ABSTRACT

MECHANICAL BEHAVIOR OF POLYSTYRENE FOAM BEAD LIGHTWEIGHT CONCRETE

by
Hai-Ying Ni

This thesis is designed to investigate the effect of porosity on the mechanical properties (strength and modulus) of concrete, and to evaluate the effect of silica fume on the mechanical properties of the polystyrene foam bead lightweight concrete. In this research we made the lightweight concrete by using polystyrene foam beads as light weight aggregate and studied its mechanical properties in detail. Due to the near zero density and modulus of foam beads, we were able to consider it as "porosity". We could then control porosity in concrete by varying foam bead volume fraction.

In our experiments we used the sand-cement paste as the control matrix, then systematically varied the foam bead volume fraction. Our results showed that the effect of porosity (foam bead content) and silica fume on the strength of the concrete followed the predictable pattern: increase in porosity decreases the strength of the concrete, increase in silica fume increases the strength of the light weight concrete. The mechanical properties of foam bead concrete was best described by equations governing porosity effects. The strength (or modulus) relationships fit very well with the porosity model proposed by Wischers (16).

In our research we treat the light weight concrete as a composite material considering sand-cement paste as matrix and the foam bead as the second phase. Test results of the modulus showed that only one of the three models of the composite theory approximately fit the relationship between the modulus and the porosity (foam bead volume

fraction).The ideal model was the Power's model (8).This model can also be used to determine the actual modulus of cement paste by extrapolating to zero porosity. We applied this method to cement matrices made with and without silica fume.

The results of this investigation show that the macroporosity of concrete has similar effects to that of microporosity, and those equations describing these phenomena are applicable up to a large volume fraction of porosity. Foam bead particles in concrete can thus be used to study the effect of porosity on concrete properties.

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by
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APPROVAL PAGE

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This thesis is dedicated to
my parents

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CHAPTER 1

INTRODUCTION

Understanding the effect of porosity on the mechanical properties of concrete is essential to advancing the field of materials engineering. In this work, we investigated the mechanical properties of lightweight concrete made with polystyrene foam beads. The porosity of the concrete was controlled by the amount of foam beads used in the concrete. In this thesis we report fundamental and practical results pertaining to the effect of porosity on the mechanical properties of concrete.

The application of polystyrene foam beads as lightweight aggregate in concrete has been reported in the past (1). There are limitations for using foam bead concrete in standard structural applications. These structural shortcomings are as follows:

1. The compressive strength achieved was low compared to conventional concrete made with dense aggregates. The applications of foam bead have been limited to low-load bearing structure or to non-structural applications.

2. Previous efforts did not utilize stronger matrix materials to improve the properties of the foam bead concrete materials.

In this work, we use silica fume material to improve the general properties of the foam bead concrete. Lightweight concrete based on incorporating polystyrene foam beads as lightweight aggregate where the cement matrix properties is optimized by adding silica fume may prove to be useful in structural applications, and in thermal and sound insulation. This will be shown in this work.

In this thesis, we treat the foam-bead concrete as a composite material considering the cement paste as the matrix and the foam bead as the second phase. We systematically vary the volume fraction of the bead and measure the compressive strength and elastic modulus of the concrete composite. We manipulate the strength of the matrix by adding silica fume to the mixture. The study deals with both fundamental and practical aspects of this composite material. We will show that the mechanical properties of the foam bead concrete is best expressed by considering foam bead volume fraction as porosity. The experimental results of this work contribute to our knowledge regarding the effect of macro porosity on the mechanical properties of concrete.

CHAPTER 2

RESEARCH OBJECTIVES

The objectives of this research are the following:

(1) To explore the mechanical properties of polystyrene foam bead lightweight concrete in the presence and absence of silica fume,

(2) To investigate the effect of foam bead volume fraction on the mechanical properties of the concrete composite,

(3) To relate the effect of foam bead to that of porosity on the strength and modulus of concrete materials,

(4) To define the volume fraction limits for making useful concrete using foam bead as lightweight aggregate,

(5) To apply and modify mathematical relationships describing the modulus and compressive strength of concrete to our situation, and

(6) To define possible application of foam-bead concrete based on the properties measured in this work.

CHAPTER 3

BACKGROUND

3.1 Material Properties

3.1.1. The Driving Forces for Using Lightweight Aggregate in the Concrete in Replacing the Natural Aggregates:

Environmental concern:

Resource conservation:

The consumption of different types of aggregates has increased enormously with the expansion of concrete-related construction. In some countries, hundreds of million tones of sand, gravel and crushed rock aggregate are being extracted out of the surface of the earth each year. The continuing extraction has created severe environmental problems, such as unrecoverable deterioration of the countryside and ecology. With increasing public concern of environmental protection, the construction industry is becoming more in favor of larger scale production and use of manufactured light weight aggregates including those generated from waste.

Environmental recycling:

Large volume of industrial waste is generated from packaging material made from polystyrene foam. The latter can be utilized as lightweight aggregates. The use of these waste can help environment recycling.

Table 1 shows recent production figures of lightweight aggregates in the countries considered

Structural benefit:

The light weight concrete reduces the deadweight of structures and consequently saves the foundation costs, reinforcements and overall size of some elements of the structure.

Other inherent advantages of the lightweight aggregates:

Table 1 FIP International survey of annual production and importation of lightweight aggregates

	Perlite and vermiculite (m^3)	Pumice (m^3)	Scoria (m^3)	Expanded clay (m^3)	Expanded shale (m^3)	Expanded slate (m^3)	Foamed slag (m^3)	Sintered pulverized fuel ash (m^3)	Date of survey
Australia			50 000						1979
Austria	130 000			380 000				850 000	1974
Belgium				900 000					1979
Brazil					87 000	100 000			19790
Bulgaria	200 000			180 000					1979
Canada	620 300	42 700		576 600	576 600	576 600	576 600		1977
Czechoslovakia	3412 000			225 000		45 000	570 000	76 000	1979
Denmark	25 000			2 000 000					1979
Finland				450 000			100 000		1979
France			60 000	70 000					1979
Federal Republic of Germany	400 000	3 200 000		850 000	65 000			65 000	1978
German Democratic				225 000		210 000	650 000	206 600	1980
Hungary	300 000						300 000		1979
Italy				1 700 000					1979
Japan	660 000				1 370 000				1978
Mexico	20 000								1972
Netherlands				10 000					1980
Norway				880 000	imported				1978
Poland				850 000	650 000		140 000	80 000	1979
Portugal				180 000					1975

(Adapted from FIP Manual of Lightweight Aggregate Concrete)

Fire resistance, low thermal conductivity, low coefficient of thermal expansion and low erection and transportation costs for precast members are among the advantages of light weight aggregates. Tables 2, and 3 show typical properties of some lightweight aggregate concretes--generally used for structural and insulation purposes.

3.1.2. Polystyrene Foam Bead Aggregates

Manufacturing Process:

Genuine polystyrene foam bead is manufactured by a quite simple process:

Plastic beads are soaked in an blowing agents that effects expansion of the beads upon exposure to a heating cycle. Another source to obtain foam beads is by grinding waste polystyrene foam materials.

Physical and Mechanical Properties:

The properties of the polystyrene foam bead used in this research are shown in Tables 4, and 5.

Table 4 Grading of the Polystyrene Foam Bead

Sieve	Percentage retained
3/8	0
4	26.8
8	70.0
16	3.2

Table 2 Typical properties of some lightweight aggregate concretes-used for structural purposes

	Bulk density of aggregate kg/m^3			Cement	Quantity per m^3 of concrete Aggregate(m^3)			Air-dry density kg/m^3	28-day compressive strength N/mm^2	Modulus of elasticity (E) KN/mm^2	Drying shrinkage (approx.) %
Aggregate type	Fine	Medium	Coarse	kg	Fine	medium	Coarse				
Expanded clay (made in a rotary kiln)	640	370	320	310	0.65	---------	0.65	1050	8.5	3.5 to 10.5	0.055 to 0.07
				350	0.60	---------	0.60	1200	10.5		
				440	0.60	0.60	---------	1300	14.0		
				350	0.40	---------	0.80	1350	15.5		
				330	0.45	0.80	---------	1500	17.0		
Expanded shale	960	700	590	390	0.75	0.65	---------	1500	21.0	14 to 18	0.04 to 0.06
				440	0.75	0.70	---------	1550	26.0		
				480	0.70	0.70	---------	1600	31.5		
Expanded slate	860	670	560	450	0.60	---------	0.80	1600	27.5	11 to 18	0.04 to 0.045
				500	0.60	---------	0.80	1650	34.5		
				540	0.55	---------	0.80	1650	41.5		
Sintered pulverized fuel-ash	1040	835 (single size)	770	320	0.55	---------	0.70	1550	22.5	12 to 18	0.04 to 0.07
				500	0.40	---------	0.80	1600	37.5		
				550	0.35	---------	0.80	1650	45.0		
Foamed slag	920	---------	670	480	0.85	---------	1.10	1900	21.0	18 to 24	0.04 to 0.06
				540	0.85	---------	1.10	2000	27.5		
				570	0.90	---------	0.85	2000	34.5		

(Adapted from FIP Manual of Lightweight Aggregate Concrete)

Table 3 Typical properties of some lightweight aggregate concretes-used for insulation purposes

Aggregate type	Bulk density of aggregate kg/m3	Mix proportions (by volume) Cement: aggregate	Air-dry density kg/m3	28-day compressive strength N/mm2	Drying shrinkage (approx.) %	Thermal conductivity (K) W/moC
Exfoliatd vermiculite	60 to 90	1:8	400	0.7	0.35 to 0.45	0.09 to 0.15
		1:6	480	0.9		
		1:4	560	1.2		
Expanded perlite	100 to 150	1:6	480	2.1	0.14 to 0.20	0.09 to 0.15
		1:5	569	3.4		
		1:4	640	4.7		
Expanded polystyrene	120 to 150	1:37	300	0.3	0.10 to 0.20	0.09 to 0.32
		1:10	600	2.0		
		1:8	900	6.0		
Diatomite	400 to 500	1:9	690	2.2	0.25 to 0.35	0.17 to 0.26
		1:6	770	4.5		
		1:4	930	8.3		
Graded Wood particles	120 to 200	1:4	640	1.7	0.25 to 0.50	0.20 to 0.28
		1:3	880	4.8		
		1:2	1200	12.1		
Pumice	500 to 800	1:6	1200	14.0	0.10 to 0.12	0.29 to 0.55
		1:4	1250	19.0		
		1:2	1450	29.0		

(Adapted from FIP Manual of Lightweight Aggregate Concrete)

Table 5 Physical and Mechanical Properties of the Polystyrene Foam Bead

Property	Units	ASTM Test
Density(Nominal)	pcf	1.25
Thermal Conductivity(at 40 F)	BTU(hr.)	0.235
Thermal Resistance(at 40 F)	per inch	4.25
Capillary	-------	none
Strength Properties:		
Compressive 10% Deformation	psi	13-18
Tensile	psi	17-21
Shear	psi	23-25
Modulus of Elasticity	psi	250-310

(Adapted from HIBCO Plastics, INC. 1993)

3.1.3. Silica Fume

Introduction:

Silica fume is a by-product resulting from the reduction of high purity quartz with coal in electric arc furnaces in the manufacture of Ferro silicon and silicon metal. The condensed fume, which has a high content of amorphous silicon dioxide consists of very fine spherical particles (average diameter about 0.1 μm), is collected by filtering the gases escaping from the furnaces. Condensed silica fume (CSF) addition influences the physical and mechanical properties of fresh and hardened concrete. Significant increases occur in the compression strength and the impermeability (3).The formation of increased Ca-silicate hydrate by the reaction of lime and CSF in concrete contributes to higher strengths and impermeability (4).

Chemical Composition:

The chemical analysis of condensed silica fume used in the research is shown in table 6.

Table 6 Chemical Composition

Silicon dioxide	(SiO_2)	94.7
Aluminum oxide	($Al2O_3$)	0.1
Ferric oxide	(Fe_2O_3)	0.4
Calcium oxide	(CaO)	0.4
Magnesium oxide	(MgO)	0.6
Sulphur trioxide	(SO_3)	0.1
Sodium oxide	(Na_2O)	0.2
Potassium oxide	(K_2O)	0.9
Loss of ignition		1.6

(Supplied by the A.F.Manufacturer 1993)

3.1.4. Superplasticizer

Introduction:

Superplasticizer used in this research is high molecular weight condensed Naphthalene Sulfonate liquid with a 30.3% concentration level of Naphthalene Sulfonate [Fig. 1]. Superplasticizer causes cement agglomerates to disperse, i.e., reduces aggregation.

According to a report by the Cement and Concrete Association (4), the mode of action is best described as follows:

" These admixtures are thought to be adsorbed onto cement particles, causing them to become mutually repulsive as a result of the anionic nature of superplasticizers, which causes the cement particles to become negatively charged. In principle, this

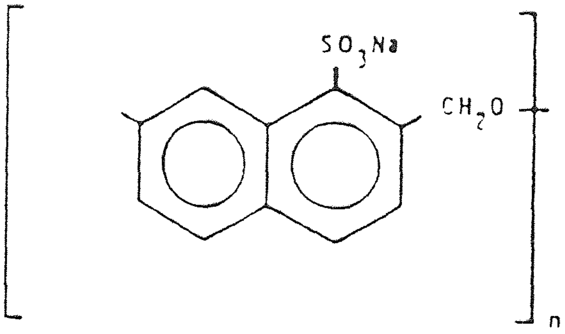


Figure 1 Molecular Structure of Sulfonated Napthalene Formaldehyde

adsorption and dispersing effect is similar to that formed for normal anionic plasticizers."

When added to normal Portland cement Superplasticzer can enormously increase its workability thus can make possible reductions in its water content, consequently increase the strength of concrete.

