

THESIS

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BEBEK, ISTANBUL

PAGE

FOR REFERENCE

NOT TO BE TAKEN FROM THIS ROOM

AN INVESTIGATION OF THE

ELASTIC PROPERTIES OF CEMENT -

LIGHTWEIGHT AGGREGATE (PERLITE)

- AND SAND MORTARS

By

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I N T R O D U C T I O N

Although much importance has been given to lightweight aggregates and lightweight concretes in recent years, this does not imply that they are new materials of construction. It is reported in a paper by Washa (1) that lightweight aggregate was first used by Romans who embedded large pieces of pumice in the walls and domes of some of their larger buildings. From the fall of the Roman Empire until the present century only small amounts of lightweight aggregate was used.

The Germans started using slag in 1822, and slag as coarse aggregate was first used in the United States in 1890. The use of cinders from coal-burning furnaces followed it. Then the granting of the Haydite patent in 1918 brought another lightweight aggregate into the American Market (1). During the past 30 years other materials such as pumice, vermiculite, and perlite have been widely used. Cellular or foam concretes have been developed and have had their greatest use in Europe. The development of lightweight industry after the first World War in the United States and in Europe is surprising (2).

An important factor that has contributed to the increasing use of lightweight aggregate is this: in the latter part of the nineteenth century, the introduction of structural steel and structural concrete brought a radical change in building design. The old method of designing buildings to carry loads by means of heavy load-bearing walls was discarded, and another method came into use. In this method, the load was carried by a framework of beams and

nd columns, Lightweight aggregates and this new design method made possible the construction of skyscrapers and long-span bridges (1). Saving in wall and floor weight was extremely important, but heat insulation problems arisen by using thin walls must have been considered, too, and lightweight aggregates also helped to solve this problem.

Another important factor is that the use of lightweight aggregate brought an appreciable amount of saving in money expenses due to its light weight, high sound-absorbing and heat-insulating characteristics.

With the growth in the number and the productive capacity of lightweight aggregate plants, and the increasing demands of designers for light weight coupled with high strength, appreciable fire resistivity, good insulating capacity and acoustical properties, lightweight aggregates are finding an important position in the structural, insulating, and masonry concrete fields for precast and cast-in-place applications.

The growing interest in lightweight aggregate concrete has created a demand for reliable design data beyond a knowledge of its weight, its insulating and acoustical properties. Therefore lots of investigations were undertaken to compare the performance of lightweight and normal-weight concretes so that engineers familiar with standardized design procedures would have would have representative values for use with lightweight concretes.

Although many investigations are made on lightweight concretes, still there is not an over-all theory concerning all lightweight aggregates and lightweight concretes. This is mainly due to wide variations in the properties of concretes prepared by using different aggregates in different ways. Therefore most of the com-

panies use their own specifications for their specific aggregates and their own method of conducting concreting.

Lightweight aggregate can be considered as a new concept in Turkey, and the industry of its develops very slowly. This slow development can be attributed to some hindering factors both economical and technical, such as the difficulties in importing expansion furnaces, the absence of a regular magazine informing the interested persons of the latest news and developments, lack of advertisement, economical unrest and troubles, the inadequate help of the other branches of industry, and lack of intensified experimental work which can give reliable results, expressing the various characteristics of different lightweight aggregates and lightweight concretes which are going to be used for various purposes in various building applications.

The first attempt in Turkey was made by Betocel firm in 1959, by using lightweight cellular concrete in various building applications. Increasing insulation problems together with needs for better sound absorptivity, better acoustical properties, and discoveries of rich perlite ores gave birth to other firms like Hima, Perlitas, and Perliton. Besides all these, natural lightweight aggregates like the ones from Kayseri have been in use also for many years.

The C.E. Department of the Robert College School of Engineering has undertaken an investigation, considering that this field still needs a thorough study. Emphasis is put on general properties (3), insulating and thermal properties (4), strength properties (5), and on elastic properties of lightweight concretes with particular reference to perlite lightweight aggregate.

This paper is a part of this investigation program of Robert

College.

Although many investigations are carried out on concretes made with lightweight aggregates, little is done on concretes prepared by using lightweight aggregate together with normal aggregate, and in this paper the properties of cement-lightweight aggregate (perlite)- and normal aggregate (sand) mortars are investigated.

This work consists of two parts:

I- Theoretical Part, dealing with survey of literature on lightweight aggregates and lightweight concretes, lightweight aggregate production and uses in Turkey, and survey of literature on elastic properties of lightweight concretes.

II- Experimental Part, dealing with tests to determine the elastic properties of cement-perlite-sand mortars, results of tests, and discussion of these results, comparisons, and conclusions.

The major conclusions can be expressed as follows:

- f'_c , f_{sp} , density, modulus of rupture, initial tangent modulus, and secant modulus at $0.5 f'_c$ for cement-perlite and cement-sand mixes decrease linearly as aggregate proportion is increased.

- For cement-perlite-sand mixes, the values of the above properties increase with addition of sand, reach a maximum value at a certain proportion, and then begin to decrease.

- The following relations were obtained between various properties:

$$R = 7.0 \sqrt{f'_c}, f_{sp} = 3.6 \sqrt{f'_c}, f_{sp} = 0.54 R, \text{ and } E = 27.0 w^{\frac{3}{2}} \sqrt{f'_c}$$

where R = modulus of rupture, psi

f'_c = compressive strength, psi

f_{sp} = cylinder splitting strength, psi

E = initial tangent modulus, psi

and w = density, pcf.

- Cement-perlite mixes, and 1-3-1, 1-4-1 cement-perlite-sand mixes can be used as insulating lightweight concrete; and 1-3-2, 1-3-3 and 1-4-2 mixes as structural lightweight concrete, 1-3-3 being the best mix.

- σ - ϵ relation gives a flatter curve for lightweight aggregates than for normal aggregates.

- The value of $n = E_s/E_c$ for our structural mixes is about 28.0 .

- The modulus of elasticity for insulating mixes ranges between 220,000 to 460,000 psi for a compressive strength range of 260 to 560 psi, and between 880,000 to 1,100,000 psi for structural mixes for a range of compressive strength of 960 to 1130 psi.

PART - 1

THEORETICAL

A - LITERATURE SURVEY ON LIGHTWEIGHT AGGREGATES AND
LIGHTWEIGHT CONCRETES

LIGHTWEIGHT CONCRETES

Definition and Classification :

Lightweight concrete is defined by Davis and Kelly as " concrete having a unit weight of less than about 120 pcf." (7)

Lightweight concrete can be produced by the use of air or lightweight aggregate or combination of both. According to these factors causing light weight, Washa classifies lightweight concretes into two main groups: (1)

- 1- Cellular or foam concrete,
- 2- Lightweight aggregate concrete.

1- CELLULAR OR FOAM CONCRETE

Valore defines cellular concrete as "a concrete weighing from 10 to 100 pcf and having a homogeneous void or cell structure." (8). This type of concrete is usually made of portland cement, water, and foaming agent, and may contain lime, silica, fly ash, expanded shale, volcanic ash, or pumice dust. A large amount of air, usually exceeding 25 %, in the form of small bubbles, is incorporated to reduce weight (1).

Valore proposed to divide cellular concretes into two major groups: (8)

- a- Moist cured cellular concretes,
- b- Autoclaved cellular concretes.

Properties of cellular concretes

Table (1) gives the general properties of cellular concretes

Cellular concretes weighing as little as 10 or 20 pcf may be used for thermal insulation. Densities of load bearing cellular concretes may range from 35 to 100 pcf, "Fill" concrete form a third category; insulation is combined with modest compressive strength in roof and floor fills (8).

Compressive strengths of cellular concretes are functions of density, and ranges from 250 to 1000 psi for 30 pcf, 400 to 2000 psi for 40 pcf, and 800 to 3000 psi for 50 pcf densities.

Property	Cellular Concrete	Normal Concrete
Dry Specific Wt, pcf	20-60	144-156
f'_c , psi	100-2000	2000-5000
Mod. of Rupt., psi	50-500	11-23 f'_c
E , psi $\times 10^3$	70-500	1500-5500
Water abs by volume	20-45 %	
Drying shrinkage, %	0.01-0.15 Autoc 0.05-0.50 Moist	0.032-0.082
Coef. of thermal expans. Per degr. F $\times 10^6$	4.5-7.0	5.37-6.77
Ther. Cond, K, Btu/ft ² /hr/F	0.5-2.0 /in	0.8-1.7/ft

Table (1) - Properties of cellular concretes (1).

(The same properties are also given for normal concretes for comparisen.)

Flextural strength is approximately 1/5 to 1/3 of the compressive strength. The relation between compressive strength and flextural strength obtained by Graf for autoclaved cellular concretes of various compositions and cell-forming processes is shown in Fig.(1).

(9)

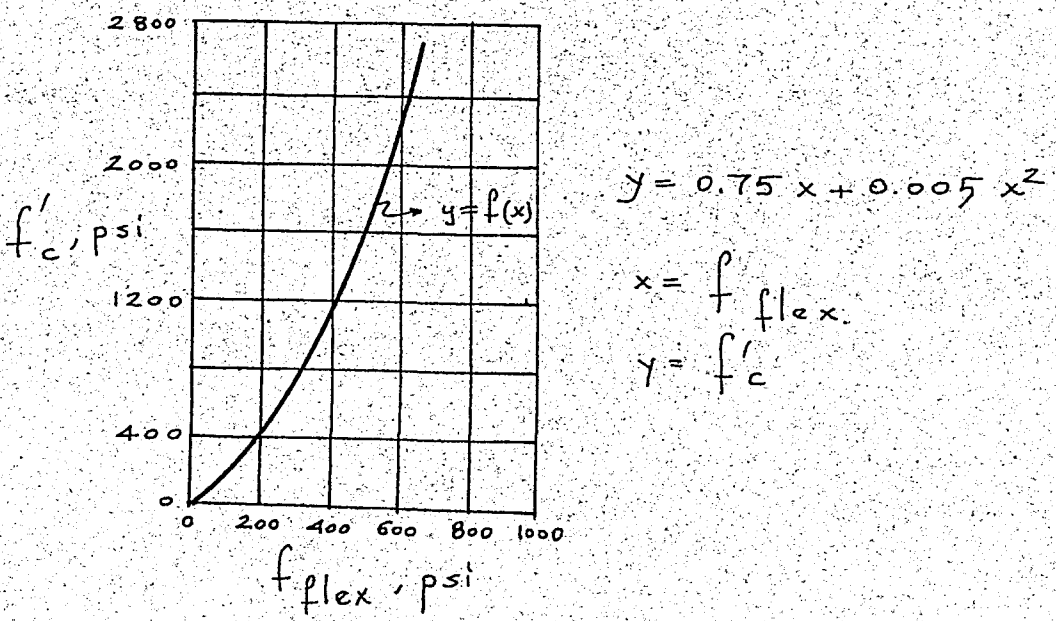


Fig (1)- Relationship of flextural to compressive strength for autoclaved cellular concretes made by various processes (9).

Average values for a static modulus of elasticity of Swedish cement-silica cellular concrete are reported as in Table (2).

(9)

Density, pcf	f'_c , psi	E , psi $\times 10^3$
32.4	360	195
40.5	705	324
47.4	820	376
51.1	985	452

Table (2)- Relation between density, compressive strength, and modulus of elasticity of Swedish cement-silica cellular concret

2- LIGHTWEIGHT AGGREGATE CONCRETE

a) Lightweight Aggregates

Before investigating the properties of lightweight aggregate concretes, a general consideration will be given to lightweight aggregates.

ACI Building Code defines lightweight aggregate as "aggregate having a dry loose weight of 70 pcf or less. (10)

Table (3) shows the general classification of lightweight aggregates.

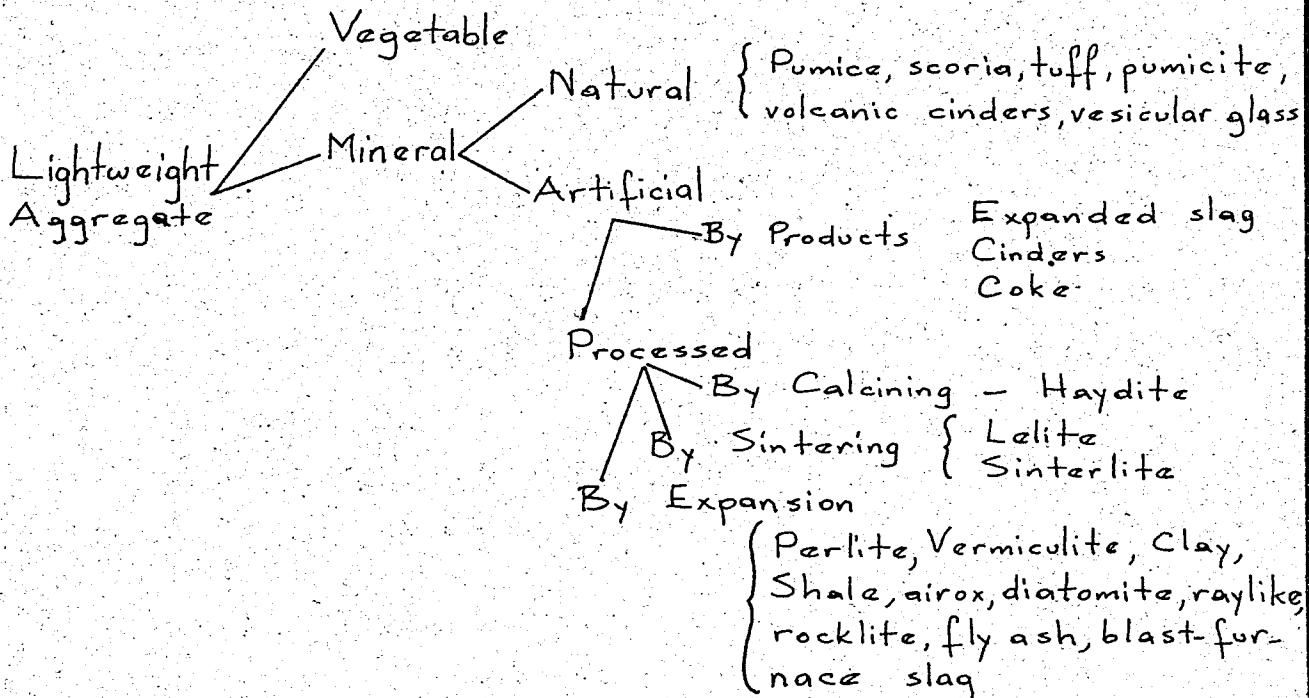


Table (3)- Classification of lightweight aggregates. (1), (3),

(7), (11)

Lightweight aggregates can be considered under two headings; vegetable and mineral (1). The former have not been as widely used as the latter.

In the following survey the emphasis is put on artificial mineral lightweight aggregates, since they are the ones most widely used for lightweight concretes.

Properties of lightweight aggregates :

Washa summarizes the desirable properties of lightweight mineral aggregates as follows (1):

- They should be uniform in composition and properties,
- They should be suitably graded for their intended use,
- They should have a low specific weight, and the desired special properties associated with light weight, such as high thermal insulation, and sound-absorption,
- They should have a large number of small, well dispersed internal voids,
- Individual pieces should have adequate strength and should be firm and hard enough to withstand handling and mixing without size breakdown,
- The particles must bond well with the cement paste and be chemically inert with respect to reactions with both cement and reinforcing steel,
- They should have good resistance to weathering, moisture, insects, and fungi.

In Table (4), Washa summarizes the properties of various classes of lightweight mineral aggregates (1).

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Aggregate	Sp. wt., pcf	Bulk sp. gr.	Abs, % by wt.	Crushing Str. at 2" Compac, psi
Exfoliated Vermic	6-12	0.9-1.3	20-35	35-45
Expanded Perlite	4-16	0.7-1.1	10-50	60-400
Expanded Slag	30-70	1.2-2.4	5-25	150-2,000
Exp. shale, clay	35-75	1.1-2.2	5-20	2,000-16,000
Sintered fly ash	40-60	1.7-2.1	8-15	1,000±
Pumice	25-60	1.0-1.7	8-50	1,000-2,000

Table (4)- Properties of lightweight mineral aggregates (1)

They are representative only, and they do not include all possibilities. It should be realised that the spread in the values may be due to differences in source of raw material and method of manufacture.

Properties of various lightweight aggregates, as reflected by those of the resulting concretes, vary greatly. For example, the strength of concrete made with expanded shale and clay is relatively high and compares favourably with that of ordinary concrete. Pumice, scoria, and some expanded slags produce a concrete of intermediate strength; perlite, vermiculite, and diatomite produce a concrete of very low strength.

The insulation properties of the low-strength concrete, however, are better than those of the heavier, stronger concrete.

b) Lightweight Aggregate Concrete

Davis and Kelly separate lightweight concretes into four principal types (7):

1- Structural.- Monolithic concrete for buildings, floors, roofs, partitions, bridge decks, ships, etc. The main purpose is to reduce weight and thus to economize in design.

2- Fireproofing.- Overcoating for structural steel.

3- Masonry Units.- Precast units for walls and partitions, either load-bearing or non load-bearing. Light weight and moderate strength are requisite; good insulating and sound-deadening properties are desirable.

4- Insulation or Fill.- Monolithic lightweight concrete for overcoating and/or forming partitions and walls or for floor and roof fills. Lightness and a high degree of insulation are desired; strength is not important.

Grading requirements for lightweight aggregates for each type of lightweight aggregate concrete are represented in ASTM Designations C 331-53 T (for concrete masonry units), C 332-54 T (for insulating concretes), and C 330-53 T (for structural concrete) (12). Table (5) and Table (6), taken from ASTM Specifications (12), give the types of lightweight aggregates and unit weight requirements for each type of lightweight aggregate concrete.

Size Designation	Dry Loose Weight, max, lb per cu ft.		
	Concrete Mas. Units	Insulating Concrete	Structural Concrete
Fine Aggreg.	70	70	70
Coarse Aggreg.	75	75	75
Combined	65	65	65

Table (5) - Unit weight requirements for lightweight aggregates (12)

Concrete Mas. Units	Insulating Concretes	Structural Concretes
<p>- Aggregates prepared by expanding, calcining, or sintering products such as blast furnace slag, clay, diatomite, fly ash, perlite, shale, slate, or vermiculite.</p> <p>- Aggregates prepared by processing natural materials, such as pumice, scoria, or tuff.</p> <p>- Aggregates consisting of cinders derived from the combustion of coal or coke.</p>	<p>Group. I. - Aggregates prepared by expanding products such as perlite or vermiculite.</p> <p>Group. II. - Aggregates prepared by expanding, calcining, or sintering products such as blast furnace slag, clay, diatomite, fly ash, shale, or slate.</p> <p>- Aggregates prepared by processing natural materials, such as pumice, scoria, or tuff.</p>	<p>- Aggregates prepared by expanding, calcining, or sintering products such as blast furnace slag, clay, diatomite, fly ash, shale, or slate.</p> <p>- Aggregates prepared by processing natural materials, such as pumice, scoria, or tuff.</p>

Table (6) - Types of lightweight aggregates used for lightweight concretes (12).

Properties of lightweight aggregate concretes:

Table (7), by Washa, summarizes the properties of lightweight aggregate concretes.

Investigations have shown that thermal conductivity of dry lightweight concrete varies with unit weight and lightweight aggregate type has little effect (13).

Tests to compare the properties of lightweight concrete and normal concrete showed that the ratio of flexural strength to compressive strength, creep, and shrinkage upon drying is greater for lightweight concrete than for conventional concrete (13), (14). Slump of lightweight concrete is about half of that of regular concrete (13), and the modulus of elasticity for lightweight concrete

is relatively low in the order of 2,000,000 psi for structural concrete, and 400,000 psi for insulating concrete.

Absorption of initially dry, porous lightweight aggregate during the concrete mixing period causing large changes in the consistency have been noted, and this necessitated the prewetting of such aggregate (14).

Property	Insulating	Masonry Unit	Structural
Dry spec. wt, pcf	20-80	65-100	65-115
f'_c , psi	50-1000	1200-3000	1000-5000
Mod. of Rupture, psi	15-150	200-450	150-500
E, psi $\times 10^3$	30-500	500-1500	400-2500
Water abs. by volume	15-50 %	10-18 pcf	5-30 %
Drying Shrinkage, %	0.05-0.50	0.02-0.14	0.04-0.15
Coef. of therm. exp. $\frac{1}{F \times 10^6}$	4.5-7.0	2.0-4.5	4.5-6.0
Therm. Cond., K	0.5-2.0	1.5-4.0	1.5-4.0

Table (7)- Properties of Lightweight Aggregate Concretes (1).

