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

a factor in causing fatigue or in exceeding the mechanical strength of the concrete. For this reason it is of some importance to know the magnitude of moisture and thermal volume changes and the various conditions affecting these changes.

Moisture volume changes in pastes and concretes are generally understood and well recognized, but the thermal volume changes occurring within cement paste, an integral part of concrete, are hardly recognized at all; only the variations of thermal characteristics of concrete aggregates are known. For the same kind of concrete, regardless of its storage condition, age, or relative humidity, the thermal volume changes are practically always assumed to be constant for a given temperature range. Actually, apparent thermal expansion of hardened portland cement pastes and concrete is variable, the magnitude depending largely upon the relative humidity within the hardened paste

METHOD OF TESTING HUMIDITY AND THERMAL EXPANSION

The method of determining relative humidity within cement and concrete prisms mainly follows that of Dunmore (*1*),[1] except that a more simplified means of measuring conductance was used. Because the small size of the test-pieces allowed only a $\frac{5}{16}$-in. hole to be cast or drilled in them, the bifilar winding was dispensed with and in its place a small glass rod with a platinized surface was used. This surface was separated into two parts, forming the terminals of the conducting system. A humidity-sensitive film connected the two platinized surfaces. Polyvinyl acetate "Solvar" in an alcoholic solution was made moisture-absorbing, thereby increasing the conductance of the film, by containing varying concentrations of lithium chloride. A single cell will not satisfactorily cover the whole range of humidity, and different concentrations of lithium chloride are used for different cells, depending upon the range to be covered. For highest humidities only a small concentration of lithium chloride is used; for dryer conditions more is required.

The humidity cells were kept in atmospheres of controlled humidity when not in use.

[1] Italicized figures in parentheses refer to references listed at the end of the paper.

These were easily made by placing certain salts in contact with their saturated solutions in small wide-mouth bottles with close-fitting rubber stoppers, each stopper having a hole into which a rubber fitting on the top of the humidity cell made an air-tight seal. Since the humidity cells were not entirely stable it was necessary to calibrate them before use if any length of time elapsed between tests.

Changes of temperature affected the conductivity of the cells in both the bottles and in the cement test-pieces, requiring that measurements be made at or near a constant temperature; 70 deg. F. was chosen.

Figure 10 shows the apparatus for measuring the conductivity of the humidity cells.

The source of current used was the ordinary lighting circuit of 110 volts. A very large resistance was used to reduce the current, so that even if the leads were shorted the microammeter range would not be exceeded. Slight variations in line voltage were compensated for by a small rheostat in series so that when the leads were shorted just before tests a standard current was obtained. To eliminate polarization the current through the humidity cell was a.c., while the current measured by the microammeter was rectified to d.c.

The test-pieces used were made in autoclave form molds. They were 1 in. in cross-section with an effective 10-in. length. Measurements were made in a comparator reading to 0.0001 in. An invar bar was used to standardize the comparator and correct for any fluctuations of room temperature.

The test-pieces were heated in a thermostatic air-circulating oven. The comparator was attached to the oven in such a way that the prisms could be measured within the oven, without changing temperature, while the comparator was still exposed to the air of the room.

VARIATION OF THERMAL EXPANSION WITH HUMIDITY

Figure 1 and Table 1 show the variation of the linear thermal coefficient of expansion of hardened, neat cement which had been mixed with 24 per cent of water and, after a short period of ageing, stored in air of constant humidity at 70 deg. F. for 4 months to allow moisture equilibrium to be attained throughout the specimens. The air surrounding the prisms in the different storage conditions was

kept at a constant humidity by various salts in contact with their saturated solutions. An exception is the 30 percent relative humidity in the drying storage, where only dry magnesium perchlorate dihydrate was used; this should have given zero humidity. With the other storage conditions, the measured hu-
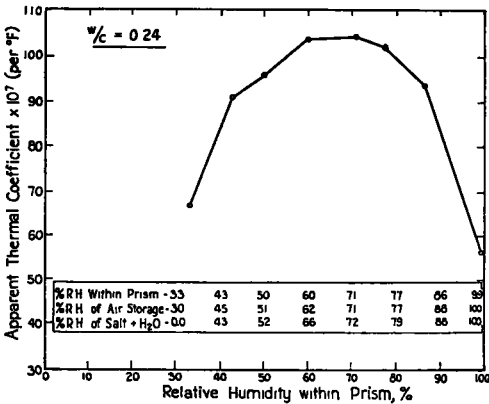

Figure 1. Influence of Degree of Drying (in terms of relative humidity) on the Apparent Thermal Coefficient of Neat Prisms Stored in Air Having Different Relative Humidities at 70 deg. F. for 4 Months

TABLE 1

CHANGE OF COEFFICIENT OF PRISMS STORED IN AIR OF CONTROLLED HUMIDITY

Neat .24 W/C Type I		Type I Autoclaves		Limestone Concrete		Quartz Concrete	
% R.H.	Coeffi- cient	% R.H.	Coeffi- cient	% R.H.	Coeffi- cient	% R.H.	Coeffi- cient
33	67	39	61	30	33	30	57
43	91	44	59	40	32	40	58
50	96	50	60	58	35	52	60
60	104	66	60	67	36	66	61
71	103	88	59	79	34	79	59
77	102	100	60	88	29	88	57
86	94			100	23	100	52
99	57						
Range of Co- efficient....	47		2		13		9

midity of the air storage and the measured humidity within the prisms were close to the desired humidity. (See humidity results in Fig. 1.)

