

THESIS

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BEBEK, ISTANBUL

PAGE I

FOR REFERENCE

NOT TO BE TAKEN FROM THIS ROOM

AN INVESTIGATION OF PERLITE
AS STRUCTURAL LIGHTWEIGHT CONCRETE

by

Halûk Günerman

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PAGE III

THE AUTHOR WISHES TO EXTEND HIS GRATITUDE
TO PROF. FERRUH KOCATAŞKIN FOR HIS GENEROUS
HELP AND INTEREST, AND TO PROF. NECMİ TANYOLAÇ
AND HİMA A.Ş. FOR THEIR VALUABLE AID.

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INTRODUCTION

Lightweight Structural Concrete is considered to be a material weighing not more than 115 lb per cu ft and one developing a compressive strength not less than 1000 psi, by R. W. Kluge (13). According to this definition Perlite concrete is not included to be among structural lightweight concretes. As for the ASTM Specifications (9) in a table, the value of 2000 psi is given corresponding to a unit weight of 115 lb per cu ft as the minimum value of the table. Also in the article of J.J. Shideler (7) among the given examples of lightweight structural concrete, Perlite is not included. Therefore, one sees that although Perlite aggregate is in accordance with the specifications for lightweight aggregates, concrete made from Perlite is not included in the class of Lightweight structural concretes. But in spite of that in roof slabs or in similar small load bearing parts of constructions, Perlite concrete can be used as a structural lightweight concrete with the added advantage of improved insulation.

As for insulating purposes, Perlite is mostly used in USA and all over the World, being within the limits of the ASTM Specifications (9). Lime-Perlite, or gypsum-Perlite mixes are used in making plaster, which has good insulating properties (25).

In the present study, Perlite is considered as a structural lightweight aggregate and the compressive, tensile and flexural strengths of the concrete made from Perlite-cement mixtures are investigated. First Part is a theoretical one, containing literature survey and analysis, and in the second experimental part, the results of tests on Perlite aggregate and concrete are presented.

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The strengths of small cylinders and large cylinders and samples made of coarse Perlite aggregates and fine Perlite aggregates are compared. Furthermore, some results of another investigation (20) using cement-sand-perlite mixes are also included, in order to approach a sound conclusion. The results show that, Perlite Concrete is not a structural lightweight concrete with respect to its strength properties.

PART I
THEORETICAL

A Literature Survey about
The Lightweight Aggregate Concretes

I.

LIGHTWEIGHT AGGREGATES

A. Specifications: The specifications for lightweight aggregates for structural concrete are as follows: (9)

Grading: The grading shall conform to the requirements shown in table (1) ASTM C 330 - 53 T.

Size Designation	Percentages (by weight) Passing Sieves					
	3/8 in	No. 4	No. 8	No. 16	No. 50	No. 100
Fine Agg. No 4 to 0	100	85-100	.....	40-80	10 - 35	5-25
Coarse Agg. 3/8 in to No. 8	80-100	5-40	0-20	.....	.....	.....
Combined Coarse and F. 1/2 in to 0	.....	50-80	.....	.....	5-20	2-15
3/8 in to 0	90-100	65-90	35-65	.....	10-25	5-15

TABLE (1) GRADING REQUIREMENTS FOR LIGHTWEIGHT AGGREGATES
FOR STRUCTURAL CONCRETE (9)

Unit Weight: The Unit Weight of the lightweight aggregates shall conform to the requirements shown in Table (2)

General Characteristics: a) Two general types of lightweight aggregates are covered by these specifications as follows:

Aggregates prepared by expanding, calcining, or sintering products such as blast furnace slag, clay, diatomite fly ash, shale or slate.

Aggregates prepared by processing natural materials such as pumice, scoria or tuff.

b) The Aggregate shall be composed predominantly of lightweight cellular and granular inorganic material.

Size Designation	Dry Loose Weight max, lb per cu ft
Fine Aggregate	70
Coarse Aggregate	55
Combined F. and C.	65

TABLE (2) UNIT WEIGHT REQUIREMENTS OF LIGHTWEIGHT AGGREGATES FOR STRUCTURAL CONCRETE (9)

Concrete making properties:

Concrete specimens containing lightweight aggregate under test shall meet the following requirements:

a) Compressive strength, Unit Weight, And Absorption- It shall be possible to produce structural concrete, using the lightweight aggregates under test, such that one or more of the compressive strength requirements in the following table (3) will be satisfied without exceeding the limits. Intermediate values may be established by interpolation.

b) **Drying shrinkage:** The drying shrinkage of concrete specimens prepared and tested in accordance with ASTM C 157 shall not exceed 0.10 per cent.

c) **Popouts:** Concrete specimens prepared and tested in accordance with ASTM C 151 shall show no surface popouts.

B. Types of Aggregate:

Average 28-day compres. Strength, min, psi	Average unit wgt. max, lb per cu ft
4000	115
3000	110
2000	105

TABLE (3)

Lightweight Aggregates are classified with regard to source as either natural or artificial. (24) The Artificial aggregates are either specially manufactured or by-products of some industrial operation. Natural aggregates are, Pumice, Scoria and volcanic cinders. Some examples of by products are cinders and coke. Materials which are specially manufactured are clay, shale slate, blast furnace slag, diatomaceous shale, fly ash, pumice obsidian, perlite, and vermiculite. (24)

Pumice: True Pumice is a light spongy lava rock through which steam escaped while the rock was still in the molten state. Commercially, volcanic ash, is also referred as Pumice. It is processed by crushing and screening.

Cinders: In localities where cinders are available as a by-product from the burning of coal, they are the most widely used of any lightweight aggregate.

Expanded clay or Shale: Lightweight aggregates usually of vesicular structure are produced by calcining certain clays and shales to a temperature of incipient fusion, when expansion usually takes place.

Processed Diatomaceous Earth or Shale: Lightweight Aggregates are produced from Diatomaceous Earth or Shales which are first sized by crushing and which are then calcined in such manner as to prevent the individual pieces from sticking together.

Processed volcanic glasses: Some of the pumices, are composed of particles of volcanic ash weakly cemented together. These may be processed by calcining in a rotary kiln, so as materially to increase their strength and decrease their absorption. Perlite is included in this class. When heated quickly, perlite expands with disruptive force and breaks into small expanded particles.

Expanded Vermiculite: Another aggregate of extremely small weight is made by sudden heating of Vermiculite.

Expanded Slag: By sudden cooling of blast furnace slag with water or steam under controlled conditions, as the slag flows from the furnace, or is poured from a ladle, the molten slag can be broken up and its structure greatly expanded to produce a lightweight aggregate. (24)

II.

STRUCTURAL LIGHTWEIGHT CONCRETE

Lightweight Structural Concrete is usually considered to have a unit weight less than 115 lb per cu ft and a compressive strength of not less than 1000 psi. Expanded shale, slate and clays are used as lightweight aggregates for structural use. (13) Although there can be made a lightweight concrete by adding an admixture such as finely powdered aluminum, magnesium or zinc to normal concrete, the strength of it is usually too low to permit its use as a structural concrete. (22)

J.J. Shideler and R.W. Kluge made series of tests to determine the properties of Structural concretes. They found out that, the aggregates they use are turned to be satisfactory in using for structural lightweight concrete. Shideler used expanded shale, expanded clay, expanded slate, expanded slag, and for comparison purposes elgin sand, in his tests. Kluge on the other hand used Pumice, expanded slag, and expanded shale in his tests. Both of them obtained structural lightweight concrete with each of the lightweight aggregates. However, the control of quality in the field was a problem, because the peculiar absorptive properties of most lightweight aggregates. Also, fine aggregate gradation had a relatively greater influence on concrete yield and water required than was the case for conventional dense aggregate. Therefore closer control was required with respect to uniformity of aggregate from batch to batch. (7) (13)

III.

PERLITE AGGREGATE AND CONCRETE

Perlite is a non-metallic mineral, a siliceous volcanic rock. When crushed to size and heated quickly to a suitable temp. in its softening range (above 1500° F), the select perlite expands to form high-quality perlite aggregate, a lightweight, non-combustable, glass-like material of cellular structure. (23) The unit weight of a well-graded aggregate is usually in the order of 10-12 lb per cu ft. The aggregate is employed in concretes, where a high degree of insulation is desired and low strength is permissible. (24)

Lightweight: Perlite aggregate is about 1/10 of the weight of the sand. Perlite concrete is the lightest of all mineral concrete. While ordinary sand-gravel concrete weighs 120-150 lb per cu ft. When used for concrete roof decks, roof fill, floor slabs and floor fill, it makes possible immense savings in dead-weight.

Insulating: Perlite Concrete offers up to 20 times greater insulating value than ordinary concrete. Perlite concrete has a high thermal insulation value, because its millions of microscopic sealed vacuum cells are permanent insulating agents that reduce heat transmission losses. Consequently, it has a good lightweight insulating concrete for roof decks, roof fill, floor slabs and floor fill. (23) Perlite Concrete is used in the roof of the Hunter College Library for its insulating value. (16)

Fire Resistant: Perlite concrete offers four times greater fire resistance value than ordinary concrete. It withstands temperatures up to 2300° F without melting. Mixed with cement to form concrete, Perlite adds inherent fire proofing qualities to concrete.

Because of this property of Perlite concrete, they used it in many buildings in the States, such as The Hunter College Library Building, and The Mile High Center Transportation Building. (16)

Typical Chemical Composition of Perlite: (25)

silicon dioxide (SiO_2)	71-75 per cent
Aluminum Oxide (Al_2O_3)	11-18 per cent
Potassium Oxide (K_2O)	4-5 per cent
Sodium Oxide (Na_2O)	2.9-4 per cent
Calcium Oxide (CaO)	0.5-2 per cent
Ferric Oxide (Fe_2O_3)	0.5-1.5 per cent
Magnesium Oxide (MgO)	0.1-0.5 per cent
Sulphates	none
Others	0-0.2 per cent

Typical Physical Properties of Perlite: (25)

Color	white
Softening point	1600-2000° F
Fusion point	2300-2450° F
pH	6.6-8
Specific Heat	0.20
Specific gravity	2.2-2.4
Refractive index	1.5
% free moisture, max.	0.5

IV.

METHODS OF PROPORTIONING OF LIGHTWEIGHT CONCRETE

Several Methods and articles have been published on proportioning structural Lightweight Concrete. Among them there are, "A C I Standard Recommended Practice for Selecting Proportions for Structural Lightweight Concrete" "Proportioning, Control, and Field Practice for Lightweight Concrete" by Jones and Stephenson (19), "Lightweight Structural Concrete Proportioning and Control" by Nelson and Frei (21), and "Permalite Lightweight Concrete Mix Designs" (23)

The Articles, mostly discuss the methods for proportioning a special Lightweight Concrete and give tables for mix designs. Only the ACI method is a general one. However, in this chapter all of them will be discussed.

According to ACI Standard 613A-59 (14) the difficulties involved in proportioning lightweight concretes may be summarized as follows:

a) Some lightweight aggregates have absorption values of more than 12 per cent and so may have more than 200 lb of absorbed water per cu yd of concrete. The question of how much water is absorbed and how much water actually occupies space in the concrete is the principal difficulty in proportioning by absolute volume procedures, when applied to this class of lightweight aggregates. The high values of absorption, and the fact that the absorption may continue at an appreciable rate for several days make it difficult to determine correct values of absorption and specific gravity of the aggregate. Because of these complications the established relationships cannot be applied with the same confidence as for normal weight aggregates.

b) The net water-cement ratio of most lightweight aggregate concretes can not be established with sufficient accuracy for use as a basis of mix proportioning. Lightweight aggregate concrete mixes are determined by a series of trial mixes proportioned on a cement content basis at the required consistency. (14)

In the estimation of cement and water requirements the ACI Standards (14) do not give a definite value. Instead, it suggests to abide by the recommendations of the producers of the various lightweight aggregates. Because they have devoted considerable time to studies of their particular aggregates, their recommendations provide the best estimate of the required cement content and other mix proportions. However, a general method is outlined in the ACI Standards (14). In that method, the absorption and the specific gravity of the aggregate is not used, because it is difficult to determine a satisfactory value for them. The first step is to determine the dry loose unit weight according to ASTM C 330. An example of a trial mix given in the ACI Standards (14) will be quoted.