The advantages and disadvantages of lightweight concretes can be summarized as follows:

Advantages:

- Light weight causes a saving in structural steel, reduces the bearing area of the foundations, and decreases the expenses for concrete forms,
- Rough texture of surfaces have good acoustical properties,
- Light weight allows more distant markets and easier handling of precast slabs and blocks,
- High insulation values are obtained by numerous voids,
- Lightweight plaster has less tendency to crack and its resistance to heat makes it a good material for fireproofing structural steel.

Disadvantages:

They are the results of certain physical properties which make the lightweight aggregate concrete more advantageous compared with normal concrete.

- The aggregates are sharp and angular, and this tends to make concrete harsh and unworkable,
- The fines have a higher unit dry weight than the coarse aggregate and the method of manufacture produces an extremely dry material; both factors combine to make a product that segregates badly if not counteracted,
- The aggregates are highly absorptive and the rate of absorption is variable, making it impractical to use specific gravity values in batch proportion computations and creating a problem in maintaining uniform workability on the job,
- The aggregates are lighter than the concrete in which

they are used, causing coarse aggregate to float to the surface when improperly handled,

- The light weight of the concrete increases the normal concrete tendency to entrap air and form honeycomb,
 - Cost of raw material is higher, because of small facilities and the additional processing.
-

c) Perlite Aggregate and Perlite Concrete

Since all our tests are conducted on mortars prepared by using perlite aggregate, this and perlite concrete will be treated in more detail.

Perlite Aggregate:

Perlite is the mineralogical name for a volcanic, siliceous rock. When heated quickly, it expands with disruptive force and breaks into small expanded particles. Under properly controlled conditions, agglomerations of expanded particles remain bound together at their points of contact to produce an aggregate of high void content and extremely light weight. The unit weight may change between 8 to 16 pcf. The aggregate is used in the manufacture of concretes having a compressive strength of about 300 psi, for which the unit weight may be as low as 35 pcf (7). As a result, the aggregate is employed in concretes where a high degree of insulation, and good sound-absorbing and fire-proofing capacities are desired, and where low strengths are permissible.

Manufacture of perlite lightweight aggregate

The usual manufacturing process is as follows: after mined ores are subjected to preliminary drying and crushing, they are trucked to mills, and there rock is reduced and screened in size to a 16 mesh with a minimum amount passing a 100-mesh screen. After receiving perlite rock at expanding plants, it is introduced into expansion furnaces which produce perlite aggregate. Expanded aggregate should weigh 7.5 to 10 pcf. Furnace types generally recognized as most satisfactory include the horizontal rotary kilns, with a preheater and the stationary vertical kiln with a rotating co-current preheater (16).

Perlite Ores in Turkey

The main deposits of perlite ores are around Çanakkale, and Biga has the richest quarries of this region (3). Mining of this rock is begun in 1954. Lately, perlite deposits are discovered in Foça by Perlitaş Firm. But these ores did not show much value from industrial point of view. Another deposit is discovered in Bilecik by Hima Firm. Other parts of Turkey still need exploration. There is great hope that an extensive investigation program will be undertaken in mining this rock. Many tests performed showed that most of the perlite deposits in Turkey are suitable for producing lightweight aggregates having satisfactory properties.

Perlite Concrete:

Principal advantage of perlite concrete is its insulative value and a secondary one is its light weight.

Table (8) shows some physical properties of 1:6 perlite concrete according to Brouk (16). (1:6 mix the one most widely used for insulation purposes).

Weight (fresh), pcf	35
Weight (oven dry), pcf	25
f'_c , 28 days, psi	170
Tensile Str., psi	32
E, psi	117,000
Mod. of Rupt., psi	41
Thermal Conduct, K	0.55
Thermal Coeff. of Exp.	0.48×10^{-5}
Shrinkage at 28 days, %	0.114
24-hr water abs, pcf of concrete	15

Table (8)- Physical Properties of 1:6 Perlite Concrete (16)

Due to its lightness, insulating value, and permanence, perlite concrete can be used for:

- Roof insulation over structural roof decks of concrete, wood, or metal deck,

- Lightweight structural decks over steel-ribbed metal lath, asbestos board, paper-backed welded wire-mesh, or other suitable forms.

- Floor slabs in basementless homes, minimizing costly heat loss into the ground, and preventing moisture condensation on the floor surface during hot and humid weather.

Perlite aggregate is used, blended with other aggregates, to develop special properties in concretes. A blend of 1 part of expanded shale aggregate with 4 parts of perlite by volume and mixed with 1 bag of cement makes an excellent nailing concrete which weighs only 55 pcf and develops a strength of over 1000 psi at 28 days. One bag of cement, 2.5 cu ft of perlite, and 2.5 cu ft of gravel will produce a concrete weighing 100 pcf which develops a strength of over 2500 psi (16).

d) Proportioning and Field Practice of Lightweight Aggregate Concrete.

- Proportioning:

There are two methods generally in use for proportioning lightweight concrete:

The first (17) requires the determination of the total volume of aggregate needed to produce 1 cu yd of concrete on a moisture-free basis. This volume is converted to weight for the basic design weights, being corrected for moisture such as may be contained in the stockpiled aggregate. Mixing water is added by trial until the proper slump is obtained.

The second method (18) requires the determination of the absorption and saturated, surface-dry specific gravities of the fine and coarse aggregate. These values are used to calculate the solid volumes of the aggregates for design purposes as is customary in the

design of conventional heavyweight concrete.

- Field Practice:

After the mixer has been charged with the first batch on any given job it should be mixed for the required time, the air content should be determined, and a slump test should be made. (13) Measuring concrete consistency by the slump test gives a very good indication of the free mixing water in a given batch design and serves as a good field check for controlling the water.

Aggregates for any given placement of concrete should have a uniform moisture content. Otherwise the quantity of water to be added will have to be adjusted for every batch.

Thorough mixing of the concrete batch is imperative in producing quality concrete. Due to big differences in unit weight between cement paste and aggregate, it is necessary to run conventional mixers at slightly higher speeds than with sand and gravel to get best results (15)

Forms for lightweight concrete can be designed for much lighter loads than is customary for sand-gravel concrete. The lighter weight of materials increases the tendency of concrete to honeycomb and form voids due to entrapped air. These defects can be eliminated by proper vibration (18). Strength of properly vibrated lightweight concrete may be 50 % or more higher than for the same mix rodded in the usual manner. Excessive floating or troweling works large aggregate to the surface just as the excessive vibration does. Therefore best results are obtained when the surface is finished with a minimum number of floating and troweling operations.

B - LITERATURE SURVEY ON STRENGTH AND ELASTICITY
OF LIGHTWEIGHT CONCRETES

In this section, strength characteristics and elastic properties of lightweight aggregate concretes are discussed, and relations between compressive, flexural, and splitting tensile strengths are given together with the factors affecting strength and elastic properties.

Compressive Strength and Its Relation to Unit Weight

The unit weight of lightweight concretes depends on the unit weight of the aggregates, the richness of the mix, and the quantity of air entrained. The latter has a rather important effect because of the relatively large percentages of air usually entrained in lightweight aggregate concretes. In general the heavier the aggregate the greater its crushing strength, a factor which influences the compressive strength of the concrete. Aggregate gradation may also be an important element in the strength-weight relationship; therefore, it would appear possible to vary this ratio within certain limits by modifying the gradation, all other things being equal.

The lighter-weight aggregates and the mixes containing the larger quantities of entrained air, are generally represented in the lower limits of concrete weight. It is evident that larger percentages of cement are necessary with these aggregates and mixes to increase their strength proportionately as compared to the heavier and usually stronger aggregates.

The dry densities of compacted lightweight concretes made with different aggregates vary from about 80 to 126 pcf for compressive strengths ranging from 1,000 to 5,000 psi (2). The relationship between compressive strength and unit weight varies considerably, however, for concretes made with different types of aggregates as shown in Fig. (2)

For sand and gravel concrete, the measured density ranges from about 140 pcf for a 28-day cube strength of about 1000 psi to about 144 pcf for a cube strength of about 4000 psi. For the same

strengths the dry density of expanded clay concrete ranges from 82 to 101 pcf, respectively, when the mix contains only lightweight aggregate; when the fines consist of sand and lightweight material in equal parts, the corresponding densities vary between 93 to 109 pcf, respectively.

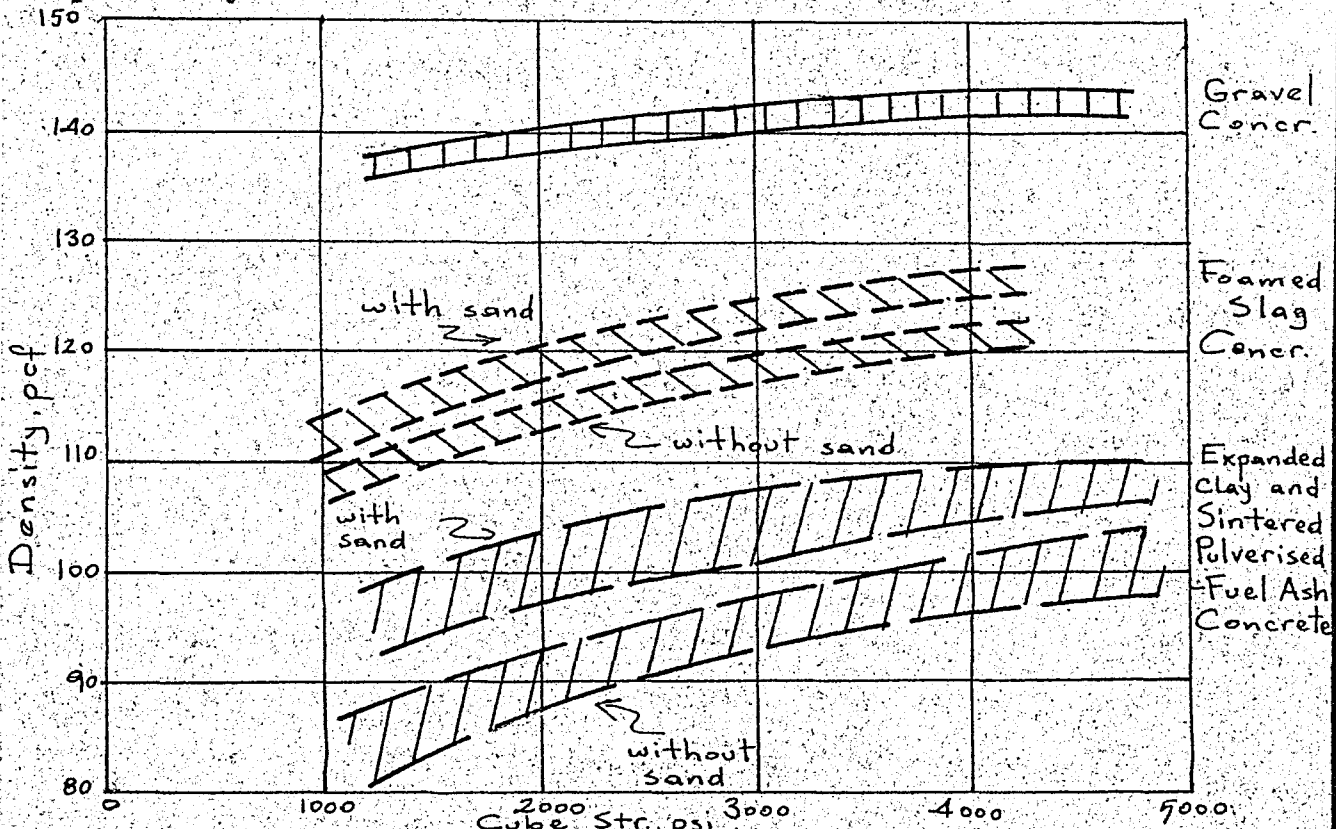


Fig.(2)-Relationship between the cube strength and the dry density of various types of concretes at 28 days (2).

Thus, while for the same strengths, the weight of concrete containing only lightweight aggregate is 60-70 % of the weight of gravel concrete. If sand is added to lightweight concrete mixes, then the density of the lightweight concrete mixes becomes somewhat higher and so does the compressive strength. This can be seen from Fig.(3), by Short and Kinniburgh, (2), and from Fig.(4), by Lewis (11).

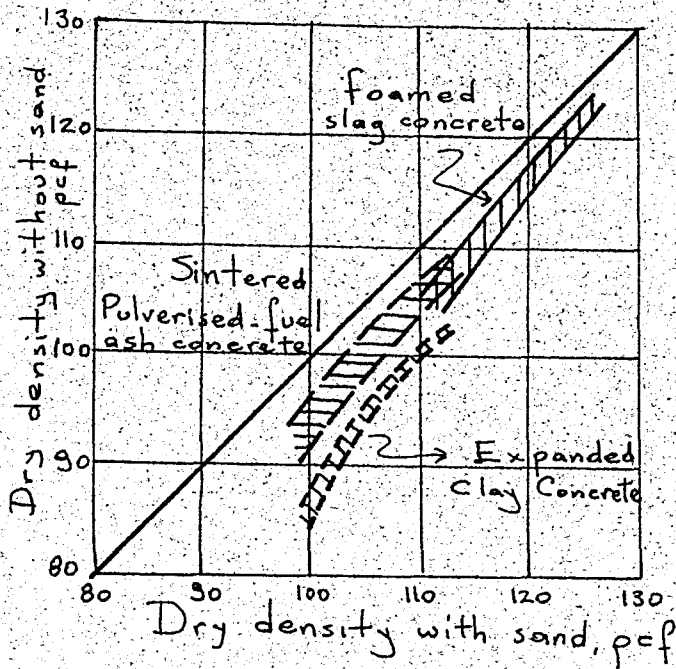


Fig.(3)-The effect on the dry density of lightweight concretes of replacing one-half of the fine lightweight aggregate by sand, for the same cube strength, ranging from about 1000 to 4500 psi.(2)

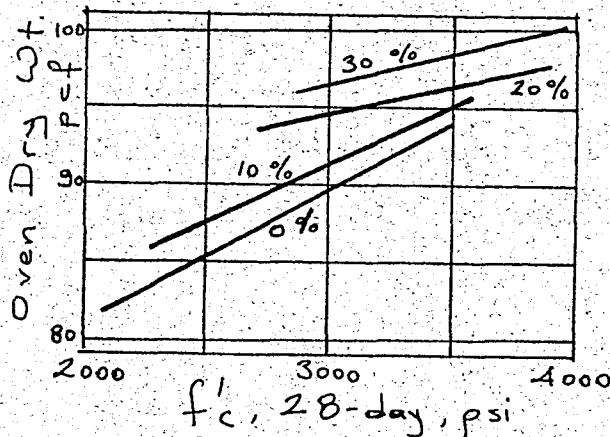


Fig.(4)- The effect of natural sand on strength and oven-weight of structural lightweight concrete made with expanded slag, sand contents shown are percentages of the fine aggregate on a loose volume basis),(11).

Compressive Strength and Its Relation to Cement Content

Fig.(5), after Nelson and Frei (18), shows the relationship between cement content and 28-day compressive strength for expanded-shale concrete. Compressive strengths ranged from 800 psi at 3 sacks per cu yd to 5200 psi at 9 sacks. The gain at later ages appeared to be normal.

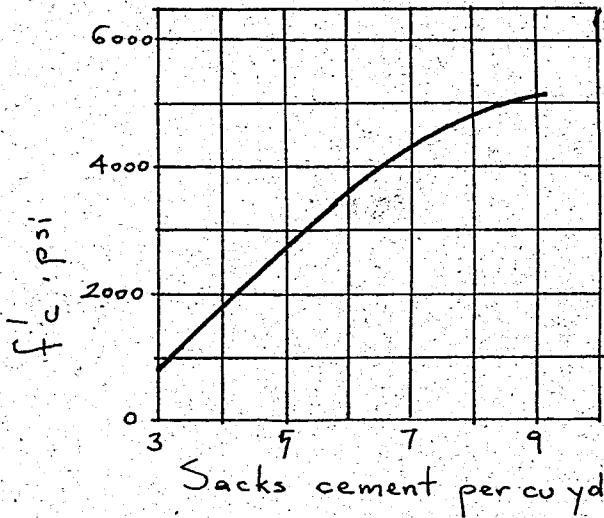


Fig. (5). - Relation between compressive strength and cement content (18).

For a given aggregate, substantial variations in cement content are possible for a given strength, or conversely, substantial variations in strength are possible for a given cement content. Since it is presumed that the crushing strength of a particular aggregate is constant in such instances, since it is assumed further that the air content and consistency of the particular mix are reasonably constant, the difference 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.(11)

Fig.(6) summarizes the relationships of cement factor, air content, oven dry weight, and 28-day compressive strength for expanded slag 3/8 " to 0 size (11).

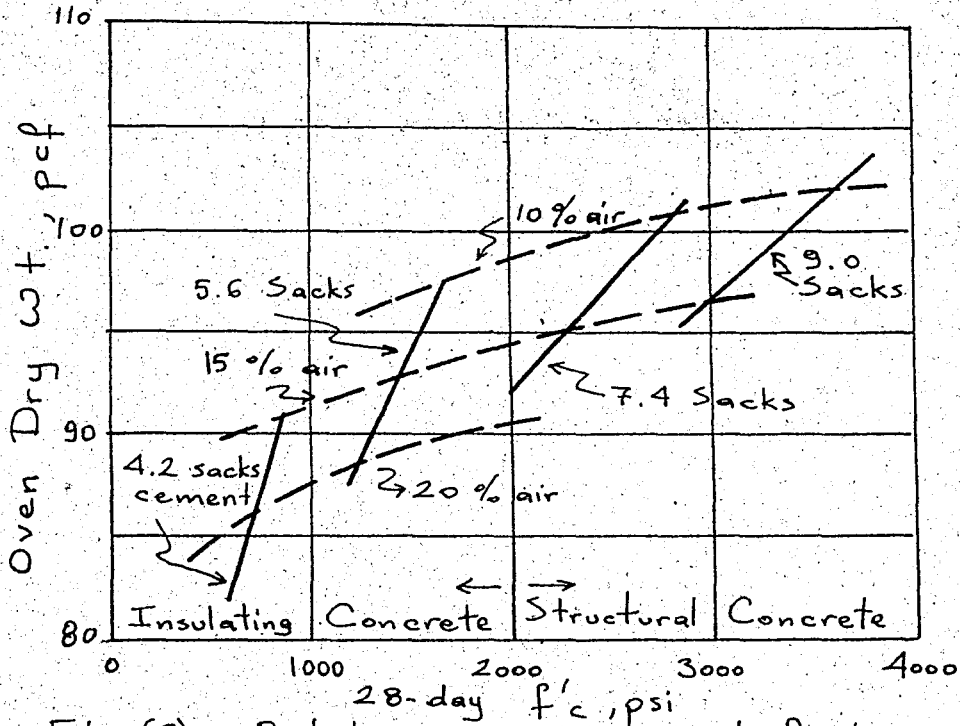


Fig. (6). - Relationship of cement factor, air content, weight, and strength of lightweight concrete made with expanded slag.

In the structural concrete mixes the effect of air content on strength is more pronounced than for lean mixes, as shown by the flatter slope of the curves. This shows the importance of keeping air contents as low as is consistent with proper workability for high strength structural concrete made with expanded slag.

The effect of natural sand substitutions on strength for the different cement factors are shown in Fig.(7)...(11).

The increase in strength with use of natural sand is quite large in the 7-sack per cu yd mixes; somewhat smaller with the 8 1/2 sacks. A mix with 7 sacks of cement and natural sand as 30 % of the fine aggregate had a strength about the same as an 8-sack mix without sand. Weight increases with natural sand substitutions are larger with lower strength mixes than with high

strength mixes.

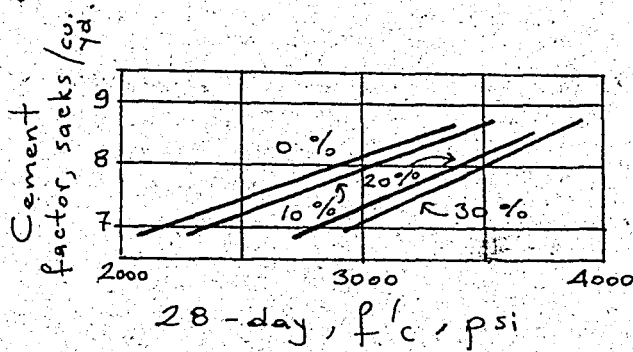


Fig. (7). - Effect of natural sand on strength and cement factor of structural lightweight concrete made with expanded slag (11).

The design curves correlating the cube strength and the water-cement ratio of dense, gravel concrete do not apply to lightweight aggregate concretes. Due perhaps to their porosity and inferior workability, the latter generally need a higher water content for the same strength. As can be seen from Fig. (8), there exists a broad relationship between cube strength and water-cement ratio (2). This relationship is different for every type of lightweight aggregate and has to be considered separately.