At both high and low relative humidities the coefficient has a low value, but at humidities of 60 to 70 percent it reaches a maximum.

Figure 2 shows changes of length and of weight of the neat prisms during controlled humidity storage. The curve indicates no

change of length at 95 percent R.H., but a gain above this point and a loss below. The weight curve indicates no change at 85 percent R.H., with a gain above this point and a loss below. This further indicates that hydration would continue below 85 per cent R.H., because hydration could use the available water present in the larger capillaries without the specimen as a whole undergoing any change in weight.

Table 1 and the upper part of Figure 3 show the constant value of the thermal coefficient of steam-autoclaved prisms which had
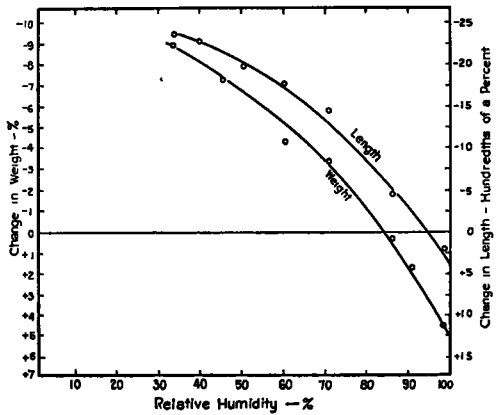

Figure 2. Length and Weight Changes of Prisms Stored at Different Humidities

The curves represent for prisms made of the same paste the change in weight or length from the original condition at the time of removal from molds and before being placed into controlled air storage.

been stored in air of different relative humidities. The test results do not differ any more than would be expected from variations of the method even if all the specimens were identical. When neat cement paste is autoclaved, practically no cement gel is present. The internal surface area of the microcrystalline structure is low and moisture and thermal volume changes are low. Since autoclaved specimens are low in cement gel content and do not exhibit changes in thermal coefficients with changes of relative humidity, it would appear that such changes of coefficient in ordinary neat hardened cement paste are dependent on its gel content.

In the lower part of Figure 3 is shown the relation between relative humidity and linear

thermal expansion of limestone and quartz concrete prisms. Just as adding aggregate to paste reduces moisture volume changes by restraining its movement, so the range between maximum and minimum thermal coeffi-

Figure 3. Effect of Degree of Drying (in terms of relative humidity) on the Thermal Coefficient of Autoclaved Neat Paste and Two Kinds of Concrete

midities is reduced as much in concrete having high thermal coefficient aggregates as with low-coefficient aggregates, assuming that the compressibility of both aggregates is the same and that the richness of the mix is the same. The thermal coefficient of the aggregates is not affected by variations in relative humidity as is the paste in concrete. (A possible exception would be a fine-structured porous aggregate with void diameters in the same size range as those of cement gel.)

Neat cement paste that has aged over long periods does not show as large a maximum thermal coefficient, nor does it have as great a range between maximum and minimum coefficient; also, the maximum coefficient is not near 70 percent R.H., but lower, sometimes approaching 40 percent.

In Figures 4A, B, and C, the upper curves represent test pieces up to about six months of age, while the lower curves represent test pieces aged 12 to 18 months. Figure 5 shows how the range of coefficient is decreased at 15 and 16 yr. of age. No humidity measurements were made on test-pieces represented by the upper curves. The humidities are assumed
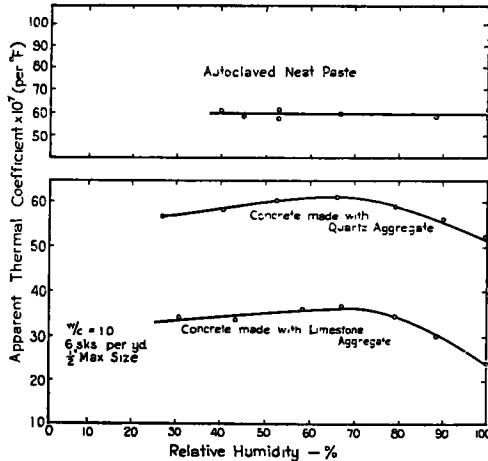
TABLE 2
EFFECT OF AGE IN REDUCING RANGE OF COEFFICIENT

