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PROPERTIES OF STRUCTURAL LIGHTWEIGHT CONCRETE USING SINTERED FLY ASH AGGREGATE

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The paper reports the properties of structural lightweight concrete prepared with a lightweight sintered fly ash aggregate. The cement contents of the concrete mixes vary between 17 to 30 bags per 100 ft³ of concrete. The relationship between the compressive strength and other properties of lightweight concrete such as dry density, tensile strength, modulus of rupture, bond strength, and modulus of elasticity are compared with those for the gravel concrete of comparable strength. The economics and scope of application of lightweight concrete is also discussed.

IN continuation of the research project on the development of lightweight aggregates in India,[1, 2, 3, 4, 5] the present paper reports the properties of the structural concrete prepared with sintered fly ash aggregate, the latter being produced at the Central Building Research Institute on a pilot plant scale[6]. The primary object of the present investigation was to collect experimental data on the properties of the structural lightweight concrete with a view to utilizing it in designing reinforced concrete members and also to evaluating the relative advantages and scope of the use of lightweight aggregate concretes.

Materials and moulding of specimens

The lightweight aggregate used in this investigation was a sintered fly ash aggregate[2] and its properties are listed in *Table* 1. The coarse fraction of the aggregate was graded from $\frac{3}{4}$ in to $\frac{3}{8}$ in. Either crushed sintered aggregate or natural sand was used as fine aggregate, the grading conforming with that recommended in IS 383: 1952. Gravel was used in making dense concrete. The physical properties of the aggregates are given in *Table* 2. The cement used was ordinary Portland cement conforming with IS 269 : 1958.

The proportioning of concrete mixes can be done either on volume or weight basis. Since the volume of the aggregate varies with the method of its handling, the proportioning cannot be controlled effectively in the former. The latter was, therefore, adopted. The concrete was mixed in a 2·5 ft³ hand mixer to ensure uniform mixing. In view of the high water absorption of lightweight aggregate, it was first wetted in the mixer by adding a part of the mixing water, and the mixer was given a few revolutions to distribute the water uniformly. The cement and the remaining water were then added and the entire mass mixed thoroughly for about five minutes. In mixing dense concrete, all the ingredients were first mixed dry and a predetermined amount of water was then added. The workability was controlled in either case.

The slump test has not been found to be a suitable method for measuring the workability of lightweight concretes. Most of the mixes used at the Building Research Station in England had slumps between 0 and 1 but these could be easily compacted. The compacting factor method was, therefore, adopted and the range of compacting factors for

TABLE 2 Physical properties of aggregates

Tests	Coarse aggregate: Gravel	Coarse aggregate: Sintered fly ash	Fine aggregate: Sand	Fine aggregate: Crushed sintered fly ash
Sieve analysis, per cent passing				
3/4 in	94·7	100·0		
3/8 in	15·7	50·0		
3/16 in	2·2	0		
B.S. no. 7			97·6	71·5
14			89·4	51·5
25			40·2	39·3
52			4·9	30·1
100			0·80	20·0
Fineness modulus	6·38	6·50	2·67	2·86
Bulk density, lb/ft³	105	42	90	63
Water absorption by volume	0·74	17·7	—	—
Bulk specific gravity, gm/cm³	2·68	1·37	—	—

lightweight concretes was found to be smaller than for ordinary dense concrete. In the present study, the compacting factor for lightweight concrete was adjusted between 0·70 and 0·75, and for dense concrete between 0·80 and 0·85. Concretes with this workability were found suitable for proper compaction by vibration.

The specimens were cast in steel moulds with machined steel base plates and a thin coat of mould oil was applied to the internal surfaces.

The specimens for compressive strength, dry density, and water absorption were 4-in cubes. The flexural strength and dynamic modulus of elasticity were performed on 4 in × 4 in × 20 in beams; the indirect tensile strength and static modulus of elasticity on 6 in × 12 in cylinders. For bond strength tests, $\frac{3}{4}$-in round mild steel bars were embedded vertically in 6-in concrete cube specimens. The shrinkage specimens were 2 in × 2 in × 10 in bars.

