FACTORS AFFECTING VOLUME CHANGES IN CONCRETE AND THEIR SIGNIFICANCE IN DESIGN

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SYNOPSIS

A committee report on the factors affecting the volume changes of concrete, and their significance in the design of concrete mixtures, and the structures in which the concrete will be used The existing information is reviewed and the significance of the results of tests is analyzed The effects of cement, proportions, consistency, curing, age, water content, temperature, aggregates, admixtures, and combined stresses upon volume changes due to stress and to causes other than stress are discussed in detail Important factors in need of additional research are, relationship between modulus of elasticity of concrete and characteristics of aggregates, plastic flow of concrete, and thermal properties of concrete

This report presents a brief discussion of the factors affecting the volume changes that may be expected to occur in a finished concrete structure and attempts to point out the need for further research in this field The committee is presenting but little new data and is not attempting a new interpretation of existing data Most of the material has been published but is not in such a condensed form that it is likely to be utilized to the fullest extent by the engineer designing a concrete mixture for a certain specific purpose or in utilizing this concrete in the design of a structure

Recent progress in the study of the design of concrete mixtures has reached such a stage that the knowledge of the strength which the concrete will attain is such as to justify the use of much higher working stresses than has customarily been the practice Before these maximum usable stresses can be used safely it is, however, important that complete consideration be given to subsequent volume changes which may occur and possibly quite radically change the stress distribution originally assumed Difficulties in making complete use of the present information are pointed out

For purposes of analysis these volume changes may be divided into two groups:

1 Volume changes due to stress
2. Volume changes due to causes other than stress

In general, the engineer is chiefly interested in the changes in linear dimensions which accompany or cause these volume changes. Only in the case of three dimensional loading is the actual volume change of particular significance

Volume changes due to stress can be divided into two general classifications; elastic deformation measured by the modulus of elasticity and Poisson's ratio, and the inelastic or plastic deformations usually spoken of as "flow" or "creep"

The factors which may be expected to affect these characteristics in concrete are:

1. Cement.
2. Quantity of cement (richness of mix)
3. Water-cement ratio
4. Consistency of the concrete
5. Method of curing
6. Age of the concrete
7. Water content of the hardened concrete
8. Temperature of the concrete
9. Character of the aggregate
10. Gradation of the aggregate
11. Shape of coarse aggregate
12. Quantity of aggregate
13. Admixtures, inert or chemically active
14. Effect of combined stress, stress variation, etc

In studying the effect of these variables upon the extent of volume change produced by stress in concrete, the way in which the properties, modulus of elasticity, Poisson's ratio, and plastic flow are affected by each variable will be considered

Cement Very little work has been done to determine directly the effect of variations in chemical composition or fineness of grinding of the cement upon any of these properties It is probable that the chief effect of the cement as such is exhibited through the effect it has upon the strength of the concrete

In general, there is little, if any, indication of relationship between Poisson's ratio and strength of concrete

The value of the modulus of elasticity increases with the compressive strength of the concrete Walker (1)[1] found that the value of the modulus of elasticity of concrete for mixtures leaner than 1 3 could be represented by the equation $E = CS^m$, where $E =$ the modulus of elasticity of the concrete, C is a constant, $S =$ the compressive strength of the concrete, and (m) is an exponent Walker also reports that the shape of the stress strain diagram is a curve which can be represented by the equations $s = Kd^n$, where $s =$ the unit stress in the concrete, K is a constant which depends upon the strength of the concrete, and n is an exponent approximately constant

Earlier investigations all seemed to indicate the correctness of this form of stress strain curve but some contemporary and later investi-

[1] Figures in parenthesis refer to reports listed in the bibliography

gations have indicated that up to the elastic limit and well above any ordinary working stress, a straight line relationship existed.

Probably all are substantially correct. Earlier investigations dealt largely with lean mixtures and relatively low values of compressive strength and modulus of elasticity; later investigations indicate that for richer mixtures and stronger concretes the curve more nearly approaches a straight line and within working limits, it may be assumed to be such.

Davis (2) reports increased resistance to plastic flow with increased strength of the concrete.

Summing up the probable effect of the cement upon these factors it would seem that there is a lack of any considerable data indicating variations due to cement except as it affects the strength of the concrete.

Quantity of Cement. The quantity of cement has the effect of increasing the compressive strength of the concrete and the modulus of elasticity. The effect of certain aggregates upon the value of the modulus is, however, so great that in many cases the leaner concrete being denser may have a higher modulus of elasticity at ages up to six months than the richer mixture in a stronger concrete. Noble (3) reports that there is no relationship between the richness of mix and the value of Poisson's ratio. Tests by Davis and Troxell (4) are in agreement with this conclusion.

Data on the effect of richness of mix or cement content upon the plastic flow of concrete is rather limited. The most extensive work in this field has been reported by Davis, his conclusions are that, other things being equal, the leaner the mix the greater the flow. Variations in gradation of aggregate have a more marked effect upon lean mixes than upon the richer ones. A 1:7 mix with fineness modulus of 6.60 had double the flow of a 1:4 mix of the same fineness modulus, with a fineness modulus of 3.52 the 1:7 mix had a flow three times as great as the 1:4 mix.

Water-Cement Ratio. The general effect of the water-cement ratio is to increase the compressive strength of the concrete as the water content decreases, with a consequent increase in the value of the modulus of elasticity with the same possible exceptions as noted for richness of mix. For the same water-cement ratio the value of the modulus of elasticity will increase with a decrease in the cement content. Practically all investigators whose data bear upon this point report no variation of Poisson's ratio with the water-cement ratio. The effect of this variable upon plastic flow has not been investigated except as it influences the strength of the concrete.

