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Design and testing of precast reinforced lightweight concrete slabs

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Load tests on precast reinforced lightweight concrete slabs using sintered fly ash aggregate in the concrete are reported. The data show that the slabs fulfil all requirements specified in both the British and the American codes of practice. Furthermore, in comparison to *in situ* construction, the use of precast slabs saves 9 to 21 per cent concrete and 12 to 21 per cent steel.

In continuation of the load tests on lightweight concrete members reported earlier[1], a study of the behaviour of precast reinforced slab units, using sintered fly ash aggregate for the concrete, was carried out to obtain information on their flexural rigidity, elasticity, and ultimate load carrying capacity. The tests were performed according to British and American Standards[2,3]. The findings, are reported in this paper, together with a review of the technical advantages and economics of precast lightweight construction.

The materials used in making lightweight concretes, their proportioning, mixing and properties have been described earlier[4]. In this case, crushed sintered aggregate was used as fine aggregate. Corresponding to a 1:2:4 dense concrete specified by the IS code of practice for reinforced concrete[5], the mix proportions for lightweight concrete were found to be 1:1·5:3 by volume. This had a compressive strength of 3,444 lb/in² at 28 days under laboratory condition of curing and gave a minimum cube strength of 2,450 lb/in² and a cylinder strength of 1,810 lb/in² under field conditions of curing.

Design of slabs

Round mild steel bars conforming to IS:432:1953 were used for reinforcement. The slabs had spans of 8 and 12 ft and were designed according to the elastic theory for a live load of 40 lb/ft². The width was 1 foot. The safe permissible compressive stress in the concrete, *c*, and the safe tensile stress in the steel, *t*, was taken as 750 and 18,000 lb/in², respectively[5]. The modular ratio *m* was taken as 28[4]. The design procedure for the 8-ft span is given in Appendix 1. The 12-ft span was designed in a similar manner. The salient design features of the two slabs are shown in *Fig* 1.

Fabrication

The slabs were cast in rigid wooden frames tightened with mild steel clamps at an interval of about 2 ft to avoid warping and bulging out. Galvanised iron pipes placed in

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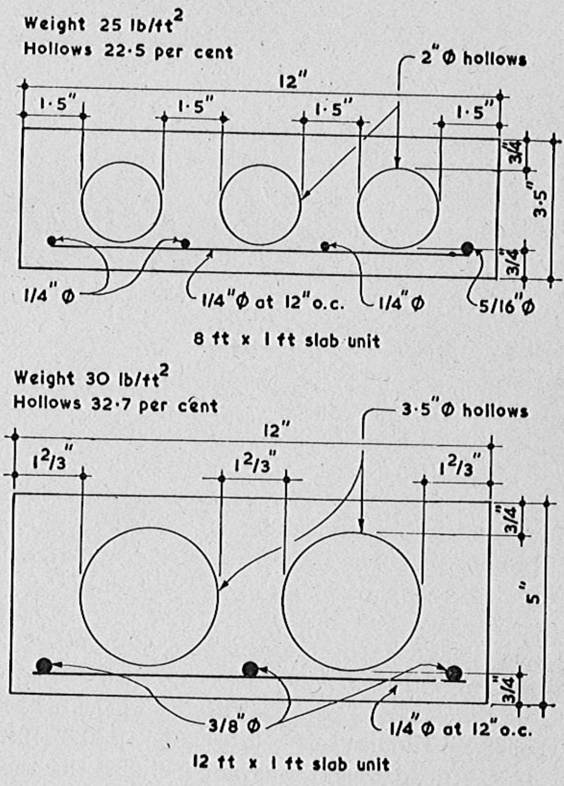

Fig 1. Details of the cross section of precast lightweight concrete slab units used in this investigation

the moulds to form the hollows (*Fig* 2). The reinforcement extended up to one inch short of the end of the slab and ¼ in dia bars were welded to the main reinforcement at 12 in c.c. to keep it in position and also to distribute the load uniformly. A thin coat of mould oil was applied to the internal surfaces of the moulds and outer surfaces of the pipes to prevent the concrete from sticking to them. The concrete was compacted in the moulds by means of surface vibrators. At least three 4-in cubes were cast from the same batch of concrete and cured along with the slab under identical conditions. About an hour after casting the concrete the galvanized iron pipes were drawn out by gently rotating them with the help of a short lever (*Fig* 3). The slabs were removed from