The specimens were cast from different mixes (see *Table* 3) on a table vibrator. The cubes and beams were filled in two layers and vibrated for about two minutes. The cylinders

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TABLE I Properties of sintered aggregates

Aggregate	Bulk density (lb/ft³): Upgraded	Bulk density (lb/ft³): Graded	24-hour water absorption, per cent by volume: Upgraded	Aggregate crushing strength, tons	Residual fuel at 750°C for 4 hrs, per cent	Stain index value
Bokaro	40·0	55·0	19·6	5·50	1·02	20 (very light stain)
Kanpur	38·0	54·0	26·6	1·20	3·7	40 (light stain)
Madras	40·0	58·0	21·9	1·20	2·28	60 (moderate stain)

TABLE 3 Physical properties of sintered fly ash and gravel concretes

Mix by volume	*Water cement ratio by weight*	*Compaction factor*	*Cement content per 100 ft³, bags*	*Dry density, lb/ft³*	*Water absorption by volumes, per cent*	*Compressive strength, lb/in²*		*Tensile strength at 28 days, lb/in²*	*Flexural strength at 28 days, lb/in²*	*Bond strength at 28 days, lb/in²*	*Modulus of elasticity, lb/in² × 10⁶*		*Shrinkage at 100 days, per cent*
						at 7 days	*at 28 days*				*Static*	*Dynamic*	
Lightweight concretes with fine and coarse sintered fly ash as aggregates													
1:2:4	0·99	0·715	17·3	86·0	26·9	1,370	2,170	280	430	350	1·62	1·67	0·064
1:1·7:3·3	0·85	0·715	20·4	89·5	25·4	1,835	2,842	340	494	476	1·80	1·86	0·074
1:1·5:3·3	0·77	0·73	22·4	93·9	24·0	2,229	3,444	375	547	552	1·93	1·97	0·074
1:1·3:2·7	0·70	0·72	24·0	98·5	22·8	2,840	4,298	418	625	651	2·10	2·16	0·079
1:1:2	0·58	0·725	30·0	101·8	20·5	3,182	4,760	444	659	710	2·24	2·29	0·084
Lightweight concretes with natural sand and coarse sintered fly ash as aggregates													
1:2:4	0·88	0·75	17·7	92·5	24·2	1,560	2,456	302	457	386	2·09	2·22	0·059
1:1·7:3·3	0·76	0·73	20·9	99·5	23·2	1,920	3,192	360	535	525	2·26	2·44	0·068
1:1·5:3	0·67	0·735	22·8	103·6	23·2	2,544	3,892	390	570	602	2·63	2·60	0·069
1:1·3:2·7	0·61	0·746	25·0	108·2	21·7	3,140	4,690	445	647	690	2·82	2·83	0·073
1:1:2	0·50	0·745	30·6	111·0	19·3	3,421	5,208	467	682	759	3·03	3·00	0·075
Dense concretes with natural sand and gravel as aggregates													
1:2:4	0·54	0·82	16·2	145·0	13·7	2,450	3,750	388	572	595	3·91	4·07	0·049
1:1·7:3·3	0·515	0·83	18·9	146·8	12·6	2,940	4,648	417	630	640	4·31	4·55	0·059
1:1·5:3·0	0·464	0·837	20·8	150·1	11·8	3,500	5,249	445	655	715	4·99	5·17	0·055

were cast in layers of about 4 inches, each layer being vibrated for one minute. Six specimens were cast for each of the tests except that for the modulus of elasticity. For the latter, three specimens were tested for each of two series to determine the static and dynamic modulus of elasticity.

Curing

All specimens were cured at a relative humidity of over 90 per cent for the first 24 hours. Thereafter, the moulds were struck off and the specimens were stored under water at 27 ± 2°C till the time of testing.

Testing

The cement contents of concrete mixes were determined on the basis of the compacted density of fresh concrete. All the specimens were tested at the age of 28 days, except those for shrinkage which were tested at 7 days. The 7-day compressive strength of all the mixes was also determined. The specimens for dry density and water absorption were first air dried for three days, and then in an oven maintained at 110 ± 2°C till a constant weight was attained. They were then cooled and weighed, and immersed in water at 27 ± 2°C till the weight was constant. This was followed by weighing to find water absorption.

The specimens for compressive strength were tested according to normal procedure. The indirect tensile strength of the concrete was determined by means of the splitting test.[7] The specimens for flexural strength were tested in a compression testing machine under central loading on a span of 10 in. The pull-out test[8] was carried out to determine the bond strength, and it was assumed to be the average value obtained by dividing the applied load by the surface area of the embedded length of the bar. The static modulus of elasticity was determined by loading the specimen in the 80-ton compression testing machine. Lamb's roller extensometer with a gauge length of 8 in and a sensitivity of 0·0001 in was used to record the deformation. The observations were taken at intervals of 2 tons. The dynamic modulus of elasticity was determined by finding the resonant frequency of prismatic specimens excited in the flexural mode[9].

