

DILATOMETER METHOD FOR DETERMINATION OF THERMAL COEFFICIENT OF EXPANSION OF FINE AND COARSE AGGREGATE

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SYNOPSIS

The thermal coefficients of the paste and aggregate components of concrete to a considerable extent govern the degree of physical compatibility of the components and hence may affect the durability of concrete subject to changes in temperature.

The described dilatometer method is suitable for the determination of the thermal coefficient of expansion of sand and coarse aggregate. The method is particularly adaptable to the study of sands and also provides a means of obtaining and testing a representative sample of a heterogeneous coarse aggregate or of the various mineralogical portions comprising the coarse aggregate.

The apparatus consists of a one-liter dilatometer flask to which is attached a capillary-bulb arrangement containing electrical contacts, the latter spaced over a calibrated volume. In operation, the flask is filled with aggregate and water, and the apparatus allowed to equilibrate at one of the controlling electrical contacts, automatically heating and cooling the water bath surrounding the dilatometer as required. The equilibrium temperature is noted (Beckmann thermometer) and the procedure is then repeated at the other electrical contact. The apparatus is reasonably automatic and, after proper calibration, the only measurements required during an actual determination are the weight of water placed in the dilatometer flask, and the temperature required to produce an expansion equivalent to the volume between the electrical contacts.

The method determines the cubical thermal coefficient of expansion from which the mean linear thermal expansion may be calculated. With the present apparatus, the thermal coefficient is measured over a range of approximately 7 deg. F. Both the temperature increment and the base temperature used in the determination can be easily modified.

The accuracy of the apparatus has been verified by the comparison of results obtained with materials of known thermal coefficients of expansion. The thermal coefficients of expansion of various fine and coarse aggregates are included. The mean linear thermal coefficients of the natural aggregates tested extended from a low of 3.0×10^{-6} per deg. F. to a high of 7.1×10^{-6} per deg. F.

Mortars and concretes are heterogeneous mixtures of cement paste and aggregate particles which must be compatible in both a chemical and physical sense in order to obtain a product of high durability. Although the chemical aspects of this required compatibility are being continually studied, there appears to be considerable need for the proper evaluation of the extent and the manner in which the degree of physical compatibility of the concrete components may affect the durability of concrete.

The fine and coarse aggregate materials in concrete normally comprise about 75 percent of the concrete and therefore the physical

characteristics of this predominant component may have a considerable effect on the quality of the concrete. The thermal expansivities of the aggregate and the paste components of the concrete to a considerable extent govern the degree of physical compatibility of these components and hence may affect the durability of concrete subjected to thermal changes.

This study was undertaken to develop a suitable experimental method for determining the thermal expansion characteristics of aggregates, both fine and coarse, as one phase in the problem of evaluating the effects of the several physical characteristics of aggregates and other factors determining the weather resistance of concrete.

The thermal coefficients of expansion of numerous aggregates have been carefully de-

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termined by several investigators. The data of these investigators indicate that the thermal expansivities of aggregates vary widely, both with mineralogical type and geographical location. The data also demonstrate that aggregates of the same general type and source may differ significantly in measured thermal characteristics. These observed variations preclude the use of previous data in estimating the thermal expansivities of other aggregates unless identifiable with those tested. Also, since aggregates used in concretes are com-

mal coefficient of expansion of a heterogeneous mixture of different aggregate types as commonly found in sands and gravels used in concrete, or the individual types of aggregates can be separated and studied singly.

TEST METHOD

Apparatus. The dilatometer apparatus for the determination of the thermal coefficient of expansion of aggregate is shown schematically in Figure 1. The apparatus consists of a one-liter dilatometer flask to which is attached a laboratory constructed capillary-bulb arrangement containing electrical contacts, the latter spaced over a calibrated volume. In operation, the flask is filled with aggregate and a weighed amount of water, and the apparatus allowed to equilibrate at one of the controlling electrical contacts, automatically heating and cooling the water bath surrounding the dilatometer as required. The equilibrium temperature is observed by means of a Beckmann thermometer immersed in the water bath and the procedure is then repeated at the other electrical contact. The apparatus is reasonably automatic and after proper calibration, the only measurements required during an actual determination of the thermal coefficient of expansion of an aggregate are the weight of water placed in the dilatometer flask with the aggregate and the temperature increment required to produce an expansion equivalent to the volume between the equilibrating electrical contacts.