An example of a trial mix: Assume that the mix is to contain 6 bags of cement per cu yd, and that the dry loose unit weights of the fine and coarse aggregates are 56 and 45 lb per cu ft, respectively. A slump of about 2 in. is required. About 32 cu ft of dry loose aggregate (sum of uncombined fine and coarse volumes) are required to produce a cubic yard of concrete. If the aggregate is produced in two sizes, fine and coarse, these are proportioned in equal volumes. Water is added to produce the required slump. A trial batch of approximately 1 cu ft would then require:

$$\text{Cement} \quad \frac{6 \times 94}{27} = 20.9 \text{ lb}$$

$$\text{Fine aggregate } \frac{16 \times 56}{27} = 33.2 \text{ lb}$$

$$\text{Coarse aggregate } \frac{16 \times 45}{27} = 26.7 \text{ lb}$$

$$\text{Water } \frac{480}{27} = 17.8 \text{ lb}$$

$$\text{Total weight } = 98.6 \text{ lb}$$

The wet unit weight is 97.0 lb per cu ft and the air content test indicates 2.5 per cent entrapped air. The yield $98.6/97$ is 1.016 cu ft. Quantities per cu yd of concrete are obtained by multiplying the batch quantities by the ratio of cu ft in a yard to cubic foot of batch $27/1.016 = 26.6$.

Cement	556 lb per cu yd	(5.91 bags per cu yd)
Fine aggregate	882 lb per cu yd	
Coarse aggregate	710 lb per cu yd	
Water	473 lb per cu yd	

Additional trial mixes could be made by estimating cement and aggregate quantities and establishing the yield, cement and water content, and other fundamental relationships. However, by the use of a "specific gravity factor" for the aggregate, all other trial mixes with this aggregate can be proportioned with considerable confidence. The specific gravity factor is obtained in the following manner:

Solid volume of cement	$\frac{556}{62.4 \times 3.15}$	= 2.83 cu ft
Volume of water	$\frac{473}{62.4}$	= 7.58 cu ft
Volume of entrapped air	2.5 percent	= 0.67 cu ft
		<u>11.08 cu ft</u>

The aggregate then occupies $27 - 11.08 = 15.92$ cu ft. The coarse and fine aggregate were used in equal parts by volume so they each occupy 7.96 cu ft. This is not precisely correct, but the error becomes unimportant when the specific gravity factor method is used. The specific gravity factor expresses the relationship between the dry weight of the aggregate and the space it occupies, assuming that no water is absorbed during mixing.

Specific gravity factor fine aggregate	$\frac{882}{62.4 \times 7.96}$	= 1.78
Specific gravity factor coarse aggregate	$\frac{710}{62.4 \times 7.96}$	= 1.43

This is only a factor and not a specific gravity value defined by ASTM, because the method does not account for any water absorbed during mixing. However, in subsequent mixes with this aggregate in the same moisture condition, the volume of water absorbed during mixing is nearly constant.

The specific gravity factor can then be used as though it were the apparent specific gravity and additional mixes can be proportioned by a procedure similar to the absolute volume method outlined in ACI 613-54.

Besides this, a recommended procedure for arriving at mix proportions for expanded shales and clays is given by T.R. Jones and H.K. Stephenson, (19) as follows:

1) Assume a basic design satisfying the requirements for strength, durability, and workability such as: two parts coarse aggregate, 5 bags cement per cu yd, 3 in slump, 5 percent air content.

2) Place from 1/2 to 2/3 the estimated amount of mixing water needed, containing the neutralized Vinsol resin, in the mixer. Measure the amount of water.

3) Measure quantities of coarse and fine aggregate in accordance with the assumed mix design, such as 2 cu ft coarse and 1 cu ft fine, weigh these quantities, and place in the mixer. If the aggregate is dry, allow mixer to run 15 or 20 min so that the absorption rate of aggregate will level off and not affect the concrete slump too greatly.

4) Assume a concrete yield of 70 to 80 percent of the total aggregate used and determine the amount of cement to be added. Add this cement to the mixer. In this example the estimated yield would be 80 percent of 3 cu ft or 2.4 cu ft. The total cement per cubic yard = $5 \times 94 = 470$ lb, and the cement for this batch = $(2.4/27)(470) = 41.8$ lb

5) Add sufficient additional water to give the required slump. (Measure the water)

6) Determine the air content (ASTM C 231-54, plus vibrating the specimen.

7) Determine the total weight of concrete in the batch and the weight per cu ft (ASTM C 138-44, plus vibrating the specimen). Divide the total weight by the weight per cu ft to determine volume of concrete produced, using the measured quantities for this first trial batch.

8) Check the amount of cement used against the amount of cement required for this quantity of concrete and the air content obtained against that desired for this batch.

9) Correct the quantities and repeat all steps until the desired batch is obtained.

According to Jones and Stephenson (19) mix proportions should be set up with lightweight aggregates on a dry, loose volume basis, proportions can best be determined by trial batches. Also special care should be taken to assure through mixing time is longer than that of normal concrete; the mixer speed should be faster. (19)

Nelson and Frei (21) in their article also mention the difficulties about finding the absorption and specific gravity of the lightweight aggregates, and propose a method without using the two. The method they propose is essentially the same as the ACI Method, which uses "specific gravity factors". However the article is about expanded shale aggregates.

An important conclusion from this article is the fact that the use of usual methods of batching and control shows variations in yield and performance beyond those considered acceptable in heavyweight concrete practice. Proposed new mixing and control methods involving the use of a specific gravity factor as determined from prepared concrete, provide easy and accurate control of lightweight concrete quality and yield as confirmed both by laboratory investigations and by commercial field batching operations.

As an example of the recommended mix designs by the producers of the aggregates, the mix design table of the Permalite Concrete, which uses perlite as its lightweight aggregate can be mentioned. The Table (4) is as follows:

TYPICAL PROPERTIES						MIX PROPORTIONS (by Volume)			
Density (oven-dry) lb/cuft	Compr. Strength psi 28d	Thermal Conductivity K	Tensile Strength psi 28d	Bond Strength psi 28d	Modulus of Elas. in compr. psi 28d	Sacks of Cement	Perlite cu ft	Water per sack cement gals.	Air entraining agent pints
35	450	.85	69	83	245 000	1	4	9	1/2
29	270	.67	46	53	123 000	1	5	11	5/8
26	190	.59	32	23	114 000	1	6	12	3/4
23	130	.53	25	-	90 000	1	7	14	7/8
21	100	.50	17	-	68 000	1	8	16	1

TABLE (4) TYPICAL MIX DESIGN TABLE (23)

V.

PROPERTIES AND USES OF STRUCTURAL LIGHTWEIGHT CONCRETE

The properties of several important types of light-weight aggregate concretes are summarized in table (5). The values for each property and for each type of concrete represent only the range in which most of the values are normally found. Additional information is also given in the following paragraphs. (3)

A. Unit Weight: ASTM C 330- 53T has the following under the title of, Loose unit weight of Aggregates: Tentative Method of Test for Unit Weight of Aggregate (ASTM C 29) utilizing the shoveling procedure described in Section 7 of Method C 29 except that the aggregate shall be tested in an oven-dry condition. (9)

The unit weight of lightweight concrete itself is usually below 115 lb per cu ft. It depends upon the unit weight of aggregates, the richness of the mix, and the quantity of air entrained. In the Article of Kluge (13) the unit weight of Structural lightweight concrete is between the ranges of 55 to 110 lb per cu ft fresh, and from 50 to 109 lb per cu ft dry. Those weighing less than about 60 lb per cu ft , developed compressive strengths less than 1000 psi, so that for all practical purposes this seemed to be the lower limit for structural concrete according to the initially assumed definition. (13)

In Hanson's article (11) the range is between 90 to 111 lb per cu ft.

In the book of Short and Kinniburgh (12) the range is between 80 to 126 lb per cu ft.

Property	Concrete made with lightweight mineral aggregates		
	Insulating	Masonry unit	Structural
Dry specific weight lb per cu ft	20 - 80	65 - 100	65 - 115
Compressive strength psi	50 - 1000	1200 - 3000	1000 - 5000
Modulus of rupture psi	15 - 150	200 - 450	150 - 500
Modulus of elasticity psi $\times 10^3$	30 - 500	500 - 1500	400 - 2500
Water absorption by volume	15 - 50 %	10 - 18 lb/cuft	5 - 30 %
Drying shrinkage percent	0.05 - 0.50	0.02 - 0.14	0.04 - 0.15
Coefficient of therm. expansion per deg. F $\times 10^6$	3.0 - 7.0	2.0 - 4.5	4.5 - 6
Thermal conductivity K	0.5 - 2.0	1.5 - 4.0	1.5 - 4.0

TABLE (5). PROPERTIES OF LIGHTWEIGHT CONCRETE

B. Compressive Strength: Compressive Strength of lightweight concrete directly varies with the unit weight. Therefore by adding sand to compacted lightweight mixes, both density and compressive strength will increase considerably. (12)

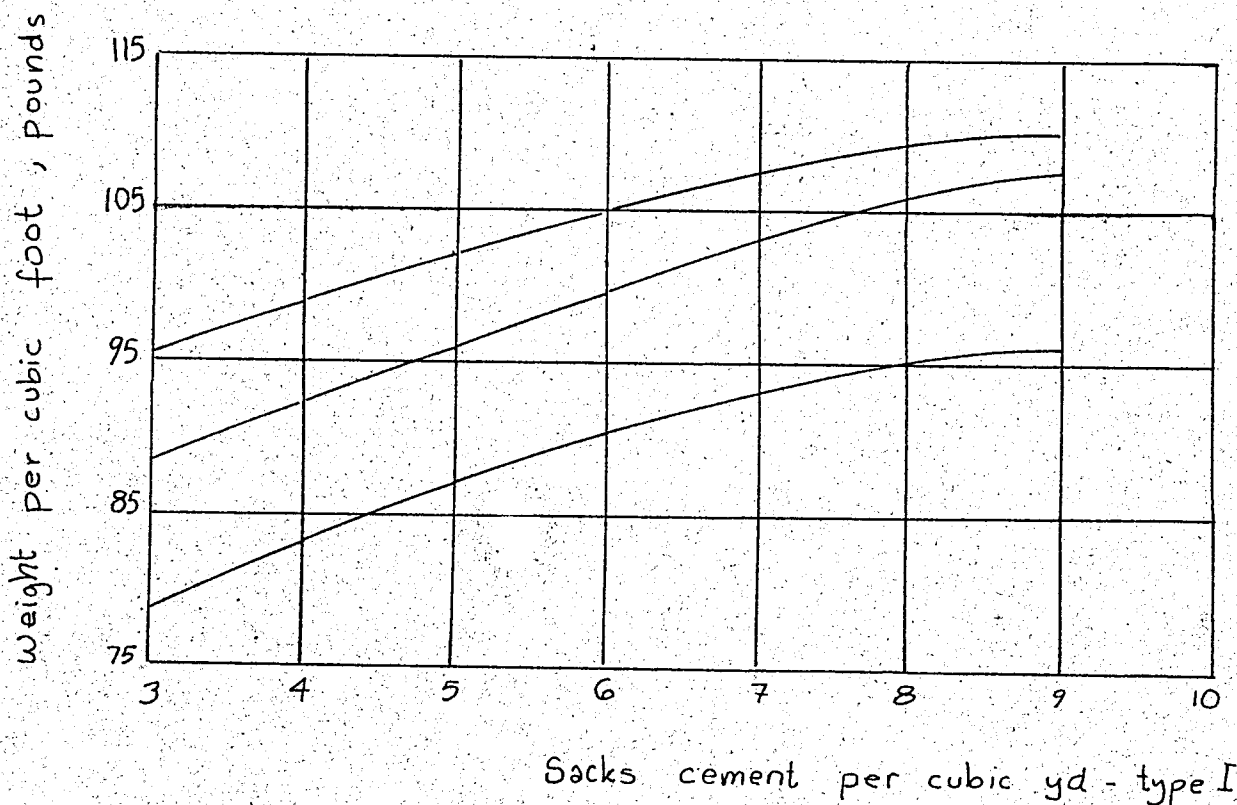


FIG. (1). RELATION BETWEEN WEIGHT OF CONCRETE AND CEMENT CONTENT (21)

In the investigations described in reference (21) tests were conducted on 6x12 in. moist cylinders. Additional cylinders were made for the air dry and oven-dry weight determination. Tests were made at ages of 7 days, 28 days, 6 months and 1 year. The obtained relationship between compressive strength and unit weight is shown in Fig (1)

The 28 day compressive strengths ranged from 800 psi at 3 sacks per cu yd to 5200 psi at 9 sacks of cement.