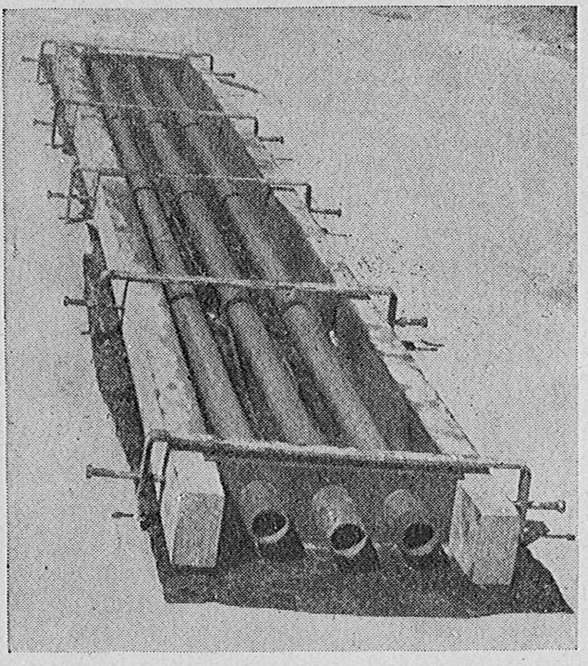

Fig 2. Showing the mould for casting the slabs. Galvanized iron pipes were used to form the hollows

the moulds a day after casting and cured under wet gunny bags for 28 days.

Testing

For testing, the slabs were simply supported on 1½-in dia round steel bars laid on the top of rigid supports, the distance of 8 ft 3½ in between the supports being for the 8-ft spans and 12 ft 5 in for the 12-ft spans. The testing was carried in accordance with both the British and the American Standards [2,3]. The loading was provided by dense concrete blocks stocked on the slabs with a gap of about 3 in between the stacks. The slabs were first loaded to equal the representing dead load, and then to the specified test loads. Two dial gauges with a reading accuracy of 0·001 in were fixed in the centre of each slab to record the deflections in the loaded and unloaded states (*Fig.* 4). The deflection due to the dead weight was not included in the test measurements when checking the stiffness of the slab.

Since roof slabs are subject to reversal of loads, the slabs were tested for alternate loading and unloading cycles after they were tested as above. The test load was kept on the slab for 24 hours and it was then removed and the slab left undisturbed for 24 hours. The deflections of the slab were recorded after 24 hours of loading, immediately after removing load, and 24 hours after unloading, thus completing one cycle (*Tables* 1 and 2). Five such cycles were repeated. The slabs were then tested to destruction, care being taken to prevent arching within the loaded material as it causes unequal distribution of the load.

Discussion of the results obtained

The major structural requirement for a roof slab is that it should have a reasonable degree of stiffness and elasticity. The deflection of a slab due to superimposed

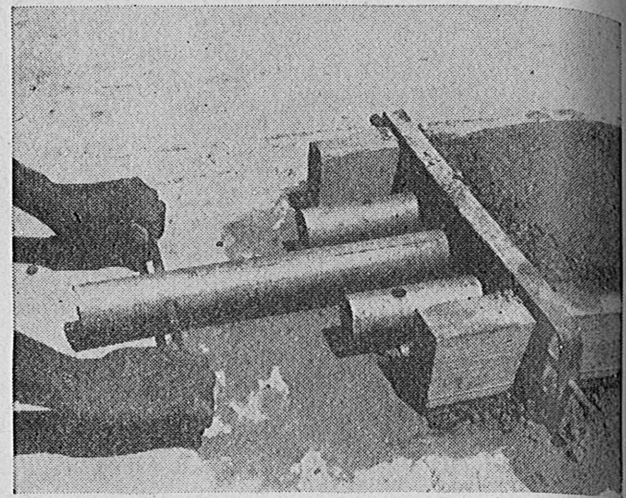

Fig 3. Drawing the galvanized iron pipes out by gently rotating them with the help of a short lever. This was done less than an hour after the concrete was cast

loads should not be excessive and it should recover appreciably when the load is removed. The British standard specifies that the structure should be subjected to superimposed load equal to one and a quarter times the specified load (test load of 50 lb/ft²) and this load should be maintained for a period of 24 hours before removal. If within the 24 hours of the removal of the load, the structure does not show a recovery of at least 75 per cent of the maximum deflection shown during the 24 hours under load, the test loading should be repeated and the recovery after the test should not be less than 75 per cent of the maximum deflection shown during the second test.