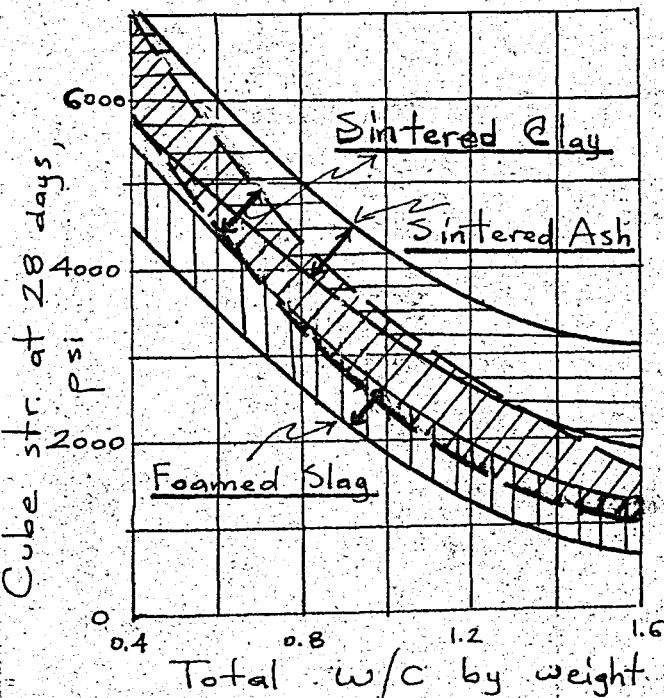


Fig. (8). - Approximate relationship between the total w/c and the cube strength of structural lightweight concretes made with different aggregates (2).

The Effect of the Admixture of Sand

Generally a part of the fine lightweight aggregate is replaced with quartz river sand in lightweight concrete mixes, so as to increase the compressive strength and bond strength of the resulting concrete, to improve its durability, workability, and the protection against corrosion it can afford to the reinforcement, to reduce the cement requirements and the shrinkage of the concrete. Since it has been shown that the addition of sand also increases the density of the concrete, the question arises as to the degree to which this disadvantage can be balanced by the advantages of adding sand to the mix in practice. The increase in density is less serious with foamed slag concrete but is relatively more important for the lighter, sintered aggregate(2).

The effect of the addition of sand on bond strength of lightweight concrete is not very great, nor is its effect on durability very noticeable. The shrinkage of lightweight concrete is reduced by the addition of sand, which acts as a stabilising element in the structure of the matrix (2)

For the same workability and compressive strength the sand replaces some proportion of the cement in the binder and may reduce the cement requirements for some types of lightweight aggregates (Fig.9)...(2)

For various types of lightweight concretes and various mixes, the cement requirements were reduced by 13-25 % by weight, if half of the lightweight fines by volume was replaced by river sand.

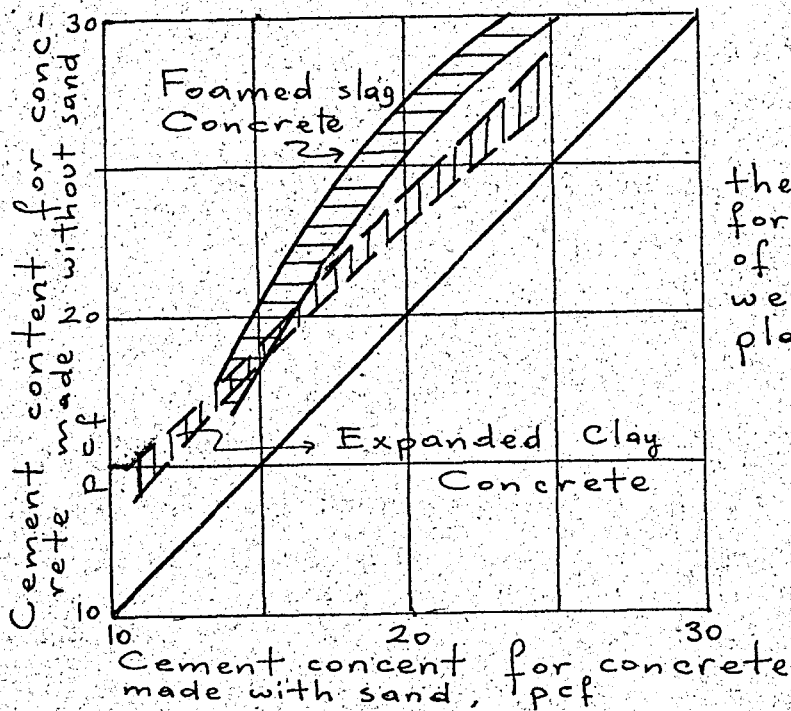


Fig. (9) - The effect on the cement content required for lightweight concrete mixes of one-half of the fine lightweight aggregate being replaced by sand (2).

The percentage increase in density as well as the reduction in cement consumption which can be attained with the addition of sand to a lightweight concrete mix, tend to become less important as the compressive strength increases. In general, weak mixes are more sensitive to the addition of sand or of other materials.

Interrelation of Tensile Strength, Modulus of Rupture, and Compressive Strength of Lightweight Concretes

Results obtained in England (2) from modulus of rupture and cylinder splitting tests with various lightweight aggregate and concrete mixes have been compared with the performance of gravel concrete. These results indicated that in general the modulus of rupture and the splitting strength of lightweight concretes tend to be of the same order as, or slightly higher than, that obtained with the gravel concrete having the same compressive strength.

The modulus of rupture obtained for concretes made with different types of aggregates is shown in Fig.(10) in relation to the compressive strength. For compressive strengths ranging from 1000 to 5000 psi, the moduli of rupture tend to vary from 250 to 550 psi.

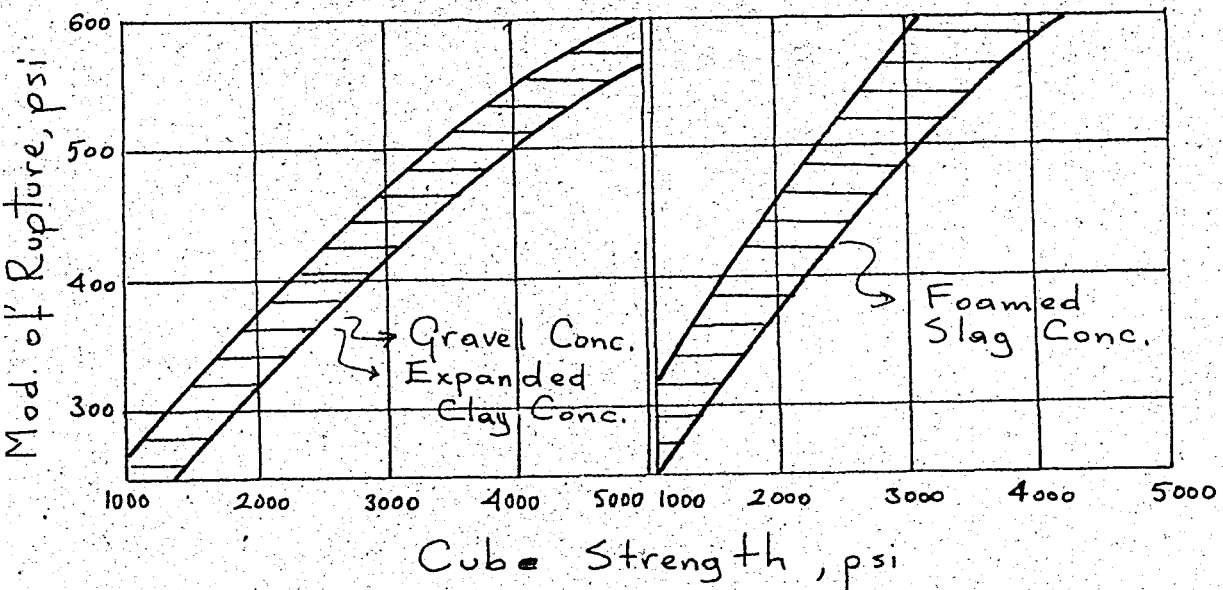


Fig (10). - Relationship between the cube strength, and the modulus of rupture for different types of concrete. (2)

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 lightweight aggregate concrete and gravel concrete was found to be best represented by a parabolic equation of this form :

$$R = 8.0 \sqrt{f'_c}$$

where R denotes the modulus of rupture and f'_c is the cube strength. The relation of the cylinder splitting strength to cube strength obtained from tests at the Building Research Station can be expressed approximately by the following equation (2)

$$f_{sp} = \alpha \sqrt{f'_c}$$

The coefficient α , may vary from about 4.5 to 6.0, the average value being about 5.0 .

The results of split cylinder tests made by Hanson (20), indicate that the split cylinder strength 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.

It appears that the two types of test, i.e. modulus of rupture and cylinder splitting tests, do not represent the same property of the concrete although both may serve as an indication of the tensile strength. In general, the cylinder splitting strength is about 60 % of the modulus of rupture (2).

Tests carried on concretes prepared with ten different lightweight aggregates showed that the splitting-tensile to flexural strength ratios of the lightweight aggregate concretes range from 57 to 88 % with an average ratio of 76 %, and the ten-

ratio to compressive strength ratios range from 5.3 to 11.2 % with an average ratio of 8.0 % (21). The relations between flexural, compressive, and splitting tensile strengths for lightweight aggregate concretes are shown in Fig.(11) and Fig.(12). The same relations for gravel concrete and crushed stone concrete are also shown for comparison.

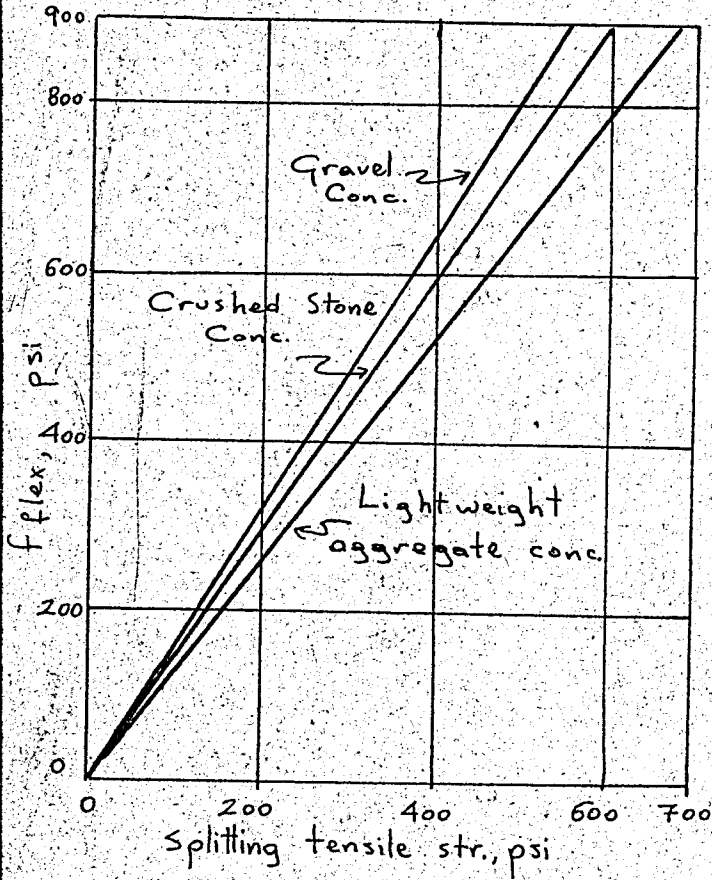
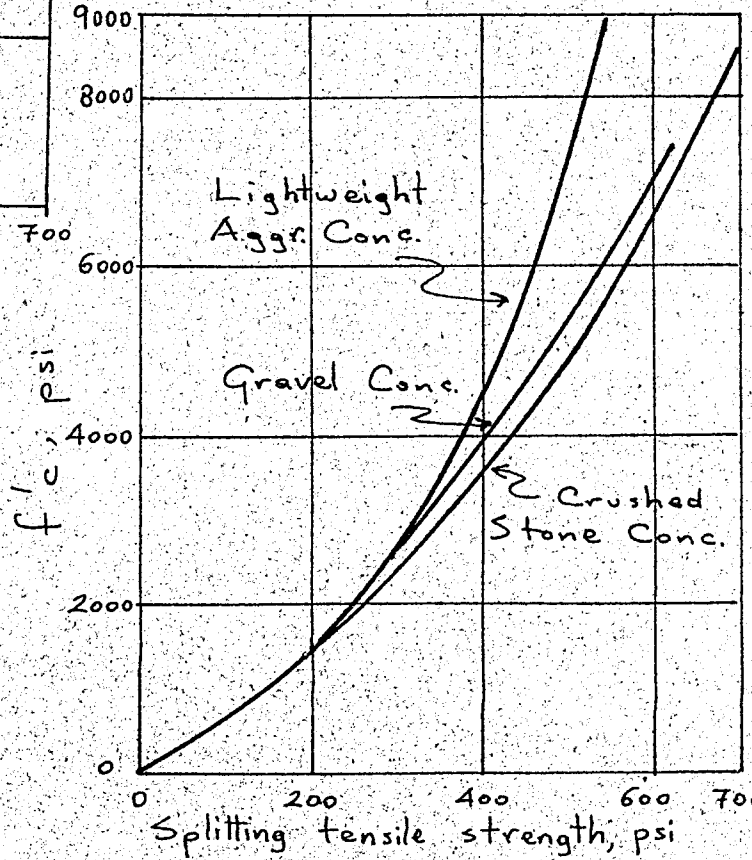


Fig. (11). - Relation between flexural strength and Splitting tensile strength for three types of aggregates (21).

Fig (12). - Relation between f'_c and splitting tensile strength for three types of aggregates. (21)



For insulating concretes the ratio of flexural to compressive strength may be higher than for structural concrete and highest for the materials of lowest compressive strength. Approximate ratios of flexural to compressive strength for some insulating concretes (75 to 500 psi compressive strength) are shown in Table (9).

Aggregate	f_{flex}^i / f_c^i
Perlite	0.20 to 0.45
Vermiculite	0.25 to 0.50
Expanded slag	0.25 to 0.30
Expanded shale	0.30
Sand (cellular)	0.20 to 0.35

Table (9)- Flexural to compressive strength ratios for some insulating concretes (14).

The tensile strength of concrete is greatly affected by its moisture content. On the other hand, for denser gravel concrete the tensile strength was found to be slightly higher for the dry than for the saturated material (20).

Also, the effect of drying on relation between flexural strength and splitting tensile strength; and between compressive strength and splitting tensile strength of lightweight aggregate concretes is considerable, this effect is shown Fig.(13) and in Fig. (14) .

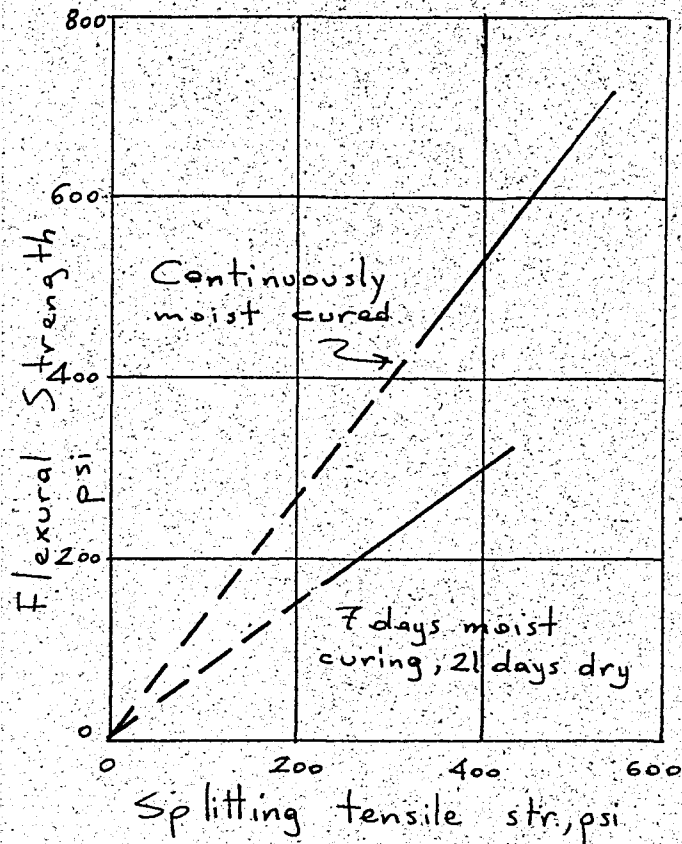
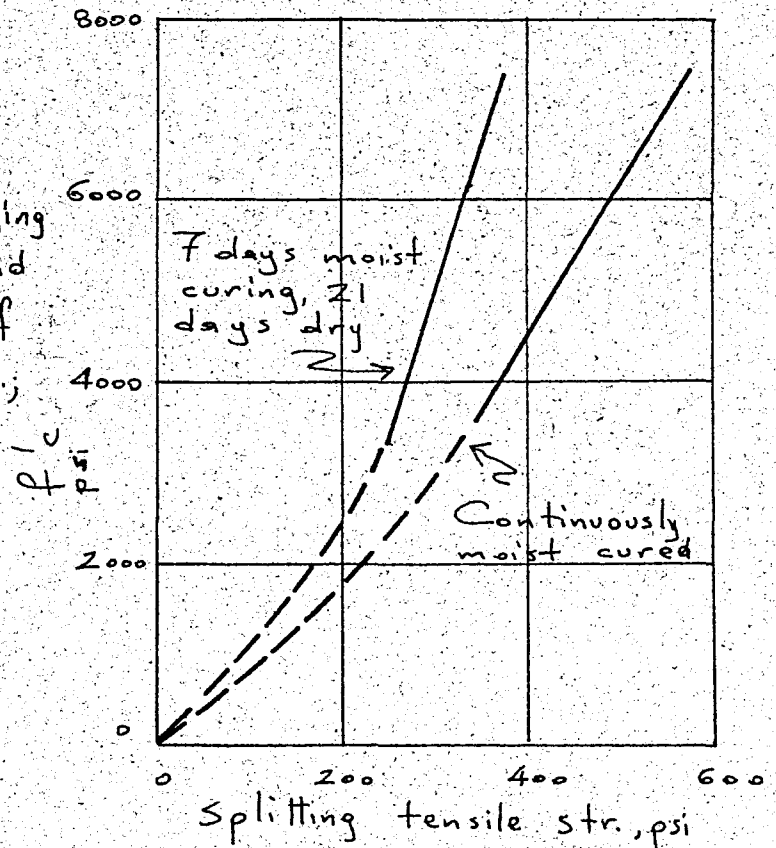


Fig. (13).- Effect of drying on relation between flexural strength and splitting tensile strength of lightweight aggregate concrete, Age 28 days. (21).

Fig. (14).- Effect of drying on relation between f'_c and splitting tensile strength of lightweight aggregate conc., Age 28 days (21).



MODULUS OF ELASTICITY OF LIGHTWEIGHT CONCRETES

The one physical property of all lightweight concretes about which little is known is the modulus of elasticity and how it varies with the design mix.

In general, the modulus of elasticity of lightweight plastic concrete is relatively low as compared with that of concrete containing ordinary aggregate. The modulus varies roughly with the strength, as in the case of ordinary concrete. For structural lightweight concrete, modulus of elasticity is usually of the order of 2,000,000 psi. For concretes of extremely light weight and low strength such as expanded perlite and vermiculite concrete which are used for insulation purposes, the modulus may be as low as 200,000 psi (7).

Laboratory investigators have reported moduli of elasticity of 50 % to as high as 90 % of the equivalent sand-gravel concretes (17). But it is difficult to correlate these independent laboratory tests with job conditions. However, it is shown that the modulus of elasticity may vary considerably without affecting design calculations seriously.

