NATIONAL BUREAU OF STANDARDS REPORT

7112

Insulating Concretes

by

T. W. Reichard

Report to
the Departments of
the Air Force, the Army, and the Navy

NBS

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

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A description is given of a series of tests with insulating concretes of several types designed to develop data for the purpose of determining: (1) Elastic properties and strength as a function of size and shape of specimen, cure, density, and composition; (2) the drying shrinkage; (3) thermally induced movements; and (4) the behavior of reinforced insulating concrete slabs under short-term and long-term loads.

About 120 batches of insulating concrete were made using 2 brands of vermiculite, 3 brands of perlite, and 2 brands of preformed foam making liquids. Data are presented to show that in testing insulating concrete specimens for strength, the cure, size and shape of specimen, and test conditions must be precisely defined in order to obtain meaningful results. For instance, vermiculite concrete specimens which had been damp cured showed as much as 50 percent increase in compressive strength when oven dried before testing. Data are presented which show that although the relative strengths of various size specimens were affected by the curing method, the cubical specimen consistently showed a significantly higher strength than the cylindrical one with a height to diameter ratio of about two.

It is shown that the compressive strength of these concretes can be estimated from their fresh density if segregation is prevented and the water content is known. The data indicate that the cement-aggregate ratio is important in controlling the strength only in so far as the density of the concrete is affected.

There were significant differences in the drying shrinkages of the 3 types of concretes and also in the shrinkages of the concretes made from the 3 brands of perlite.

1. INTRODUCTION

During FY1958 and 1959, the National Bureau of Standards was engaged in a study of insulating concretes initiated as a Tri-Service Project. [1] This final report presents data developed during the last year. Some data reported previously in interim reports [1] and [2][2] are included in this report, but only where needed for clarity or continuity.

This work was initiated for the purpose of developing data needed for evaluating the usefulness of perlite, vermiculite, and cellular insulating concretes. Due to a curtailment of funds for FY1959 the work planned was not entirely completed, especially with the cellular type concretes.

The data presented were developed for the following specific purposes:

1. Determine the strength and elastic properties of the 3 types of insulating concretes as a function of size and shape, cure, density, and composition.

2. Determine the drying shrinkage of the concretes as a function of composition.

3. Determine the thermally induced movements of the concretes.

4. Determine the behavior of reinforced insulating concrete slabs under short-term and long-term loads.

Two brands of vermiculite aggregates, 3 brands of perlite aggregate, and 2 brands of preformed foam-making liquids were used in making the concretes for this investigation.

2. MATERIALS, MIXING AND FABRICATION

2.1 Aggregates

Three brands of perlite concrete aggregate were used. They are designated as perlites A, B, and C.

Two brands of vermiculite concrete aggregate were used and are designated as vermiculite D and E. Vermiculite D was expanded from a domestic ore; vermiculite E was expanded from a South African ore.

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[1] Tri-Service Projects are sponsored jointly by the Departments of Army, Navy, and Air Force.

[2] Numerals in brackets denote references listed at the end of this report.

Table 1 gives the sieve analysis on the 5 aggregates. The samples used for the sieve analysis were taken from single bags of aggregate by a sample splitter.

Table 2 gives average dry loose unit weights of the aggregates. One shipment of perlite C which was mentioned in [1] as being heavy was not included in the average. Some bags of the vermiculite D were received in a noticeably damp condition, but had reached an equilibrium weight before being used.

Table 3 gives the crushing strength test results on the aggregates; this test was included in the study although its significance has not been determined. The method used is described on page 9 of the Bureau of Reclamation Report No. C385 entitled, "Properties of Concretes Made With Typical Lightweight Aggregates."

An air-entraining agent is added to the perlite A and the vermiculite E at the processing plant. Vermiculite D is normally sold as a stabilized aggregate, i.e., one containing an air entraining agent added at the plant, but the unstabilized aggregate was used in this investigation.

Perlite C is a "coated" aggregate. The "coating" is said to make the use of entrained air unnecessary to prevent segregation in the fresh concrete. Concretes made from each of the aggregates are designated by the appropriate letter in the batch numbers in Table 5 through 8.

2.2 Air Entraining and Preformed Foam Agents

The air entraining agent used with vermiculite D, perlite B and some batches of perlite C was a 10 1/2 percent solution of neutralized vinsol resin furnished by a vermiculite producer. Approximately 16 oz of this solution per bag of aggregate is the amount recommended by the producers.

Two preformed foam systems designated as F and G were used in making the cellular concretes. Both foaming agents were made from hydrolized waste proteins. The concretes made using the G and F foam systems are designated in Table 9 by letters "G" and "F", respectively, in the batch number.

2.3 Cement

The Type I and Type III cements used were Lehigh portland cements manufactured in Allentown, Pennsylvania. The letters "R" and "H" in the batch numbers designated cements of Type I and III, respectively.

2.4 Mix Proportions

2.4.1 Perlite and vermiculite concretes

The mix proportions recommended by the producers of the aggregates are shown in Table 4. In most cases the recommended water contents were adopted although in some batches extra water was used to simulate possible field use or to obtain a pourable mix of 6 to 9 in. slump.

In several batches of perlite C concrete the mix proportions recommended for the other two perlite aggregates were used.

Air entrainment was recommended by the manufacturers for all the aggregates except perlite C.

The actual proportions used for each batch of concrete are given in Tables 5, 6, 7, 8, and 10. (See also Table 1 of [2]).

2.4.2 Cellular concretes

Most of the cellular concretes were made from cement, water and preformed foam, but two batches designated as 30 FSH and 35 FSH (Table 9) were made with an additive which replaced about half of the cement. The additive was furnished by the manufacturer of the F foam system.

The water-cement ratio of cellular concrete is usually specified as about 0.6 by weight, but a water-cement ratio of 0.45 was specified for the mixes with the special additive. The addition of the preformed foam adds some water to the mix resulting in a slightly higher w/c ratio than indicated by the specified water content.

The actual w/c ratios used in the cellular concrete mixes are given in Table 9.

2.5 Mixing Procedure

All of the concretes, except those made with perlite C were mixed in a 3 cu ft paddle type mortar mixer at a nominal speed of 40 rpm. The perlite C concretes were mixed, as recommended by the manufacturer, in a 3 cu ft tilt drum concrete mixer at a nominal speed of 30 rpm.

The normal mixing schedule was 1/2 min with the cement and water, and 2 min with the aggregate or preformed foam. The mixing time for perlite C concrete varied somewhat as additional time was sometimes required to bring the concrete to a pourable consistency (6 in. to 9 in. slump).

In the batches where it was necessary to add an air entraining agent separately (vermiculite D and perlite B), the additive was added to the cement-water slurry and mixed for 15 sec before the aggregate was added.

The unit weight of the concrete was determined when freshly mixed and recorded as the wet density.

2.6 Fabrication of Specimens

The following types of test specimens were cast from most batches of concrete except for the batches from which the 24- by 48- by 3-in. reinforced slabs were cast:

3- by 3-in. cylinder
3- by 6-in. cylinder
6- by 12-in. cylinder
3- by 4- by 16-in. prism
2- by 2- by 11-in. prism

In addition to the above specimen types, 2-in. cubes were cast from a few batches of vermiculite concrete.

The 3-in. cylinders were molded in pint and quart ice cream containers of waxed paper. The actual diameter of these specimens was 3.37 in. Because the cast top and bottom surfaces of these cylinders were not flat, a slice was cut from both top and bottom of each specimen when removed from the paper mold at 24 hr. The average height to diameter ratio for these cylinders as tested was 1.8 for the nominal 3- by 6-in. and 0.85 for the 3- by 3-in. specimens.

The 6- by 12-in. cylinders were cast in machined cast iron molds. The prisms were cast in steel molds.

The concrete was consolidated in all molds by jiggling or shaking the molds. In most cases the metal molds were overfilled with concrete and the excess cut off just prior to stripping.

The 24- by 48- by 3-in. slabs were cast in plywood forms as described in [2] and were screeded off at the time of casting.

All specimens were covered with a vapor barrier until stripped at 20 to 24 hr.

3. CURING OF SPECIMENS AND SCHEDULE OF TESTS

In scheduling the strength tests for the concretes made with Type III cement it was assumed that a 7-day test would be equivalent to the 28-day test for Type I cement. It was also assumed that a 3-day test for Type III would be equivalent to the 7-day for Type I.

The cure and test schedules for the strength specimens were set up as shown in Table 11. Not all the specimens indicated in Table 11 were made from each batch but from most batches of concrete the following minimum number of strength specimens was made:

3 - 6- by 12-in. cylinders for "A" cure
4 - 3- by 6-in. cylinders for "Early" test
4 - 3- by 3-in. cylinders for "Early" test
4 - 3- by 6-in. cylinders for "A" cure
4 - 3- by 3-in. cylinders for "A" cure
3 - 3- by 4- by 16-in. prisms for "A" cure
4 - 3- by 6-in. cylinders for "C" cure

In addition, 2- by 2- by 11-in. shrinkage test specimens were cast from all except the slab concretes. Following removal from molds at 24 hr these shrinkage specimens were placed in water at room temperature for 6 days if made with Type I cement or for 2 days if made with Type III cement.

The test slabs were given the "A" cure by storing under damp burlap for the required period.

4. TEST PROCEDURE

4.1 Static Compressive Test

As a result of work reported in [1] it was decided not to cap the compressive test specimens. The load bearing surfaces of the test specimens were prepared by grinding the ends to a smooth flat surface on a concrete plate.

The specimens were loaded to failure through a spherically seated head in a 60,000 lb capacity hydraulic testing machine. They were loaded at a rate of not more than the estimated maximum load per minute.

The static compressive stress-strain determinations were made on single 6- by 12-in. cylinders from each batch. Strain readings were made by means of bonded wire strain gages at convenient load increments without interrupting the continuous application of the load. The static modulus of elasticity reported is the secant value defined here as the slope of the line drawn through the origin and the point on the stress-strain curve at half the ultimate stress.

4.2 Dynamic Modulus of Elasticity

The dynamic (sonic) modulus of elasticity E_D was computed using the relation

$$E_D = V^2 \rho$$

where V = velocity of sound through the specimen

$V = 2\ NL$

N = fundamental longitudinal resonance frequency in cycles/sec

L = length of specimen, in inches

ρ = density of specimen/g; density in lb/in.^{3} and g = 386.0 in./sec^2

The fundamental longitudinal resonance frequencies of the 6- by 12-in. and 3- by 6-in. cylinders were determined using the procedure described in ASTM C215 just prior to the compressive test.

4.3 Modulus of Rupture Test

The three 3- by 4- by 16-in. prisms from each batch were tested for modulus of rupture in accordance with ASTM C293-57T except that the specimens were not kept damp until time of test. These specimens were given the "A" cure (see Table 11). The rate of loading was adjusted to not more than half the expected maximum load per minute.

4.4 Indentation Test

The indentation tests were made in the hydraulic testing machine on the broken halves of the modulus of rupture prisms. This test was performed on the same day as the modulus of rupture test. A 1 1/8-in. diameter steel disc, placed on the specimen, was loaded through a steel ball until there was evidence of crushing. The indicated load at crushing was recorded as the indentation strength.

Crushing was assumed to have occurred when the load indicator did not show an increase in the applied load with a continued movement of the testing machine cross head relative to the lower platen. Movement of the cross head was determined by means of a 0.0001 in. dial gage mounted on the lower platen.

4.5 Drying Shrinkage Measurements

The three 2- by 2- by 11-in. specimens from each batch were molded with stainless steel inserts at each end, and the effective gage length was assumed to be 10 in. The specimens were placed in water at room temperature upon removal from the molds at the age of 1 day. The specimens made from concretes with Type I cement were left in the water for 6 days. The specimens made from concretes with Type III cement were left in the water for 2 days.

Upon removal of the specimens from the water they were placed on a drying rack in a room controlled at 73 ± 3°F and 50 ± 3 percent R.H. Initial weight and length measurements were made immediately upon removing the specimens from the water and thereafter the changes in weight and length were measured at certain elapsed drying times.

Measurements of changes in length were made using a vertical comparator equipped with a 0.0001-in. micrometer screw and a 0.0001-in. dial gage. The instrument was checked by means of an invar standard bar each time measurements were made.

4.6 Thermal Movement Measurement - Saturated Condition

The specimens used were the 2- by 2- by 11-in. shrinkage specimens which were placed in a controlled temperature water bath at the desired temperature. Measurements of change in length were made with the same vertical comparator that was used in making the drying shrinkage measurements. The specimens, which were about one year old, were placed in the water batch for 7 days before any measurements were made.

Two thermal regulators were used with the water bath. One regulator was adjusted to maintain a water temperature of 135°F ± 1/4° and the other regulator maintained a temperature of 35° ± 1/4°F. The water temperature was changed by inserting the proper regulator in the control circuit. Approximately 6 hr was needed to bring the bath temperature from 35° to 135° and 5 hr to bring the temperature to 35° from 135°.

The specimens were removed from the bath individually, placed in the comparator, and a reading taken. This procedure was completed in about 10 sec which was rapid enough so that the readings could be taken before the specimen had cooled sufficient to appreciably effect the readings. It was found, by watching the dial gage on the comparator, that about 15 sec were needed before cooling of the specimen or heating of the comparator frame affecting the readings. When the specimens were removed from the 35°F water an appreciably longer period was needed before warming of the specimen affected the readings.

Five complete cycles were made with a minimum of three repeated readings at each temperature per cycle. These three readings were taken at about half hour intervals.

The difference between the comparator readings taken at the two temperatures (R_1 - R_2) divided by the temperature difference (100°F) and the gage length (10 in.) gave the coefficient of thermal expansion,

$$K_w = \frac{(R_1 - R_2)}{1000} \qquad \text{coefficient of thermal expansion}$$

4.7 Thermal Movement Measurements - Oven-Dry Conditions

The specimens used were 2- by 2- by 11-in. shrinkage specimens which were dried to constant weight in a 220°F oven. Two bonded wire resistance strain gages were cemented with an epoxy resin cement to opposite sides of the dried specimen. Each specimen was then sealed in a polyethylene bag to prevent any change in moisture content. The strain gages were connected to a strain indicator through a switching box.

Compensating and active strain gages were cemented to a fused silica plate which was placed in the test chamber with the test specimens. The active gages on the fused silica were used as a check on the operation of the compensating gages. Since the active and compensating gages were placed back to back on the silica plate, the indicator readings should be the same at any temperature of the specimen. These readings varied slightly (10 micro inches for the 100°F temperature change), but it was assumed that the compensating gages were operating as predicted and no correction was made other than that necessary for the thermal movement of the fused silica. The coefficient of thermal expansion was $0.306 \times 10^{-6}/°F$ for the fused silica.

All test leads to the gages in the chamber were cut to the same length from the same spool of wire, and with equal lengths of wire within the chamber. Direct and reverse readings were made for each set of readings in order to adjust for any change in the external gaging circuit.

After a few trial determinations it was found that satisfactory results could be obtained only by using readings made the same day. The inconsistency of measurements made on different days was probably due to a shift in the strain gage resistance with time.

The temperature of the circulating-air test chamber could be held constant to ± 1/2°F and was measured by means of five thermocouples placed near the specimens. It was assumed that there would be a temperature gradient from top to bottom of the chamber, but by placing all the specimens in the same horizontal plane the temperature of all specimens would be equal.

The temperature of the chamber was varied from about 40°F to about 140°F. It took about 2 hr to change the chamber from one temperature to the other and about 3 hr was allowed for the specimens to reach equilibrium with the chamber. One cycle could be completed each working day and the results reported are from three thermal cycles.

The difference between strain gage readings at the two temperatures ($R_1 - R_2$) divided by the change in temperature (ΔT) plus the correction (K_{si}) for the fused silica compensating gage gave the thermal coefficient (K_D) for the oven-dry specimens

$$K_D = \frac{R_1 - R_2}{\Delta T} + K_{si}$$

4.8 Absorption

Broken halves of modulus of rupture specimens were cut to regular shapes of about 3- by 3- by 6-in. and then used for water absorption determinations. A single specimen from each batch was used. All specimens were stored in a 73°F room (humidity uncontrolled) for at least nine months following the modulus of rupture tests. They were then dried in a ventilated oven at 220°F for 48 hr and cooled to room temperature before the start of the absorption tests. The specimens were then immersed in water for 24 hr at 73°F, after which they were boiled in water for 5 hr and then allowed to cool for 16 hr while immersed. The specimens were weighed in air after oven drying, cold soaking, and boiling. They were also weighed in water after the 24 hr cold soaking.

The absorptions were calculated as follows:

$$\text{Absorption, percent by weight (24 hr cold)} = \frac{W_C - W_D}{W_D} \times 100$$

$$\text{Absorption, percent by weight (5 hr boil)} = \frac{W_B - W_D}{W_D} \times 100$$

$$\text{Absorption, percent by volume (24 hr cold)} = \frac{W_C - W_D}{W_C - W_W} \times 100$$

$$\text{Absorption, percent by volume (5 hr boil)} = \frac{W_B - W_D}{W_C - W_W} \times 100$$

where W_D = oven dry weight, in air

W_C = weight after 24 hr cold soaking, in air

W_B = weight after 5 hr boil, in air

W_W = weight after cold soaking, in water

4.9 Reinforced Insulating Concrete Slabs

4.9.1 Perlite concrete slabs

The procedures used for testing the perlite concrete slabs were discussed in [2].

4.9.2 Vermiculite concrete slabs

The vermiculite concrete slabs were tested without formboard at the age of 28 days. The test methods used were as described in [2] for the perlite concrete slabs.

All the vermiculite slabs were reinforced with 4- by 4-in. welded wire fabric of No. 12 gage wire which was laid free in the slab form 0.2 in. from the bottom.

The sustained load tests on the two vermiculite slabs were conducted in a temperature and humidity controlled room (75 ± 3°F, 50 ± 5 percent R.H.). The sustained load was, as for the perlite slabs, half the estimated ultimate load.

5. DISCUSSION OF RESULTS

5.1.1 Strength vs. Density for 6- by 12-in. Cylinders

Figures 1 through 5 show the relation between the wet density and the 6- by 12-in. cylinder strength for the concretes investigated. Figures 6 through 10 shows the relationship between the oven dry density and the cylinder strength. All the 6- by 12-in. cylinders were given cure "A" and tested as indicated in Table 12.

Some of the scatter in the data presented is probably caused by variations in gradation or physical properties of the aggregate used. The effects of these variations would be exaggerated by the relatively small amount of aggregate (2 cu ft) used in each batch of concrete.

Figure 3 shows a considerable scatter in the data for the C perlite concrete which was made without an air entraining agent in accordance with the producers recommendations. However, segregation of this perlite aggregate from the cement-water grout was quite severe in several batches and, at best, was mild in most. It is thought that much of the scatter of data in figure 3 is due to this segregation. It is noted that those batches of C perlite concrete which contained entrained air showed less segregation and higher strength than the corresponding batches without air entrainment.

It appears from the study of the data in figures 1 through 5 that the minimum compressive strength can be estimated from the wet density of concrete containing a given aggregate provided the mix is a non-segregating one and that the amount of water used is the minimum required to produce a mix of pourable consistency. This relationship between the minimum compressive strength and the wet density is indicated by curves which form lower boundaries to the arrays of points in figures 1, 2, 4, and 5.

The amount of mixing water recommended by the manufacturer is not necessarily the amount yielding a mix of pourable consistency. For instance, the points above the dashed line in figure 2 (perlite B) correspond to mixes with recommended water contents and these mixes proved to be too stiff to be placed by pouring. Similarly, in figure 1 (perlite A), the points below the curve are from mixes having about 25 percent excess water; the excessive amount of water in these batches caused some segregation in what would have otherwise been a satisfactory mix.

Figure 3 (perlite C) illustrates an extreme example of scatter caused by segregation which ranged from mild to severe. It will be recalled that the C perlite concrete was made without the use of entrained air. Also the amount of mixing water recommended, and used, was considerably greater than was recommended for the other two perlites. The extreme scatter of data in figure 3 made it inadvisable to indicate the lower boundary of the data which would serve to establish a relationship between the minimum compressive strengths and the wet densities as in the other graphs. The curve in figure 3 is used only to separate the data from mixes having severe segregation from those exhibiting mild segregation.

Figure 4 establishes the relationship between the compressive strengths and wet densities for vermiculite concretes. It is worth noting that for vermiculite concretes as well as for perlite concretes a given aggregate exhibits a well defined lower boundary in the array of points which defines the relationship between the minimum strength and the wet density. A similar grouping of points can be seen in figure 5 for the cellular concretes made with the two different foam systems.

The relationships between the compressive strengths and the oven-dry densities shown in figure 6 through 10 are of the same general nature as those given in figures 1 through 5. Moreover, it was found that when oven-dry densities were used as a basis of comparison, the minimum compressive strength-density relationship was more nearly independent of the source of a given aggregate than was the case with wet densities. This was to be expected since the amount of mixing water was of less importance. It is noted though, that this observation is limited to non-segregating mixes. Although the data for the non-air-entrained C perlite concretes given in figure 8 show less scatter than comparable data in figure 3, the minimum compressive strength-density relationship in figure 8 does not conform to those established for the other perlite concrete mixes given in figures 6 and 7.

The observation that minimum strength-oven-dry density relationship is independent of the source of a given type of aggregate is also true for the vermiculite concretes.

From the data available it seems that, to a great extent, the mix proportions are important in determining the strength of these concretes only in so far as they affect the dry density of the concrete.

For the purposes of this investigation, it was assumed that the 7 day strength of concrete made with Type III cement would be about the same as the 28 day strength of concretes made with Type I. For the vermiculite concretes (figures 4 and 9) this seems to be true. However, for the perlite and cellular concretes the strengths for Type III cements are slightly higher than for Type I.

A compilation of the results from all the concrete made in this study are presented as average results for typical mixes in Table 12 and figures 11, 12, and 13.

5.1.2 Modulus of Rupture

The modulus of rupture values are plotted against 6- by 12-in. cylinder compressive strengths in figure 14. Although relationships are not too well defined, the lines were drawn on the graph to indicate the probable trends. It can be seen that the ratio of the compressive strength to modulus of rupture was significantly greater for perlite concretes than for the vermiculite concretes. This was true for concretes made with either Type I or Type III cement.

It is probable that the higher compressive strength - modulus of rupture ratio observed for concretes made of Type III cement was due to the fact that these concretes were tested at 7 days and had a higher moisture content and, consequently, a greater moisture gradient than concretes made of Type I cement which were tested at 28 days. The greater moisture gradient across the section of a specimen used in the transverse tests may be associated with a corresponding stress gradient induced by shrinkage. There is reason to believe that as the specimens approach equilibrium, the shrinkage becomes more nearly uniform across the section of the specimen, and the stress gradient is reduced.

5.1.3 Indentation Strength

From the scatter of points shown in figure 15, where the indentation strength is plotted against compressive strength, it would seem that no clear cut relation can be found for all the concretes. From a close study of the data it appears that a separate relation probably exists for each of the three types of concretes. Each point shown is an average of at least six determinations, half of which were made on a cast surface of the specimen and the others made on the top-screeded surface sanded smooth. The effect of the type of surface on the results was considerable in some cases, but in general was inconclusive. It has been suggested that this type of test may yield better results if a blunt needle were used in place of the disc so that surface finish would have less effect. Benjamin [5] presents some data suggesting the possible use of a Proctor needle for strength tests of cast in place insulating concretes.