Calibration. The volume capacity of the dilatometer flask is determined by weighing the flask before and after filling with water at 25°C. and converting the net weight to a volumetric basis by means of the appropriate density of water.

The volume so determined does not include the volume of water contained in the capillary bulb attachment, which in normal operation is thermally shielded from the water bath and at relatively constant room temperature. The minor variation in this temperature during a determination and the relatively small volume of water in the capillary-bulb attachment make the effect of volume changes in this attachment negligible. However, after proper insulation of the electrical circuits, the capillary-bulb attachment may be submerged in the water bath.

The volume increment between the lower and upper regulating contacts is obtained from

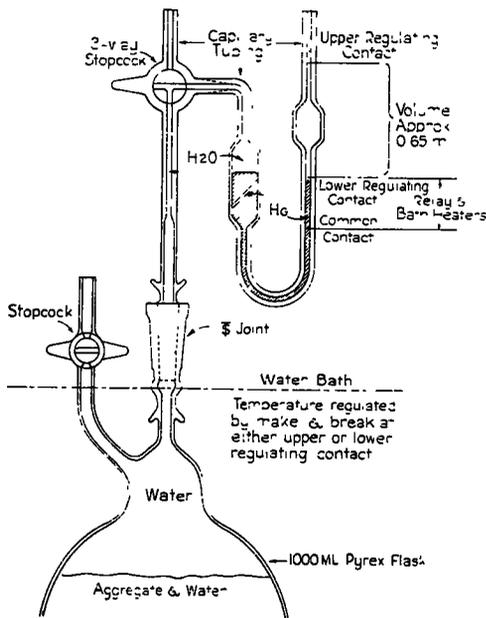


Figure 1. Apparatus for the Determination of Thermal Coefficient of Expansion of Aggregate

monly a heterogeneous mixture of different mineralogical types any calculations or generalization by proportion might be of questionable significance.

The dilatometer method to be described measures the cubical thermal coefficient of expansion of the aggregate. The method is independent of crystal orientation and grain size and will not reveal the anisotropic thermal behavior observed in some minerals. The method is most adaptable to the study of small particles of aggregate and may be used to determine the thermal coefficients of sands and gravels. It is particularly useful in that it can be applied to obtain the overall average ther-

the difference in weight of the controlling unit filled with mercury at a known temperature from the three-way stop-cock to the lower regulating contact and after filling to the upper contact. The filling can be conveniently and accurately performed by the use of a small hypodermic needle.

For calibration, it is essential to determine the cubical thermal coefficient of expansion of the dilatometer flask itself. This is accomplished by test with only air-free water of which the thermal coefficient is accurately known within the dilatometer. However, the cubical thermal coefficient of expansion of water varies considerably with temperature and it is therefore necessary to know the absolute setting of the Beckmann thermometer within about $\pm 0.01^\circ\text{C}$. This degree of accuracy is conveniently obtained by means of an accurately calibrated reference thermometer. Since the thermal coefficient of expansion of water varies significantly with temperature, this factor has been incorporated in the calculations directly as the specific volumes of water at the water bath temperatures corresponding to equilibration at the upper and lower electrical contacts. The specific volume values were obtained by linear interpolation between the 0.100°C . increments of accepted values for the specific volume of water as a function of temperature as given in the International Critical Tables.

Calculations: The volume changes that occur in going from T_1 to T_2 at constant pressure are:

$$\Delta V_w + \Delta V_a - \Delta V_c = \Delta V$$

Now:

$$\Delta V_w = G_w (v_2 - v_1) = V_w \frac{(v_2 - v_1)}{v_1}$$

$$\Delta V_a = V_a \alpha_a (T_2 - T_1)$$

$$\Delta V_c = V_c \alpha_c (T_2 - T_1)$$

Therefore:

$$\frac{V_w}{v_1} (v_2 - v_1) + V_a \alpha_a (T_2 - T_1)$$

$$- V_c \alpha_c (T_2 - T_1) = \Delta V$$

Or,

$$\alpha_a = \frac{1}{V_a (T_2 - T_1)}$$

$$\left[\Delta V + V_c \alpha_c (T_2 - T_1) - V_w \frac{(v_2 - v_1)}{v_1} \right]$$

For calibration since:

$$V_a = 0, \quad V_w = V_c$$

$$\alpha_c = \frac{1}{T_2 - T_1} \left[\frac{v_2 - v_1}{v_1} - \frac{\Delta V}{V_w} \right]$$

Notation

T_1 = Temperature at lower contact—deg. C.