For concretes of high strength the percentage difference is somewhat greater than for weaker mixes, but in general the moduli of elasticity of lightweight concretes range between $1/2$ and $2/3$ of the moduli of elasticity of the corresponding gravel concrete mixes, (Fig. 15)

The modulus of elasticity increases with the cube strength and with the density of the concrete; various empirical expressions have been derived by different research workers to correlate

these properties (22), (23), (24), and they are going to be stated in the coming pages. For lightweight concretes it varies between about one and three million psi for different strengths, different aggregates, under short duration loading. (Fig. 16)

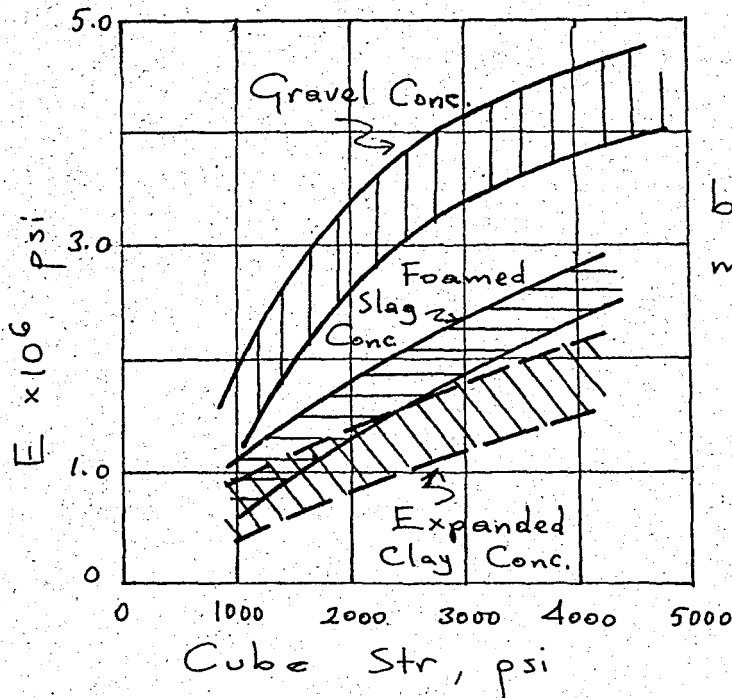
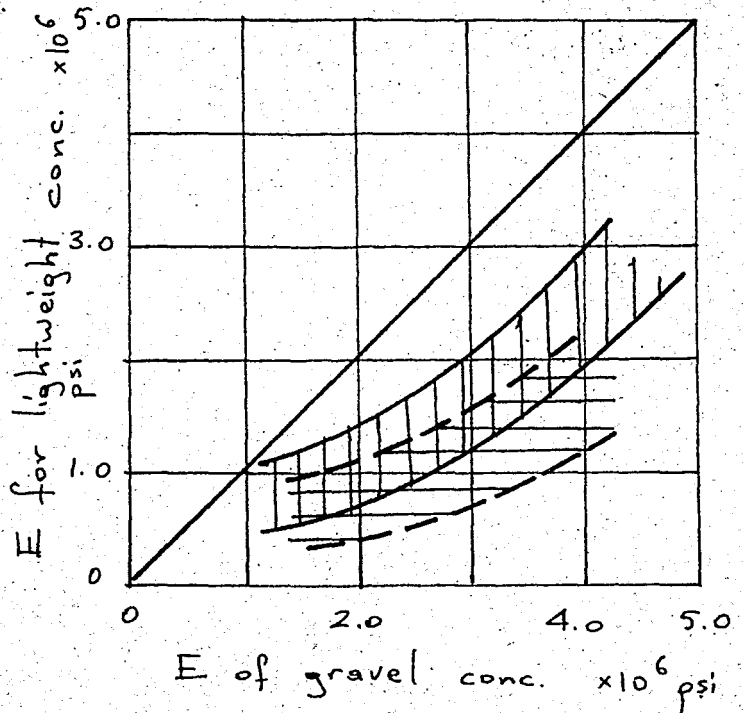


Fig (16).- Relationship between cube strength and modulus of elasticity (2).

Fig. (15).- Relationship between moduli of elasticity of gravel conc. and lightweight concretes having the same crushing strength (2).



The modulus of elasticity is of special importance for structural/lightweight concrete construction, because of its effect on the deflections 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 (13).

The work of Richart and Jensen (13), which represents the first and most extensive research yet reported on the structural properties of expanded-shale concrete, definitely shows this concrete to have an initial tangent modulus of 50 to 55 % that of sand-gravel concrete of equal strength (13). Fig. (17) represents very closely results of their tests, being practically linear, it can be expressed by the following equation (13):

$$E = 1,500,000 + 160 (f'_c - 1000)$$

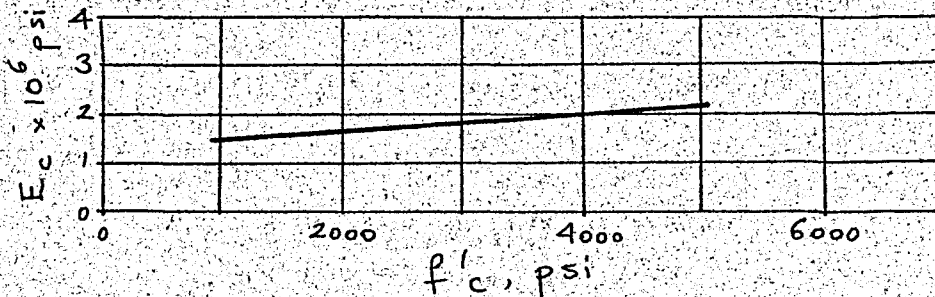


Fig. (17). - Relation between modulus of elasticity and compressive strength (13).

Ranges in compressive secant moduli for various lightweight aggregate concretes are shown below, in Table (10). (The slope of the secant drawn through the origin and point on the stress-strain curve at one-half the ultimate stress is one definition of the secant modulus).

Aggregate, proportions	f'_c	secant mod., 1000 psi
Perlite, 1:8 to 1:4	80 to 450	70 to 250
Vermiculite, 1:8 to 1:3	70 to 370	40 to 140
Sand (cellular), 1:3	150 to 550	150 to 700
None (cellular), 1:0	85	70

Table (10).-Ranges in compressive secant moduli for various lightweight aggregate concretes (14).

Secant moduli for concretes made with pumice, expanded shale, expanded slag aggregate, and having 28-day compressive strength of about 500 psi, have ranged from 700,000 to 900,000 psi (14). For air-entrained (25 to 35 %) no-fines concretes made with the same aggregates, secant moduli values were approximately 1000 times the compressive strength values in the 28-day compressive strength range 160 to 530 psi (14). Values of secant moduli at 0.3 times the compressive strength of sand-gravel concretes and lightweight concretes having various compressive strengths and prepared with expanded clay and shale aggregate are reported in a paper, by Shideler (25). The ratio n of the modulus of elasticity of steel to that of concrete is compared to values of n established by the ACI Building Code (10), ($n = 30,000/f'_c$), in the following table (25), (Table. 11)

Values established by the two definitions are in fair

agreement for the lower strength sand-gravel concrete. However, for high-strength sand-gravel concretes and for lightweight concretes there is a large difference between the values established by the two formulas.

Aggregate	f'_c , 28-day, psi	E_s/E_c	$30,000/f'_c$
Sand and gravel	3000	9.4	10.0
Sand and gravel	4200	8.8	7.2
Sand and gravel	7000	7.2	4.3
Sand and gravel	9500	6.5	3.2
Lightweights	3000	14 to 20	10.0
Lightweights	4500	10 to 16	6.7
Lightweights	8500	12.0	3.5

Table (11).-Comparison of n values for sand and gravel concretes and lightweight concretes, obtained in two different ways, experimentally and by the use of ACI formula ($n = 30,000/f'_c$), (25).

STUDIES TOWARDS GETTING EMPIRICAL FORMULAE INTERRELATING AGGREGATE TYPE, DENSITY, VOID AMOUNT, COMPRESSIVE STRENGTH, AND MODULUS OF ELASTICITY

The Effect of the Density and the Compressive Strength of Concrete on its Modulus of Elasticity:

With the rapid expansion of the use of lightweight aggregate concretes in recent years, the need for a suitable empirical relationship for the modulus of elasticity of these concretes has become increasingly apparent. It has been observed by many investigators that the modulus of elasticity of lightweight aggregate concrete is considerably lower than the values of normal weight concrete of comparable compressive strength and that the modulus appears to a function of the weight. It is known that all mineral aggregates have about the same absolute specific gravity. The difference in weight of various types of concrete is therefore primarily the result of voids in the concrete, whether they be due to purposely entrained air, or due to the vesicles in lightweight aggregates. From these considerations it was suspected that it might be possible to obtain a satisfactory approximation by expressing the value of the modulus of elasticity by an empirical relationship of the form (23)

$$E_c = A w_c^{3/2} \sqrt{f'_c}$$

- where E_c = Static modulus of elasticity of concrete, psi
 w_c = Air-dry weight of the concrete at time of test, pcf
 f'_c = Compressive strength of the concrete, psi
 A = A suitable constant

To determine the value of A test results of Richart and

Jensen (25), Shideler (25), and Hanson (20) are used. E_c is plotted as a function of $w^{3/2} \sqrt{f'_c}$, and using the method of least squares the value of the constant A was found to be 32.43. This value is recomputed for concretes produced with relatively weak aggregates such as the pumices and perlites, and it came out to be 33.6. Thus for both normal and lightweight structural concretes, the static modulus of elasticity may be determined by the approximate empirical formula (23)

$$E_c = 33 \cdot w^{3/2} \sqrt{f'_c}$$

Considering the limitations of the data available, the correlation between the reported moduli of elasticity and the values predicted by the above formula appears rather remarkable. In view of many other variables involved in concrete design, it is believed that this equation is adequate for most design purposes. As a further check on the validity of the proposed formula, a generalized form was analyzed:

$$E_c = A \cdot w^B (f'_c)^C$$

By writing it in logarithmic form:

$\log E_c = \log A + B \log w + C \log f'_c$, a linearized equation was obtained which was susceptible to a non-orthogonal regression analysis. This analysis yielded the formula

$$E_c = 13.82 w^{1.79} f'_c^{0.44}$$

with all the data included, and the formula

$$E_c = 158.1 w^{1.51} f'_c^{0.30}$$

when the data for concretes having a compressive strength of less than 2000 psi were omitted (23). The exclusion of these data is believed to be justified since the modulus of elasticity is gene-

rally of interest only in the case of structural quality concrete.

The above stated formulae have obvious limitations. The modulus of elasticity of concrete changes with the age, and the empirical constant A is based only on concrete specimens tested at 28 days. None of them can evaluate the effect of different mix proportions. Most important of all, more recent investigators have found no definite relationship between the modulus of elasticity and the compressive strength when different aggregate types are used. (22) Concretes with the same compressive strengths but made from different aggregates were observed to have considerably different moduli.

Assuming a relationship between the modulus of elasticity and the compressive strength is primarily a method of convenience since the compressive strength test is relatively simple to perform and is commonly used to control concrete quality. In addition, when a given aggregate is used in a concrete, it has been observed that factors which affect the compressive strength also affect the modulus of elasticity in a similar manner (22).

The Effect of Aggregate and Voids on the Modulus of Elasticity of Concrete

Several research workers have attempted to correlate the modulus of elasticity of concrete, cement mortar, and cement paste to the modulus of elasticity of the component materials, and the conclusions can be summarized as follows:

Hansen (24) suggested the following formula for concretes made with aggregates having a lower modulus of elasticity than the matrix:

$$E_c = V_m E_m + V_a E_a$$

- where E_c = Modulus of elasticity of concrete,
- E_m = Modulus of elasticity of cement mortar,
- E_a = Modulus of elasticity of aggregates,
- V_m = Fractional volume of cement mortar,
- V_a = Fractional volume of aggregates.

In a recent treatise Hirsch (22) suggested that the modulus of elasticity of cement mortar can be written as a function of the modulus of elasticity of aggregates and cement paste in the following way:

$$E_m = \frac{1}{K_1 \frac{V_a}{E_a} + K_2 \frac{V_{cp}}{E_{cp}}}$$

- where E_{cp} = Modulus of elasticity of cement paste,
- V_{cp} = Fractional volume of cement paste,

$$K_1 = 1 - \frac{2Z}{\pi} \left[1 - \frac{1}{\frac{E_{cp}}{E_a} (1 - V_a) + V_a} \right]$$

$$K_2 = 1 - \frac{2Z}{\pi} \left[1 - \frac{1}{(1-V_a) + V_a \frac{E_a}{E_{cp}}} \right]$$

Z = An empirical constant which was found to be approximately equal to 0.785.

It will be noted that this hypothesis makes no specific allowances for the effect of the size, shape, or arrangement of the aggregate particles. These factors are believed to have only a minor effect on the over-all modulus of a concrete specimen provided the specimen is large compared to the maximum aggregate size and provided the aggregate particles have a random shape and arrangement within the concrete mass.

Ishai (26) proposed:

$$E_m = (1 + k V_A) E_{cp}$$

for the modulus of elasticity of cement mortar expressed as a function of the modulus of elasticity of cement paste and fractional volume of the aggregates. k is a function of the elastic properties of aggregates and cement paste.

Since lightweight aggregate concrete is made with aggregates having a lower modulus of elasticity than the matrix, the formula suggested by Hansen (24) will be taken into account here:

$$E_c = V_m E_m + V_a E_a$$

This formula is deduced from the model in Fig.(18) for two-phase materials consisting of particles of an elastic material dispersed in a matrix of another elastic material, based on the assumption that the average strain in a two-phase material due to applied load is the same in matrix and in particles.

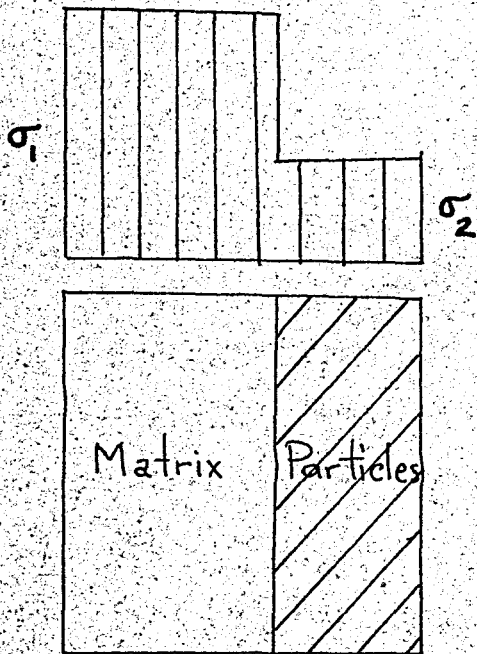


Fig.(18)- Model of two-phase material with particles of low modulus of elasticity embedded in a matrix of high modulus of elasticity.(24)

The above stated formula can be modified for cement mortar in the following way:

$$E_m = V_{cp} E_{cp} + V_a E_a$$

The straight line (I) in Fig.(19) stands for $\frac{E_a}{E_{cp}} = \frac{1}{10}$, and it is an extreme upper boundary for the moduli of elasticity of two-phase materials, which is reached only when the true material structure closely resembles the column structure in the model.

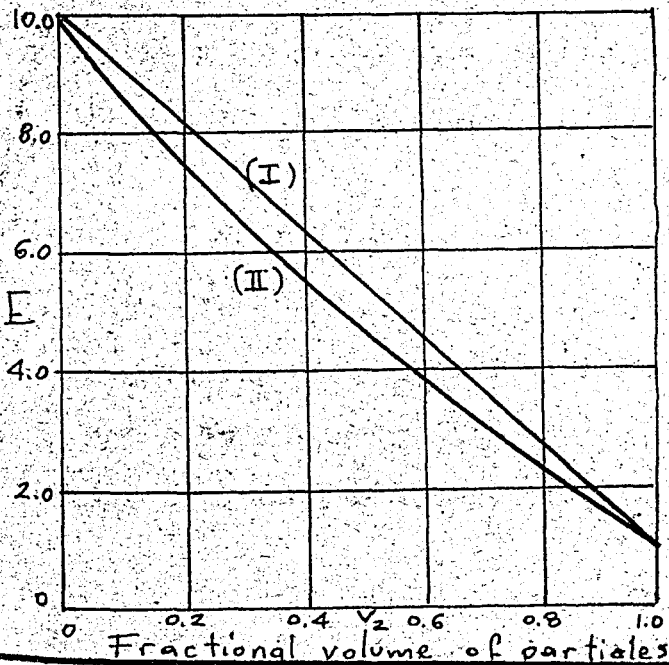


Fig.(19)-Graph showing theoretical variation of modulus of elasticity of heterogeneous material with fractional volume of particles. (24)

As another approach to the problem Hashin (24) derived the following equation for a two-phase material consisting of spherical particles evenly distributed in a continuous matrix:

$$E = \left[\frac{(1-V_2) E_1 + (1+V_2) E_2}{(1+V_2) E_1 + (1-V_2) E_2} \right] E_1$$

Modifying it for cement mortar:

$$E_m = \left[\frac{(1-V_a) E_{cp} + (1+V_a) E_a}{(1+V_a) E_{cp} + (1-V_a) E_a} \right] E_{cp}$$

gives the theoretical variation of the modulus of elasticity of cement mortar with fractional volume of aggregates.

The curve (II) in Fig.(19) represents this equation for

$$\frac{E_a}{E_{cp}} = \frac{1}{10}$$

The moduli of elasticity of concretes made with aggregate particles having a lower modulus of elasticity embedded in cement mortar with a higher modulus of elasticity should theoretically follow Hashin's equation for $E_2 < E_1$. Fig.(20) shows the only data available to test this hypothesis. In these tests, soft limestone particles were embedded in cement mortar. The data are shown in relation to curves (I) and (II) drawn according to the formulae of Hansen, and Hashin, respectively

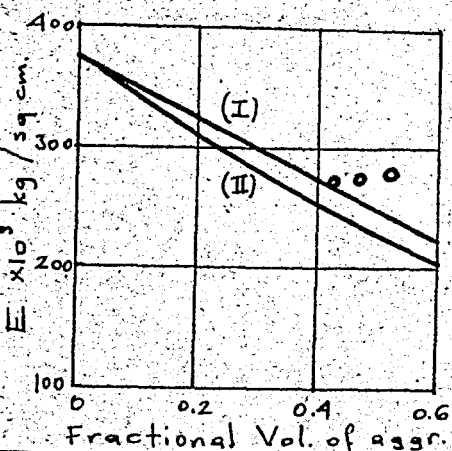


Fig.(20)-Graph showing the variation of modulus of elasticity of concrete with fractional volume of soft limestone particles.(24)

Tests have shown that the modulus of elasticity of concrete is a function of the modulus of elasticity of its cement paste matrix and of its aggregate constituents. The degree to which the elastic properties of one of the ingredients affects the modulus is a function of the quantity present in the batch, and also the modulus of elasticity of cement paste is a function of its water-cement ratio and of its age. Typical values range from one to four million psi (22).

To obtain better correlation between theoretical and experimental data more refined models would have to be used. However, it is believed that the theories presented give an essentially correct, albeit rather crude, solution to the problem, and that the formulae proposed give results which are sufficiently accurate for most practical purposes.

P A R T - II

E X P E R I M E N T A L

A- TESTS TO DETERMINE THE PROPERTIES OF PERLITE LIGHTWEIGHT AGGREGATE

a- Grading of perlite lightweight aggregate and normal aggregate:

Table (12) shows the grading of fine lightweight aggregate, and that of fine normal aggregate as specified by ASTM Designations C 330-53T, and C 33-53T (12), respectively, and also the grading of our samples which were used in the tests.

Designation	% passing sieves having square openings (by weight)						
	3/8"	# 4	# 8	# 16	# 30	# 50	# 100
Fine Lightweight Aggr. (ASTM C 330)	100	85-100		40-80		10-35	5-25
Fine natural Aggr. (ASTM C 33)	100	95-100	80-100	50-85	25-60	10-30	2-10
Fine perlite Lightwt. Aggr.-Sam.I		100	99.5	96.4	77.4	47.5	18.4
Fine perlite Lightwt. Aggr.-Sam.II		99.5	99.1	93.9	74.5	46.0	20.0
Fine natural Aggr - Sand		100	95.4	44.7	9.7	4.0	0.9

Table (12).- Grading of Aggregates.

50 grams of perlite aggregate were sieved as specified by ASTM Designation C 330-53T for a nominal weight of 5 to 15 pcf.

As is seen from this table, our samples did not conform with the requirements of ASTM Specifications. Perlite aggregate is finer, and normal aggregate is coarser than those specified in ASTM.

Sieve analysis is performed in accordance with ASTM C 136-46, and a sieving time of 5 minutes was used as specified for grading of lightweight aggregates.

Fineness moduli are 1.61 for perlite aggregate Sample I, 1.67 for Sample II, and 3.75 for natural sand.

b- Unit weight determination of perlite lightweight aggregate and normal aggregate

Unit weight determinations were performed in accordance with ASTM C 29-55T (12), and the following data were obtained:

Unit weight of water at 16.7°C = 62.355 pcf,

Weight of water to fill the measure = 15.5 lb,

Factor to be used = $\frac{62.355}{15.5} = 4.02,$

Weight of natural sand to fill the measure = 22.154 pcf,

Unit weight of the sample = Factor x Weight of sample to fill the measure,

Unit weight of natural sand = 4.02 x 22.154 = 89.0 pcf,

Unit weight of perlite changed from time to time, depending on the humidity of the room where it was stored, and its value was determined before every mixing operation, and it was seen that it changed from 8.0 to 10.8 pcf.