The results of the tests carried out in accordance with British standards are given in *Table* 1. The maximum deflection shown during 24 hours under load ranged from 1/624 to 1/758 and 1/640 to 1/756 of the span for the shorter and the longer slabs, respectively, against a maximum value of 1/250 of the span[6]. The data further indicate that none of the slabs showed a recovery of 75 per cent of the maximum deflection shown during 24 hours under load. Accordingly the test was repeated. The recovery after the second test was

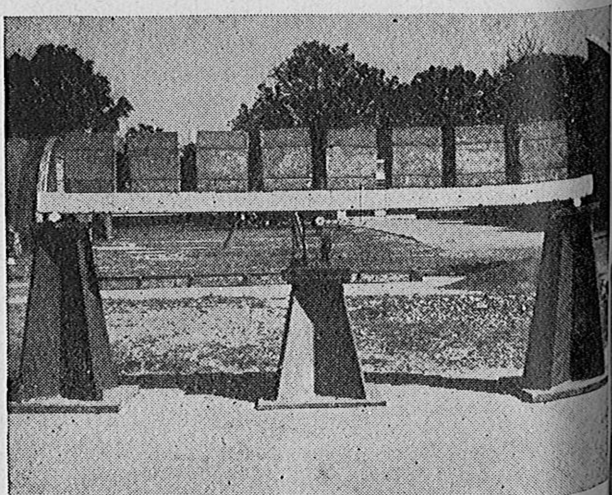

Fig 4. Testing a lightweight concrete slab. Testing was carried out in accordance with both the British and the American standards

TABLE 1 Results of tests carried out in accordance with British Standards

Deflection after 24 hours of loading, in	*Residual deflection, in*		*Span ÷ deflection,*	*Recovery, per cent*	
	Immediate	*After 24 hours*		*Immediate*	*After 24 hours*
D_1	D_2	D_3	$\frac{L}{D_1}$	$100\frac{D_1 - D_2}{D_1}$	$100\frac{D_1 - D_3}{D_1}$
8 ft × 1 ft slab					
			First loading		
0·149	0·067	0·054	667	55·0	63·7
0·160	0·066	0·055	624	58·7	65·6
0·143	0·060	0·049	695	58·0	65·7
0·131	0·056	0·042	758	57·3	68·0
0·150	0·070	0·059	664	53·5	60·4
0·137	0·063	0·051	726	54·1	62·8
			Second loading		
0·110	0·035	0·024	904	68·1	78·1
0·118	0·038	0·028	841	67·7	76·4
0·101	0·034	0·024	985	65·5	75·4
0·092	0·029	0·017	1081	68·5	81·5
0·101	0·027	0·015	985	73·3	85·1
0·096	0·032	0·017	1035	66·6	82·3
12 ft × 1 ft slab					
			First loading		
0·223	0·094	0·075	669	57·7	66·4
0·206	0·091	0·071	724	55·8	65·6
0·197	0·085	0·067	756	57·9	66·0
0·216	0·098	0·078	690	54·6	63·8
0·215	0·095	0·080	693	55·8	62·6
0·233	0·102	0·086	640	56·1	63·0
			Second loading		
0·164	0·051	0·034	908	68·0	79·3
0·151	0·040	0·030	921	73·5	80·2
0·146	0·045	0·033	1020	69·2	77·5
0·155	0·053	0·034	961	65·7	78·0
0·170	0·055	0·040	876	67·6	76·5
0·168	0·048	0·037	886	71·5	78·0

TABLE 2 Results of tests carried out in accordance with American Standards

Deflection after 24 hours of loading, in	*Residual deflection, in*		*Span/deflection*	
	Immediate	*After 24 hours*		
D_1	D_2	D_3	$\frac{L}{D_1}$	$\frac{L}{D_2}$
8 ft × 1 ft slab				
0·336	0·165	0·128	296	603
0·297	0·149	0·125	335	668
0·310	0·157	0·122	321	634
0·314	0·142	0·111	317	700
0·291	0·139	0·113	343	716
0·323	0·152	0·117	308	654
12 ft × 1 ft slab				
0·470	0·226	0·196	317	660
0·452	0·214	0·180	329	696
0·485	0·222	0·190	306	671
0·439	0·193	0·166	340	771
0·468	0·204	0·174	318	730
0·426	0·202	0·171	349	736

found to be more than 75 per cent of the maximum deflection shown during the second test. Alternate loading and unloading cycles showed that in each cycle the recovery was more than 75 per cent of the maximum deflection shown during that cycle.

