Industrial waste utilization for foam concrete

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Abstract. Foam concrete is an emerging and useful construction material - basically a cement based slurry with at least 10% of mix volume as foam. The mix usually containing cement, filler (usually sand) and foam, have fresh densities ranging from 400 kg/m³ to 1600 kg/m³. One of the main drawbacks of foam concrete is the large consumption of fine sand as filler material. Usage of different solid industrial wastes as fillers in foam concrete can reduce the usage of fine river sand significantly and make the work economic and eco-friendly. This paper aims to investigate to what extent industrial wastes such as bottom ash and quarry dust can be utilized for making foam concrete. Foam generated using protein based agent was used for preparing and optimizing (fresh state properties). Investigation to find the influence of design density and air-void characteristics on the foam concrete strength shows higher strength for bottom ash mixes due to finer air void distribution. Setting characteristics of various mix compositions are also studied and adoption of Class C flyash as filler demonstrated capability of faster setting.

1. Introduction

Foam concrete is a cement based slurry, with a minimum of 10% to 20% (by volume) foam mixed into the plastic mortar. It is also referred to as foamcrete or foamed cement because it is a mixture of only cement, filler (normally fine sand) and foam without any coarse aggregate. The density of the mix usually varies from 400 kg/m³ to 1600 kg/m³ hence making it a light weight concrete and it is normally controlled by substituting part of the fine aggregate with foam. Foam concrete possess high flowability and requires little to no compaction, vibrating or levelling. It has good thermal insulation and an outstanding resistance to frost and also provides a high level of sound insulation. Improvements in the quality of foaming agents and production equipment has enabled the use of foam concrete on a much larger scale such as building blocks, floor screed, roof insulation, road sub-base etc.

The annual power generation in India is expected to be 180,000 MW by the year 2020, which may release about 190 MT of Coal Combustion Residue (CCR) per annum (expected by 2020) and of this the Bottom Ash generation may be increasing to 40–50 MT per annum*. The quantity of Quarry Dust produced cannot be quantified as it varies with locality and apart from its minimal use in construction quarry dust is utilized for cooling asphalt pavements after laying.

Two major drawbacks with respect to foam concrete are the large consumption of fine sand as filler material and the slow setting characteristics. Usage of different solid industrial wastes as fillers in foam concrete can reduce the usage of fine river sand significantly and make the work economic and eco-

* CEA, Central Electricity Authority Annual report, Government of India, 2014-15
friendly. Materials and methods aimed at accelerating the setting process will allow earlier stripping, re-use of mould/form, and thereby reduce the cost and duration of the production. This study aims at the utilization of industrial wastes for making foam concrete with improved properties. The objectives and scope of work are to;

- Obtain stable foam using a Protein Based Foaming Agent.
- Proportion foam concrete mixtures at different densities using industrial wastes, viz., bottom ash and quarry dust as filler materials
- Study the relationship between foam concrete strength and internal air-void distribution
- Study the setting and strength characteristics by altering the filler material and through chemical additives.

2. Background Literature

The following review of earlier investigations are classified into the studies on foam properties, the role of filler materials in the fresh state and hardened state properties of foam concrete and the works related to the setting behaviour.

2.1. Foam Properties

As per the studies done by D. K. Panesar [1], it was concluded that protein based foaming agents resulted in stable foam with more uniform and smaller sized air voids when compared to synthetic foaming agents which were further reviewed by Y.H. Mugahed Amran, et al. [2]. Ali J. Hamad, [3] studied the production, properties of aerated lightweight concrete and observed that protein based agents were suitable for density ranges from 400 kg/m$^3$ to 1600 kg/m$^3$. Tests on density and stability of foam done by Indu Siva Ranjani and K. Ramamurthy [4] showed that the initial foam density must be measured immediately after its generation while the stability of foam has to be assessed by free drainage test prescribed by Def. Standard 42–40.