T_2 = Temperature at upper contact—deg. C.

ΔV_w = Volume expansion of the water in the dilatometer—ml.

ΔV_a = Volume expansion of the aggregate in the dilatometer—ml.

ΔV_c = Volume expansion of the dilatometer itself—ml.

ΔV = The volume increment between the lower and upper regulating contacts—ml.

G_w = Weight of water in the dilatometer—g.

V_w = Volume of water in the dilatometer at T_1 —ml.

V_c = Volume capacity of the dilatometer at T_1 —ml.

V_a = Volume of aggregate in the dilatometer at T_1 , = $V_c - V_w$ —ml.

v_1 = Specific volume of water at T_1 —ml. per gm.

v_2 = Specific volume of water at T_2 —ml. per gm.

α_a = Cubical thermal coefficient of expansion of aggregate from T_1 to T_2 —ml./ml. per deg. C.

α_c = Cubical thermal coefficient of expansion of dilatometer itself from T_1 to T_2 —ml./ml. per deg. C.

Temperature Range. The temperature increment over which the thermal coefficient of expansion of the aggregate is determined is approximately 4°C . when the 1 liter dilatometer flask and a volume increment of 0.65 ml. are used at 25°C . This temperature increment will vary as a function of the temperature at which the dilatometer is operated, the ratio of the volume increment between the contacts to the flask volume, the degree of filling of the dilatometer flask with aggregate and, of course, with the thermal characteristics of the aggregates. Greater temperature increments can be obtained, if desired, by increasing the ratio of the volume increment between the regulating contacts to the volume capacity of the dilatometer flask.

The use of water as a confining liquid in the dilatometer is entirely suitable for measure-

ments in the range normally desired. However, for measurements below the freezing point of water, a non-reactive liquid (such as toluene) that does not freeze in the desired temperature range could be substituted for water as the confining dilatometer fluid.

Effect of Pressure. The displacement of the mercury from the lower to the upper regulating contacts during a determination would normally increase the hydrostatic pressure within the dilatometer flask. This potential increase in pressure would compress the water within the flask and would also tend to dilate the dilatometer flask itself. Although these effects can be measured and included in the computations it was found to be more expedient to maintain a constant pressure within the dilatometer, compensating for the pressure increment between the contacts by the application of an equivalent reduced air pressure to the system just above the upper contact when equilibrating at this contact or by the application of air pressure when equilibrating at the lower contact.

Physical Interference. It was at first considered a possibility that physical interference between the aggregate and the dilatometer walls might occur, which eventually would have necessitated the use of a double-walled dilatometer flask. This potential interference could result because of the greater thermal expansivity of the aggregate relative to the flask (pyrex) which might tend to distend the flask as the temperature of the dilatometer was elevated. However, no indication of this effect could be detected in any of the experiments. Apparently sufficient physical slippage (about 0.004 percent) occurs among the aggregate particles to accommodate the differential expansion between the aggregate and the flask.

Preparation of Aggregate. The described apparatus will accommodate aggregate up to approximately $\frac{1}{4}$ -in. in size. However, the maximum permissible size of aggregate may be increased by using a tapered joint having a larger throat dimension.

Various procedures may be used in the preparation of the aggregate. Sands may be used as received or crushed or screened. Coarse aggregate is crushed to the desired size with or without the separation of the sample into individual mineralogical types. The sample weight (approximately 1500 gm.) used and the crushing of the coarse aggregate assures

that the sample obtained can be satisfactorily representative of a heterogeneous aggregate stockpile.

Test Procedure. The aggregate is dried to constant weight, introduced into the dilatometer flask, weighed and the flask containing the aggregate evacuated by means of a vacuum pump through an auxiliary tapered joint-stopcock arrangement attached to the flask. The stopcock between the flask and the vacuum pump is closed and the flask completely filled with air-free water through the side arm of the flask, the bore of the stopcock in the side arm being filled with water prior to evacuation. It has been found expedient to have several dilatometer flasks for use with the capillary-bulb arrangement. Each flask can be filled by the described technique several days before the thermal measurements are made. This procedure avoids delay between determinations and also allows an initial aggregate absorption period which reduces systematic thermal drift during a determination. The effect of aggregate absorption will be discussed later. The previously prepared flask is equilibrated in the water bath at 25°C. The weight of the flask completely filled with water from the side arm stopcock to a reference mark (previously used for flask calibration) in the throat of the tapered joint is determined. The capillary-bulb arrangement is attached and the vertical stem of the capillary-bulb filled by the addition of water through the flask side arm. The mercury level in the capillary is adjusted and connected directly to the flask by rotation of the three-way stopcock.