Consistency of the Concrete. Again there are very few data to show whether this variable in any way affects the properties under consideration except as the strength may vary due to changes in cement content and water-cement ratio

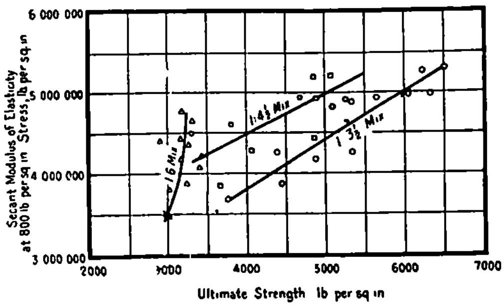

Figure 1 Relation between Ultimate Strength and Secant Modulus at 800 Lbs Per Sq. In Sandstone Concrete. From Davis and Troxell, " Modulus of Elasticity and Poisson's Ratio for Concrete and the Influence of Age and Other Factors upon These Values." Proceedings American Society for Testing Materials, Vol 29

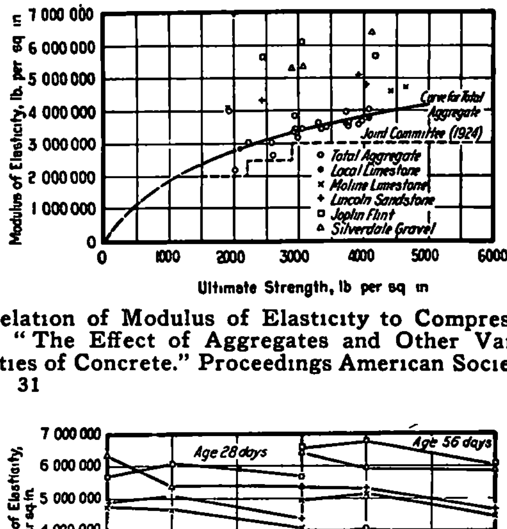

Figure 2. Relation of Modulus of Elasticity to Compressive Strength. From Noble's, " The Effect of Aggregates and Other Variables on the Elastic Properties of Concrete." Proceedings American Society for Testing Materials, Vol 31

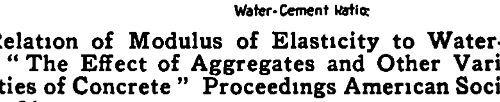

Figure 3 Relation of Modulus of Elasticity to Water-Cement Ratio. From Noble's, " The Effect of Aggregates and Other Variables upon the Elastic Properties of Concrete " Proceedings American Society for Testing Materials, Vol 31

Method of Curing Practically no data are available except as curing may affect the strength of the concrete and thus indirectly, the other properties Its effect upon the moisture content of the finished concrete may also be significant.

Age of Concrete A number of carefully conducted researches have been reported showing the effect of age upon the elastic properties and plastic flow of concrete and all are in substantial agreement

The value of the modulus of elasticity increases rapidly during early ages, particularly the first six months Then the rate of increase slows down rapidly becoming nearly zero at 3 years In fact, no substantial increase occurs after the second year Some investigators report a decrease with age, but it is probable that unaccounted for changes in moisture content produced this result Rich mixes continue to show an increase in the value of the modulus for a much longer time than do lean mixes It is generally agreed that the value of Poisson's ratio increases with age for about one year, varying from about 0 15 to about 0 21

The effect of age at time of loading upon plastic flow is also fairly well established In general, concrete loaded at early ages seems to

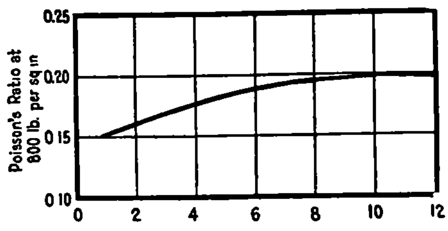

Figure 4 Effect of Age upon Poisson's Ratio Granite Concrete. From Davis and Troxell, " Modulus of Elasticity and Poisson's Ratio for Concrete and the Influence of Age and Other Factors upon These Values " Proceedings American Society for Testing Materials, Vol 29

reach a state of equilibrium where plastic flow practically ceases much sooner than does concrete loaded at later ages (5)

Water Content of the Hardened Concrete Much is yet to be learned of the effect of the water-content of hardened concrete upon its physical properties It is generally known that a saturated test specimen will show a lower compressive strength than a dry one It is not generally known that drying lowers the modulus of rupture and the modulus of elasticity Most investigators are in agreement that the value of the modulus of elasticity decreases with the decrease of water content of the concrete Concrete which has been oven-dried does not recover its original value when the moisture is re-absorbed

Variations in moisture content have little if any effect upon the value of Poisson's ratio

Plastic flow is much greater for dry than for wet concrete, being in some instances 70 per cent greater

Temperature of the Concrete Although it would seem reasonable to expect that the temperature of the concrete at the time of test or loading would affect the elastic properties and plastic flow, no data on this point are available. Prof R E Davis at the University of California has reported some indications that the temperature at the

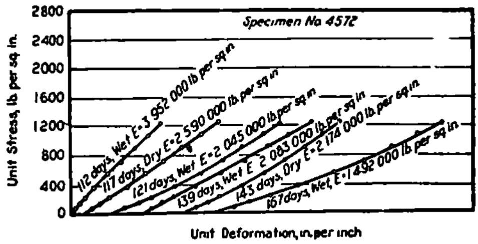

Figure 5. Effect of Oven Drying on Modulus of Elasticity Oven Temperature 100° C. From Noble's "The Effect of Aggregates and Other Variables on the Elastic Properties of Concrete. Proceedings American Society for Testing Materials, Vol 31

time of test changed the strength of the concrete but he was not able to give positive data as to its effect

Character of the Aggregate Of all the known variables that affect the value of the modulus of elasticity of concrete the coarse aggregate introduces variations greater than all others combined. Noble (6)

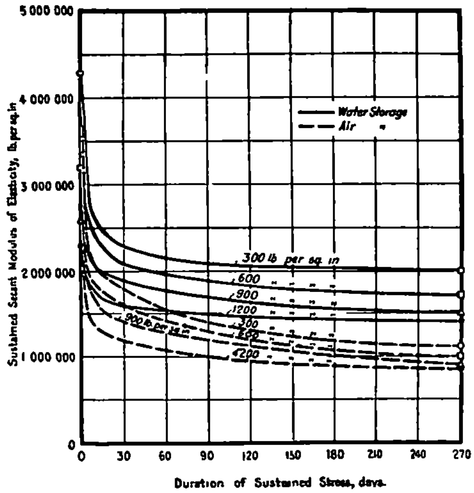

Figure 6 The Effect of Sustained Stress upon the Sustained Modulus of Elasticity, Stress Applied Three Months. From Davis and Troxell, " Modulus of Elasticity and Poisson's Ratio for Concrete and the Influence of Age and Other Factors upon These Values " Proceedings American Society for Testing Materials, Vol. 29

shows that for similar strength concretes of equal ages, variations of approximately 100 per cent in the value of the modulus may occur (See Figures 2 and 3)

Strange to say, such striking variations in the value of the modulus of elasticity do not seem to produce corresponding changes in the value of Poisson's ratio.

There are no data indicative of the effect of the coarse aggregate upon the plastic flow of concrete.

