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Experiments on Foamed Concrete for the Development of Building Blocks

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Abstract: ***Foamed concrete is an innovative and versatile lightweight building material, which is a cement-based mortar consisting of at least 20% of its volume filled with air. Use of lightweight foamed concrete blocks with densities less than 1800 kg/m³ as infills will lead to the design of slender sections. Further, the thermal insulation properties of foamed concrete blocks made it more popular in construction industry. This paper discusses the development of foamed concrete building blocks for load bearing and non-load bearing structures. To make the mix more sustainable, the feasibility of fly ash as a partial replacement to cement is also explored. The variables considered for the production of foamed concrete are foam volume, water/powder (mix of cement and fly ash) ratio, fly ash content and sand/powder ratio. Analytical model is also developed for compressive strength and dry density of foamed concrete considering different variables and it is validated. Compressive strength is found to be increasing with the increase in dry density and with increase in fly ash content. Thermal conductivity is observed to be reduced by the addition of fly ash content.***

Keywords: ***Foamed concrete, fly ash, compressive strength, sustainability, thermal conductivity words or phrases in alphabetical order, separated by commas.***

I. INTRODUCTION

Brick is the common building unit used in construction since ancient times. Production of conventional bricks and hollow or solid concrete blocks causes depletion of natural resources and create environmental pollution, which have led the researchers to find a more sustainable solution. Formed concrete (FC) offers a viable solution to overcome the ill effects of brick making, since large quantities of industrial wastes can be utilized for its manufacture. FC is a special type of light weight concrete in which stable foam is used as one of the ingredients. A suitable foaming agent may be used for the production of stable foam with the help of a standard foam generator. The main specialty of this concrete is the absence of coarse aggregate. A minimum of 20% volume of foam is entrained into the plastic mortar to form FC of density varying from 400 kg/m³ to 1800 kg/m³ (Kearsley and Wainwright 2001a, b, Jones and McCarthy 2005). The stable foam consists of millions of evenly distributed, consistently sized air bubbles or cells. While adding this into the prepared cement mortar, it sets around the foam bubbles and subsequent degeneration of foam makes the paste to have sufficient strength to maintain its shape around the voids (Kearsley and Mostert 2005, Siram 2012). Hence, the major factors, which are to be considered with prime importance while producing foamed concrete are method of preparation of foam, addition of air, selection of ingredients and proper mixture design (Kearsley and Wainwright 2002, Dawood and Hamad, 2013).

Several investigations carried out on foamed concrete describe in detail regarding the composition, physical properties and uses of it (Kearsley and Mostert, 2005). Later, models were developed to predict the compressive strength of foamed concrete by the influence of fly ash (Nambiar and Ramamurthy 2006 c). Further, Nambiar and Ramamurthy (2006 a, b) investigated the effect of replacing large volumes of fine aggregate with fly ash and came out with high compressive strength, which is attributed to the finer size of sand and fly ash. It has been observed by Kearsley and Mostert (2005) that foamed concrete is more sensitive to water demand than normal concrete. It was also observed that coarse aggregate being absent in foamed concrete makes FC to have more drying shrinkage value, which has been confirmed by Jones and McCarthy (2005). Shrinkage of foamed concrete generally occurs within 20 days of casting and drying shrinkage got reduced when cement was replaced with fly ash (Richard and Ramli 2013). Mix with fine sand resulted in high compressive strength compared to coarse sand due to uniform distribution of pores in foamed concrete with fine sand (Nambiar and Ramamurthy (2006 a, b), 2007, 2008).

A state-of-the-art review on the characteristics of surfactants and foam done by Sahu et al. (2018), suggests that the selection of surfactant and foam prediction parameters play a vital role in the properties of foam, which in turn affects the properties of FC. Role of foaming agent in FC is to create small enclosed air bubbles by reducing the surface tension of the solution, which facilitates the formation of stable air bubbles. Protein type foaming agent has been found to result in smaller isolated air bubbles than synthetic type foaming agent (Panesar 2013, Richard and Ramli 2013).