The lower regulating contact and the common contact are connected to the water bath temperature control circuit, the system allowed to equilibrate at the lower contact level and the equilibrium temperature observed. The bath temperature controls are changed to the upper regulating contact, a reduced air pressure equivalent to the displacement of the mercury levels applied above the upper regulating contact, the equilibration procedure repeated, and the equilibration temperature observed. The use of auxiliary high-wattage bath heaters expedites the transition of the water bath temperature from the temperature corresponding to the lower contact to that corresponding to the upper contact. The transitions from the lower to the upper and the upper to the lower regulating contacts may be

upper contact and again at the lower contact determined on four consecutive days increased

TABLE 2
THERMAL COEFFICIENT OF EXPANSION OF
VARIOUS MATERIALS
(Nominal Temperature Range, 25-29°C)

Material and Source	Lot No.	Thermal Coefficient of Expansion $\times 10^{-6}$			
		Cubical		Mean Linear ^a	
		Per deg. C	σ^b	Per deg. C	Per deg. F
Pyrex Glass	18152	10.48	0.47	3.49	1.94
Marble, Georgia "Tate"—Gray	—	16.13	0.32	5.38	2.99
Marble, Georgia "Tate"—White	—	16.29	0.08	5.43	3.02
Trap Rock, Penn.	—	23.27	0.07	7.76	4.31
Granite, Camak, Ga.	18017	24.10	0.07	8.04	4.47
Granite, Lithonia, Ga.	18018	25.25	0.14	8.42	4.68
Trap Rock, Wis.	18263	25.59	0.18	8.53	4.74
Slag, Birmingham, Ala.	17983	27.68	0.28	9.23	5.12
"Sand-Gravel," Platte River, Schuyler, Nebr.	18154	28.05	0.07	9.35	5.20
Limestone, New York Dolomitic	16441	28.38	0.04	9.46	5.25
"Sand-Gravel," Platt River, S. Bend, Nebr.	17701	29.66	0.15	9.89	5.49
Limestone, Elmhurst, Illinois	17838	30.83	0.14	10.28	5.71
"Sand-Gravel," Florence Switch, Kansas Sand, Elgin, Illinois.	17834	30.88	0.07	10.29	5.72
"Sand-Gravel," Republican River, McCook, Nebr.	18172	30.94	0.10	10.32	5.73
Dolomite, Wis.	15203	31.03	0.03	10.34	5.75
Gravel, Eau Claire, Wisconsin	18278	32.05	0.06	10.68	5.94
Sand, Beloit, Wis.	—	32.35	0.06	10.79	5.99
Slag, Ensly, Ala.	17981	33.72	0.21	11.24	6.25
Limestone, Thornton, Illinois	—	34.61	0.02	11.54	6.41
Slag, Woodward, Alabama	17982	35.05	0.01	11.69	6.49
Sand, Standard, Ottawa, Ill.	—	35.53	0.02	11.84	6.58
Sand, Roquemore, Montgomery, Ala.	17854	35.69	0.14	11.90	6.61
Gravel, Roquemore, Montgomery, Ala.	17855	36.22	0.14	12.07	6.71
Sand, Victoria, Texas	17360	36.24	0.02	12.08	6.72
Sand, Chattanooga, Tenn.	17842	36.33	0.07	12.11	6.73
Gravel, Chattanooga, Tenn.	17843	36.34	0.17	12.12	6.73
Gravel, Chert, Grand River, Okla.	18382	37.87	0.25	12.63	7.02
Gravel, Victoria, Texas	17359	38.59	0.07	12.86	7.13
Copper	—	50.31	0.02	16.77	9.32

^a Calculated as $\frac{1}{3}$ of cubical coefficient.
^b Standard deviation

throughout the period. This slow increase represents the absorption of water by the aggregate with time, each additional increment of

absorption potentially reducing the gross volume of the flask contents and therefore requiring slightly higher temperatures to maintain the constant volume represented by either of the electrical contact positions. The amount of absorption that the slow temperature rise reflects may be calculated and in this particular example the average rate of absorption of water by the trap rock during the interval from 6 to 10 days is estimated as only 20 millionths of one percent per hour. In instances where aggregate absorption causes a significant reduction in fluid volume during a determination, the effect may be circumvented by re-