The Role of Superplasticizers in Concrete Incorporating Condensed Silica Fume:

The specific surface of silica fume is of the order of 20,000 m^2/kg. Because of the extreme fineness of the silica fume, the water demand of mortars and concretes incorporating silica fume increases with increasing amounts of silica fume. For example, at 30% cement replacement for concrete at a water-to-cement ratio of 0.64, the water demand has been found to increase by almost 30% [Fig. 2]. This problem of high water demand has been overcome by the use of superplastcizers. The strength development characteristics of silica fume concrete are shown in Fig. 3.

The introduction of superplasticizers combined with silica fume has made it possible to develop ultra high strength concretes. Bache (5) has reported the development of superplasticized silica fume concretes with strengths of the order of 150 Mpa at 100 days.(typically 1 to 4% of the weight of cementitious materials+silica fume). Mix proportion of

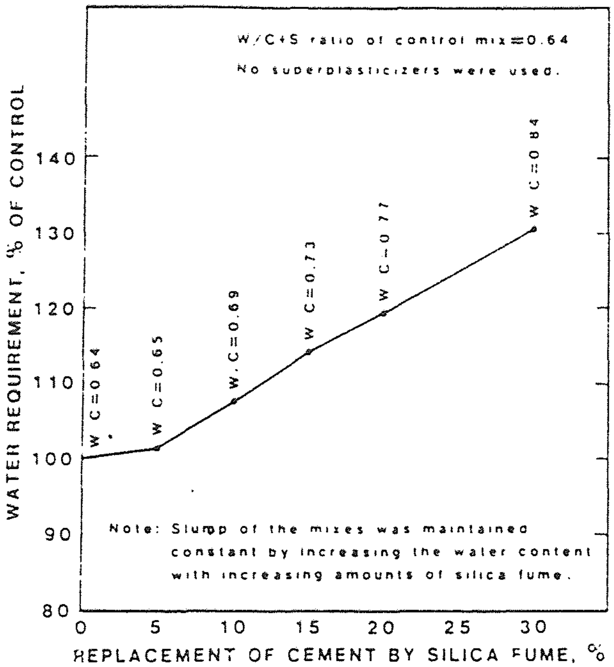


Figure 2 Water Reguirement For Silica Fume Concrete (3)

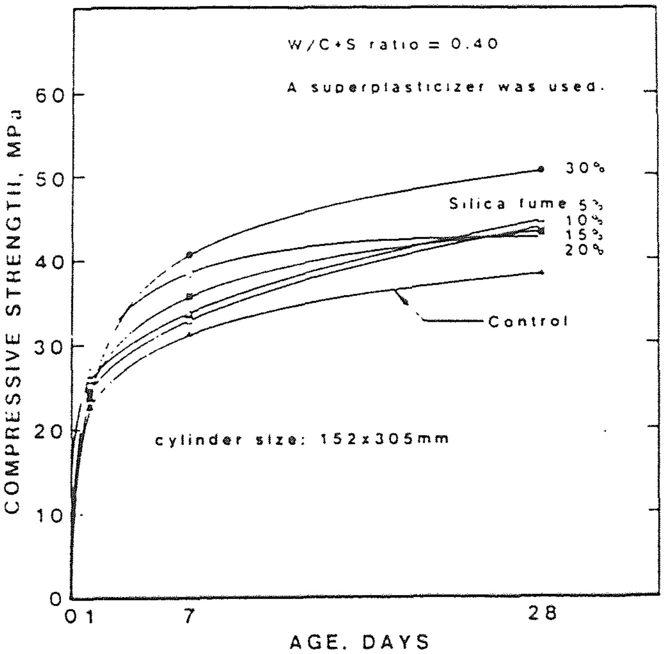


Figure 3 Age Versus Compressive Strength Relationship For Superplasticizerd Concrete With a Water-to-(Cement Plus Silica Fume) Ratio of 0.4 (3)

one such type of concrete are shown in table 7, and strength development with age is shown in Fig. 4, 5.

Table 7 Mix Proportions of Ultra-High Strength Superplasticized concrete (5)

Mix Proportion	Kilogrames per Cubic Meter
Silica fume	133
Portland cement	400
Qurtz sand 1/4-1mm	141
Quartz sand 1-4 mm	5
Crushed granite 8-16 mm	1153
Sulfonated naphthalene-superplasticizer	13.5
Water	100
Consistency of fresh concrete:	soft
Compaction: Vibration for10 to 20 sec at 50 Hz	

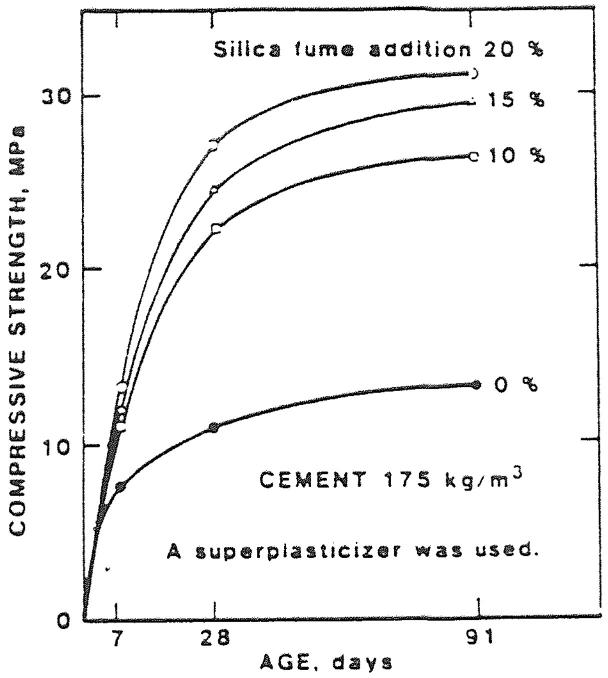


Figure 4 Age Versus Compressive Strength Relationship For Superplasticizered Very Lean Concrete (3)

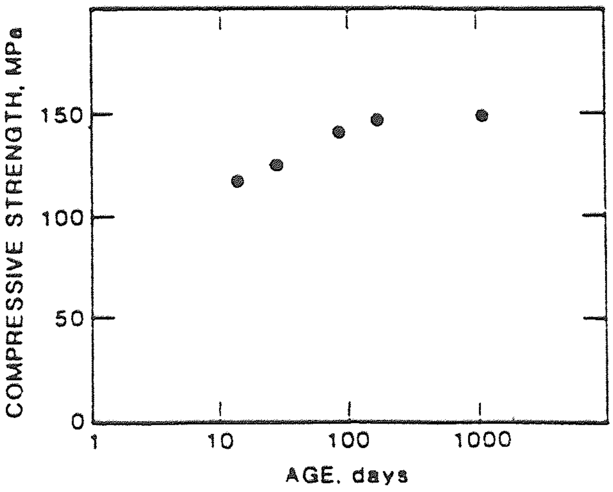


Figure 5 Compressive Strength of High Strength Concrete Cured at 20⁰C in Water (5)

3.2 Mechanical Properties

3.2.1. Elastic Modulus of Concrete Materials

Two Phase Model (6):

Concrete is a multiphase composite material consisting of unhydrated cement, cement gel, water, air, and aggregates. The geometries of these various constituents are complicated in themselves, when they are mixed together it becomes so confused that it is impossible to analyze the real material to determine the forces and deformation of each constituents. But concrete can be treated as a two-phase composite material, consisting only of h.c.p. (hardened cement paste) and aggregate. It is reasonable to assume that the interfacial effects are negligible and hence the elastic modulus of the concrete can be found from a model incorporating:

(1) a suitable geometrical arrangement of the phases,

(2) the property values representing each of the phases.

The three parameters needed to define the elastic properties of the concrete composite are elastic modulus of the aggregate (E_a), elastic modulus of the h.c.p. (E_p), volume concentration of the aggregate (V).

In general, the E_c (elastic modulus of the composite material) is given by

$$E_c = f(E_a, E_p, V) \qquad (3\text{-}1)$$

where the form of the function f depends on the geometrical configuration adopted. Three possible arrangements are shown in Fig. 6. All the models consist of unit cubes. In the models A and B have the phases arranged as adjacent layers. Model C has the aggregate set within the h.c.p. such that the height of the aggregate block equals its base area. Models A and B differ in that under the applied uniaxial compressive stress, model A suffers uniform strains in the two phases. This is in contrast to model B where model B carry the same stress. Model C is treated as three separate layers, two of h.c.p. alone and the third of h.c.p. and aggregate in parallel (as in model A) . The actual distributions of

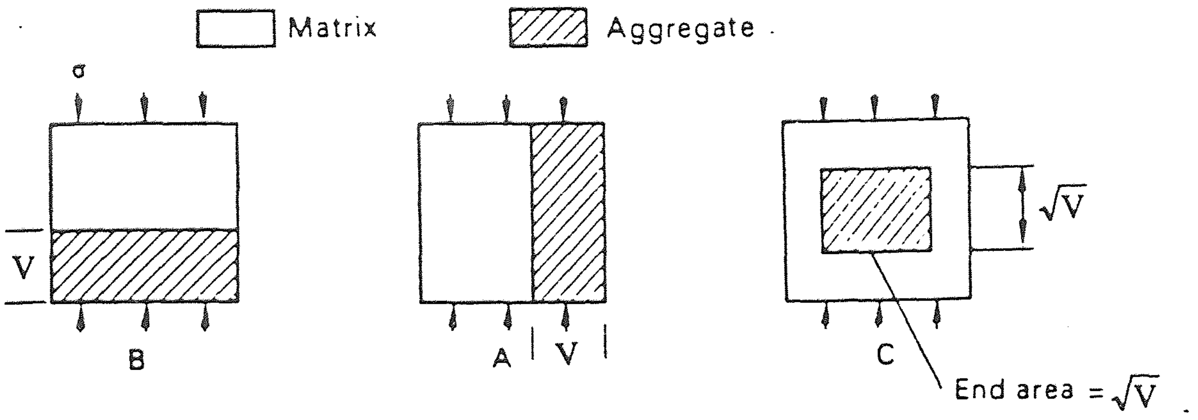


Figure 6 Simple Two-Phase Models for Concrete

stress and strain within concrete show great variations, but the models are concerned with the prediction of average behaviour.

The derivation of equations for three models:

Assumptions used for the the three models are:

(a) The applied uniaxial compressive stress remains uniaxial and compressive throughout the model.

(b) The effects of lateral continuity between layers can be ignored.

(c) Any local bond failure or crushing does not contribute to the deformation.

Model A-----Upper bound to the predicted Ec

The strain in the concrete, ε_c, is equal to the strain in both the aggregate, ε_a, and the h.c.p.,ε_p, i.e.

$$\varepsilon_c = \varepsilon_a = \varepsilon_p \qquad (3\text{-}2)$$

Equilibrium. The total force aplied to the model is given by applied stress acting on unit area.Thus

$$\sigma \times 1 = \sigma_a \times V + \sigma_p(1-V) \qquad (3\text{-}3)$$

Where

σ = total stress applied to the model

σ_a= stress applied to the aggregate

σ_p= stress applied to the h.c.p.

Constitutive Relation. Both constituent materials are elastic, and so is the concrete.

$$\sigma = \varepsilon_c \times E_c \qquad (3\text{-}4)$$

$$\sigma_a = \varepsilon_a \times E_a \qquad (3\text{-}5)$$

$$\sigma_p = \varepsilon_p \times E_p \qquad (3\text{-}6)$$

Substituting in Equation 3-3 from Equation 3-4, 3-5, and 3-6

$$\varepsilon_c E_c = \varepsilon_a E_a V + \varepsilon_p E_p (1-V) \qquad (3\text{-}7)$$

ad hence, from Equation 3-2

$$E_c = E_a V + E_p (1-V) \qquad (3\text{-}8)$$

Model B----Lower bound to the predicted Ec

$$E_c = \left\{ \frac{V}{E_a} + \frac{(1-V)}{E_p} \right\}^{-1} \qquad (3\text{-}9)$$

Model C

$$E_c = \left\{ \frac{\left(1-\sqrt{V}\right)}{E_p} + \left\{ \frac{\left(1-\sqrt{V}\right)}{\sqrt{V}} E_p + E_a \right\}^{-1} \right\}^{-1} \qquad (3\text{-}10)$$

Model B (the lower bound) is more nearly correct when the aggregate if stiffer than the h.c.p.--- (Ea/Ep) > 1. This is the zone in which most natural aggregate lie. Lightweight aggregate are less stiff than the h.c.p.--(Ea/Ep) < 1 and thus the elastic modulus of lightweight concretes are considerably lower than those of normal concrete. In the zone of softer aggregates it is the upper bound that is nearer to the experimental observations, but the predictions of model C are the best and it can apply to a full range of aggregate stiffness.

Porosity Model:

The effect of porosity on the elastic modulus was given by Powers (7) with the following empirical equation:

$$E_{h.c.p.} = E_g(1-V_p)^3 \qquad (3\text{-}11)$$

Where

$E_{h.c.p.}$ = elastic modulus of hardened cement paste

E_g = a constant, the elastic modulus of the solid phase when the V_p is zero

V_p = porosity in hardened cement paste

Practical Method to Determine Elastic Modulus:

The above three models have limited applicability since the vital data--the modulus of aggregate and h.c.p. must be known first. An alternative relationship must be available. The most favored one is the relationship between elastic modulus and strength, and it has the great advantage that strength is the one quantity that is virtually always known by the engineer.

The formulae are proposed by different authors; as they are based on regression analysis of tests in different conditions they only give mean values and the real values can be quite different. Pauw (8) was the first to present the following formula;

$$E_c = 0.04\sqrt{p^3 f_{cu}} \qquad (3\text{-}11)$$

Where

E_c = elastic modulus of the light weight concrete.

p = density of the light weight concrete.

f_{cu} = cubic compressive strength of the light weight concrete.

Berge (9) proposes the following formula based on 193 American test results;

$$E_c = 3.05\ p f_{cyl}^{1/3} \qquad (3\text{-}12)$$

Where

f_{cyl} = cylinder compressive strength of the light weight concrete.