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After reviewing the above investigations, the following observations are made. (1) All the previous studies were focused on the characterization of FC as a structural material. But as suggested by Jones and Mc Carthy (2005), the high drying shrinkage and low tensile strength and stiffness performance limits the straight substitution of foamed concrete for normal weight concrete (2) But, as a material with reasonably good compressive strength at low dry density makes foamed concrete blocks a viable substitute for conventional bricks or solid/ hollow concrete blocks, which are presently available at densities ranging from 1800 kg/ m^3 to 2400 kg/ m^3.

Very few works are noted on the viability of FC as a material for the manufacture of load bearing and non-load bearing building units. (3) Possibility of incorporation of high volumes of industrial wastes in the production of masonry blocks will contribute to a sustainable construction practice. (4) Also, in all the previous studies, rich mix of 1:1 or 1:2 had been used to get high strength.

Accordingly, this investigation is aimed at developing a design methodology for the production of foamed concrete for load bearing as well as non-load bearing building block with fly ash as a replacement for cement and with mix ratios 1:3 and 1:4. The properties studied are 7 & 28 days compressive strength, dry density, water absorption and thermal conductivity. The influence of sand powder ratio, water powder ratio, fly ash content and foam volume on dry density and strength development are also reported. An analytical model has been developed for predicting the compressive strength and dry density of FC, which will help practicing engineers for the commercial production of FC.

II. EXPERIMENTAL PROGRAMME

A. Materials

Ordinary Portland cement of 53 grade as per IS 12269:2013, Manufactured sand (M Sand) of specific gravity 2.53 and fineness modulus 2.34 and synthetic type foaming agent were used for the study. Specific gravity and pH of foaming agent are 1.07 and 6.7 respectively, which has been mixed with water in the ratio 1:35 to make the pre-formed foam solution. Stable foam of density 78.5 kg/m3 was then produced using a standard foam generator. Cement was partially replaced by class F fly ash of specific gravity 2.44. Mix proportions of FC were developed as per ASTM C796 – 97.

B. Casting and testing of Specimen

In most of the literatures, it has been noticed that sand powder ratio has been kept less than 2, which makes the cost of such concrete very high. Hence in this study, importance has been given to economize the concrete production by choosing the powder sand proportion as1:3 and 1:4. Various mixes of powder (fly ash and cement) sand ratio in proportions of 1:3 and 1:4 and with water powder ratios 0.45, 0.55 and 0.65 were prepared for proposed densities of 1800 kg/m^3, 1600 kg/m^3 and 1400 kg/$m^3$and with 20 %, 30 % and 40 % foam volume for the design. For w/p ratio less than 0.45, it has been found that it is difficult to get a mix of good consistency without the use of super plasticizers. Hence the above three ratios were selected for the study. The major aim of this investigation is to develop sustainable and economical building block, which can replace the existing bricks and hollow/solid concrete blocks. Hence the experiment has been limited to only three densities as mentioned above. The details of these mix proportions and mix ID for powder/sand ratio 1:3 with water/powder ratio 0.45 are presented in Table 1. Similar method of mix designation is followed for the remaining and for 1:4 mix with different water/powder ratios. The stable foam produced through the foam generator was mixed uniformly and homogeneously with already prepared base mix using foam concrete mixer as shown in Fig. 1. Feeding of stable foam into the mixer is as shown in Fig.2. Foam concrete mixer is a horizontal type mixer having a mixing speed of 60 rpm. While preparing the mix itself, the wet density was checked and compared with the design density to verify the density ratio (ratio of wet density to design density) to be nearly unity (Nambiar and Ramamurthy 2006 a, Amarnath and Ramachandrudu 2013). The cube moulds were then filled with the prepared foamed concrete and levelled by shaking the moulds. The cubes of size 100 mm x 100 mm x 100 mm were cast for the determination of compressive strength, water absorption and dry density. Since holes are to be drilled to conduct thermal conductivity test, 150 mm x 150 mm x 150 mm specimens (3 nos.) were also prepared. Fifteen cube specimens were cast from each mix for the conduct of various tests. Altogether 54 design mixes were prepared and 810 cubes were cast and tested for the analysis. The specimens were demoulded after 24 hours and cured. For calculating dry density, the specimens were dried to attain constant weight in hot air oven at 110 ℃ and then cooled to room temperature. Thermal conductivity was measured using thermal conductivity meter by means of the probe, by inserting it into the specially made holes in the specimens as shown in Fig. 3.