According to American Standards, the maximum 24-hour midspan deflection due to a test load of twice the designed live load should not exceed 1/160 of the span, and the residual deflection immediately after removing the test load should not exceed 1/400 of the span. The results of the tests carried out in accordance with these standards are given in *Table* 2. The maximum deflection under load during 24 hours varied from 1/288 to 1/343 and 1/306 to 1/349 of the span for the short and the long slabs, respectively. The residual deflection varied from 1/603 to 1/716 and 1/660 to 1/771 of the span for the two lengths of slab, respectively. Alternate loading and unloading cycles showed that in each cycle the maximum 24-hour deflection and the residual deflection were much less than the specified limits. The foregoing discussion indicates that the test slabs fulfilled the requirements of both the British and American standards.

The other structural requirement for a roof slab is that it should have an ample load factor against collapse. The British and the American codes of practice require a minimum load factor of 2·0 and 1·8, respectively. The revised Indian code IS:456–1964 specifies that the member should be designated to carry without failure a load equal to 1·5 times the dead load + 2·2 times the live load.

The details of the load-carrying capacity of the slabs are given in *Table* 3. For the sake of comparison, the ultimate load-carrying capacity of the slabs were also calculated from Whitney's equation[7] (*Appendix* 1) and the values are given in the table.

The data indicate that the experimental values of ultimate moment, *Mex*, were higher than the calculated moment *Mu*.. The ratio of *Mex*/*Mu* ranged from 1·11 to 1·18 and 1·10 to 1·18, and the load factors, ranged between 2·87 to 3·06 and 2·81 to 3·01 for the two spans, respectively. The slabs failed at 242 to 276 lb/ft² and were higher than that specified by the Indian standard.

Economics

The economical advantages of structural lightweight concrete over dense concrete in *in-situ* construction has been discussed earlier[4]. It was pointed out that the use of lightweight concrete in roof slabs saves 11 per cent

TABLE 3 Ultimate strength and load factors

Design moment × 10², *in lb* M_D	*Ultimate moment due to applied load* × 10² *in lb*	*Self weight moment* × 10², *in lb*	*Total ultimate moment* × 10², *in lb* M_{ex}	*Calculated ultimate moment* × 10², *in lb* M_u	$\frac{M_{ex}}{M_u}$	*Load factor* $\frac{M_{ex}}{M_D}$
8 ft × 1 ft slab						
86·50	237·00	25·39	262·39	223·90	1·17	3·02
86·50	240·00	25·39	265·39	223·90	1·18	3·06
86·50	228·30	25·39	253·69	223·90	1·13	2·92
86·50	224·20	25·39	249·59	223·90	1·11	2·88
86·50	231·30	25·39	256·69	223·90	1·15	2·98
86·50	240·00	25·39	265·39	223·90	1·18	3·06
86·50	223·00	25·39	248·39	223·90	1·11	2·87
86·50	229·50	25·39	254·89	223·90	1·14	2·94
86·50	232·10	25·39	257·49	223·90	1·15	2·97
86·50	223·00	25·39	248·39	223·90	1·11	2·87
86·50	231·00	25·39	256·39	223·90	1·15	2·97
86·50	235·90	25·39	261·29	223·90	1·16	3·01
12 ft × 1 ft slab						
204·00	531·10	69·30	600·40	510·84	1·16	2·96
204·00	499·80	69·30	569·10	510·84	1·10	2·78
204·00	513·50	69·30	582·80	510·84	1·12	2·85
204·00	502·00	69·30	571·30	510·84	1·11	2·81
204·00	541·00	69·30	610·30	510·84	1·18	2·99
204·00	519·90	69·30	589·20	510·84	1·13	2·88
204·00	539·90	69·30	609·20	510·84	1·17	2·99
204·00	545·00	69·30	614·30	510·84	1·18	3·01
204·00	531·00	69·30	600·30	510·84	1·16	2·95
204·00	512·50	69·30	581·80	510·84	1·12	2·85
204·00	526·00	69·30	595·30	510·84	1·15	2·93
204·00	545·20	69·30	614·50	510·84	1·18	3·01