The specimens for shrinkage were removed from water at the age of seven days. The initial length measurements were taken on a laboratory built comparator consisting of a channel frame with one fixed gauge point and a dial capable of reading upto 0·0001 in at the other end. The specimens were then stored in a room maintained at a temperature of 27 ± 2°C and 50 ± 5°C relative humidity. The measurements for the linear shrinkage were continued over a period of 100 days.

Results and discussions

Five lightweight concrete mixes were included in the study. In one series sand was used as fine aggregate and in the other crushed lightweight aggregate was used. Three mixes of gravel concrete of equivalent strengths were also included in the study for comparison. The physical and strength properties of all the concrete mixes are reported in *Table* 3. The concrete prepared with sintered fly ash aggregate will henceforth be termed as lightweight concrete.

Dry density and water absorption

Dry densities of lightweight concretes made with different aggregates have been reported to range between 80 and 126 lb/ft³ against 140-150 lb/ft³, for dense concretes[10]. In the present study they were found to range from 86 to 102 lb/ft³. The use of sand as fine aggregate increased the density range from 92·5 to 111 lb/ft³. For gravel concretes, the density ranged from 145 to 150 lb/ft³.

The water absorption of lightweight concrete is usually reported on a volume basis and is known to be higher than that of gravel concrete[11,12]. The high water-absorption values of lightweight concretes reported in *Table* 3 appear to be due to the higher water absorption of the sintered fly ash aggregate (*Table* 2). This is also evident from a decrease in the value of water absorption when lightweight aggregate fines were replaced by natural sand.

Compressive strength

The compressive strengths of lightweight concretes without sand range from 2170 to 4760 lb/in², and of those containing sand as fine aggregate range from 2456 to 5208 lb/in², indicating an increase in strength by 9·5 to 13·5 per cent in the latter case. The compressive strengths of dense gravel concrete are 3750, 4648, and 5249 lb/in² for 1 : 2 : 4, 1 : 1·7 : 3·3, and 1 : 1·5 : 3 mixes, respectively. The mix composition of lightweight concrete should, therefore, be not leaner than 1 : 1·5 : 3 in order to satisfy the code requirements for reinforced concrete construction, as its strength is comparable to that of 1 : 2 : 4 dense gravel concrete.

The compressive strengths of various concrete mixes increase with increase in cement content (*Table* 3). For