B- TESTS TO DETERMINE THE PROPERTIES OF CEMENT-LIGHTWEIGHT AGGREGATE (PERLITE)-AND NORMAL AGGREGATE (NATURAL SAND) MORTARS

a- Materials :

- Natural sea sand (Gradation and unit weight were given in Page 50),
- Cement (Type I),
- Perlite lightweight aggregate (obtained from Hima firm, and its gradation and unit weight were given in Page (50),
- Water (Public city water was used for all mixing and curing purposes).

b- Mix Proportions:

Dry loose volume basis was used for this purpose, and mix proportions were grouped in four categories:

- I- Cement-perlite mortar mixes: 1-3,1-4,1-5,1-6;
- II- Cement-perlite-sand mortar mixes: 1-3-1,1-3-2,1-3-3;
- III- " " " " " : 1-4-1,1-4-2,1-4-3;
- IV- Cement-sand mortar mixes: 1-5,1-6,1-7.

c- Specimens:

- For compression: two cylindrical specimens 6 in. in diameter and 12 in. in length.
- For cylinder splitting: the same specimens as for compression
- For flexure: two rectangular beams 6 in. in width, 12 in. in length, and 3 in. in height.

d- Mixing and Curing:

An electrically driven barrel type concrete mixer was used for mixing, and the procedure was carried on as recommended by ASTM C192-55 (12) under Section 4c.

Flow test method was used to check the workability. This test and molding of specimens were conducted in accordance with ASTM C 87-52.

Instead of storing the specimens in moist condition as specified in ASTM C 192-55 under Section 11, they were stored in water for three days after removal from the molds, and then they were kept at room temperature till the time of test.

e- Testing:

The specimens were tested at the age of 28 days.

Compressive strength tests were in accordance with ASTM C 39-49, and flexural strength tests with ASTM C 78-49. Cylinder splitting strength tests were done as described by Hanson (20).

To obtain stress-strain relationships a compressometer gage was attached to the test cylinder and consecutive readings were taken.

We used the Universal Testing Machine for all test purposes.

C- TEST RESULTS

All the values obtained as the results of the tests are given in Table (13 a), and Table (13 b).

Mix Prop. (by vol.) Properties	1-3-0	1-4-0	1-5-0	1-6-0	1-3-1	1-3-2	1-3-3
f'_c , psi	348	318	319	260	562	960	1130
f_{sp} , psi	74	48	49	38	86.5	141	146
R (mod. of rupt)	11.7	92.3	71	62.5	128.5	251.5	261.5
density (fresh), pcf	77.5	76.0	75.2	71.6	95.4	112	127
density (oven dry)	51.4	48.5	46.3	42.7	73.5	91.8	98.8
E_1 (initial tang.) $\times 10^4$ psi	46	44	24	22	41	110	134
E_2 (secant), at 0.5 f'_c $\times 10^4$ psi	40	33	19	16	30	88	120

Table (13 a) - Test Results

Mix Prop. Properties	1-4-1	1-4-2	1-4-3	1-0-5	1-0-6	1-0-7
f'_c	841	1070	462	1370	884	644
f_{sp}	102	141	75	169	106	81.5
R	197	261	161	278	270	228
density (fresh)	95.4	106.5	115	129	125	124
density (oven dry)	74.3	91.2	102.3	116	113	111
E_1	42	88	75	130	100	73
E_2	42	76	70	115	94	52

Table (13 b) - Test Results (Mix Proportions are in cement-perlite-sand order)

D- DISCUSSION OF TEST RESULTS

a- Relations of f'_c , f'_{sp} , Modulus of Rupture, Initial Tangent Modulus, and Secant Modulus to Mix Proportions of cement-perlite-sand mortars

These relations can be seen from :

Fig. (21) for f'_c ,

Fig. (22) for f'_{sp} ,

Fig. (23) for R (R = Modulus of Rupture),

Fig. (24) for E_1 (E_1 = Initial Tangent Modulus), and

Fig. (25) for E_2 (E_2 = Secant Modulus at $0.5 f'_c$).

Having examined the above mentioned figures, one can face the following facts;

- The curves giving all the stated relations for each category follow similar patterns.

- f'_c , f'_{sp} , R, E_1 , and E_2 values for Categories I and IV decrease linearly as the aggregate amount is increased.

- The same values for Category II increase at a diminishing rate as the amount of sand is increased. However, the maximum values could not be obtained from these curves, because they seem to fall outside the range of our test mixes.

For this category the strength lowering effect of increasing aggregate amount is continuously overcome by the strength increasing effect of adding sand to perlite lightweight aggregate.

- For Category III the stated values increase at a diminishing rate between proportions of 1-4-1 and 1-4-2. At the latter proportion they reach their maximum values, and when the sand proportion is increased above two, then they decrease at a rapid rate.

For sand proportions of more than two, the strength-increasing effect of adding sand to perlite is overcome by the strength-lowering effect of increasing aggregate amount.

- The following mixes have a total aggregate proportion of 5:

- 1-5-0 from Category I,
- 1-3-2 " " II,
- 1-4-1 " " III,
- 1-0-5 " " IV.

If we compare the properties of these mixes, we see that:

- 1-5-0 mix of Category I has the lowest values as:

f'_c around 320 psi,
 f'_{sp} " 50 " ,
 R " 80 " ,
 E_1 " 250000 " ,
 E_2 " 200000 " .

- 1-0-5 mix of Category IV has the highest values as:

f'_c around 1370 psi,
 f'_{sp} " 170 " ,
 R " 280 " ,
 E_1 " 130000 " ,
 E_2 " 120000 " .

- The remaining 1-3-2 and 1-4-1 cement-perlite-sand mixes have values between the two extremes obtained by the former two mixes. The values for 1-3-2 mix are higher than the ones for 1-4-1 mix.

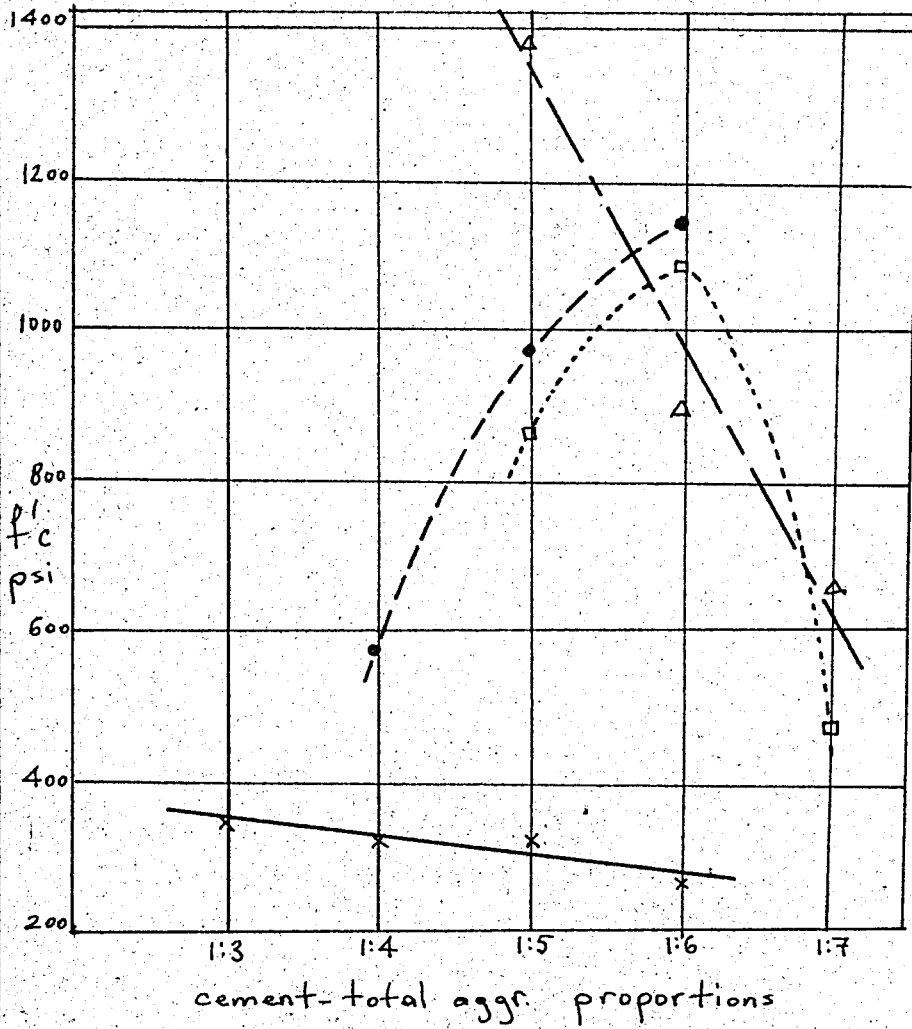
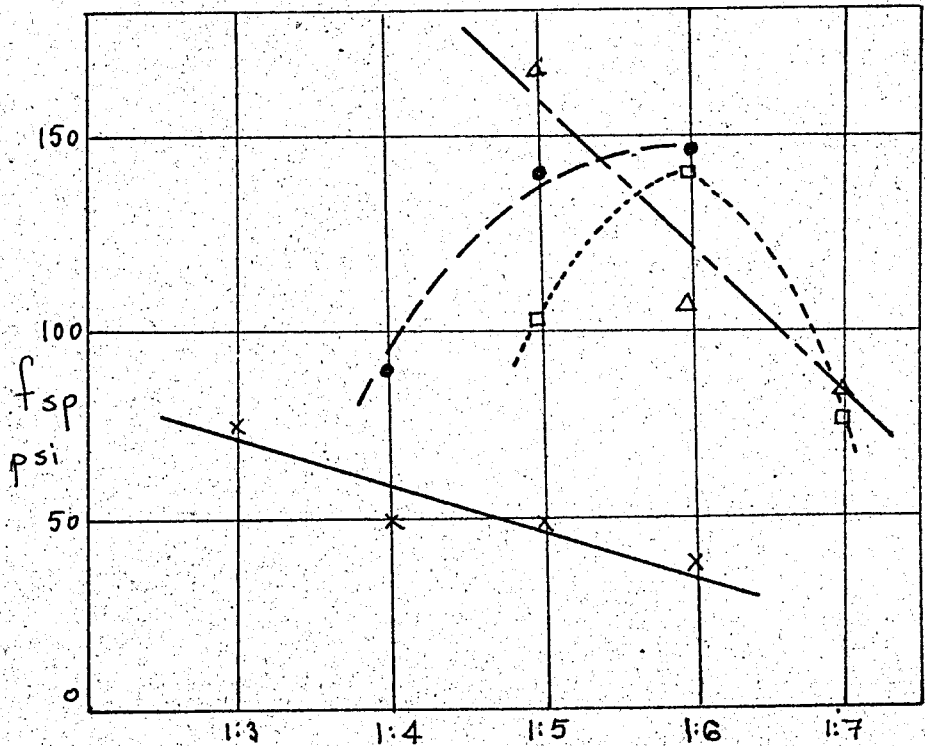


Fig. (21). - Relation of f'_c to cement-total aggr. proportions

- x — x — 1-3, 1-4, 1-5, 1-6
cem.-perl. mixes
- - Δ - - Δ 1-5, 1-6, 1-7
cement - sand mixes
- · - · - 1-3-1, 1-3-2, 1-3-3
cem.-perl.-sand mixes
- - \square - - \square 1-4-1, 1-4-2, 1-4-3
cem.-per.-sand mixes

Fig. (22) - Relation of f_{sp} to cement-total aggr. proportions.



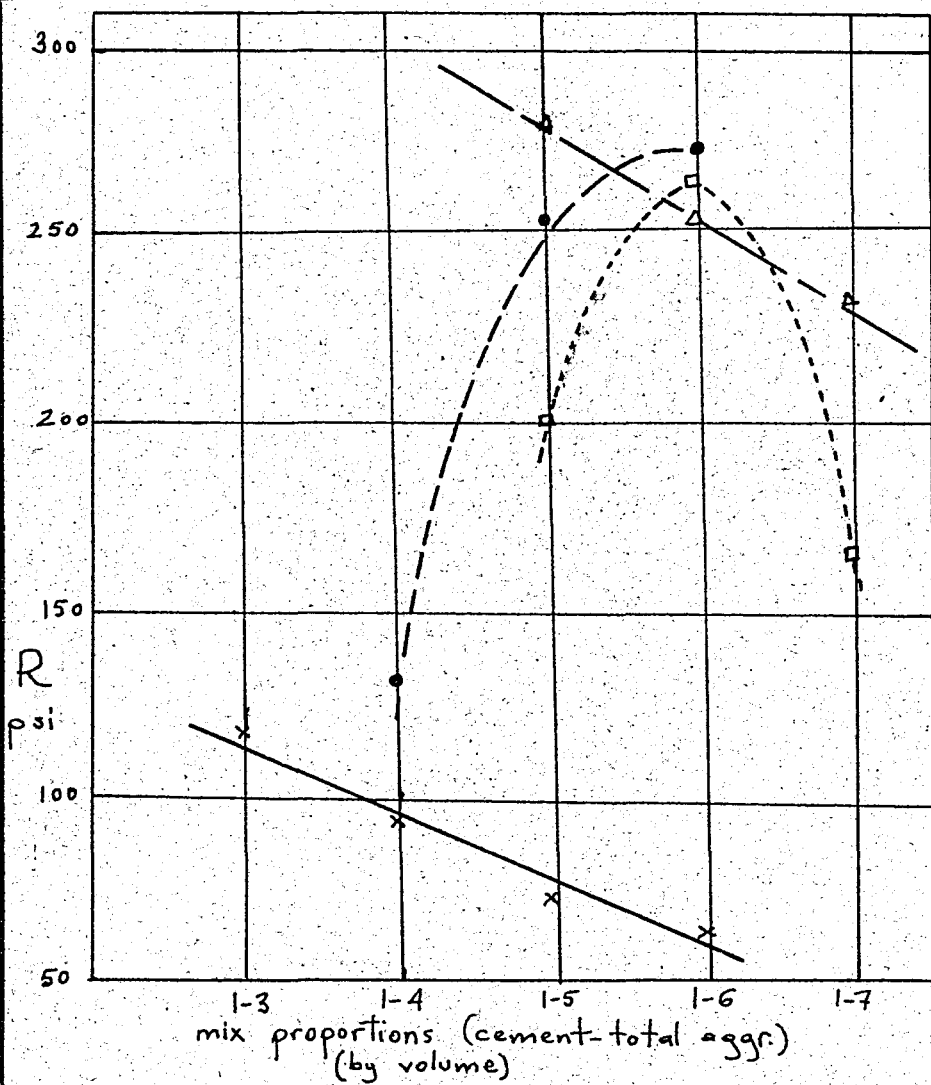
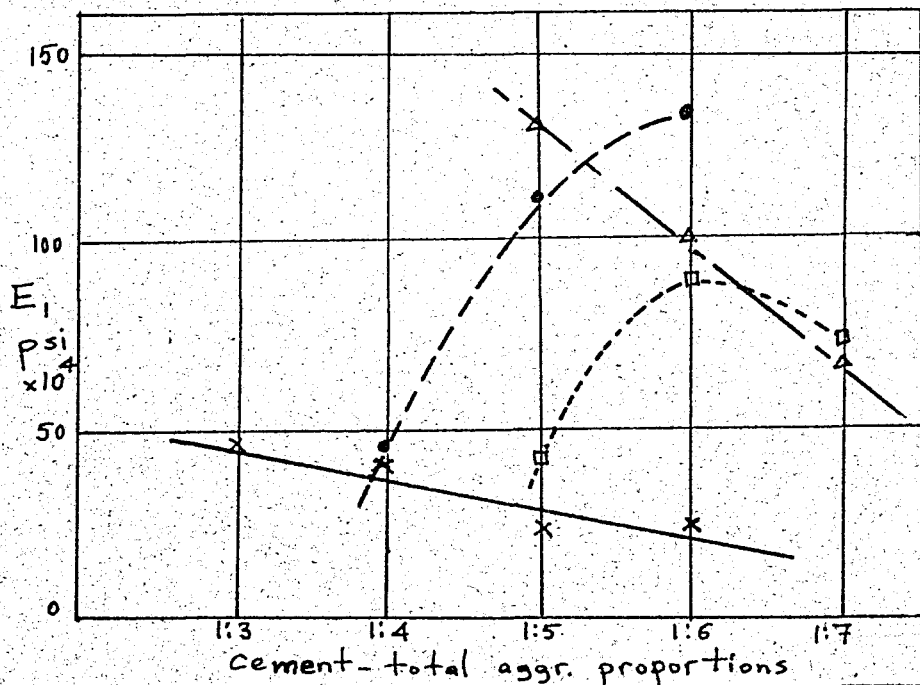


Fig. (23) - Relation of R to cement-total aggregate proportions.

Fig. (24) - Relation of initial tangent modulus to cement-total aggregate proportions.



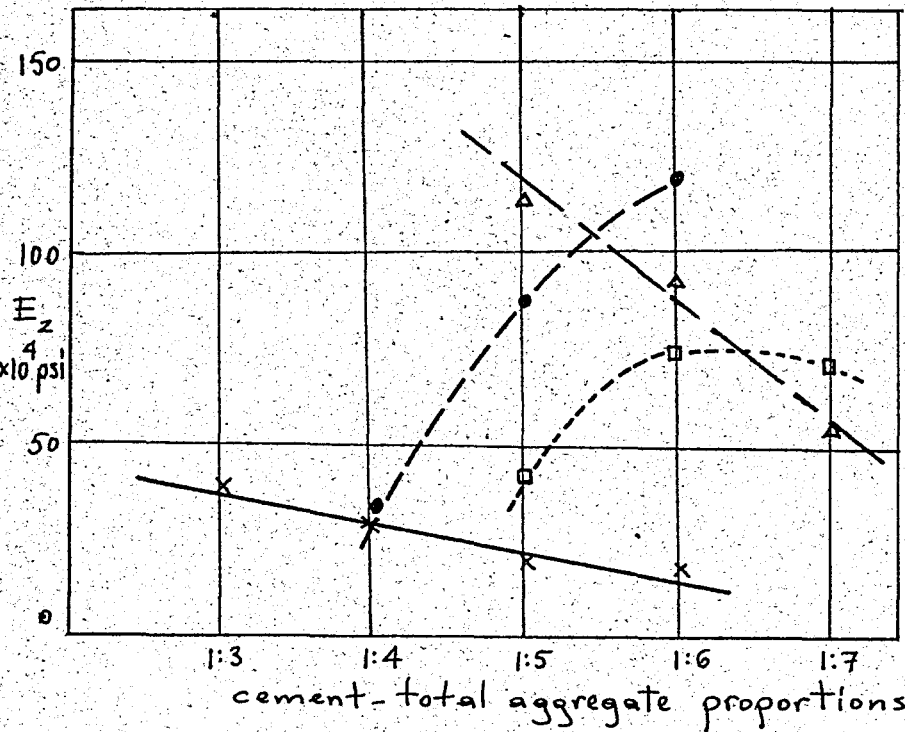


Fig. (25) - Relation of secant modulus at $0.5 f'_c$ to cement-total aggr. proportions.

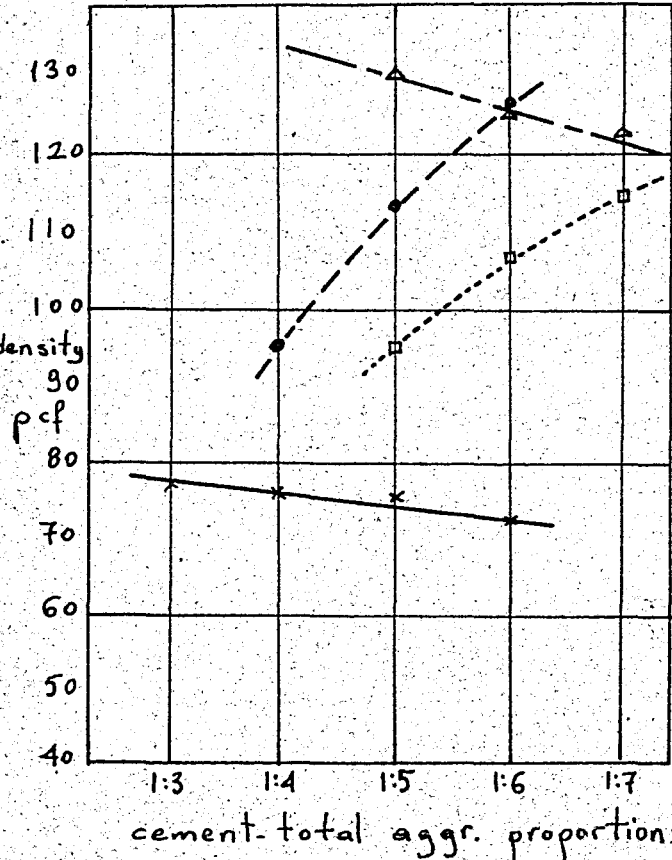


Fig. (26 a) - Relation of wet density to cement-total aggr. prop.