Gradation of Aggregate and Effect of Shape of Particle Information concerning the effect of the gradation of the aggregate or the shape of the particles upon these properties of concrete is inadequate In general, if the concretes have equally satisfactory strengths an increase in the fineness modulus with a decrease in cement content, will cause a higher modulus of elasticity. No data are available on the effect of shape of particle Other things being equal, a lower fineness modulus and lower strength increases the plastic flow (See remarks under " Quantity of Cement ")

Quantity of Aggregate For the same strength of concrete the leaner the concrete is the higher the modulus of elasticity will be In certain instances at ages up to one or two years, this tendency may off-set a considerable increase in cement content and compressive strength

The value of Poisson's ratio is apparently little affected by the quantity of aggregate.

No data are available on the effect of quantity of aggregate upon plastic flow in which the strengths of the concrete are the same If the strengths are allowed to vary, the general effect is as noted under " Cement Content "

Effect of Admixtures No data are available on the effect of admixtures upon the elastic properties and plastic flow of concrete. Noting the variables previously discussed, it will be observed that those affecting the quality or character of the paste had little influence upon the value of either the modulus of elasticity or Poisson's ratio excepting as they changed the strength or the water content of the hardened concrete.

Effect of Combined Stress, Stress Variation, etc The effect of combined stress, repeated loadings and continuous loading upon the elastic properties of concrete is very marked Richart, Brandtzaeg, and Brown (7) show that the initial tangent modulus under three dimensional compressive loading is from one-fifth to one-half of the initial modulus shown by a simple compression test.

In general, the effect of previous loading is to increase slightly both the value of the modulus of elasticity and Poisson's ratio Previous loading tends to straighten the stress strain diagrams both for axial and lateral deformations The value of the secant modulus of elasticity decreases slightly for rich mixes with the increase of unit stress up to a value of approximately 50 per cent of the ultimate load. From this value on, the decrease in the apparent value is very rapid until failure occurs.

The value of Poisson's ratio remains approximately constant for about 50 per cent of the ultimate load and then gradually increases until near the ultimate load when its value increases very rapidly.

Plastic flow occurs more rapidly under high stress than under low stresses, but the material reaches a stage of practical equilibrium under high stress much quicker than under low stress (See Figure 6.)

VOLUME CHANGES DUE TO CAUSES OTHER THAN STRESS

A very excellent summary of investigations of volume change in concrete due to causes other than stress has been made by Davis (8). These changes are principally caused by two forces each independent of the other although they usually occur simultaneously and are affected by many of the same variables. The chief of these is variation of temperature and the second is variation in moisture content

The variables which may be expected to modify the magnitude of volume changes caused by temperature and moisture are the same as

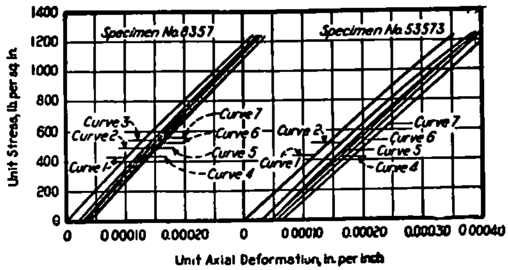

Figure 7. Effect of Repeated Loading upon Modulus of Elasticity. From Noble's, "The Effect of Aggregates and Other Variables on the Elastic Properties of Concrete. Proceedings American Society for Testing Materials, Vol. 31

those which modify the volume change due to stress, except that "size and shape of specimen or member" should be listed instead of "Effect of Combined Stress etc" (See page 241)

The effects of these variables upon variation in volume change due to temperature changes and absorption or loss of water in the mass of concrete will be discussed individually.

Cement. Considerable information is available as to the variations in the thermal coefficient of expansion for different cements both as neat pastes and as mortars and concretes

The maximum range for neat cement seems to be from 0 0000059 to 0.000009 per 1°F. within a normal temperature range. These extremes were reported by different observers. Prof. W. K. Hatt, Purdue University, in a study of seven cements found a variation for ordinary temperatures much less than this The coefficient for mortars is less than for neat cements and for concretes it is probable the variation due to cement would be negligible. Figure 8 shows the result of tests at Kansas State College on the coefficient of thermal expansion of an early strength cement and standard portland cement.

Most researches indicate that variations in the cement have much more influence upon the coefficient of moisture expansion than upon the thermal coefficient

Both the chemical composition and the fineness of grinding seem to affect the volume change due to gain or loss of water This is especially noted in neat cements the variation for mortars being much less marked Bates of the Bureau of Standards has shown that regrinding and the addition of gypsum considerably increases this

TABLE I

THERMAL COEFFICIENT OF EXPANSION OF CONCRETE

Material	Coefficient of Expansion per 1° F	Authority
Neat Cement	0 000 006 8	Meier
Neat Cement	0 000 008 1	Meier
Neat Cement	0 000 007 9	Adie
Neat Cement	0 000 005 9	Bouniceau
Neat Cement	0 000 007 6	Hyatt
Neat Cement	0 000 007 8	Hyatt
Neat Cement	0 000 007 0	Keller
1 3 Mortar	0 000 006 6	Bouniceau
1 1 Mortar	0 000 006 1	Keller
1 2 Mortar	0 000 005 6	Keller
1 4 Mortar	0 000 005 8	Keller
1 6 Mortar	0 000 005 1	Keller
1 8 Mortar	0 000 005 3	Keller
1 2 4 Bedford limestone concrete	0 000 005 5	Pence
1 2 4 Kankakee limestone concrete	0 000 005 6	Pence
Granite (average)	0 000 004 5	Bouniceau, Adie, Hurst, Dana
Limestone (average)	0 000 005 1	Bouniceau, Dana, Pence
Marble (average)	0 000 004 2	Bouniceau, Adie, Ganot
Sandstone (average)	0 000 006 9	Haswell, Ganot, Dana, Adie, Thurston

effect Hatt of Purdue, and White of Michigan confirm these results for neat cements. In concrete it is certain that the influence of the cement will be much less marked and the chief effect will be to vary the required water content for a given strength and workability. Figures 9 and 10 from data at Kansas State College show the effects of a finely ground early strength cement compared with those of a standard cement

Quantity of Cement (Richness of mix) The coefficient of thermal expansion is greater for a rich mix than for a lean one, some data (Table II) indicating that doubling the cement content increased this coefficient by about ten per cent