Year Made	1933	1934	1934	1935	1936
Type of cement . .	I	I	I		I
Compounds . .	9-10-13-64	9-9-23-50	9-10-20-54	C₄AF	9-9-14-60
W/C	.40	.24	24	19	.225
Max. Coefficient	114	118	121	112	119
Min. Coefficient	52	52	53	70	50
Range of Coeff. . .	62	66	68	42	69

	AFTER 14–17 YEARS									
	%R. H.	Coeff.	%RH	Coeff.	% R. H.	Coeff.	% R. H.	Coeff	% R.H.	Coeff.
	100	53	100	52	100	53	100	77	99	55
	96	55	92	70						
	90	70	86	72	68	83	80	80	83	66
	65	81	81	77	50	93	75	80	60	97
	54	80	55	93	44	85	40	89	58	99
	40	85	44	94	35	69	36	91	44	96
Range of Coeff. for Aged Pastes		32		42		40		14		44

cient is reduced in concrete. If the concrete contains aggregate with a low coefficient of expansion, its thermal coefficient is reduced considerably over the whole range of humidity, while if the aggregate has a high thermal expansion rate the thermal expansion of the concrete, as compared with the paste it contains, is not reduced as much; but the range of change of thermal coefficient at different hu-

from later experiences with similar pastes at the same age.

Figure 6 shows the effect of drying to different relative humidities during early storage periods of a few months, then increasing the relative humidity. Those prisms kept humid during early storage appear to have slightly higher coefficients.

Figure 7 shows a comparison of hardened

pastes with added voids in the visible range, and without added voids. Little effect is evident.

Figure 8 shows the relation between change of length due to moisture changes between 40 percent R.H. and saturation, and change in thermal coefficient. Some of the materials rep-

solids is a great deal more than that of liquids. This, coupled with the enormous surface area present in cement gel (2), suggests that there is considerable force striving to reduce the surface of the gel and increase particle size, but being opposed by the rigidity of the gel; however over a long period of time, and be-
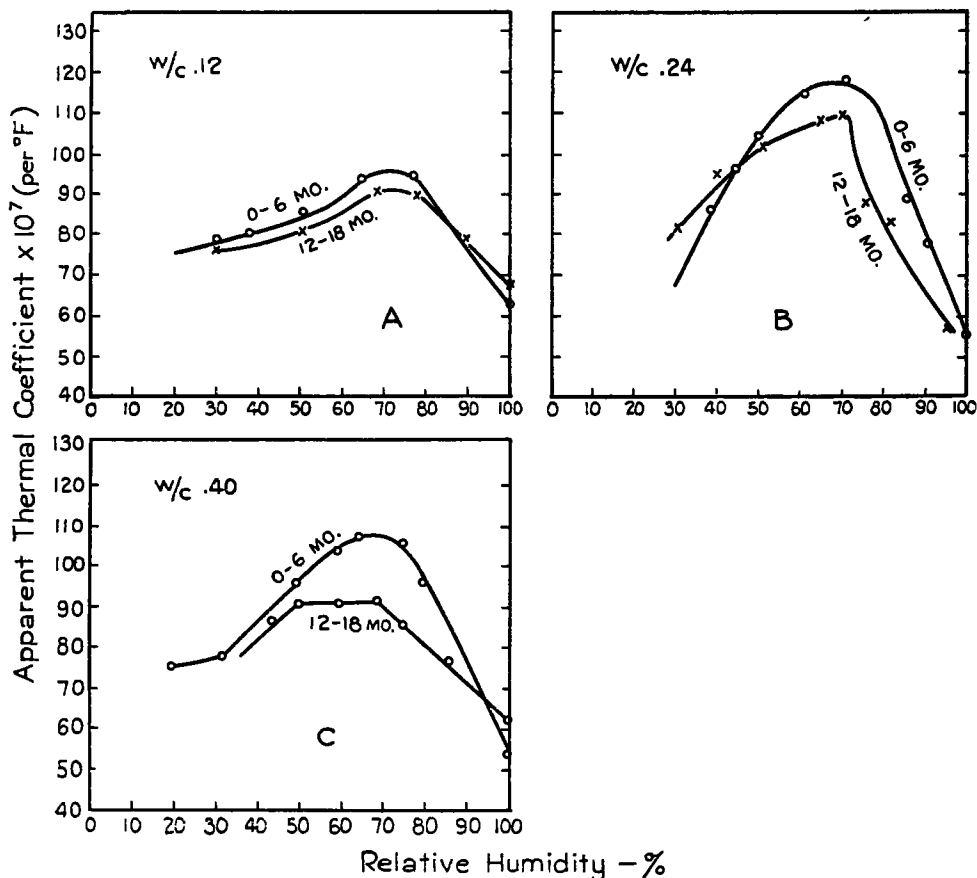

Figure 4. Effect of Age on Pastes Having Different Water—Cement Ratios
The two curves represent tests made on the same specimens.

resented are colloidal materials other than cement. Generally, those materials having a large moisture volume change have a corresponding large range of apparent thermal coefficient.