Over the range of cement contents the wet weight of the concrete varied from 96 lb per cu ft at 3 sacks to 111 lb per cu ft at 9 sacks. The air dry weights were from 3 to 8 lb per cu ft lighter, the richer mixes tending to retain their original moisture longer. Wet concretes weighing 98.5, 102.5 and 110 lb per cu ft, developed strengths of 2000, 3000 and 5000 psi respectively. (21)

Compressive strength and its Relation to Cement Content:
In Fig. (2) the relation between compressive strength and cement content for pumice concrete is shown according to Kluge. (13)
The plotted data, were generally confined to mixes having a slump of 6 in. or less and most were for slumps of 4 in. or less. It appears that for a given aggregate, substantial variations in strength are possible for a given cement content. If it is assumed that the crushing strength of a particular aggregate and that the air content and consistency of the particular mix are reasonably constant, the differences appear to result from variations in gradation with concomitant differences in water required. It would therefore seem desirable in proportioning mixes, to give careful consideration to the proper gradation of aggregate, and maintaining the selected gradation in subsequent mixing operations. (13)

Shape Factor And Compressive Strength of Lightweight Concrete:

The load carrying capacity of lightweight concretes seems to follow a different law than in dense concretes. Failure in the former starts at local points so that the shape of the specimen has much less influence than in the latter.

The relation between shape factor and compressive strength has received considerable study, culminating in ASTM Specification Designation C 42-49. Anderegg (28) suggested that load carrying capacity C should be proportional to the amount of matter in a given space or to the density and inversely proportional to the voids.

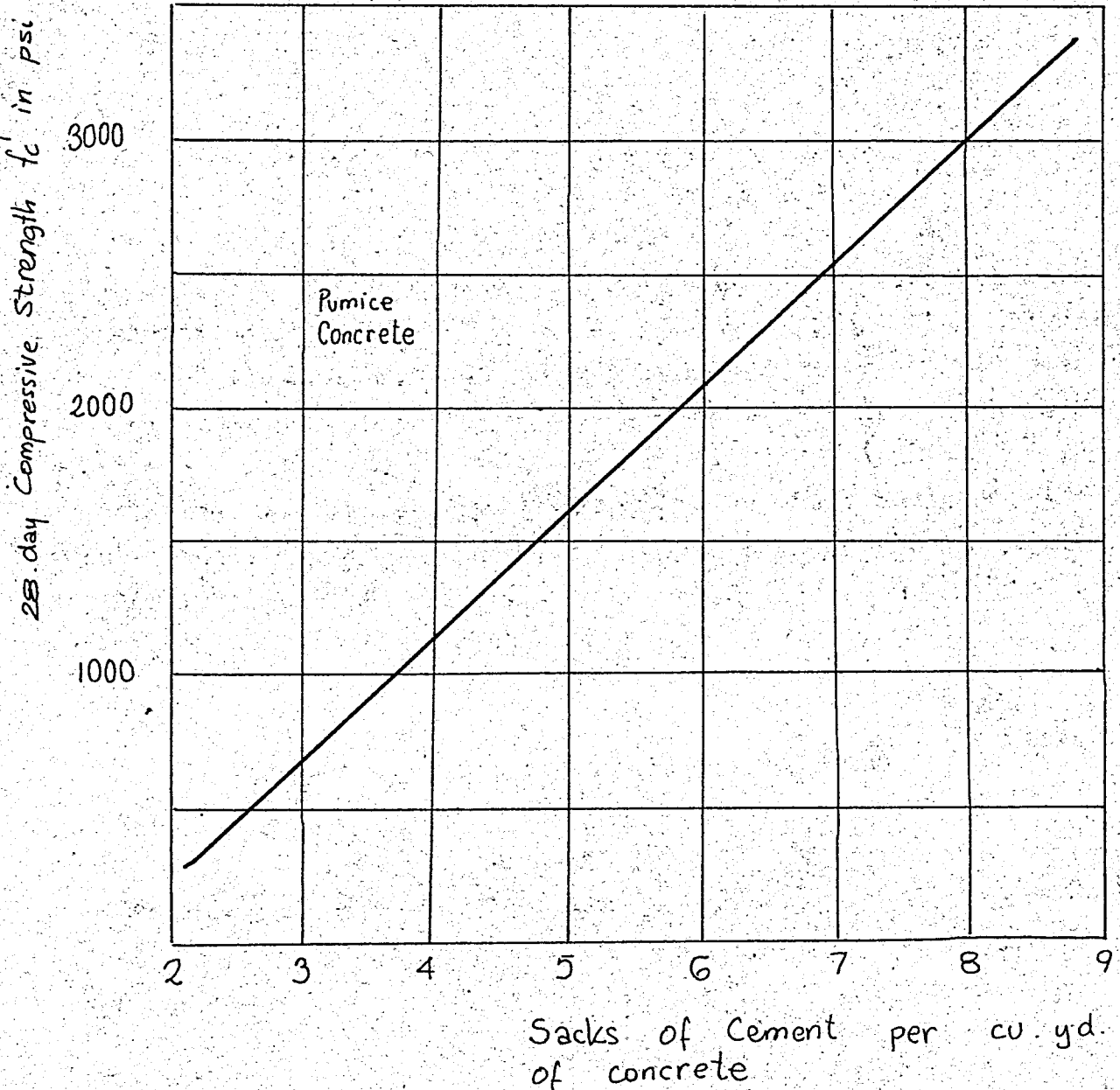


FIG. (2) RELATION OF COMPRESSIVE STRENGTH AND CEMENT CONTENT

The relation he suggested is as follows:

$$G = kS/A-S \quad (28)$$

where S is unit weight of the given concrete and A is weight of a cubic foot of the concrete having no voids. The constant k depends upon the nature of the cementing material and the history of the concrete.

Aggregate	Cement	Curing Age, days	Water - Cement ratio	Parameters		
				a	b	M, pcf
Perlite	Type I	wet 28	various	11.9	0.56	13
Perlite	Type III	wet 7	various	14.3	0.60	15
		28	various	14.3	0.75	15
		90	various	14.3	0.95	15
Vermiculite	Type I	Oven-dry 28	low	3.43	0.333	13
			medium	3.43	0.450	13

TABLE (6). CONSTANTS FOR LIGHTWEIGHT CONCRETE (28)

Recently, considerable study has been given to Perlite concrete and it was found that when testing concrete weighing less than 50 lb per cu ft that failure did not always result in the formation of the double cone with cylinders. Instead it seemed to start almost anywhere within the specimen. (28)

The following analysis is proposed by F.O. Anderegg (29) for concrete made from expanded aggregates.

Load carrying capacity depends upon the amount of material present in a given space in excess of a minimum M required to carry any load at all. In such concrete one finds a series of slender columns and beams whose load carrying capacity is a function of the square of the thickness of the microscopic member. The following relationship might be written

$$C = a(S-M) + b(S-M)^2 \quad (29)$$

where a and b are constants. Table (6) gives experimental values for these. These constants depend upon the type of cementing material and upon the history of concrete, the type of concrete is also a factor. Most of the Perlite concretes contained rather large amounts of entrained air. In the study of Perlite concrete, specimens were made from a single batch in the 2 in. cube shape in 3×6 and in 6×12 in. cylinders. Strengths from these usually agreed within an experimental error of ± 5 percent. (28)

G. Tensile Strength And Modulus of Rupture:

The tensile strength of concrete is difficult to determine because standard tests are necessarily subject to the influence of a large number of variables either unknown or not possible to control. Standard cylinder tests are adopted to determine an index, rather than an absolute measure, of the crushing strength of concrete. Various methods have been tried to obtain at least an index of the tensile strength of concrete but none proved entirely suitable. (12) The cylinder -splitting Test (Brazilian) is used recently as a measure of the tensile strength. (11)

The Modulus of Rupture obtained for concretes made with different types of aggregate is shown in Fig. (3) in relation to the compressive strength. (12)

The relationship between modulus of rupture and density varies considerably for different types of concrete and a consistent relationship is difficult to establish. The approximate correlation of compressive strength and modulus of rupture for both gravel concrete and lightweight concrete was found to be best represented by a parabolic equation of the form:

$$R = \alpha_1 \sqrt{u}$$

where R denotes the modulus of rupture, α_1 denotes a variable in the order of 8, and u is the cube strength. (12) α_1 is a variable which is a characteristic of the specific aggregate.

The relationship of the cylinder splitting strengths to cube strengths obtained from the tests at The Building Research Station can be expressed approximately by the following equation:

$$f_{sp} = k \sqrt{u} \quad 4.5 < k < 6$$

The results in split-cylinder tests in reference (11) indicate that the split cylinder strengths of saturated lightweight concrete is generally equal or lower than that of gravel concrete of equal cylinder crushing strength for a wide range of compressive strengths. In general the cylinder splitting strength is about 60 percent of the Modulus of Rupture.

There is one major conclusion that may be drawn from all the various investigations reported on this indirect measurement of tensile strength. This is that the splitcylinder can furnish

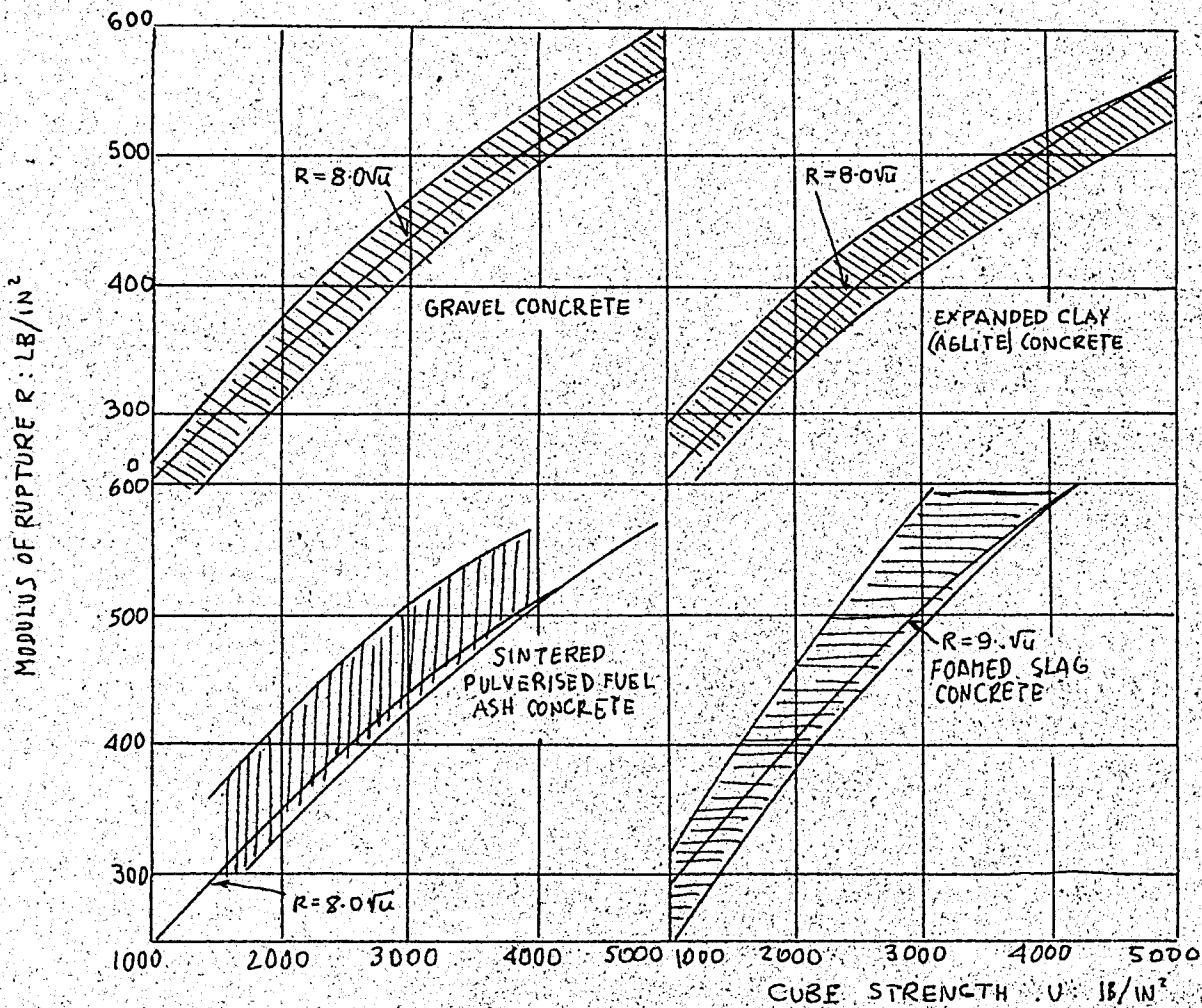


FIG. (3) RELATION OF MODULUS OF RUPTURE WITH THE COMPRESSIVE STRENGTH

a reliable measure of the relative tensile strength of concrete provided that several samples are employed. (11)