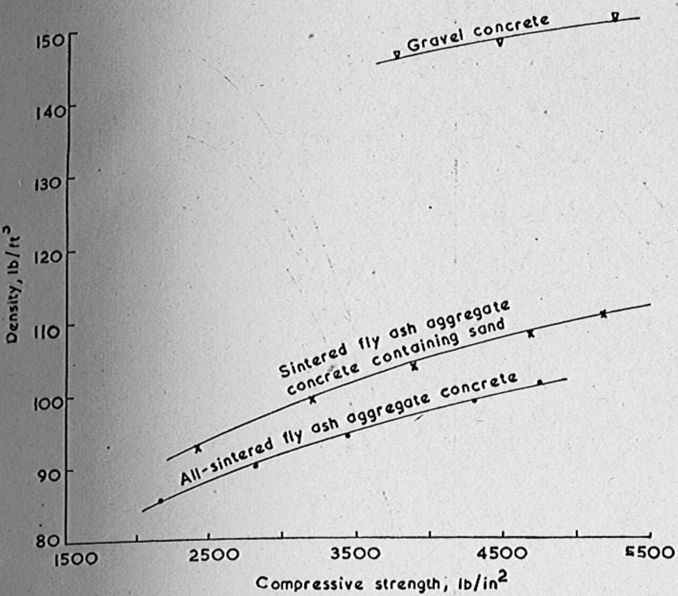

Fig 1 Relationship between compressive strength and dry density

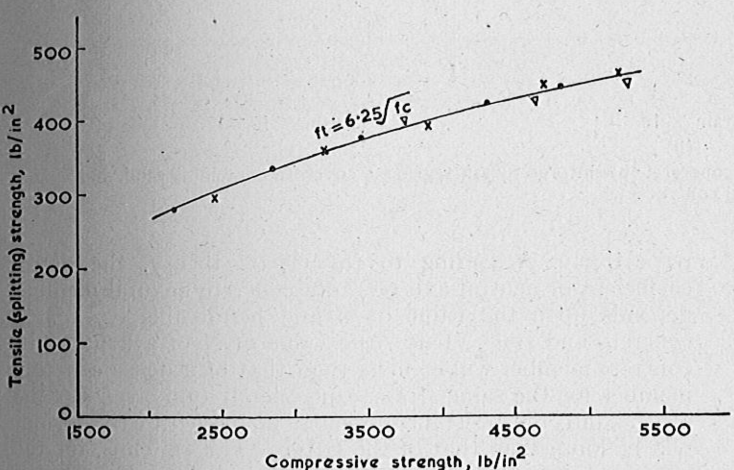

Fig 2 Relationship between compressive strength and tensile strength

comparable strengths, the cement requirement of the lightweight concretes is more than that of gravel concretes. For example, 100 ft³ of 1 : 1·5 : 3 all-lightweight concrete and 1 : 1·5 : 3 lightweight concrete containing sand as fine aggregate require 22·4 and 22·8 bags of cement, respectively, against 16·2 bags for a 1 : 2 : 4 dense concrete of equivalent strength. But this increase in cement content must be viewed against increased strength : weight ratio of the lightweight structural members. The latter for lightweight concrete is about 1·4 to 1·5 times that of dense concrete and is known to result in a saving of steel[4].

The relationship between compressive strength and dry density for lightweight as well as dense concrete mixes is shown in *Fig* 1. It will be seen that for the same compressive strength the bulk density of lightweight concrete is 27 to 34 per cent lower than that of dense concrete. The use of sand as fine aggregate in lightweight concrete increases its density by 6-7 per cent.

Tensile strength and modulus of rupture

The tensile (splitting) strengths of the various mixes range from 280 to 467 lb/in² and are 9 to 13 per cent of the compressive strengths. The relationship between the compressive strength (f_c) and the tensile splitting strength (f_t) is shown in *Fig* 2 and can be expressed by the following equation :

$$f_t = 6{\cdot}25\sqrt{f_c}$$

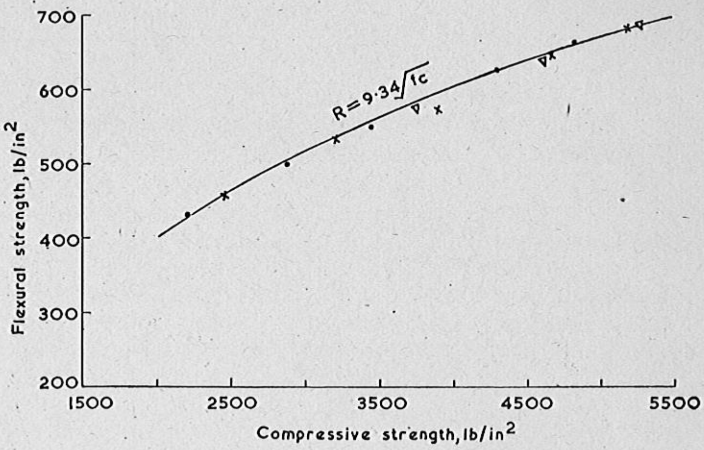

Fig 3 Relationship between compressive strength and modulus of rupture

This relationship holds good for both lightweight and dense concrete. These results confirm the earlier results of Hanson[14].

The flexural strengths of the various mixes vary from 430 to 682 lb/in² and are 12·5 to 19·8 per cent of the compressive strength. The relationship between the compressive strength (f_c) and the modulus of rupture (R) for both lightweight and dense gravel concrete is shown in *Fig* 3 and can be represented by a parabolic equation :

$$R = 9{\cdot}34\sqrt{f_c}$$

The results also indicate that, in general, the modulus of rupture of lightweight concrete is of the same order as that obtained with gravel concrete having equal compressive strengths. This is also in agreement with the observations of other workers[6,14].

In the region of low compressive strengths, the ratios of both the tensile and flexural strengths to the compressive strengths are higher than when the compressive strengths are high.

Bond strength

The data obtained with pull-out tests are reported in *Table* 3 which shows that bond strengths are much higher than those recommended by the B.S. Code of Practice[8] and the factor of safety against bond failure is more than 3 (*Fig* 4). For plain round bars the bond strengths for lightweight concretes have been reported to be either equal or somewhat lower than that of the dense concrete[10,15]. In the present study, the bond strengths for lightweight and dense concrete are almost equal for equal strengths (*Fig* 4).