3.2.2. Compressive Strength of Concrete Materials (11~15)

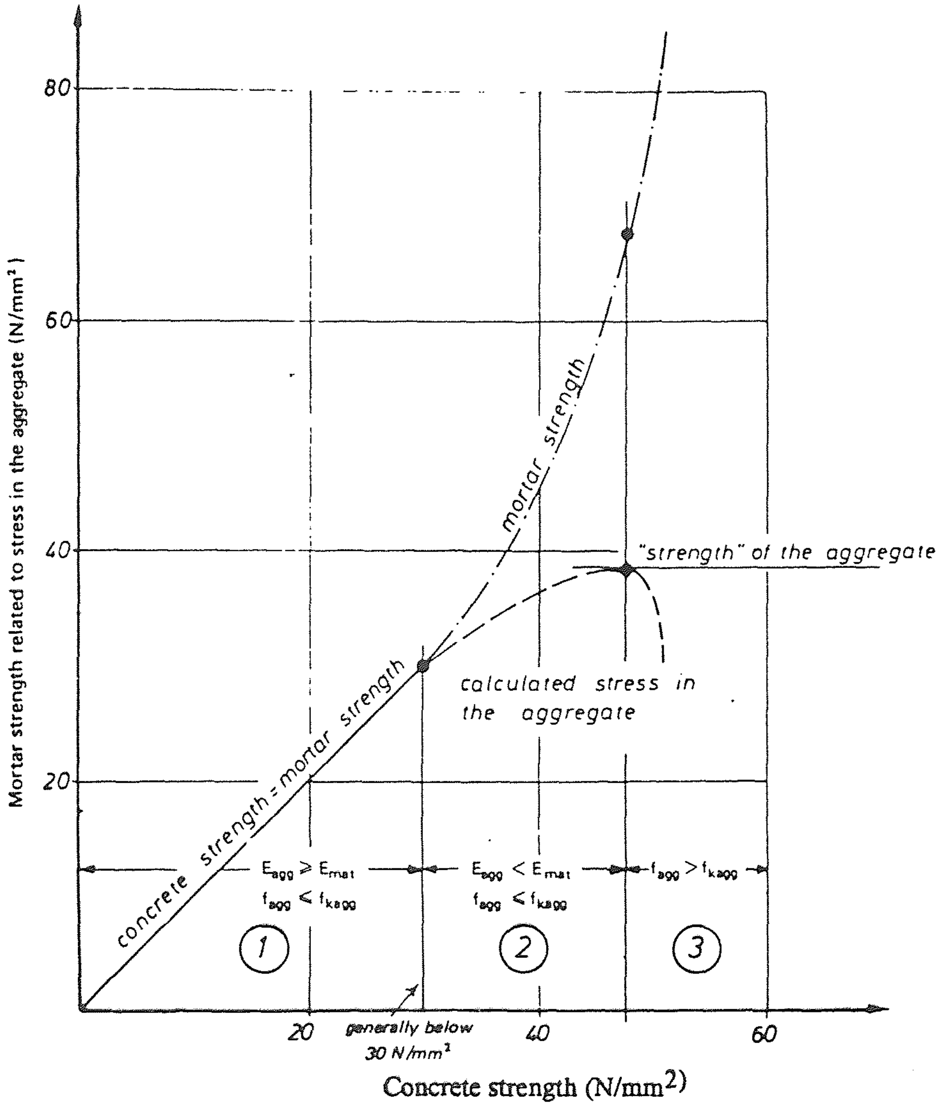
The Difference of Limiting Compressive Strength Between Lightweight and Normal Weight Concrete:

The strength of concrete is determined primarily by the strength (both compressive and tensile), deformation modulus and Poisson's ratio of the matrix and the aggregate in the concrete. With conventional concrete, the aggregates have an essentially higher density and also a higher modulus of deformation compared with the mortar. Due to this fact, short-term strength of a conventional concrete can be considered as a function of the strength of the mortar only, which both depends on the w/c ratio and the strength of the cement.

Lightweight aggregates have lower strength and modulus of deformation than matrix. Therefore, the influence of the aggregates on the strength of lightweight concrete must be taken into account. This becomes clear by comparing the relationship between the strength of the mortar and that of the lightweight aggregate concrete, made with this mortar [Fig. 7]. In the range 1 where modulus of deformation of the aggregate is greater (or equal) than modulus of deformation of the mortar [Fig. 7], the compressive strength of the light weight aggregate concrete and the mortar is approximately equal. Differences can occur, depending on different values of the modulus of deformation of the aggregate and on the amount of water absorbed by the aggregates from the mortar. In the range 2, 3 where modulus of deformation of the aggregate is less than the mortar, the load to be carried by the mortar will be greater than the aggregate, if the higher strength light weight concretes are required, then a mortar strength far exceeding the concrete strength will be necessary.

Fracture Type:

The value of the limit strength depends on the lightweight aggregate used and becomes higher when the modulus of deformation of the aggregate is higher. Above the limit strength, the compressive strength of the lightweight concrete increases more slowly than



E_{agg} = modulus of deformation of the aggregate
E_{mat} = modulus of deformation of the mortar
f_{agg} = calculated stress in the aggregate
f_{kagg} = "strength" of the aggregate

Figure 7 Simplified Relationship Between the Strength of the Concrete, That of the Matrix and the Calculated Compressive Stress Transmitted by the Aggregate (13) that of the mortar. This is due to the fact that the modulus of deformation of the mortar becomes larger than that of the aggregate. This inversion of stiffness causes another stress distribution within the lightweight concrete which differs from that within normal weight concrete. Below the limit strength, the aggregate takes the force due to its greater modulus of deformation, and the fracture type (fracture type I, Fig. 10) follows the normal weight concrete pattern. Above the limit strength, a great part of the force will be diverted around the aggregate because of its lower modulus of deformation [Fig. 8].

We can assumed that the cracks which lead to fracture will be initiated at places in the concrete where the tensile stress exceeds the actual tensile strength. With normal weight concrete, the tensile stress will be generated on the interface between aggregate and mortar working transversely to the direction of the external loading. With lightweight aggregate concrete, the tensile stress also acts transversely to the direction of the external loading, but immediately above and below the aggregate. As soon as the crack has started the external load can be increased if the internal balance is maintained. For the purpose, the internal force which is not transmitted after the crack has started must be moved [Fig. 9].

It can be assumed that this increased force will be taken up by the aggregate. This presupposes that the strength of the interface between aggregate and mortar is high enough. Especially at an early stage, the lower bond strength prevents the diverting of the force. The crack therefore propagates along the surface of the aggregate. This kind of fracture (fracture type II, Fig.10) takes place in the range immediately above the limit strength . If the strength of the interface between aggregate and mortar is high enough, the aggregate takes up the diverted force and the external load can be increased. Due to the larger load, the cracks propagate into the mortar. Therefore the diverted force also increases and leads to a tensile stress in the lightweight aggregate.

The aggregate will be fractured when its tensile strength is reached. With aggregates having a low tensile strength this will occur before the cracks in the mortar

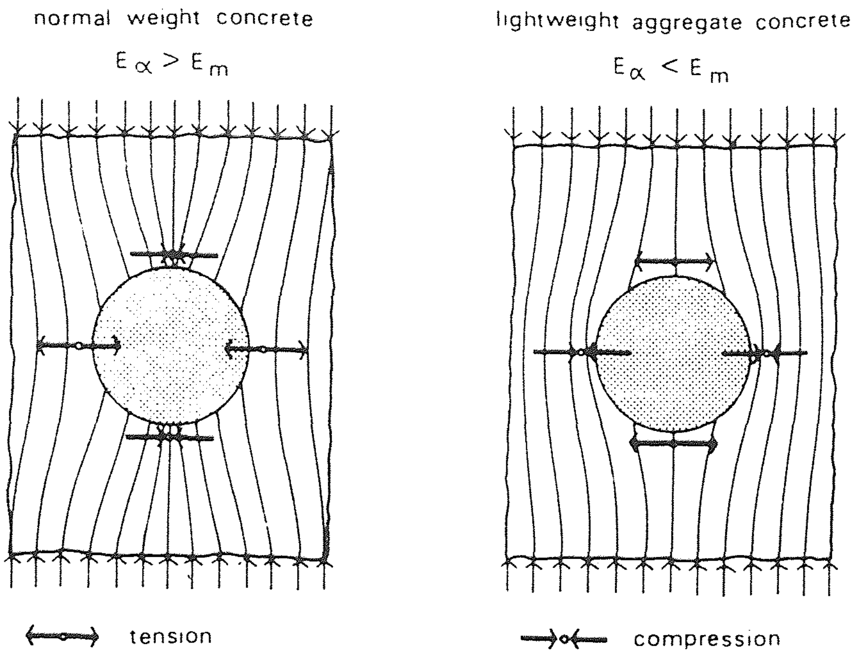


Figure 8 Model of Normal Weight and Lightweight Aggregate Concrete Under a Compressive Load (15)

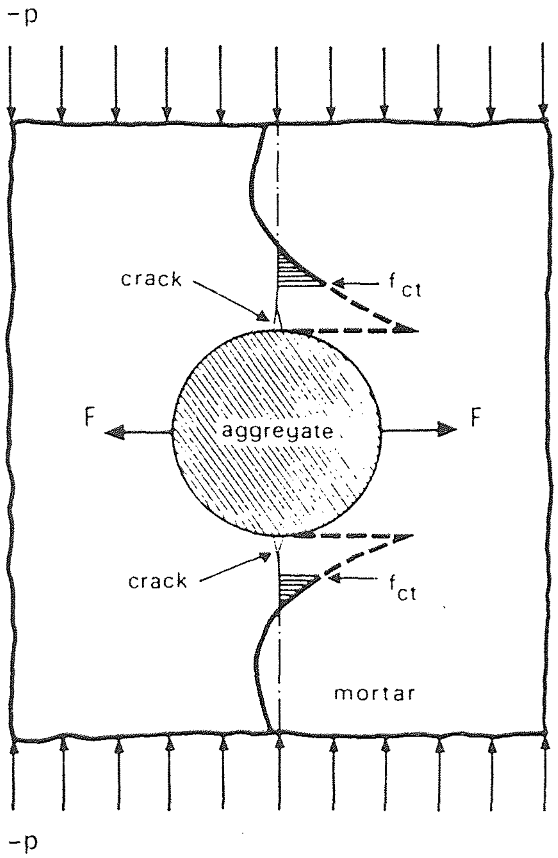


Figure 9 Model of Lightweight Concrete After Cracks Have Started in the Mortar (14)

have reached the interface of the neighboring aggregates (fracture type III, Fig. 10), Otherwise the cracks in the matrix will reach their maximum length (fracture type IV, Fig. 10), which is limited by the distance between the single pieces of aggregate. This distance is a function of the aggregate content of the concrete. In the case of a mortar with a high tensile strength, the tensile stress in the aggregate can reach its tensile strength without cracks in the matrix. Then the strength of the lightweight concrete is governed by the tensile strength of the aggregate (fracture type V, Fig. 10). Under otherwise constant conditions, the lightweight concrete then reaches its highest possible strength, the limit compressive strength.

When testing a light weight concrete with a normal composition, the different kinds of fractures are not always visible, because the concrete consists, in general, of aggregates of different sizes, which have different modulus of deformation as well as different tensile strengths. The experimentally determined relationship between the strength of the mortar and that of the light weight concrete is a curve of which the slope varies only slightly, and the change from one type of fracture to the other is not marked.

Influence of Mortar Strength and Age:

Under otherwise constant conditions, the tensile strength of the aggregate governs the limit compressive strength of the light weight concrete, which increases with increasing tensile strength of the aggregate. On the other hand, it is possible to increase the compressive strength by increasing the strength of the mortar. This can be done by reducing the w/c ratio or by using cement of a higher quality.

The development of strength of normal weight concrete is proportional to that of the mortar, whereas lightweight concrete shows different behavior, because of the influence of the lightweight aggregate discussed above. It is not possible to give any generally accepted factors for the ratio between the compressive strength at any early age and the age of 28 days.