The theory of elasticity indicates that a uniform tensile stress at right angles to the direction of load application must exist over a substantial part of the interior of a cylinder subjected to concentrated loads at the opposite ends of a diameter. This, then is, determined by the formula:

$$f'_{sp} = \frac{2P}{\pi DL}$$

where f'_{sp} is the uniform tensile stress, P is the magnitude of the load, and D, and L are the cylinder diameter and length respectively. (11)

The tensile strength appears to be an important criterion of the liability to cracking in different types of concrete. Since it is such a heterogeneous material, the tensile strength of concrete will tend to vary considerably and its composition will affect not only the tensile stress at which cracking occurs but also the mechanism of the process itself. In gravel concrete, for example the strength and stiffness of the aggregate itself is usually very great, both in compression and in tension. Failure in tension will therefore almost invariably occur as a result of a breakdown of the bond between the matrix itself, not as a result of fracture of aggregate. The aggregate particles themselves are not very compressible and are not in general subject to appreciable shrinkage. The tensile stresses induced in the matrix through shrinkage of the latter due to loss of moisture are therefore all the more important and increase the liability of the matrix to cracking. (12)

D. Relation of Tensile Strength to Compressive Strength:

Fig. (4) of reference (12) shows the split-cylinder tensile strength as a percentage of the compressive strength. This program did not include 28-day moist cured compression tests, so the assumption was made that the 28-day compressive strengths of the dry and moist cured concretes were equal. This assumption is well justified from an examination of Shideler's data (7) on similar concretes. For the dry concretes, the tensile strengths of the lightweight concretes range from approximately 9.5 percent

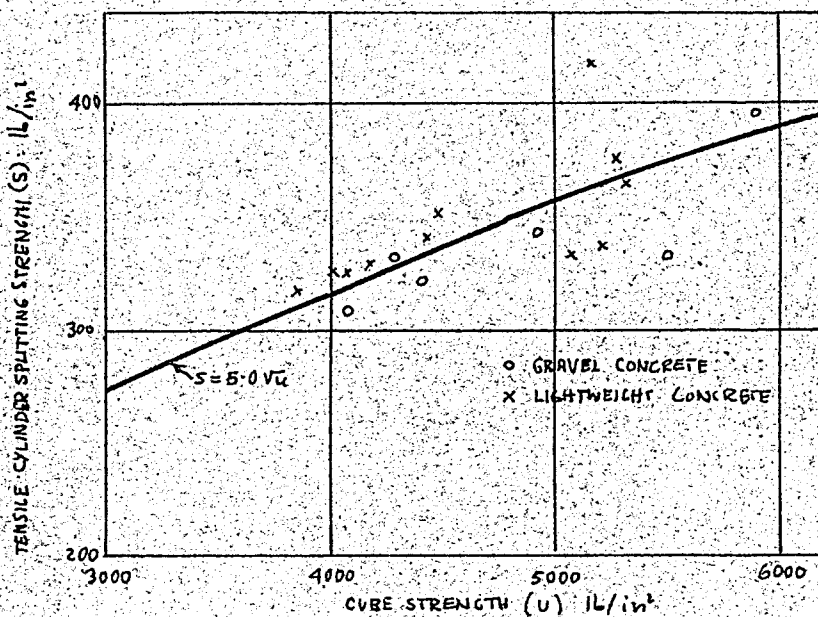


FIG. (4) RELATIONSHIP BETWEEN THE CUBE CRUSHING STRENGTH AND THE TENSILE SPLITTING STRENGTH OF DIFFERENT TYPES OF CONCRETE. (12)

of 3000 psi compressive strengths down to some 7 percent at the 4500 psi level. Certainly the data indicate that tensile strength is not a constant proportional part of the compressive strength but that the proportionality ratio decreases as compressive strength increases. Since tensile strength then can not be considered as a linear proportion of compressive strength, many investigators have related tensile resistance to the square root of the compressive strength, such as $f'_{sp} = k \sqrt{f'_c}$ as mentioned. (11)

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E. Modulus of Elasticity:

For the same compressive strength, the modulus of elasticity of lightweight concrete is in general considerably lower than that of dense, gravel concrete. For concrete of high strength the percentage difference is somewhat greater than for weaker mixes, but in general the E-value of lightweight concrete ranges between 1/3 and 2/3 of the E-value of the corresponding gravel concrete mix. (12) The secant modulus of elasticity is found as $0.3 f'_c$ is reported. (7) For expanded shale concrete in Fig. (5) the heavy line represents a linear relation and can be expressed by the following equation:

$$E = 1.5 \times 10^6 + 160 (f'_c - 1000) \quad (13)$$

Values of E obtained from other sources for expanded shale concrete are, in general equal to or lower than those expressed by the above equation.

The tangent modulus and compressive strengths are plotted in the Fig. (5) (21) These values range from 1,240,000 at 1000 psi to 1,850,000 at 3000 psi and up to 2,450,000 at 5000 psi.

The modulus of Elasticity is a special importance for for structural lightweight concrete construction because of its effect on the deflection of flexural members, on the distribution of internal forces in the cross-section of compression members and on the critical load in the case of members liable to failure due to elastic instability where the lower E value of Lightweight concrete has an unfavorable influence. On the other hand, the resistance of lightweight concrete members to impact loads may be enhanced by their lower modulus of elasticity. (12)

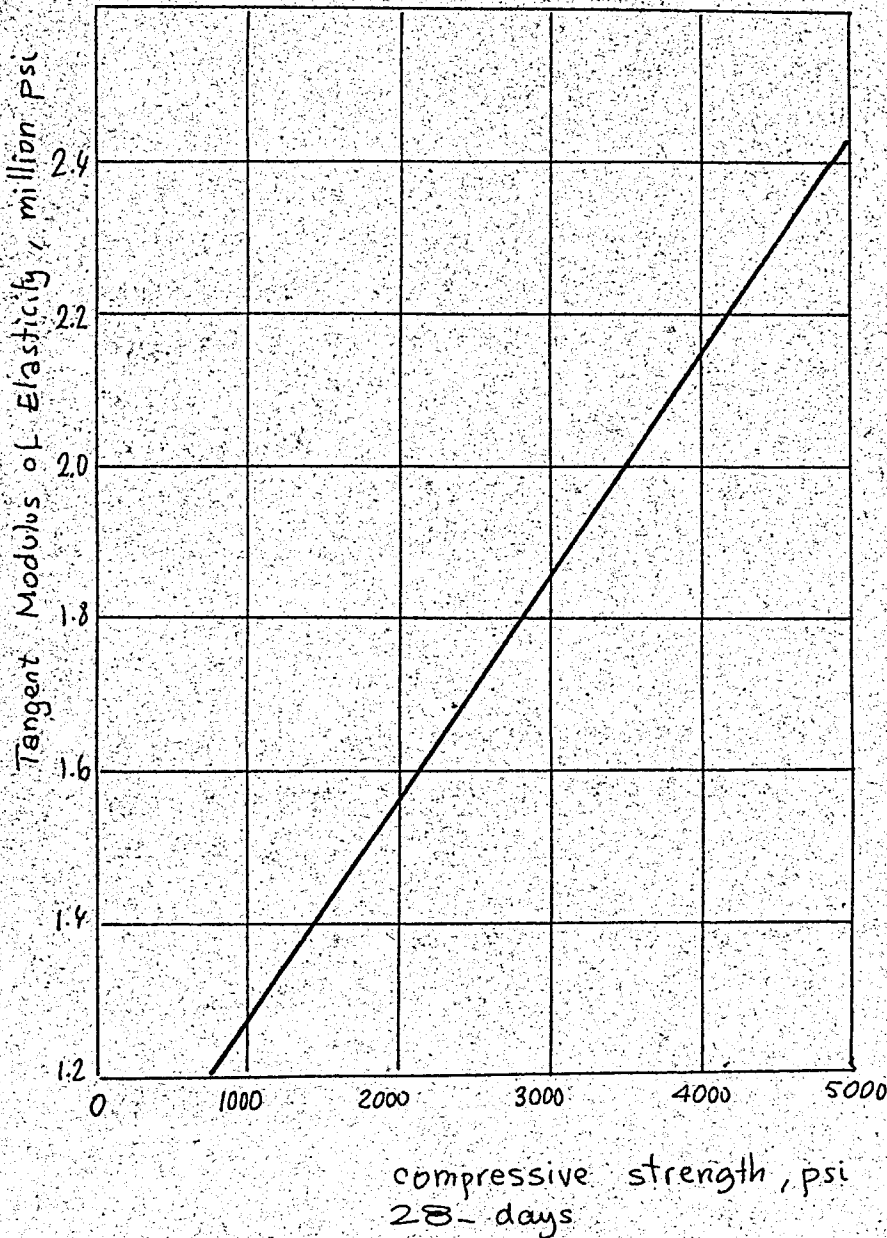


FIG. (5). RELATION OF TANGENT MODULUS OF ELASTICITY TO 28-DAY COMPRESSIVE STRENGTH (21)

The Permalite Institute gives the Modulus of Elasticity as follows: For 1:4 mix, 245,000, for 1:5 mix, 123,000, for 1:6 mix, 114,000 psi.

F. Uses of Structural Lightweight Concrete:

Concrete which is considerably lighter than normal concrete is sometimes used for the decks of long-span bridges, as fire protection for the steel work of tall buildings, as filling for thick floor or roof slabs, as thermal insulation, and for concrete ships, building blocks, and filler walls. From the two recently developed lightweight aggregates, Perlite and Vermiculite neither of them is suitable for high strength structural concrete, but they have formed many other uses as for concrete partitions and roofs, insulating plaster, etc. (22)

Uses of various mix designs of Perlite Aggregate Concrete are quoted from the reference (23): 1:6 mix is used in basic roof deck designs. It best meets average requirements of strengths, weight and insulating value. 1:4 mix is frequently used instead of the standard 1:6 mix. When used in place of the standard mix, the architect and the engineer must consider the extra density of the cement and the need for increasing the thickness of the cement to maintain a given U value. 1:7 mix possesses excellent insulating properties and more than average strength for use as an insulating and drainage fill over structural roof decks. The compressive and indentation strengths of this mix are equal to and in most cases far in excess of those of rigid insulation board. 1:8 mix has a very low density and excellent insulating value. Its compressive and indentation strengths are equal to and exceed those of most of the rigid insulation boards. When used as an insulation and/or drainage fill over structural roof decks, it will provide an excellent, monolithic base for a built-up roof. It is much more economical than most rigid board installations. (23)

PART II.
EXPERIMENTAL

I.

TESTS ON PERLITE AGGREGATE

A. Unit Weight Determination of Perlite Aggregates

A unit weight test according to ASTM C29-55T is performed. Apparatus: It consists of, a balance, sensitive to 0.5 percent of the sample to be weighed, a tamping rod, a metal measure cylindrical in form.

Calibration of the Measure: The measure was calibrated by determining the weight of water at 16.7° C required to fill it. The factor was obtained by dividing the unit weight of water at 16.7° C (62.355 lb per cu ft) by the weight of water at 16.7° C required to fill the measure.

Procedure: The Procedure was the Shoveling Procedure. The measure was filled to overflowing by means of a shovel, the aggregate being discharged from a height of not to exceed 2 in. above the top of the measure. Care was taken to prevent segregation of the particle sizes of which the sample was composed. The surface of the aggregate was then leveled off. The net weight of the aggregate in the measure was then obtained by multiplying the net weight of the aggregate by the factor found as described before.

Determination of The Factor: Unit weight of water at 16.7° C is 62.355 lb per cu ft. The weight of the water to fill the measure was 15.5 lb. The factor to be used is $62.355/15.5 = 4.02$

The unit weight of Perlite Aggregates is determined before each mixing procedure, because the unit weight varies with the varying humidity in air. The unit weights thus found was between 6.8 and 10 lb per cu ft (115 - 169 kg/m³).

These are within the limits of the Specification for lightweight Aggregates for insulating concrete ASTM C332-54T, but much less than the limits in the specifications for lightweight aggregates for structural concrete ASTM C 330-53T.

B. Gradation of Expanded perlite Aggregates:

According to the ASTM Specifications (C 330-53T) for the structural lightweight aggregate, the grading shall conform to the requirements shown in table (7) in the first part of this study. The same table is also reproduced in this part for the purpose of comparison.