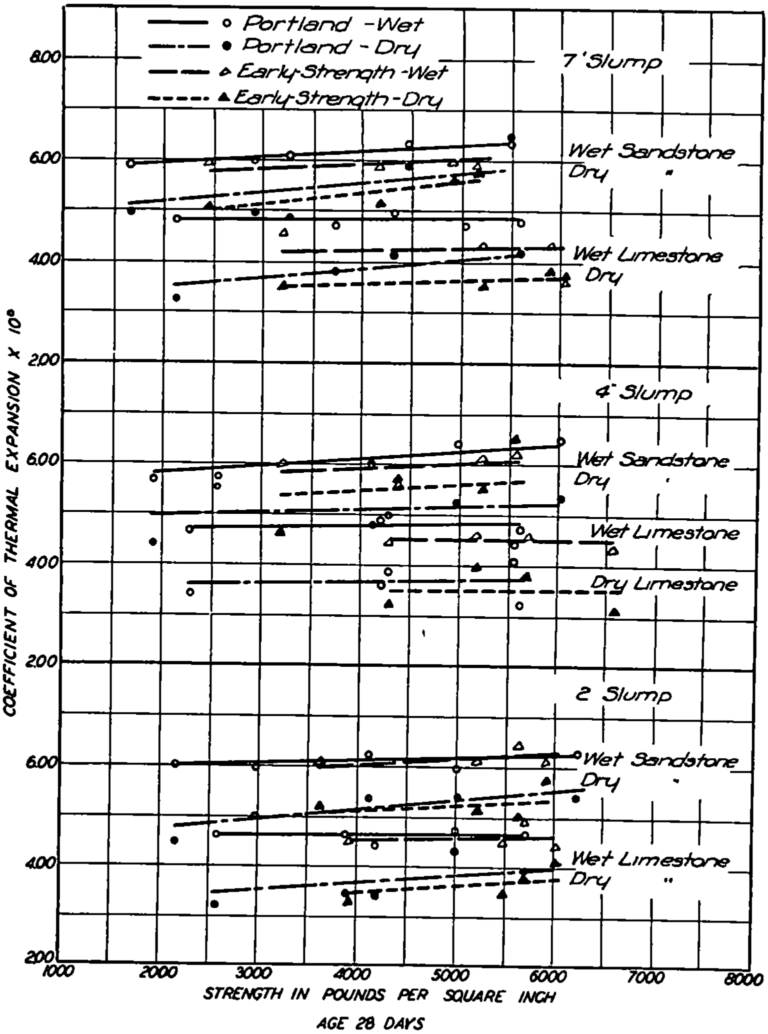

Figure 8 Coefficient of Thermal Expansion Per Degree Fahrenheit Versus 28-Day Compressive Strength

TABLE II

THERMAL COEFFICIENT OF EXPANSION AS INFLUENCED BY RICHNESS OF MIX (DAVIS AND TROXELL)

(Table VI from Proceedings A S T M, Vol 30, Part I, page 671)

Mix	Thermal Coefficient of Expansion per 1° F	
	2 In Slump	6 In Slump
1 3	0 000 006 44	0 000 006 39
1 4½	0 000 006 00	0 000 005 81
1 6	0 000 005 80	0 000 005 56

The quantity of cement exerts a very large influence upon the volume change that occurs with variation in moisture content of the concrete.

Table III from Matsumoto of the University of Illinois shows the effect of cement content upon shrinkage.

TABLE III

EFFECT OF RICHNESS OF MIX UPON VOLUME CHANGE (MATSUMOTO)

Mix	Percentage Expansion, Wet Storage, 60 Days	Percentage Net Contraction, Air Storage, 58 Days	Percentage Net Contraction Oven Drying, 29 Days
1 1 .	0 0124	0 046	0 157
1 2 .	0 0100	0 049	0 124
1- 3	0 0101	0 050	0 108
1 1 2	0 0091	0 036	0 081
1 2 4	0 0055	0 033	0 064
1 3 6	0 0019	0 036	0 062

Without question the most generally useful information now available for predicting such volume changes is shown in Figure 11, which is a diagram from the Research Laboratory of the Portland Cement Association. This shows the probable shrinkage for a given water loss, a known water-cement ratio, and a known cement content.

Water-cement Ratio Omitting the variation in cement content which usually accompanies changes in the water-cement ratio, there

TABLE IV

EFFECT OF WATER-CEMENT RATIO ON VOLUME CHANGE (DAVIS AND TROXELL)

(Proceedings A S T M , Vol 31, Part II, page 679)

Mix	Water Cement Ratio	Percentage Change in 3 Months: Expansion in Water	Percentage Change in 3 Months: Contraction in Air
	0 98	0 0184	0 068
1 4	1 07	0 0204	0 072
	1 16	0 0165	0 080
	0 98	0 019	0 064
1 6	1 07	0 019	0 064
	1 18	0 018	0 069

is very little if any, effect on the coefficient of thermal expansion due to this variable. The same also holds true for volume changes caused by changes in moisture content of the concrete It is so difficult to separate the variables of cement content and water-cement ratio that they need to be considered together. Figures 8 to 10 show some interesting relations from data at Kansas State College.

Consistency of Fresh Concrete. This condition is again intimately tied up with cement content, water ratio, and the quantity and grading of aggregate. Except as it is modified by these variables, its effect is not known and it probably exerts little influence.

Method of Curing. The final effect of method of curing upon either the coefficient of thermal expansion or the volume change due to moisture condition is not known. The method of curing and character of