Table 3 shows that old pastes adsorb less moisture than younger pastes at 52 percent R.H., indicating that they contain less cement-gel and therefore less specific surface.

The free surface energy (surface tension) of

cause of movements within the gel, some decrease of gel or reduction of surface area would be expected.

Doelter (3) in discussing colloidal minerals, says "only a limited number of compounds have the property of enduring as gels for a long period; the majority soon become crystalline". S. Giertz-Hedstrom (4) in discussing the physical structure of hydrated cements, says, "The cement gel is in its colloidal form
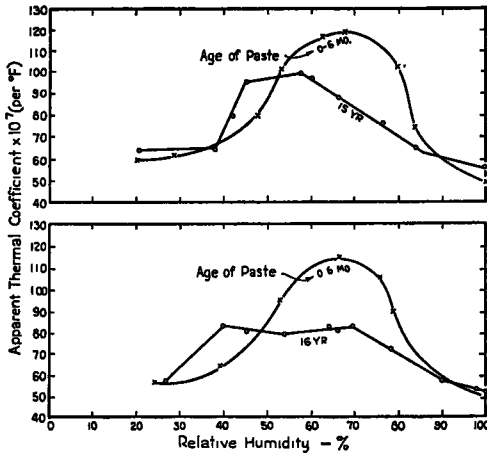
Figure 5. Effect of Age

STRUCTURE OF HARDENED CEMENT PASTE

When cement and water are mixed into a paste there results a loose aggregation of solid, unhydrated cement particles with void or capillary spaces filled with water between the particles. As chemical reaction between cement and water proceeds, solids plus water of hydration increase the bulk of solids with the formation of cement gel. (5) The characteristics of the cement gel are extremely fine pore structure, with pore diameter only a few millimicrons, and a very large internal surface area.

The larger capillary voids of the paste, initially filled with water, decrease in size by gel bulking. As hydration proceeds the smaller paste capillaries may be completely filled. As the paste approaches a fairly well
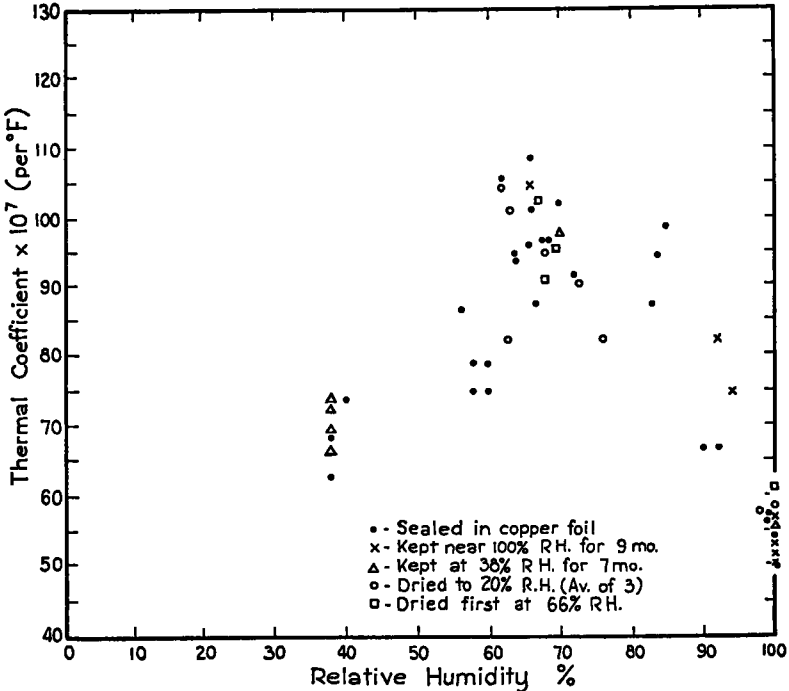

Figure 6. Effect of Drying in Different Relative Humidities During Early Storage Periods
Prisms made from the same paste were dried under different initial drying conditions, kept at this dried condition for some time, and were then subjected to cycles of changing humidity. During this time the apparent thermal coefficients were measured.

not a final stable product, but must, by gel coarsening and crystalline growth, go the same way as other inorganic colloids in nature".

hydrated condition there are possibly present in the hardened paste: (1) Capillaries, or submicroscopic voids, filled with water or air and not completely filled with cement gel.

(2) Cement gel with many pores, relatively small compared with the paste capillaries.
(3) Crystalline bodies, such as calcium hydroxide, calcium sulpho-aluminate and carbonated materials; also some unreacted clinker residues.

