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# Building Blocks Using Foamed Concrete with Industrial Waste Materials

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## Abstract

Clay bricks or hollow/solid concrete blocks are used as infills for reinforced concrete framed structures in the present construction scenario. There is substantial depletion of natural resources during the production of conventional bricks, which create environmental pollution due to burning of bricks. Also, for the production of hollow/solid cement concrete blocks, large quantities of cement and natural aggregates are being used. This enforces researchers to develop a more feasible, lighter and greener alternate material for infills. Foamed concrete (FC) is such an innovative and versatile material, which consists of a cement based mortar having minimum 20% of volume filled with air. The effective consumption of industrial by-products for the production of FC lead to preservation of natural resources, solving disposal issues of these wastes. FC is found to be economically viable, light in weight, durable, thermally resistive as well as environmentally sustainable. This research focuses on the feasibility of utilizing the industrial waste materials such as fly ash and GGBFS as partial substitute for cement and quarry dust as substitute for fine aggregate. The influence of these waste materials on foamed concrete and the development of properties like compressive strength, dry density, water absorption and thermal conductivity were studied.

**Keywords:** Foamed Concrete; Sustainability; Manufactured Sand; Fly Ash; GGBFS; Quarry Dust

## Introduction

Brick is the most commonly adopted building material in construction industry. But, for the manufacture of brick, the topsoil is to be smashed out, which may create lot of environmental issues. Hence, at present, hollow or solid concrete blocks are also used as in-fills in framed construction works. But, for the abundant productions of such blocks, huge quantities of fine and coarse aggregates are required, which cause diminution of natural resources creating lot of conservational issues. This has led the researchers to find a greener solution to overcome all these issues. One of such feasible solutions is the development of foamed concrete. This research focuses to modify the existing method of production of foamed concrete to overcome the ill effects of brick production and other block production, with the usage of large quantities of industrial waste materials. Foamed concrete blocks of densities less than 1800 kg/m3 with reasonable compressive strength can be produced with these waste materials. The properties such as compressive strength (7 days and 28 days), dry density, water absorption and thermal conductivity were studied. Ultrasonic pulse velocity test was performed as a non-destructive test. Tests such as sulphate and chloride attack tests and RCPT tests were also conducted to test the durability of foamed concrete blocks.

Dawood and Hamad [1], have conducted studies on high performance lightweight foamed concrete with glass fibres as additives in it. It has been reported that compressive strength, direct tensile strength and splitting tensile strength have increased with the addition of glass fibres in foamed concrete. The increase in compressive strength has been observed to be 56.6%. Falade, et al. [2], have conducted studies on the flexural performance of foamed concrete containing pulverized bone as a partial replacement. Cow bone has been pulverized to size retained on 0.15 mm for the study. Further, it has been observed that the use of reinforcement significantly improved the flexural performance of foamed concrete. It has been inferred that an increase in pulverized bone content has not influenced the formation and propagation of cracks leading to failure of concrete. Chen, et al. [3], discusses about the necessity of reducing $SO_2$, which is generated as environmental contamination from various power stations and heating plants all over the world. It has been pointed out that, at lower water solid ratio, the consistency was higher so that water reducers may be added more. The obtained results have shown that 70% combustion fly ash can be very effectively utilized for the production of foamed concrete of required compressive strength. Munir, et al. [4], discusses about the influence of palm oil fuel ash (POFA) on the properties of foamed concrete. It has been informed that, foamed concrete specimens were prepared using cement and POFA only. The results have indicated that, the addition of 20% POFA has achieved foamed concrete of acceptable compressive strength to be used for non-structural applications. Falade, et al. [5] have conducted study on the effect of pulverized bone on the properties of foamed concrete and have reported that compressive strength of foamed concrete with pulverized bone up to 10% has got compressive strength of 15.78 $N/mm^2$ at a dry density of 1652 $N/mm^2$. Fapohunda, et al. [6] confirmed that density has a vital role in designing foamed concrete. Here also, it has been confirmed that water cured samples are showing the maximum compressive strength. It is to be noted that a maximum strength of 17.68 $N/mm^2$ has been achieved for foamed concrete containing 5% pulverized bone as cement replacement. It has also been pointed out that the strength of foamed concrete is getting increased with the age of curing. Awang and Alijoumaily [7] have reported that 30% by weight of GGBS in foamed concrete has come out with a compressive strength of 12.48 $N/mm^2$. It has been revealed that the amount of foam required was found to be decreasing with respect to the addition of GGBS, which may be due to the lower specific density of both GGBS and OPC. Alqahtani, et al. [8] have conducted studies on lightweight concrete containing manufactured plastic aggregate and have reported that replacement level up to 25% can be used in structural and non-structural applications requiring moderate strength and ductility. Sahu, et al. [9] have made a review on the characteristics of surfactants and foam and they have reported that the choice of surfactant and foam production parameters play a vital role in the properties of foam, which affects the properties of foamed concrete. It has been concluded that, dry foam with lesser liquid fraction produced by compressed air method was relatively stable and was recommended for foam concrete production. Chen, et al. [10] have conducted studies on fly ash based foamed concrete and has been reported that the fluidity and compressive strength of FC has been affected by the water/binder ratio. Further, it has been pointed out that, the ratio of ash/cement has only negligible influence on the fluidity of FC. But, with the increase of ash/cement ratio, there was a hike in compressive strength to a certain extent. It has been pointed out that, an increase in water binder ratio and ash/cement ratio also had increased the water absorption.