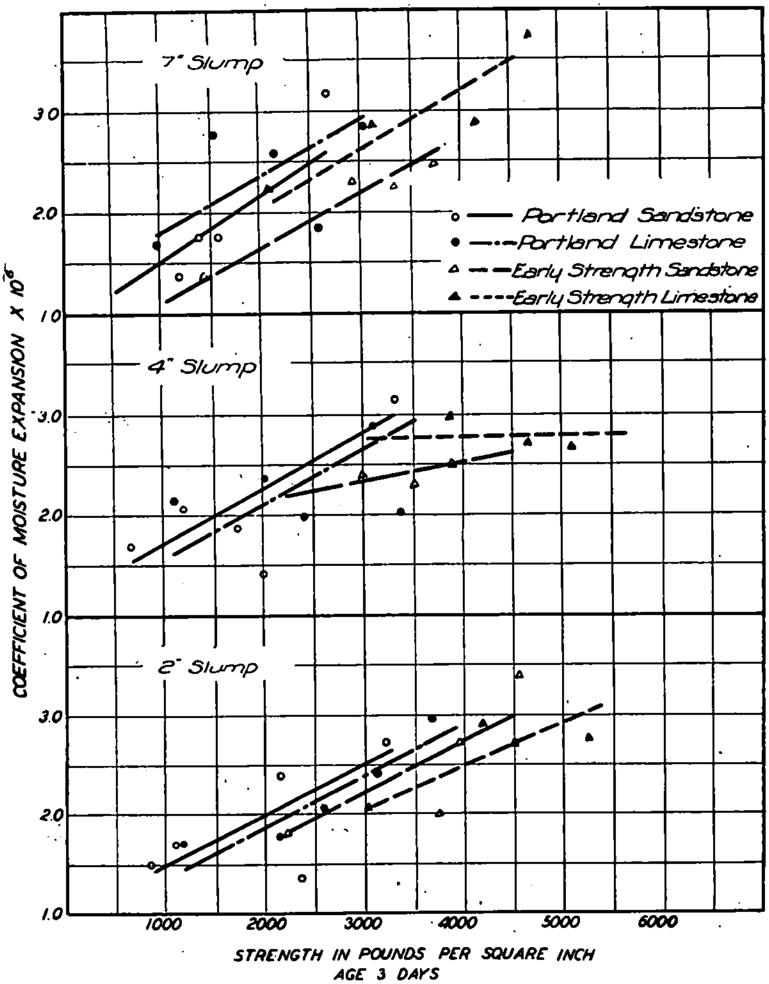

Figure 9. Coefficient of Moisture Expansion (Per Cent of Saturation) Versus Three-Day Compressive Strength

the forms whether absorptive or non-absorptive, may have a very marked effect upon initial shrinkage and volume change. Pearson of the Bureau of Standards and Dawley of Kansas State College have reported upon this. It is very likely that early volume changes in concrete pavements, influenced by methods of curing, has a marked effect on slab strength and the formation of cracks.

Age of Concrete The effect of age of concrete upon these factors is not known Probably after the first few months the age of the concrete has practically no effect upon the coefficient of thermal expansion Test specimens stored in water apparently continue to expand very slowly for perhaps as long as ten years and specimens in air

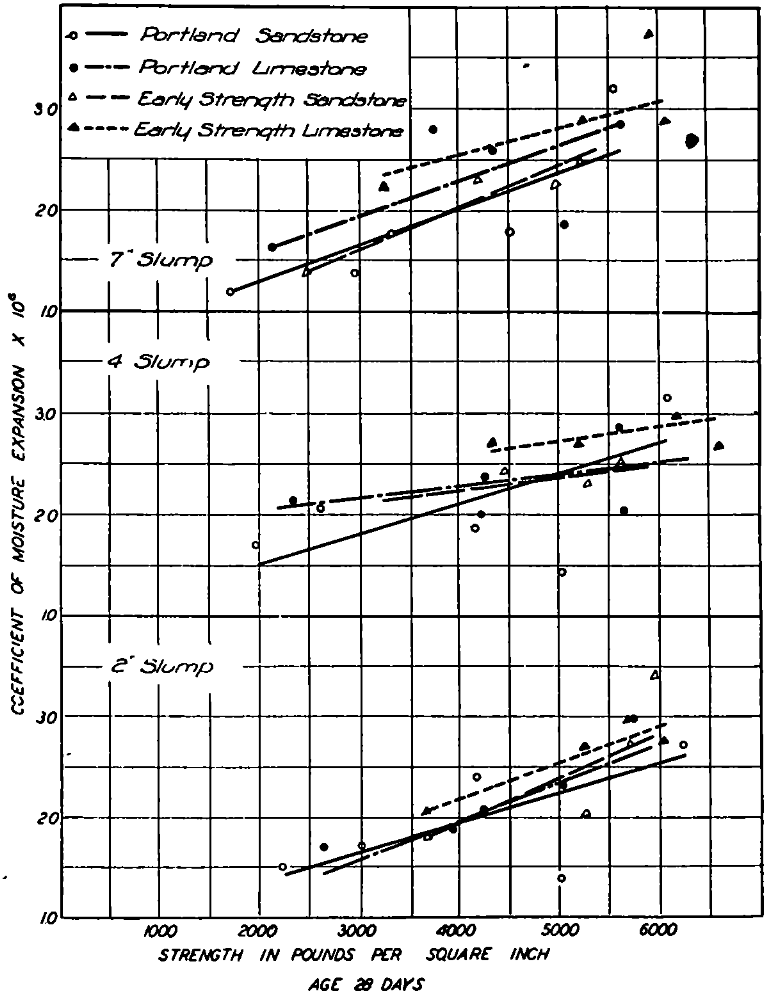

Figure 10. Coefficient of Moisture Expansion (Per Cent of Saturation) Versus 28-Day Compressive Strength

slowly shrink for several years varying with slight changes in humidity

Water Content of the Hardened Concrete The water content of the hardened concrete exerts considerable influence both upon the thermal coefficient of expansion and upon the volume change due to variations in this water content Figure 11 shows the importance of this factor It is intimately connected with the cement content, the water-cement ratio, and the consistency or slump of the fresh concrete Figures 12 (a, b, c) and 13 (a, b, c) from data at Kansas State College are of interest in this connection

One difficulty in studying this variable is the lack of a satisfactory method of measuring the water content Oven drying at tempera-