Fig. 1.Foam concrete mixer with foam generator

Fig. 2.Feeding stable foam into the foam concrete mixer

Fig. 3.Testing the Thermal conductivity of FC specimen

C. Designation of Mix ID

Table I: Mix proportions and mix ID

Sl. No.	Powder/sand ratio	Water/powder ratio	Volume of Foam (%)	Percentage of fly ash	Mix ID
1	01:03	0.45	20	0	$0.45F_320A$
2			20	20	$0.45F_320B$
3			20	40	$0.45F_320C$
4		0.45	30	0	$0.45F_330A$
5			30	20	$0.45F_330B$
6			30	40	$0.45F_330C$
7		0.45	40	0	$0.45F_340A$
8			40	20	$0.45F_340B$
			40	40	$0.45F_340C$

Fig. 4.Samples of specimen

III. RESULTS AND DISCUSSION

The results for 28-day compressive strength, dry density, water absorption and thermal conductivity are tabulated in Table 2 and 3. Samples of specimen after testing the compressive strength are shown in Fig.4. The variation of compressive strength with foam volume for mixes with powder/sand ratio 1:3 are presented in Fig. 5 to 7. The similar trend is seen for the mixes with powder/sand ratio 1:4. It can be observed that, the dry density as well as compressive strength of foam concrete decreases as foam volume, which is an indicator of air voids in FC, increases. This can also be attributed to the merging of foam bubbles resulting in large voids, which in turn lead to the reduction in strength. It can also be observed that compressive strength increases with fly ash content. This is in agreement with the study by Nambiar and Ramamurthy (2006 b). The increase in strength may be due to the fineness of fly ash and also its pozzolanic nature. The variation of compressive strength with water/powder ratios for mixes with water/powder ratios 1:3 and 1:4 are presented in Fig. 8 and 9. The interesting observation is that the compressive strength of FC increases marginally with increase in water content in contrast to that of ordinary concrete. This may be due to the fact that less foam is required at higher water powder ratio to reach the same target density. Appropriate quantity of water enhances the consistency and stability of the mix and thus plays a key role in the production of FC of required density. Water absorption is seen to increase steadily with increase in foam volume and fly ash content, but is seen to reduce marginally with increase in water/powder ratio. But in all cases, percentage of water absorption is much lower than burnt bricks of equal strength. Thus, FC of strength from 3 N/mm^2 to 12 N/mm^2 can be made with 40 % to 20 % foam and with fly ash content up to 40 %, which will cater to both load bearing and non-load bearing construction purposes. In all the previous studies, rich mix had been used to get higher strength. From this study, it has been observed that, even lean mixes with 20% and 30 % FV comes out with comparable strength as that of existing country burnt bricks and hollow/concrete blocks.

The thermal conductivity of normal FC ranges between 0.40 and 0.50 W/m.K (Watts per meter Kelvin) and that of FC with density 1000 kg/m^3 is one-sixth of the value of typical cement sand mortar (Ramaurthy et al. 2009, Chen and Liu 2013). A reduction in foamed concrete density by 100 kg/m^3 results in a lessening in its thermal conductivity by 0.04 W/m.K (Mydin et al. (2015). One important finding of the present study is that the thermal conductivity decreases with the addition of fly ash. For the mix with w/p 0.65 and 40 % foam volume, the thermal conductivity dropped by 24 % by the addition of 40 % fly ash (from 0.187 W/m.K to 0.142 W/m.K). This is in agreement with the finding of Demirboga (2007), which indicated a drop of 23 % of thermal conductivity by the addition of 30 % replacement of fly as in ordinary concrete. This may be attributed to the fact that the fineness of cement is enhanced through the utilization fly ash, which causes a larger interface area, which act as a thermal barrier (Zhao et al. 2015). Variation of thermal conductivity with fly ash content for 1:3 mix and 1:4 mix are shown in Fig.10 and 11 respectively.