2.2. Role of Filler Materials

Ameer A. Hilal, et al. [5], studied the properties of pre-foamed foam concrete and methods to enhance properties using additives. It was observed that the strength properties of foamed concrete were improved when using mineral additives such as silica fume and fly ash. An earlier study [6] on the incorporation of ultra-fine GGBS has shown enhancement in the compressive strength of foam concrete. E.K. Kunhanandan Nambiar and K. Ramamurthy [7] studied on the influence of filler type on foam concrete and the study indicated that an increase in fly ash content also increases the strength. The consistency of pre-formed foam concrete mixtures mainly depends on the filler type, i.e. consistency will be higher for mixes with fly ash as filler compared to mixes with sand as filler. An increase in fineness of sand or filler resulted in a higher strength to density ratio, which was further proved by Siong Kang Lim, et al. in [8] and concluded that w/c ratio, compressive strength, flexural strength, and ductility were increased with finer sand aggregate.

An increase in the w/c ratio or a decrease in foam content resulted in the reduction in the consistency of the mix ([2], Secondary Reference) and showed that when an excessive amount of foam is added to the mix the stability, as well as fresh density, reduces. Compressive strength is affected by various parameters such as the amount of foaming agent, the w/c ratio, the filler type, curing methods, and cement : sand ratio. The addition of fibers to the mix and mineral admixtures improves the tensile strength of foam concrete. The influence of bottom ash as a filler replacement in foam concrete was studied by Patchara Onprom et al. [9]. It was observed that with the addition of bottom ash, the density of foam concrete decreases with lower compressive strength. Increased water absorption was also noticed with higher bottom ash replacement levels. Jijo Abraham Joy, et al. [10] studied the effect of quarry dust as a filler replacement in foam concrete and concluded that partial replacement of sand with quarry dust resulted in an increase in the compressive strength.

An investigation by E.K. Kunhanandan Nambiar and K. Ramamurthy [11] on the air-void parameters such as volume, size, and spacing of air voids and their influence on strength and density concluded that
the shape of the air-void does not influence the strength and a narrower air-void size distribution showed higher strength. Ameer A. Hilal et al. [12] studied the microstructure to understand the effect of different additives on the strength of foam concrete by characterizing air-void size and shape. It was observed that additives such as flyash helped to improve the air-void structure and distribution in foamed concrete. Smaller sized and uniformly distributed void pattern yielded higher strength.

2.3. Setting Behaviour
J. Sathya Narayanan and K. Ramamurthy [13] tried to identify set accelerators for foam concrete block manufacturing. Setting Characteristics with various accelerators such as Calcium Chloride, Calcium Nitrate, Tri Ethanol Amine, Class C-Fly Ash, Alum have been studied. The setting behavior of foamed concrete studied by She Wei, et al. [14,15] indicated that the curing temperature, the amount of fly ash in the mix and wet density had a great impact on setting behaviour of foam concrete. Curing temperature affects the rate of hydration of concrete and fly ash does not allow microstructure formation.

A study on pozzolanic reactivity enhancing methods done by Caijun Shia and Robert L. Day [16,17] concluded that the addition of 4% Na$_2$SO$_4$ increased both the early and later strengths of cement pastes when the curing temperature ranges from 23°C to 65°C. At 23°C, the presence of Na$_2$SO$_4$ significantly increased the early strength of the pastes. The addition of Na$_2$SO$_4$ accelerated the pozzolanic reaction rate mainly during the first day. The presence of 4% CaCl$_2$.2H$_2$O decreased the early strength but increased the later strength at 23°C, and increased both the early and later strengths of the paste at a higher temperature of curing.

3. Experimental Details
Foam concrete was prepared by using the pre-foaming method. The cement slurry was first made by mixing cement, filler, and water and only after getting a homogeneous mix, the required foam content was introduced into the mix. The fresh wet density of the foam concrete mix was compared with the target design density and appropriate corrections were made in mix composition.

3.1. Materials Used
The combinations of the following materials were used to produce the various foam concrete specimens for testing.