TABLE 4 Quantity of materials required for cast *in-situ* and precast slabs

Type of slab	Thickness of slab, in		Steel reinforcement, lb		Saving, per cent			
					Concrete		Steel	
	10 × 8 ft room	15 × 12 ft room	10 × 8 ft room	15 × 12 ft room	10 × 8 ft room	15 × 12 ft room	10 × 8 ft room	15 × 12 ft room
Cast *in-situ*	3·0	4·25	101·40	337·15	—	—	—	—
Precast	3·5	5·0	88·88	267·84	9·5	20·8	12·30	20·4

steel. In the light of the present investigation, it is further brought out that roof slabs built with precast units are economical than those constructed *in-situ*. For example, in the construction of one-way roof slabs, the use of precast units would result in a saving of concrete of 22·5 and 32·7 per cent, for the short and the long span, respectively. There would also be a saving in materials when precast units are used for roof slabs of 10 ft × 8 ft and 15 ft × 12 ft rooms. The saving in concrete by the use of the precast units would be 9·5 and 20·8 per cent and the saving in steel 12·3 and 20·4 per cent for the two lengths of slab (*Table* 4). There would also be a reduction in the cost of formwork and scaffolding and an increase in productivity. The use of precast lightweight slab units is, therefore, recommended. There is a good scope of their use in prefabrication and the construction of multistoreyed buildings.

Conclusions

Precast reinforced lightweight concrete slabs, when designed as described in this paper, fulfil the requirements of both the British and American standard codes of practice. The load factors are found to range between 2·81 and 3·06. The ultimate load varies between 242 to 276 lb/ft² and is higher than that specified by the revised Indian standard code of practice IS: 456–1964.

In one-way roof slabs, the use of 8 ft × 1 ft and 12 ft × 1 ft precast slabs results in a saving of concrete of 22·5 and 32·7 per cent, respectively. Design data for roof slabs for 10 ft × 8 ft and 15 ft × 12 ft rooms show that precast slabs save 9·5 and 20·8 per cent concrete and 12·3 and 20·4 per cent steel, respectively.

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APPENDIX I

Design of 8 ft × 1 ft precast reinforced lightweight concrete slab

Mix composition = 1:1·5:3 by volume

Permissible stress in concrete, c = 750 lb/n²

Permissible stress in steel, t = 18,000 lb/in²

Modular ratio, m = 28

Depth coefficient of neutral axis, N = 0·536

Coefficient of lever arm, J = 0·821

Resistance moment factor, Q = 165

Assume the thickness of slab at span/30 = 3·5 in, say

Live load = 40 lb/ft²

Self weight = 25 lb/ft²

1½-in wearing coat = 18 lb/ft²

Total load W = 83 lb/ft²

$$\text{Maximum bending moment} = 83 \times \frac{(8\cdot 32)^2}{8} \times 12 = 8650 \text{ in lb}$$

$$\text{Effective depth} = \sqrt{\frac{8650}{165 \times 12}} = 2\cdot 1 \text{ in.}$$

(The B.S. Code of practice, CP 114 (1957), specifies a minimum thickness of span/30, *i.e.* 3·5 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 the reinforced structural lightweight concrete, therefore the British code has been taken as a guide in limiting the minimum thickness of the slab).

Effective depth of slab = 2·75 in

$$\text{Tension reinforcement} = \frac{8650}{18000 \times \cdot 821 \times 2\cdot 75} = 0\cdot 212 \text{ in}^2$$

Use 3 bars ¼ in dia and one bar $\frac{5}{16}$ in dia.

The slab is safe in shear and bond.

There can be three hollows of 2 in dia each, giving a percentage of hollow of 22·5.

Ultimate load carrying capacity

The calculated ultimate moments M_u were obtained from the following equation due to Whitney.

$$\frac{M_u}{bd^2} = p f_y \left[1 - \left(0\cdot 59\, p \frac{f_y}{f_c}\right)\right]$$

M_u = calculated ultimate moment, in lb

b = width of slab = 12 in

d = effective depth to the centre of gravity of reinforcement = 2·75 in

A_s = area of tension reinforcement = 0·224 in²

$p = \frac{A_s}{bd} = 0\cdot 00677$

f_y = yield stress of mild steel reinforcement = 40,000 lb/in²

f_c = compressive strength of 6 in × 12 in cylinder

= 0·75 × minimum cube strength (2,250 lb/in²) = 1,700 lb/in²

$$\frac{M_u}{12 \times 2{\cdot}75^2} = 0{\cdot}00677 \times 40{,}000 \left[1 - \left(\frac{0{\cdot}59{\cdot}00677 \times 40{,}000}{1{,}700}\right)\right]$$

$$= 0{\cdot}00677 \times 40{,}000\ [1 - 0{\cdot}094]$$

$$M_u = 12 \times 2{\cdot}75^2 \times 0{\cdot}00677 \times 40{,}000 \times 0{\cdot}906$$

$$= 22{,}390 \text{ in lb.}$$

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