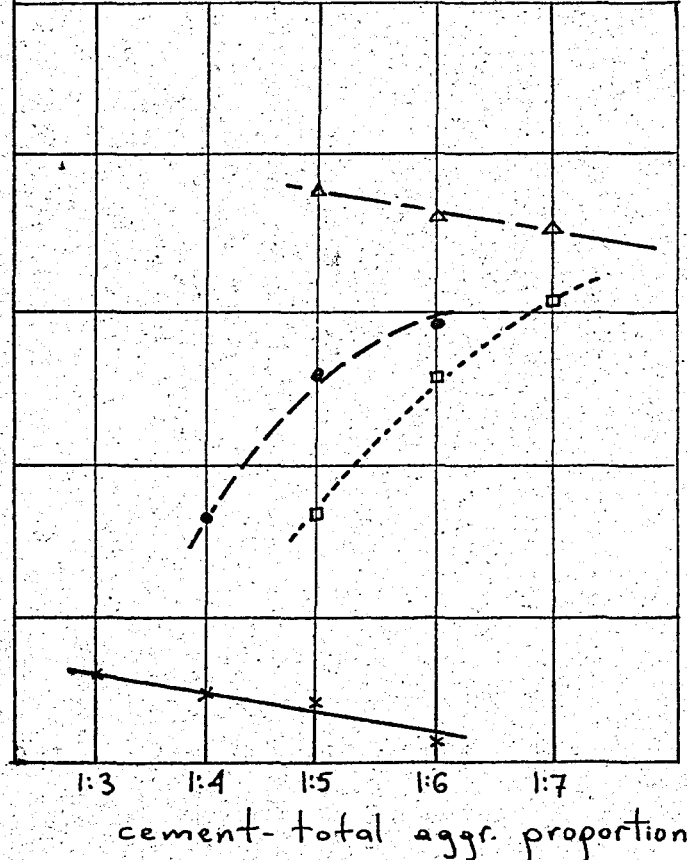


Fig (26 b) - Relation of oven-dry density to cement-total aggr. prop.

- If we apply the same kind of analysis to the mixes which have a total aggregate proportion of 6, we see that:

- 1-6-0 mix of Category I has the lowest values as:

f'_c around 250 psi,
 f_{sp} " 35 " ,
 R " 60 " ,
 E_1 " 200000 " ,
 E_2 " 150000 " ,

- 1-3-3 mix of Category III has the highest values as:

f'_c " 1130 psi,
 f_{sp} " 150 " ,
 R " 275 " ,
 E_1 " 1350000 " ,
 E_2 " 1200000 " .

- The remaining 1-4-2 and 1-0-6 mixes have values between those of the above two mixes. f'_c , f_{sp} , and R values for 1-4-2 mix are higher than those of 1-0-6 mix; whereas E_1 and E_2 values are lower.

- Ranges of values of various properties for each category are shown in Table (14).

RANGES FOR						
	Mix Prop. (by volume)	f'_c , psi	f_{sp} , psi	R , psi	E_1 ($\times 10^4$ psi)	E_2 ($\times 10^4$ psi)
Category I	1-3-0-1-6-0	350-250	80-30	120-60	50-20	40-15
" II	1-3-1-1-3-3	600-1150	90-150	130-270	40-135	30-120
" III	1-4-1-1-4-3	1100-450	140-80	260-160	40-90	40-75
" IV	1-0-5-1-0-7	1400-600	160-80	280-220	130-70	120-50

Table (14). - Ranges of values for various properties of test mixes.

- It is observed from the related figures that the values of the above mentioned properties are higher for the mixes of Category IV, namely cement-sand mixes, than the ones for the other categories for total aggregate proportions less than $5\frac{3}{4}$, and greater than 7, and are less for proportions between $5\frac{3}{4}$ and 7.

b- Relation of Densities to Proportions of Cement-perlite-sand

For this purpose Fig.(26) must be consulted.

As are seen from this figure:

- Wet densities of cement-perlite mortar mixes are between 70 to 80 pcf, and dry densities between 40 to 50 pcf.

- For cement-sand mortars these ranges change to 120 to 130 pcf for wet densities, and 110 to 120 pcf for dry densities.

- For cement-perlite-sand mortars, these values are scattered between 95 to 130 pcf for wet densities, and 70 to 105 pcf for dry densities.

- For cement-perlite and cement-sand mixes, the relationship between densities and aggregate amounts follow somewhat linearly decreasing patterns with increases in aggregate amounts.

- For cement-perlite-sand mixes, densities increase with the addition of sand, where perlite amounts are kept constant at 3 for Category II, and 4 for Category III, and the rate of this increase is in a diminishing order.

c-Relation of f'_c to Dry Unit Weight of the Mortar Mixes

Fig. (27) shows the relation between oven dry density and f'_c for all the four categories of mortar mixes.

- Oven dry densities increase as the compressive strength increases, rate of change being lowest for the cement-sand mixes, and highest for the cement-perlite mixes.

- For the same f'_c , the weight of cement-perlite-sand mixes is 60-85 % of that of cement-sand mixes.

- Addition of sand increases the compressive strength and oven dry density of the mix; the increase in the compressive strength being much more considerable.

- For cement-sand mortars changes in compressive strength does not affect the oven dry density very much.

d- Relation of f'_c to Modulus of Rupture (R), and Cylinder Splitting Strength

These relations are shown in Fig.(28) and Fig.(29) for f'_c -R relation and for f'_c - f_{sp} relation, respectively.

- For compressive strengths ranging from 200 to about 1150 psi, R tends to vary from 60 to 270 psi, and f_{sp} from 35 to 150 psi.

- The ranges of f'_c , R, and f_{sp} for each category are indicated in Table (14)

It is assumed that, R and f_{sp} are directly proportional to the square root of f'_c (2), namely

$$R = \alpha \sqrt{f'_c}, \text{ and } f_{sp} = \beta \sqrt{f'_c}.$$

the values of α and β are obtained by plotting $\ln R$ and $\ln f_{sp}$ vs.

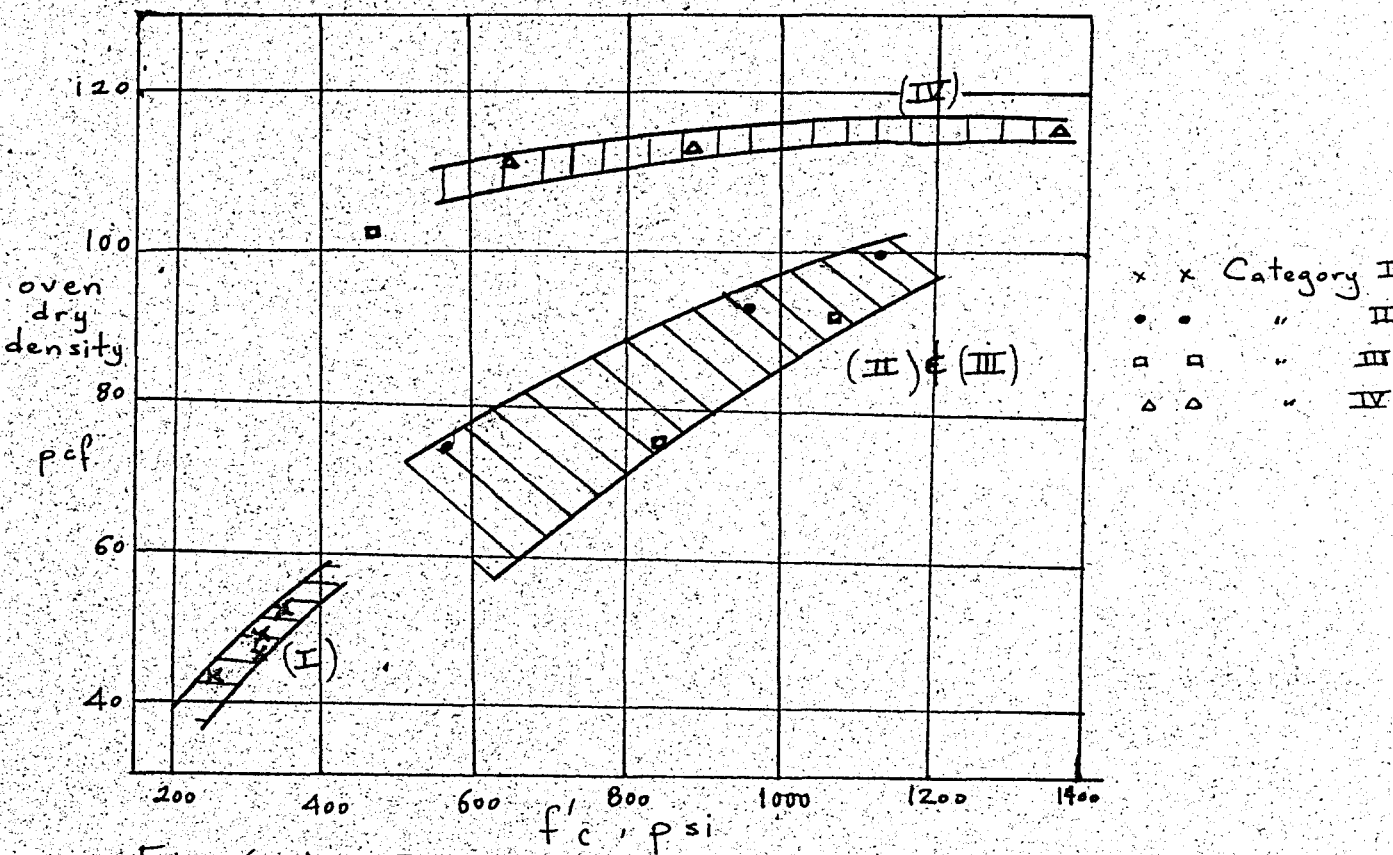


Fig. (27). - Relation between oven dry density and f'_c
(Numbers in parentheses refer to the Categories.)

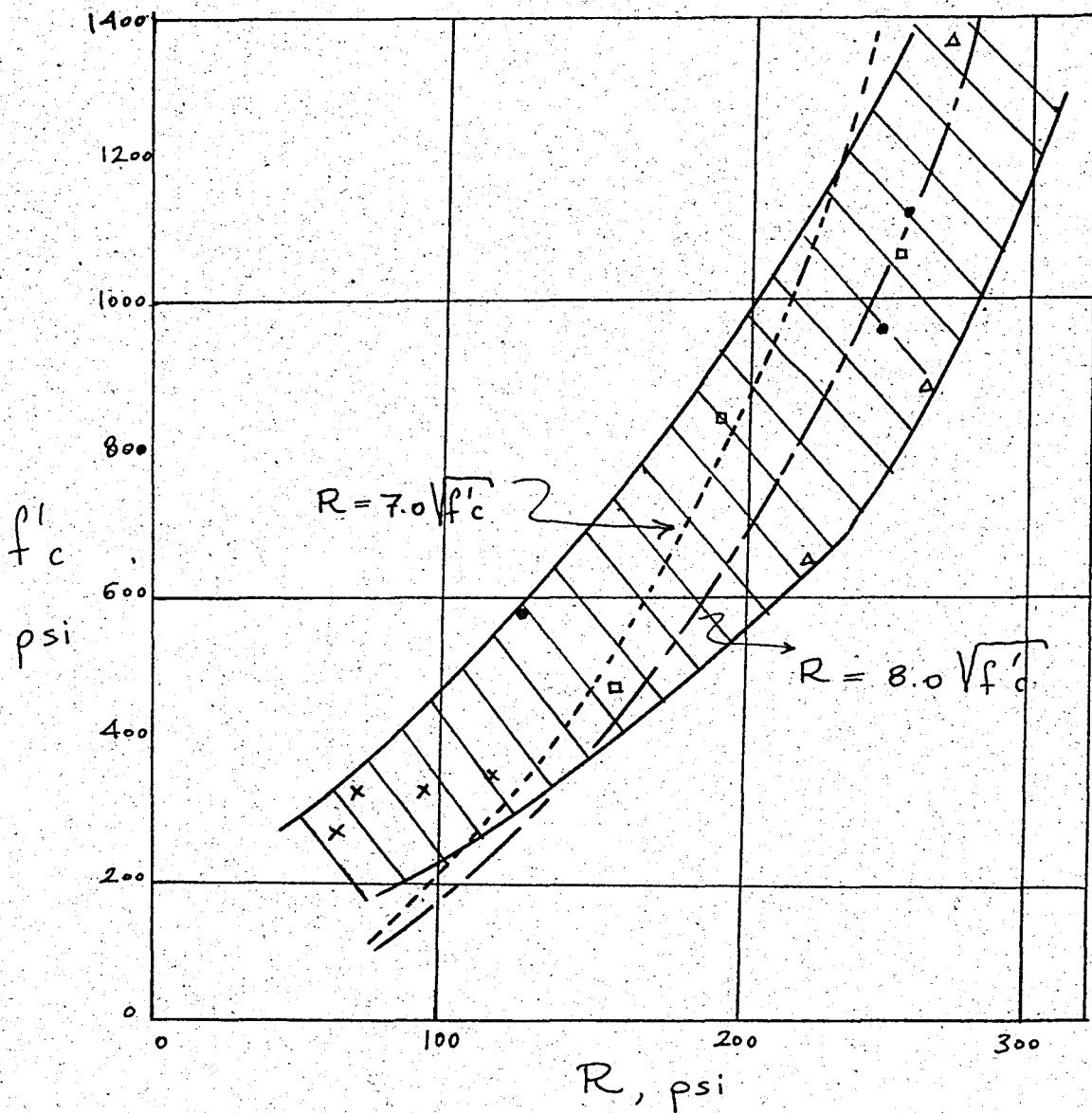


Fig (28).- Relation of compressive strength to Modulus of rupture.

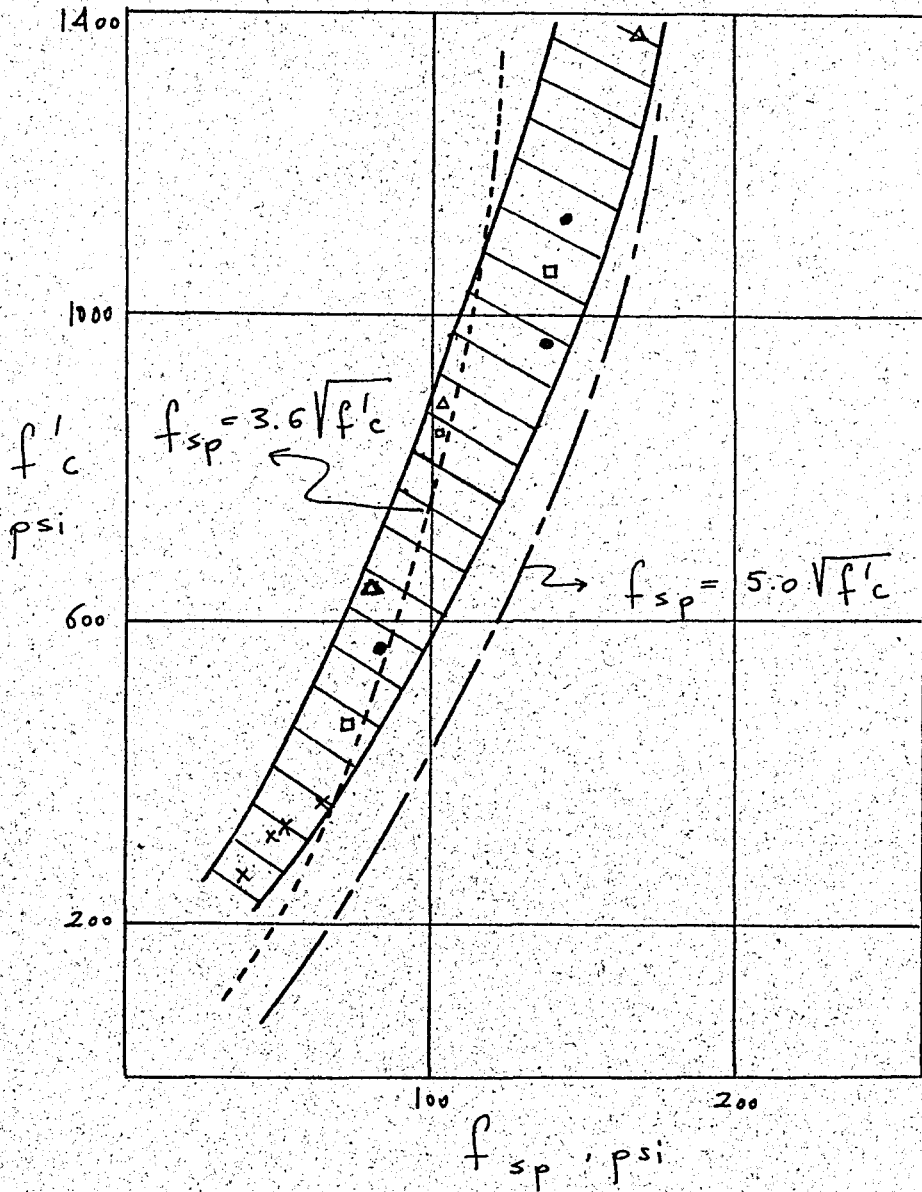


Fig (29) - Relation of compressive strength to cylinder splitting strength.

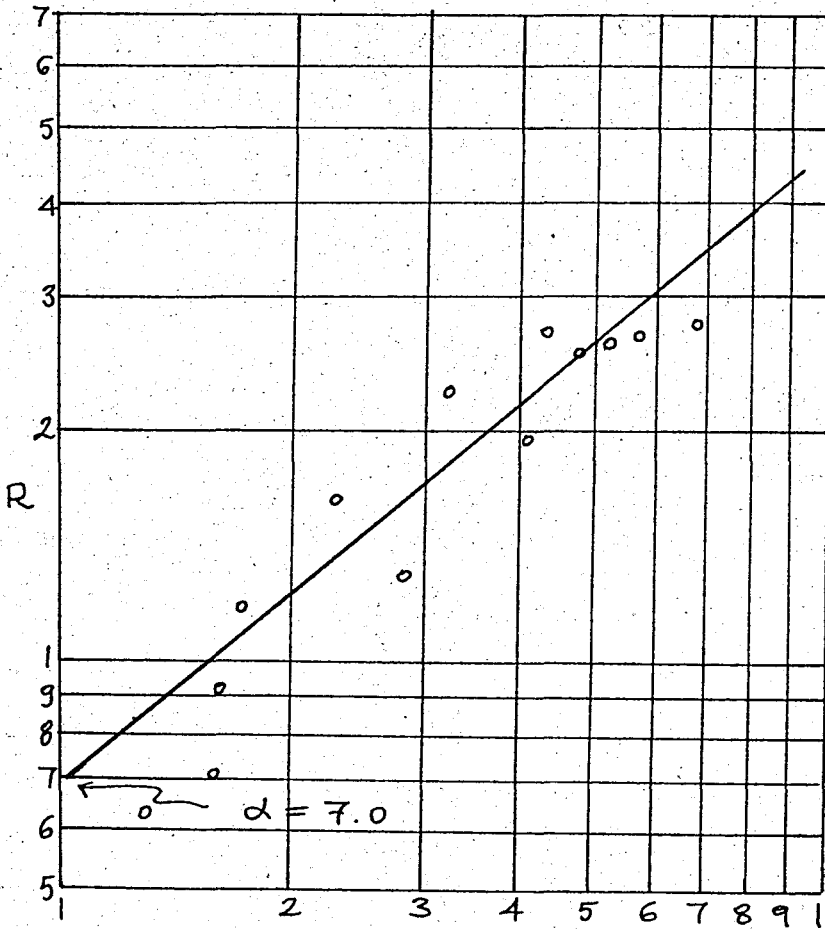


Fig (30).- Determination of the value of α in $R = \alpha \sqrt{f'_c}$ by using logarithmic relations.

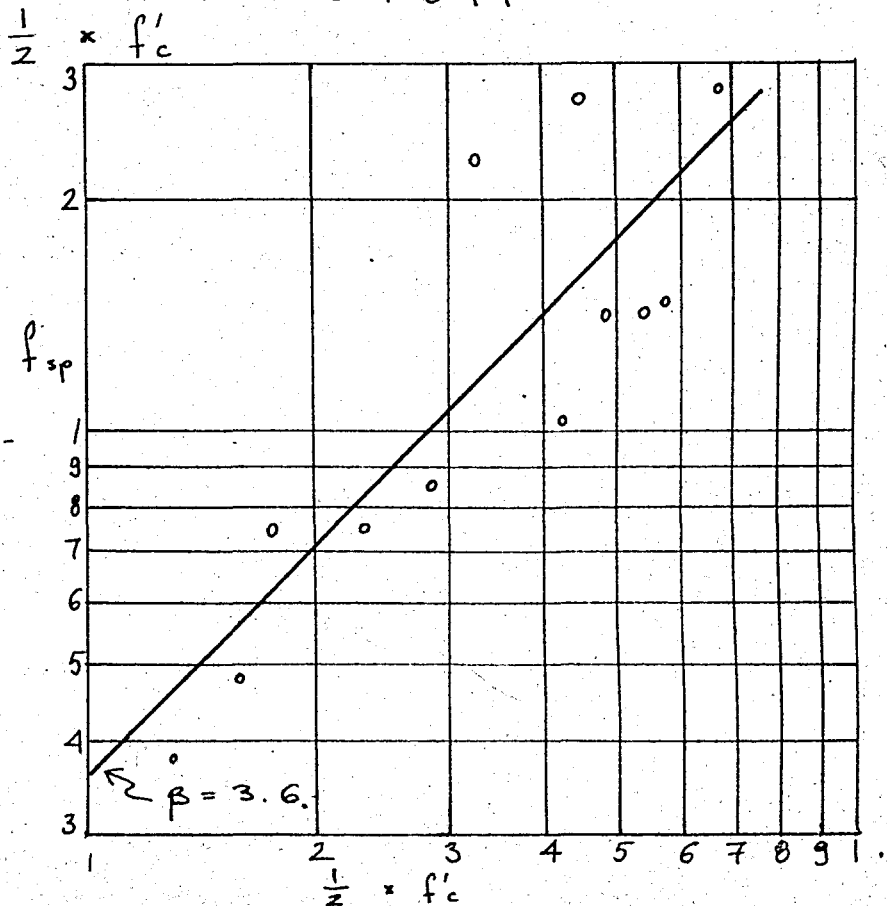


Fig. (31).- Determination of the value of β in $f'_{sp} = \beta \sqrt{f'_c}$ by using logarithmic relations.