Size designation	Percentages (by weight) passing				
	No 4	No 8	No 16	No 50	No 100
Combined coarse and fine aggr.	65-90	35-65	.....	10-25	5-15
Fine aggregate	85-100	.....	40-80	10-35	5-25

TABLE (7). GRADING REQUIREMENTS FOR LIGHTWEIGHT AGGREGATES FOR STRUCTURAL CONCRETE

Since the perlite aggregate which we used to make lightweight aggregate concrete consisted of only fine aggregates, the second row of table (7) should be used for comparison. The gradation of the perlite aggregates from HIMA, was even finer than the limits of the specification for the fine aggregates.

The samples for the sieve analysis were 50 grams each as it was stated in ASTM C 330-53T, Table III, for unit weights of aggregates between 5 and 15 lb per cu ft. Two sieve analysis tests were made and their results were compared with the specifications. In the case of No. 16 and No. 50 sieves, the test results were finer than the specifications' values. Test results are shown in table (8).

Sample no.	Percentage (by weight) passing				
	No.4	No. 16	No 50	No 100	F Modulus
1st sample	100	96.4	47.5	18.4	1.61
2nd Sample	99.5	93.9	46	20	1.67

TABLE (8). GRADING OF PERLITE SAMPLES

A sieving time of 5 minutes was used as specified for grading of lightweight aggregates.

II.

MIX PROPORTIONS, MIXING, PREPARING AND CURING PROCEDURES

The Perlite Concrete was proportioned using standard mix ratios as recommended by the Perlite Institute. Since these mixes were for insulating concrete, a mix of richer cement content was added to the series. Mix ratios of 1:3, 1:4, 1:5 and 1:6, by volumetric proportions, without air entrainment were used. These mixes were made twice, once by an electrically driven, paddle type, mortar mixer, and once by a barrel type concrete mixer conforming to site conditions. Mixing operation by the mortar mixer was done according to the ASTM C 305-55T. Procedures for flow test and for molding specimens followed the specification ASTM C 87-52. Other series were mixed in the normal concrete mixer and then hand mixed in a large pan. First water and cement were put in the mixer, than perlite was added and mixed thoroughly until it became homogeneous.

Apparatus: a) Molds: Molds were rigid and non-absorptive. For compression test specimens, they were cylindrical in form, having a metal base plate, and oiled before use.

b) Tamping Rod: It was a standard one having one end rounded to a hemispherical tip.

Molding Specimens: The test specimens were formed by placing the concrete in the mold in three layers. The concrete was distributed by a circular motion of the tamping rod. Each layer was rodded by 25 strokes of the tamping rod. After the top layer was rodded, the surface of the concrete was struck off with a trowel. In the case of type A and B concretes, the concrete was placed without tamping.

The cylindrical molds were of two sizes. One had a diameter of 2'' and a height of 4'', The other having a diameter of 6'' and a height of 12''.

Molding of specimens were according to ASTM C 31-55, except that in the capping procedure gypsum was used and instead of curing the specimens in a humidity chamber, the samples were immersed in water for three days and then kept in air until they are tested.

Specimens for the flexure test, were beams of having dimensions, 3 x 6 x 15 in. The forms were 3 inches longer the required span length. These specimens were also cured as described in the preceding paragraph.

In this study, four types of concrete were tested.

Type A: Concrete prepared by using coarse perlite particles and cement, mixed in the mortar mixer. table (9)

Type B: Concrete prepared by using normal fine perlite aggregate plus cement, mixed in mortar mixer. table (10)

Type C: Concrete prepared by using normal fine perlite aggregate plus cement, mixed in normal concrete mixer. table (11)

Type D: Concrete prepared same as type C, but with less water than the preceding one. table (12)

Mostly in this paper, the results of type C concrete are given, but the comparisons of all of them are given in tables (40, 42, 43, 45, 51, 56). Also comparisons with an additional type containing sand are presented in following sections.

mix	cement kg	Perlite ft ³	water lit
1 : 3	42.5	3	26.5
1 : 4	42.5	4	34

TABLE (9) BATCHES FOR TYPE A

mix	cement kg	Perlite ft ³	water lit
1 : 3	42.5	3	36.5
1 : 4	42.5	4	32
1 : 5	42.5	5	39
1 : 6	42.5	6	36

TABLE (10) BATCHES FOR TYPE B

mix	Cement kg	Perlite ft ³	water lit
1 : 3	20	1.41	24
1 : 4	20	1.8	26
1 : 5	20	2.35	28.5
1 : 6	20	2.83	32

TABLE (11) BATCHES FOR TYPE C

mix	cement kg	Perlite ft ³	water lit
1 : 3	25	1.77	21
1 : 4	25	2.35	23

TABLE (12) BATCHES FOR TYPE D

Water-cement ratios shown in the tables are not real water-cement ratios, because of the absorption of perlite and the amount of water in perlite is unknown; therefore one can not calculate the true value of water-cement ratio.

III.

TESTS ON PERLITE CONCRETE

A. Unit Weight:

Weights and dimensions of oven-dry and wet concrete when molding samples were determined at the age of 28-days and when molding. Volumes and weights per cubic foot were computed from the obtained average data. The obtained results are presented in table (13) below.

Type	Mix	Wet unit weight lb per cu ft	Oven-dry unit wt. lb per cu ft
A	1:3		
	1:4		
B	1:3		79
	1:4		76
	1:5		
C	1:6		
	1:3	77.5	51.4
	1:4	76	48.5
	1:5	75.2	46.3
D	1:6	71.6	42.7
	1:3		56.5
	1:4		56

TABLE (13) UNIT WEIGHTS OF VARIOUS MIXES

The unit weights obtained are smaller in value than they are specified in specifications and in various articles. (12) (7)

B. Compressive Strength of Perlite Aggregate Concrete:

The cylindrical test specimens were prepared conforming to the ASTM Method C 31-55. The specimens were cylindrical and having a height equal to twice the diameter. Standard cylindrical molds were 6 in. to 12 in., but 2 in. by 4 in. cylinders were used also for comparison.

Instead of curing the specimens in a humidity chamber the samples were immersed in water for three days and then kept in air until they are tested.

Capping of specimens: The test specimens were capped using gypsum plaster rather than sulfur or cement paste. This is done because, gypsum is cheaper than sulfur and its setting and hardening time is very small compared to cement paste.

Testing of specimens: The load was applied slowly, continuously and without a shock. In our case the machine was a screw type so the rate was constant and standard. The load was increased until the specimen failed, and the maximum load carried by the specimen during the test was recorded. Then the compressive strength was calculated by dividing this load by the average cross-sectional area. The results are presented in table (14) below. Also the relationships of mix ratios to compressive strengths are given in figures (6) and (7).

type	mix	compressive strength 28 day	
		2x4 cylinders psi	6x12 cylinders psi
A	1:3	1450	—
	1:4	1218	—
B	1:3	1900	1230
	1:4	1350	1082
C	1:3	624	348
	1:4	414	320
	1:5	350	305
D	1:6	304	265
	1:3	—	531
	1:4	—	488

TABLE (14). COMPRESSIVE STRENGTHS OF PERLITE CONCRETE

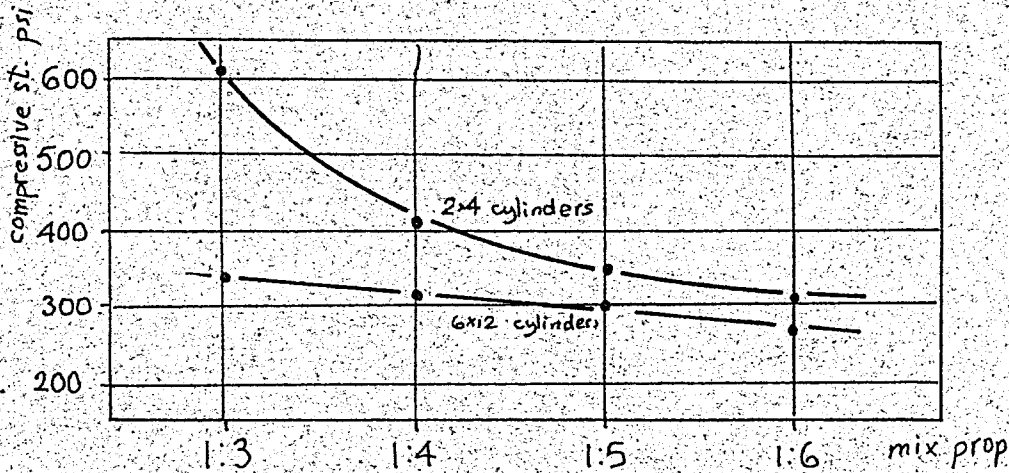


FIG. (6). RELATION OF MIXES TO COMPRESSIVE STRENGTH

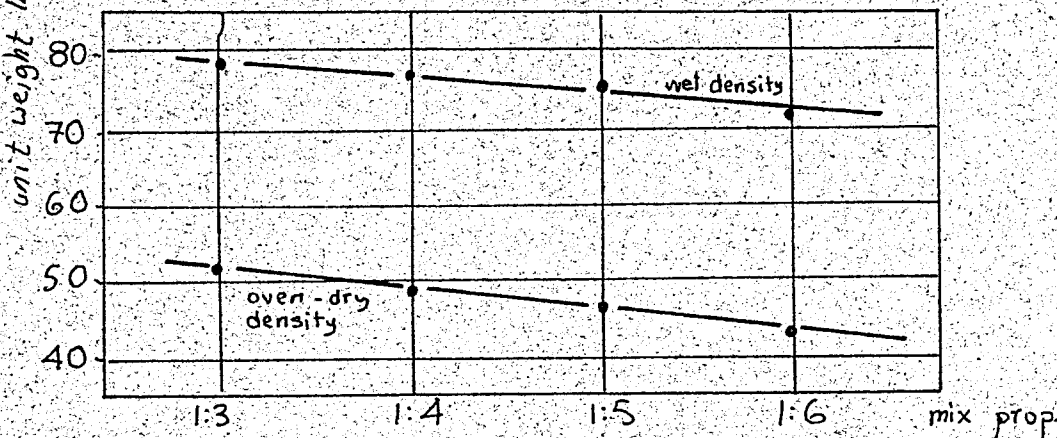


FIG. (7). RELATION OF MIXES TO UNIT WEIGHT

C. Tensile Strength:

General: To determine the tensile strength of concrete, the cylinder-split test was used. The 6x12 cylinders which were used in determining the compressive strength of lightweight concrete were also tested in the cylinder split test procedure. The method of test was similar to the method that Hanson (11) described in his article.

Apparatus: Universal Testing Machine

Procedure: The samples were put under the machine and compressive force was applied from the sides of the cylinders along one generatrice. The load which caused failure was determined, and the tensile strength was calculated from the formula:

$$f'_{sp} = \frac{2P}{\pi DL}$$

where P is the magnitude of the load, f'_{sp} is the uniform tensile stress, and D and L are the cylinder diameter and length respectively.