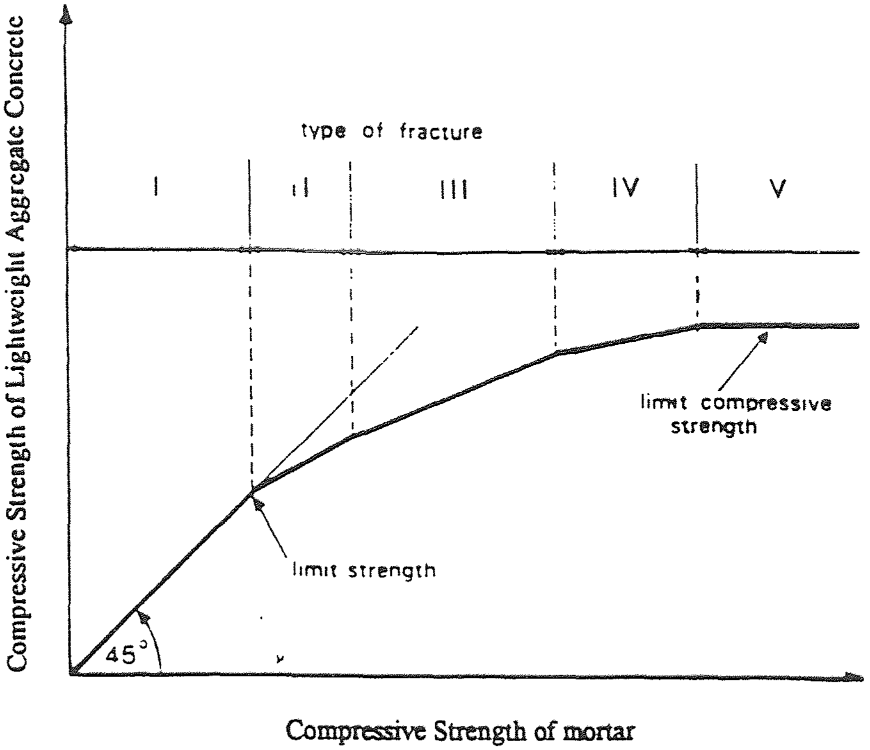


Figure 10 Relationship Between the Compressive Strength of the Matrix and That of Lightweight Aggregate Concrete (14)

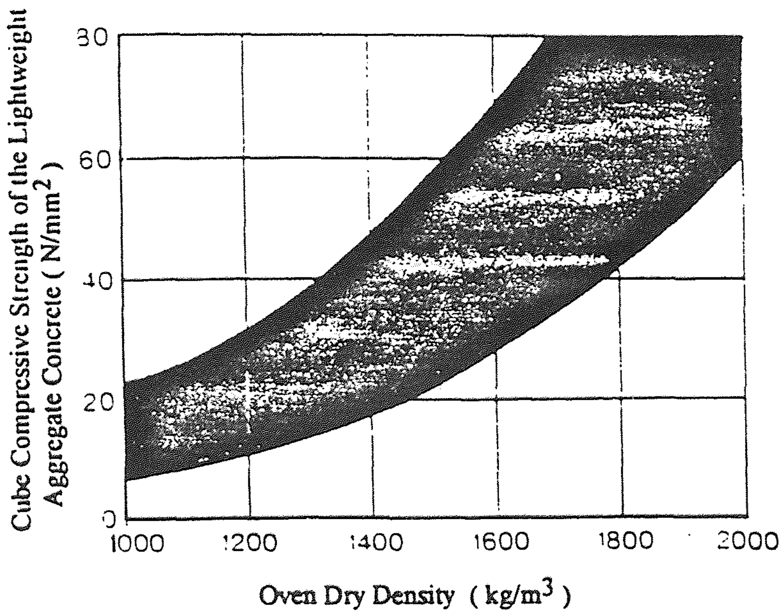


Figure 11 Cube Compressive Strength in Relation to the Oven Dry Density of the Lightweight Aggregate Concrete (13)

Relationship Between Compressive Strength and Density:

As mentioned above, the decisive influences of the aggregate on the compressive strength of the concrete are those of the modulus of deformation and the tensile strength of the aggregate. As these properties are not closely related to the density of the aggregates, the density of the aggregates and therefore that of the concrete can not be a suitable value to characterize the compressive strength. Therefore, the relationship between the density and the compressive strength can only be described by a range as given in Fig. 11.

CHAPTER 4

EXPERIMENTAL PROCEDURES

4.1. Mix Design

The specimen group I were cast using cement-sand mix as control mix, half of the group I using silica fume as reinforcement. The specimen group II and III were made by introducing different foam bead volume fraction into the control mix and correspondingly decrease the sand content to alter the density of the lightweight concrete. These two group specimens were mainly used to observe the effect of foam bead on the strength of light weight concrete. The specimen group IV made by fixing the cement, sand, W/c, but changing the silica fume content. The third group specimen used to measure the effect of silica fume on the compressive strength of foam bead lightweight concrete. The detail mix design see Table 8, 9, 10, 11.

4.2. Experimental Procedure

Specimen mold---Cylinder mold with size: 2 x 4 in. 4 specimens were molded for each test age and test condition.

Mixing Procedures:

(a) Without silica fume:

1. Mix cement and sand without addition of water until they are thoroughly blended.
2. Add foam bead and mix the entire mix without addition of water until the foam beads are uniformly distributed throughout the batch.
3. Add water and mix the mass until the lightweight concrete is homogenous in appearance and to the desired consistency.

(b) With silica fume and superplasticizer:

1. Mix cement and silica fume without addition of water until they are thoroughly

Table 8 Specimen Group I (Unit is KN/m^3)

Mix No.	Mix Date	Cement	Sand	water	Super P	w/c
NC	07/06	4.6	16.1	2.3	0	0.4
NSC	07/06	4.6	16.1	2.3	0.2	0.4

Table 9 Specimen Group II (Unit is KN/m^3)

Mix No.	Mix Date	Cement	Sand	Foam Bead lb/m^3	Water	w/c
LC1	07/07	4.6	11.51	0.19	1.84	0.4
LC2	07/07	4.6	9.21	0.28	1.84	0.4
LC3	07/08	4.6	6.91	0.38	1.84	0.4
LC4	07/08	4.6	4.61	0.47	1.84	0.4
LC5	07/08	4.6	2.32	0.56	1.84	0.4
LC6	07/09	4.6	0	0.66	1.84	0.4
LC7	07/09	4.6	0	0.99	1.84	0.4

Table 10 Specimen Group III (Unit is KN/m^3)

Mix No.	Mix Date	Cement	Silica fume	Sand	Foam Bead lb/m^3	water	w/c	Super P
LSC1	07/09	4.6	1	11.51	0.19	1.84	0.4	0.1
LSC2	07/09	4.6	1	9.21	0.28	1.84	0.4	0.1
LSC3	07/10	4.6	1	6.91	0.38	1.84	0.4	0.1
LSC4	07/10	4.6	1	4.61	0.47	1.84	0.4	0.1
LSC5	07/10	4.6	1	2.32	0.56	1.84	0.4	0.1
LSC6	07/11	4.6	1	0	0.66	1.84	0.4	0.1
LSC7	07/11	4.6	1	0	0.99	1.84	0.4	0.1
LSC8	07/11	4.6	1	0	1.32	1.84	0.4	0.1

Table 11 Specimen Group IV (Unit is KN/m^3)

Mix No.	Mix Date	Cement	Silica Fume	Sand	Foam Bead lb/m^3	water	w/c	Super P
LSRC1	06/01	4.6	0.4	12.5	0.13	1.84	0.4	0.09
LSRC2	06/01	4.6	0.7	12.5	0.13	1.84	0.4	0.095
LSRC3	06/01	4.6	1	12.5	0.13	1.84	0.4	0.1
LSRC4	06/02	4.6	1.3	12.5	0.13	1.84	0.4	0.105
LSRC5	06/02	4.6	1.6	12.5	0.13	1.84	0.4	0.11
LSRC6	06/03	4.6	1.9	12.5	0.13	1.84	0.4	0.115
LSRC7	06/03	4.6	2.2	12.5	0.13	1.84	0.4	0.12

blended.

2. add sand into the mix without addition of water until they are thoroughly blended.

3. soak foam bead in the superplasticizer for 5 minutes.

4. add soaked foam bead into the sand-cement-silica fume mix without addition of water until they are uniformly distributed.

5. add 80% of the water requirement and mix the mass until the mass is almost homogeneous.

6. mix 20% of the water requirement with superplasticizer, and add into the mass, mix for 10 minutes.

Consolidation:

table vibration.

Rodding method was tried, but the paste didn't come out, ended up with honey-comb surface specimen.

Curing:

All specimens were moist cured at $23 \pm 1.7^\circ C$ from the time of molding until the moment of test.

4.3 Elastic Modulus of Lightweight Concrete

In the test we measured the secant modulus of the specimens according to ASTM C469, " Method of Test for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression. "

Calculation formula:

$$E = (S_1 - S_2)/(\varepsilon - 0.000050) \qquad (4\text{-}1)$$

Where

E = Secant Modulus, psi

S_2 = Stress corresponding to 40% of ultimate load.

S_1 = Stress corresponding to a longitudinal strain of

450 millionths, psi.

ε = Longitudinal strain produced by stress S_2.

4.4 Polystyrene Foam Bead Volume Fraction Calculation

$$\omega_v = \frac{W_c - W_l}{d_c V_s} \qquad (4\text{-}2)$$

Where

ω_v = volume fraction of the foam bead light weight concrete.

W_c = dry weight of sand-cement control mix of

constant sample volume

W_l = dry weight of the foam bead lightweight concrete.

d_c = dry density of sand-cement control mix.

V_s = the volume of the specimen.

CHAPTER 5

RESULTS, DISCUSSION, AND CONCLUSIONS

5.1. The Effect of Foam Bead Volume Fraction on the Compressive Strength of the Lightweight Concrete with and without Silica Fume

With the introduction of foam bead, the strength of both control mixes drops considerably. The compressive strength of mixes drops by 40% at the first introduction of around 13% foam bead volume fraction. The lowest density the foam bead lightweight concrete we could make without segregation is about 500 kg/m^3 [Fig. 12., table 11, 12].

5.2. The Effect of Reinforcement of Silica Fume on the Polystyrene Foam Bead Concrete

With the increase of silica fume, the strength of the foam bead lightweight concrete increases. But when silica fume level reaches 20% of the cement content, the silica fume has little effect on the strength improvement of the lightweight concrete. This result is in agreement with the results of the effect of the silica fume on the normal weight concrete [Fig. 13, 14]. The addition of silica fume in our case is important with regard to improving strength.

5.3. The Strength and Predictability

The compressive strength and bead volume fraction relationships can be predicted by a model suggested by Wischers (16) [Fig. 15, 16]. Due to very low (near zero) elastic modulus of the foam bead, the space occupied by foam beads in the cement matrix can be considered to be equivalent to voids in the matrix. The theoretical and experimental formulae suggested by Wischers are as followings:

theoretical:

Table 12

Mix No.	Dry density kg/m^3	Y.S.(28 Days) N/mm^2	V.F.(%)
NC	2190.3	36.8	0.0
LC1	1884.3	22.0	14.0
LC2	1713.3	16.0	21.8
LC3	1525.1	12.2	30.4
LC4	1329.5	8.8	39.3
LC5	1052.2	4.6	52.0
LC6	769.9	1.9	65.0
LC7	541.6	0.6	75.0

Table 13

Mix No.	Dry density kg/m^3	Y.S.(28 Days) N/mm^2	V.F.(%)
NSC	2142.0	55.5	0.0
LSC1	1867.9	32.2	12.8
LSC2	1672.4	21.7	21.9
LSC3	1507.9	16.5	29.6
LSC4	1301.7	10.5	39.2
LSC5	1057.9	5.7	50.6
LSC6	796.9	3.4	63.0
LSC7	684.0	2.2	68.0

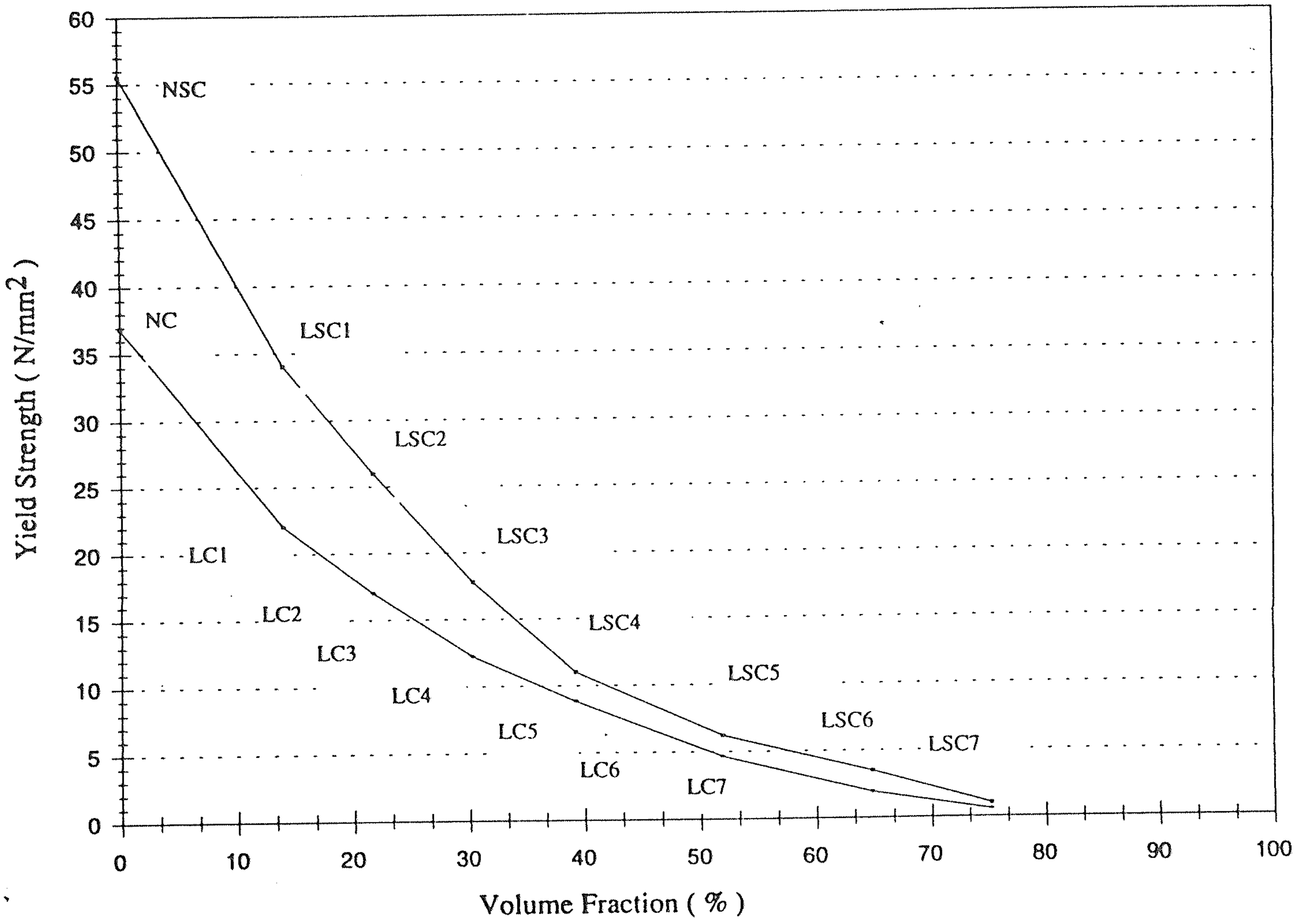


Figure 12 Compressive Strength of Foam Bead Lightweight Concrete (With and Without Silica Fume) via Its Foam Bead Fraction