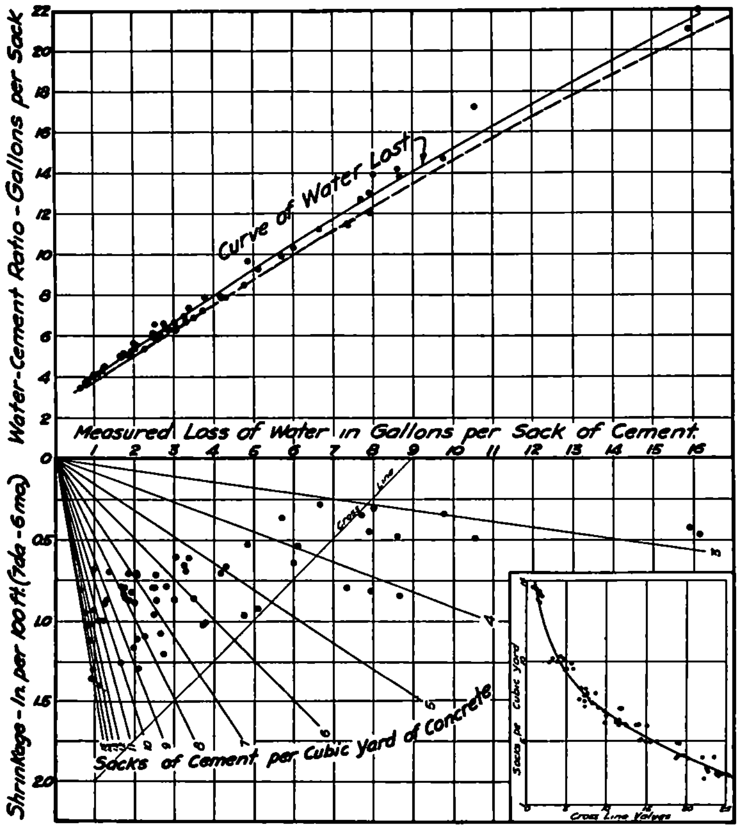

Figure 11. Interrelationship of Shrinkage, Loss in Weight, Cement Content and Water-Cement Ratio. From the Research Laboratory, Portland Cement Association

tures as high as 100° C produces changes in the concrete that permanently affect many of its properties

Davis and Troxell remarked that it has been observed at Kansas State College, that as specimens approach equilibrium between moisture content and the humidity of the air or storage room minor changes in humidity produce measurable changes in dimensions without noticeable change in weight