Results: The results are shown in table (15) and in fig (8)

type	mix	P, lb	f'_{sp} psi	kg/cm ² f'_{sp}
C	1:3	8400	70	5.1
	1:4	5440	49	3.5
	1:5	5580	49.5	3.6
	1:6	4320	38	2.75

TABLE (15). TENSILE STRENGTH TEST RESULTS (split-cylinder)

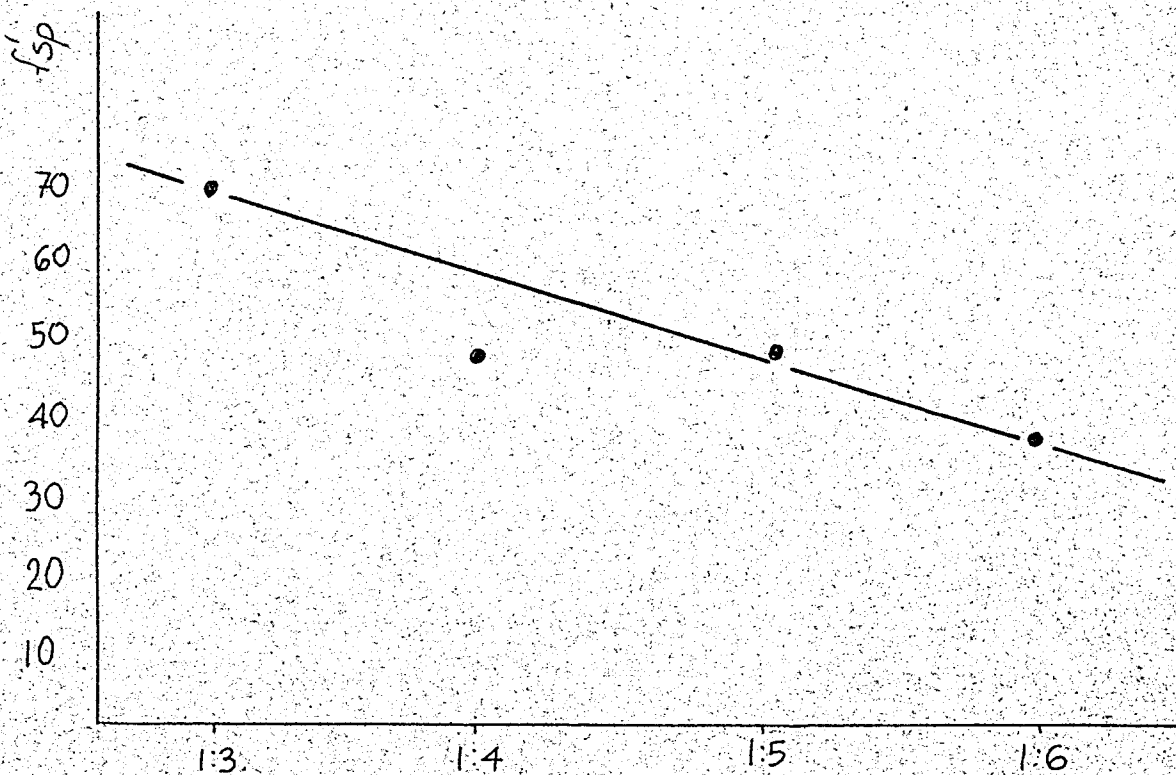


FIG. (8) SPLIT-CYLINDER TENSILE STRENGTH VS. MIX PROPORTIONS OF TYPE C CONCRETE

Each point represents a single test result.

D. Flexural Strength:

The Flexural strength tests were carried out according to the third point loading procedure as described in ASTM C 78-49. The dimensions of the beams were 6''x3''x12'', the middle figure, namely the height of the beams, varied between 2 3/4'' and 3 1/4'' from sample to sample. The loads which caused failure were recorded and then, the flexural strengths were calculated by dividing the moment at the middle portion of the beam by the section modulus of the beam. (15)

Results are presented in table (16) and fig. (9).

type	mix	P, lb	R, psi	R, kg/cm ²
C	1:3	2580	129	9.4
	1:3	2470	105	7.8
	1:4	2440	116	8.6
	1:4	2260	69	5.0
	1:5	2340	71	5.3
	1:6	2280	53	4.0
	1:6	2380	72	5.4

TABLE (16) . FLEXURAL STRENGTH TEST RESULTS

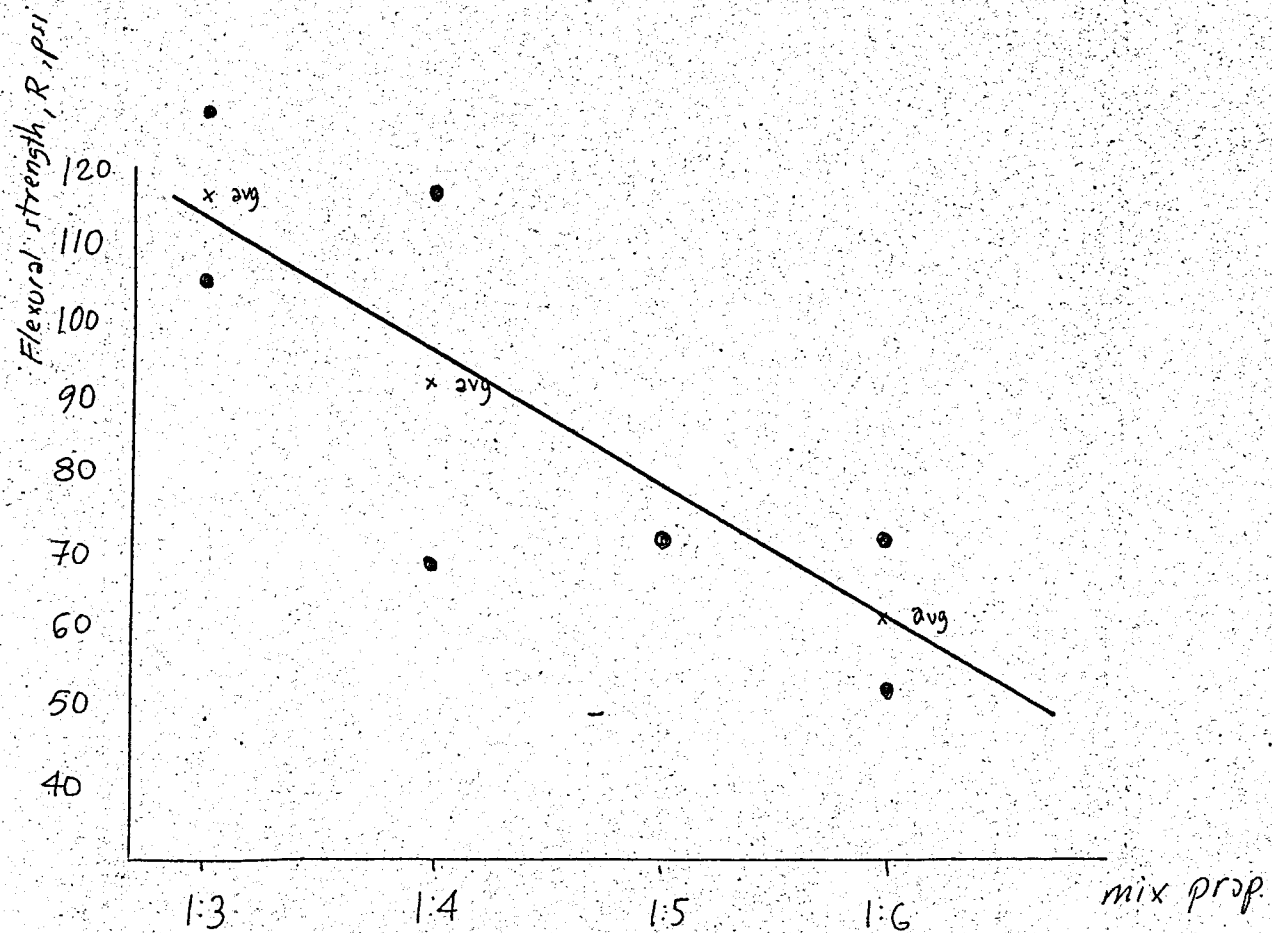


FIG (9) . FLEXURAL STRENGTH VS. MIX PROPORTIONS

Each point represents a test result.

IV. DISCUSSION OF TEST RESULTS

A. Relation of Compressive Strength to Unit Weight:

As stated in Part I, section V B, the compressive strength is directly proportional to the unit weight. When unit weight increases the strength increases. This is shown in the following table (17).

type	mix	oven-dry unit weight		wet density		Compressive st. 2x4 cylinders	
		lb per cu ft	kg/m ³	lb/cu ft	kg/m ³	psi	kg/cm ²
C	1:3	51	860	77	1300	624	46
	1:4	48.5	800	76	1280	414	30
	1:5	46.2	771	75	1260	350	25.5
	1:6	42.7	715	72	1210	304	22

TABLE (17). RELATION OF COMPRESSIVE STRENGTH TO UNIT WEIGHT

It is also seen that the unit weight and the compressive strength decreases as cement content in the concrete decreases.

In type B concrete the unit weights are much higher than in type C and accordingly the compressive strengths are higher.

B. Relation of Large Cylinder Compressive Strength to Small Cylinder Compressive Strength:

As stated by Troxell and Davis (22) and by Murdock and Kesler (18) the compressive strength of a specimen varies with the size and L/D ratio of the test specimens. When the specimen is large its compressive strength is less, or when L/D ratio is high, for example, 2, the strength is less than the strength of a cylinder having a L/D ratio equal to 1. These statements are given for ordinary gravel concrete, but qualitatively they hold true for lightweight aggregate concrete also. In the table from Troxell and Davis' Book (22) table (18), the effect of size of compression specimen on indicated strength of concrete is given.

Size of cylinder	relative compr. strength, %
2 x 4	109
3 x 6	106
6 x 12	100
8 x 16	96

TABLE (18). SIZE EFFECTS OF CYLINDERS.

The specimens used throughout our experiments for compressive strength had always an L/D ratio of 2, therefore there is no need for a reduction for the effect of L/D ratio. In our case the relative compressive strengths are shown in tables (19) and (20).

Mix	Compress. str. of 2x4 cyl. psi	Compressive str. of 6x12 cylinder, psi	Relative compressive strength of 2x4 cylin. if 6x12 cylin. is 100
1:3	624	348	190
1:4	414	320	130
1:5	350	305	115
1:6	304	265	115

TABLE (19). RELATIVE COMPRESSIVE STRENGTH FOR TYPE C CONCRETE

Mix	Compressive strength in psi		Relative compr. strength of 2x4 cy. if 6x12 is 100
	2x4 cyl.	6x12 cyl.	
1:3	1930	1230	156
1:4	1350	1082	125

TABLE (20) RELATIVE COMPRESSIVE STRENGTH FOR TYPE B CONCRETE

As it is seen from the tables (19) and (20) the relative strengths of lightweight concretes decrease as the compressive strength itself decreases. But in the case of ordinary gravel concrete this is not true. The values given in table (18) are valid for all compressive strengths of gravel concrete.

Therefore one may state that the effect of size of test cylinders is considerably important, in the case of lightweight aggregate concretes, or true to say in the case of Perlite concrete.

If one plots, the compressive strength of 2x4 cylinders as the abscissa and the compressive strength of 6x12 cylinders as the ordinate, the parabolic relation

$$y^2 = 240 x$$

approximately holds true. Where y is the compressive strength of 6x12 cylinders and x is the compressive strength of 2x4 cylinders. The curve of the above mentioned parabola is plotted in the fig. (10) with the actual curve of the experimental results,

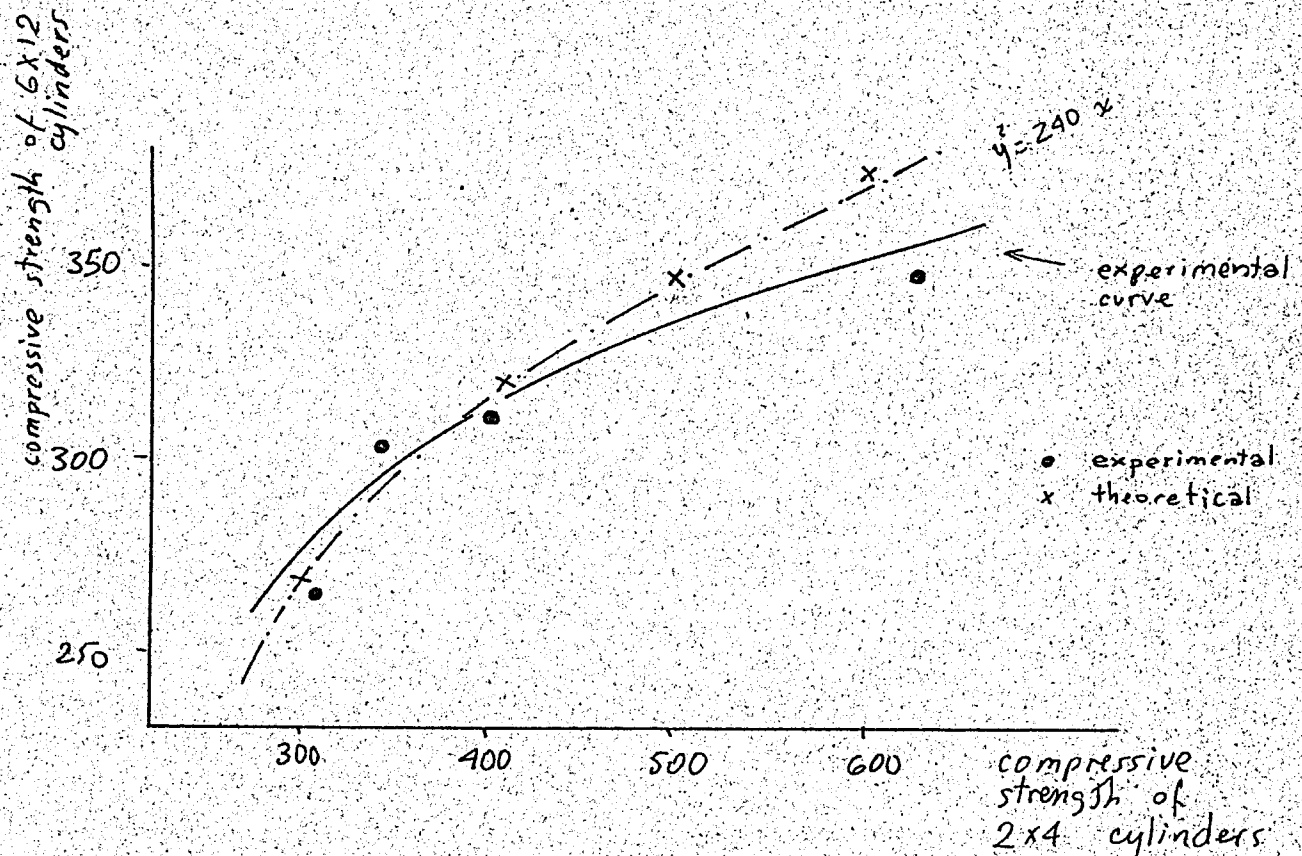


FIG (10) . COMPRESSIVE STRENGTH OF 2x4 CYLINDERS
VS. COMPRESSIVE STRENGTH OF 6x12 CYLINDERS

C. Relation of Compressive Strength of Concrete Made from Coarse Perlite to the Concrete Made From Fine Perlite:

Before discussing this, it would be useful to know the gradation of coarse Perlite, from which type A concrete is made. Table (21) gives values for gradation of coarse Perlite.