5.1.4 Modulus of Elasticity (E), Secant and Dynamic

The secant E is plotted against the dynamic E in figure 16 for perlite and vermiculite concretes. The ratio of the dynamic to the secant values of E is about 1.2 for the data presented, which were developed using "A" cured 6- by 12-in. cylinder test specimens. The amount of moisture in the specimen at test greatly affects the value of the dynamic modulus as is shown in figure 17.

The exact effect of the same amount of moisture on the secant value was not determined, but from figure 16 the effect must be of the same magnitude as for the dynamic modulus. The ratio of dynamic to secant modulus is independent of the test age (Type I vs. Type III cement) and hence independent of the moisture content which is greater for the concretes made with Type III cement and tested at the age of 7 days.

From figure 16 it appears that the secant E can be estimated from the dynamic E, but from figure 18 it can be seen that there is no definite relationship connecting the dynamic E values (and indirectly the secant E) and the compressive strengths of the three different types of concrete. However, a closer examination reveals that somewhat better concordance was observed for some of the aggregates from an individual source.

5.1.5 - 7 Day Strength vs. 28 Day Strength, Type I Cement (3 day vs. 7 day strength, Type III cement)

Figure 19 shows the relation between the 7 day and the 28 day strengths of "A" cured 3- by 6-in. cylinders of insulating concretes made from Type I cement. In figure 20, the 3 day strength is plotted against the 7 day strength for concretes made from Type III cements. It is significant that all three types of concrete appear to define the same relationship between the 7 and 28 day strengths for the Type I cement and 3 and 7 day strengths for the Type III cement. This was to be expected since the strength of insulating concretes is largely determined by the strength of the cement paste. The relationships plotted are considered reliable for the cements used in this investigation, but should not be considered representative for all brands of cements, or cements of the same brand but different mills.

5.1.6 Effect of Moisture on Compressive Strength

It is well known that proper moist curing is essential for development of the compressive strength of concrete. However, it is not generally known to what extent the amount of moisture present in the specimen at the time of test affects the compressive strength of insulating concretes. In order to provide this information, the strengths of "C" cured specimens tested moist were compared with strengths of similar "C" cured specimens which were oven-dried at 220°F just prior to test. The results of this comparison are shown in figure 21.

As can be seen the vermiculite concrete specimens show about 50 percent increase in strength after oven drying. The cellular type concretes indicate quite a scatter; this was to be expected since these concretes exhibit considerable shrinkage cracking of the specimens when oven dried. The effect of drying on the strengths of the perlite concretes was slight, and the reason for this unexpected result is not known. It is possible that there also could be some physical damage to the perlite specimens caused by oven drying.

It appears that the effect of different amounts of moisture at the time of test on the strength of specimens must be determined by some method other than the one used in this investigation so that rapid oven drying would not be necessary. It seems probable that without rapid drying and possible associated damage to the specimen, moisture content would affect strengths of all the insulating concretes studied in a manner similar to that exhibited by the vermiculite concretes in the NBS study.

5.1.7 Effect of Size and Shape of Test Specimen on Compressive Strength

Except in certain curing methods, the effect of size and shape is complicated by moisture content and also by the length of the drying period relative to the damp curing period. In figure 22 the 3- by 6-in. cylinder strengths of some insulating concretes which received cure "A" are plotted against the 6- by 12-in. cylinder strengths and the plot indicates that the 3- by 6-in. cylinder strengths develop about 90 percent of the 6- by 12-in. cylinder strength. This is no doubt true for the "A" cured specimens shown in this figure but is not necessarily true for specimens cured in some other way. In Interim Report No. 1, Table 12, it was shown that 3- by 6-in. cylinders developed only about 60 percent of the strength of 6- by 12-in. cylinders when both sizes were damp cured for only 2 days and allowed to air dry 26 days until tested. The effect of damp curing time on the relative strength of various size specimens is shown graphically in figure 23.

Since the drying rate is greatly affected by the size of the specimen, special care must be taken in choosing data which will show only the effect of size and shape. In figure 24 are presented some data from sets of identically cured 3- by 6-in. and 3- by 3-in. cylinders. Because of the relatively small differences in drying rates, it is felt that the 12 to 15 percent greater strength indicated in figure 24 for the 3- by 3 in. cylinder over the 3- by 6-in. cylinder represents the actual effect of the reduced height of specimens. Much of the data shown in figure 24 is from "C" cured specimens which are tested damp. Similar data plotted in figure 25 indicate that the 2-in. cubes have an equal advantage over the 3- by 6-in. cylinders.

It is thought that either a 3- by 6-in. cylinder or a 4-in. cube would be an acceptable compressive test specimen from the standpoint of providing adequate size for the type of cure which is regarded as being realistic. Either specimen should be damp cured for about 7 days and could be air dried to a reasonable moisture content in about 21 days without oven drying. If oven drying is thought to be necessary before testing, a relatively cool oven (150°F) could probably be used without differential shrinkage damage to the specimen. The oven drying should take place just prior to test when the moisture content of the concrete would be reasonably low.

The 4-in. cube is thought to be a better specimen than the 2-in. cube for two reasons:

(1) Due to the friction on the mold sides, prevention of air voids becomes more of a problem as the specimen size is reduced. Satisfactory 4-in. cube specimens can be molded without the puddling which is sometimes necessary to remove air voids from the 2-in. cube specimen sides.

(2) If the cubes are cut from a larger specimen the weakened edge portions, caused by the sawing will have less effect on the larger 4-in. cube. There is considerable chipping and weakening of the corners when sawing the more brittle concrete.

5.2 Moisture Properties

5.2.1 Drying Shrinkage

The term drying shrinkage as used here, is the measured change in length of the concrete specimen as it dried. Most of this change was probably caused by the loss of moisture, but some, no doubt, was caused by carbonation of the cement paste. It was coincidental that the specimens were dried at the reported optimum [3] humidity condition for carbonation.

The average drying shrinkage curves for 3 types of concrete are shown in figure 26. The average values obtained for individual batches of these concretes are plotted in figure 27 as a function of a cement content.

From Table 13, which gives the values of drying shrinkage for all the concretes tested, it can be seen that the C perlite concretes showed a significantly lower value of drying shrinkage than the concretes made from the other brands of perlite. The maximum drying shrinkage recorded for the C perlite concretes was at a drying period of 90 days. After the 90 day reading the specimens showed a slight increase in length over the previous reading at 90 days. The 650 day reading indicated that the drying shrinkage was about 20 percent less than at 90 days. Figure 28 is a comparison of the long term shrinkage characteristics of the 3 perlites. It is believed that the reversal shown for the B and C perlites is characteristic of perlite concretes. The amount is probably dependent on the method of manufacturing the aggregate, history of the aggregate, and moisture conditions of the concrete in use.

According to Hill [4] this reversal in the time-shrinkage curve is due to a slight expansion of the perlite which he attributes to a rehydration of the perlite aggregate. It is thought that some of the differences in drying shrinkages recorded for the 3 perlite concretes may be due to the differences in their expansion rates since the normal drying shrinkage and the expansion occur simultaneously.

In order to determine the order of magnitude of any expansion in a perlite concrete, shrinkage specimens were cast from each of four batches of A perlite concrete. One specimen from each batch was stored in the 73°F fog room. It was assumed that no carbonation of the concrete would take place in the fog room and that the expansion would occur.

After 480 days of storage in the fog room the average expansion of the four specimens was only .08 percent. This seems to indicate that the A perlite will cause very little long term expansion.

There is no indication that vermiculite or cellular concretes will exhibit this type of expansion.

5.2.2 Rate of Drying (change in weight)

Figure 29 shows the change in moisture content of two types of specimens with drying time. The 2- by 2- by 11-in. prisms were the drying shrinkage specimens dried at 73°F and 50 percent R.H. The 6- by 12-in. cylinders were dried at 73°F in a laboratory where the humidity though uncontrolled, averaged about 50 percent.

Figure 30 shows the change in weight of the shrinkage specimens at an enlarged scale to exaggerate the gain in weight of the specimens after about 20 days drying period. This increase in weight is attributed to carbonation of the cement although some of the gain in the perlite concretes may be due to the rehydration of the aggregate as suggested by Hill [4].

5.2.3 Absorption

Absorptions of the concretes are listed in Table 13. It is indicated that for the perlite and vermiculite concretes absorption is a function of the density of the concrete.

5.3 Thermal Movements

Thermal expansion coefficients of the perlite and vermiculite concretes are listed in Table 13. It appears that the density or cement content of these concretes have very little effect on the thermal expansion.

The saturated concretes show a significantly higher value of thermal expansion than the oven dry specimens, particularly for the perlite concretes.

5.4 Reinforced Insulating Concrete Slabs

Some of the deflections recorded for both the reinforced perlite and vermiculite concrete slabs under sustained load must be attributed to the warping of the slab as it dries out. This warping is due to the drying shrinkage of the concrete which is restrained by the steel in the lower section of the slab. No estimate has been made of the amount of the measured deflection which is caused by this warpage.

5.4.1 Perlite Concrete Slabs
Sustained Load Test (1/2 Ultimate)

Figure 31 which is an extension of the data shown in figure 5 of [2] indicates that deflections of the perlite slabs were probably still increasing slightly although the individual readings are still being affected by fluctuations of the temperature and humidity conditions in the test room. No serious cracks were observed on either slab.

5.4.2 Vermiculite Concrete Slabs
Short-Term Tests

Figure 32 shows the load-deflection curves for the 7 slabs tested under short-term conditions. Loss of bond between the steel and the concrete was the cause of failure in the first 4 slabs (SL-1 through 4). Fracture of the steel caused the failure of the other 3 slabs tested (SL-6, 8 and 9). From these data it appears that a vermiculite concrete strength of about 300 psi was sufficient to provide the necessary bond between the concrete and the 4- by 4-in. 12/12 ga welded wire fabric to develop the full strength of the steel.

5.4.3 Vermiculite Concrete Slabs
(Sustained Load Test (1/2 Ultimate)

The results of the sustained load test are shown on figure 33.

Slab No. 7 developed a diagonal tension crack which was observed on one edge at 28 days after loading. At the time of the last reading (270 days) the crack had progressed across the width of the slab and was visible on the opposite edge. No serious cracking was observed on Slab No. 10.

6. CONCLUSIONS

1. The minimum compressive strength of an insulating concrete can be estimated from the wet density of the concrete containing a given aggregate, provided segregation is prevented and the water content is the minimum required to produce a mix of pourable consistency. The wet density may be used as a field control of compressive strength.

2. The minimum compressive strength of an insulating concrete of a given type of aggregate may be estimated from the oven-dry density of the concrete. This relationship is also only valid for non-segregating mixes.

3. The addition of extra mixing water does not appreciably affect the relationship between compressive strength and the oven-dry density but it increases the wet density and may cause segregation.

4. The static secant modulus of elasticity can be estimated from the dynamic modulus.

5. The compressive strength of insulating concretes at 7 days can be used to estimate the 28 day strength.

6. The moisture content of test specimen at the time of test can greatly affect the measured compressive strength.

7. The length of the damp cure period can greatly affect the relative strengths of various sizes of compressive test specimens.

8. The cubical compressive test specimen will indicate a higher strength than a cylindrical specimen with a height of diameter ratio approaching 2.

9. A considerable difference in drying shrinkage exists between the 3 types of concrete, as well as between concretes made from different brands of perlite.

10. The absorption is inversely proportional to the dry density of these concretes.

11. Except for the oven-dry perlite concrete the coefficient of thermal expansion for these concretes is not significantly different from the values reported for other portland cement products.

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Table 1. Sieve analysis of aggregates

Aggregate	Weight of sample	Percent by weight passing sieve No.						
		3/8	4	8	16	30	50	100
	gm							
Perlite A	70.7	100	100	99.2	62.4	26.7	15.1	9.2
Perlite B	82.5	100	100	99.9	76.5	34.8	12.6	3.1
Perlite C	57.0	100	100	85.3	53.7	27.7	17.2	10.0
Vermiculite D	68.7	100	99.9	91.2	58.3	29.2	10.0	2.6
Vermiculite E	55.0	100	100	76.0	31.0	8.0	3.0	2.0

Table 2. Dry loose unit weight of aggregates

Aggregate	Nominal	As Used	Bag size
	pcf	pcf	cu ft
Perlite A	7.5	8.0	4
Perlite B	7.5	8.0	4
Perlite C	7.5	7.6	4
Vermiculite D	6.0	7.7	4
Vermiculite E	6.0	6.5	3

Table 3. Crushing strengths of aggregates

Aggregate	Crushing strength, psi, average of 3 tests		
	For 1-in. compaction	For 2-in. compaction	For 3-in. compaction
Perlite A	47	150	381
Perlite B	48	128	336
Perlite C	25	87	299
Vermiculite D	31	85	139[1]
Vermiculite E	10	26	40[1]

[1] At 2 1/2 in. compaction

Table 4. Mix proportions recommended by manufacturers

Aggregate	Mix[1]	Cement	Aggregate	Water
		sacks	cu ft	lb
Perlite A and B	1:6	1	6.0	100
	1:5	1	5.0	92
	1:4	1	4.0	75
Perlite C	LD-4	1	8.0	162
	LD-5	1	6.4	133
	LD-6	1	5.3	112
Vermiculite D	1:8	1	8.0	200
	1:6	1	6.0	146
	1:5	1	5.0	119[2]
	1:4	1	4.0	92
Vermiculite E	1:6	1	6.0	158
	1:5	1	5.0	129
	1:4	1	4.0	108

[1] Manufacturer's designations.

[2] Water requirement estimated - not a recommended mix

Table 5. Concretes made from Perlite "A"

Batch No.	Ratio cement to aggregate by volume	Cement content per cu yd of concrete	Mix water per sack cement	Type of cement	Densities			Compressive strength 6- by 12-in. cylinder	Modulus of rupture	Inden-tation strength	Dynamic "E"
					Wet	Test	Oven dry				
		sacks	lb		pcf	pcf	pcf	psi	psi	psi	psi
6ARA	1:6	4.35	99	I	39.0	28.5	26.4	233	73	248	.138 x 10^6
6ARB	1:6	5.50	129	I	55.7	38.1	34.0	357	--	--	.244
5ARA	1:5	5.27	94	I	44.5	33.1	30.2	357	115	503	.196
5ARB	1:5	6.49	110	I	59.6	43.9	38.1	611	--	--	.298
5ARC	1:5	6.37	110	I	57.5	42.4	36.9	523	--	--	.271
5ARD	1:5	6.05	110	I	54.6	36.9	32.7	364	--	--	.227
4ARA	1:4	6.92	75	I	51.8	42.1	37.7	581	187	935	.289
4ARB	1:4	7.43	94	I	60.4	48.3	41.5	674	--	--	.324
6AHA	1:6	4.33	99	III	38.8	31.0	25.6	201	37	286	.147
6AHB	1:6	5.35	135	III	53.8	42.6	33.0	423	--	--	--
6AHC	1:6	5.42	135	III	55.6	43.8	33.9	465	--	--	--
6AHD	1:6	5.38	135	III	55.3	43.5	33.6	463	--	--	--
5AHA	1:5	6.20	94	III	52.4	46.7	38.0	648	68	1000	.347
5AHB	1:5	5.13	94	III	43.3	35.2	29.6	259	--	--	--
5AHC	1:5	5.11	94	III	43.3	35.4	29.4	258	--	--	--
5AHD	1:5	6.54	94	III	55.4	46.1	39.1	433	--	--	--
5AHE	1:5	5.59	94	III	48.4	43.7	32.6	418	--	--	.262
5AHF	1:5	5.11	94	III	43.5	39.1	29.9	293	--	--	.202
4AHA	1:4	6.17	75	III	46.0	39.4	33.1	379	53	487	.227
4AHB	1:4	8.52	76	III	63.5	--	47.5	886	--	--	--
4AHC	1:4	6.14	76	III	45.8	41.3	33.4	402	--	--	--
4AHD	1:4	7.30	76	III	54.4	48.2	38.4	665	--	--	--

Table 6. Concretes made from Perlite "B"

Batch No.	Ratio: cement to aggregate by volume	Cement content per cu yd of concrete	Mix water per sack cement	Type cement	Densities			Compressive strength 6- by 12-in. cylinder	Dynamic "E"
					Wet	Test	Oven dry		
		sacks	lb		pcf	pcf	pcf	psi	psi
6BRA	1:6	4.16	102	I	37.8	28.2	25.3	195	.120 x 10^6
6BRB	1:6	4.11	120	I	40.0	27.5	25.4	179	.129
6BRC	1:6	4.22	120	I	41.0	28.0	25.8	199	.137
6BRD	1:6	4.18	120	I	40.7	27.8	25.7	191	.136
6BRE	1:6	4.07	120	I	39.5	28.6	25.9	179	--
6BRF	1:6	4.32	120	I	42.1	29.6	26.6	214	--
6BRG	1:6	4.80	120	I	46.7	32.7	28.9	303	--
5BRA	1:5	4.75	112	I	43.3	30.4	27.8	247	.151
5BRB	1:5	4.96	112	I	45.2	32.4	29.2	276	.165
5BRC	1:5	5.10	112	I	46.5	34.2	30.5	300	.114
4BRA	1:4	6.05	90	I	48.5	36.6	32.4	337	.175
4BRB	1:4	5.92	90	I	47.4	34.7	31.5	336	.199
4BRC	1:4	6.25	90	I	49.9	36.5	32.9	383	.216
6BHA	1:6	3.80	102	III	34.5	27.9	22.6	130	.112
6BHB	1:6	3.76	143	III	39.4	26.8	22.5	155	--
6BHC	1:6	3.75	143	III	39.2	27.1	22.5	156	--
6BHD	1:6	3.73	138	III	39.0	27.1	22.9	162	--
5BHA	1:5	4.61	94	III	39.1	32.6	26.0	261	.162
5BHB	1:5	4.96	104	III	43.8	33.3	28.2	236	--
5BHC	1:5	4.75	93	III	39.9	35.1	26.2	232	--
5BHD	1:5	4.75	93	III	39.9	35.0	26.9	258	.180
4BHA	1:4	5.78	76	III	43.5	38.8	30.7	350	.225

Table 7. Concretes made from Perlite "C"

NBS batch No.	Ratio: cement to aggregate by volume	Cement content per cu yd of concrete	Mix water per sack cement	Type cement	Densities			Compressive strength 6- by 12-in. cylinder	Dynamic "E"
					Wet	Test	Oven dry		
		sacks	lb		pcf	pcf	pcf	psi	psi
8CRA	1:8	4.82	161	I	56.7	38.7	33.1	334	.212 x 10^6
8CRB	1:8	4.07	162	I	48.5	34.4	30.5	211	---
8CRC	1:8	4.17	162	I	50.2	34.9	31.0	218	---
8CRD	1:8	3.89	162	I	46.2	33.0	29.7	166	---
6CRA[1/]	1:6	4.08	123	I	40.0	26.3	24.3	129	---
6CRB	1:6.4	5.67	134	I	58.7	42.9	36.2	406	.247
6CRC	1:6.4	4.81	133	I	48.5	35.8	30.6	186	---
6CRD	1:6.4	4.71	133	I	47.7	34.5	29.9	155	---
6CRE	1:6.4	5.65	133	I	58.5	40.1	34.1	326	---
5CRA[1/]	1:5	5.14	92	I	43.0	32.0	29.0	178	---
5CRB[1/]	1:5	5.62	92	I	47.1	35.4	31.2	220	---
5CRC	1:5.3	5.44	113	I	49.8	36.8	31.5	295	.149
8CHA	1:8	3.59	162	III	42.5	33.2	27.1	117	.118
8CHB	1:8	4.72	162	III	56.0	43.0	33.9	175	.175
8CHC	1:8	4.64	162	III	55.0	42.8	33.9	187	.175
8CHD	1:8	3.75	162	III	44.5	33.9	26.1	130	.118
8CHE	1:8	3.55	177	III	44.6	34.4	26.9	120	.121
8CHF	1:8	3.26	162	III	38.7	26.1	21.4	73	.077
8CHG	1:8	3.48	162	III	40.9	35.0	26.6	108	.122
8CHH	1:8	4.07	162	III	47.7	39.8	30.2	156	.153
8CHI	1:8	4.79	162	III	56.3	42.9	32.6	233	.195
6CHA[1/]	1:6	4.14	100	III	37.0	31.6	25.2	150	.131
6CHB	1:6.4	4.55	133	III	46.8	36.8	29.4	171	.148
6CHC	1:6.4	4.55	133	III	46.8	40.4	31.2	158	.153
6CHD	1:6.4	4.45	133	III	45.9	36.1	28.5	209	.157
6CHE	1:6.4	5.35	133	III	55.1	45.3	32.6	257	---
6CHF	1:6.4	5.03	155	III	56.7	48.4	36.6	325	---
6CHG	1:6.4	5.28	133	III	53.9	43.9	32.8	234	---
5CHA[1/]	1:5	4.73	92	III	39.4	33.4	27.1	172	.153
5CHB	1:5.3	5.18	112	III	47.9	38.9	31.2	297	.209
5CHC	1:5.3	5.92	112	III	54.5	46.5	36.5	381	.268
5CHD	1:5.3	5.70	112	III	52.7	43.4	34.3	387	.244
5CHE	1:5.3	6.00	112	III	55.3	47.8	37.6	416	.293
5CHF	1:5.3	6.37	112	III	58.1	49.0	36.9	361	---
5CHG	1:5.3	6.14	112	III	56.0	47.5	35.4	368	---
5CHH	1:5.3	6.21	112	III	56.7	48.8	36.7	376	---
4CHA[1/]	1:4	5.87	75	III	43.4	38.9	31.3	266	.206

[1/] Indicates batches containing air entraining agent.

Table 8. Vermiculite concretes

NBS Batch No.	Ratio: cement to aggregate by volume	Cement content per cu yd of concrete	Mix water per sack cement	Type cement	Densities			Compressive strength 6- by 12-in. cylinder	Modulus of rupture	Indentation strength	Dynamic "E"
					Wet	Test	Oven Dry				
		sacks	lb		pcf	pcf	pcf	psi	psi	psi	psi
8DH	1:8	2.85	196	III	38.1	30.7	20.0	47	13	93	---
6DH	1:6	3.97	156	III	44.6	37.9	24.8	110	24	165	---
5DH	1:5	5.00	125	III	48.4	41.1	29.0	155	33	217	$.128 \times 10^6$
4DH	1:4	6.71	102	III	57.2	46.7	35.5	280	56	396	.214
8DR	1:8	3.15	196	I	42.2	22.7	21.2	78	42	120	.045
6DR	1:6	3.74	150	I	41.2	24.5	22.8	82	40	102	.054
5DR	1:5	4.78	125	I	47.0	30.9	27.9	156	71	219	.099
4DR	1:4	5.91	110	I	51.5	34.8	31.1	280	88	323	.158
6ER	1:6	4.98	151	I	52.6	32.3	28.7	177	107	232	.145
5ER	1:5	5.81	118	I	52.8	35.5	31.0	186	114	227	.156
4ER	1:4	7.65	75	I	56.4	42.5	36.5	320	188	382	.235

Table 9. Cellular Concrete.