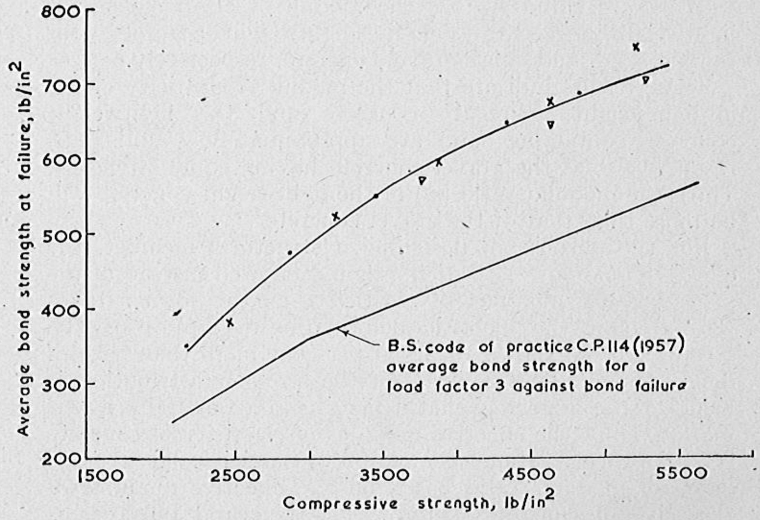

Fig 4 Relationship between compressive strength and average bond strength at failure