Size Designation	Percentages (by weight Passing				
	No.4	No.8	No.16	No.50	No.100
Sample of Fine aggregate	100	99.62	96.4	47.5	18.4
Sample of Coarse aggregate	99.68	99.26	87.1	28.40	4.5

TABLE (21). GRADATION OF PERLITE SAMPLES

In gravel concrete, the failure occurs as a result of breakdown of bond between the matrix itself, not as a result of the fracture of the aggregate (12). But in lightweight aggregate concrete the fracture of the aggregate causes the failure of concrete, therefore when the aggregate size becomes larger the concrete becomes weaker. This is well-supported by the test results. Although the gradation is nearer to the limits of the ASTM C 330-53T, the coarser Perlite is weaker in compressive strength. The comparison of the compressive strengths is presented in table (22).

mix	Compressive strength in Psi		
	type A		type B 2x4 cylinders
	2x4 cylinders	6x12 cylinders	
1:3	1930	1230	1450
1:4	1350	1082	1218

TABLE (22) COMPARISON OF COMPRESSIVE STRENGTHS OF TYPE A AND TYPE B CONCRETES

D. Relation of Tensile Strength and Flexural Strength to Compressive Strength:

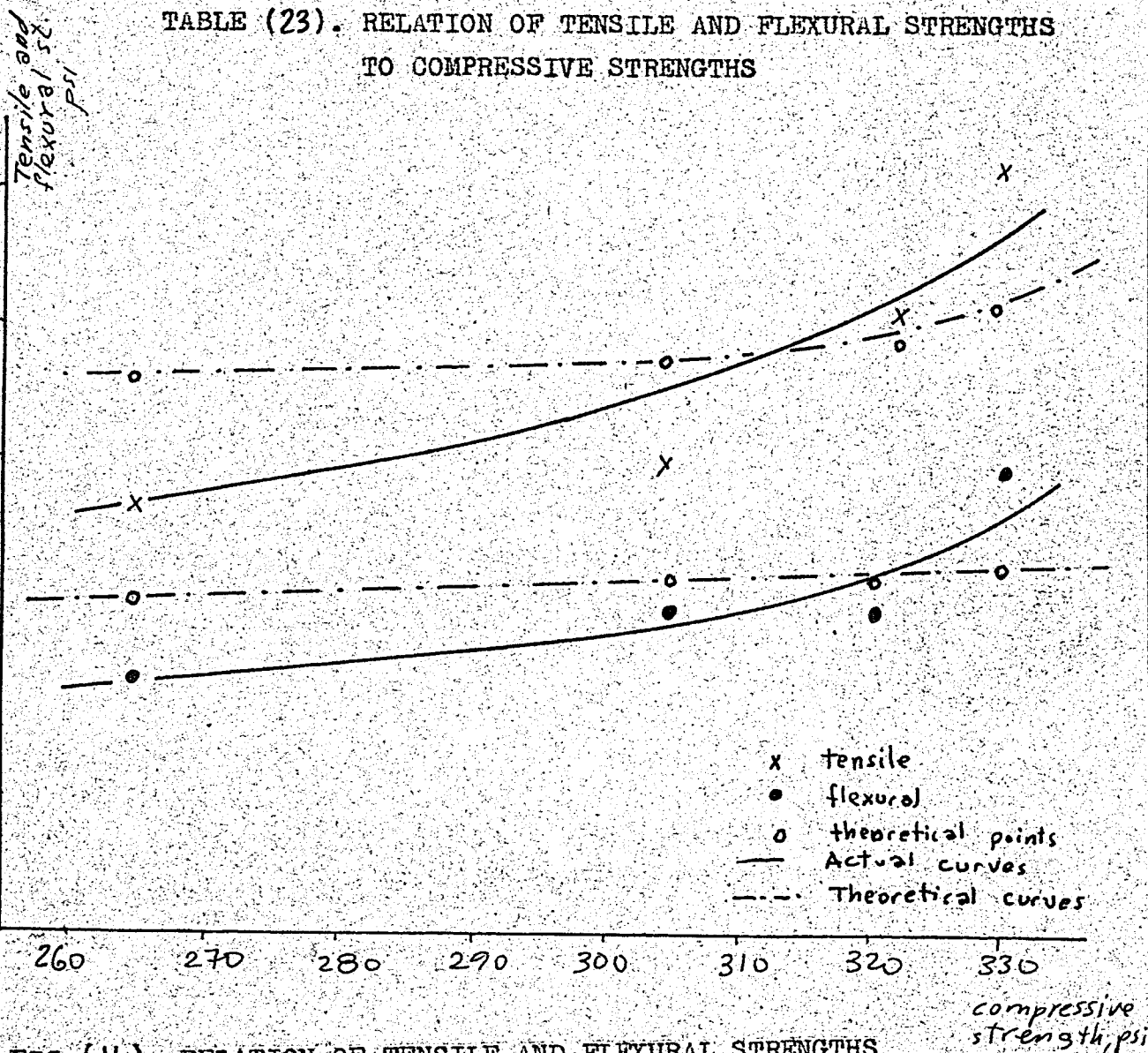
In this section, the results of only type C concrete are going to be discussed. The coefficient k, which was discussed in Part I Section V D, comes out to be different for each mix proportion of this type. When the average is taken, k is equal to 3 for split cylinder and 5 for flexural strength relation to compressive strength. In reference (12) these values are 5 and 8 respectively. Therefore the found values for perlite are less than the general values for structural light-weight concretes. These values are compared with each other in the following table (23). Also the relation of compressive strength to flexural and tensile strengths are given in fig.(11)

mix	compr. st. u , psi	tensile st. f'_{sp} , psi	$k = \frac{f'_{sp}}{\sqrt{u}}$	k from reference 12	$\alpha_1 = \frac{R}{\sqrt{u}}$	α_1 from (12)
1:3	348	70	3.75	4.5-6	6.2	8
1:4	320	49	3	4.5-6	5.2	8
1:5	305	49.5	2.82	4.5-6	4.1	8
1:6	265	38	2.32	4.5-6	3.8	8

$k_{avg} = 3$

$\alpha_{1,avg} = 5$

TABLE (23). RELATION OF TENSILE AND FLEXURAL STRENGTHS TO COMPRESSIVE STRENGTHS



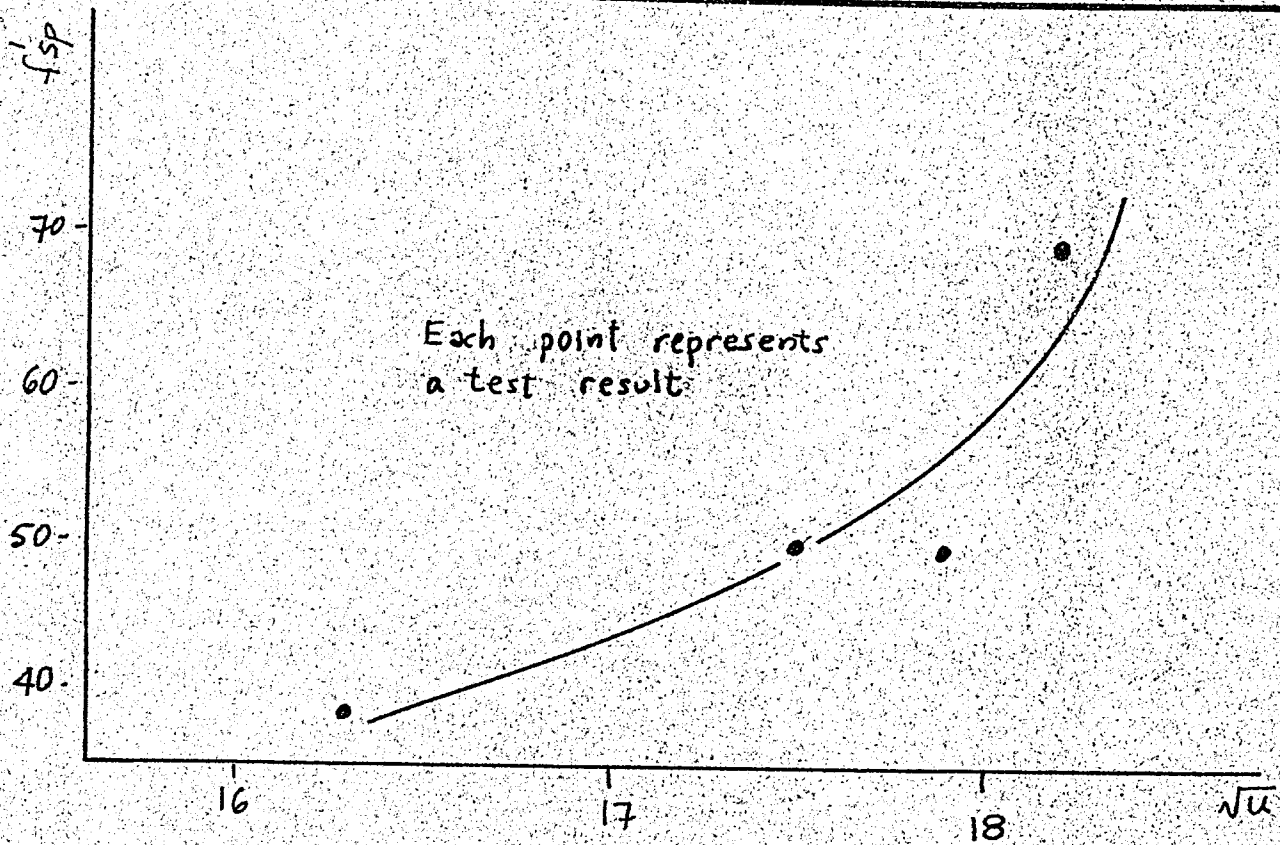


FIG. (12) RELATION OF TENSILE STRENGTH TO SQUARE ROOT OF COMPRESSIVE STRENGTH

In reference (11) it was stated that the tensile strength of lightweight aggregate concrete is about 60 percent of the Modulus of Rupture. In our case, the percentage varies as the mix proportions vary. For 1:3, 1:4, 1:5 and 1:6 mixes the percentages of tensile strength to Modulus of Rupture are 60, 53, 70 and 61 respectively. The average is 61 percent, therefore this fact has been verified by the tests so far.

E. Effect of Water Content to Strength:

The effect of water content to the strength of lightweight concrete is considerable. As in the case of gravel concrete, the strength decreases as the water cement ratio increases. But in this study, the term water cement ratio is avoided, for the real

water cement ratio can not be determined, since the absorptive value of Perlite is unknown. Only the apparent water content will be referred throughout the section.

Type C and type D concrete are compared in table (24). Type D concrete has the same preparing conditions as type C but its water content is lower than type C. The flow test made by the flow table gave zero flow for type D concrete, whereas a flow of 1/2 times the diameter was obtained by type C concrete. Although type D is a concrete which should not be used according to the specifications, it has a considerably great strength than type C due to less amount of water used.

In table (24) the results are presented.

type	mix	compr. str. psi	tensile str. psi	flexural str. psi	Apparent w/c kg/lit
C	1:3	348	74	117	1.20
	1:4	318	48	92.3	1.30
D	1:3	531	78.4	90.3	0.84
	1:4	488	72.9	63.3	0.92

TABLE (24). COMPARISON OF TYPE C AND TYPE D CONCRETE

As it is seen from the table the water content is considerably less for type D concrete and the compressive strength is considerably high. The compressive strength of type D is 153 percent higher than type C.