Batch No.	Cement content per cu yd concrete	Water cement ratio by weight[1]	Air[2] content by volume	Type cement	Densities wet	Densities test	Densities oven dry	Compressive strength 6- by 12-in. cylinder	Modulus of rupture	Indentation strength	Dynamic "E"
			%		pcf	pcf	pcf	psi	psi	psi	psi
20FH	5.26	.64	72	III	30.0	23.3	20.2	91	20	165	$.051 \times 10^6$
20GH	5.44	.67	70	III	31.4	25.3	20.9	53	10	121	.042
25FH	6.06	.66	67	III	35.2	28.6	24.0	168	34	306	.079
25GH	6.52	.57	66	III	36.8	31.5	25.7	85	16	292	.078
30FH	7.45	.59	62	III	41.0	33.6	28.6	213	40	499	.082
30GH	7.92	.58	61	III	43.7	37.1	31.1	230	38	492	.117
35FH	8.42	.56	59	III	45.6	38.0	32.3	235	45	400	---
20FR	5.68	.65	69	I	32.4	24.2	23.2	52	18	139	---
25FR	6.06	.66	68	I	34.5	26.8	25.0	103	37	215	.050
25GR	6.29	.60	68	I	35.0	26.3	25.0	57	-	--	.035
30FR	7.13	.57	65	I	39.0	30.1	28.1	130	23	192	---
35FR	8.38	.56	59	I	45.3	36.0	33.6	211	37	339	
35GR	9.44	.57	53	I	51.6	41.8	38.6	351	55	722	.139
30FSH[3]	7.90[4]	.49	64	III	40.8	31.6	29.7	147	--	--	.063
35FSH[3]	9.20[4]	.50	58	III	48.0	37.1	35.0	253	--	--	.114

---

[1] Includes water in preformed foam.

[2] Calculated from theoretical air free density of cement paste.

[3] Tested at 28 days.

[4] Cement content values includes 50% by weight special additive.

Table 10. Vermiculite concrete slabs

NBS batch No.	Ratio: cement to aggregate by volume	Cement content per cu yd concrete	Mix water per sack cement	Densities			Compressive strength (2" cube)	Type of test	Type of failure
				wet	test	oven dry			
		sacks	lb	pcf	pcf	pcf			
SL-V 1	1:6	4.65	184	56.0	32.7	28.0	280	Short term	Bond
SL-V 2	1:6	4.50	175	53.0	29.9	25.9	260	Short term	Bond
SL-V 3	1:6	4.74	167	54.4	32.6	27.5	260	Short term	Bond
SL-V 4	1:6	4.34	163	49.4	29.7	25.0	220	Short term	Bond
SL-V 5	1:6	4.50	163	51.2	29.0	25.5	200	Broken accidently	--
SL-V 6	1:4	6.56	111	58.0	39.8	34.7	380	Short term	Steel
SL-V 7	1:6	4.74	162	53.5	---	26.0	200	Long term	--
SL-V 8	1:4	5.98	108	52.0	37.3	31.7	290	Short term	Steel
SL-V 9	1:4	7.09	113	62.9	44.3	37.2	530	Short term	Steel
SL-V 10	1:4	6.86	112	60.7	--	36.1	430	Long term	--

Table 11. Cure and test schedule for strength specimens

Cure	Type of specimen	Type I Cement			Type III Cement		
		Age at test	Damp cure period[1]	Test condition[2]	Age at test	Damp cure period[1]	Test condition[2]
		days	days		days	days	
Early test	3 x 6 and 3 x 3 cylinder	7	4	air dry	3	2	air dry
"A"	3 x 3, 3 x 6, 6 x 12 cylinder 2-in. cube, 3 x 4 x 16 prisms, and slabs	28	4	air dry	7	2	air dry
"A-1"	3 x 3 and 3 x 6 cylinder	29	4	oven dry	8	2	oven dry
"C"	3 x 3, 3 x 6, and 2-in. cube	28	28	damp	7	7	damp
"C-1"	3 x 3, 3 x 6, and 2-in. cube	29	28	oven dry	8	7	oven dry

---

1/ The damp cure period includes 24 hr in mold, and the balance of the period in the 73°F fog room.

2/ Air dry indicates that the specimen was allowed to dry in the lab air from end of damp cure until tested; oven dry indicates that the specimen was dried in a 220°F ventilated oven just prior to test.

Table 12. Typical insulating concretes (average results)

Aggregate	Mix proportions: cement to aggregate	Cement content per cu yd of concrete	Water per sack of cement	Density		Compressive strength 6 x 12 cyl. 3/	Modulus of 1/ rupture	Modulus of 2/ elasticity	No. of batches averaged
				wet	oven dry				
		sacks	lb	pcf	pcf	%	%	%	
Perlite A and B	1:6	4.4	122	43.4	27.1	250	60	.14 x 10^6	17
	1:5	5.4	100	47.7	31.3	350	80	.17	17
	1:4	6.6	82	51.1	35.9	500	110	.23	10
Perlite C	1:8.0	4.1	163	48.3	29.5	170	40	.10	13
	1:6.4	5.0	135	51.9	32.2	240	60	.14	10
	1:5.3	5.9	112	53.9	35.0	360	80	.18	8
Vermiculite D and E	1:8	3.0	196	40.2	20.6	60	25	.05	2
	1:6	4.2	152	46.1	25.4	120	50	.08	3
	1:5	5.2	123	49.4	29.3	170	70	.10	3
	1:4	6.8	98	55.0	34.4	290	110	.15	3
Cellular F and G	---	5.5	61	31.3	21.4	65	--	--	3
	---	6.2	58	35.4	24.9	100	--	--	4
	---	7.6	53	41.1	29.4	180	--	--	4
	---	8.9	52	47.6	34.9	260	--	--	4

1/ Estimated from figure 11.

2/ Secant modulus for 1/2 f'_c estimated from figures 13 and 15.

3/ Cure "A"

Table 13. Thermal Expansion and Moisture Properties of Some Insulating Concretes.

NBS Batch No.	Type concrete	Coefficient of Thermal Expansion		Absorption by weight		Absorption by volume		Drying shrinkage in 180 days
		Saturated condition	Oven-dry condition	24 hr cold soak	5 hr boil	24 hr cold soak	5 hr boil	
		$10^{-6}/°F$	$10^{-6}/°F$	%	%	%	%	%
8DH	Vermiculite D	---	---	---	---	---	---	.294
6DH	do	6.43	---	143	206	58	84	.380
5DH	do	6.88	6.0	103	164	51	81	.433
4DH	do	6.98	6.2	62	129	38	79	.465
8DR	do	---	---	172	248	60	87	.304
6DR	do	6.55	---	154	222	58	84	.369
5DR	do	7.25	6.3	115	174	55	83	.353
4DR	do	7.33	6.2	85	156	44	81	.417
Avg. 3 batches	Vermiculite E	---	---	---	---	--	--	.398
6AHA	Perlite A	6.42	---	107	136	48	60	.183
5AHA	do	6.38	4.6	42	67	27	43	.185
4AHA	do	6.51	4.7	79	101	45	58	.255
6ARA	do	6.18	---	108	145	47	64	.182
5ARA	do	6.48	4.8	73	117	38	61	.197
4ARA	do	6.53	4.8	43	82	28	53	.238
6BRA	Perlite B	---	---	---	---	--	--	.263
Avg. 3 batches	Perlite C	---	---	---	---	--	--	.164
Avg. 12 batches	Cellular	---	---	71	174	39	84	.616
Avg. 2 batches	Cellular plus Additive	---	---	---	---	--	--	.426

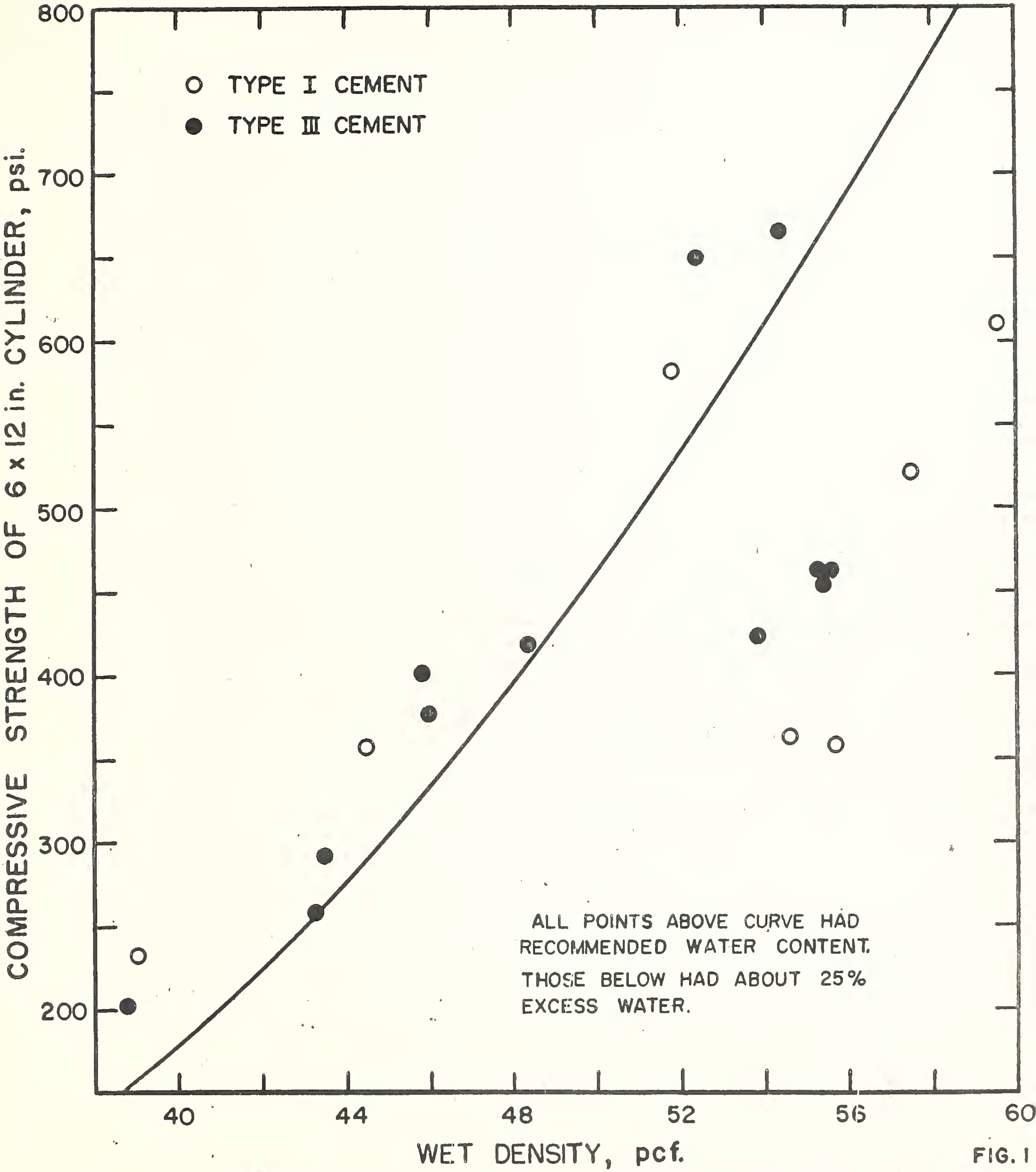
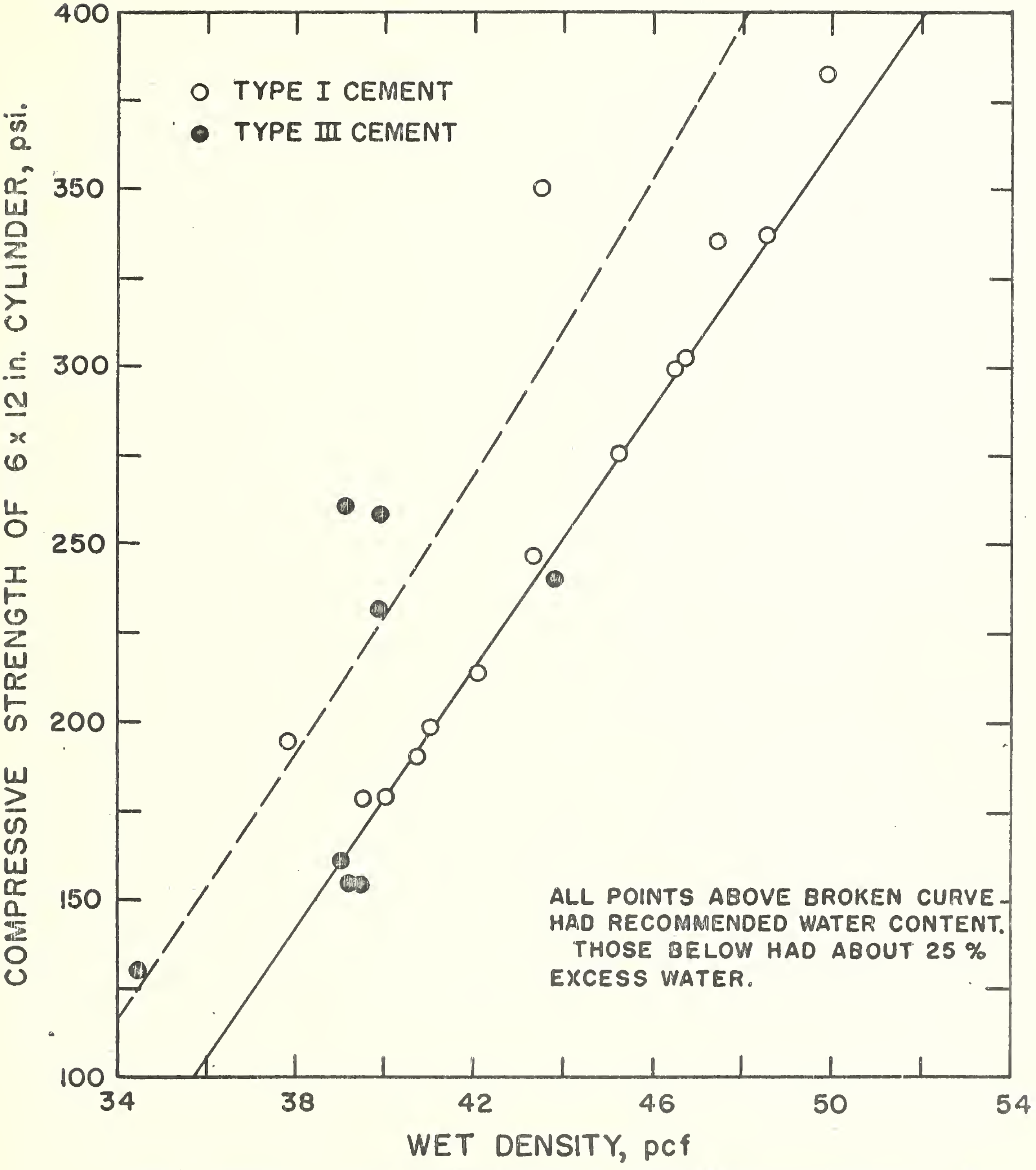


FIG. 1

WET DENSITY VS. COMPRESSIVE STRENGTH–PERLITE A



WET DENSITY VS COMPRESSIVE STRENGTH-PERLITE B

FIG. 2

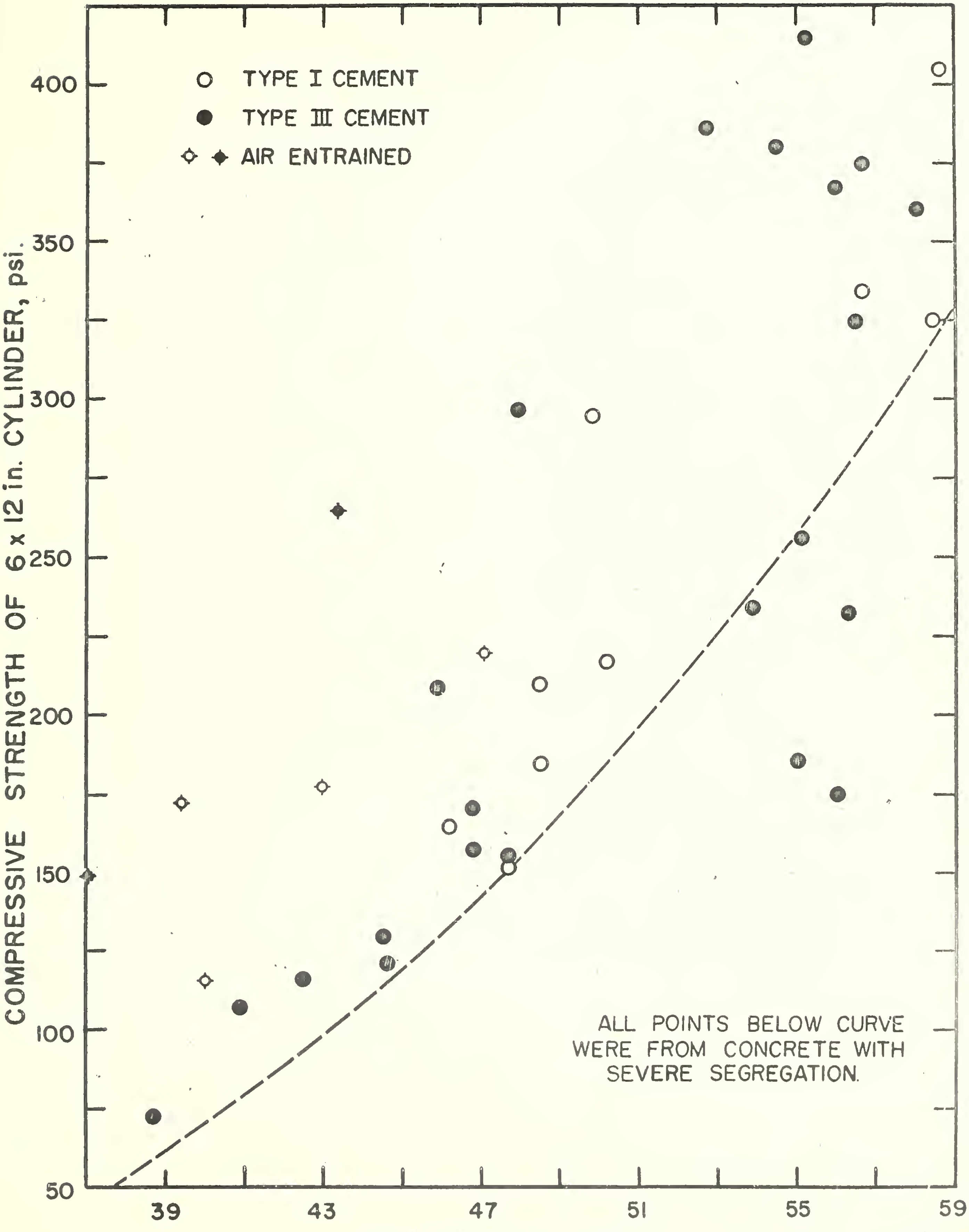
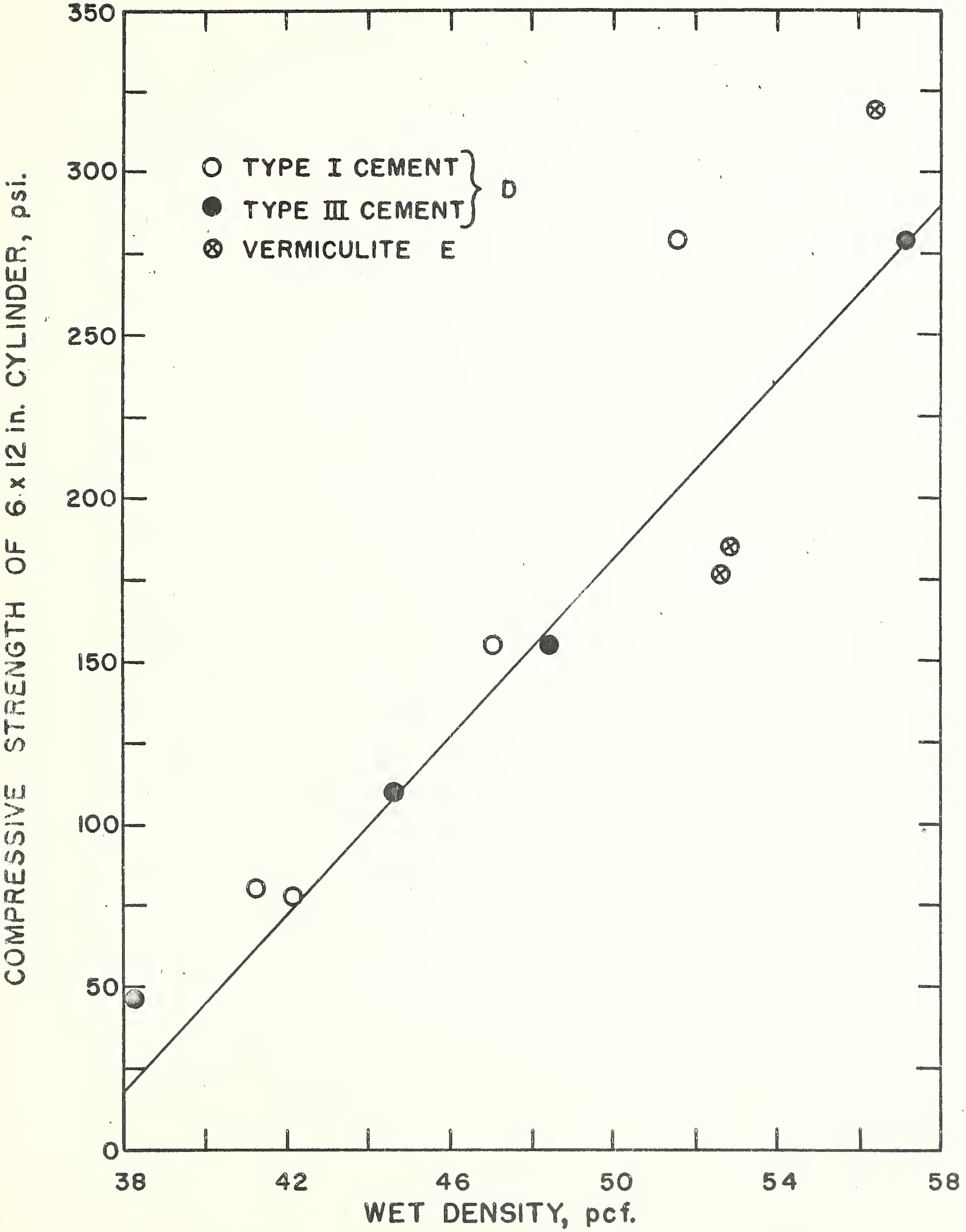