(a) Cement: 53 grade OPC with specific gravity 2.98, confirming to IS 12269: 1987
(b) Filler: The industrial wastes shown in Table 1 were used as filler.

| Table 1. Filler Materials and Properties |
|----------------------------------------|
| Filler       | Quarry Dust | Coal Bottom Ash | Class C Fly Ash | Class F Fly Ash |
| Specific Gravity | 2.52        | 2.43           | 2.4            | 2.2             |
| Fineness     | Finer than 300μm | Finer than 1.18mm | Finer than 150μm | Finer than 150μm |

(c) Anhydrous Sodium Sulphate was used as a chemical admixture at 4% by weight of flyash added
(d) Foaming Agent: Protein based agent was used for this study and its properties are given in Table 2. The foam was generated using foam generator by altering diluted foam agent at controlled pressures.

| Table 2. Properties of Foaming Agent $^a$ |
|------------------------------------------|
| Chemical Characterization               | Ethoxylate of Vegetable Protein Extract |
| Physical State                          | High Viscous Liquid                   |
| Appearance/Odor                         | Hazy yellow-pink liquid with slight odor |
| pH                                      | 7.5 ( Experimentally Found )          |
| Specific Gravity                        | 1.075 ( Experimentally Found )        |

$^a$ as provided by the manufacturer
3.2. Foam Generation and its Properties
Foam density and stability are the most important criteria in foam characterization. The foaming agent was diluted to different concentrations and multiple trials at different pressures were done for each concentration. The density of the foam was calculated by collecting the freshly formed foam in a vessel with known volume and density found by dividing the volume of foam in the vessel with the vessel’s volume. The stability of foam was assessed by free drainage test. To check the stability, the procedure followed was similar as mentioned in Def. Standard 42-40[18]. The foam was collected in a vessel and its initial density was found, and after 5 minutes the accumulated water in the vessel was drained and weighed and corresponding density was obtained. The most suitable one was selected for use in the foam concrete mix.

3.3. Mix Proportions
For making 1m$^3$ of foam concrete, the target density of the resultant mix as ‘P ’ kg/m$^3$ was assumed, cement content was denoted as ‘c ’ kg/m$^3$, filler content as ‘f ’ kg/m$^3$, total water content as ‘wc ’ kg/m$^3$ and foam content as ‘fo ’ kg/m$^3$

$$P = c + f + wc + fo$$

Here the cement content and filler content was together called solids content ‘s ’ kg/m$^3$ and since the foam content ‘fo ’ was negligibly smaller compared to others, the equation became

$$P = s + wc$$

Assuming constant values for target density ‘P ’ and using the water-solids ratio to find the water content ‘wc ‘ the amount of solids ‘s ‘ for each mix was obtained. With the defined mix ratio, the amount of cement and filler are estimated.

3.4. Fresh State Properties of Foam Concrete
A good workable foam concrete mix has to be self-flowing and self-compacting. It was checked by measuring the mix consistency by finding its spreadability. The spreadability of foam concrete was determined by mini slump cone test as spread percentage. It was done using a mini slump cone of top diameter 20mm, height 50mm, and bottom diameter 40mm. The mix was poured into the cone and the cone is lifted up. The final spread diameter was measured. The more the percentage, the workability was more. The mini slump flow percentage between 80% and 120% is generally considered as highly workable based on ASTM C 359 - 13.

3.5. Compressive Strength of Foam Concrete
The 28th day compressive strength test of foam concrete for three densities 1200 kg/m$^3$, 1400 kg/m$^3$ and 1600 kg/m$^3$ was determined on 50mm cube specimens as per Appendix A of IS 2250:1981 [19]. The tests were done with all the mix ratios prepared with both filler materials at different densities.

3.6. Air-Void Characterisation
The relationship between compressive strength and the internal air-void distribution was found out by cutting the selected cubes using a 2mm round blade parallel to its casting surface. Then polishing was done with emery paper till the surface was smooth. It was painted blue and then tale powder was spread over the painted surface till the pores were filled. The magnification of the metallurgical microscope was fixed as 50x by rotating the object lens. Images of the painted specimens were captured as they were placed on the microscope. The number of air voids and each of their diameters was measured.