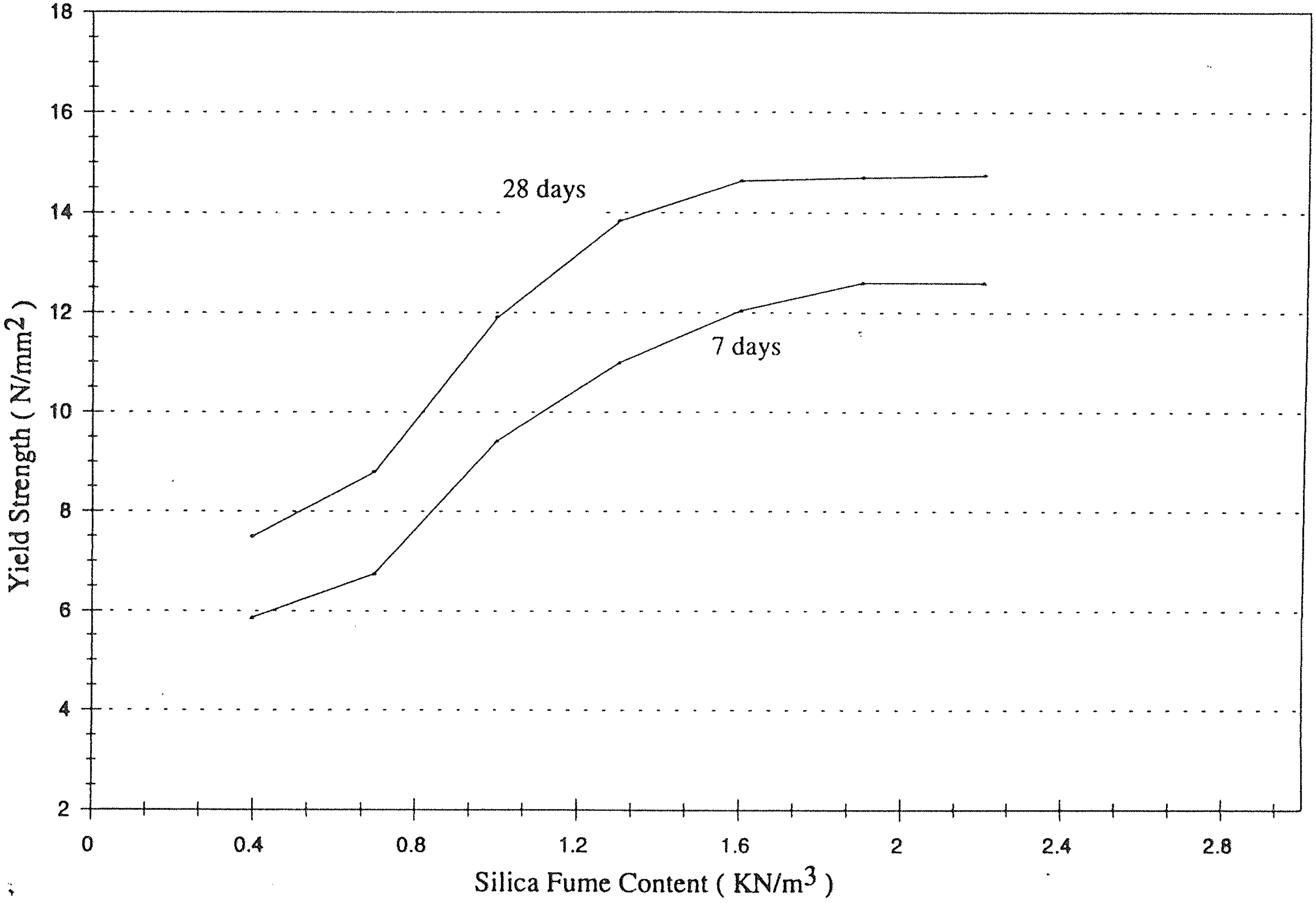


Figure 13 The Effect of Silica Fume Reinforcement on the Compressive Strength of Foam Bead Concrete

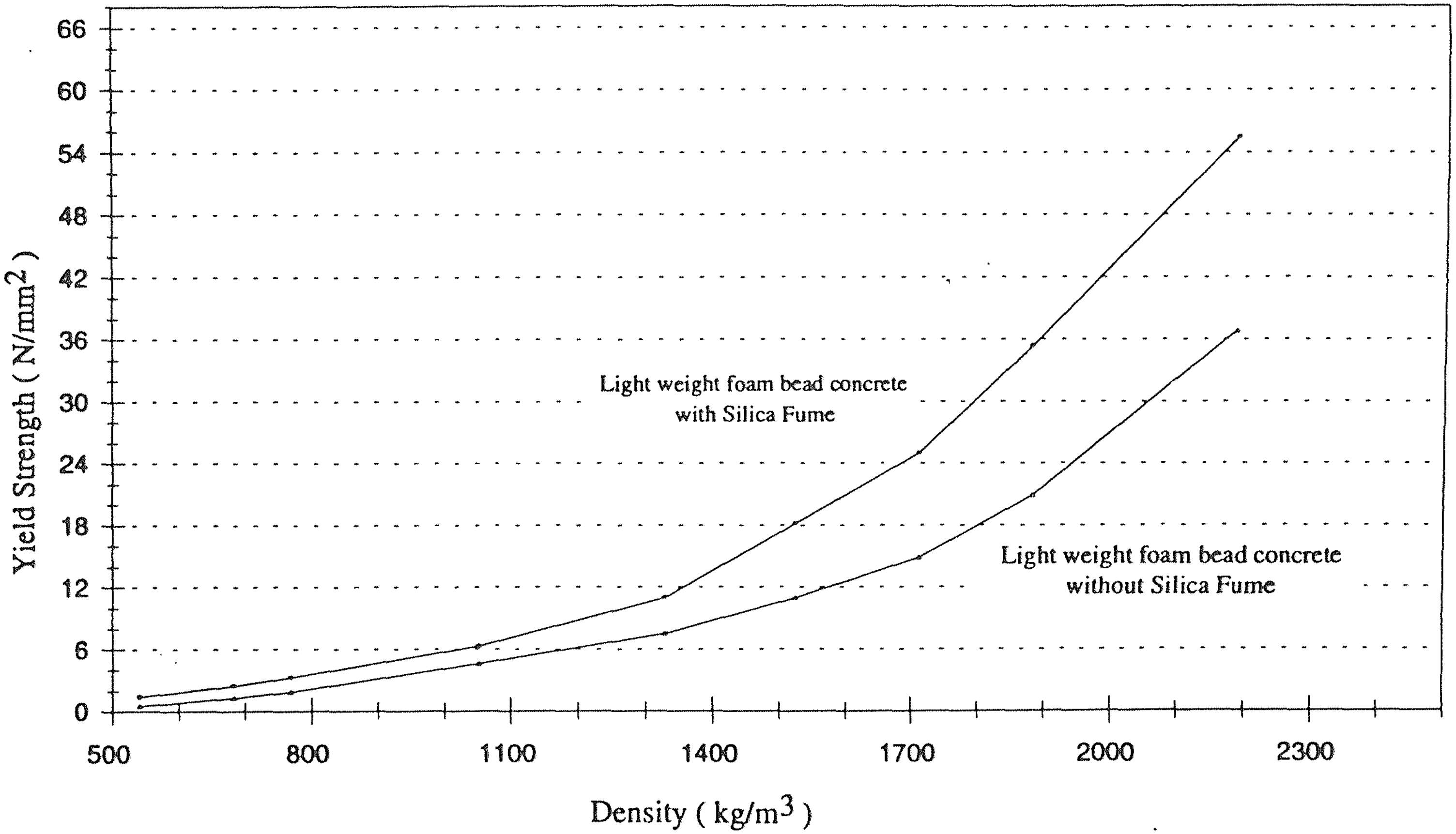


Figure 14 The Compressive Strength Improvement of Foam Bead Concrete with 22% Silica Fume Reinforcement via Its Density

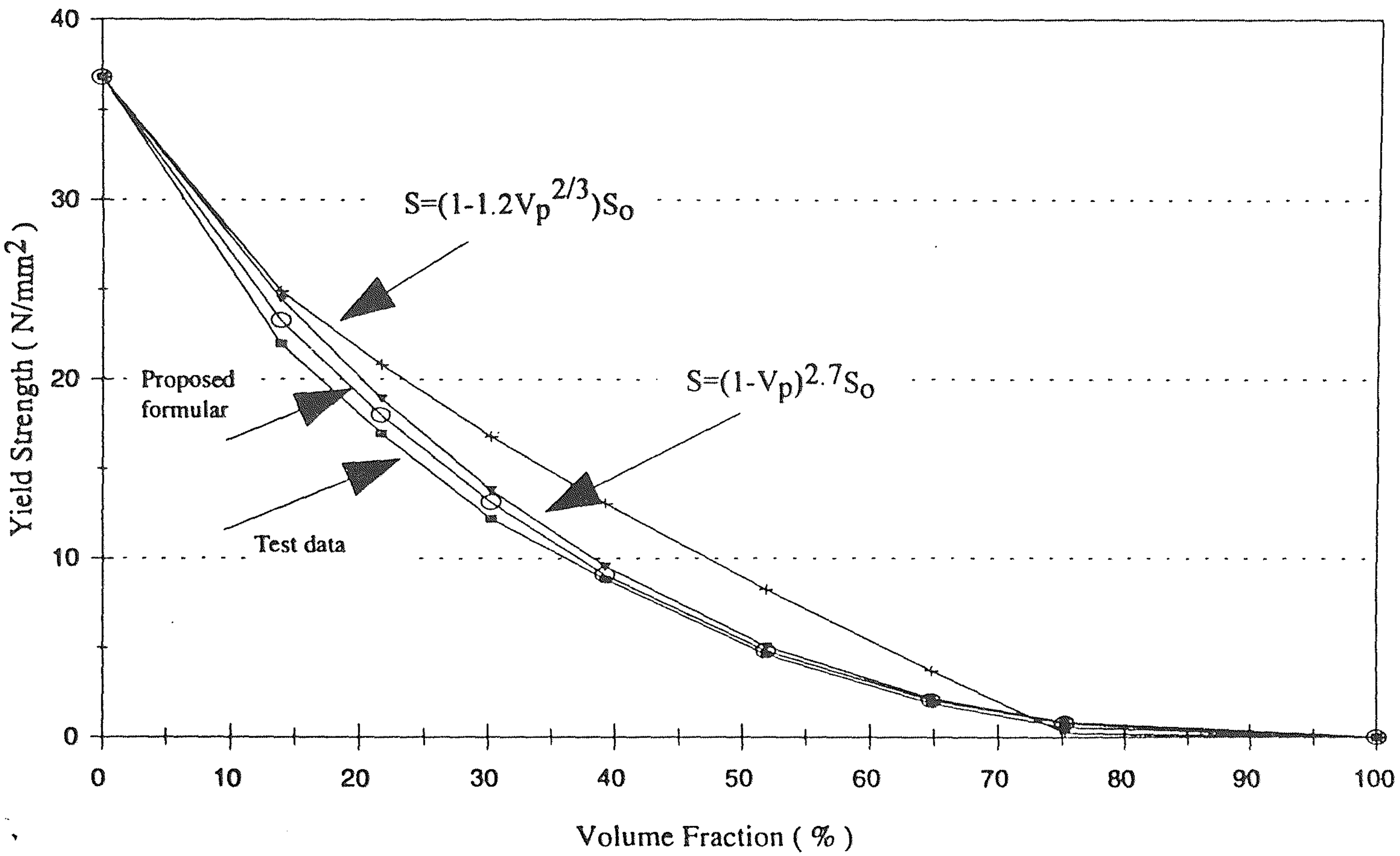


Figure 15 Compressive Strength of Foam Bead Concrete (Without Silica Fume) via Its Foam Bead Fraction