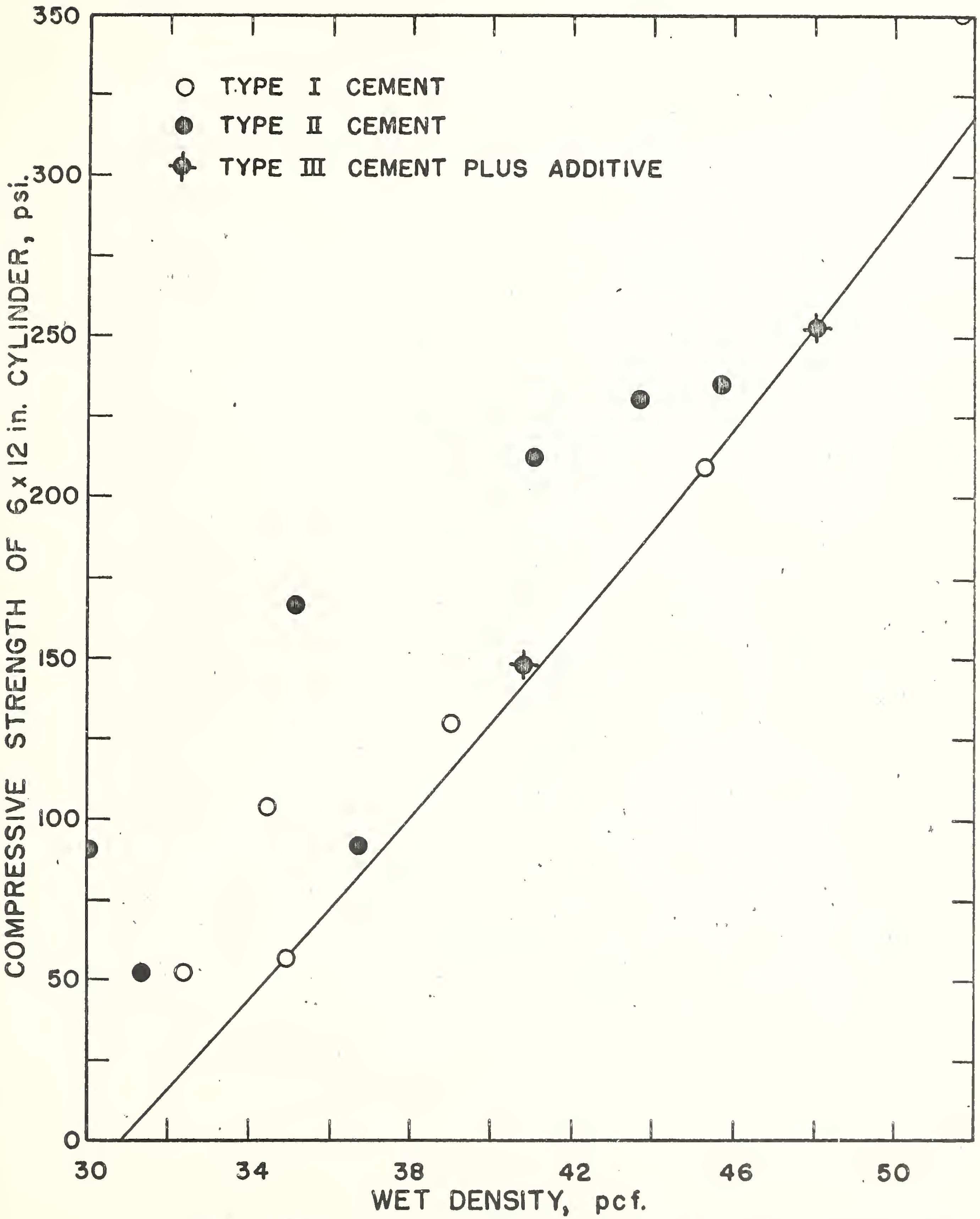
FIG. 3

WET DENSITY VS. COMPRESSIVE STRENGTH–PERLITE C



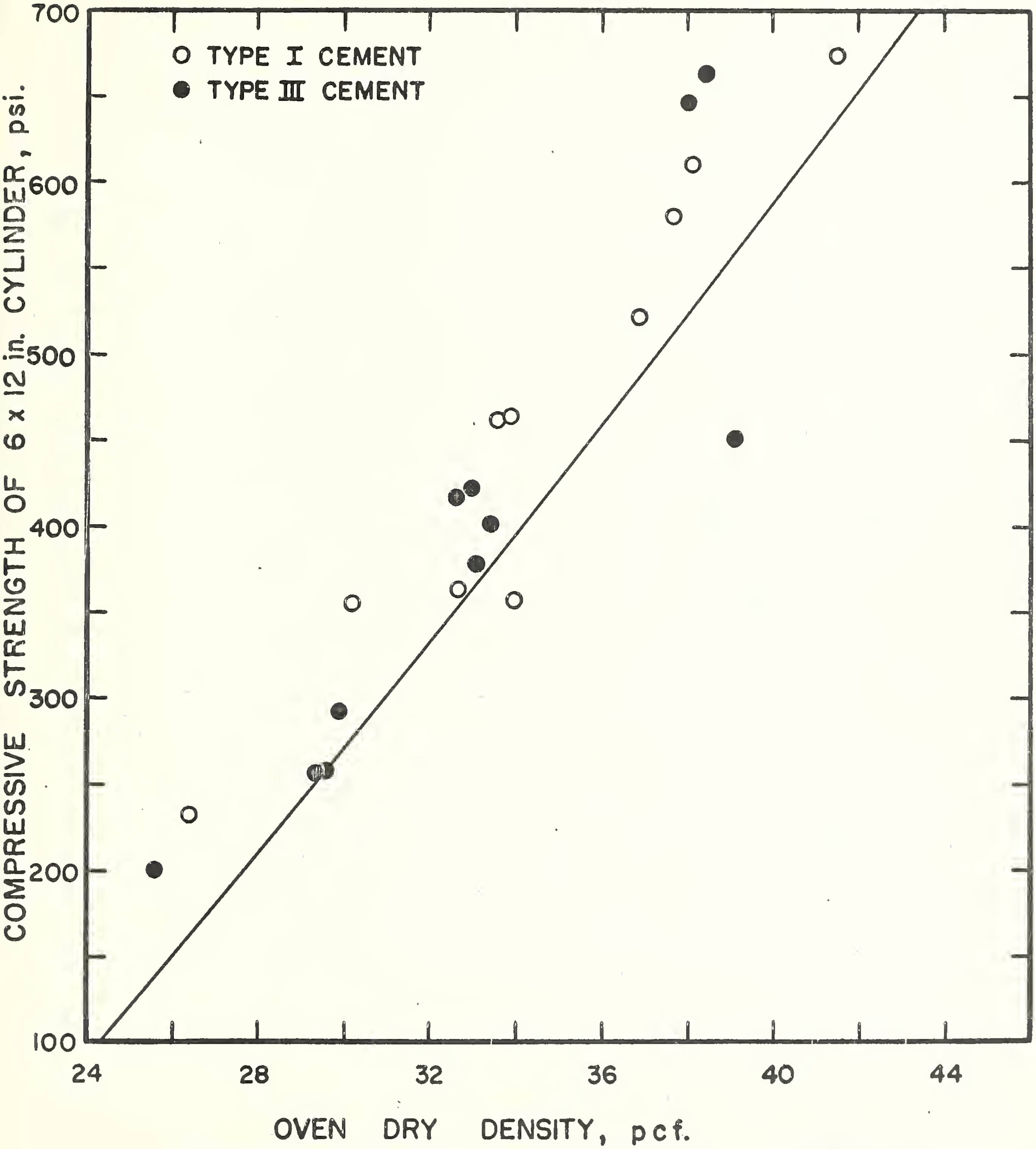
WET DENSITY VS. STRENGTH — D & E VERMICULITES

FIG. 4



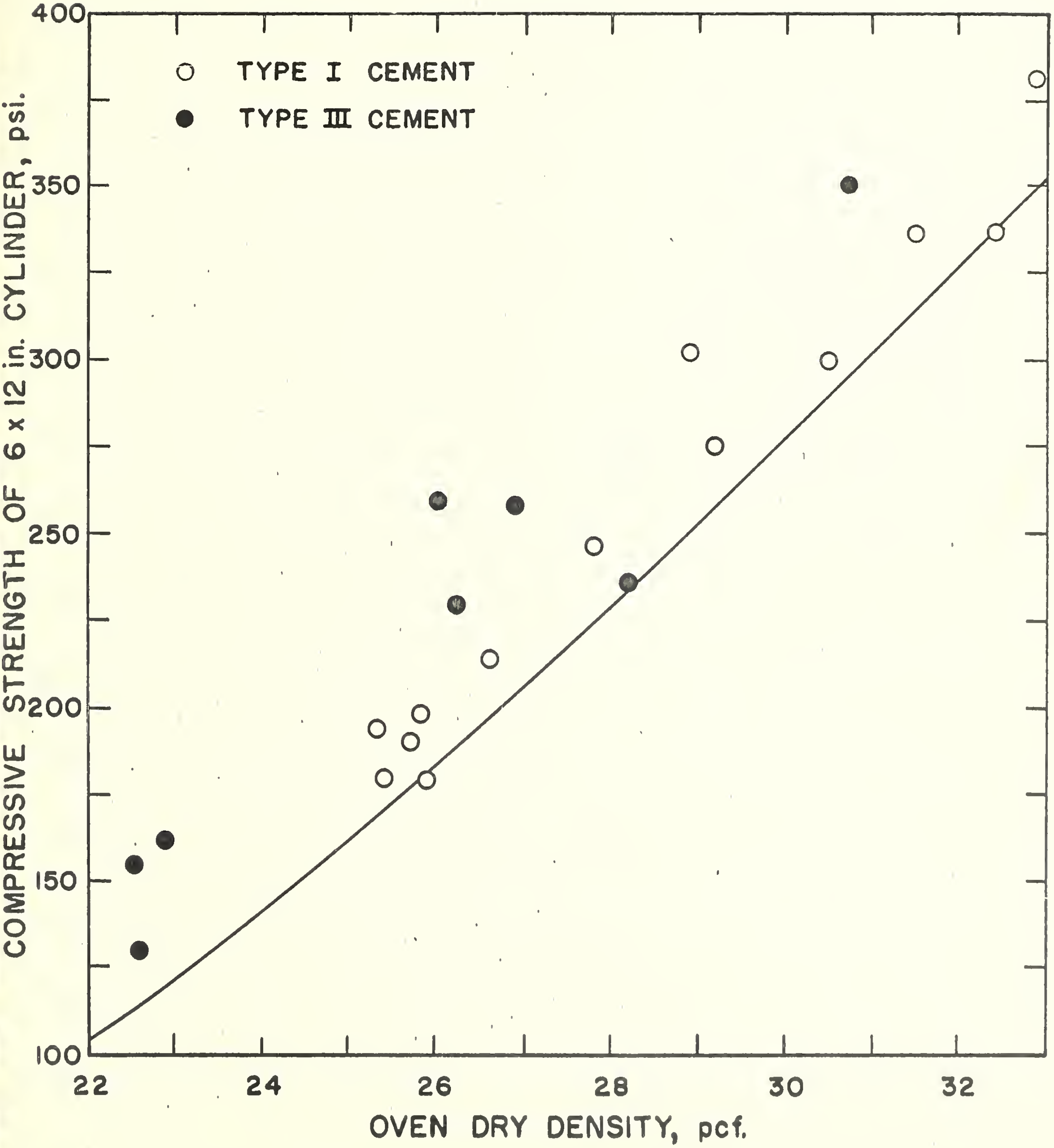
WET DENSITY VS. STRENGTH OF CELLULAR CONCRETES

FIG.



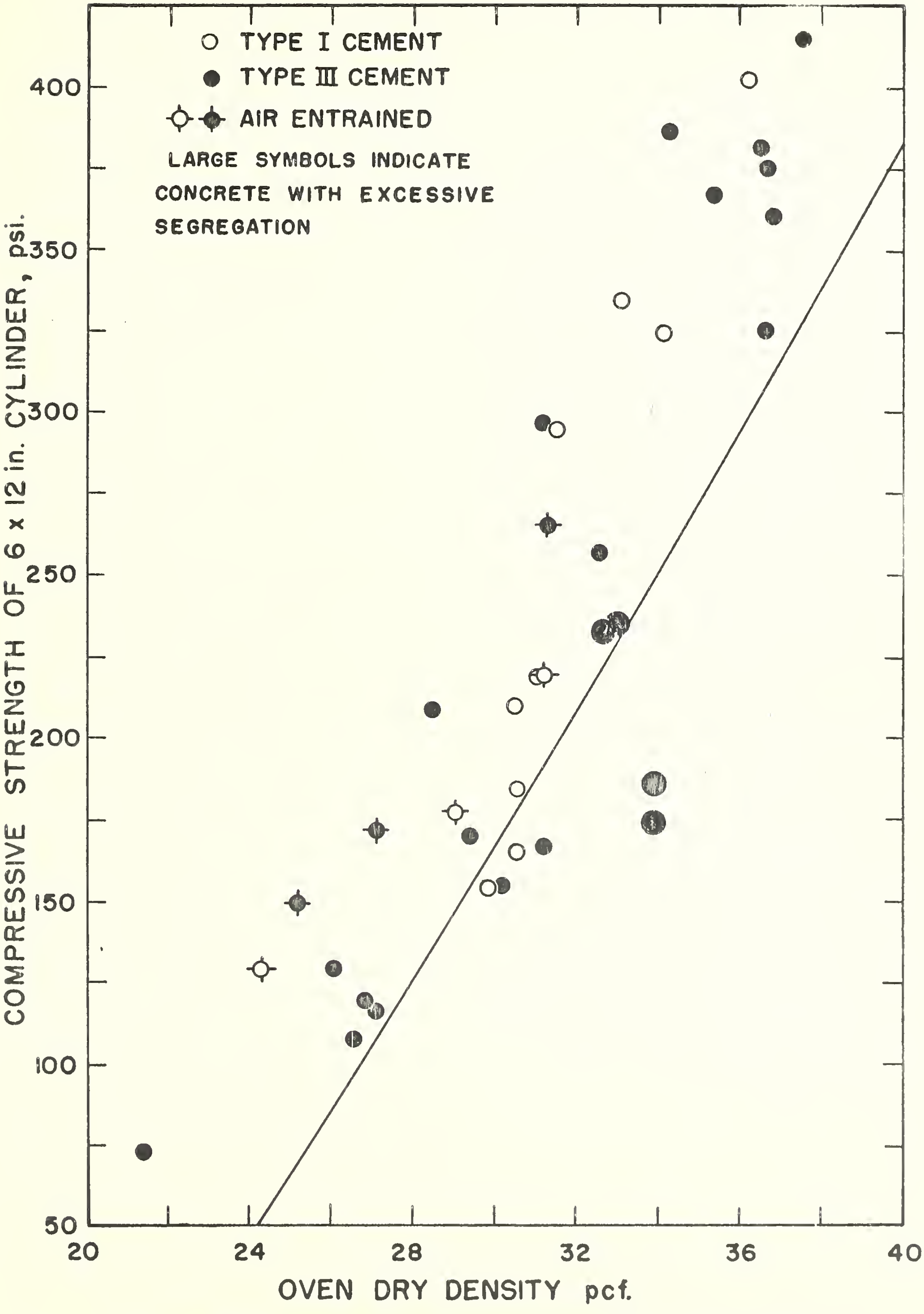
OVEN DRY DENSITY VS. STRENGTH — PERLITE A

FIG. 6



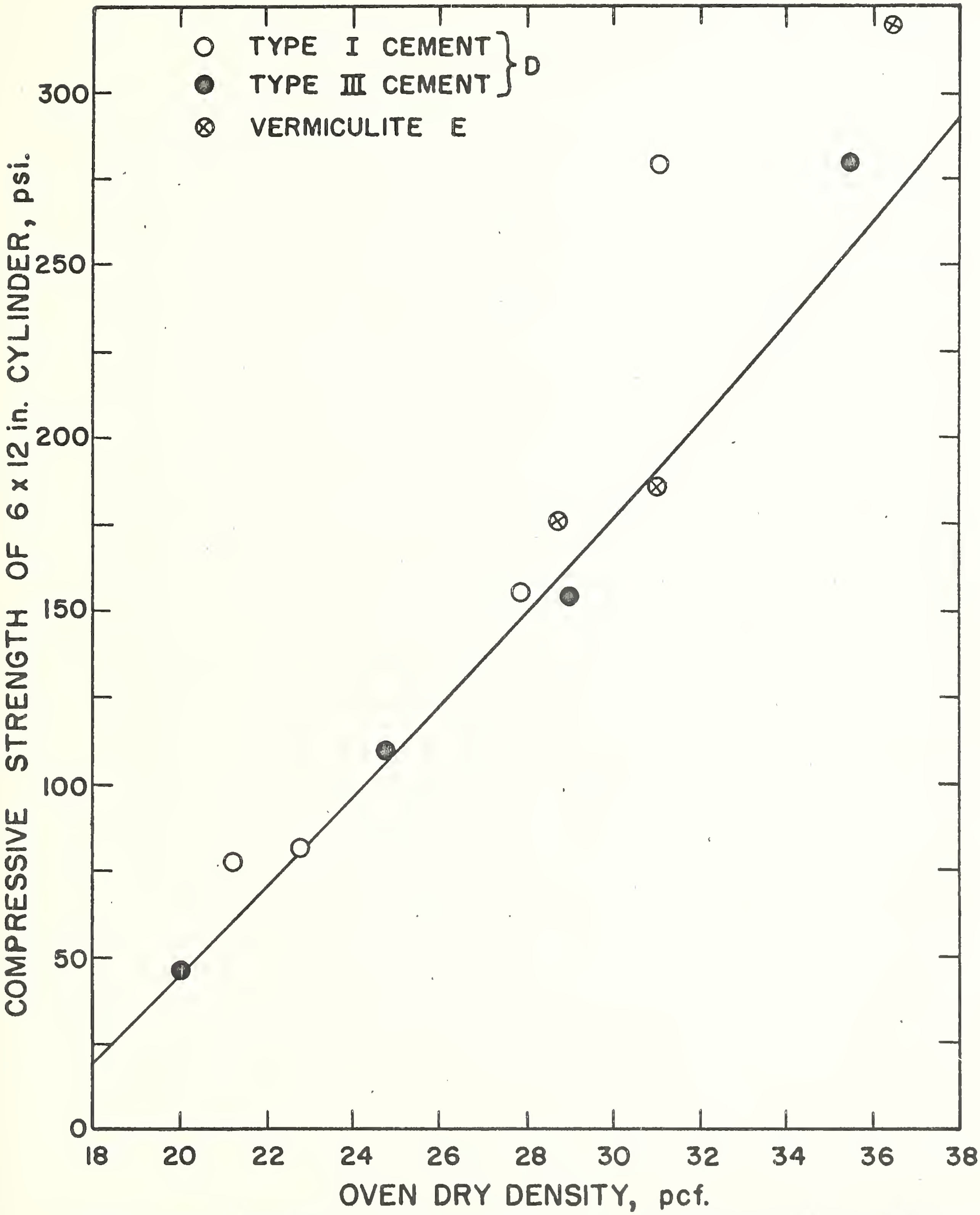
OVEN DRY DENSITY VS. STRENGTH — PERLITE B

FIG. 7



OVEN DRY DENSITY VS. STRENGTH — PERLITE C

FIG. 8



OVEN DRY DENSITY VS. STRENGTH OF VERMICULITE CONCRETE

FIG. 9

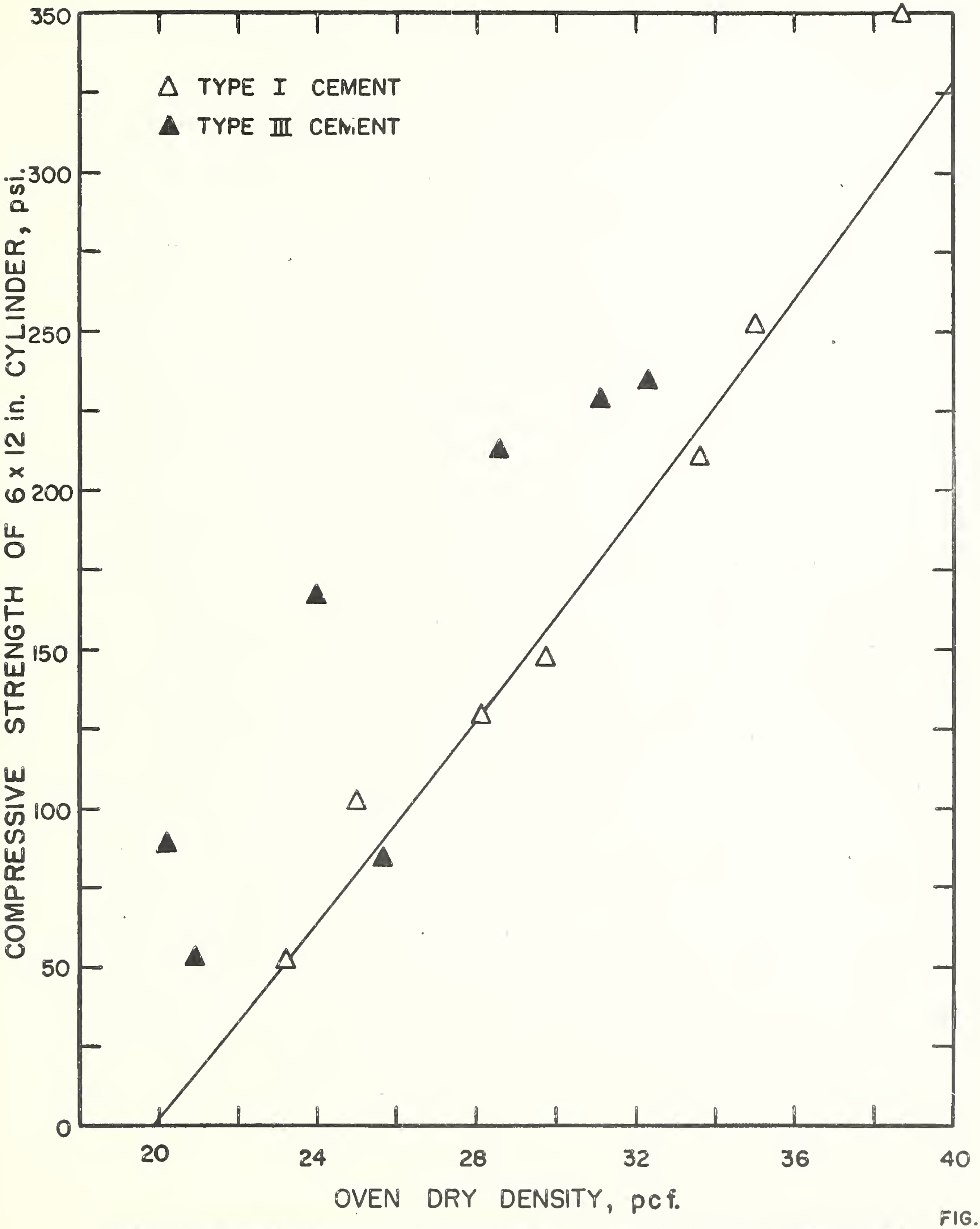
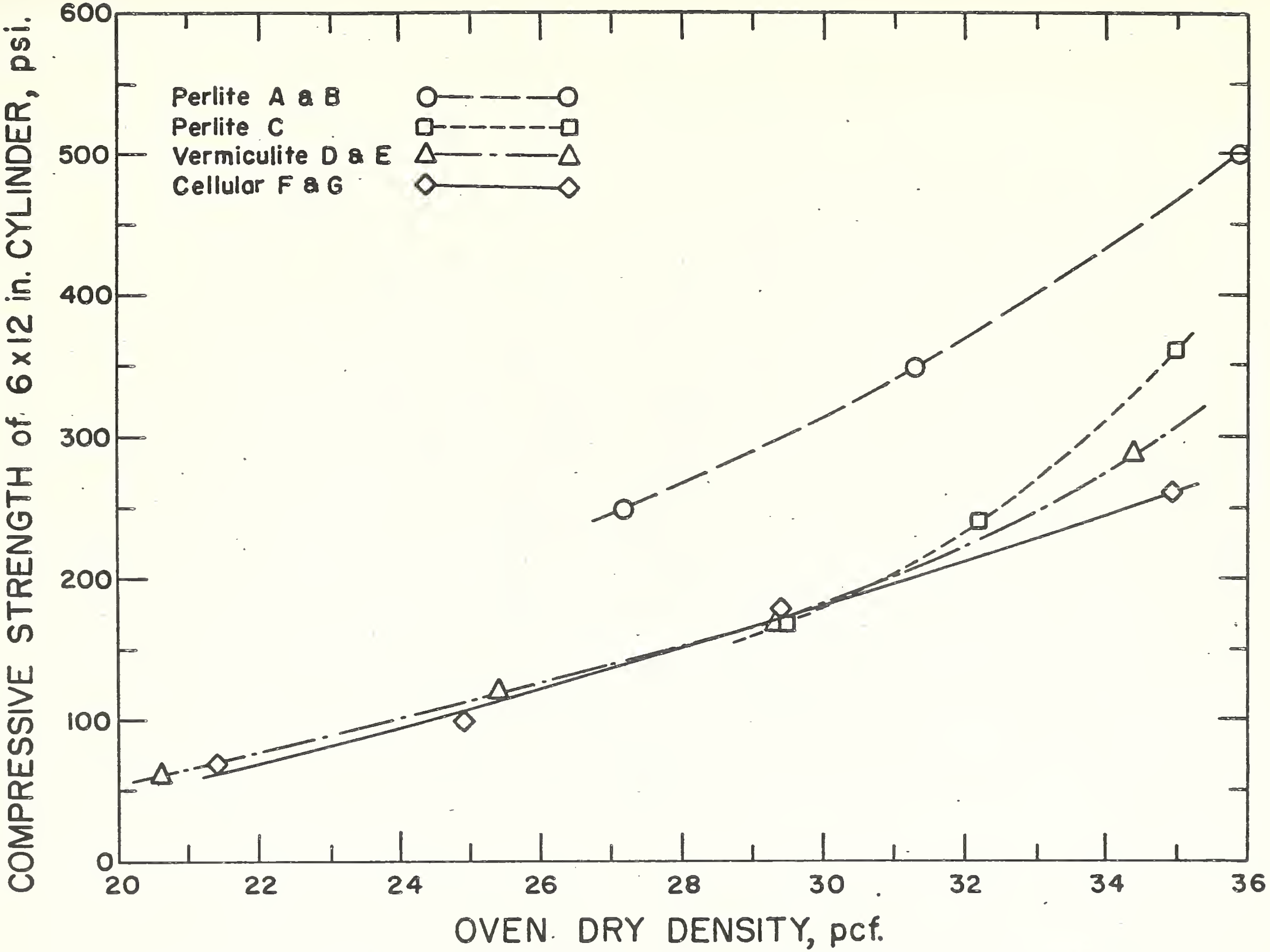