From a total of 24 specimens, 12 specimens each for both quarry dust and bottom ash were prepared. Of these 12 specimens, 4 specimens were for each design density 1200 kg/m$^3$, 1400 kg/m$^3$ and 1600 kg/m$^3$. Ten trials were done from the 4 specimens, each of size 2.6 mm x 2.2 mm (Area = 5.72 mm$^2$). Hence a total area of 57.2mm$^2$ was covered for each mix tested.
3.7. Setting Properties & Tests
For checking the setting, a mix ratio of 1:1:1 has been adopted with the combinations being cement : filler : flyash. Quarry dust and bottom ash were separately used as fillers and class C and class F flyash were used independently as well. Fly ash was added to check if it affects the setting time. Anhydrous Sodium Sulphate was used as an admixture to check if it affects the early strength and setting time of foam concrete and the quantity used was 4% by weight of the flyash used. A single mix with a ratio of 1:2 has been adopted with cement and class C flyash alone. A target density of 1400kg/m$^3$ was fixed for all mixes and six 50mm cubes casted for each of the selected mixes for compressive strength testing. The details of all the mixes done are mentioned in Table 5.

Demoulding test was done by casting several cubes, demoulding them individually at periodic intervals and noting the time at which a perfect stripping was possible. Vicat test was also done along with the demoulding tests to find the initial setting time and hence compare with the mould stripping time. The initial setting time was checked using the standard Vicat mould and 1mm Needle both based on IS 5513:1996 (which matches with ASTM C191 – 13). The total mass of the moving unit, complete with all attachment was 300±1g. The procedure followed was based on of IS 4031-Part 5: 1998

4. Results and Discussions

4.1. Foam Density and Stability
The density of foam was calculated by dividing the weight of foam in the vessel by the volume of vessel used. For the selection of a foaming agent, the next most important parameter is foam stability which was found using free drainage test. Foam stability influenced the density of foam which was required to calculate the amount of foam to be added for achieving the desired density of foam concrete. This is done using the free drainage test prescribed by Def. Standard 42-40 [18]. A perfect stable foam is one which has a little to no change in density after 5 minutes. Table 3 shows the density obtained initially and after 5 minutes. From Table 3, it was concluded that a stable foam of density 40kg/m$^3$ was obtained when the foaming agent was mixed with water at a concentration of 1:35 at 250KPa.

4.2. Fresh State Characteristics and Strength
Mixes with cement : filler ratio of 1:1 were adopted and design target densities of 1200 kg/m$^3$, 1400 kg/m$^3$ & 1600 kg/m$^3$ were selected for each mix. Since the filler sizes were small, instead of water cement ratio, water solids ratio (w/s) was taken. The w/s ratio changes for each mix and as the foam volume percentage increases the w/s ratio reduces. The need to change the w/s arises because the foam volume can only range from 10% to 40%. For a specific density, when the foam volume is less than 10% the mix turns runny and when it is above 40% it can turn the mix stiff. All the mixes were checked for fresh density and mini slump value and only the mixes which satisfied both criteria were selected for casting cube specimens. The details of the selected mixes with bottom ash and quarry dust as fillers for testing and casting are mentioned in Table 4 and it shows the fresh wet density, mini slump flow percentage.

Table 3. Foam Density and Stability

| Concentration | Pressure (KPa) | Density (kg/m$^3$) |
|---------------|---------------|--------------------|
|               |               | Initial           | After 5 minutes    |
| 1:35          | 200           | 31.579            | 22.368             |
|               | 250           | 56.579            | 30.263             |
|               |               | 34.211            | 25.000             |
|               |               | 42.105            | 27.632             |
|               | 300           | 46.053            | 32.263             |
|               |               | 44.737            | 30.895             |
|               |               | 34.211            | 25.000             |
|               |               | 32.895            | 23.684             |
|               |               | 34.211            | 23.684             |
Table 4. Details of Selected Mixes for testing