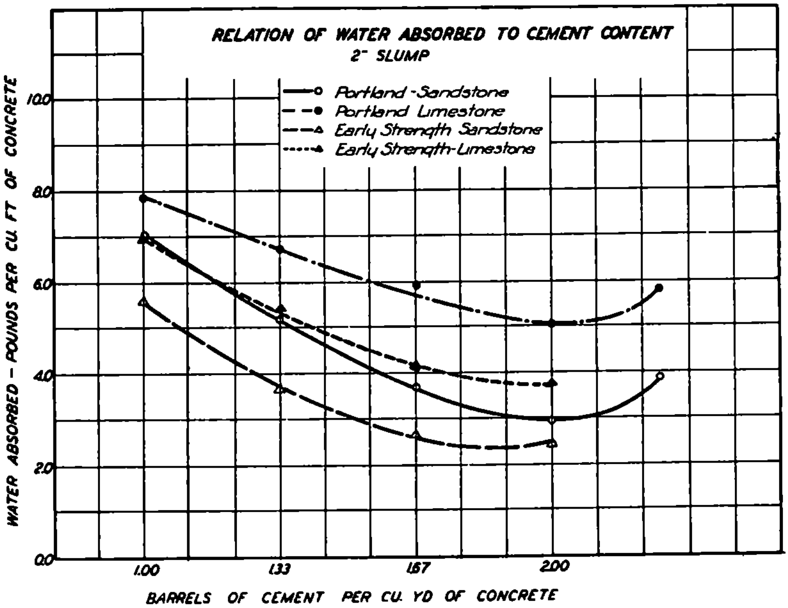

Figure 12a

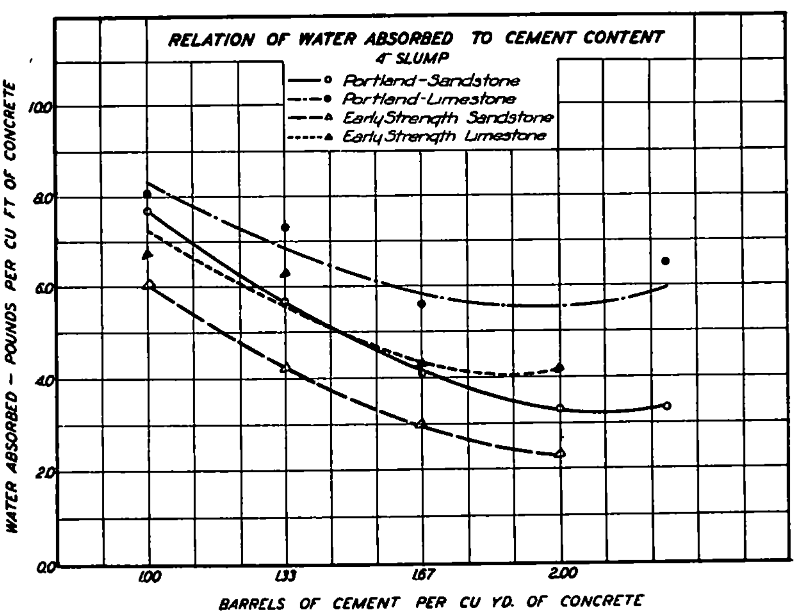

Figure 12b

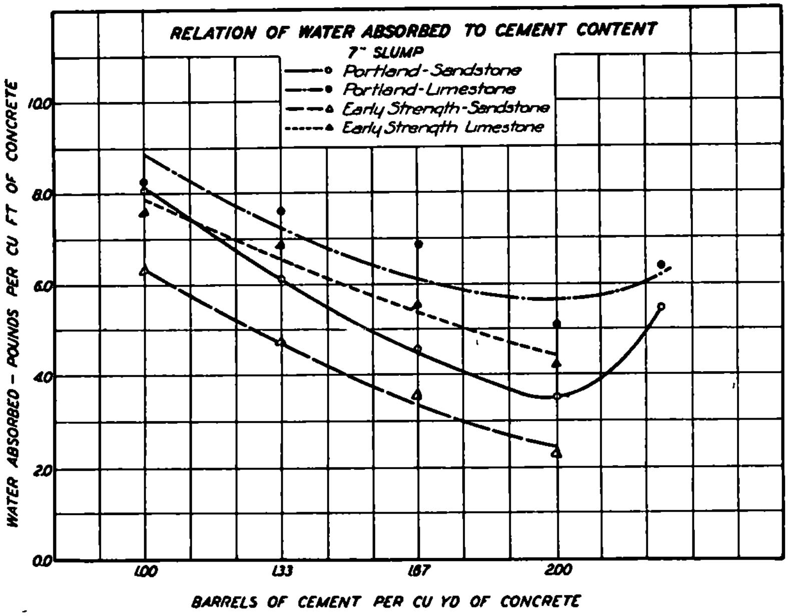

Figure 12c

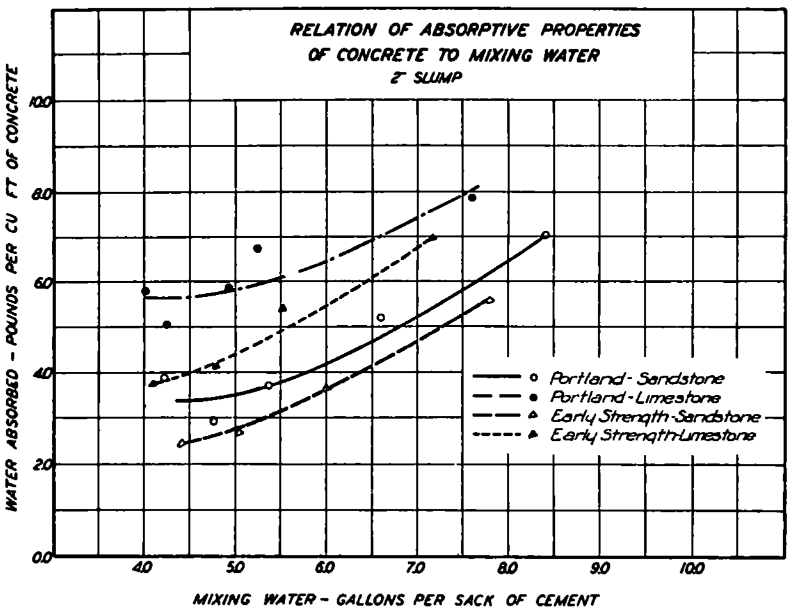

Figure 13a

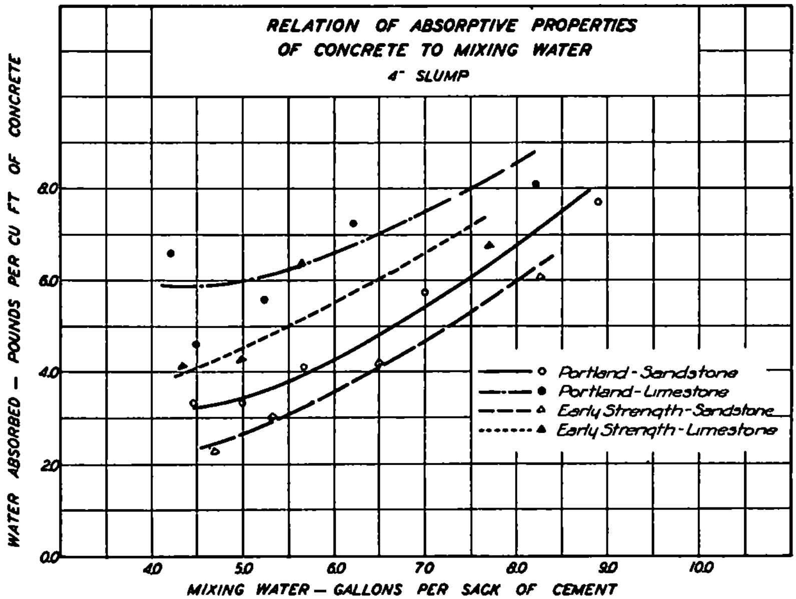

Figure 13b

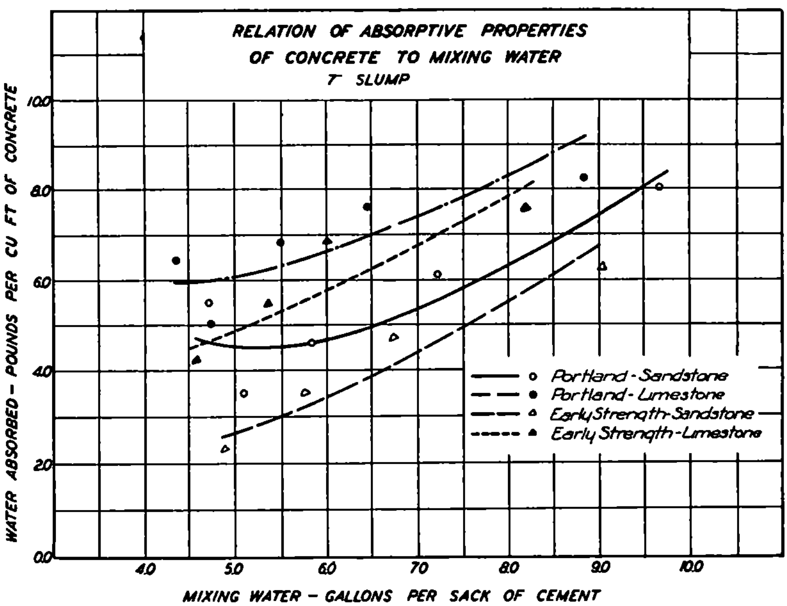

Figure 13c

The thermal coefficient of expansion is higher for wet than for dry concretes Figure 8 from Kansas State College shows values for a normal temperature range

Temperature of the Concrete This variable is not of special significance under normal conditions Tests at high temperatures by Norton and others show a slight increase to about 600° F and then a decrease in the thermal coefficient of expansion Such temperatures would, however, permanently change the character of the concrete if long continued

Character and Gradation of the Aggregate The character of the aggregate again completely over-shadows the effects of most of the other variables The value of the thermal coefficient of expansion varies by nearly 10 per cent with different coarse aggregates The effect of differences in fine aggregate is not so marked and few data are available on its influence

Table V, from data by Davis, Proceedings A. S T M, Vol 30, Part I, page 671, gives some idea of the range that may be encountered as the only variable was the aggregate·

TABLE V

Aggregate	Coefficient of Expansion per 1° F
Quartz	0 0000066
Sandstone	0 0000065
Gravel	0 0000060
Granite	0 0000053
Basalt	0 0000048
Limestone	0 0000038

The kind of aggregate also has a great effect upon volume change due to moisture variation

Tables VI and VII show the effects of various aggregates upon shrinkage and expansion due to moisture

The effect of finely divided material is not so well known but it is quite certain that the mineral composition of the fines has some influence upon volume change

Minor variations in the gradation of the aggregate apparently have little effect Fine materials consistently show greater change Figures 8, 9, 10, 12, and 13 from data at Kansas State College show the marked effect that the aggregate has upon both the coefficient of thermal expansion and volume change due to absorption or loss of moisture

Shape of Aggregate. No data are available relative to the effect of shape of aggregate unless it may be that the consistently greater volume change due to change in moisture content found for gravel may be partly because of its shape This should be determined by a careful investigation as to the relative effect of rounded and angular particles. Some data by Davis indicate that it may be due to the mineralogical composition of the gravel rather than to the shape.