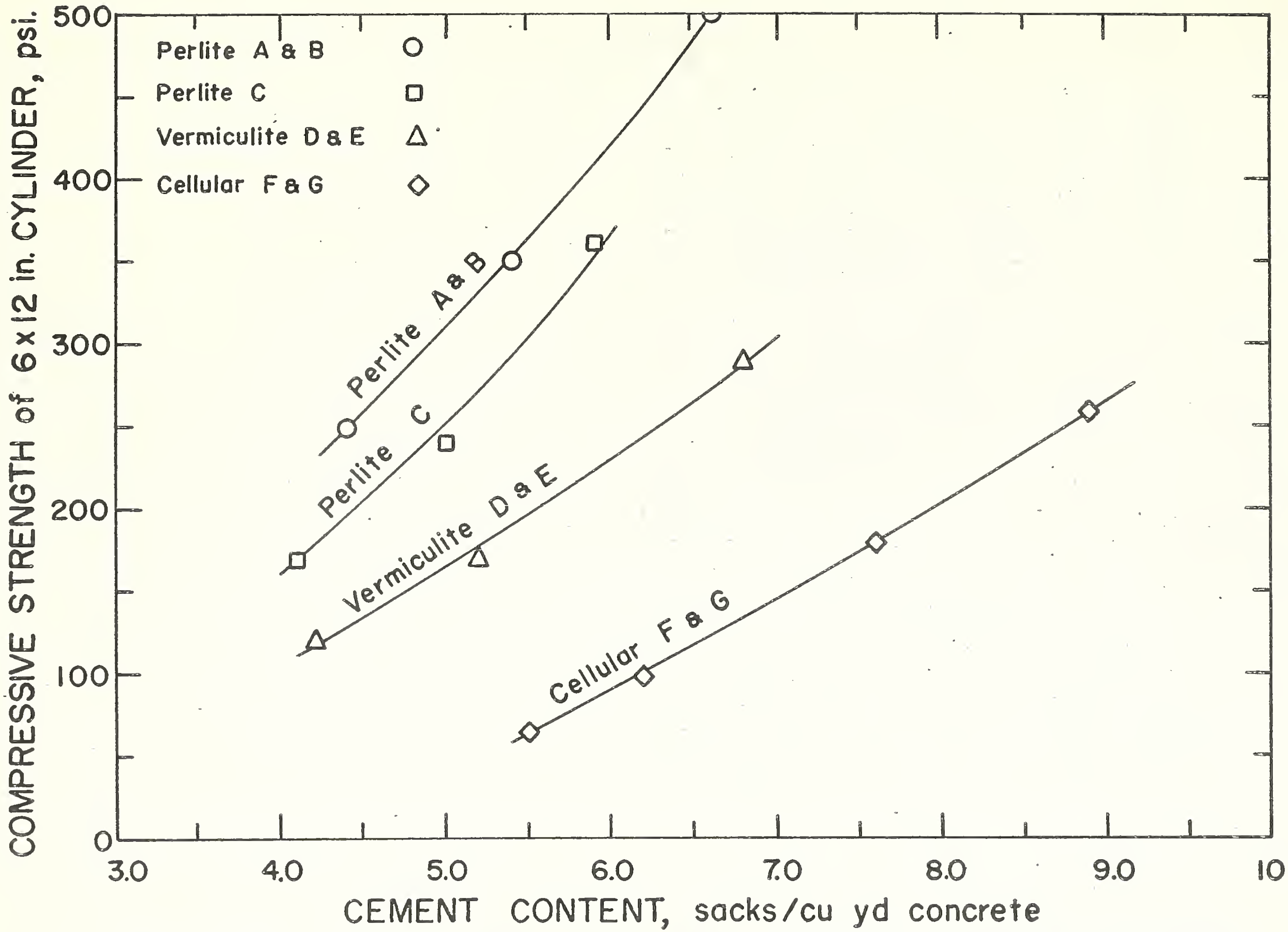
FIG. 10

OVEN DRY DENSITY VS. STRENGTH OF CELLULAR CONCRETE



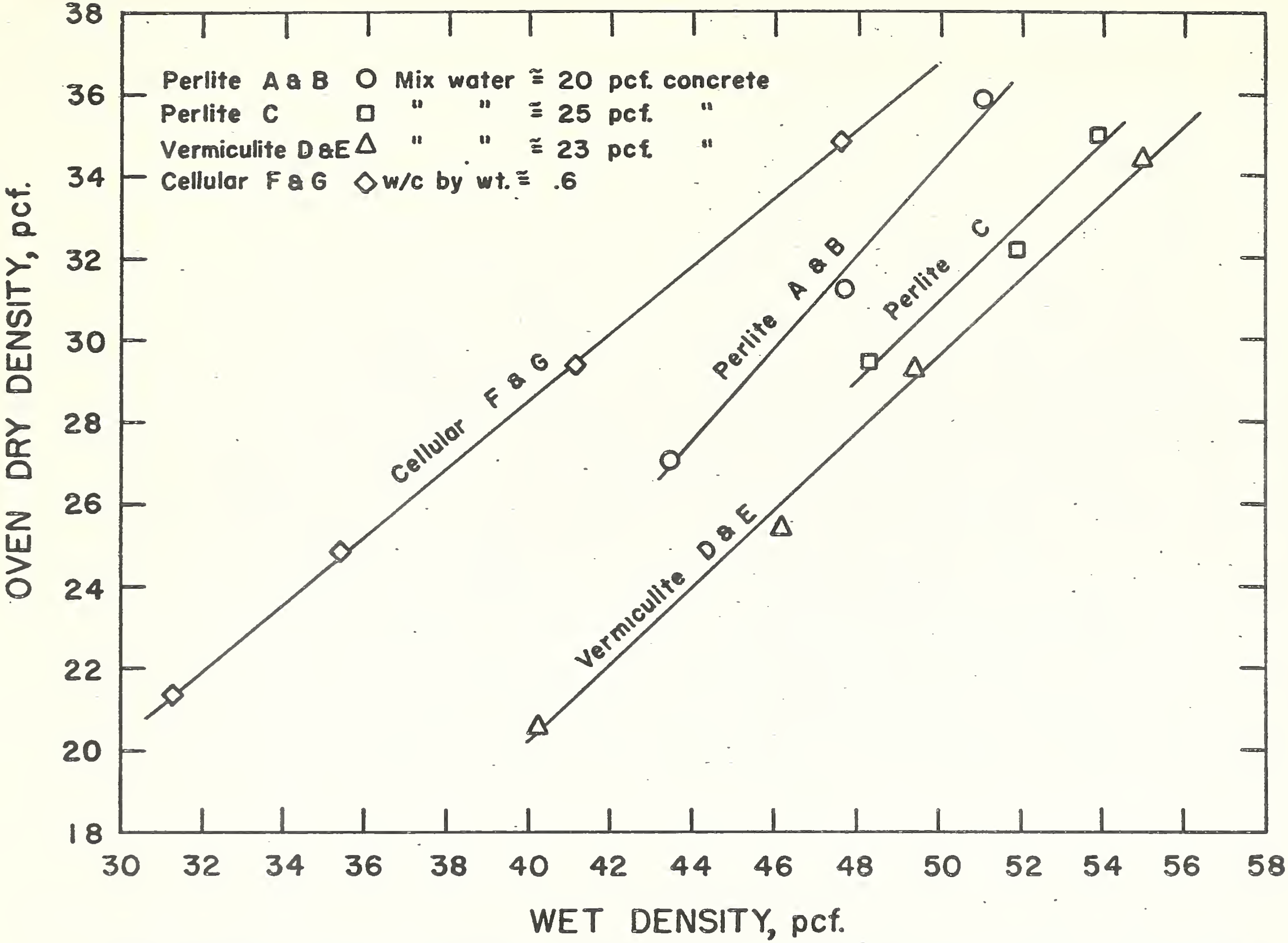
Relationships between oven dry density and compressive strength for insulating concretes. Average values for typical mixes.

FIG. 11



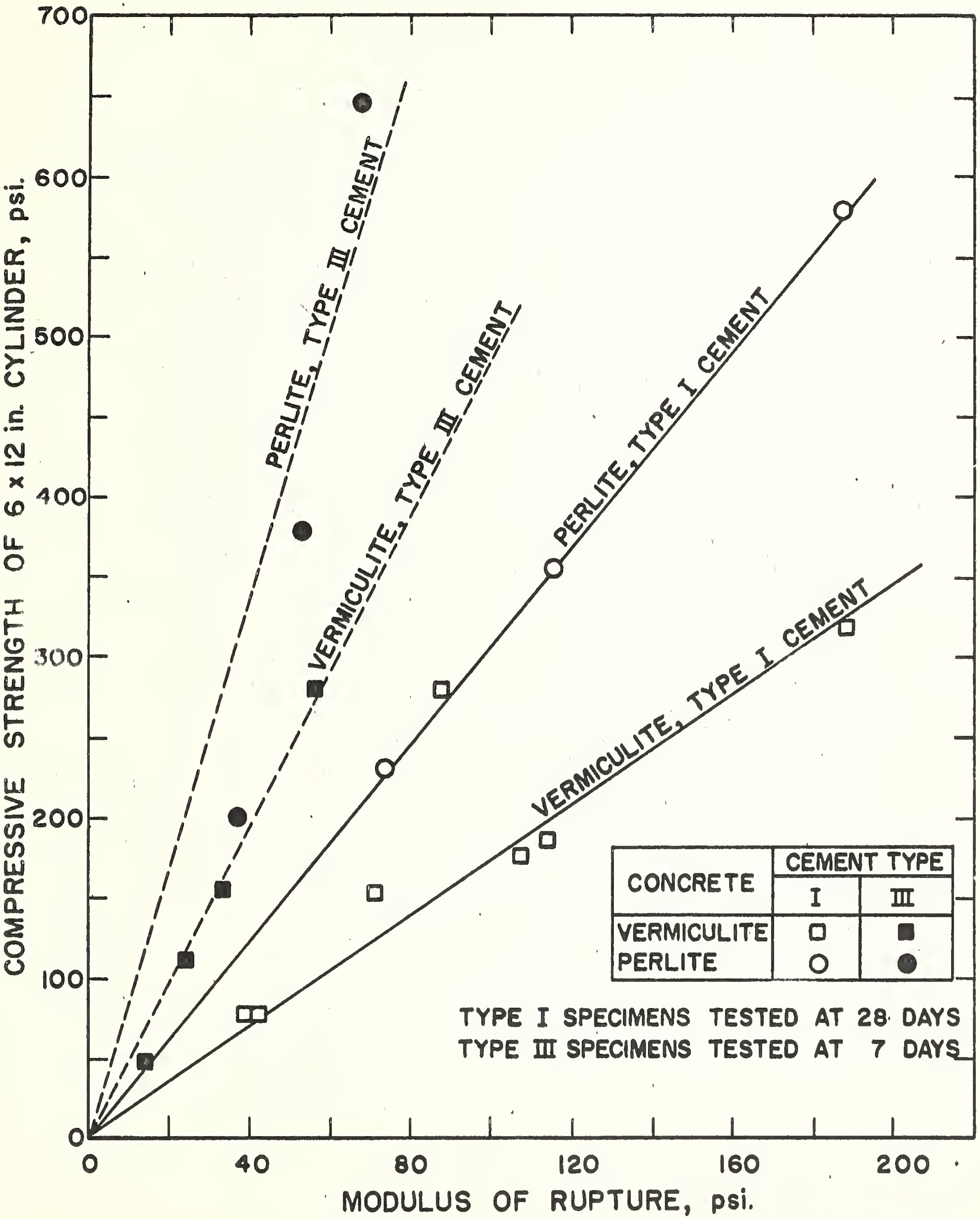
Relationships between cement content and compressive strength for insulating concrete. Average values for typical mixes.

FIG. 12



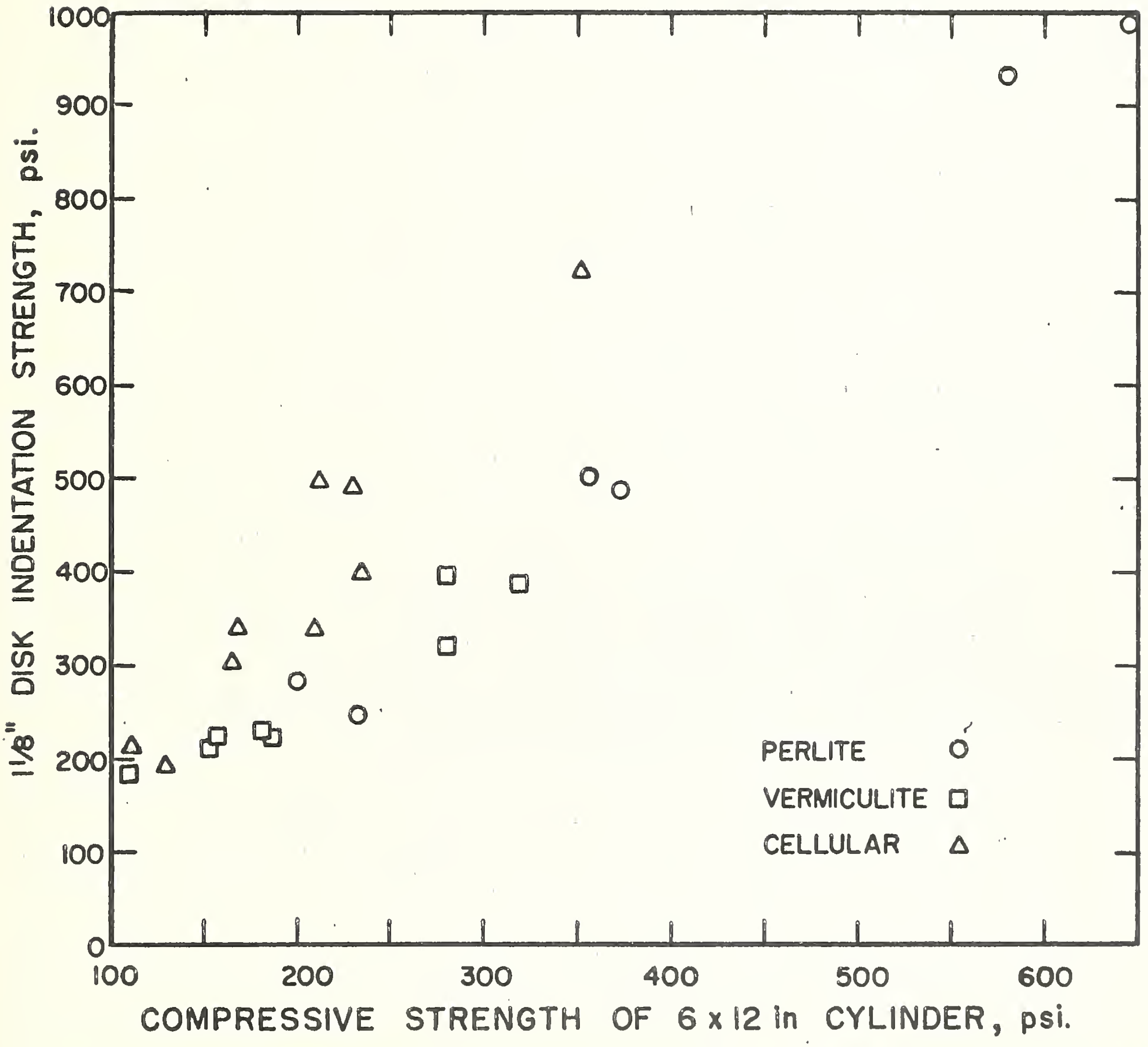
Relationships between wet density and oven dry density for insulating concretes. Average values for typical mixes.