The water in cement paste may be arbitrarily classified into evaporable water and nonevaporable or chemically combined water which is not removable under stated conditions of vapor pressure. Evaporable water consists of free water in the larger voids, partially-bound water held in capillaries, gel water, and surface adsorbed water, which is more firmly held.

If hardened cement paste is dried to remove all of the arbitrarily-defined evaporable water, and then placed in an atmosphere of very low but continuously increasing relative humidity, water would probably be taken up by the cement in the following order: first, a monolayer of water molecules covering all surfaces; next, multilayers of water molecules adsorbed on surfaces and some capillary condensation at contact points of solids; and finally, capillary condensation of water in gel-pores and, with increasing relative humidity, in paste capillaries until all accessible voids are filled.

According to Powers and Brownyard (6) all of the gel pores are not filled with water at a relative vapor pressure of about 40 percent, at which capillary condensation may begin, and some gel water is still being taken up at over 80 percent relative vapor pressure.

The apparent thermal coefficient of neat, hardened cement paste is at a minimum when completely water-saturated, i.e., when all pores and capillaries are filled with water. Owing to the great impermeability of low water-cement ratio pastes, water storage alone may not always accomplish this. Higher water saturations can be attained by vacuum treatment, covering with water, and then allowing atmosphere pressure to be applied. The test-piece should first have all of its evaporable water removed. The coefficient is also at a minimum in pastes which are "bone dry"; that is, have all their evaporable water removed. In these two cases we have the true kinetic thermal coefficient alone.

In between the conditions of 100 percent R.H. and zero R.H., there is a condition of compressive force acting on the solid phases

of the paste. Figure 9 shows the relation among capillary pressure, radius of pores, and percent relative humidity. Changes in the intensity of this compressive force, acting
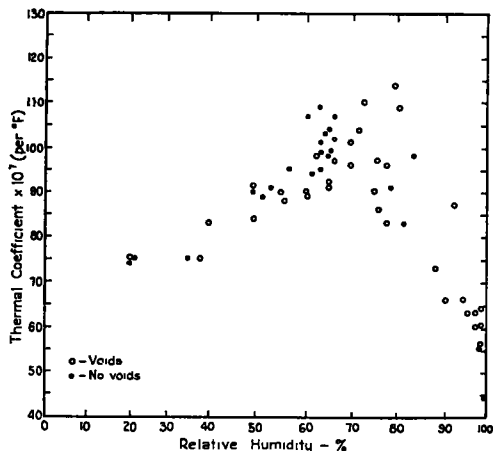
Figure 7. Apparent Thermal Coefficients of Pastes Made With and Without Macroscopic Voids

The added voids were made by introducing 10- to 20-mesh bits of sponge rubber or diatomaceous earth.

Figure 8. Comparison of Length Changes Due to Moisture Volume Changes with Thermal Coefficient Changes

through the compressibility of the solid phase, cause swelling or shrinkage in the same direction as the true thermal change, resulting in a larger apparent thermal change. In the case of cement pastes below 40 percent R.H. having no capillary condensed water and only

adsorbed water on the solid phase, the apparent thermal coefficient of expansion is low, but still greater than the true thermal coefficient indicated by water-saturated pastes.

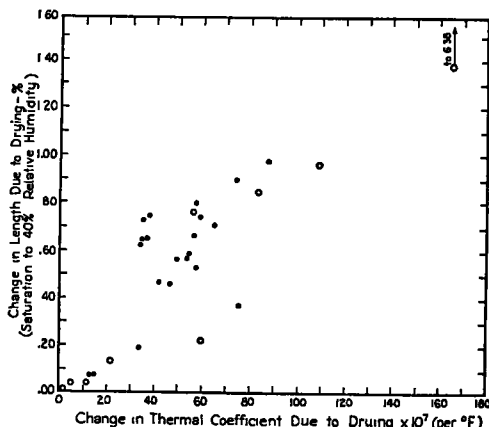The potential swelling pressure follows from Kelvin's law of vapor pressure. Changes in pressure are given by

$$- \frac{RT}{Mv_f} 2.303 \log_{10} H$$

At the higher vapor pressure where a water meniscus can form, tension exists in the liquid and compression in the solid phase. Laplace's law gives the force of capillary tension as:

$$\sigma \left(\frac{1}{r_1} - \frac{1}{r_2} \right)$$

where σ is the surface tension of water (in the cement paste), and r_1 and r_2 are radii of

TABLE 3

NON-EVAPORABLE WATER, EVAPORABLE WATER AT 52 PERCENT RELATIVE HUMIDITY, AND CARBON DIOXIDE CONTENT OF NEAT, HARDENED PASTES FROM PRISMS, AS PERCENTAGES OF ORIGINAL CEMENT CONTENT