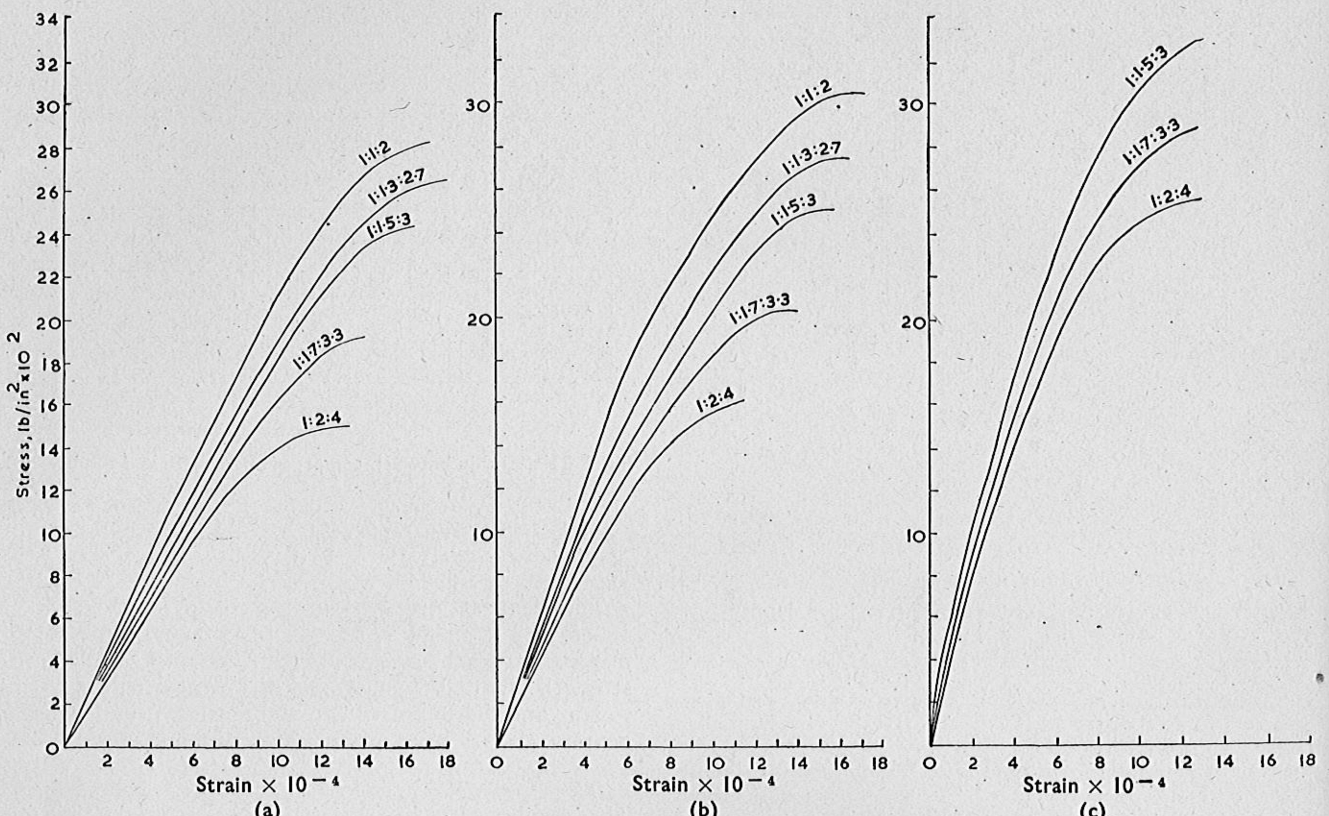

Fig 5 Stress-strain relationship for (a) all sintered fly ash aggregate concrete, (b) sintered fly ash aggregate concrete containing sand, and (c) gravel concrete

Therefore, the bond stresses recommended for gravel concretes are also applicable to lightweight concretes.

Modulus of elasticity

The modulus of elasticity of lightweight concrete prepared with various lightweight aggregates is reported to be considerably lower than that of the dense gravel concrete of comparable strength.[10, 15, 16, 17] Under short duration loading test, the correlation between stress and strain of various concrete mixes are shown in *Fig* 5. The relationship between the compressive strength and static modulus of elasticity of various mixes is shown in *Fig* 6 and the empirical expressions relating the two is as follows:

$$E_C = 1{\cdot}475 \times 10^6 + 225\,(f_c - 1500)$$
$$E_S = 1{\cdot}775 \times 10^6 + 350\,(f_c - 1500)$$
$$E_D = 2{\cdot}175 \times 10^6 + 735\,(f_c - 1500)$$

where E_C, E_S and E_D are the moduli of elasticity of all-lightweight aggregate concrete, lightweight concrete containing sand, and dense gravel concrete, respectively.

These results indicate that the moduli of elasticity of the all-lightweight aggregate concrete and the lightweight concrete containing sand are approximately $\frac{1}{2}$ and $\frac{2}{3}$rds, respectively, of the gravel concrete having equal strengths. Thus, the modular ratio (m) of the lightweight concrete will be more than that of the gravel concrete.

For the purpose of designing a structural member, the effective modulus of elasticity should be used instead of the instantaneous modulus of elasticity, as the former takes into account the inelastic deformation (creep) also. The creep has been shown to be 60 per cent more than that of dense concrete, but in view of the stress redistribution it has been recommended that it may be taken as 100 per cent more[18]. Thus, the effective modulus of elasticity of concrete is half of its instantaneous modulus of elasticity. The average value of modular ratio based on the effective modulus of elasticity of concretes suitable for structural purposes is 28, 21, 14 for all-lightweight aggregate concretes, lightweight concretes containing sand, and dense gravel concretes, respectively. According to the elastic theory, the depth coefficient of neutral axis (N) of a concrete flexural member depends upon the value of m and permissible stresses in concrete and steel. Hence, the value of N of a lightweight concrete member will be more than that of a dense concrete member for the same stresses in concrete and steel. On the other hand, the resistance moment factor (Q) of the former will be more than that of the latter (*Table* 4). Thus, for the same superimposed loads, lightweight concrete flexural members are thinner, which cause a further reduction in their own dead weight.

Drying shrinkage

The drying shrinkage of the various concrete mixes is shown in *Table* 3. For all-lightweight aggregate concretes

TABLE 4. Values of the resistance moment factor Q

f_c = permissible compressive stress in concrete
f_t = permissible tensile stress in steel
m = modular ratio
N = depth coefficient of neutral axis
J = coefficient of lever arm.

f_c, lb/in²	f_t, lb/in²	m	N	J	Q
All-lightweight aggregate concrete					
750	18,000	28	0·536	0·821	165
900	18,000	28	0·585	0·805	215
1,050	18,000	28	0·62	0·793	258
Lightweight concrete containing sand					
750	18,000	21	0·466	0·845	148
900	18,000	21	0·505	0·832	189
1,050	18,000	21	0·55	0·817	235
Gravel concrete					
750	18,000	14	0·366	0·878	121
900	18,000	14	0·41	0·863	160
1,050	18,000	14	0·446	0·851	200