FIG. 13



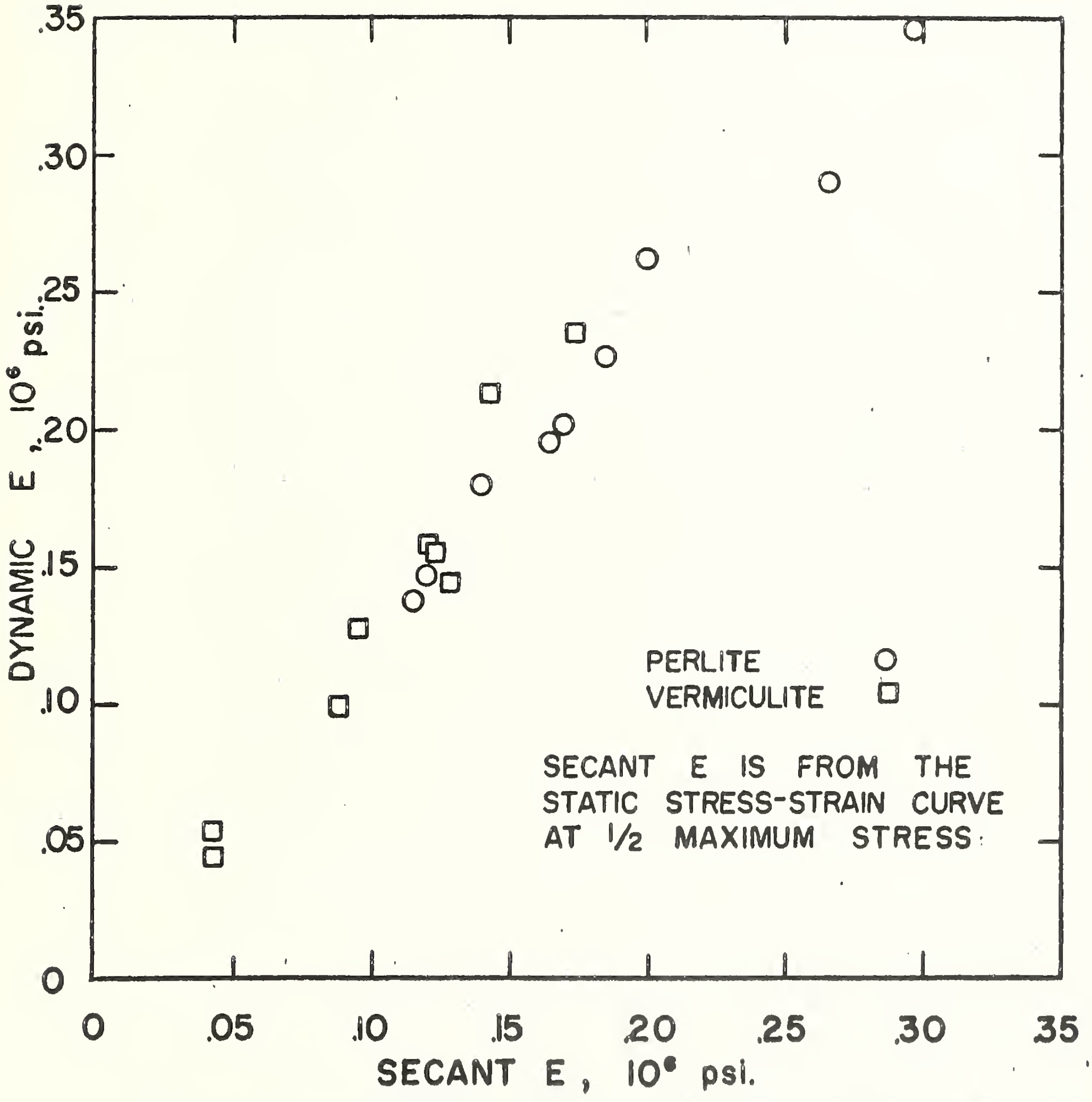
MODULUS OF RUPTURE VS. COMPRESSIVE STRENGTH

FIG. 14



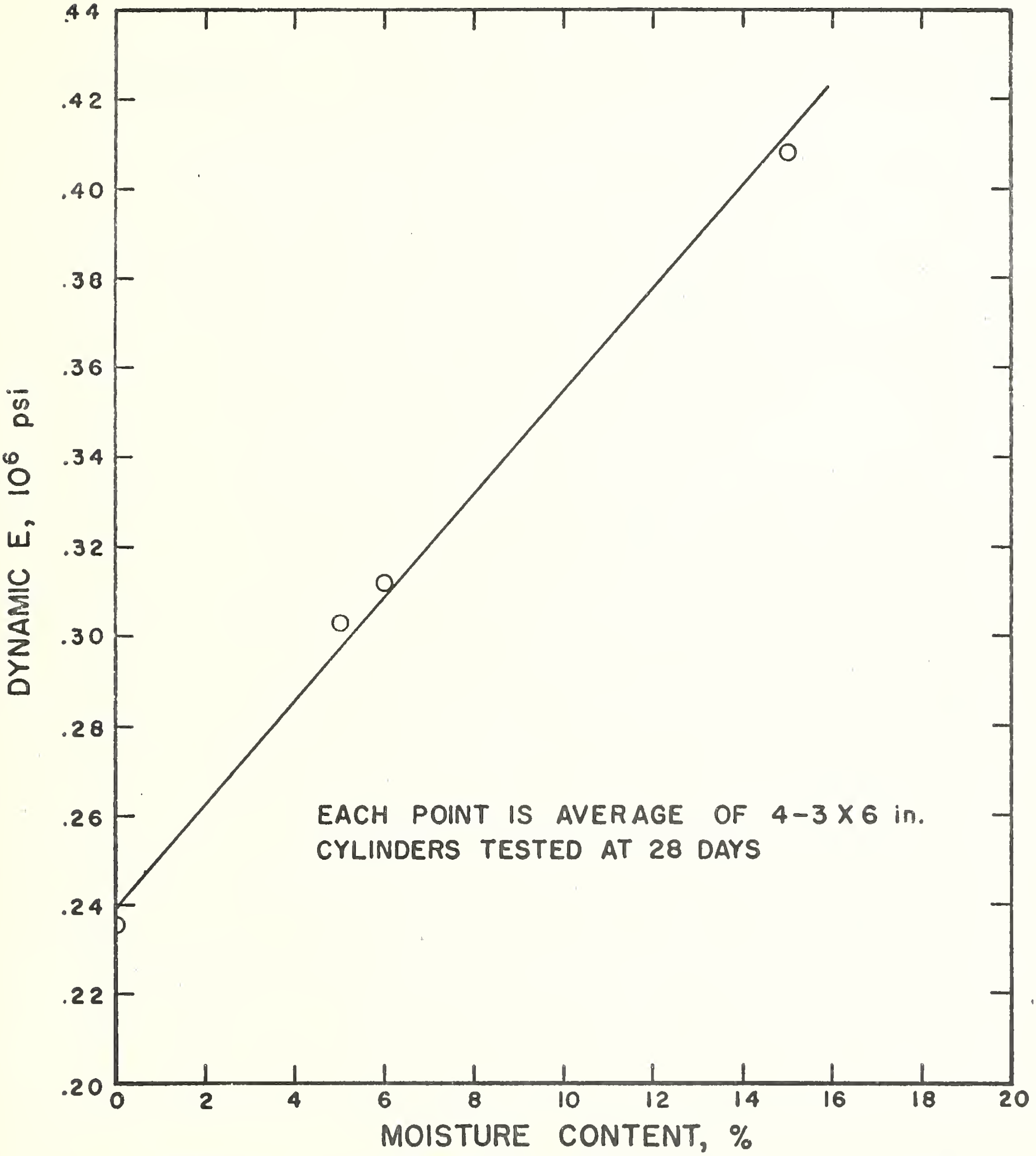
RELATION BETWEEN INDENTATION STRENGTH AND COMPRESSIVE STRENGTH

FIG. 15



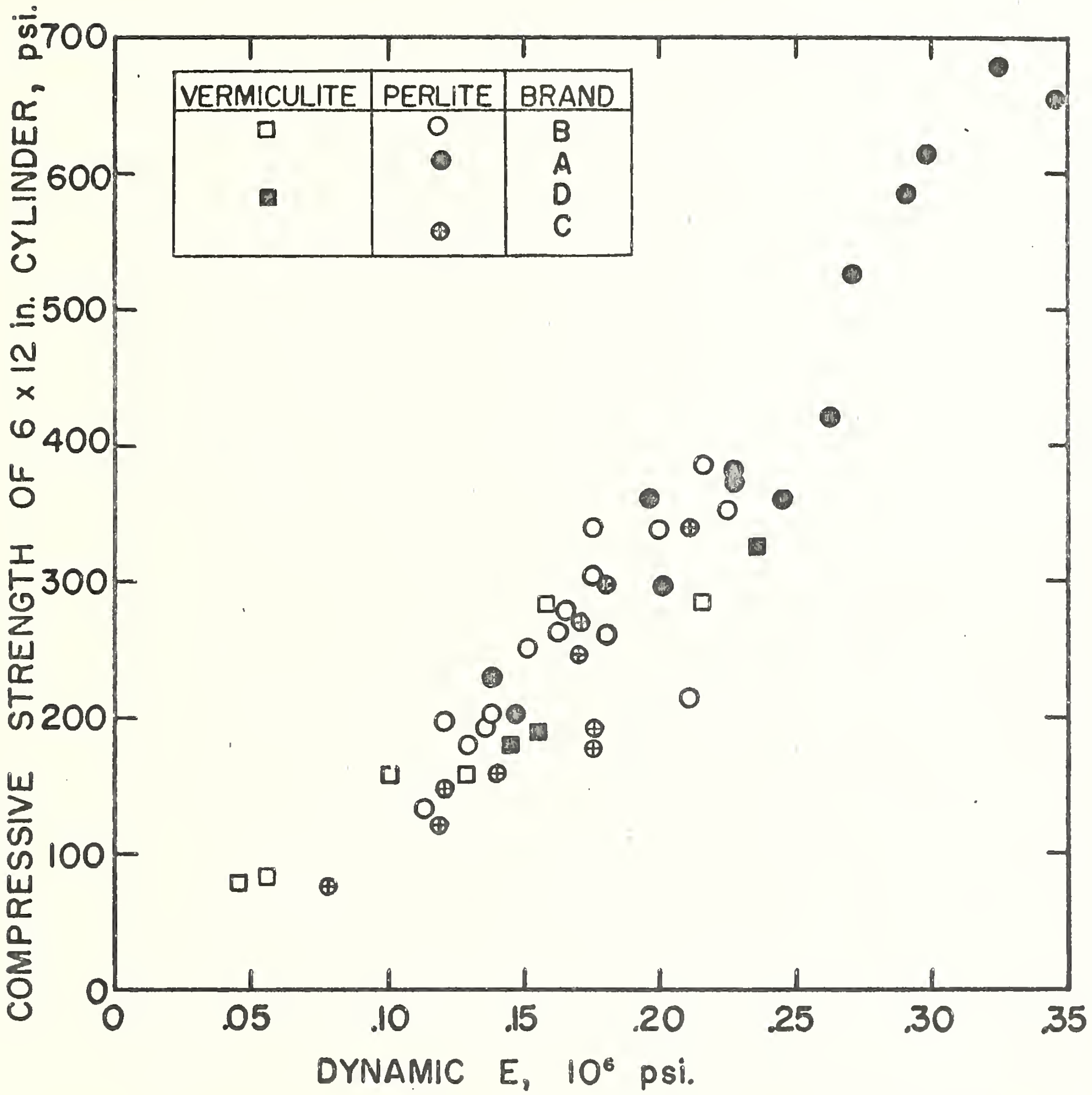
RELATION BETWEEN DYNAMIC E AND SECANT E

FIG. 16



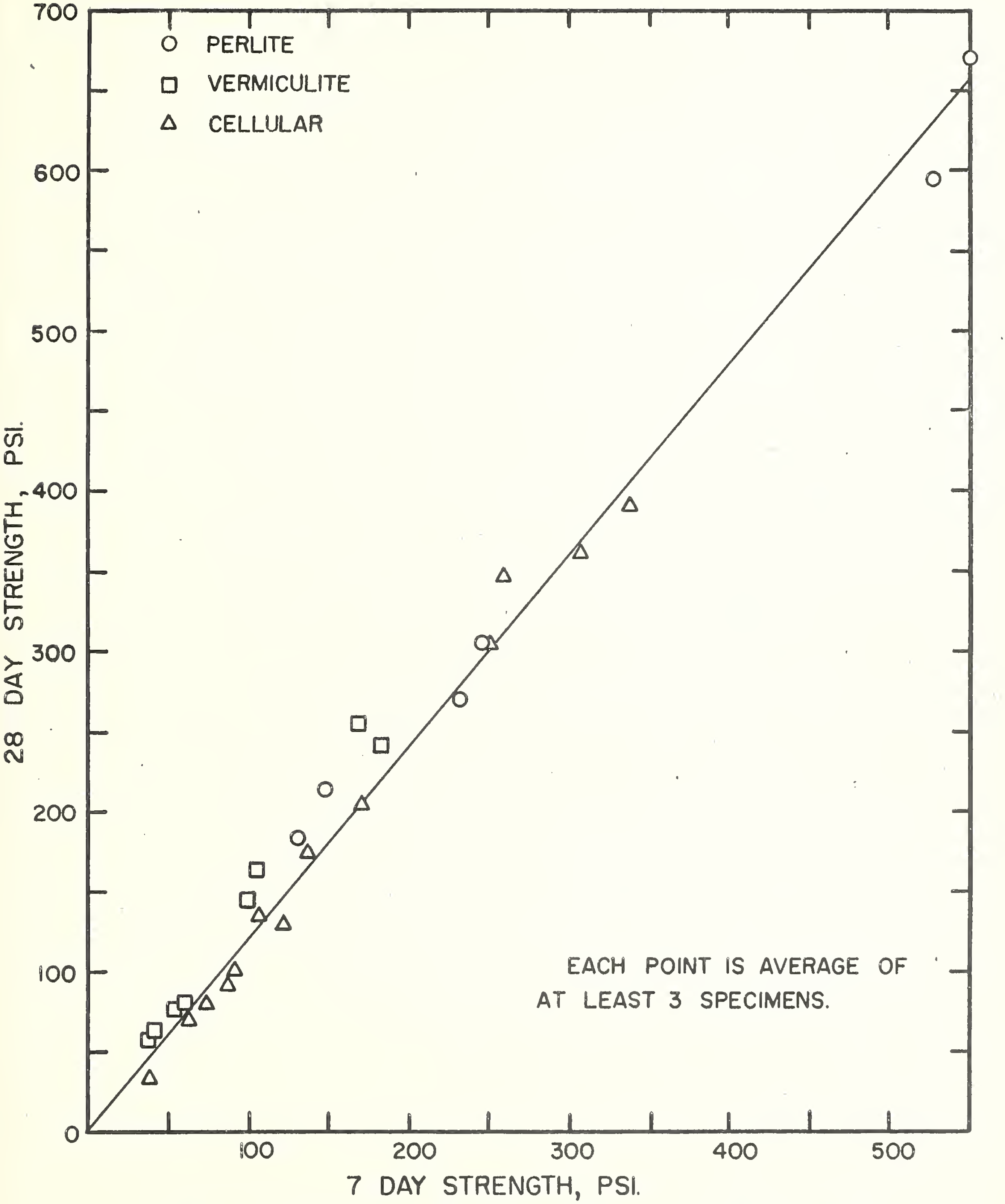
EFFECT OF MOISTURE CONTENT ON THE DYNAMIC MODULUS OF ELASTICITY OF PERLITE CONCRETE

FIG. 17



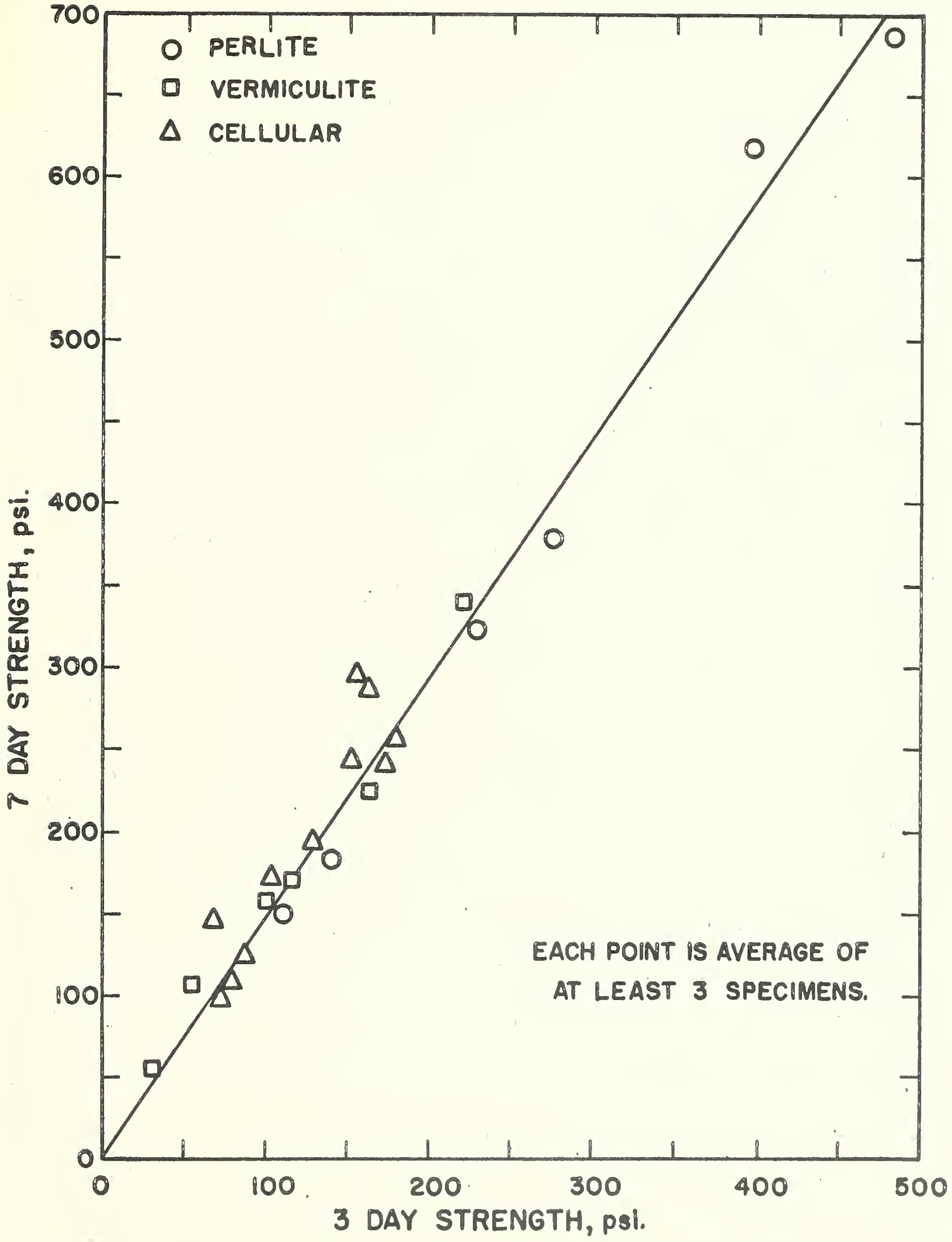
RELATION BETWEEN DYNAMIC E AND COMPRESSIVE STRENGTH

FIG. 18

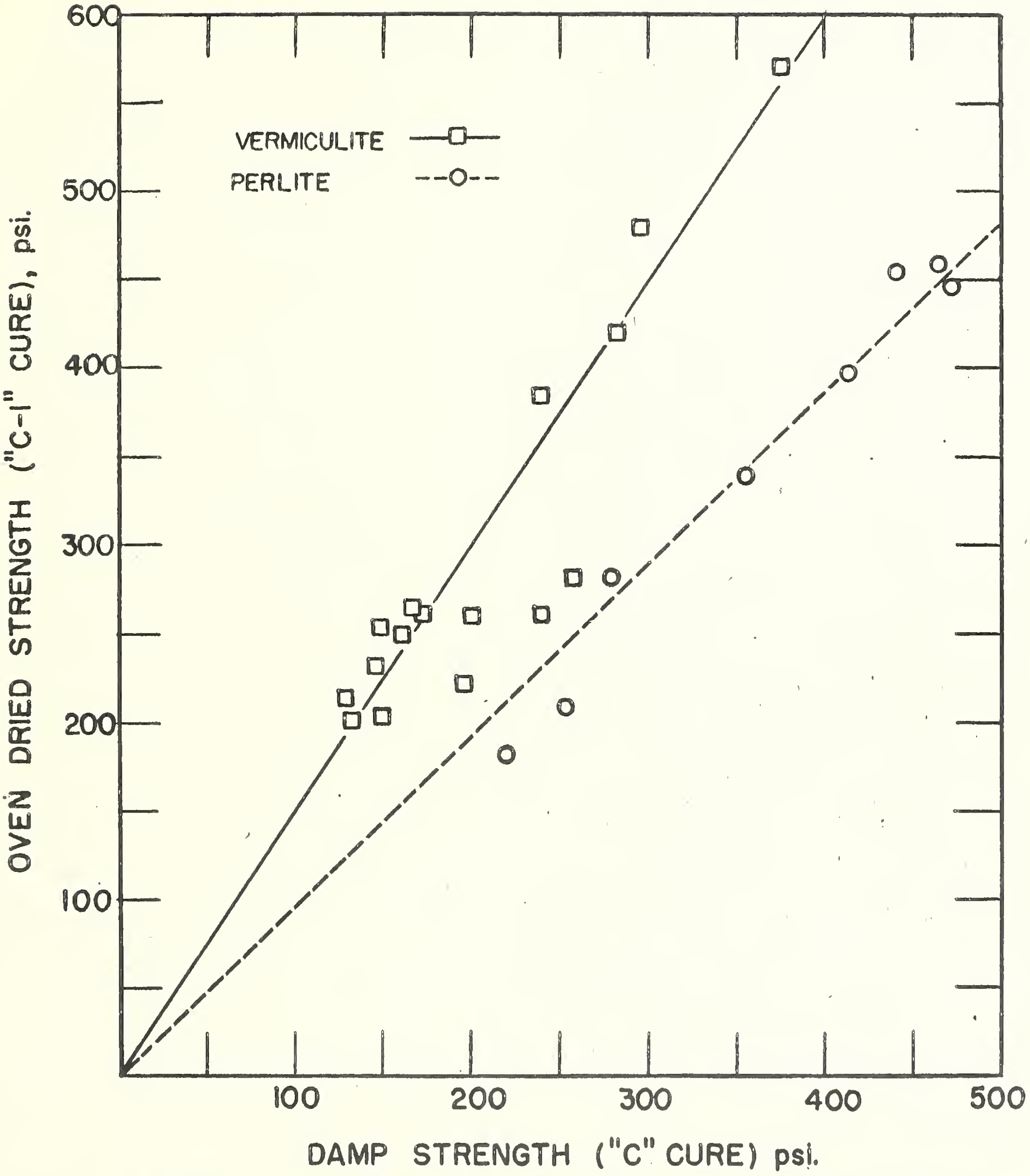


7 DAY VS 28 DAY STRENGTH FOR INSULATING CONCRETE MADE FROM TYPE I CEMENT

FIG. 19

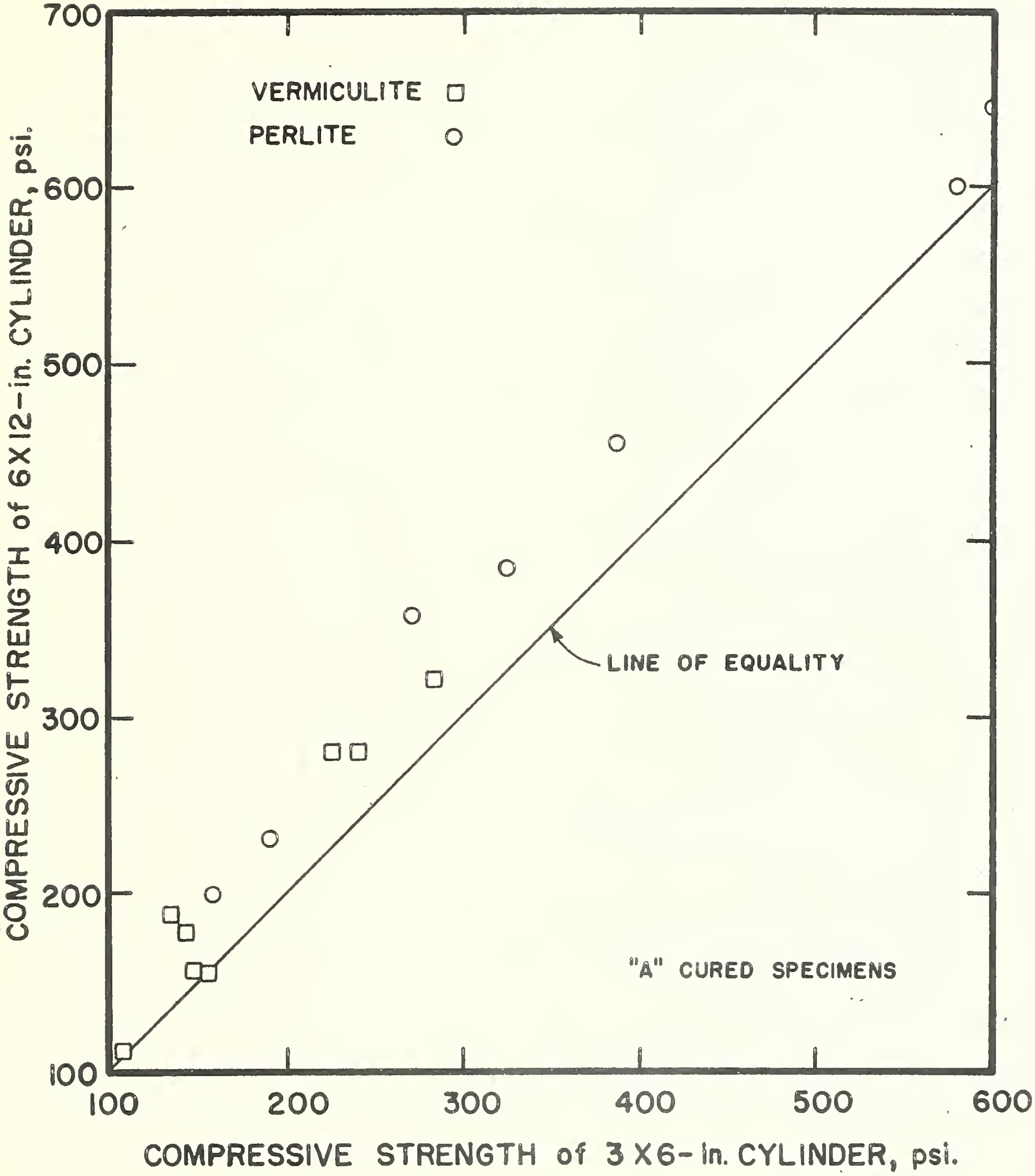


3 DAY VS 7 DAY STRENGTH FOR INSULATING CONCRETE MADE FROM TYPE III CEMENT FIG. 20



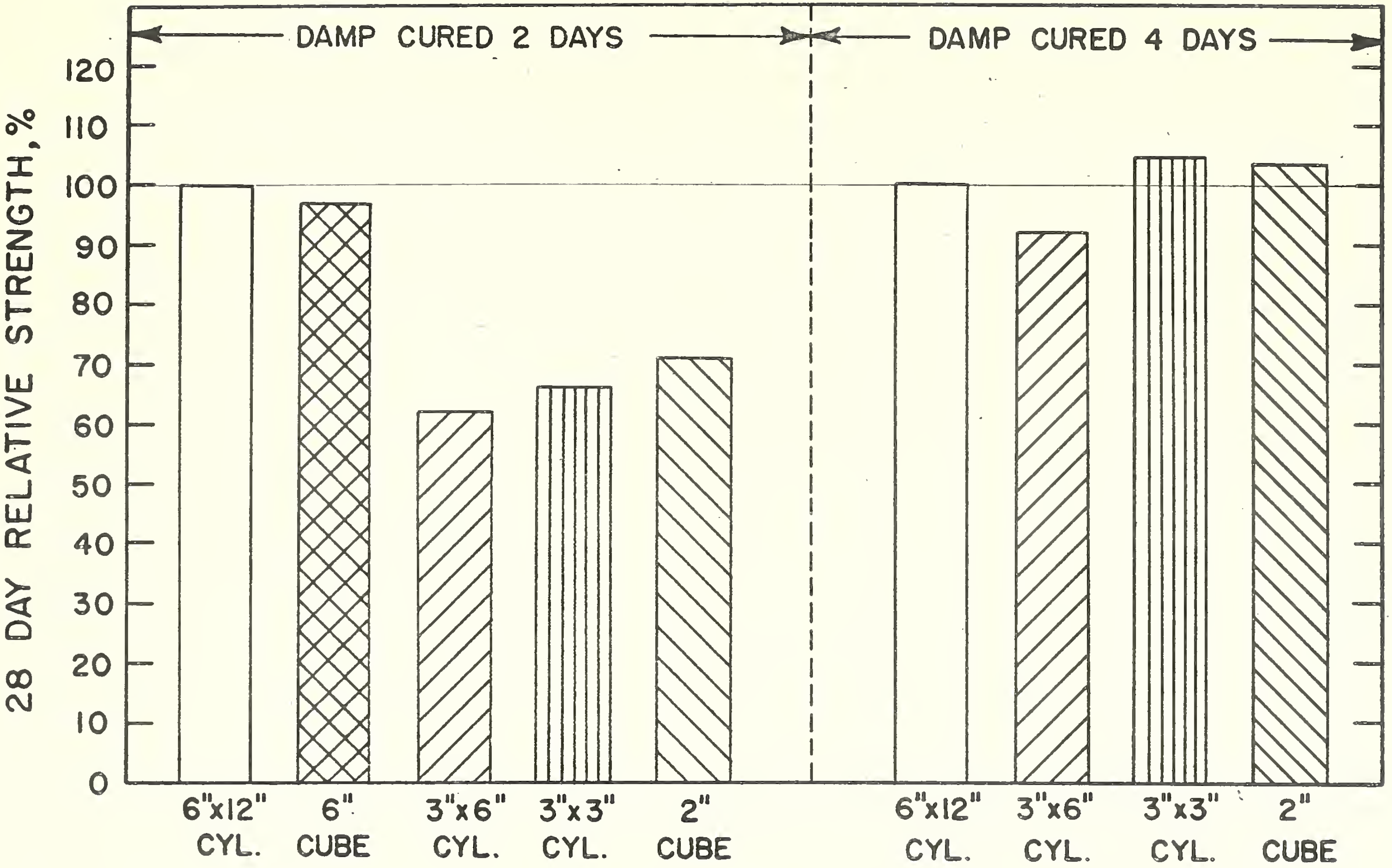
EFFECT OF OVEN DRYING ON STRENGTH OF MOIST CURED SPECIMENS OF INSULATING CONCRETE