Literature says that 1:1 and 1:2 proportions were the most commonly used mixes for the preparation of foamed concrete specimens. Further, it can be noted that fly ash and GGBFS can be used as substitutes for cement and quarry dust can be used as a substitute for fine aggregate. Again, in almost all the studies, it can be seen that river sand was used as the fine aggregate. But the extraction of riversand is nowadays banned in almost all countries. Hence, for the research it has been decided to use manufactured sand instead of river sand and again use quarry dust to replace manufactured sand partially. Fly ash and GGBFS to replace cement partially. Hence, a most sustainable foamed concrete blocks are to be produced at a reasonable price and low density without compromising compressive strength and lower thermal conductivity.

## Materials and Methods

### Materials

The experimental programme is intended to study the properties such as compressive strength, dry density, thermal conductivity and water absorption of foamed concrete using industrial by-products. The materials used for the study are cement, manufactured sand, Fly ash, GGBFS, quarry dust and foaming agent. Cement used was Ordinary Portland Cement of specific gravity 3.15. The specific gravities of manufactured sand, fly ash, GGBFS and quarry dust were 2.53, 2.44, 2.9 and 2.42 respectively. The powder (mixture of cement and the by-products combined) to sand ratio has been chosen as 1:3 and 1:4. The foam requirement for densities of 1800 $kg/m^3$ and 1600 $kg/m^3$ has been arrived as per ASTM C796-97 [11]. These two densities are selected in such a way as to get compressive strength in line with that of conventional hollow/solid concrete blocks.

### Method of preparation and testing of Specimens

Various mixes of powder (mix of cement, fly ash and GGBFS) to sand ratios 1:3 and 1:4 with the water powder ratios 0.55 and 0.65 have been prepared for the densities of 1800 kg/m$^3$ and 1600 kg/m$^3$. The volume of stable foam added was 20% and 30%. The various percentages of the industrial by-products and their proportions used for the study and the mix ID are presented in Table 1. Accordingly, 720 cube specimens, out of 48 mixes, have been prepared and tested. The key goal of this study is to make a greener, lighter and cost-effective building material, which can replace the existing building materials with densities as high as 1800 kg/m$^3$ to 2400 kg/m$^3$. Hence, the experiments have been limited to only two densities to attain compressive strength at par with that of the commercially available building materials. Blocks have been cast with the available standard dimensions as per IS 2185-Part 4, 2008 [12] for performing various tests. The demoulded specimens were water cured for 28 days. After that, they were oven-dried for the attainment of constant weight and then cooled to room temperature before performing the tests.

| Sl. No | Mix ID | w/p | fv (%) | Industrial by- products (%) | | | Cement content (%) | Manufactured Sand (%) |
|---|---|---|---|---|---|---|---|---|
| | | | | FA | GGBFS | QD | | |
| 1 | 0.55M$_3$20 A | 0.55 | 20 | 10 | 10 | 20 | 80 | 80 |
| 2 | 0.55M$_3$20 B | 0.55 | 20 | 20 | 20 | 30 | 60 | 70 |
| 3 | 0.55M$_3$20 C | 0.55 | 20 | 30 | 30 | 40 | 40 | 60 |
| 4 | 0.55M$_3$20 D | 0.55 | 20 | 40 | 20 | 50 | 40 | 50 |
| 5 | 0.55M$_3$20 E | 0.55 | 20 | 40 | 30 | 60 | 30 | 40 |
| 6 | 0.55M$_3$20 F | 0.55 | 20 | 40 | 40 | 60 | 20 | 40 |
| 7 | 0.65M$_4$30 A | 0.65 | 30 | 10 | 10 | 20 | 80 | 80 |
| 8 | 0.65M$_4$30 B | 0.65 | 30 | 20 | 20 | 30 | 60 | 70 |
| 9 | 0.65M$_4$30 C | 0.65 | 30 | 30 | 30 | 40 | 40 | 60 |
| 10 | 0.65M$_4$30 D | 0.65 | 30 | 40 | 20 | 50 | 40 | 50 |
| 11 | 0.65M$_4$30 E | 0.65 | 30 | 40 | 30 | 60 | 30 | 40 |
| 12 | 0.65M$_4$30 F | 0.65 | 30 | 40 | 40 | 60 | 20 | 40 |