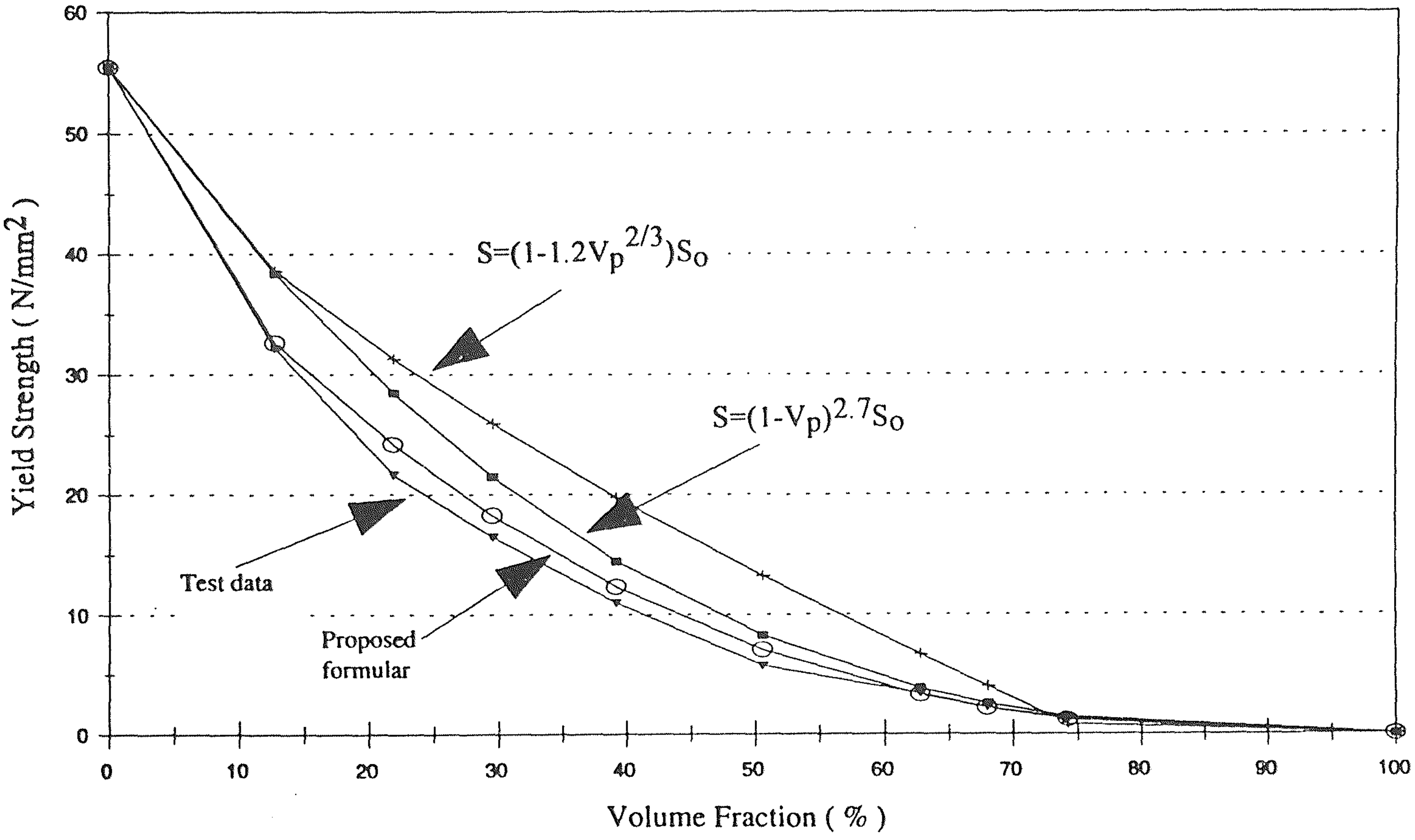


Figure 16 Compressive Strength of Foam Bead Concrete (With Silica Fume) via ItsFoam Bead Fraction

$$S = (1 - 1.2\, V_p^{2/3})\, S_o \qquad (5\text{-}1)$$

experimental:

$$S = (1 - V_p)^{2.7}\, S_o \qquad (5\text{-}2)$$

Based on our results, the following is our revised formula of Wischers' model:

$$S = 0.9\, (1 - V_p)^{2.7}\, S_o \qquad (5\text{-}3)$$

Where

S = Compressive strength

V_p = Foam bead volume fraction

S_o = Compressive strength of cement matrix.

5.4. The Elastic Modulus of the Polystyrene Foam Bead Lightweight Concrete

With the introduction of foam bead, the plasticity of the concrete improves considerably. [Fig. A3 ~ A6].

The Basic assumption of composite theory is that the matrix and aggregate work together as a whole when under stress. Model A arrangement would give unrealistic high modulus considering the fact that cement paste modulus is much higher than that of foam bead modulus. Also, Model B would give unrealistic low modulus in this case. Model C arrangement is more appropriate for the concrete as particulate composite and still gives higher modulus than the test result. This is due to the fact that the introduction of foam bead only creates the 'honeycomb' effect in the cement paste matrix with little contribution to the composite as a whole [Fig. 17, 18].

The models suggested by Pauw and Berge give higher elastic modulus than the test result. This implies that the models developed with aggregates whose strength is higher than that of the cement paste can not be used to describe the elastic modulus of foam bead lightweight concrete [Fig. A1, A2].

5.5. Elastic Modulus and Predictability

Even though the elastic modulus of the foam bead lightweight concrete cannot be described by the two-phase model or by the practical method models suggested by Pauw and Berge, the porosity model suggested by Power can predict the elastic modulus in this case quite accurately. [Fig. 19]. The porosity model can also be used to extrapolate the zero porosity modulus of the light weight concrete [Fig. 19].

5.6. Conclusions

Due to its low elastic modulus, the polystyrene foam bead as lightweight aggregate lowers the strength of cement matrix considerably. Foam bead contribution to the matrix is equivalent to that of voids. We found that the compressive strength of foam bead lightweight concrete can be predicted by the model suggested by the Wischers. Silica fume has improved foam bead lightweight concrete strength up to a limit (20%). This result is in agreement with conventional weight concrete.

None of the particulate composite theory model (two-phase model) or the practical method models could adequately describe the elastic modulus and compressive strength of foam bead lightweight concrete as a function of foam bead volume fraction. We found that the mechanical behavior of foam bead concrete is best expressed in terms of porosity equations / models. In light of our work, the porosity effects of concrete can be investigated by incorporating foam beads with various sizes and volume fraction as a second phase of concrete. Both modulus and strength of foam bead concrete were in agreement with porosity equations, even at high volume fraction. The results of this work provide information regarding the effect of " macroporosity " on concrete mechanical properties.

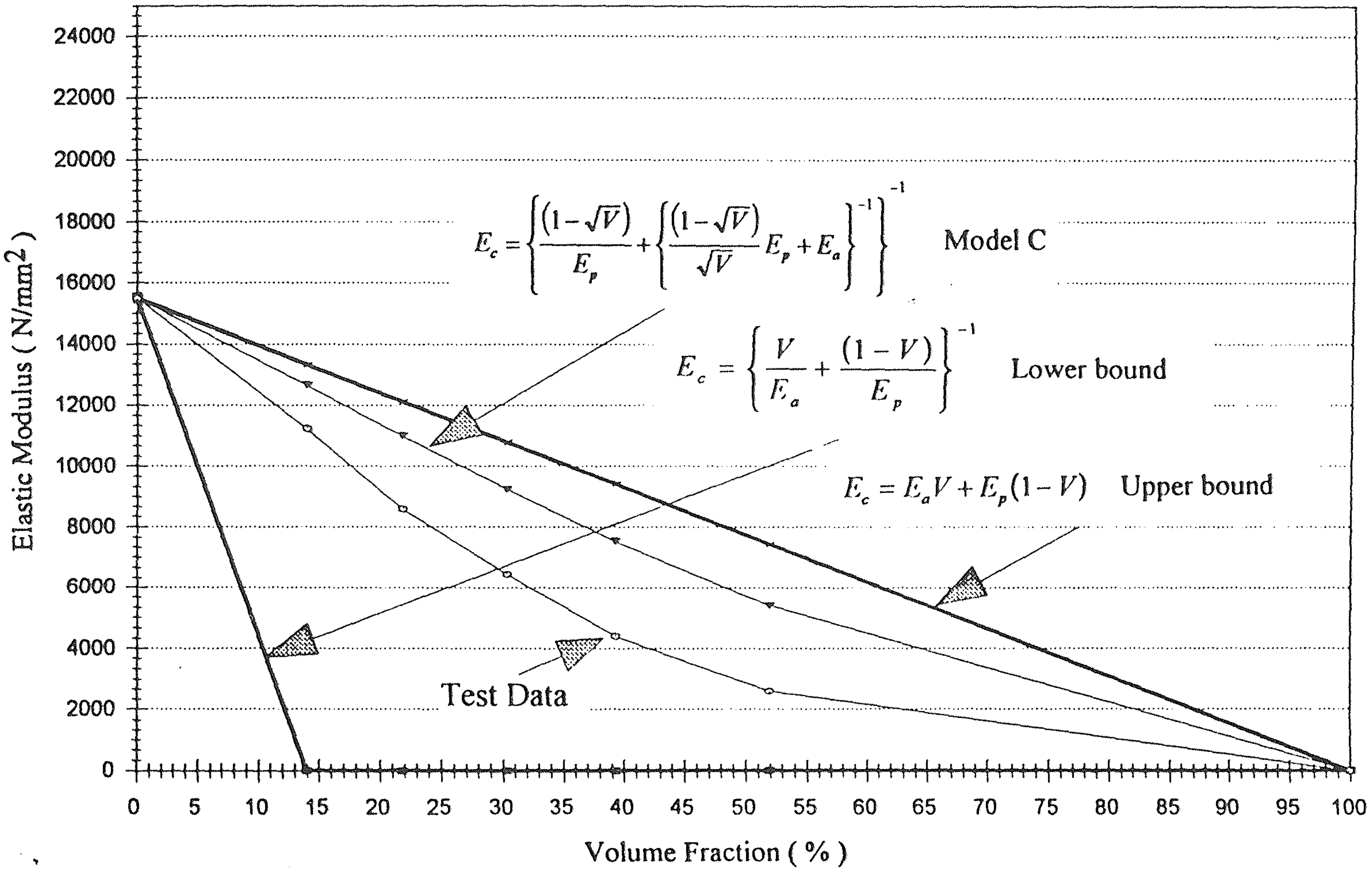


Figure 17 Elastic Modulus of Foam Bead Concrete (Without Silica Fume) via Its Foam Bead Volume Fraction

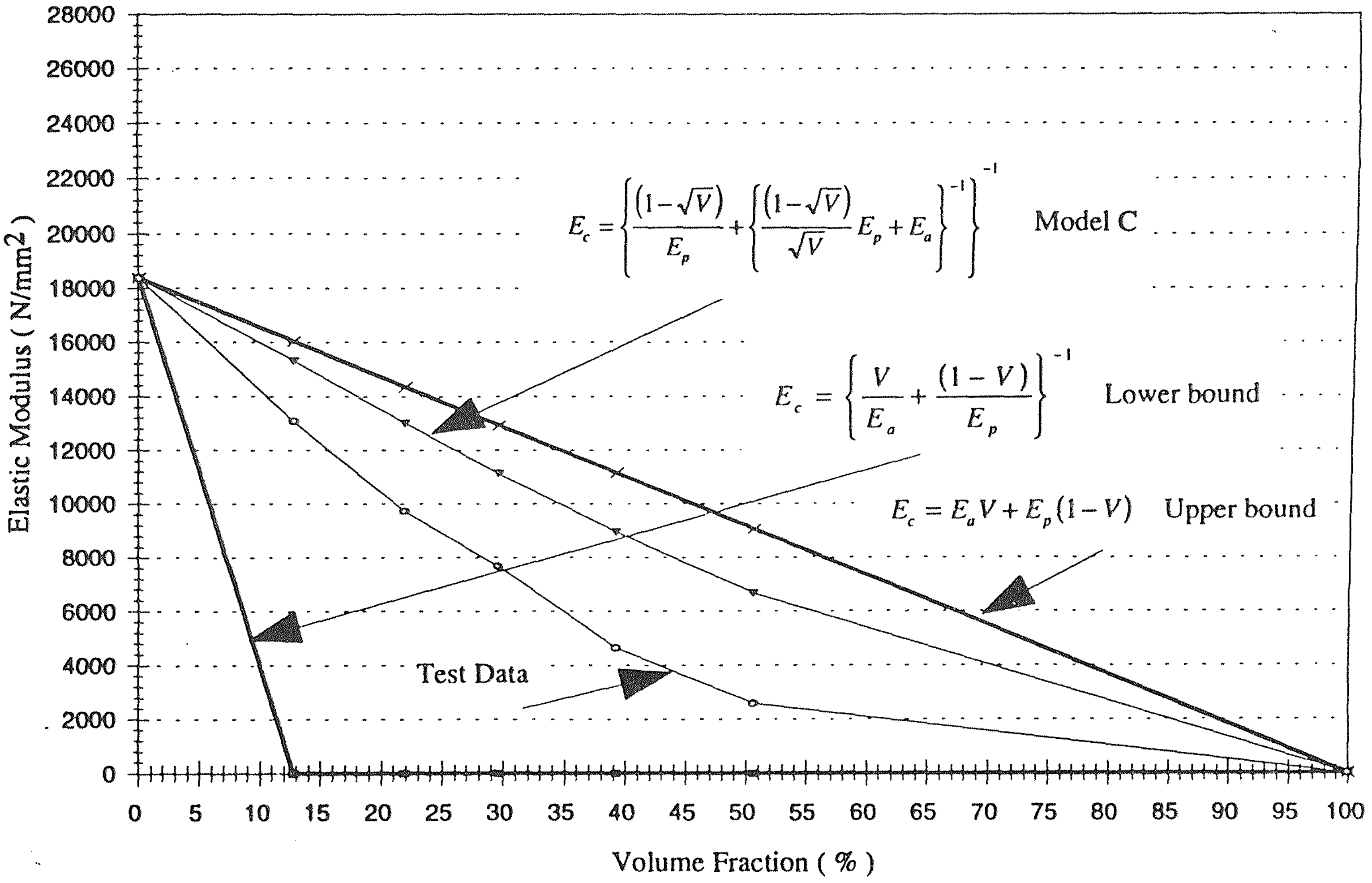


Figure 18 Elastic Modulus of Foam Bead Concrete (With Silica Fume) via Its Foam Bead Volume Fraction