FIG. 21



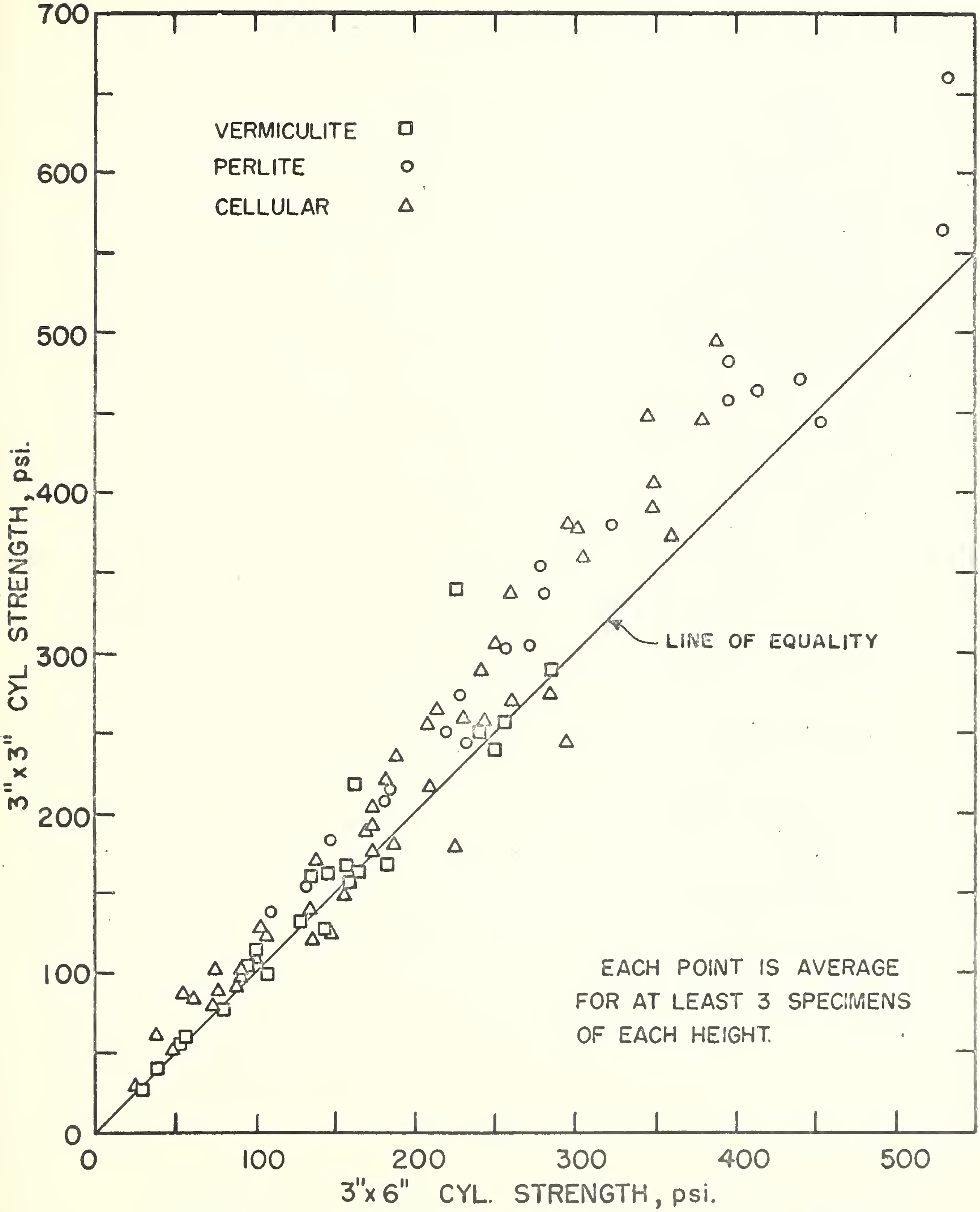
6-X 12-in VS 3-X6-in. CYLINDER STRENGTH

FIG. 22



EFFECT OF DAMP CURING PERIOD ON RELATIVE STRENGTH OF VARIOUS SPECIMENS

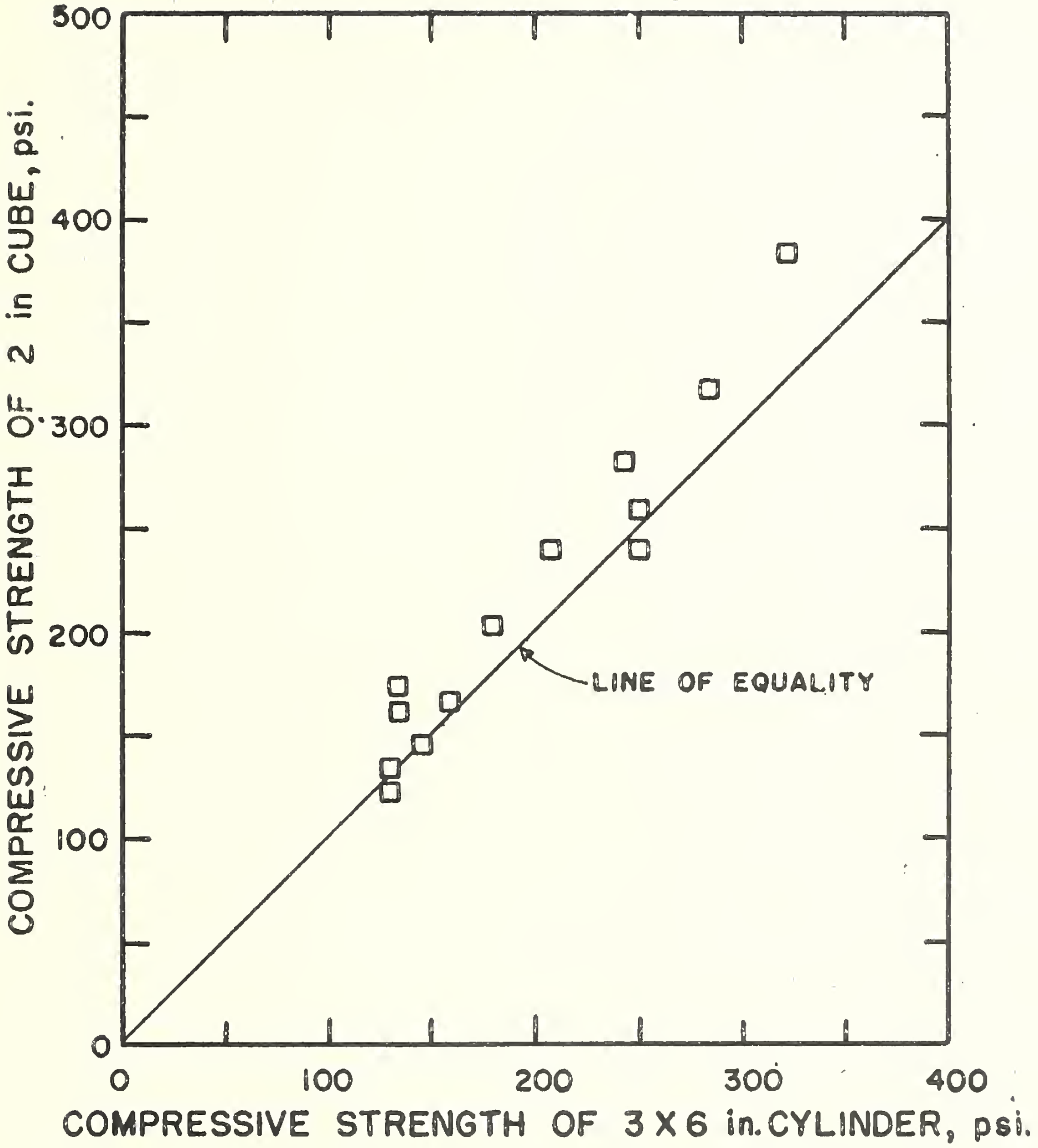
FIG. 23



EACH POINT IS AVERAGE FOR AT LEAST 3 SPECIMENS OF EACH HEIGHT.

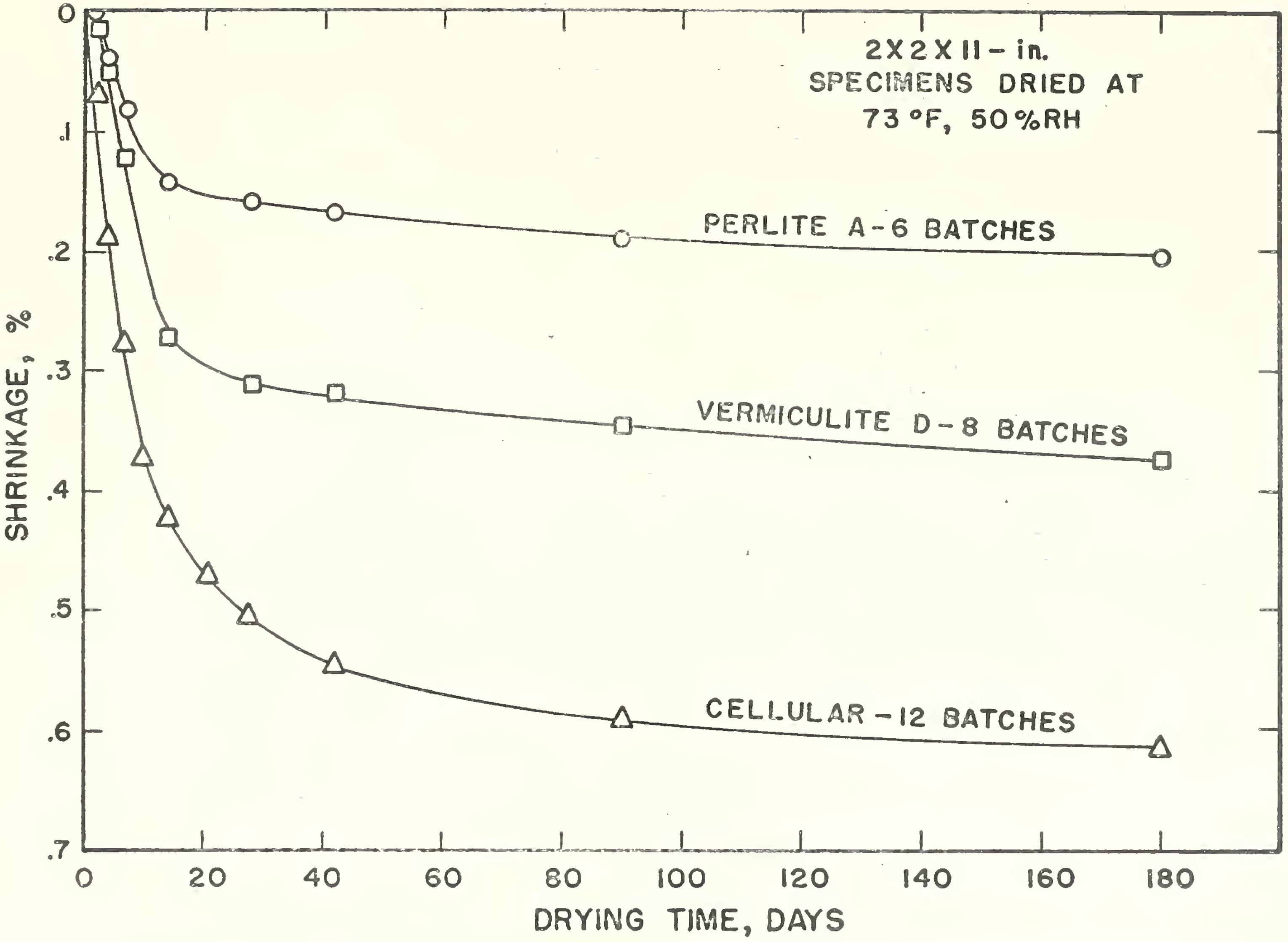
EFFECT OF HEIGHT OF SPECIMEN ON COMPRESSIVE STRENGTH OF INSULATING CONCRETE

FIG. 24



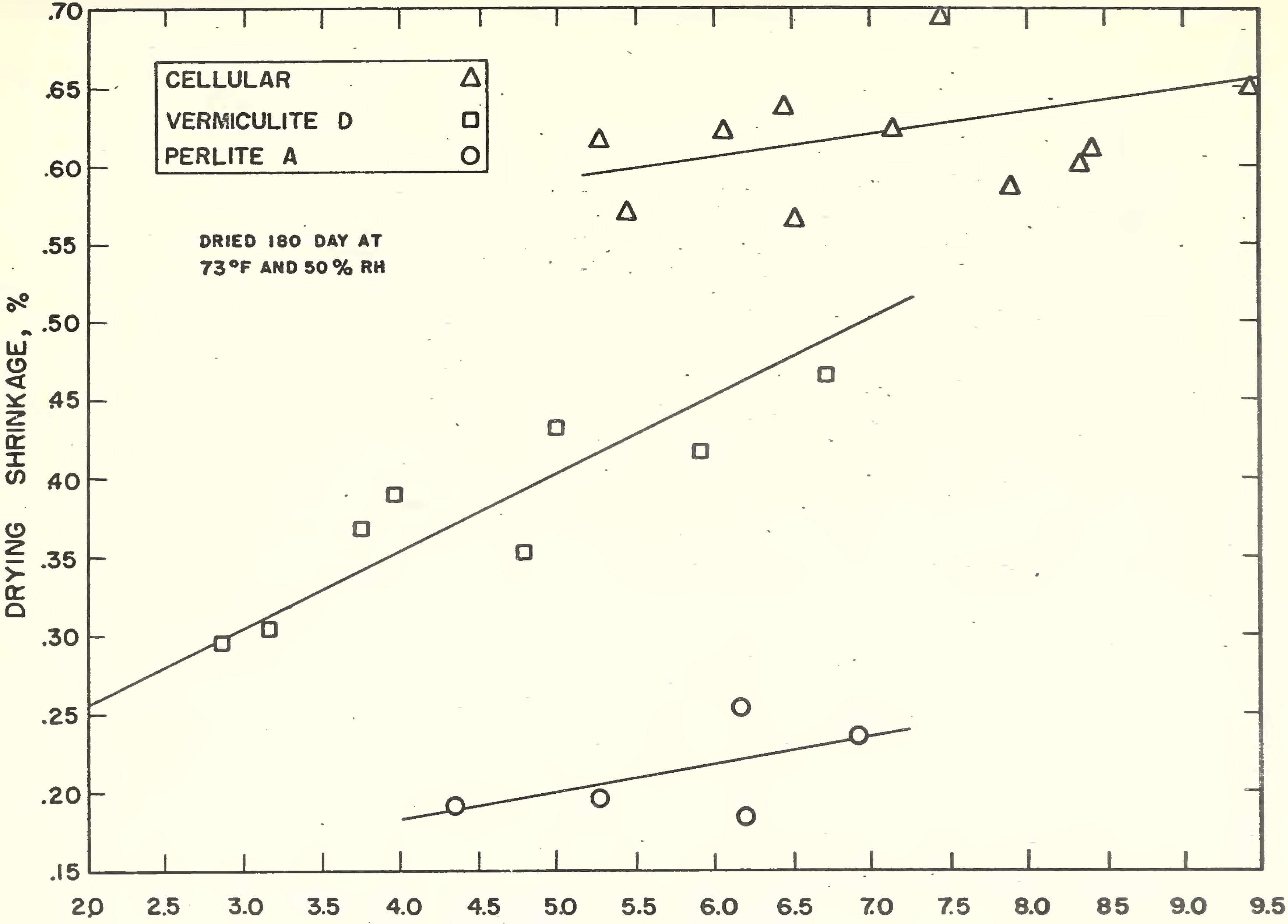
RELATION BETWEEN CYLINDER AND
CUBE STRENGTH FOR VERMICULITE
CONCRETE (IDENTICAL CURES)