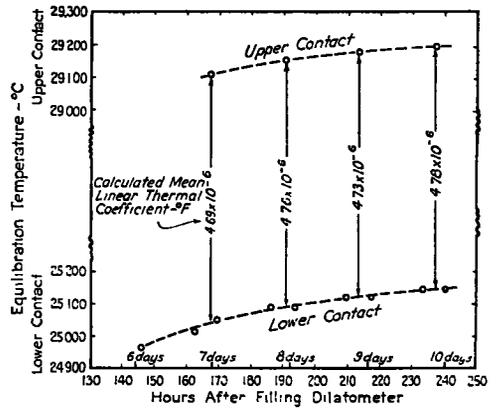


Figure 2. Effect of Continued Aggregate Absorption on the Dilatometer Equilibrium Temperatures Determined on Consecutive Days
Aggregate—Traprock from Dresser, Wis. (Lot No. 18263)

determining the temperature corresponding to the lower contact following the normal lower and upper contact equilibrations and interpolating between the two temperatures at the lower contact to the time of equilibration at the upper contact. Examples of this procedure as well as the thermal coefficient of expansion determined on each of the four consecutive days are shown schematically in Figure 2.

It has also been observed in these studies that the rate of water absorption of the aggregate, and hence the rate of temperature rise reflecting the change in fluid volume due to the absorption at any time after the addition of the water to the aggregate in the flask, is considerably less with more finely divided aggregate. Therefore in instances of excep-

tionally high aggregate absorptions during a determination, this effect can be appreciably reduced by crushing the aggregate sample to a finer size before use.

SUMMARY

The described dilatometer method is suitable for the determination of the thermal coefficient of expansion of sands and coarse aggregates and should be of value in conjunction

with the study of the effect of this factor on the degree of physical compatibility of the various components within concrete when subjected to temperature changes.

The method is particularly adaptable to the study of sands and also provides a means of obtaining and testing a representative sample of a heterogeneous coarse aggregate or of the various mineralogical portions comprising the coarse aggregate.

THERMAL EXPANSION CHARACTERISTICS OF HARDENED CEMENT PASTE AND OF CONCRETE

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SYNOPSIS

The apparent thermal coefficient of expansion of hardened, neat portland cement varies with its relative humidity, or state of moisture.

With relatively young pastes (less than one year old) the thermal coefficient is low at low relative humidities. As the humidity increases the apparent thermal coefficient reaches a maximum at about 70 percent, but as the relative humidity increases beyond this, the apparent coefficient again decreases, reaching a minimum, or true kinetic, thermal coefficient at water-saturation, or 100 percent relative humidity. This last condition is best attained by means of vacuum saturation.

Older pastes show the same thermal characteristics as young pastes, but to a lesser degree. The range of variation of coefficient with change of relative humidity is less; also the maximum coefficient appears to be somewhat below 70 percent relative humidity.

Generally the range between high and low coefficients of a hardened paste depends on the quantity of cement-gel present (i.e. extent of cement hydration), but there are exceptions indicating that some other factor, such as the structure of the gel or the diameter of its pores, is of some importance.

The apparent thermal expansion of concrete also varies with its state of relative humidity. The range between maximum and minimum coefficients is small compared with the range found in hardened, neat pastes, since the aggregate, having only a true coefficient independent of changes of swelling pressure with changes of temperature, restrains the greater thermal volume change of the paste within the concrete.

In general there is a relation between the magnitude of the moisture volume changes of a paste and the magnitude of change, or range, of the apparent thermal coefficient.

Other capillary materials possessing capillary voids within, or close to, the range in size of portland cement-gel pores also have a variable apparent coefficient of expansion, and their volume change with moisture change is also related to the extent of change of their apparent coefficient.

Under certain extreme conditions, such large volume expansions as are caused by alkali-aggregate reactions, or by sulphate action, are recognized as being harmful to concrete durability. Whether the lesser expansions and contractions due to moisture

changes and to thermal changes are harmful to concrete is still largely speculative. It is possible that thermal changes, acting in the same direction and in addition to other volume changes, or adding further strain to that already caused by mechanical stress, might be