in vacuo* and the thermal expansion remeasured. As is shown there is little change in the coefficient.

#### *Effect of soaking specimens in liquids other than water*

As part of another investigation, specimens of 1 : 4½ gravel concrete, w/c=0.45, were cured in dry storage for three months and then saturated with diesel oil. The value of the thermal expansion before soaking was 7.6 whereas the value after soaking was 7.7.

Meyers<sup>(21)</sup> has soaked concrete specimens in kerosene and glycerol and has found no change in thermal expansion with either liquid.

#### DISCUSSION OF THE EFFECT OF WATER CONTENT ON THE THERMAL EXPANSION.

Before discussing the effect of moisture content on the thermal expansion of concrete it is advantageous to summarize the data obtained in this and other investigations.

1. Air-cured concrete has a higher thermal expansion than water-cured.
2. The coefficient of thermal expansion of water-saturated concrete is independent of the previous method of curing.
3. The coefficient of thermal expansion of water-saturated concrete is the same as that of desiccated concrete.
4. The coefficient of thermal expansion of air-cured concrete is not affected by soaking in diesel oil, glycerol or kerosene but an immediate reduction is obtained by soaking in water.

5. Curing in air of different humidities shows that, at humidities which should remove all the free water, values of thermal expansion are higher than those obtained with water-saturated or desiccated concrete.

6. The thorough drying of concrete previously cured in a sealed container reduces the thermal expansion.

7. The thermal expansion of wetted concrete is increased when it is partially dried over calcium chloride.

The whole of this data proves that the thermal expansions of desiccated and water-saturated concretes are identical and that concretes in conditions intermediate between those two extremes can have higher coefficients. These higher values appear to apply to concretes which have been dried to a condition where the vapour pressure of the water still retained is lower than that of a free water surface at the same temperature. This increase in thermal expansion appears therefore to be related directly to the effect of water either absorbed or held in very fine capillaries.

Powers and Brownard<sup>(25)</sup> in their discussion of "The thermodynamics of absorption of water on hardened Portland cement paste" have put forward the theory that this behaviour is caused by the effect of the potential swelling-pressure which is defined as the increase in pressure required to prevent swelling when a dry or partially dry gel has access to free water.

The authors explain the higher expansion of partly dried specimens thus:—

"Since an increase in temperature causes an expansion of the adsorbed water the surface curvature of the water in the lenses must decrease. Moreover, the surface tension of water decreases with increase in temperature. Hence the capillary tension must decrease with increasing temperature provided the water content remains constant. This in turn would mean that an increase in temperature would cause expansion owing to swelling, in addition to the thermal expansion. However, if the specimen is initially saturated, no change in swelling-pressure can occur because for this condition the capillary condition is zero, or insignificantly small. Obviously, if the specimen contains no evaporable water, no swelling due to moisture can occur when the temperature is increased."

If this theory is correct the true thermal expansion of concrete is obtained only from dry or saturated specimens and values obtained from partly dried specimens are the sum of two movements—that due to swelling and that due to thermal expansion. Further, the relation between swelling and temperature must be linear since the expansion of both wet and partly-dried specimens have been found to be linear with temperature.

It will be observed that most of the data quoted above are in agreement with this theory.

This theory indicates that the coefficient of thermal expansion is likely to vary over a wide range of water contents but should remain constant during dehydration as long as the vapour pressure remains equal to that of a free water surface at the same temperature. From this point to the point of dryness the coefficient determined at any fixed water content should be related to the temperature coefficient of the vapour pressure of the water held in the concrete since this will control the change in swelling pressure produced on changing the temperature. To substantiate this theory it would be necessary to determine the vapour pressure/temperature relation as well as the thermal expansion of concrete specimens with different water contents.

In applying these results in practice, the values obtained for the wet concrete should be directly applicable to water-retaining structures and to concrete below water or below ground level. The values for air-dry concrete will apply to structural members not exposed to the weather, though it must be remembered that in their early life there will be a slow drying shrinkage superimposed on any thermal movement and that this drying shrinkage will normally be greater in magnitude than any subsequent thermal movement. Exceptions to this are to be found in flat concrete roof slabs covered by dark bituminous roofing materials where, because of the high absorption of heat from the sun's rays, the temperature rise within the slab can be considerable.

In structures exposed to the weather, wetting and drying movements will be superimposed on the thermal movements, but whereas the latter are both diurnal and seasonal the former are mainly seasonal. Since, however, an increase in temperature will usually be associated with some degree of drying, the net movement will be less than that calculated from the thermal expansion.

### CONCLUSIONS

1. Siliceous aggregates have high coefficients of thermal expansion, limestones have low coefficients and igneous rocks occupy an intermediate position. Information in the literature shows that the coefficient of thermal expansion depends on the source as well as the geological type of the aggregate.

2. The coefficient of thermal expansion of a concrete depends largely on the type of aggregate from which it was prepared. Concretes made with siliceous aggregates have the highest expansion, those with limestone the lowest and those with igneous aggregate intermediate.

The following is a summary of the average values obtained.

TABLE 18. COEFFICIENT OF THERMAL EXPANSION OF CONCRETES

AGGREGATE	THERMAL EXPANSION OF 1 : 6 CONCRETE			
	Air Storage		Wet Storage	
	$10^{-6}$ per °F.	$10^{-6}$ per °C.	$10^{-6}$ per °F.	$10^{-6}$ per °C.
Gravel .. .. .	7.3	13.2	6.8	12.2
Granite .. .. .	5.3	9.6	4.8	8.6
Quartzite .. .. .	7.1	12.7	6.8	12.2
Dolerite .. .. .	5.3	9.6	4.7	8.4
Sandstone .. .. .	6.5	11.7	5.6	10.1
Limestone .. .. .	4.1	7.3	3.4	6.1
Portland stone .. .. .	4.1	7.3	3.4	6.2
Blastfurnace slag .. .. .	5.9	10.6	5.1	9.1
Foamed slag .. .. .	6.7	12.0	5.1	9.2

3. The thermal expansion of a concrete increases slightly as the cement content is increased. This is probably due to hydrated cement having a higher coefficient of thermal expansion than any of the aggregates tested.

4. Age appears to have only a minor effect on the thermal expansion of a concrete.

5. The coefficient of thermal expansion of desiccated and water-saturated concretes are identical and are lower than those of partly dried specimens.

6. Further study of the effect of adsorbed and capillary water on the thermal expansion may help to elucidate the mechanism of water adsorption on cement pastes.

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