Description of Prisms	Age	W/C	$W_n{}^a$	W_e at 43% R.H.	W_e at 52% R.H.	$\dfrac{W_n}{W_{e.52}}$	CO_2
Type I from ASTM Autoclave test	1 mo.	.25	10.81	1.16	1.33	8.13	.84
Type I held in steam at 200 psi. for 2 mo.	16 yr.	.24	12.04	0.27	0.28	43.00	2.45
Type I (See Fig. 4)	18 mo.	.24	13.63	4.33	4.71	2.89	0.89
Type I (See Fig. 4)	18 mo.	.40	17.87	5.66	6.18	2.89	1.02
Type III .	18 mo.	.24	14.36		5.02	2.86	0.74
Type I, Control in Aquagel series	1 mo.	.24	9.94		3.19	3.11	1.17
Low-lime, Hi-surface	18 mo.	.24	12.27		4.20	2.92	0.65
Type I, sealed storage	11 mo.	.24	17.75	4.58	5.08	3.49	0.54
Type I, initial storage 20% R.H.	11 mo.	.24	12.96	4.82	5.19	2.49	0.63
Type I, water storage	11 mo.	.24	13.46		4.66	2.89	0.50
Type I, kept at 38% R.H. for 9 mo., then water storage	11 mo.	.24	12.27		3.14	3.91	0.48
Type I, 20,000 psi. pressure molded	18 mo.	.12	5.80		1.74	3.33	0.33
Type I, 20,000 psi. pressure molded	20 mo.	.10	6.27		2.47	2.54	0.19
Type I, 20,000 psi. pressure molded	20 mo.	.10	9.11	1.98	2.25	4.05	0.48
Type I, 14,000 psi. pressure molded	14 yr.	.15	7.24		2.23	3.25	0.72
Type I, started in air storage	20 mo.	.45	13.49	5.17	5.90	2.29	2.24
Type I, started in air storage	20 mo.	.24	13.26	4.43	4.70	2.82	0.98
Type I, started water storage for long period.	20 mo.	.45	19.06		7.44	2.56	0.64
Type I, initial water storage	20 mo.	.24	13.60		5.22	2.61	1.63
Type III, low W/C	12 mo.	.27	13.55		3.40	3.99	0.59
Type III, higher W/C	12 mo.	.50	19.42		6.87	2.83	1.58
Type IIIA, very high W/C	12 mo.	.80	21.86		9.96	2.19	2.41
Type III, control	12 mo.	.40	18.39		7.43	2.48	0.60
Type III, remolded with pressure, 7,500 psi.	12 mo.	.40	20.06		8.90	2.25	0.74
Type III, remolded using 13,000 psi.	12 mo.	.40	19.61		7.65	2.57	0.78
Type III, remolded using 20,000 psi........	12 mo.	.40	19.03		7.17	2.65	0.64
Type I, kept at 43% R.H. for 8 mo...	8 mo.	.24	11.95	4.48	4.98	2.41	1.62
Type I, first 8 days at 32 deg. F..	13 yr.	.26	15.67	5.28	5.60	2.80	0.59
Type I (2% $CaCl_2$)..	16 yr.	.24	12.97	2.22	2 68	4.84	1.98
High Alumina 4-32-0-58	17 yr.	.42	22.14	3.59	3 81	5.81	0.50
Type I	14 yr.	.23	12.85		3.76	3.42	1.02
C_4AF.	15 yr.	.19	21.17		2.75	7.70	3.07
Type III, continuous water storage at 70 deg F. . .	16 yr.	.27	19.43	7.00	7.25	2.68	0.46
Type IV, 6-3-54-29 water storage at 70 deg. F..... .	16 yr.	.23	13.48	5 14	5.30	2.54	0.42
Type V, 17-0-12-63	16 yr.	.23	15.06	5.03	5.10	2.95	0.16

^{a} Corrected for CO_2

where R is the gas constant; T the absolute temperature; M the molecular weight and v_f the specific volume of water; and H the relative vapor pressure.

If either T or H varies, the potential swelling pressure varies; if H varies moisture volume changes result. If T is increased the potential swelling pressure acting on the surface of the solid phase is decreased and the volume of the solid phase increased, due to the resulting elastic deformation or extensibility. This increase of volume plus the true thermal expansion of the paste results in the larger apparent thermal coefficient.

curvature of the water meniscus. As σ decreases with rising temperature so will the compressive force acting on the solid phase, again causing an increase in volume in addition to the true thermal increase.

For those cement pastes which have not aged a long time, the maximum apparent thermal coefficient is near 70 percent R.H. At 100 percent R.H. both paste capillaries and gel pores are filled with water, no menisci are present, and H in Kelvin's equation is unity; so neither capillary tension nor potential swelling pressure is present, and no volume deformations can result from these fac-

tors. As water evaporates from the paste and the capillaries and gel pores become only partly filled, and vapor pressure decreases, these forces increase in intensity. But there probably is a point, at least in the case of capillary tension, when the effect of this increase is offset by the reduction in area of the wetted surfaces, or reduction in any cross-section which is filled with water; and this point might be 70 percent R.H. for hardened cement pastes.