| Mix Designation | Target Design Density kg/m³ | w/s Ratio | Cement kg | Filler kg | Water % | Foam Volume kg/m³ | Fresh Wet Density kg/m³ | Spread % |
|-----------------|----------------------------|-----------|-----------|-----------|---------|------------------|-------------------------|---------|
| BA 12           | 1200                       | 0.45      | 430       | 430       | 387     | 30               | 1196                    | 118.75  |
| QD 12           | 1200                       | 0.4       | 424       | 424       | 339     | 35               | 1196                    | 100     |
| BA 14           | 1400                       | 0.4       | 491       | 491       | 393     | 25               | 1394                    | 125     |
| QD 14           | 1400                       | 0.4       | 489       | 489       | 391     | 25               | 1424                    | 125     |
| BA 16           | 1600                       | 0.4       | 588       | 588       | 472     | 10               | 1581                    | 112.5   |
| QD 16           | 1600                       | 0.35      | 593       | 593       | 415     | 15               | 1575                    | 100     |

BA – Bottom ash; QD- Quarry dust

The fresh wet density obtained should be equal to or in the range of ± 50 kg/m³ of the target design density and the mini slump flow percentage should be between 90% and 125%. Figure 1 shows the 28th day compressive strengths of the different mixes.

Figure 1: Compressive Strength Comparison Chart

4.3. Strength to Air-Void Distribution Relationship

The air void distribution characteristics in foam concrete is an important parameter which influences both strength and durability. Figure 2(a) shows the typical air void distribution in the bottom ash concrete sample under 50x magnification at 1400 kg/m³ density and Figure 2(b) shows that of the quarry dust concrete sample at 1400 kg/m³ density. Figure 3 and Figure 4 shows cumulative frequency % vs. air void sizes graph of bottom ash and quarry dust foam concrete samples respectively at the three design densities.

![Figure 2: Typical Air-Void Distribution of Foam Concrete Samples](a) (b)
From Figure 2(a) and Figure 3, it was inferred that bottom ash mixes had a slightly lower concentration of larger sized air voids and showed uniformity in sizes. From Figure 2(b) and Figure 4, it was inferred that quarry dust mixes had a higher concentration of larger sized air voids and interconnectivity between the air voids. The size and shape of the air voids were not uniform when compared to bottom ash. The number of air voids also varied with each mix and it was observed that quarry dust cube specimens had a higher number of air voids in lower densities.

Mixes which have a greater number of larger sized air-voids tend to have lower strength than mixes having less number of larger sized voids. The narrower air void distribution of bottom ash samples resulted in its relatively higher compressive strength and the value increased with the density of foam concrete [11].

In order to compare the air void size distribution of different mixes and to evaluate its influence on the strength of foam concrete, the parameter used was D90. D90 represents 10% of oversized air voids of the mix or the 90th percentile. D90 was chosen because it correlated better with strength than D50 (median pore size) indicating that it was the larger pores that influenced the strength more than the smaller pores. These were found out from the cumulative frequency distribution graphs (Figure 3 and Figure 4). Figure 5 shows the variation of compressive strength with respect to wet density & air void sizes. Wet density is obtained from Table 4 and air void sizes were taken from Figure 3 and Figure 4.
From figure 5 it was inferred that compressive strength was affected equally by both wet density and air void distribution. As wet density increases their strength also increases and mixes with lower D90 values showed higher strength.

4.4. Setting Characteristics

Setting is the physical transformation of a plastic concrete mix to a hardened state. This can be a fast or even slow process depending on the mix, location and various other factors. Table 5 shows details of the different foam concrete mixes studied for their setting properties. For each of the mixes at least 4 trials were done and out of which the most appropriate one was selected. Mini slump test was done to check the spread percentage and casting were done to the selected mix with 1400kg/m$^3$ density. The selected mixes had a good mini slump flow percentage and its fresh wet density was also in range. Six 50mm cubes were casted and both 7th day initial strength and 28th day final strength was found out.