Table II: Compressive strength and dry density for 1:3 mix

Sl No	Mix ID	28^{th} day Comp. Strength (MPa)	Dry Density (kg/m3)	Water Absorption (%)	Thermal Conductivity (w/mK)
1	$0.45F_320A$	10.67	1848	2.79	0.353
2	$0.45F_320B$	11.07	1837	3.54	0.321
3	$0.45F_320C$	11.63	1782	4.23	0.305
4	$0.45F_330A$	7.17	1570	6.27	0.287
5	$0.45F_330B$	7.83	1562	7.18	0.265
6	$0.45F_330C$	8.27	1588	8.34	0.243
7	$0.45F_340A$	3.23	1365	10.45	0.216
8	$0.45F_340B$	3.93	1384	11.62	0.196
9	$0.45F_340C$	4.13	1392	12.79	0.181
10	$0.55F_320A$	10.6	1803	2.44	0.325
11	$0.55F_320B$	11.43	1848	3.27	0.304
12	$0.55F_320C$	12.1	1836	4.25	0.286
13	$0.55F_330A$	7.43	1649	4.82	0.271
14	$0.55F_330B$	8.17	1638	7.03	0.261
15	$0.55F_330C$	8.67	1644	9.79	0.243
16	$0.55F_340A$	3.63	1380	11.25	0.224
17	$0.55F_340B$	4.23	1390	11.95	0.208
18	$0.55F_340C$	4.6	1420	12.5	0.187
19	$0.65F_320A$	11.2	1825	2.25	0.311
20	$0.65F_320B$	11.73	1791	3.45	0.292
21	$0.65F_320C$	12.07	1828	4.23	0.286
22	$0.65F_330A$	7.67	1568	5.77	0.275
23	$0.65F_330B$	8.3	1608	6.26	0.253
24	$0.65F_330C$	8.97	1642	7.76	0.213
25	$0.65F_340A$	3.87	1372	9.23	0.187
26	$0.65F_340B$	4.43	1389	10.47	0.164
27	$0.65F_340C$	4.97	1414	11.28	0.142

Table III. Compressive strength and dry density for 1:4 mix

Sl No	Mix ID	Compressive Strength in Mpa 28th day	Dry Dens in kg/m3ity	Water Absorption in %	Thermal Conductivity in w/mK
1	$0.45F_420A$	8.77	1829	3.86	0.384
2	$0.45F_420B$	9.3	1852	4.54	0.355
3	$0.45F_420C$	9.87	1796	5.48	0.333
4	$0.45F_430A$	5.4	1642	7.24	0.31
5	$0.45F_430B$	5.97	1578	8.07	0.286
6	$0.45F_430C$	6.5	1554	9.12	0.262
7	$0.45F_440A$	0.1	1373	10.78	0.248
8	$0.45F_440B$	0.72	1348	11.62	0.22
9	$0.45F_440C$	1.3	1415	12.98	0.194
10	$0.55F_420A$	8.97	1856	3.64	0.365
11	$0.55F_420B$	9.63	1828	4.13	0.343
12	$0.55F_420C$	10.13	1764	5.08	0.321
13	$0.55F_430A$	5.77	1652	6.72	0.304
14	$0.55F_430B$	6.37	1638	7.43	0.267
15	$0.55F_430C$	6.87	1628	8.69	0.21
16	$0.55F_440A$	0.4	1378	10.43	0.187
17	$0.55F_440B$	0.91	1424	11.35	0.175
18	$0.55F_440C$	1.5	1460	12.86	0.162
19	$0.65F_420A$	9.3	1849	2.32	0.324
20	$0.65F_420B$	9.83	1765	3.46	0.31
21	$0.65F_420C$	10.47	1744	4.76	0.287
22	$0.65F_430A$	6	1586	3.78	0.269
23	$0.65F_430B$	6.67	1614	4.94	0.239
24	$0.65F_430C$	7	1629	5.36	0.218
25	$0.65F_440A$	0.6	1348	7.26	0.187
26	$0.65F_440B$	1.25	1394	8.43	0.163
27	$0.65F_440C$	1.8	1426	9.38	0.146