As the relative humidity of pastes that are not aged approaches lower values the coefficient also becomes less. As above, this also might be due to the percentage of wet areas, or wet volumes, decreasing with lower vapor pressures; but there is another factor which influences this condition: if cement-gel follows the same behavior as other colloidal gels, with an increase of swelling (higher water content) the bulk modulus decreases (the compressibility increases). Conversely, as the gel dries with decrease of relative humidity, its compressibility decreases and there is less volume change for a given change of compressive stress. This would reduce the value of the apparent thermal coefficient of pastes containing dryer gels. Bessey and Dilnot (7) show that the compressive strength of completely dry, aerated concrete decreases with an increase of moisture content. This they attributed to the distension and weakening of the cement gel by water absorbed into the gel.

EFFECT OF AGE ON NEAT AERATED PASTES

As Figures 4 and 5 show, aged neat pastes have a maximum coefficient at a lower relative humidity than pastes not aged to the same extent. This could be caused by one or more of the following: (1) The filling up, or sealing off, of that size of capillary most effective in creating tension in liquid in the 50 to 70 percent R.H. range. (2) The absorption of carbon dioxide, forming crystalline material at the expense of gel or microcrystalline material. (3) Reduction of gel surface, indicated by lowering of adsorption capacity. (4) Decrease of compressibility (increase of bulk modulus associated with increase of strength with age).

In Table 3 some figures are given for non-evaporable water W_n and evaporable water W_e, at 52 percent R.H., and for carbon diox-

ide content of pastes at various ages and conditions. W_n may be considered to be a measure of the extent of hydration, while W_e, at low relative vapor pressures, is a measure of the quantity of gel in the paste. As there is probably some capillary condensation at 52 percent R.H., it would have been better to have made all adsorption tests at a lower humidity; however, the tests which were made at 43 percent R.H. did not indicate a large amount of capillary condensation between these relative humidities, and probably the
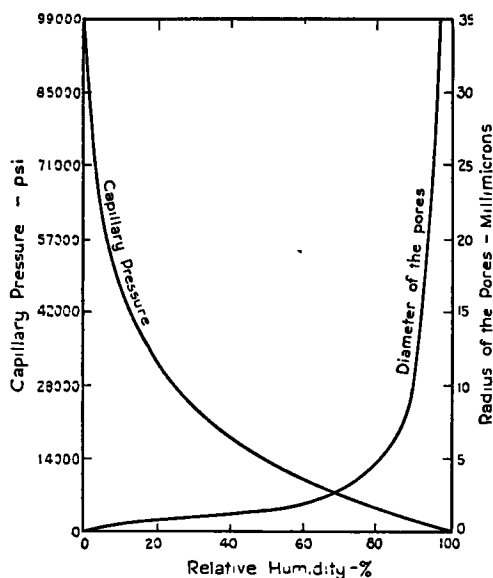

Figure 9. Relation Between Capillary Pressure, Pore Radius, and Relative Humidity
From S. Giertz-Hedström

tests at 52 percent R.H. are fairly indicative of gel content.

The column headed by $\dfrac{Wn}{W_{e.52}}$ in Table 3 then shows the ratio of hydration to gel content. In general, a high ratio is associated with a small range of apparent thermal coefficient, and a ratio between 2.5 and 3.0 is associated with high apparent coefficients. Autoclaved and steamed test-pieces show little gel and high $\dfrac{Wn}{W_{e.52}}$ ratios, and practically no variation of apparent thermal coefficient.

Pastes of unhydrated cement, mixed with a small amount of water and molded under great pressure, show little hydration, small
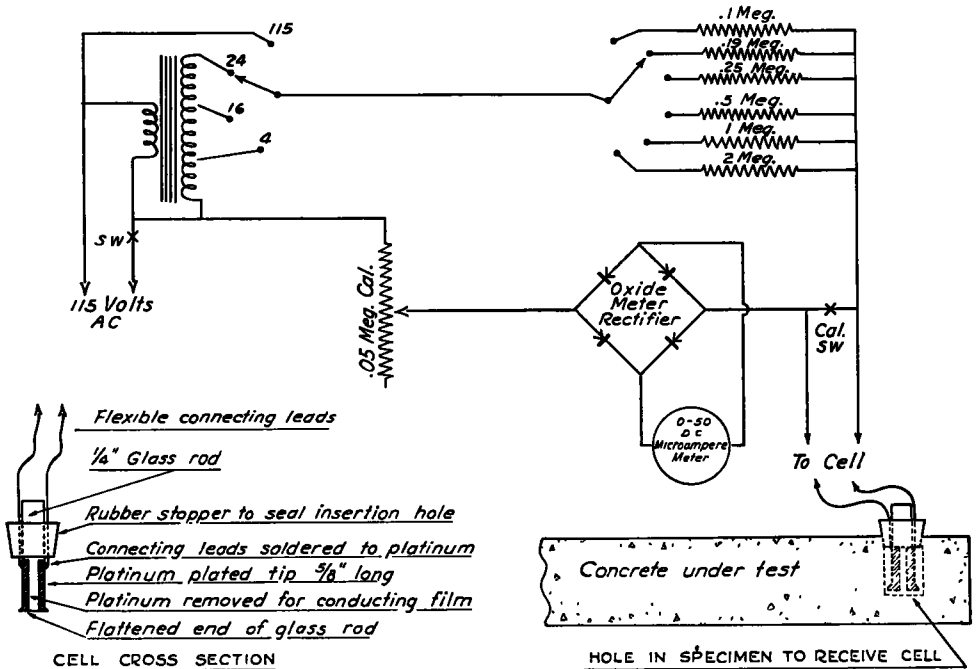
Figure 10. Apparatus for Measuring Humidity in Test Specimens