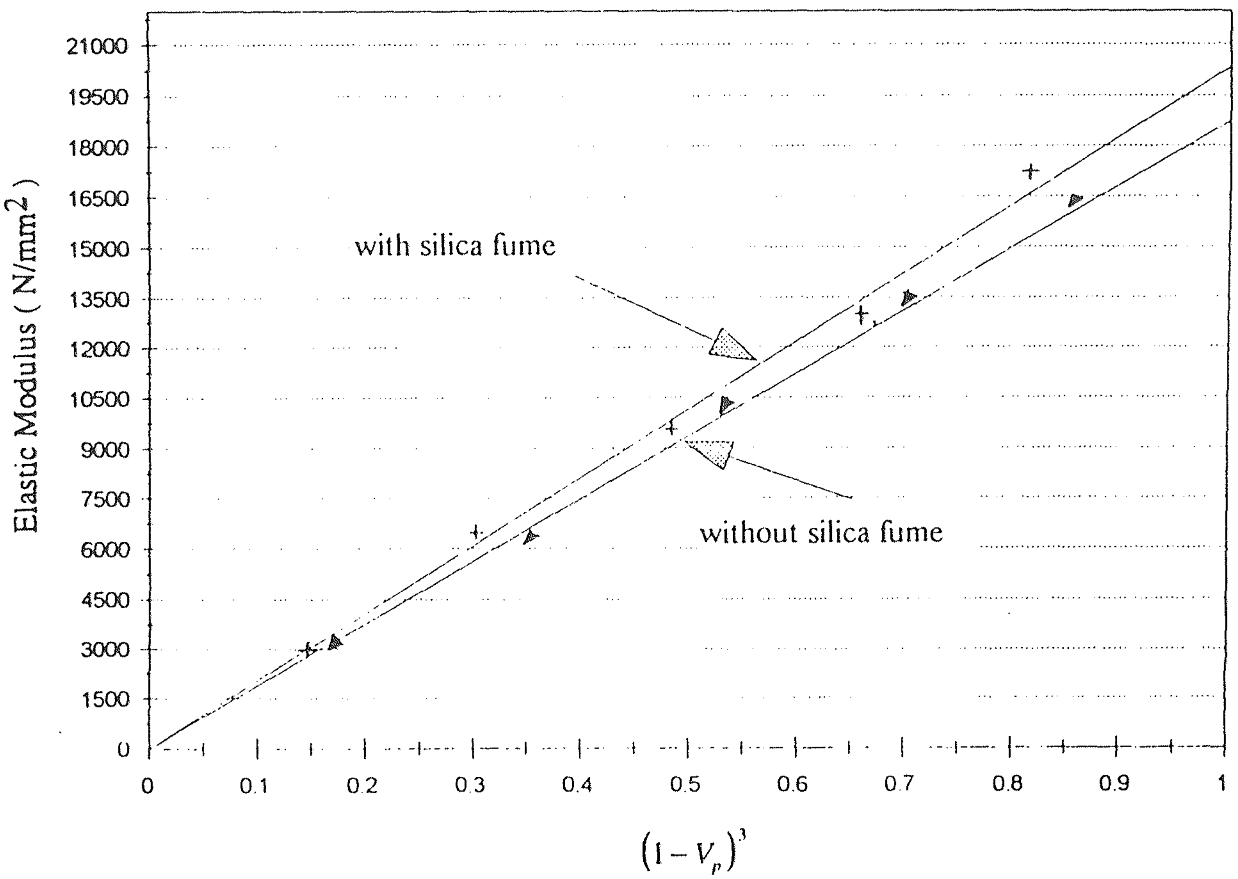


Figure 19 Power's Model of Elastic Modulus of Foam Bead Concrete (With and Without Silica Fume) of Various Foam Bead Volume Fractionvia

The foam bead aggregate increases the plasticity of the concrete, therefore it can be used as earthquake resistant structural material or impacting resistant structural material. Using foam bead as lightweight aggregate will help recycling large amounts of polystyrene foam cups and other polystyrene foam packaging materials.

With the introduction of silica fume in foam bead lightweight concrete, we can make stronger foam bead concrete, thus its application in the second and third category becomes more competitive and promising.

CHAPTER 6

APPLICATION PROPOSAL AND RECOMMENDATION FOR FURTHER RESEARCH

6.1 Application Proposal

The application of foam bead lightweight concrete can be classified into three categories:

(1) non-structural application---interior and exterior separation,

(2) low-load bearing structural application---up to six-story masonry building as load bearing wall, impacting resistant structure,

(3) as substitute for normal weight concrete.

In the first category, the density ranges from 500kg/m^3 to 900kg/m^3, the corresponding compressive strengths range from 1N/mm^2 to 4 N/mm^2 with or without silica fume as reinforcement.

In the second category, the density ranges from 1000kg/m^3 to 1400 kg/m^2, the corresponding compressive strength from 6N/mm^2 to 16N/mm^2 with silica fume as reinforcement.

In the third category, the density ranges are 1600kg/m^3 to 1800kg/m^3, the corresponding compressive strengths from 19N/mm^2 to 27N/mm^2.

6.2 Recommendation for Further Research

Further research is needed in the following areas:

(1) shrinkage of the foam bead lightweight concrete especially when silica fume is used,

(2) shear strength of the foam bead lightweight concrete;

(3) bonding strength of the lightweight concrete with steel bar,

(4) fracture property of the foam bead lightweight concrete,

(5) more efficient coating material for polystyrene foam bead.

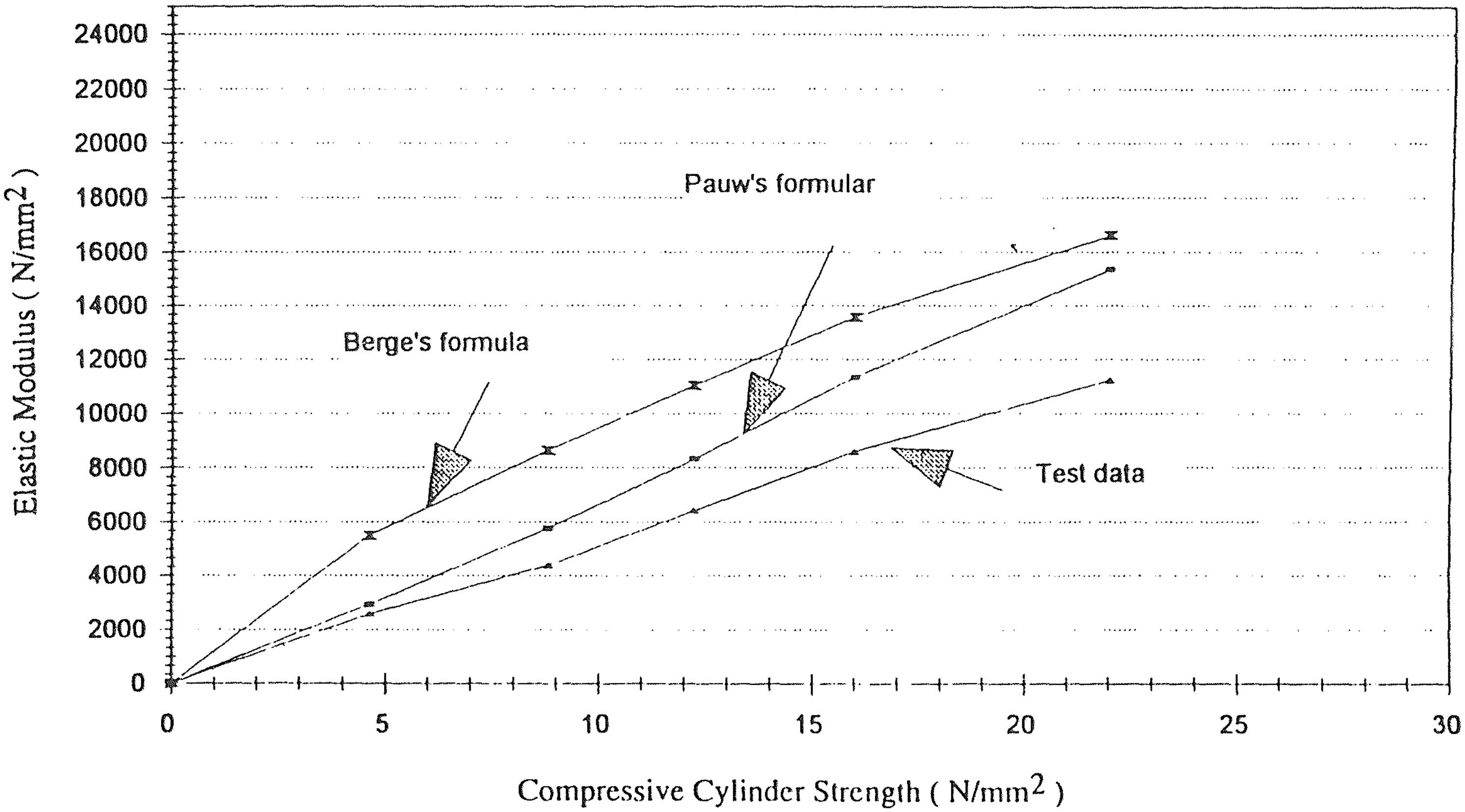


Figure A1 Elastic Modulus of Foam Bead Concrete (Without Silica Fume) via Its Compressive Strength

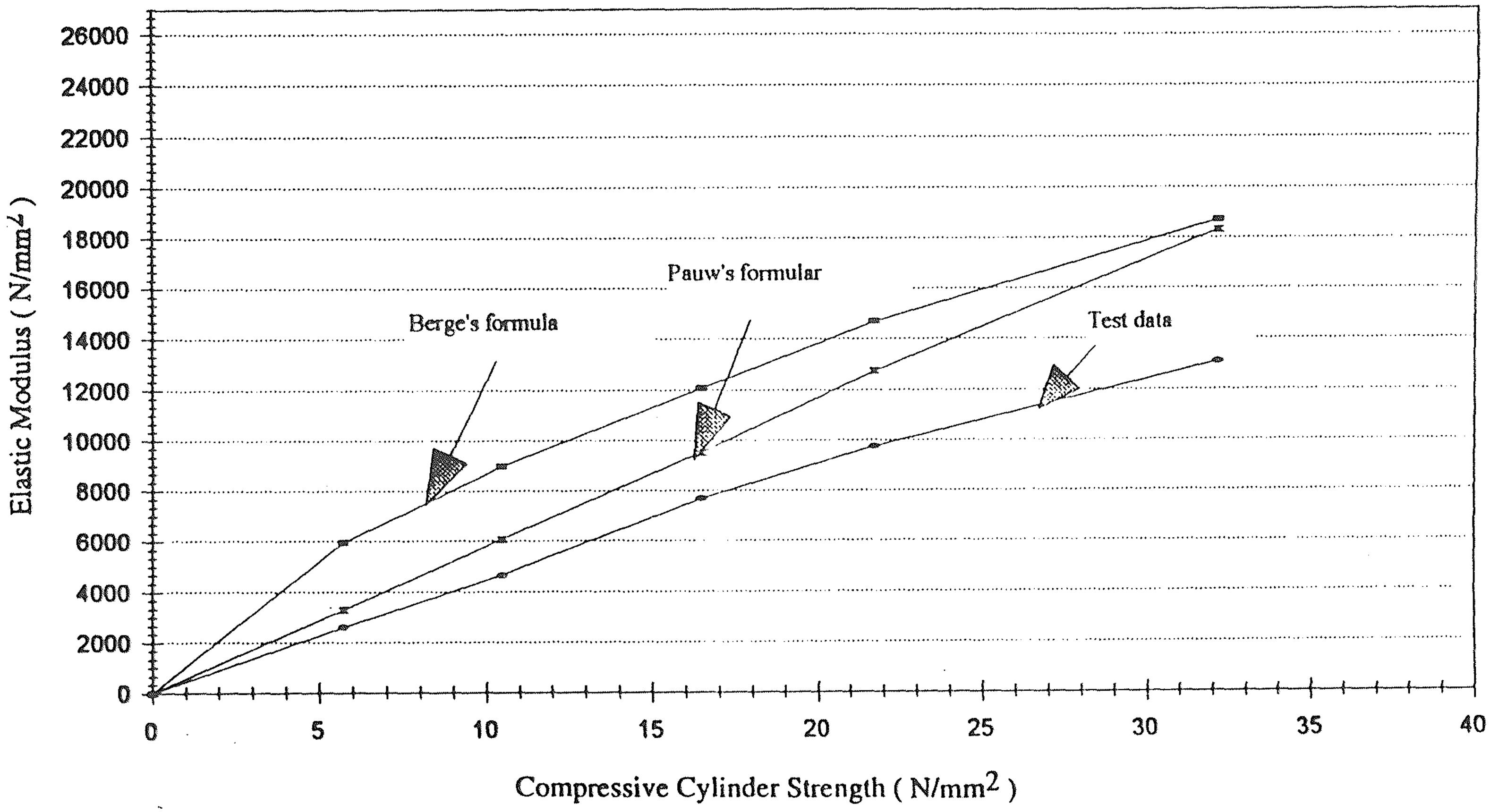


Figure A2 Elastic Modulus of Foam Bead Concrete (With Silica Fume) via Its Compressive Strength