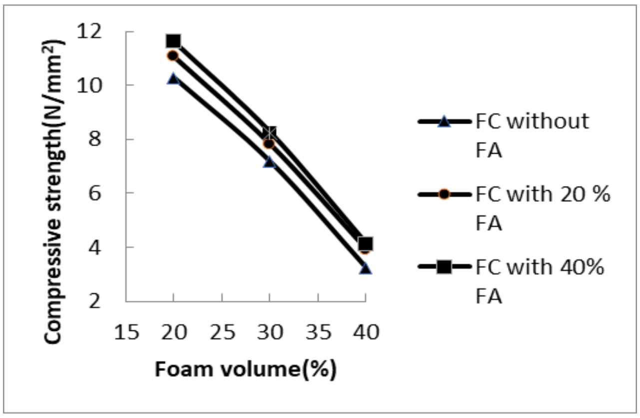

Fig. 5.Variation of Compressive strength with foam volume for 1:3 mix with w/p ratio 0.45Samples of specimen

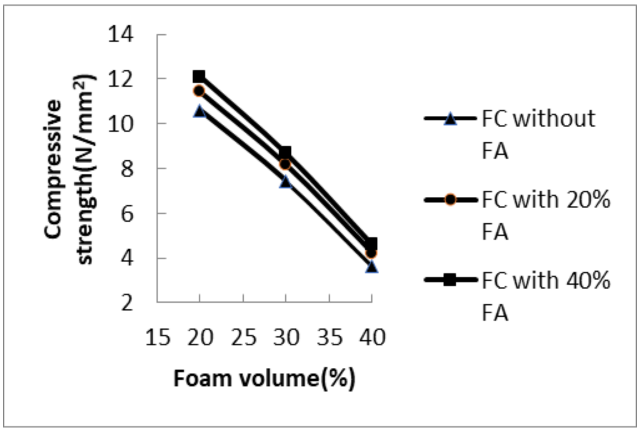

Fig. 6.Variation of Compressive strength with foam volume for 1:3 mix with w/p ratio 0.55

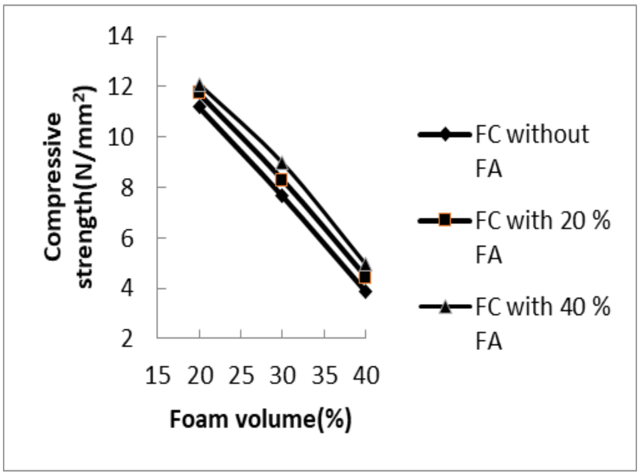

Fig. 7.Variation of Compressive strength with foam volume for 1:3 mix with w/p ratio 0.65