TABLE 4
EFFECT OF ADDING BENTONITE TO NEAT CEMENT

Control, No Bentonite			Mix of 25% Bentonite			Mix of 40% Bentonite		
Length change in .01%	% R.H.	Coeff.	Length change in .01%	% R.H.	Coeff.	Length change in .01%	% R.H.	Coeff.
Init.	79	82	Init.	95	134	Init.	100	58
−3	77	96	−32	90	142	−43	75	169
0	73	100	−15	90	144	−18	68	166
0	70	101	−21	70	134	−9	65	129
−1	60	107	−11	66	135	−28	42	114
−4 (dried)	58	114	−10	60	134	−17	35	81
0	57	105	−11	56	103			
			0	56	94			
Range of Coefficient (assuming sixty as a minimum coefficient)..	54			84				109

TABLE 5
RANGE OF CHANGE OF COEFFICIENT OF SOME NON-CEMENTITIOUS MATERIALS AND OF LENGTH CHANGE CORRESPONDING TO THE SAME HUMIDITY CHANGE

	Length Change, .01%	Coeff. Change
Wood, with the grain	13	22
Wood, across the grain.............	638	163
Porcelain pores 1μ diam.............. ...	1	2
Soapstone..	4	11
Silica-gel in plaster..	22	60
Plaster.	4	5

amounts of gel, and a relatively small range of coefficient. The large amount of unhydrated cement in low-W/C pressure neats acts to restrain volume changes; and the range of apparent coefficient is reduced because of this condition and also, perhaps, because of the very small amount of paste capillaries in very low W/C pastes.

Aged pastes subjected to changes of humidity and to varying temperatures, showed extended hydration, rather low gel content

with a high $\dfrac{W_n}{W_{e.52}}$ ratio, and a small apparent thermal coefficient range.

Pastes of remolded, hydrated cement show the opposite results, high W_n and W_e at 52 percent R.H., a low ratio between the two, and a high range of thermal coefficient. Specific gravity tests indicate that these prehydrated, remolded, pressure neats still contained paste capillaries.

NON-CEMENTITIOUS MATERIALS

In Table 4 may be seen the marked effect on the thermal coefficient of mixing bentonite with cement. The separation of montmorillonite platelets by a water layer is only about 1½ millimicrons (8). This is somewhat smaller than the order of diameter of cement-gel pores. The smaller size of pores, or separating planes, results in a greater intensity of potential swelling pressure, moisture volume changes, and apparent thermal coefficient of expansion changes.

Other colloidal materials such as wood and silica gel also show a large change of apparent thermal coefficient.

The following materials have relatively large pore diameters, and all had both small moisture volume changes and a small range of apparent thermal coefficient of expansion: plaster of Paris, porcelain ultra filters with pores in the range of 1.2 microns, soapstone, burned clay, and diatomaceous earth.

EFFECT OF VARIATION IN APPARENT THERMAL COEFFICIENT OF EXPANSION ON DURABILITY OF CONCRETE

Small concrete prisms, W/C = 1.0, mix 1:2.5:3, ¾-in. maximum aggregate, with relative humidity varying from 20 to 100 percent were made. In one case three prisms were made of coarse aggregate limestone and fine aggregate quartz, in the other three prisms of coarse aggregate quartz and fine aggregate limestone. All were sealed in copper foil and subjected to 18,000 cycles of alternately heating to 130 deg. F. and cooling to 75 deg. F. Each cycle was completed in 18 min.

Owing to part of the cycle being in cool water and part in hot air, the humidity within the concrete prisms could not be controlled as closely as desired. All expansions were small and the concretes appeared sound at the end of the test, indicating that cement pastes having a variable apparent thermal coefficient of expansion in concrete do not greatly contribute to lack of durability under the conditions of this test.

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