FIG. 25



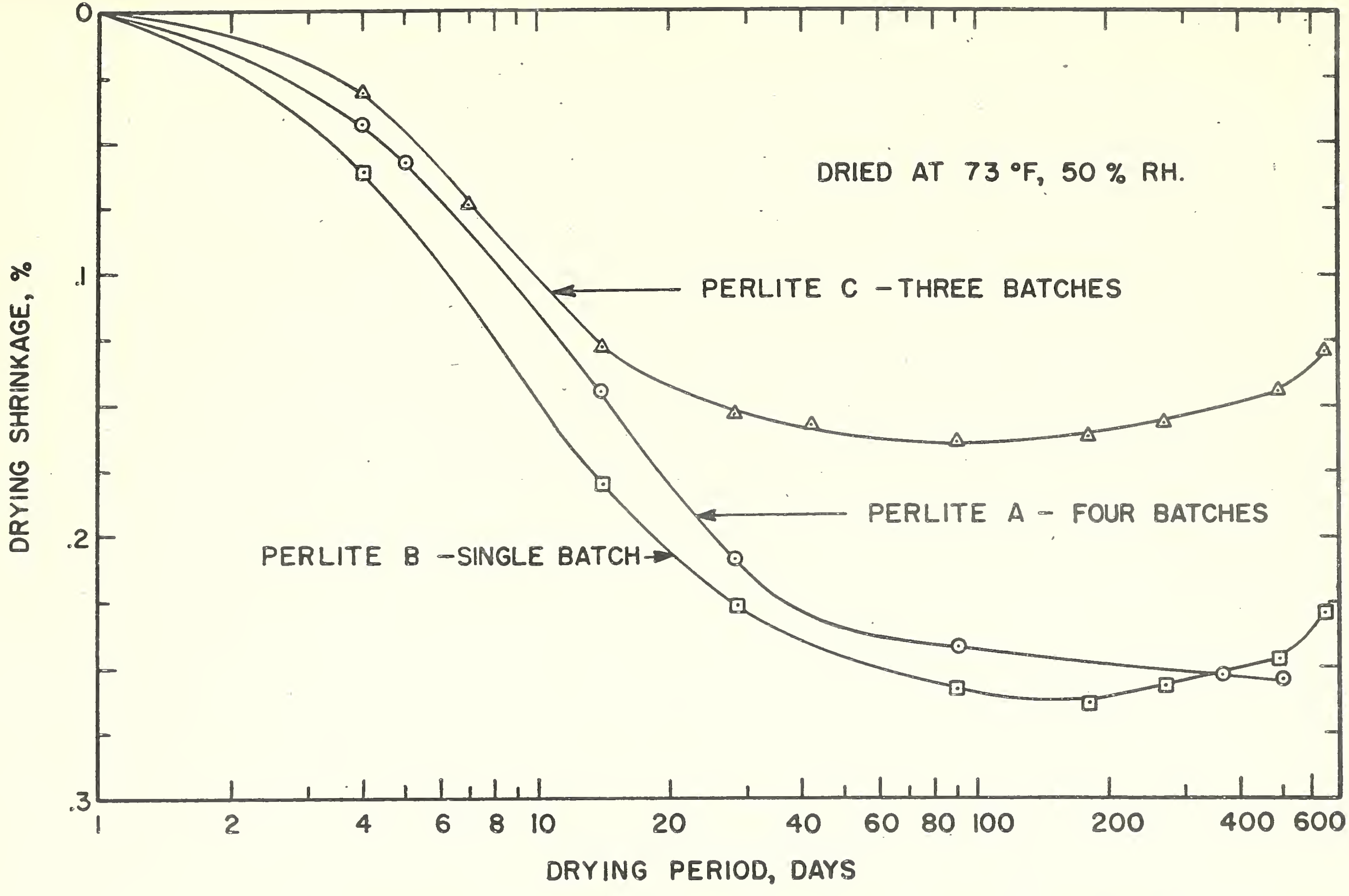
AVERAGE DRYING SHRINKAGE OF INSULATING CONCRETES

FIG. 26



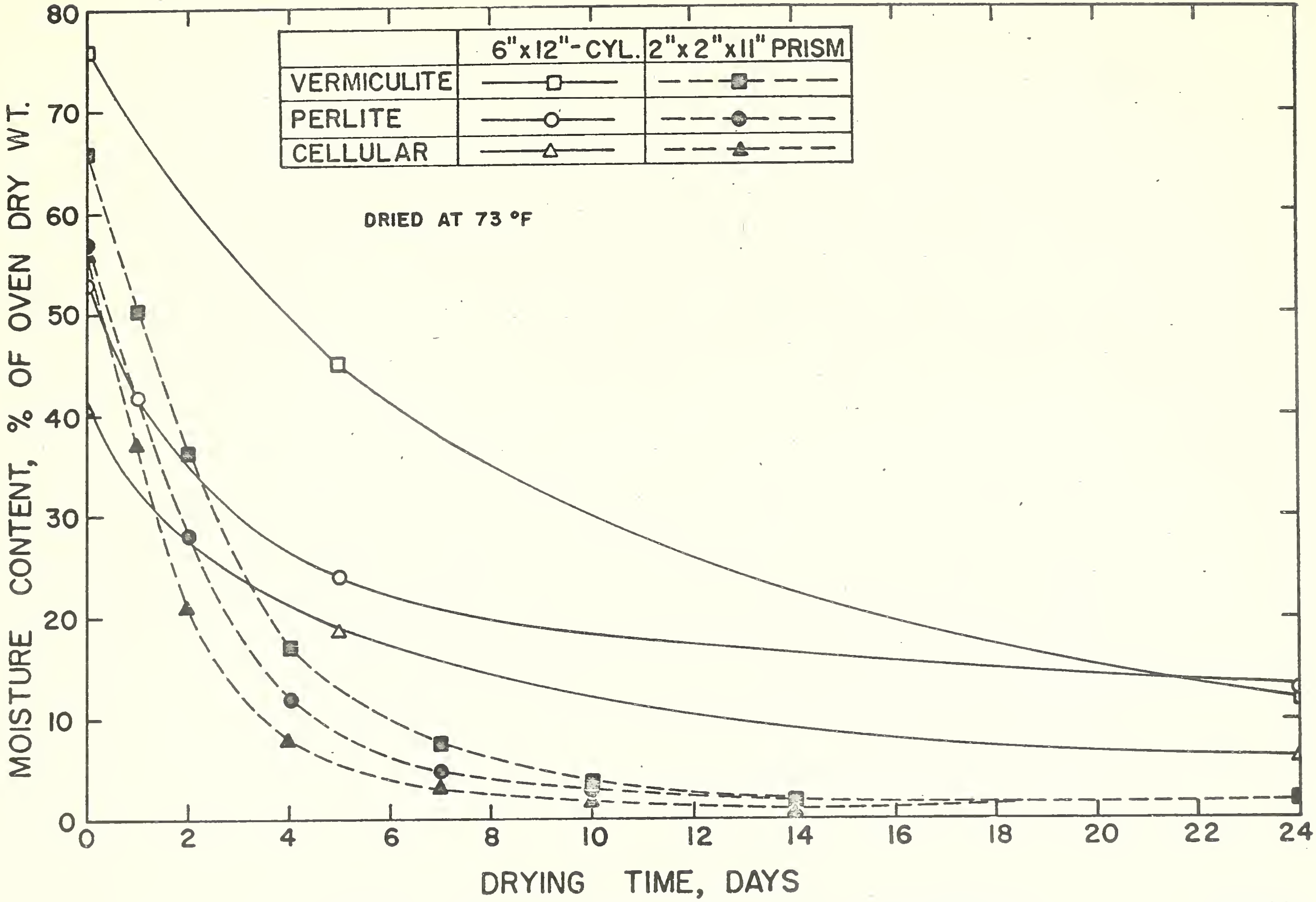
DRYING SHRINKAGE AS A FUNCTION OF CEMENT CONTENT IN INSULATING CONCRETES

FIG. 27



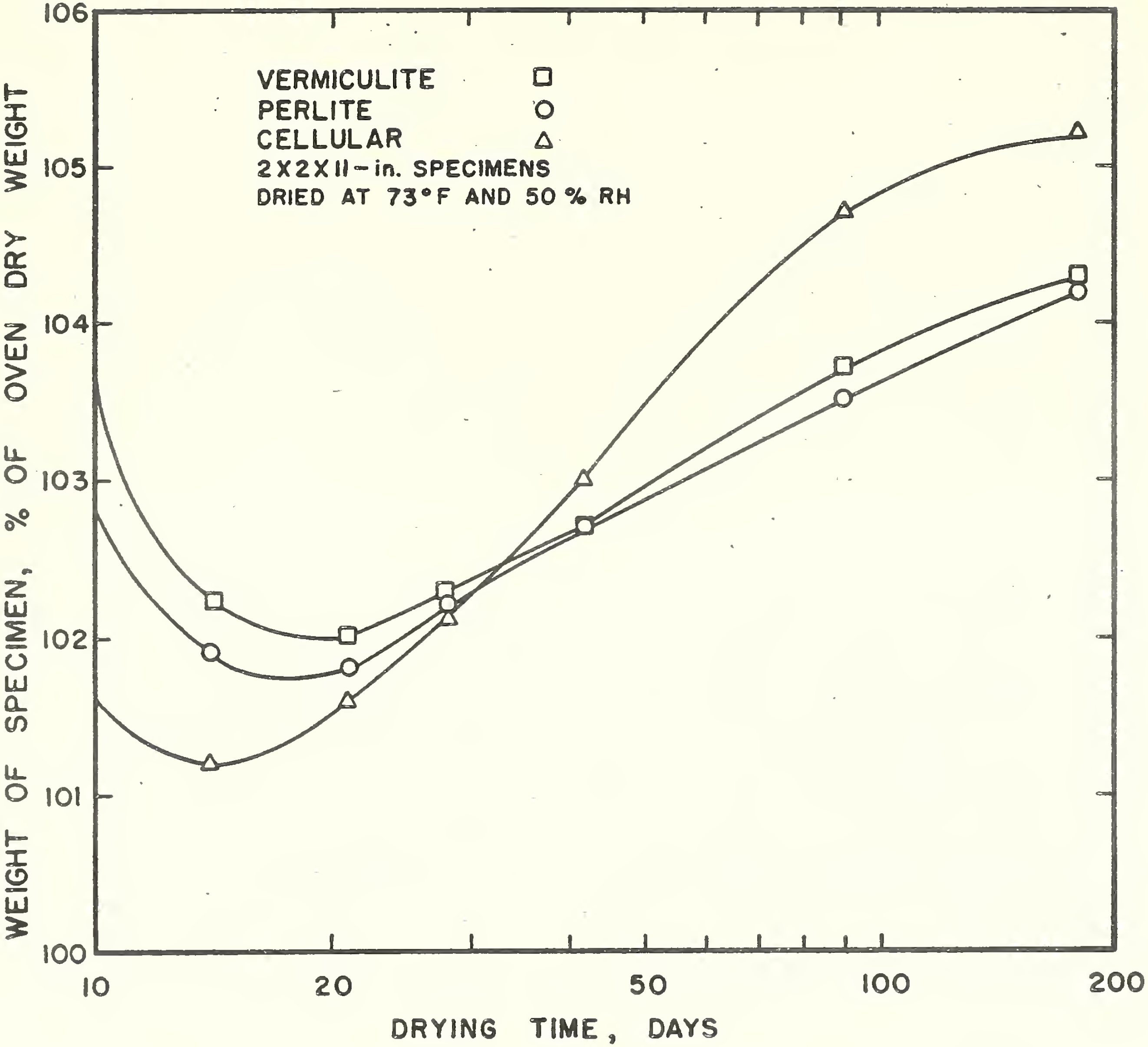
A COMPARISON OF THE DRYING SHRINKAGE CHARACTERISTICS OF CONCRETES MADE WITH THREE DIFFERENT PERLITE

FIG. 28



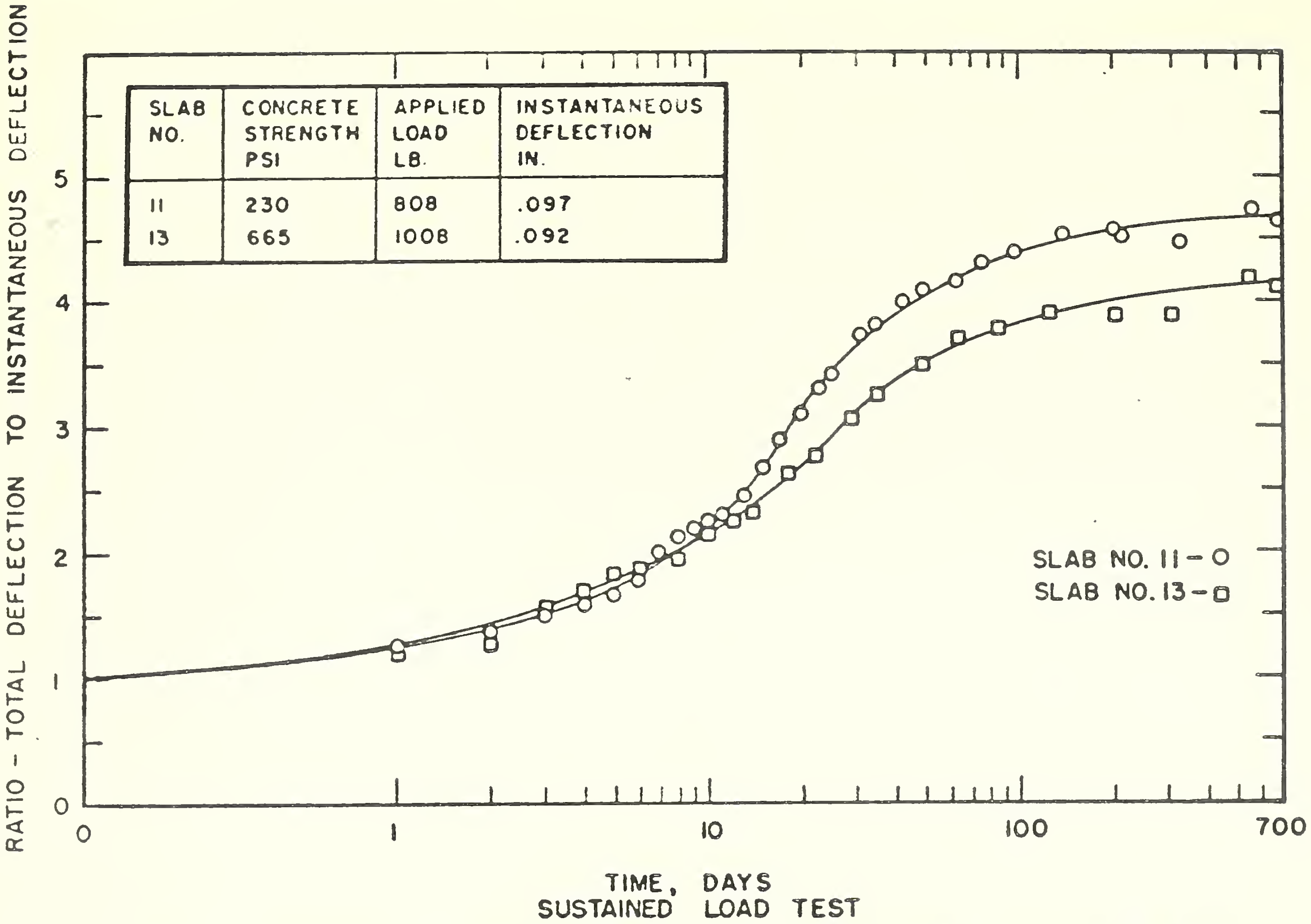
RATE OF DRYING - INSULATING CONCRETE

FIG. 29



CHANGE IN WEIGHT OF SHRINKAGE SPECIMENS WITH TIME

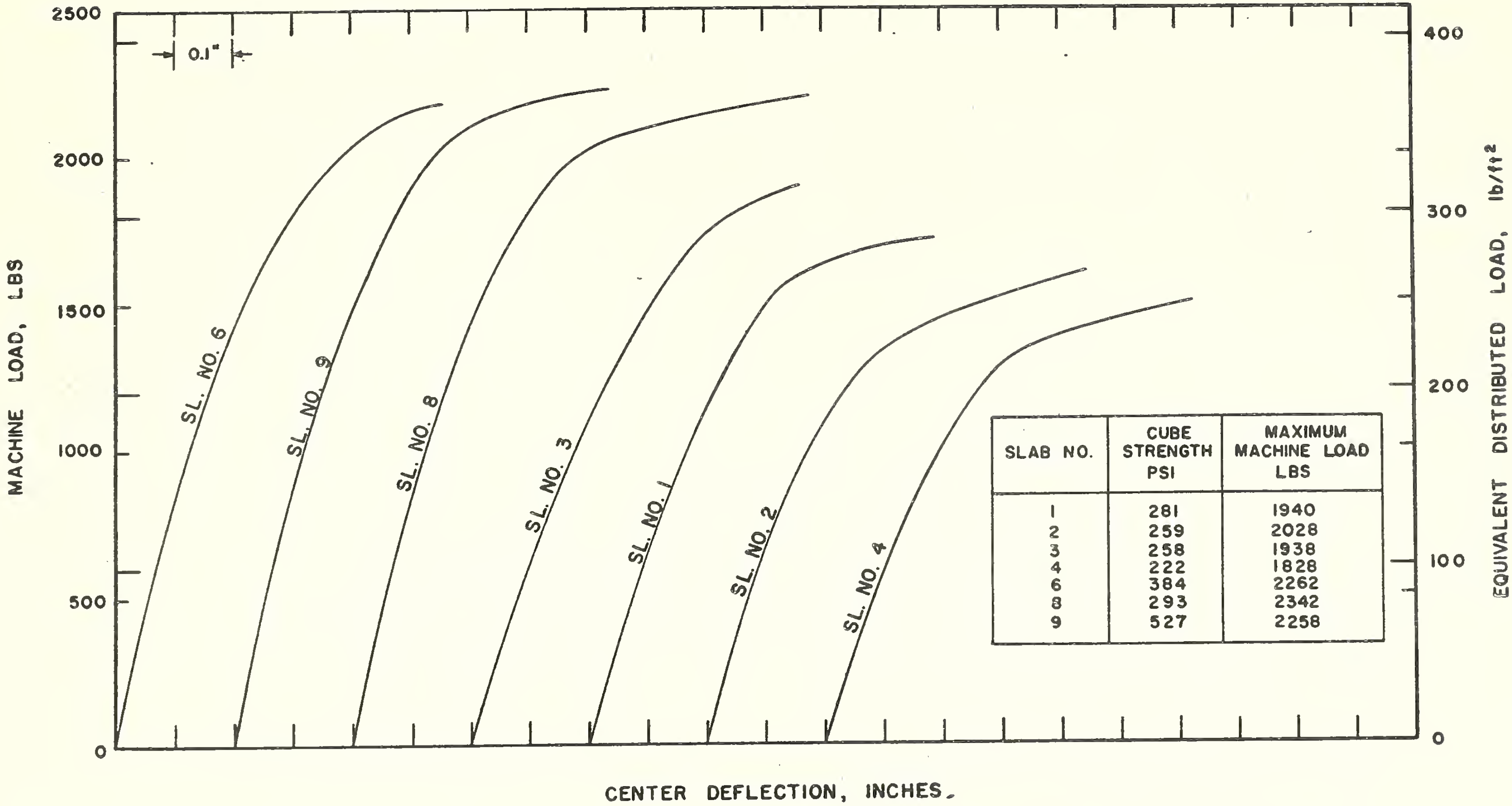
FIG. 30



SLAB NO.	CONCRETE STRENGTH PSI	APPLIED LOAD LB.	INSTANTANEOUS DEFLECTION IN.
11	230	808	.097
13	665	1008	.092

TIME VS. INCREASE IN CENTER DEFLECTION FOR PERLITE CONCRETE SLABS

FIG. 31

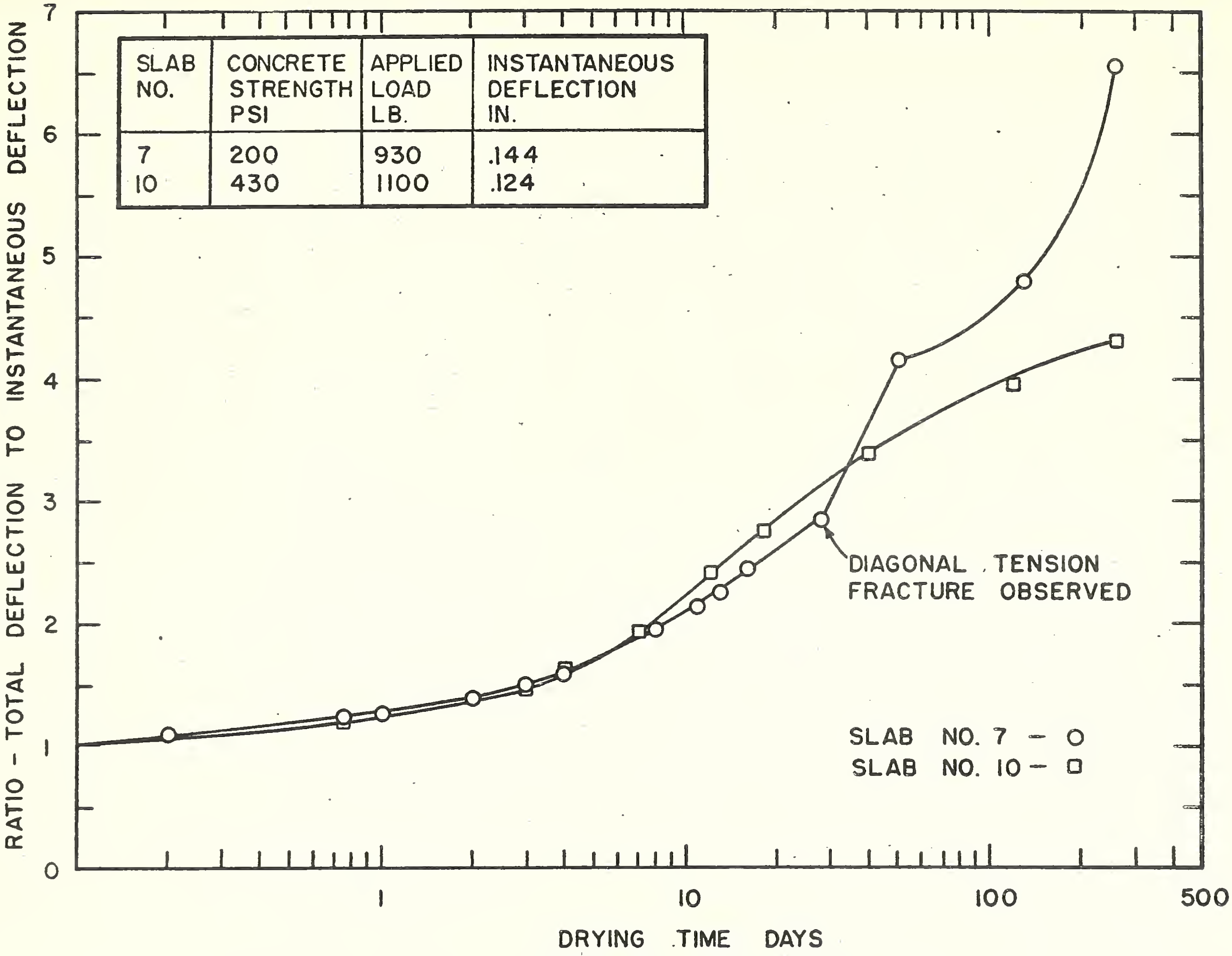


SLAB NO.	CUBE STRENGTH PSI	MAXIMUM MACHINE LOAD LBS
1	281	1940
2	259	2028
3	258	1938
4	222	1828
6	384	2262
8	293	2342
9	527	2258

SHORT–TERM TEST

CENTER DEFLECTION VS APPLIED LOAD FOR
REINFORCED VERMICULITE CONCRETE SLABS

FIG. 32



SUSTAINED LOAD TEST

TIME VS. INCREASE IN CENTER DEFLECTION FOR VERMICULITE CONCRETE SLABS

FIG. 33

U.S. DEPARTMENT OF COMMERCE
Frederick H. Mueller, *Secretary*

NATIONAL BUREAU OF STANDARDS
A. V. Astin, *Director*

THE NATIONAL BUREAU OF STANDARDS

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ELECTRICITY. Resistance and Reactance. Electrochemistry. Electrical Instruments. Magnetic Measurements. Dielectrics.

METROLOGY. Photometry and Colorimetry. Refractometry. Photographic Research. Length. Engineering Metrology. Mass and Scale. Volumetry and Densimetry.

HEAT. Temperature Physics. Heat Measurements. Cryogenic Physics. Rheology. Molecular Kinetics. Free Radicals Research. Equation of State. Statistical Physics. Molecular Spectroscopy.

RADIATION PHYSICS. X-Ray. Radioactivity. Radiation Theory. High Energy Radiation. Radiological Equipment. Nucleonic Instrumentation. Neutron Physics.

CHEMISTRY. Surface Chemistry. Organic Chemistry. Analytical Chemistry. Inorganic Chemistry. Electrodeposition. Molecular Structure and Properties of Gases. Physical Chemistry. Thermochemistry. Spectrochemistry. Pure Substances.

MECHANICS. Sound. Pressure and Vacuum. Fluid Mechanics. Engineering Mechanics. Combustion Controls.

ORGANIC AND FIBROUS MATERIALS. Rubber. Textiles. Paper. Leather. Testing and Specifications. Polymer Structure. Plastics. Dental Research.

METALLURGY. Thermal Metallurgy. Chemical Metallurgy. Mechanical Metallurgy. Corrosion. Metal Physics.

MINERAL PRODUCTS. Engineering Ceramics. Glass. Refractories. Enameled Metals. Constitution and Microstructure.

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ATOMIC PHYSICS. Spectroscopy. Radiometry. Mass Spectrometry. Solid State Physics. Electron Physics. Atomic Physics.

INSTRUMENTATION. Engineering Electronics. Electron Devices. Electronic Instrumentation. Mechanical Instruments. Basic Instrumentation.

Office of Weights and Measures.

BOULDER, COLO.

CRYOGENIC ENGINEERING. Cryogenic Equipment. Cryogenic Processes. Properties of Materials. Gas Liquefaction.

IONOSPHERE RESEARCH AND PROPAGATION. Low Frequency and Very Low Frequency Research. Ionosphere Research. Prediction Services. Sun-Earth Relationships. Field Engineering. Radio Warning Services.

RADIO PROPAGATION ENGINEERING. Data Reduction Instrumentation. Radio Noise. Tropospheric Measurements. Tropospheric Analysis. Propagation-Terrain Effects. Radio-Meteorology. Lower Atmosphere Physics.

RADIO STANDARDS. High frequency Electrical Standards. Radio Broadcast Service. Radio and Microwave Materials. Atomic Frequency and Time Standards. Electronic Calibration Center. Millimeter-Wave Research. Microwave Circuit Standards.

RADIO SYSTEMS. High Frequency and Very High Frequency Research. Modulation Research. Antenna Research. Navigation Systems. Space Telecommunications.

UPPER ATMOSPHERE AND SPACE PHYSICS. Upper Atmosphere and Plasma Physics. Ionosphere and Exosphere Scatter. Airglow and Aurora. Ionospheric Radio Astronomy.


NBS