$\frac{1}{2} \ln f'_c$ in a log-log paper as shown in Fig.(30), and Fig.(31), respectively, and they came out to be 7.0 for α , and 3.6 for β .

The curves representing $R = 7.0 \sqrt{f'_c}$ and $f_{sp} = 3.6 \sqrt{f'_c}$ were drawn in Fig.(28) and Fig.(29), respectively.

Short and Kinniburgh (2) give the value of α as 8.0, and β as 5.0. The curves for these values were also shown in the corresponding figures for comparison, and it is seen that the curves drawn using the experimentally found values fit better than the ones using Short and Kinniburgh's values.

Grieb and Werner state that (21) f_{sp}/f'_c values of concretes prepared with 10 different lightweight aggregates ranged from 5.3 to 11.2 % with an average ratio of 8.0 %. According to the results of our tests, f_{sp}/f'_c ranged from 12.2 to 16.2 % with an average ratio of 15.1 %. This shows that Grieb and Werner's average value is 53 % of our average value.

R/f'_c ranged from 22.3 % to 54.8 % with an average value of 26.4 %. Valore (14) gives this range as 20.0 to 45.0 %, which is in complete agreement with the obtained values.

e- Relation of R to f_{sp} :

This relation is represented by Fig.(32)

As is seen from this figure, there is a linear relation between R and f_{sp} , and this relationship is expressed by the following formula:

$$f_{sp} = 0.54 R$$

Short and Kinniburgh give f_{sp} as 60 % of R (2), and in our tests it came out as 54 %, which agrees quite well with the former value. By considering individual results, it is seen that f_{sp}/R

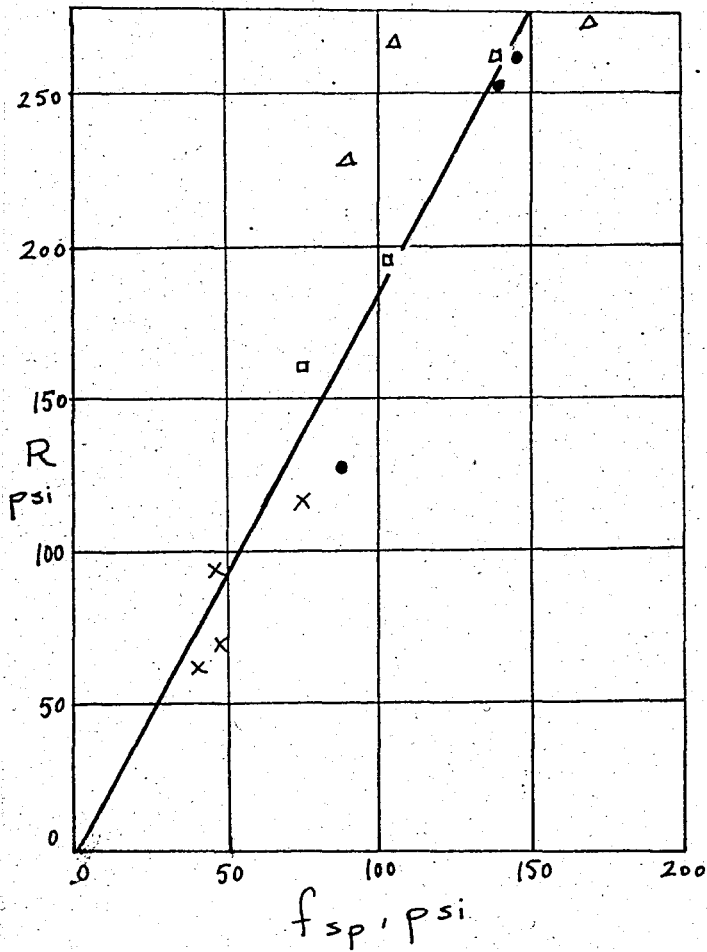
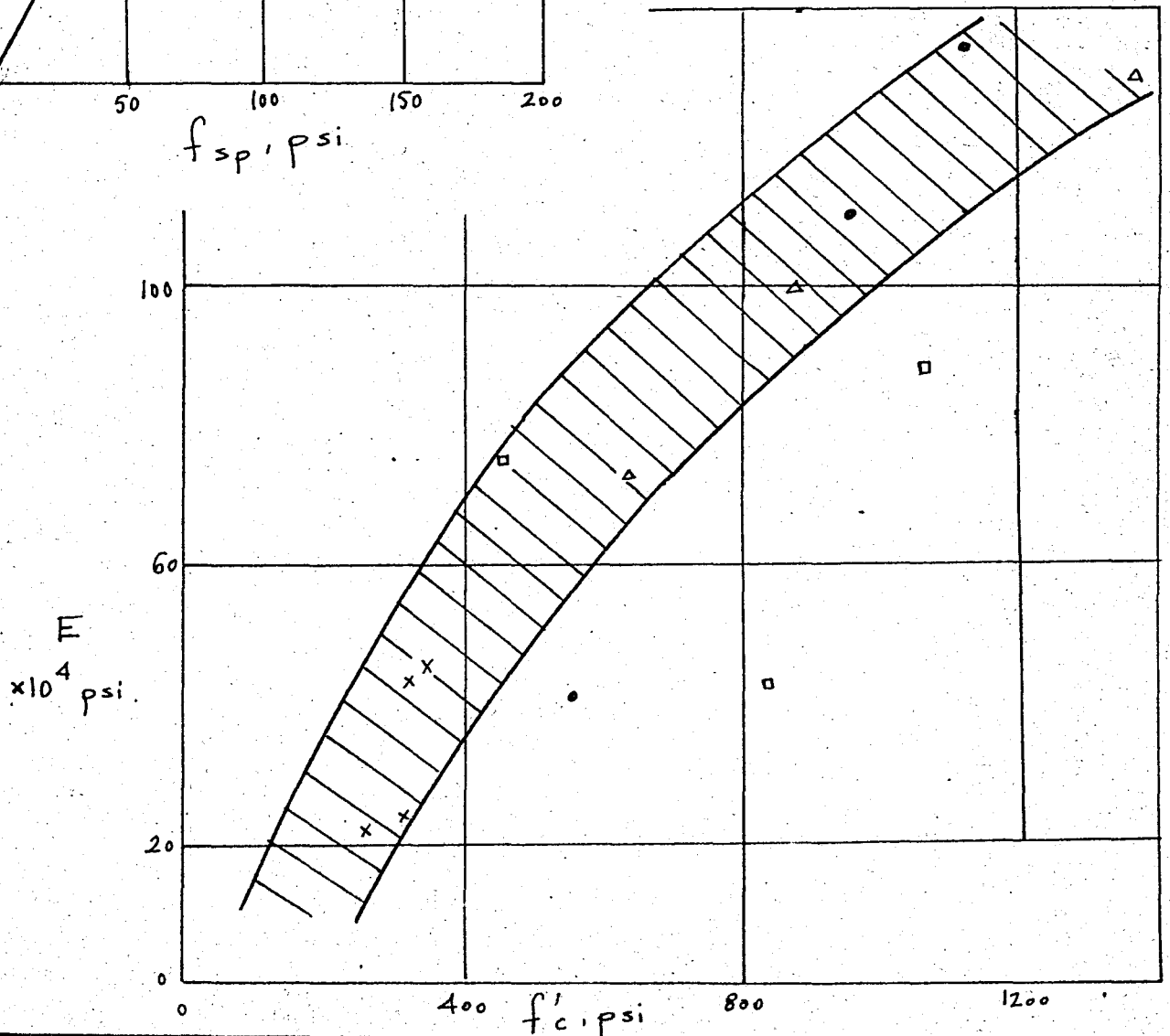


Fig (32).- Relation between Modulus of Rupture, & cylinder splitting strength.

.....
Fig. (33).- Relation between initial tangent modulus & f'c.



ranges from 47 to 69 % with an average value of 57.6 %.

Grieb and Werner (21) give this range as 57 to 88 % with an average value of 76 %, as a result of tests on concretes prepared with 10 different lightweight aggregates. Their values have a higher range than ours.

f- Relation of Modulus of Elasticity to f'_c and Density

Fig.(33) shows the relationship between the initial tangent modulus and f'_c .

E_1 has a range from 200,000 to 1,300,000 psi for a compressive strength range of 200 to 1200 psi.

Valore (14) specifies the range of E_1 for perlite insulating lightweight concrete as from 70,000 to 250,000 psi for a range of compressive strength of 80 to 450 psi. In our tests the range of E_1 of the mixes which can be used for insulation purposes is from 220,000 to 460,000 psi, for a range of compressive strength of 260 to 560 psi.

Modulus of elasticity is also related to density, and this relation is shown in Fig.(34).

As can be seen from Fig.(33) and Fig.(34), modulus of elasticity increases at a diminishing rate for increases of the compressive strength, and at an increasing rate for increases of the density. From this relation the following facts can be concluded:

- Modulus of elasticity is not linearly dependent on f'_c , and density,
- Modulus of elasticity depends on exponential values of

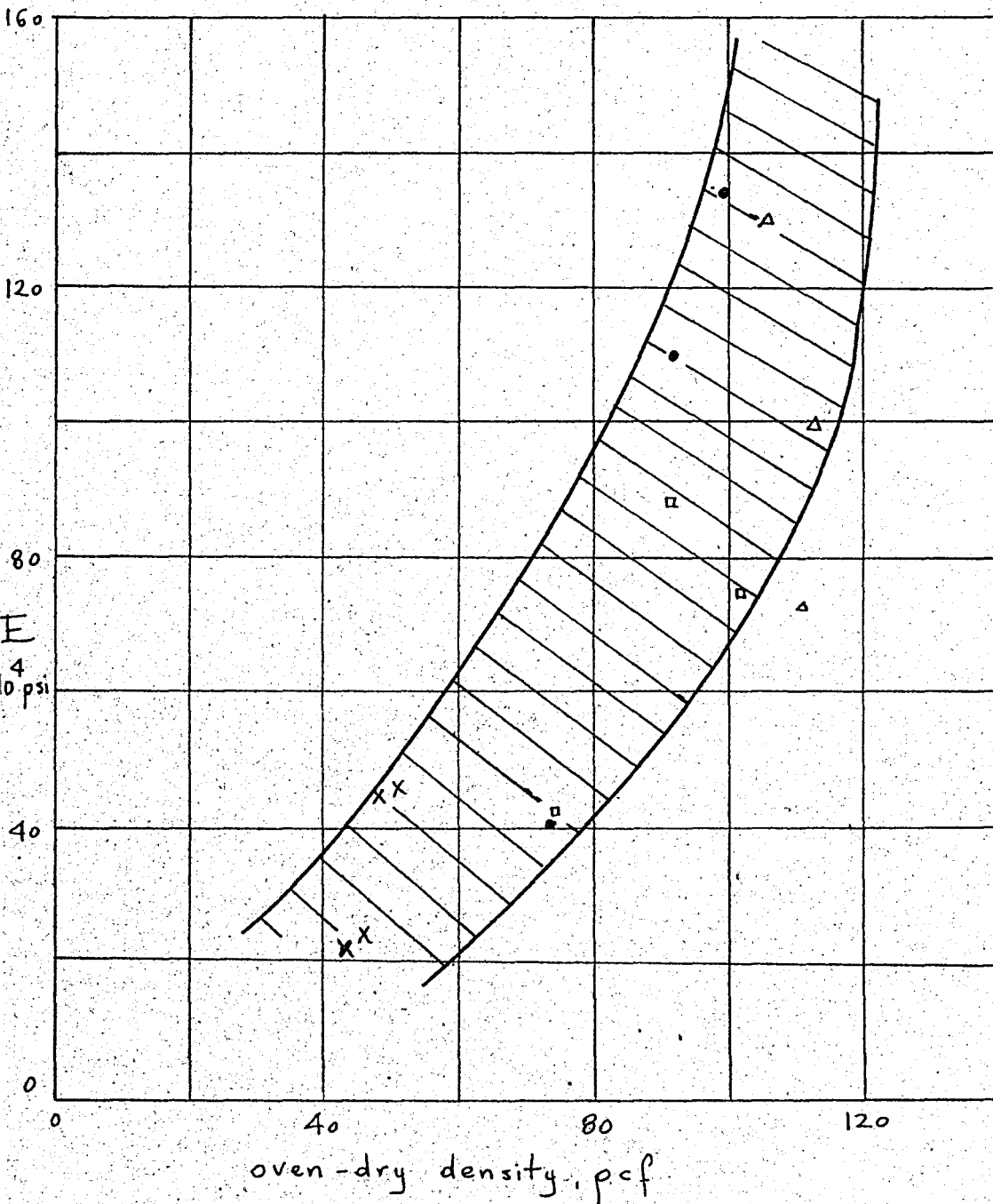


Fig. (34).- Relation of initial tangent Modulus to oven-dry density.

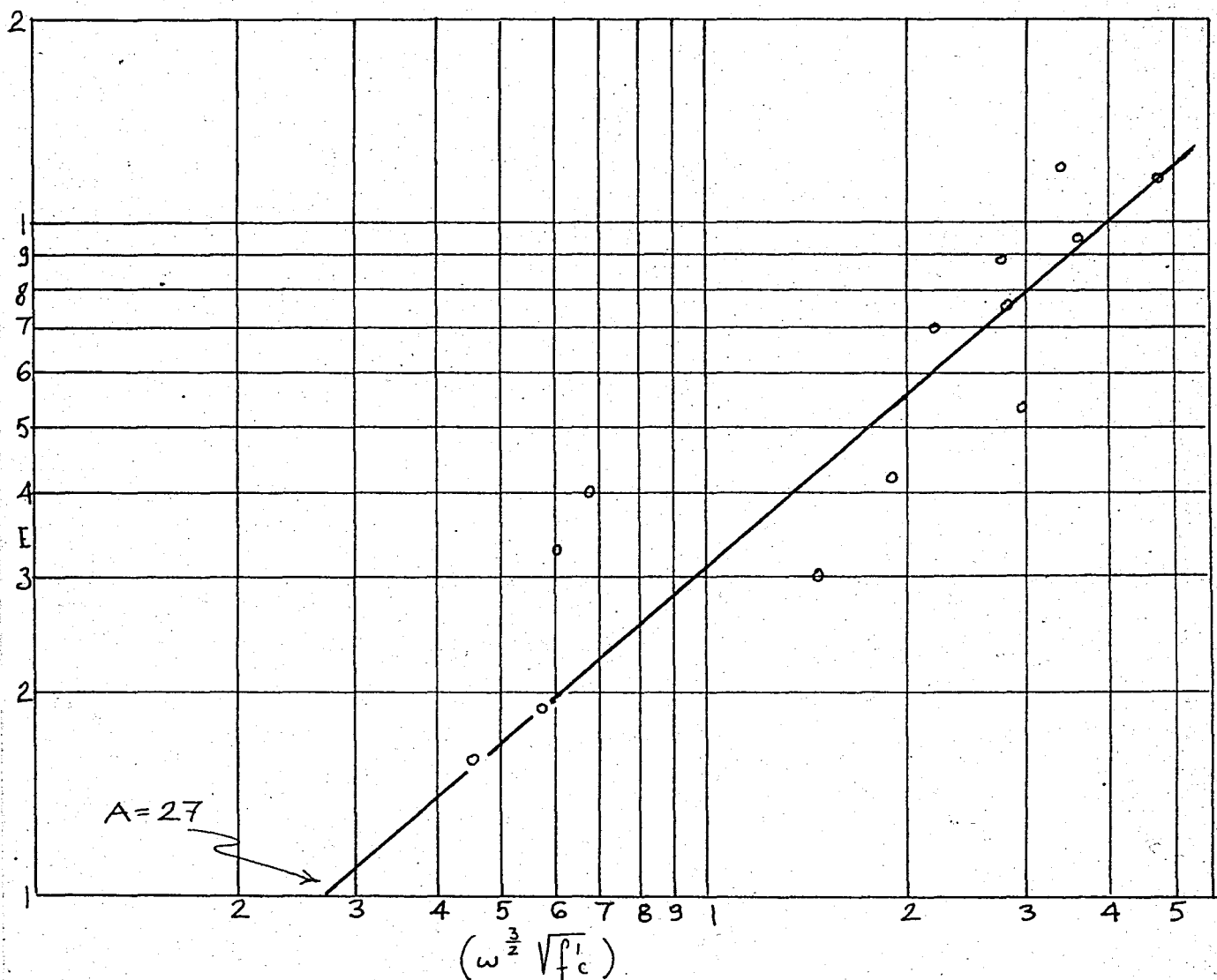


Fig. (35).- Determination of the value of A in $E = A \cdot \omega^{3/2} \sqrt{\rho/c}$, by logarithmic relations.

f'_c and density, where the exponent is less than one for f'_c , and greater than one for density.

Pauw (23) gives the exponents and the relation as:

$$E_c = A \cdot w^{3/2} \cdot \sqrt{f'_c} \quad , \text{ where } A \text{ is a constant, given as } 33.$$

Our value of A is obtained by plotting $\ln E_c$ vs. $\ln (w^{3/2} \sqrt{f'_c})$ in a log-log paper as shown in Fig. (35), and the value of A came out to be 27.0 . So the formula

$E_c = 27 w^{3/2} \sqrt{f'_c}$ is obtained in our tests, for cement-perlite-sand concrete.

g- Comparison of the Obtained Properties with the General Qualifications Attributed to Lightweight Aggregate Concretes

General properties of lightweight aggregate concretes were given in Table (7), and having compared the values stated there with the values obtained as the results of our tests as stated in Table (13), the following facts are observed:

- Category I: The qualifications of all the cement-perlite mixes are in perfect agreement with those of insulating lightweight concretes,

- Category II: 1-3-1 mix has the qualifications of insulating lightweight concretes, whereas 1-3-2 and 1-3-3 mixes can be used as structural lightweight concretes,

- Category III: 1-4-1 mix has properties of insulating lightweight concretes, 1-4-2 can be used as structural lightweight concrete, but 1-4-3 mix has qualities not in complete agreement with any type of lightweight concrete.

- Category IV: These mixes were prepared with normal aggregate only, and are considered as normal concrete.

Out of three mixes (1-3-2, 1-3-3, 1-4-2) which can be used for structural purposes, 1-3-3 is the best one satisfying the required characteristics more than the others in the following ways:

a- Its compressive strength and modulus of elasticity are 18 % and 22 % higher, respectively, than those of 1-3-2 mix, and 6 % and 52 % higher than those of 1-4-2 mix.

b- R and f_{sp} values can be considered the same, although there is an unconsiderable 4 % difference in favor of 1-3-3 mix.

c- Strength-weight ratio of 1-3-3 mix is 10 % greater than that of 1-3-2 mix, and almost the same with that of 1-4-2 mix.

d- The only disadvantage of 1-3-3 mix arises in the value of its density which is about 8 % higher than those of the other mixes. But as is seen from this percentage, this disadvantage is unconsiderable. So, 1-3-3 cement-perlite-sand mix is the best mix, as a whole, for structural purposes.

h- Stress-Strain Relations for Cement-perlite-sand Mortar Mixes

Stress-strain curves and corresponding stress-E curves drawn for all the mix proportions are shown in Fig.(36) to Fig.(39), and from these figures initial tangent modulus and secant modulus at $0.5 f'_c$ were obtained for each mix proportion, and these values were given in Table (13).

The relation of the two types of moduli of elasticity to cement-total aggregate proportions were shown in Fig.(24) and in Fig.(25), and were discussed in Page (55).