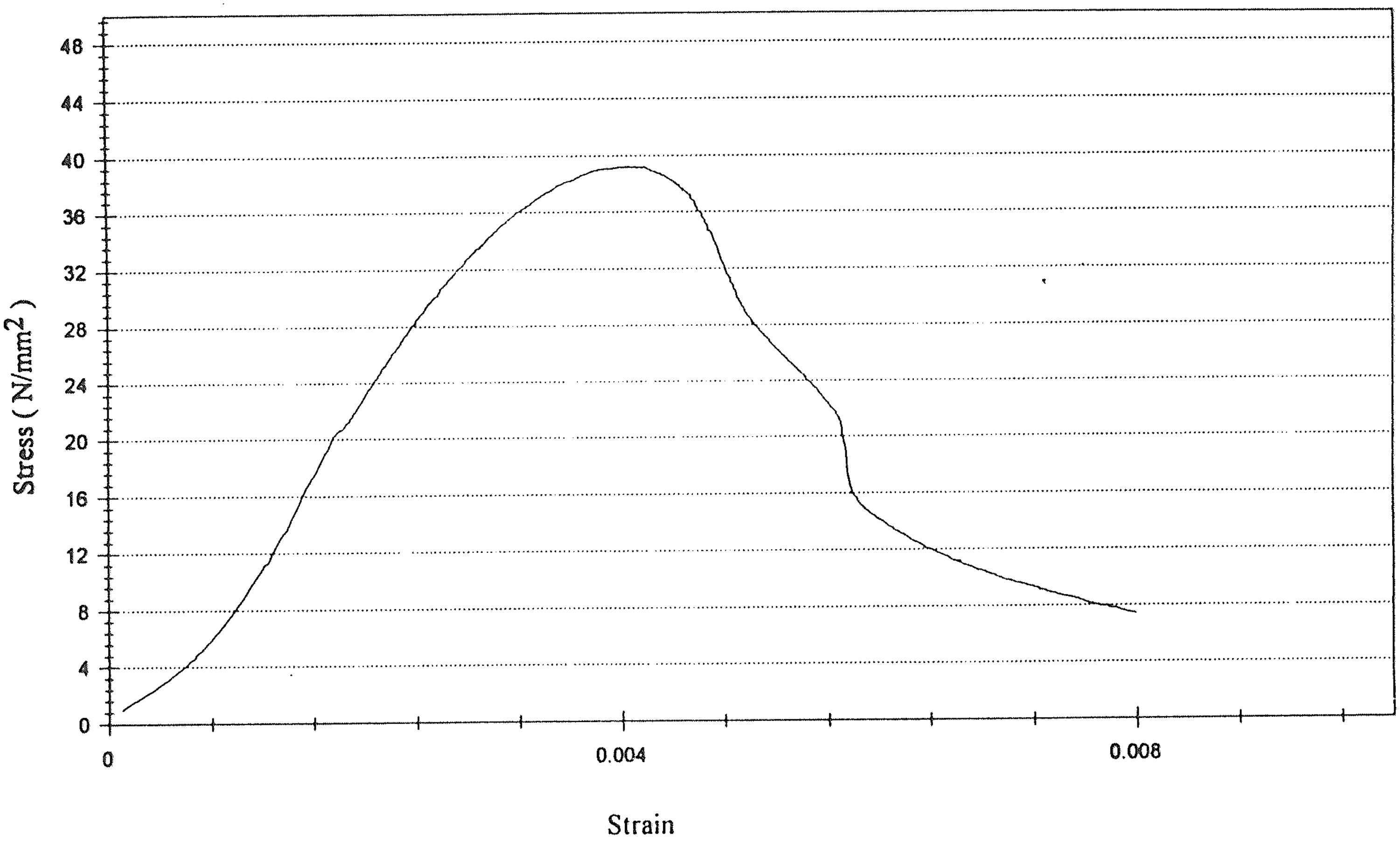


Figure A3 Cement Matrix (Without Silica Fume) Stress Strain Curve

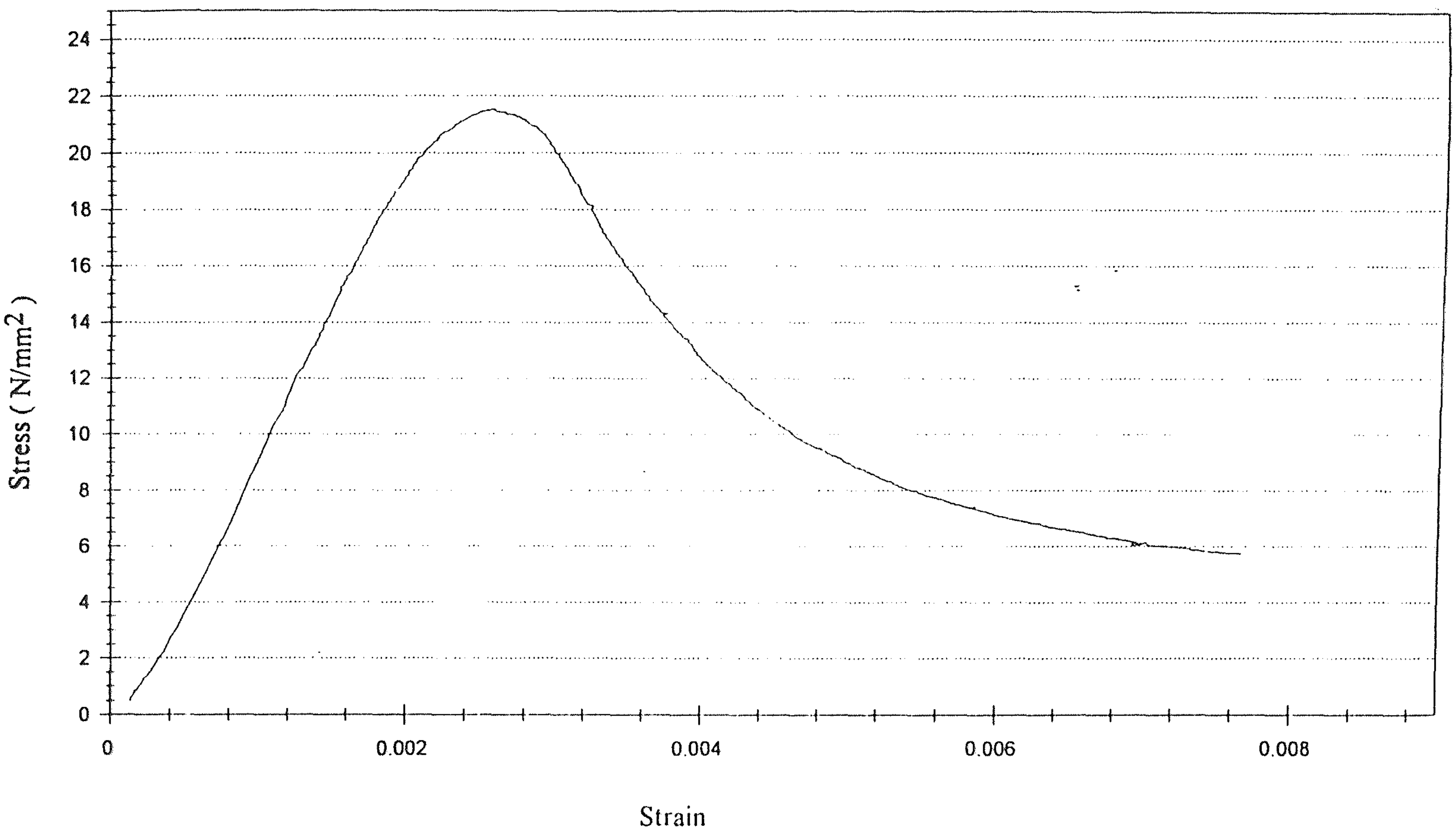


Figure A4 Foam Bead Concrete (Without Silica Fume) Stress Strain Curve with 14% Foam Bead Volume Fraction

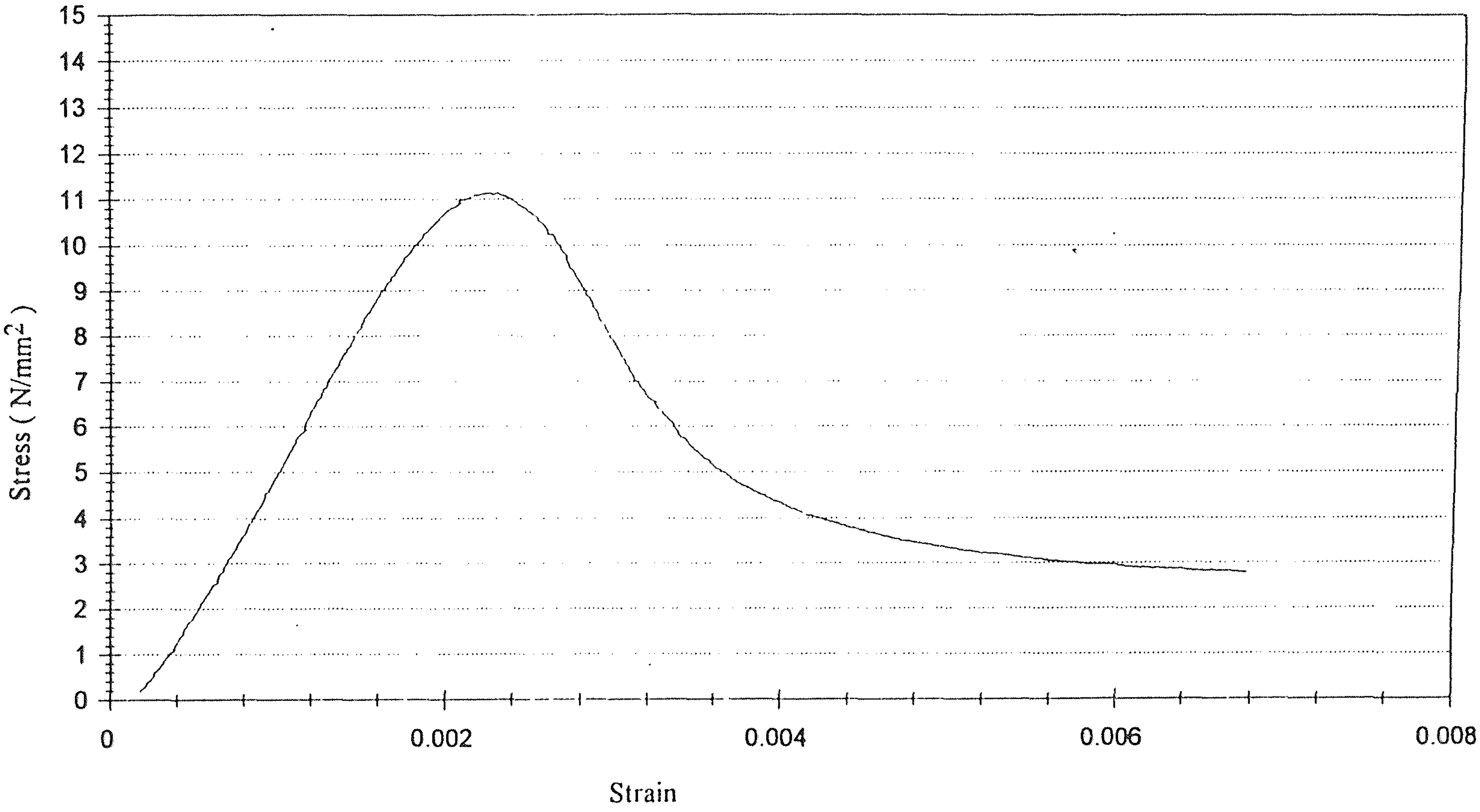


Figure A5 Foam Bead Concrete (Without Silica Fume) Stress Strain Curve with 30% Foam Bead Volume Fraction

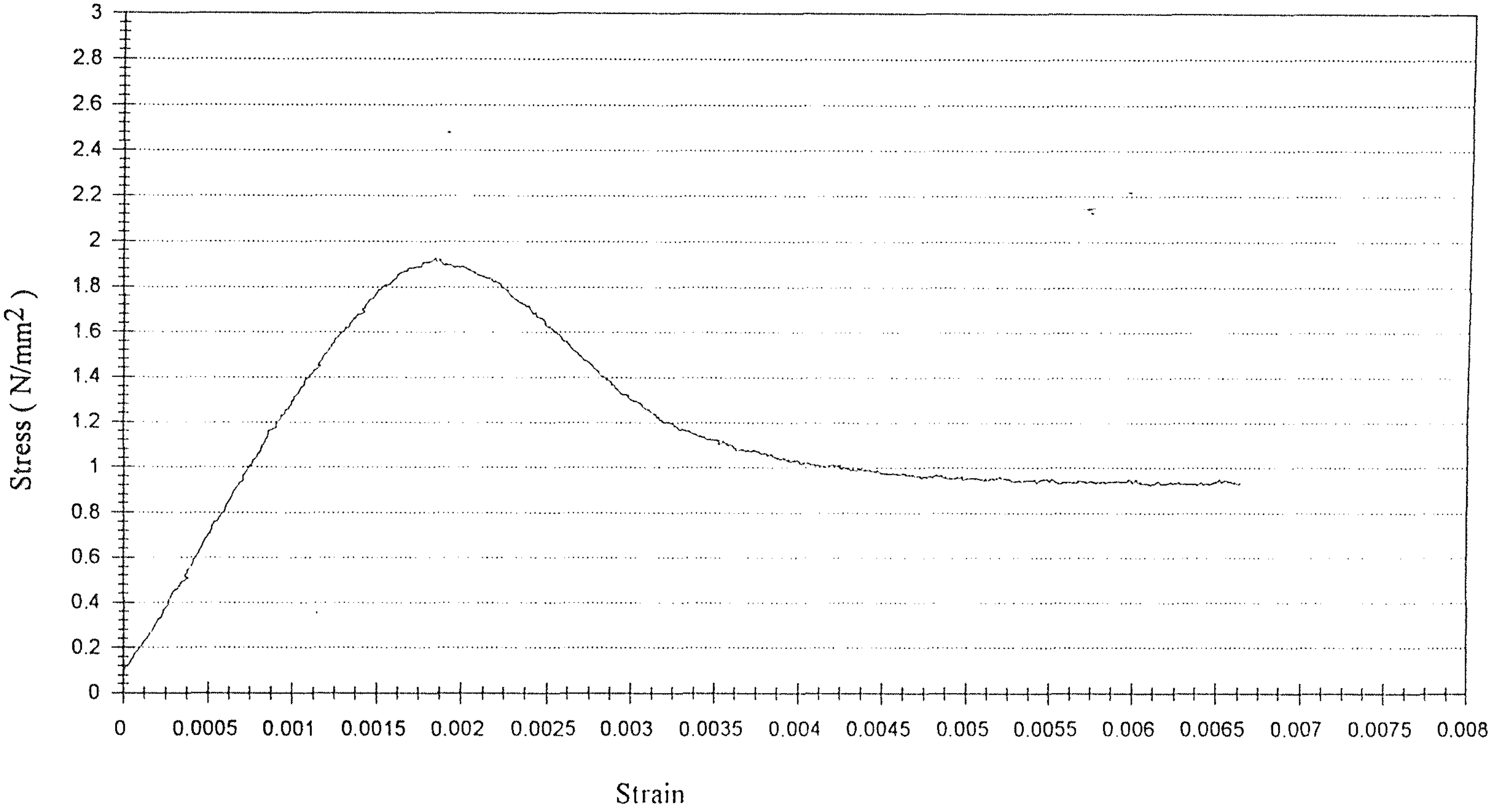


Figure A6 Foam Bead Concrete (Without Silica Fume) Stress Strain Curve with 52% Foam Bead Volume Fraction

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