Quantity of Aggregate. An increase in the quantity of aggregate in a concrete mixture tends to produce a lower strength concrete and to reduce the effect of variation in the moisture content of the paste. Variations in the proportions of fine and coarse aggregate, however, may have a marked effect upon the volume change. An increase in the sand content considerably increases the shrinkage or expansion with changes in water content. For low volume change the sand content should not exceed about 40 per cent of the total aggregate. Variations below this value cause little difference in volume change.

TABLE VI

EFFECT OF TYPE OF AGGREGATE UPON VOLUME CHANGE (DAVIS)

(Proceedings A. S. T. M., Vol. 30, Part I, page 677)

	Percentage Volume Change in 3 Months	
Aggregate	Contraction in Air	Expansion in Water
Gravel	0.079	0.0074
Sandstone	0.075	0.0055
Limestone	0.039	0.0050
Granite	0.037	0.0131
Quartz	0.036	0.0094

TABLE VII

EFFECT OF TYPE OF FINE AGGREGATE UPON AIR SHRINKAGE (CHAPMAN)

(Proceedings A. S. T. M., Vol. 30, Part I, page 676)

	Percentage Contraction	
Fine Aggregate (Screening)	1: 2 Mortar	1: 2: 4 Concrete
Conglomerate	0.21	0.075
Trap rock	0.21	0.093
Slag	0.14	0.068
Granite	0.13	0.068
Limestone	0.13	0.062

Admixtures. Admixtures either inert or chemically active have little effect except as they modify the extent or rate of change in water content of hardened concrete. Many integral water-proofing compounds make special claims that they do reduce volume change.

These claims do not seem to be borne out by test. White of Michigan and Davis and Troxell of California showed that such materials as they tested had little if any merit. The use of a high magnesium lime as a substitution up to 10 per cent was reported by Davis to reduce shrinkage in mortars stored in dry air. Substitution of clay instead of lime increased the changes.

Size and Shape of Test Specimen or Member. It is evident that the size and shape of the body undergoing volume changes due to loss of or absorption of moisture will considerably modify the rate of volume change, the extent of this change and the stresses set up by these changes in dimensions This is also true of changes in temperature Under ordinary conditions of exposure change in moisture content of large concrete masses will be very slow and if the stresses are large, plastic flow will tend to relieve them Temperature changes however, will occur so suddenly that plastic deformation will have but little effect upon the magnitude of stress developed In pouring large sections of mass concrete the internal stresses due to temperature rise during the setting period must be very large, and coming at a time when the strength of the concrete is low, it is probable that these stresses result in more or less permanent injury to the material

NECESSITY FOR FURTHER RESEARCH

The present state of our knowledge of the elastic properties of concrete is so limited as to leave the designing engineer dependent almost entirely upon empirical methods. All of our basic formulas for flexure, for stresses in rigid framed structures and for the distribution of stress between the concrete and steel in reinforced concrete members involve the use of the modulus of elasticity of the concrete At present the only information an engineer can be sure of is that it may vary as much as 50 to 100 per cent from whatever value he may assume To secure more accurate information on this point, with our present knowledge, would require the actual determination of the modulus of elasticity from test specimens of concrete made from the aggregates which are to be used. It is particularly important that further researches be made to determine the relationship between the modulus of elasticity of concrete and the physical properties of aggregates. It is not unreasonable to suppose that fairly accurate relations may be found between the modulus of elasticity of the aggregate, the ratio of the absolute volume of the aggregate to the volume of the concrete and the modulus of elasticity of the mortar In pavement construction variations in the modulus of elasticity are equally important For the same unit of elastic deformation in a pavement slab whether produced by temperature variations or absorption or loss of moisture the unit stress produced will vary directly with the modulus of elasticity This is sufficient to explain why certain types of aggregate seem to cause cracking more than others. A knowledge of these variations and proper allowance for them in the design of the pavement should eliminate these difficulties To further aggravate this situation it seems that the aggregates showing high values for the modulus of elasticity tend to show large values for the coefficient of thermal expansion.

The occurrence of plastic flow in concrete members tends to produce large variations in the distribution of the stress between the members and between the concrete and steel composing these members The unit deformation under sustained load may be increased by as much as 100 per cent As between members plastic flow probably tends to relieve stresses due to conditions not anticipated in the design but the relative portions of the load carried by the concrete and the steel are not self adjusting In pavements plastic flow may tend to relieve certain strains produced by variations in moisture content or other very slow volume changes Changes due to temperature are however so rapid that plastic flow will not be a factor in reducing such stress

The information relating to plastic flow should be supplemented by further research on the effects of variations in the aggregates.

Data as to the thermal coefficient of expansion, which is for exposed structures the largest factor affecting volume change, are not adequate It seems reasonable to expect to find close relations between this coefficient for the aggregate, and that for the mortar, and the relative portions of each in the concrete In this connection, the bond stresses set up between the aggregate and the mortar where these coefficients are widely different may be significant It has been noted at Kansas State College in making freezing and thawing tests of concrete (see proceedings of Highway Research Board, 1930) that with certain aggregates the failure nearly always seems to be due to a loss of this bond Similar conditions have been observed in structures exposed to severe weathering conditions

Many observers have commented from time to time upon the apparent fact that gravel concrete showed larger volume changes than did concrete using some other aggregates However little supporting data are available and they do not show whether the effect was due to the rounded shape of the particles of gravel or to the character of the minerals composing the gravel

A study of the effect of the shape of particles composing the aggregate upon modulus of elasticity of concrete should be made

The following condensed outline of those problems which seem to be in the most urgent need of study is presented

I *Coarse Aggregates*

1. Modulus of elasticity of the aggregate
2. Thermal coefficient of expansion of the aggregate
3. Moisture coefficient of expansion of the aggregate.
4. The possibility of determining the relationship between these values and the similar values for the concrete in which the aggregate is incorporated
5. Effect of shape of particles upon the above properties particularly the coefficient of thermal and moisture expansion

II *Fine Aggregate*

1 Effect of grading, shape of particles and mineral composition upon, plastic flow and changes in volume due to changes in temperature and to the moisture content of the concrete

2 A method for determining the free moisture content of concrete without heating to such temperature that will permanently change the properties of the concrete

III. *Cement*

A further study of the effect of fineness of grinding and chemical composition upon plastic flow, thermal coefficient of expansion and volume change due to absorption or loss of water These studies should be made upon mortars and concretes and not upon neat cements

IV

A study of the effect of temperature at time of loading should be made to determine its effect upon all of the properties of concrete with respect to volume change

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