If we examine the stress-strain curves, we see that:

- For cement-perlite mixes; the curves get flatter and flatter as the perlite amount is increased; and the linearity of σ - ϵ relation is true only for a small range of σ .

- For cement-perlite-sand mixes; the curves are getting sharper and sharper as the sand amount is increased, but flattening begins when the sand proportion is increased above two, in mixes having a perlite proportion of 4. Also the linearity of σ - ϵ relation applies for a greater range of σ .

- For cement-sand mixes ; the curves are sharpest, but as the sand amount is increased they begin to flatten. Also the range of giving rise to a linear relation between σ and ϵ is largest.

We can conclude that lightweight aggregates cause some flattening in $\sigma - \epsilon$ curves, and narrows the range of σ which gives a linear relationship between σ and ϵ .

The ratio n of the modulus of elasticity of steel to that of concrete is compared to values of n established by the ACI Building Code (10), in Table (15)

Mix Proportion	f'_c , 28-day, psi	E_s/E_c	$30,000/f'_c$
1-3-2	1100	27.3	31.2
1-3-3	1340	22.4	26.8
1-4-2	880	34.1	28.0

Table (15).- Comparison of n values for mixes which can be structurally used, obtained in two different ways.

Values established by the two definitions are in fair agreement for all three proportions of mix.

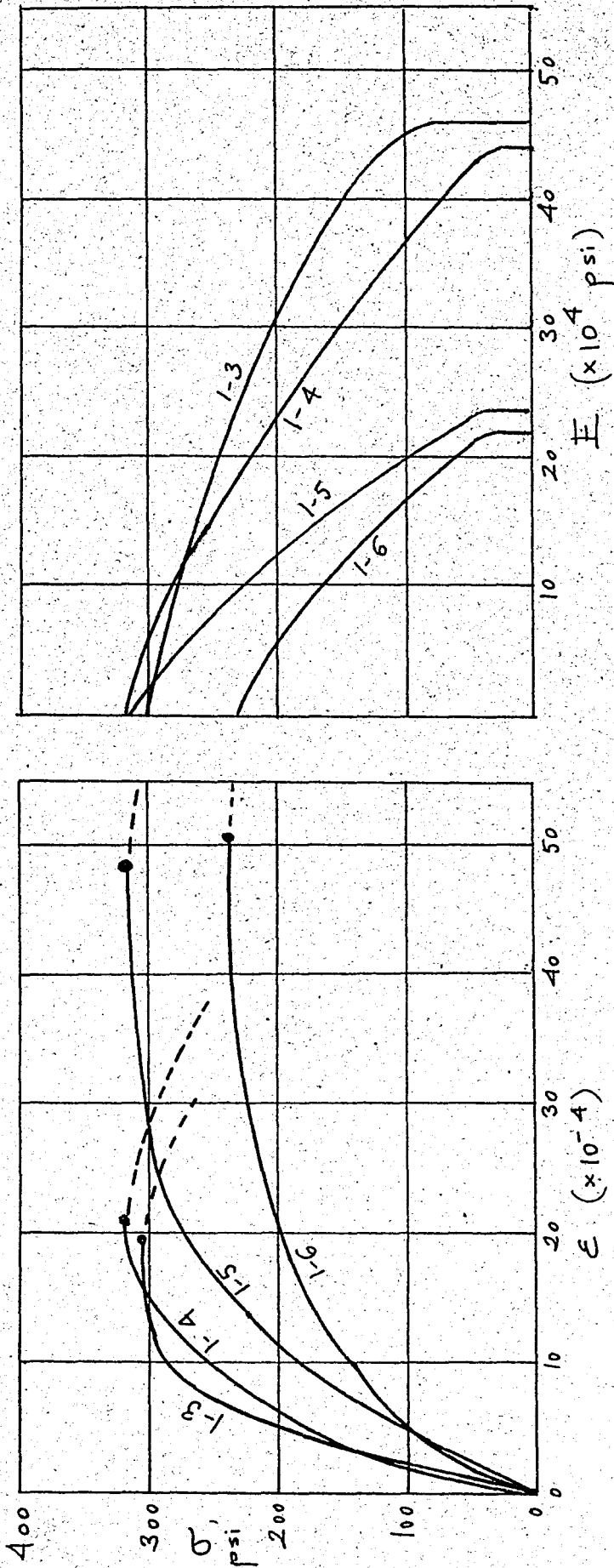


Fig. (36). - σ - ϵ and σ - E relations for 1-3, 1-4, 1-5, 1-6 cement-perlite mixes.

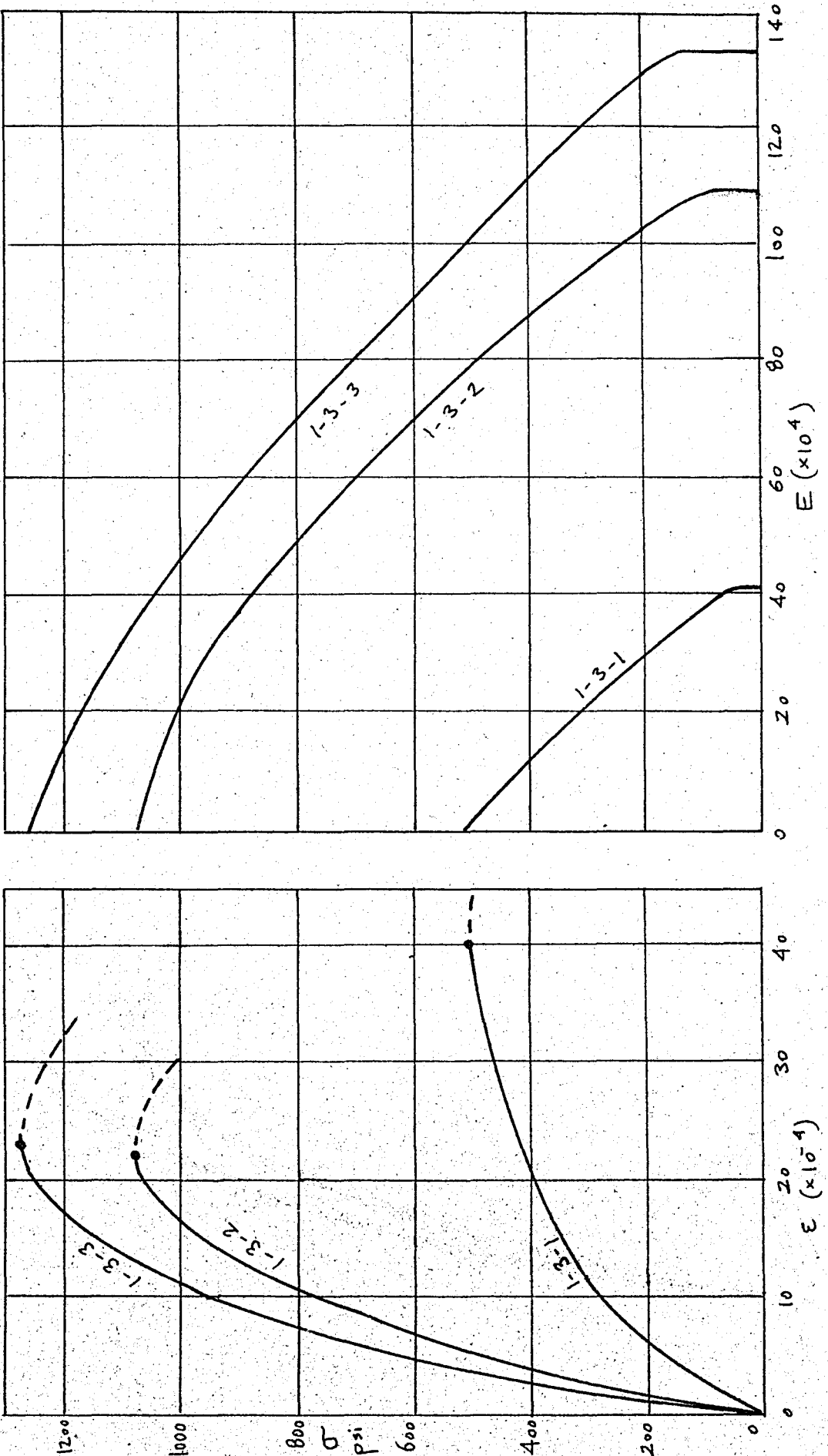


Fig. (37). - σ - E and σ - E relations for 1-3-1, 1-3-2, 1-3-3 cement-perlite-sand mixes.

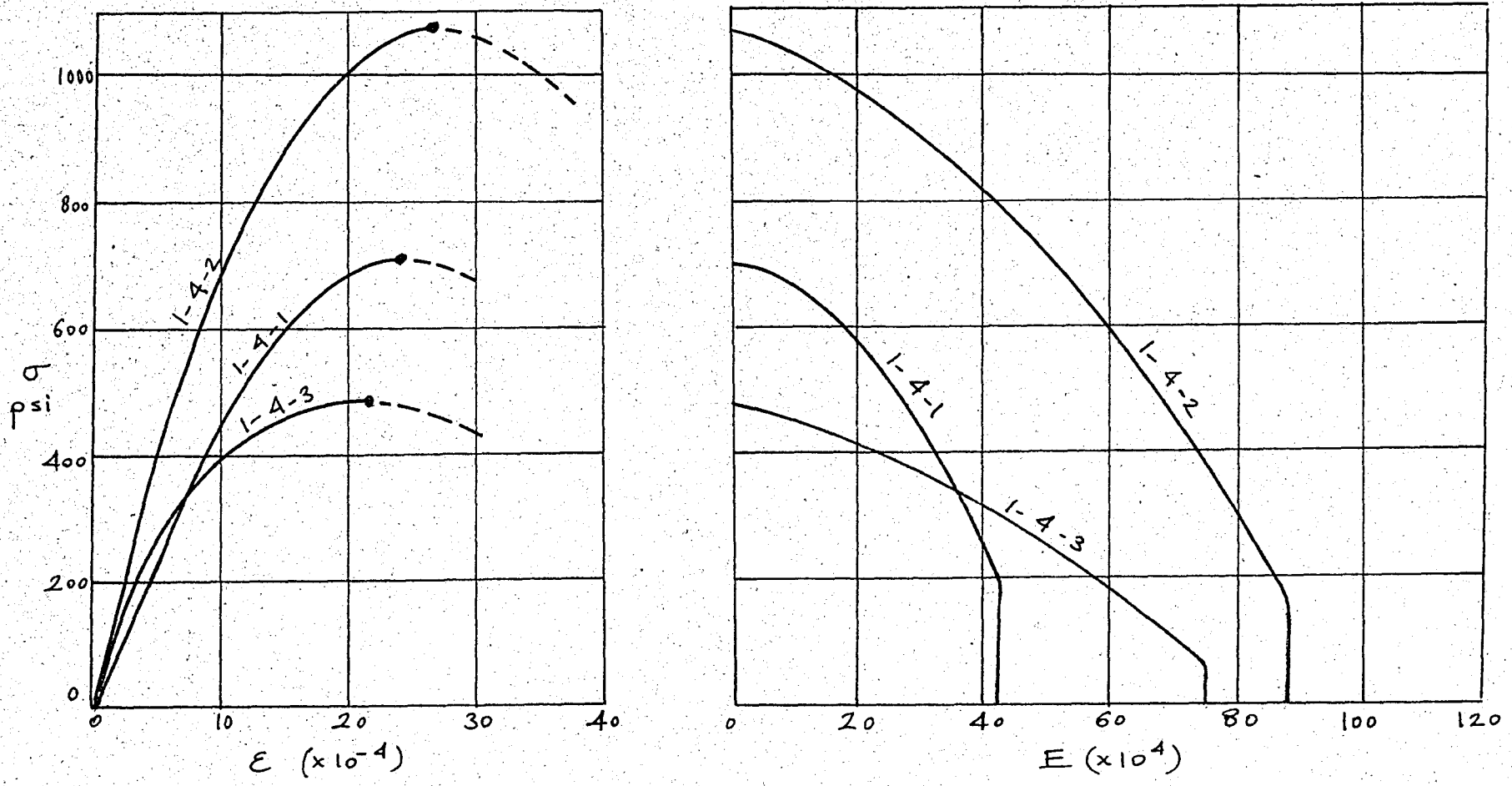


Fig. (38).- σ - E and σ - E relations for 1-4-1, 1-4-2, 1-4-3 cement-perlite-sand mixes.

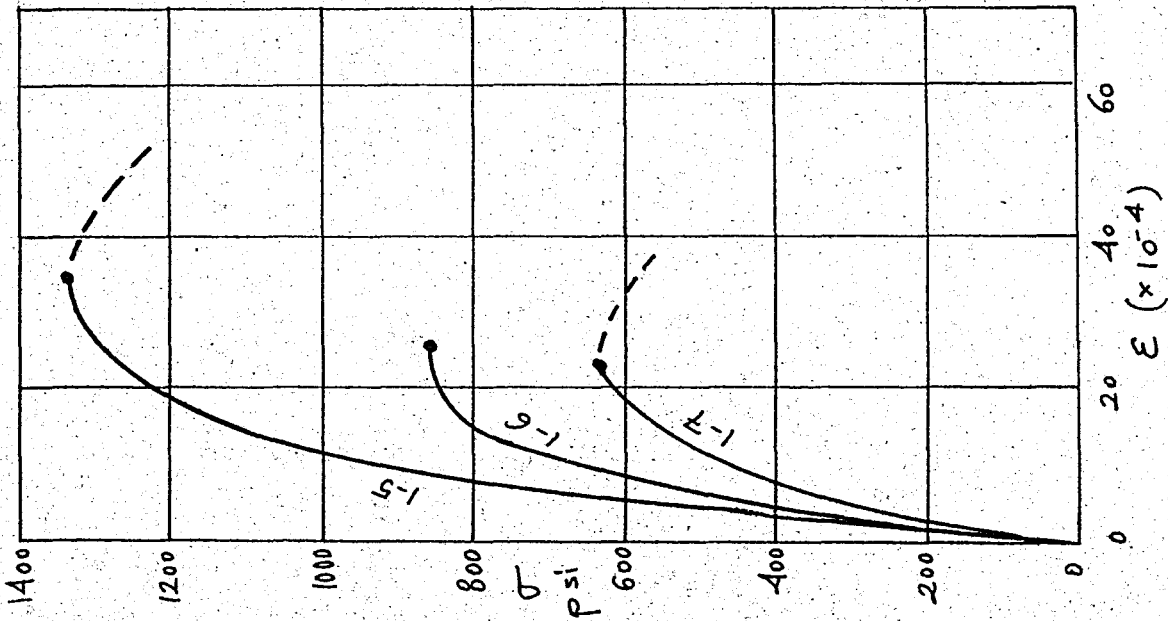
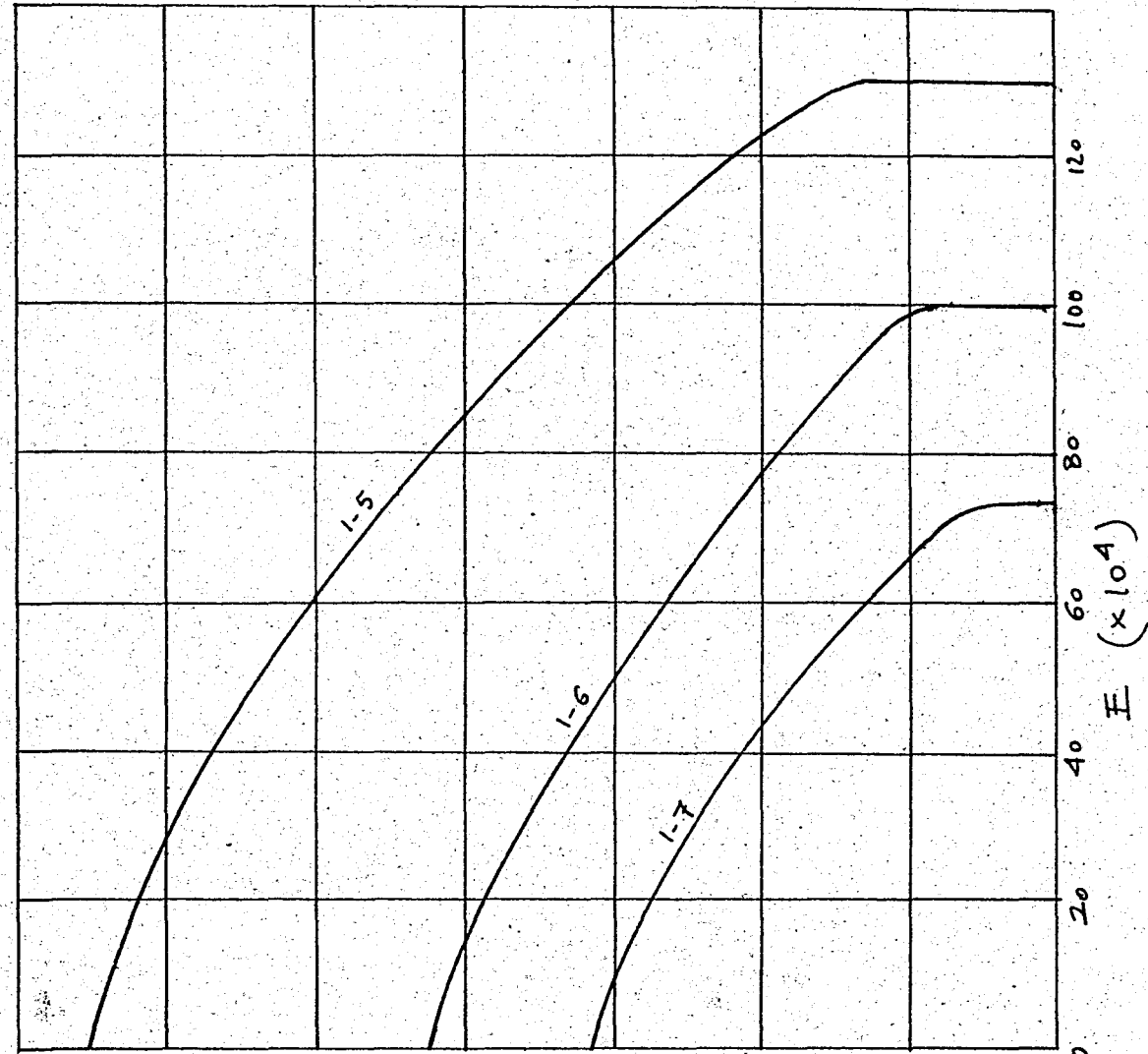


Fig (39).- σ - E and σ - E relations for 1-5, 1-6, 1-7 cement-sand mixes.

C O N C L U S I O N S

From the results of the tests and from various plottings the following conclusions can be drawn:

- f'_c , f_{sp} , density, modulus of rupture, initial tangent modulus, and secant modulus for one-type-aggregate-mortars decrease linearly as the aggregate amount is increased.

For two-type-aggregate-mortars, namely perlite and sand, the above values increase to a maximum with the increase in sand amount, perlite amount being kept constant; and then a decrease begins when the sand proportion is increased above a certain value. (The sand proportion which gives the maximum values for a perlite proportion of 3, taking that of cement as one, is somewhere between 2.5 and 3.5; and for a perlite proportion of 4, it is 2.)

The decrease in the values beyond a certain proportion is due to the fact that the lowering effect on the values of various properties, of increasing aggregate amount overcomes the increasing effect of adding sand to perlite lightweight aggregate.

- Oven dry densities increase as f'_c increases.

- The relation of modulus of rupture and f_{sp} to f'_c can be represented by parabolas as:

$$R = 7.0 \sqrt{f'_c} \quad , \quad \text{and} \quad f_{sp} = 3.6 \sqrt{f'_c} \quad .$$

- The relation between f_{sp} and R is given by:

$$f_{sp} = 0.54 R \quad .$$

- All of the cement-perlite mixes, and 1-3-1, 1-4-1 cement-perlite-sand mixes have qualifications of insulating lightweight concretes, 1:6 mix being the best for this purpose.

- The mixes which can be used as structural lightweight concrete are 1-3-2, 1-3-3, and 1-4-2 in cement-perlite-sand order.

- Initial tangent modulus of insulating lightweight concrete mixes ranges from 220,000 to 460,000 psi, for a range of f'_c from 260 to 560 psi, and of structural lightweight concrete mixes from 880,000 to 1,100,000 psi for 960 to 1130 psi compressive strength.

- The value of the constant A in the formula (23): $E = A w^{\frac{3}{2}} \sqrt{f'_c}$ was found to be 27.0 for our mixes; and the dependence of E on density and f'_c is expressed by the formula

$$E = 27.0 w^{\frac{3}{2}} \sqrt{f'_c} .$$

- Lightweight aggregate causes some flattening in $\sigma - \epsilon$ curves, and narrows the range of σ which gives a linear $\sigma - \epsilon$ relation.

- The value of $n = E_s / E_c$ for our structural lightweight concrete mixes is about 28.0.

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