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# Models relating mixture composition to the density and strength of foam concrete using response surface methodology

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**Abstract**

There have been several investigations in the past on the influence of mixture composition on the properties of foam concrete. Conventionally strength is related to density alone and few models have been developed relating strength with density, porosity, gel–space ratio, etc. Very little work has been reported in the literature in predicting the properties of foam concrete from the knowledge of its mixture proportions. This paper discusses the development of empirical models for compressive strength and density of foam concrete through statistically designed experiments. The response surface plots helps in visually analysing the influence of factors on the responses. The relative influence of fly ash replacement on strength and density of foam concrete is studied by comparing it with mixes without fly ash and brought out that replacement of fine aggregate with fly ash will help in increase in the strength of foam concrete at lower densities allowing high strength to density ratio. Confirmatory tests have shown that the relation developed by statistical treatment of experimental results can act as a guideline in the mixture proportion of foam concrete.


*Keywords:* Foam concrete; Response surface methodology (RSM); Fly ash replacement level; Filler–cement ratio; Strength–density ratio

## 1. Introduction

Several of the earlier investigations on foam concrete give a detailed discussion on its composition, physical properties and uses [1–6]. The first comprehensive review on cellular concrete including foam concrete was presented by Valore [1] and a detailed treatment by Short and Kinniburgh [3] and Rudnai [4]. A rational proportioning method of preformed foam concrete was proposed by Mc Cormick [5] based on solid volume calculations. Richard [6] reviewed the thermal and mechanical characteristics of foam concrete. Hoff [7] reported a porosity-strength model for cellular concrete made with Portland cement, water and preformed foam. Durack and Weiqing [8] proposed a strength-gel space ratio relationship for foam concrete. Nehdi et al. [9] presented a nontraditional approach to the prediction of density and compressive strength of foam concrete mixtures based on the Artificial Neural Network (ANN) technology. For moist cured foam concrete, the relation between strength and volumetric composition, particularly water content and air voids, has been formulated by Tam et al. [10] using Feret's and Power's equation, for a small range of water–cement ratios (0.6–0.8) and sand–cement ratios (1.58–1.73). Kearsley and Wainwright [11–14] investigated the effect of replacing large volume of cement with fly ash and equations based on effective water–cement ratio and binder ratio have been developed to predict the strength of foam concrete made of cement paste of different densities at different ages. Most of these studies related strength to density, gel–space ratio or porosity. Limited work has been reported on predicting the properties of foam concrete from knowledge of its mixture proportion.

Further, studies on foam concrete using fly ash as partial/complete replacement for filler have proved that

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Table 1
Physical and chemical properties of cement and fly ash used

| Properties | Cement | | Fly ash | |
|---|---|---|---|---|
| *Physical* | | | | |
| Blaine fineness ($m^2$/kg) | 391 | | 252 | |
| Specific gravity | 3.13 | | 2.09 | |
| 28-day compressive strength (MPa) | 54.7 | | – | |
| | % by mass | IS 12269-1987 (17) | % by mass | ASTM C 618 (Class F) (18) |
| *Chemical* | | | | |
| $SiO_2$ | 19.3 | – | 63.6 | – |
| CaO | 61 | – | 1.57 | <10 |
| $Al_2O_3$ | 5.687 | – | 28.19 | – |
| $Fe_2O_3$ | 6.036 | – | 2.99 | – |
| MgO | 1.875 | 6 | 0.54 | 5 (max) |
| MnO | – | – | 0.03 | – |
| $Na_2O$ | – | – | 0.05 | – |
| $K_2O$ | – | – | 0.003 | – |
| $SO_3$ | 1.67 | 2.5 | 0.26 | – |
| Loss on ignition | 0.2963 | 4 | 0.85 | – |
| Soluble residue | 1.489 | 2 | – | – |
| $Al_2O_3/Fe_2O_3$ | 0.94 | 0.66 | – | – |
| $SiO_2 + Al_2O_3 + Fe_2O_3$ | – | – | 94.78 | 70 (min) |

the use of fly ash results in higher strength to density ratio and facilitates its high volume utilization [15]. This study attempts to develop empirical models for predicting the density and compressive strength of foam concrete from the mixture composition details like filler–cement ratio, addition of fly ash as partial/complete replacement for sand and foam volume, through systematically designed experiments.

## 2. Experimental investigations

### 2.1. Materials and mixture composition

Foam was produced by aerating an organic based foaming agent (dilution ratio 1:5 by weight) using an indigenously fabricated foam generator to a density of 40 kg/$m^3$. 53 grade Ordinary Portland Cement [16], pulverized river sand finer than 300 μm (specific gravity = 2.52) and class F fly ash conforming to ASTM C 618-89 [17] were used. The properties of cement and fly ash used in this study are presented in Table 1.

Table 2
Factors and factor levels adopted

| Notation | Factor | Low level | High level |
|---|---|---|---|
| F/C | Filler–cement ratio | 1 | 3 |
| FA | Fly ash as replacement for sand (%) | 20 | 100 |
| FV | Foam volume (% of total volume of concrete) | 10 | 50 |

The mix proportions were arrived at as per the procedure given in ASTM C 796-97 [18]. As the standard deals with only cement slurry, the procedure was modified to include cement–sand–fly ash components. As the foam is added to the wet mix, the consistency of the wet mix is very important to get the desired design density [15], which is expressed in terms of water–solids ratio required to produce this consistency, and its range is narrow for a given mix. Based on several trails, the percent flow (consistency), measured in a standard flow table [19] (without raising/dropping of the flow table as it may affect the foam bubbles entrained in the mix) was arrived at as 45 ± 5%. Earlier studies by the authors have shown that within this range, the water–solids ratio does not affect compressive strength. As the water–solids requirement for obtaining this flow values varied for mixes with and without fly ash replacement (0.3–0.4 for mixes without fly ash and 0.35–0.6 for mixes with fly ash at different replacement levels), it was decided to split experimental programme into two mixes, namely cement–sand mixes ($M_1$) and cement–fly ash–sand mixes ($M_2$).

### 2.2. Experimental design and validation

With an objective of developing relationships between the parameters and response (empirical models for compressive strength and density), a statistical methods of experimental design based on response surface methodology (RSM) is adopted. For providing equal precision of estimates in all directions, a central composite design with rotatability or equal precision is selected [20]. The factors and factor levels are shown in Table 2. Mixture $M_1$ has

Table 3
Observed and predicted responses for confirmation of models

| Mix type | Mixture composition | | | Compressive strength, MPa | | | | | | Dry density, kg/$m^3$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | F/C | FA, % | FV, % | 7-Day | | 28-Day | | 90-Day | | | |
| | | | | Predicted | Observed | Predicted | Observed | Predicted | Observed | Predicted | Observed |
| $M_1$ | 1 | – | 20 | 9.0 | 7.8 | 11.6 | 10.7 | 13.2 | 12.3 | 1282 | 1318 |
| | 2 | – | 35 | 2.41 | 2.14 | 2.67 | 2.30 | 2.91 | 3.01 | 998 | 1011 |
| | 3 | – | 50 | 0.25 | 1.20 | 0.52 | 1.23 | 0.84 | 1.54 | 802 | 787 |
| $M_2$ | 1 | 70 | 10 | 13.8 | 12.3 | 18.9 | 17.8 | 24.7 | 23.0 | 1194 | 1224 |
| | 2 | 65 | 30 | 3.66 | 2.93 | 5.08 | 4.84 | 9.23 | 8.03 | 858 | 854 |
| | 3 | 50 | 40 | 1.03 | 1.87 | 1.10 | 1.96 | 3.83 | 3.01 | 664 | 650 |