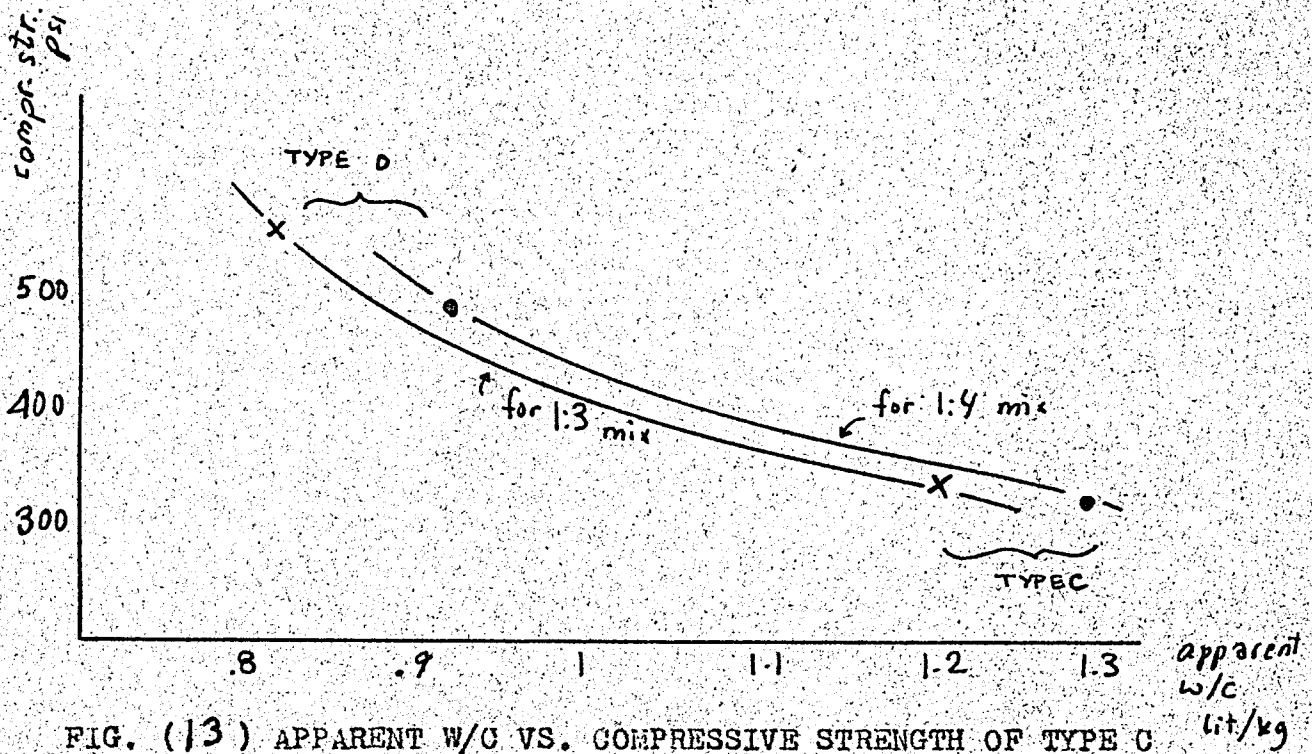


FIG. (13) APPARENT W/C VS. COMPRESSIVE STRENGTH OF TYPE C AND D CONCRETES

F. Comparison of Strength of Perlite Concrete with The Strength of Perlite-Sand Concrete:

When sand is introduced into the Perlite concrete the unit weight and the strength increase. Here, results of Ö.Erdem (20) will be compared with the strength of Perlite-concrete obtained in our study. The sand-perlite concrete is referred as type E concrete in this study. The comparison of type C and E concretes are shown in table (25).

Type	mix	compressive strength psi	tensile strength psi	Flexural strength psi	Oven-dry density	strength weight
C	1:3	348	70	116	51	6.8
	1:4	320	49	93	48.5	6.6
	1:5	305	49.5	71	46.2	6.6
	1:6	265	38	62	42.7	6.2
E	1:3:1	562	86.5	128.5	73.5	7.65
	1:3:2	960	141	251.5	91.8	10.4
	1:3:3	1130	146	261.5	98.8	11.5
	1:4:1	841	102	197	74.3	11.3
	1:4:2	1070	141	261	91.2	11.7
	1:4:3	462	75	161	102.3	4.5

TABLE (25) COMPARISON OF TYPE C AND E CONCRETES WITH RESPECT TO THEIR STRENGTH

In type E concrete two factors affect the strength of the concrete. One is the increasing unit weight, the other is the decrease in the cement content. As one goes from 1:3:1 to 1:4:3 mix, the strength shows a variation, the highest strengths obtained at 1:3:1 and 1:4:2 mixes, being 1130 psi and 1070 psi, respectively. At the 1:4:3 mix strength decreases, because the

effect of the decrease in the cement content governs. But, nevertheless, the difference in the strengths of the two types of concretes is noticeably high. Comparing 1:4 mix with the 1:3:1 mix, one observes that the density of the latter is only 150 percent more, but the compressive strength is 175 percent and tensile strength is also 175 percent of the type C concrete. This is more pronounced in comparing 1:6 mix with 1:3:3 mix. The density of type D being 230 percent of that for type C, the compressive strength is 425 percent, and tensile strength is 384 percent.

When observing the values at the table (25), one comes to the conclusion that, according to the definition of lightweight concretes in Part I of this paper, only 1:3:3 and 1:4:2 mixes can be considered as structural lightweight concretes, developing stresses more than 1000 psi and having unit weights less than 115 psi.

The values in the fig. (14) indicate that, 1:4:2 mix is the best for structural use, its strength is high enough also the unit weight is low compared to 1:3:3.

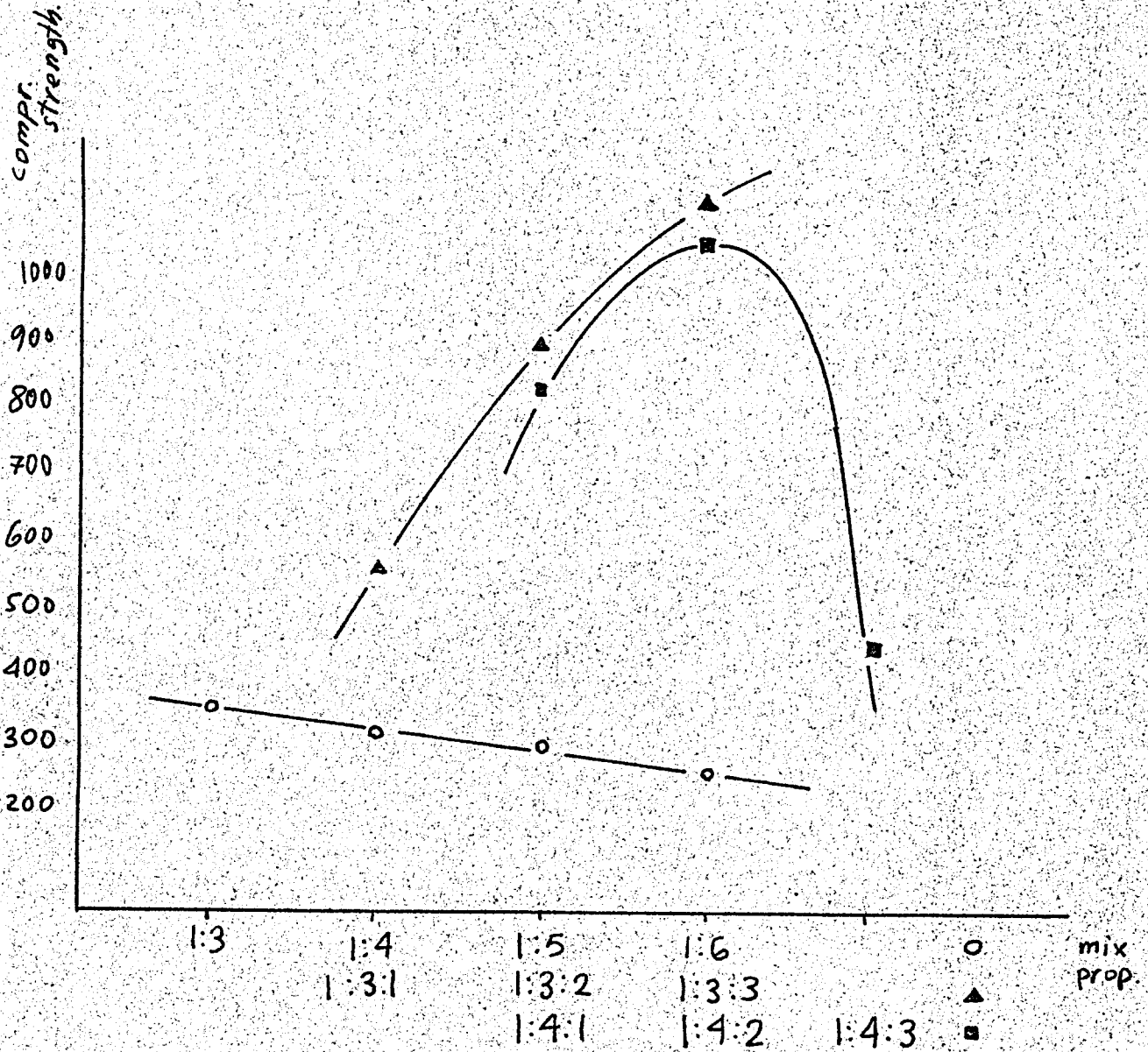


FIG (14). RELATION OF COMPRESSIVE STRENGTHS TO MIX PROPORTIONS

V. CONCLUSION

In the theoretical part of this study, the structural lightweight concrete was defined as, the concrete weighing not more than 115 lb per cu ft, and one developing a compressive strength of not less than 1000 psi. According to this definition the obtained test results indicated that, Perlite Concrete was not a structural lightweight concrete in ordinary conditions. Because none of the perlite-cement mixes mixed in the concrete mixer, had developed a compressive strength more than 624 psi when tested at the age of 28 days. This 624 psi was the result of the compression test on 2 in. by 4 in. samples, hence when 6 in. by 12 in. samples were tested the compressive strength decreases further.

Throughout the tests, structural lightweight concrete quality was reached only twice. Once when the concrete is mixed in the paddle type, mortar mixer, and the second time when sand was added to a mix of cement and perlite.

In the case of the concrete which was mixed in the mortar mixer, the strength was 1900 psi for 1:3 mix and 1350 psi for 1:4 mix. This is primarily due to the fact that very good mixing is done in the paddle type mixer. In order to provide a reasonable consistency either water should be added or the mixing procedure should be prolonged. In the paddle type mortar mixer, the consistency could be obtained by mixing well, therefore the value of water cement ratio was kept low and this resulted in the increase of strength. The apparent water-cement ratio was 0.86 in this case, and 1.2 for the type C concrete, mixed in the normal concrete mixer. Type C concrete could not be mixed to such a degree in the concrete mixer, so more water was needed to maintain a reasonable consistency, hence the strength of it had a lesser value.

In the case of type E concrete, the added sand increased the unit weight of the concrete and also the strength was increased, because normally strength increases when unit weight increases. (2) Even in the sand-perlite-cement series only two of the mixes provided an adequate strength for the limits. The mixes 1:4:2 and 1:3:3 were the only ones to pass beyond the limit of 1000 psi.

Also the test results of type A concrete, when compared to type B, indicated that when the particle size of Perlite increased the strength was decreased. This, also has been stated in the first part of this study in section VC. Because in the case of lightweight concretes the failure occurs because of the fracture of the aggregates, the size of the aggregates affect the strength in the respect that, when aggregates become larger they are more liable to be fractured.

The α value for the Perlite concrete was also lower than a typical lightweight concrete. Instead of 8 it was found to be 5 for Perlite.

When observing all the test results one concludes that, normally, Perlite concrete can not be considered as a lightweight structural concrete. One can obtain acceptable values for the compressive strength only by mixing the concrete thoroughly, or by adding sand to the mixes. First case can not be obtained in site conditions. The latter is always possible, but to proportion the cement-sand-perlite concrete is a subject to another study for it is not within the scope of this one. The size effect to compressive strength and the effect of W/C ratio need more investigation, because these are different behaviours of Perlite concrete than normal concrete. When further investigations will be made on these subjects, then this subject can be considered to approach completion.

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