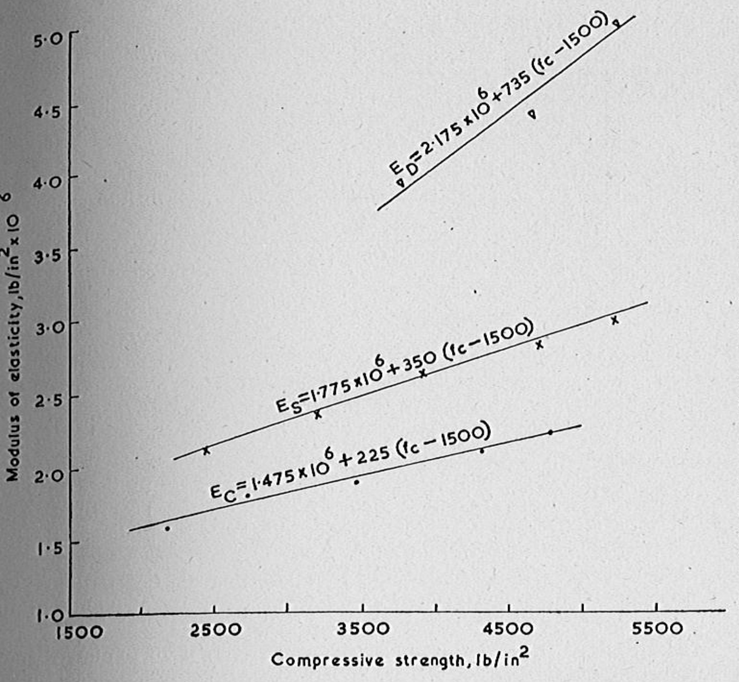

Fig 6 Relationship between compressive strength and modulus of elasticity (E_C, E_S, and E_D are the moduli of elasticity of all-lightweight aggregate concrete, lightweight concrete containing sand, and dense gravel concrete, respectively)

and lightweight concretes containing sand it ranges from 0·064 to 0·084 and 0·059 to 0·075 per cent, respectively, against 0·049 to 0·059 for gravel concretes. Although the drying shrinkage of lightweight concrete is higher than that of dense gravel concrete, the former values are within limit of 0·1 per cent specified by ASTM Designation C330-54T.

Use of lightweight concrete

The use of lightweight concrete has several technical advantages[4, 12, 17, 18]. Its use is known to result in savings in handling costs, in shuttering and formwork, and in reduced labour costs. Savings in foundation work may also result in some instances. But the most important advantage is saving in reinforcing steel. The design of a two-way slab of sintered fly ash concrete for a 15 ft × 12 ft room is given in *Appendix A*, and *Table* 5 compares it with a slab built in dense concrete. It will be seen that the use of sintered fly ash concrete results in an 11 per cent saving of steel. This saving in cost of reinforcement may sometimes be nullified by the higher cost of lightweight concrete itself.

TABLE 5 Comparative design features of a 15 ft × 12 ft reinforced concrete slab built in lightweight and in dense concrete. Live load = 40 lb/ft²

Features	1 : 2 : 4 *dense concrete*	1 : 1·5 : 3 *all-lightweight aggregate concrete**	1 : 1·5 : 3 *lightweight concrete containing sand**
Thickness of slab	4·25 in	4·25 in	4·25 in
Reinforcement along the short span	$\frac{3}{8}''$ φ at 4″ *o.c.*	$\frac{3}{8}''$ φ at 4·5″ *o.c.*	$\frac{3}{8}''$ φ at 4·5″ *o.c.*
Reinforcement along the long span	$\frac{3}{8}''$ φ at 5·75″ *o.c.*	$\frac{3}{8}''$ φ at 6·25″ *o.c.*	$\frac{3}{8}''$ φ at 6·25″ *o.c.*

* Saving in steel is about 11 per cent.

Taking the cost of materials as follows:

Cement	Rs 156 per ton
Sand	Rs 25–55 per 100 ft³
Stone aggregate	Rs 50–150 per 100 ft³
Reinforcement	Rs 700–780 per ton

the total cost of materials for a dense concrete will range between Rs 1·35 and Rs 1·80 per square foot. The cost of production of sintered fly ash aggregate has been estimated at Rs 38 per 100 ft³. Taking the selling price of the coarse aggregate as Rs 50 per 100 ft³ and that of the crushed aggregate as Rs 75 per 100 ft³, the cost of materials for a lightweight concrete slab will range between Rs 1·57 and 1·63 per square foot. The use of sand as fine aggregate in sintered fly ash concrete will reduce the cost of the slab to between Rs 1·50 and Rs 1·66 per square foot. While it is difficult to say under what situations the use of lightweight concrete is economical, because of the varying costs of materials, labour, etc, broadly speaking the use of structural lightweight concrete in multi-storeyed buildings in big towns should be generally profitable.