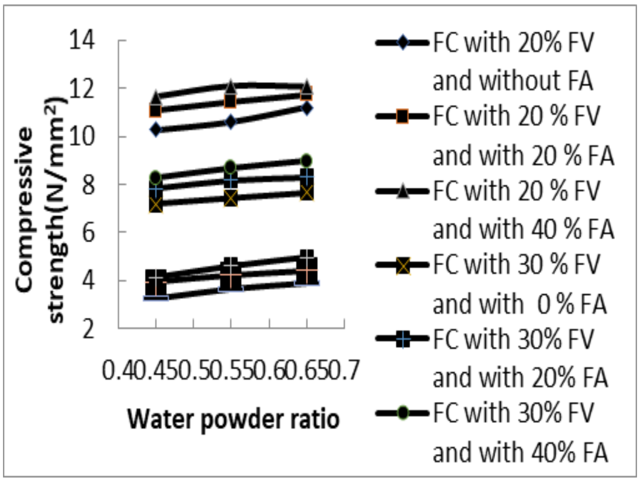

Fig. 8.Variation of compressive strength with w/p ratio for 1:3 mix

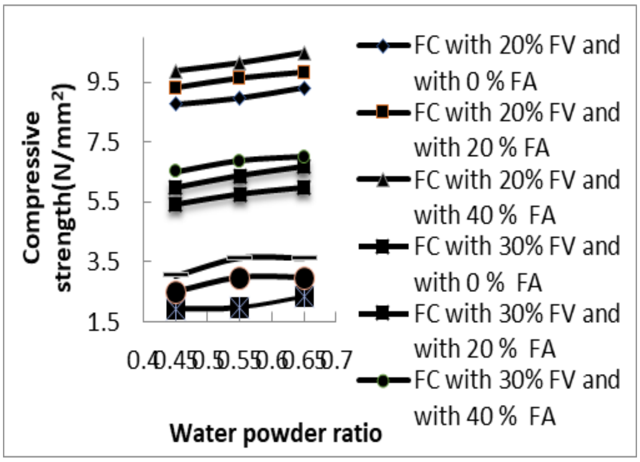

Fig. 9.Variation of compressive strength with w/p ratio for 1:4 mix

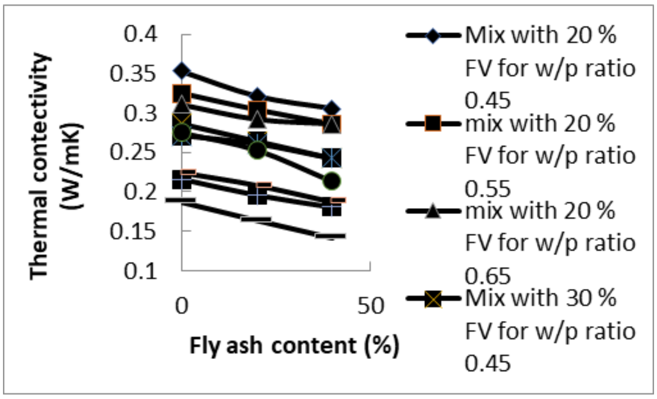

Fig. 10. Variation of Thermal Conductivity with fly ash content for 1:3 mix

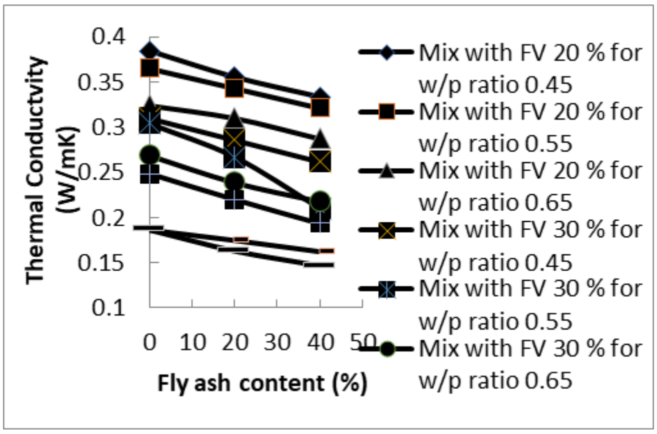

Fig. 11. Variation of Thermal Conductivity with Fly ash content for 1:4 mix

IV. ANALYTICAL MODEL FOR COMPRESSIVE STRENGTH AND DRY DENSITY

An analytical model has been developed for 28 days compressive strength (f_{28}) and dry density (D) in terms of sand/powder ratio (s/p), water/powder ratio (w/p), foam volume (fv) and fly ash (fa) content and is as follows.

$$f_{28} = 20.56 + 3.83\left(^{w}/_{p}\right)^2 - 0.068 fv^2 + 0.023\, fa - 2.63\left(^{s}/_{p}\right) \quad (1)$$

$$D = 1868.13 + 21.32\left(^{w}/_{p}\right) - 0.183(fv)^2 + 0.125 fa - 10.78\left(^{s}/_{p}\right) \quad (2)$$

Where,

f_{28} = 28 days compressive strength
D = Dry density
s/p = sand powder ratio
w/p = water powder ratio
fv = foam volume and
fa =fly ash percentage