**Table 1:** Mix Designation
*w/p* = water powder ratio *fv =foam volume*

## Results and Discussion

The properties of foamed concrete specimens tested are presented in Tables 2 & 3. It can be understood that there has been slight increase in compressive strength with the addition of industrial by-products. The optimum value of compressive strength has been obtained for foamed concrete with 30% cement, 30% GGBFS, 40% fly ash, 40% manufactured sand and 60% quarry dust. The use of waste materials and the corresponding reduction in cement consumption leads to the reduction in carbon dioxide emissions. Furthermore, due to the pozzolanic reaction and filler features of slag, the density of microstructures in foamed concrete gets improved leading to increase in compressive strength.

| Sl. No | MIX ID | 7 days Compressive strength (N/mm$^2$) | 28 days Compressive strength (N/mm$^2$) | Density (kg/m$^3$) | Water absorption (%) | Thermal conductivity (W/mK) |
|---|---|---|---|---|---|---|
| 1 | 0.55M$_3$20A | 6.63 | 9.50 | 1795 | 3.08 | 0.285 |
| 2 | 0.55M$_3$20B | 6.70 | 9.61 | 1809 | 3.23 | 0.278 |
| 3 | 0.55M$_3$20C | 6.74 | 9.76 | 1799 | 3.33 | 0.267 |
| 4 | 0.55M$_3$20D | 7.00 | 10.02 | 1817 | 3.47 | 0.263 |
| 5 | 0.55M$_3$20E | 7.08 | 10.14 | 1800 | 3.64 | 0.251 |
| 6 | 055M$_3$20F | 6.95 | 9.98 | 1788 | 3.88 | 0.248 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 7 | 0.55$M_4$20A | 2.85 | 4.13 | 1822 | 3.76 | 0.342 |
| 8 | 0.55$M_4$20B | 3.06 | 4.43 | 1808 | 3.93 | 0.321 |
| 9 | 0.55$M_4$20C | 3.23 | 4.61 | 1818 | 4.08 | 0.319 |
| 10 | 0.55$M_4$20D | 3.31 | 4.79 | 1798 | 4.21 | 0.314 |
| 11 | 0.55$M_4$20E | 3.47 | 4.96 | 1812 | 4.32 | 0.308 |
| 12 | 0.55$M_4$20F | 3.30 | 4.74 | 1803 | 4.39 | 0.301 |
| 13 | 0.65$M_3$20A | 7.41 | 10.55 | 1796 | 3.16 | 0.276 |
| 14 | 0.65$M_3$20B | 7.53 | 10.73 | 1812 | 3.34 | 0.268 |
| 15 | 0.65$M_3$20C | 7.67 | 10.94 | 1818 | 3.48 | 0.264 |
| 16 | 0.65$M_3$20D | 7.80 | 11.14 | 1798 | 3.55 | 0.260 |
| 17 | 0.65$M_3$20E | 7.91 | 11.28 | 1816 | 3.78 | 0.257 |
| 18 | 0.65$M_3$20F | 7.71 | 11.01 | 1802 | 3.88 | 0.252 |
| 19 | 0.65$M_4$20A | 3.83 | 5.51 | 1796 | 3.98 | 0.321 |
| 20 | 0.65$M_4$20B | 3.91 | 5.62 | 1789 | 4.12 | 0.314 |
| 21 | 0.65$M_4$20C | 4.03 | 5.76 | 1813 | 4.27 | 0.308 |
| 22 | 0.65$M_4$20D | 4.15 | 5.98 | 1821 | 4.44 | 0.302 |
| 23 | 0.65$M_4$20E | 4.23 | 6.09 | 1798 | 4.68 | 0.298 |
| 24 | 0.65$M_4$20F | 4.11 | 5.93 | 1796 | 4.76 | 0.296 |