Conclusions

1. Corresponding to a 1 : 2 : 4 dense concrete specified by both the B.S. Code of Practice[8] and I.S. Code of Practice[19] for reinforced concrete, the mix proportions for lightweight concrete prepared with sintered fly ash aggregate were found to be 1 : 1·5 : 3 by volume.
2. The relationship between the compressive strength (f_c), tensile strength (f_t), and modulus of rupture (R), can be expressed as

   $$f_t = 6{\cdot}25\sqrt{f_c}$$
   $$R = 9{\cdot}34\sqrt{f_c}$$

   These relationships hold true for both lightweight and dense gravel concrete.
3. The bond strength obtained with lightweight concretes is of the same magnitude as that of gravel concretes of comparable strength.
4. The modulus of elasticity of lightweight concrete is lower than that of gravel concrete. The relationships between the compressive strength (f_c) and the modulus of elasticity of the all-lightweight aggregate concrete (E_C), lightweight concrete containing sand (E_S), and of gravel concrete (E_D), are as follows:

   $$E_C = 1{\cdot}475 \times 10^6 + 225\,(f_c - 1500)$$
   $$E_S = 1{\cdot}775 \times 10^6 + 350\,(f_c - 1500)$$
   $$E_D = 2{\cdot}175 \times 10^6 + 735\,(f_c - 1500)$$
5. Design data for a roof slab (15 ft × 12 ft) shows that the use of lightweight concrete slab can result in a saving of about 11 per cent in steel compared to a dense concrete slab.

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APPENDIX A. Design of a lightweight concrete slab for 15 ft × 12 ft room

Mix composition 1 : 1·5 : 3

f_c = 750 lb/in²
f_t = 18000 lb/in²
m = 28
N = 0·536
J = 0·821
Q = 165

Assume thickness of slab $= \frac{\text{span}}{350} = 4 \cdot 25$ in, say

Live load $= 40$ lb/ft²

Deadweight $= 35$ lb/ft²

$1\frac{1}{2}$ in wearing coat $= 18$ lb/ft²

Total load, $w = 93$ lb/ft²

$$r = \frac{\text{effective span along longer side}}{\text{effective span along shorter side}}$$

$$= \frac{15 \cdot 35}{12 \cdot 35} = 1 \cdot 24$$

Load along the shorter span $= w \frac{r^4}{1 + r^4} = 0 \cdot 705 \times 93$

$= 65 \cdot 5$ lb/ft²

Load along longer span $= 93 - 65 \cdot 5$

$= 27 \cdot 5$ lb/ft²

Maximum bending moment along shorter span $= \frac{65 \cdot 5 \times 12 \cdot 35^2}{8} \times 12$

$= 15000$ in lb

Maximum bending moment along longer span $= \frac{27 \cdot 5 \times 15 \cdot 35^2}{8} \times 12$

$= 9750$ in lb

Effective depth $= \sqrt{\frac{15000}{165 \times 12}}$

$= 2 \cdot 75$ in

B.S. Code of Practice CP 114(1957) specifies a minimum thickness of $\frac{\text{span}}{350}$, *i.e.*, $4 \cdot 25$ in.

The deflection of a lightweight concrete member is greater than that of a dense concrete member, hence it is necessary to provide a certain minimum thickness for the flexural rigidity of the former.

So far there is no Indian code of practice for reinforced structural lightweight concrete, therefore the British Standard Code of Practice has been taken as a guide in limiting the minimum thickness of the slab to $4 \cdot 25$ in.

Adopt $3 \cdot 50$ in as effective depth.

Reinforcement along shorter span $= \frac{15000}{18000 \times \cdot 821 \times 3 \cdot 5}$

$= 0 \cdot 29$ in²

Provide $\frac{3}{8}$ in ϕ at $4 \cdot 5$ in o.c.

Reinforcement along longer span $= \frac{9750}{18000 \times 821 \times 3 \cdot 125}$

$= 0 \cdot 21$ in²

Provide $\frac{3}{8}$ in ϕ at $6 \cdot 25$ in o.c.

The slab is safe in shear and bond.

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