| Filler(s) | Admixture | Cube Demoulding Time | Vicat (Initial Setting Time) | Selected mixes for further testing |
|-----------|-----------|----------------------|------------------------------|-----------------------------------|
| BA        | -         | 1hr 45mins           | < 2hrs                       | ✓                                 |
| BA        | CFA       | Na$_2$SO$_4$         | 1hr 45mins                   | < 2hrs                           | ✓                                 |
| BA        | FFA       | -                    | 5hrs 30mins                  | < 8hrs 45mins                    | ✗                                 |
| BA        | FFA       | Na$_2$SO$_4$         | 6hrs                         | < 6hrs                           | ✗                                 |
| QD        | CFA       | -                    | 1hr 50mins                   | < 2hrs                           | ✓                                 |
| QD        | CFA       | Na$_2$SO$_4$         | 1hr 50mins                   | < 2hrs                           | ✓                                 |
| QD        | FFA       | -                    | 9hrs 30mins                  | ≈ 11hrs                          | ✗                                 |
| QD        | FFA       | Na$_2$SO$_4$         | 10hrs                        | < 9hrs 30mins                    | ✗                                 |
| CFA       | -         | 25mins               | < 30mins                     | ✓                                 |

$^a$QD = Quarry Dust, BA = Bottom Ash, CFA = Class C Fly Ash, FFA = Class F Fly Ash

From Table 5, it can be observed that mixes with FFA did not show satisfactory results as the setting times with FFA as filler were much longer than CFA mixes. Hence it was not considered for further
testing and only CFA mixes were used for strength testing. The contribution of Na$_2$SO$_4$ towards the reduction of setting time was negligible hence Na$_2$SO$_4$ was not added to the 1:2 CFA mix which already had the fastest setting time. Table 6 shows the results of the mini slump tests done and the fresh wet densities. Figure 6 shows the 7$^{th}$ day and 28$^{th}$ day average compressive strengths of all the mixes tested.

### Table 6. Selected Mixes with Class C Fly Ash as Filler

| Mix Designation | Fillers | w/s Ratio | Cement (kg) | Fly Ash (kg) | Water (kg) | Foam Volume (%) | Spread (%) | Wet Density (kg/m$^3$) |
|-----------------|---------|------------|-------------|--------------|------------|-----------------|-----------|------------------------|
| FC 1            | BA      | 0.45       | 318         | 318          | 429        | 20              | 100       | 1409                   |
| FC 2 $^b$       | BA      | 0.45       | 318         | 318          | 429        | 20              | 100       | 1424                   |
| FC 3            | QD      | 0.5        | 321         | 321          | 481        | 15              | 112.5     | 1393                   |
| FC 4 $^b$       | QD      | 0.5        | 321         | 321          | 481        | 15              | 100       | 1409                   |
| FC 5            | CFA     | 0.55       | 301         | -            | 497        | 15              | 125       | 1440                   |

$^a$QD = Quarry Dust, BA = Bottom Ash, CFA = Class C Fly Ash,

$^b$Na$_2$SO$_4$ is used as an Admixture

![Figure 6: Average Compressive Strength Chart](image)

Mixes with Na$_2$SO$_4$ had an increase in their initial 7$^{th}$ day strength of almost 1 MPa when compared to mixes without Na$_2$SO$_4$ and it also had an impact on the later 28$^{th}$ day strength. Generally, mixes with Na$_2$SO$_4$ had relatively higher strength than mixes without Na$_2$SO$_4$. The foam concrete with flyash alone showed a significant improvement in the later strength.

### 5. Conclusion

Within the range of materials and experimental parameters adopted, the following conclusions are drawn:

- Workability is not greatly affected by the change in the filler but was greatly affected by the change in foam volume. As the foam volume increased, the mixes become stiff and higher water to solid ratio is needed to maintain workability. Quarry dust mixes showed higher workability at lower w/s ratios when compared to bottom ash mixes.
- Bottom ash specimens had a higher strength than quarry dust specimens. Quarry Dust specimens had a greater number of larger sized air voids and the higher strength of Bottom Ash mixes was due to its narrower internal air void distribution and corresponding D90 values.
- Class C Flyash has been identified as an excellent setting accelerator for foam concrete capable of reducing the demoulding time to 25 mins when used as a complete filler replacement.
- Use of Na$_2$SO$_4$ as an admixture in foam concrete resulted in early strength for all tested mixes.
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