A. Performance Evaluation and validation of the Model

The performance evaluation of the model for compressive strength and dry density with respect to the test results from present study are analyzed and the maximum and minimum percentage variation is noted and presented in Table 4. The proposed model has been validated with limited number of results available in literature and is presented in Table 5 and 6. Even though many studies are made in FC, the parameters considered in the literatures are different from the present investigation. In the present study, river sand is fully replaced with M sand, cement is replaced partially and the foaming agent used is also different. Even then, the proposed model is able to predict compressive strength and densities of FC reasonably well. A maximum error of 21.45 % was noted for 28 days compressive strength from the study by Falade et al. (2013). From the study by Kearsley and Mostery (2005), the compressive strength values differed by 29.73 %, the value being 7 days compressive strength. The proposed model also holds good for the study by Nambiar and Ramamurthy (2006 b) for a mix with sand cement ratio 1, 10 % foam volume and with 70 % fly ash content with a predicted value of 19.82 N/mm^2 against 17.80 N/mm^2, even though the density of stable foam was different in two studies. Thus, it can be inferred that the proposed model can predict the 28 days strength of FC reasonably well using eq 1. It can also be seen that the values predicted for dry density using eq. 2 are in very good agreement with the actual experiment values available in the literature. The maximum variation was 2.92 % for the study by Richard and Ramli (2013) and 0.69 % for the study by Falade et al. (2013)

Table IV: Performance evaluation of model for compressive strength and density

Sl No.	Compressive strength MPa		Error %	Sl No	Dry Density (kg/m^3)		Error %
	Observed	Predicted	(maximum and minimum)		Observed	Predicted	
1	3.23	2.57	19.83	1	1365	1548.32	-13.43
2	8.17	8.17	0	2	1782	1772.92	0.51

Table V:Validation of the model for compressive strength

w/p	s/p	fv (%)	fa (%)	Compressive Strength (N/mm^2)				
				Predicted	Falade et al. (2005)	Variation (%)	Kersley and Mostert (2005)	Variation (%)
0.32	0	23.2	33.3	18.07			16	12.94
0.3	0	22.4	50	18.63			16.5	12.91
0.29	0	22	60	18.97			15	26.47
0.28	0	21.7	66.7	19.2			14.8	29.73
0.5	3	20	0	10.91	13.89	-21.45		
0.5	3	20	5	11.02	13.24	-16.77		
0.5	3	20	10	11.14	12.81	-13.04		
0.5	3	20	15	11.26	12.11	-7.02		
0.5	3	20	20	11.37	11.34	0.26		

Table VI: Validation of the model for dry density

w/p	s/p	fv (%)	fa (%)	Dry density in kg/m^3				
				Predicted	Richard and Ramli, (2013)	Variation (%)	Falade et.al. (2013)	Variation (%)
0.3	2	22.94	0	1726.85	1752.19	-1.47		
0.3	2	25.11	10	1686.59	1734.36	-2.83		
0.3	2	25.11	20	1686.42	1735.6	-2.92		
0.3	2	24.09	30	1710.91	1738.54	-1.61		
0.3	2	22.22	50	1756.3	1764.39	-0.46		
0.5	3	20	0	1810.43			1800.26	0.56
0.5	3	20	5	1811.85			1800.89	0.6
0.5	3	20	10	1813.26			1801.51	0.65
0.5	3	20	15	1814.68			1802.14	0.69
0.5	3	20	20	1816.09			1802.76	0.73

V. CONCLUSIONS

Based on the study conducted on foamed concrete using fly ash, the following conclusions are made.

- Using suitable foaming agent, good quality load bearing and non-load bearing foamed concrete blocks can be developed at a much lower density than solid/hollow concrete blocks or burnt clay bricks, thereby reducing the dead load on the structure. This can lead to slender sections with savings in reinforced cement concrete, steel reinforcement, plastering etc. for framed structures.
- It is confirmed that the volume of foam counteracts the strength of foamed concrete. In general, as the foam increases, the compressive strength and dry density decreases. The compressive strength of foamed concrete increases marginally with the water content.
- Addition of fly ash enhances compressive strength and reduces thermal conductivity of foamed concrete.
- Utilization of fly ash for the development of good quality building blocks with thermal insulation properties ensures environment friendly disposal of waste materials.
- An analytical model is developed for 28 days compressive strength and dry density with sand/ powder ratio, water/powder ratio, foam volume and fly ash content as variables. This enables practicing engineers to design blocks of required density and compressive strength ensuring sustainable construction practices.
- It is found that lean mixes also provide higher strength, so that foamed concrete blocks can replace the existing hollow/solid concrete blocks or country burnt bricks.

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