**Table 2:** Properties of FC with 20 % FV using industrial by-products for 1:3 and 1:4 mixes.

| Sl. No | MIX ID | 7 days Compressive strength (N/mm$^2$) | 28 days Compressive strength (N/mm$^2$) | Density (kg/m$^3$) | Water absorption (%) | Thermal conductivity (W/mK) |
|---|---|---|---|---|---|---|
| 1 | 0.55$M_3$30 A | 5.72 | 8.62 | 1582 | 3.26 | 0.275 |
| 2 | 0.55$M_3$30B | 6.11 | 8.78 | 1593 | 3.37 | 0.271 |
| 3 | 0.55$M_3$30C | 6.25 | 8.93 | 1578 | 3.48 | 0.266 |
| 4 | 0.55$M_3$30D | 6.40 | 9.18 | 1569 | 3.63 | 0.260 |
| 5 | 0.55$M_3$30E | 6.62 | 9.43 | 1598 | 3.77 | 0.254 |
| 6 | 055$M_3$30F | 6.39 | 9.17 | 1582 | 3.86 | 0.249 |
| 7 | 0.55$M_4$30A | 2.80 | 4.01 | 1593 | 4.07 | 0.306 |
| 8 | 0.55$M_4$30B | 2.91 | 4.12 | 1574 | 4.19 | 0.298 |
| 9 | 0.55$M_4$30C | 3.04 | 4.23 | 1586 | 4.31 | 0.291 |
| 10 | 0.55$M_4$30D | 3.21 | 4.58 | 1587 | 4.47 | 0.284 |
| 11 | 0.55$M_4$30E | 3.30 | 4.69 | 1598 | 4.69 | 0.278 |
| 12 | 0.55$M_4$30F | 3.15 | 4.49 | 1588 | 4.75 | 0.271 |
| 13 | 0.65$M_3$30A | 6.65 | 9.56 | 1556 | 3.47 | 0.255 |
| 14 | 0.65$M_3$30B | 6.80 | 9.82 | 1562 | 3.56 | 0.248 |
| 15 | 0.65$M_3$30C | 7.02 | 9.96 | 1558 | 3,68 | 0.241 |
| 16 | 0.65$M_3$30D | 7.14 | 10.13 | 1566 | 3.76 | 0.234 |
| 17 | 0.65$M_3$30E | 7.36 | 10.48 | 1587 | 3.89 | 0.227 |
| 18 | 0.65$M_3$30F | 7.00 | 10.05 | 1560 | 3.96 | 0.221 |
| 19 | 0.65$M_4$30A | 3.35 | 4.83 | 1552 | 4.15 | 0.262 |
| 20 | 0.65$M_4$30B | 3.41 | 4.91 | 1558 | 4.28 | 0.253 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 21 | 0.65$M_4$30C | 3.54 | 5.06 | 1560 | 4.39 | 0.247 |
| 22 | 0.65$M_4$30D | 3.68 | 5.25 | 1556 | 4.56 | 0.240 |
| 23 | 0.65$M_4$30E | 4.01 | 5.66 | 1560 | 4.78 | 0.234 |
| 24 | 0.65$M_4$30F | 3.68 | 5.23 | 1557 | 4.92 | 0.229 |

**Table 3:** Properties of FC with 30 % FV using industrial by-products for 1:3 and 1:4 mixes.

### Ultrasonic Pulse Velocity Test

Ultrasonic pulse velocity (UPV) test is an in-situ, non-destructive test to check the quality of concrete. This test is conducted by passing a pulse of ultrasonic wave through the concrete specimen to be tested and measuring the time taken by the pulse to get through it. Higher velocities indicate good quality and continuity of the material, while slower velocities may indicate concrete with many cracks or voids. The test results of UPV and the other properties like compressive strength, thermal conductivity and the dry density are presented in Table 4.

| Sl No | Mix ID | Ultrasonic Pulse Velocity (m/s) | Compressive strength (N/mm$^2$) | Thermal Conductivity (W/mK) | Dry Density (kg/m$^3$) |
|---|---|---|---|---|---|
| 1 | 0.65$M_3$30A | 2534 | 9.56 | 0.255 | 1556 |
| 2 | 0.65$M_3$30B | 2586 | 9.82 | 0.248 | 1562 |
| 3 | 0.65$M_3$30C | 2615 | 9.96 | 0.241 | 1558 |
| 4 | 0.65$M_3$30D | 2693 | 10.13 | 0.234 | 1566 |
| 5 | 0.65$M_3$30E | 2746 | 10.48 | 0.227 | 1587 |
| 6 | 0.65$M_3$30F | 2780 | 10.05 | 0.221 | 1560 |
| 7 | 0.65$M_4$30A | 2275 | 4.83 | 0.262 | 1552 |
| 8 | 0.65$M_4$30B | 2320 | 4.91 | 0.253 | 1558 |
| 9 | 0.65$M_4$30C | 2364 | 5.06 | 0.247 | 1560 |
| 10 | 0.65$M_4$30D | 2391 | 5.25 | 0.240 | 1556 |
| 11 | 0.65$M_4$30E | 2426 | 5.66 | 0.234 | 1560 |
| 12 | 0.65$M_4$30F | 2454 | 5.23 | 0.229 | 1557 |

**Table 4:** UPV values of foamed concrete with other properties.

The variation of compressive strength and UPV values for various mixes in 1:3 and 1:4 proportions are shown in Figures 1 & 2. The variation of thermal conductivity and UPV values for various mixes in 1:3 and 1:4 proportions are shown in Figures 3 & 4.

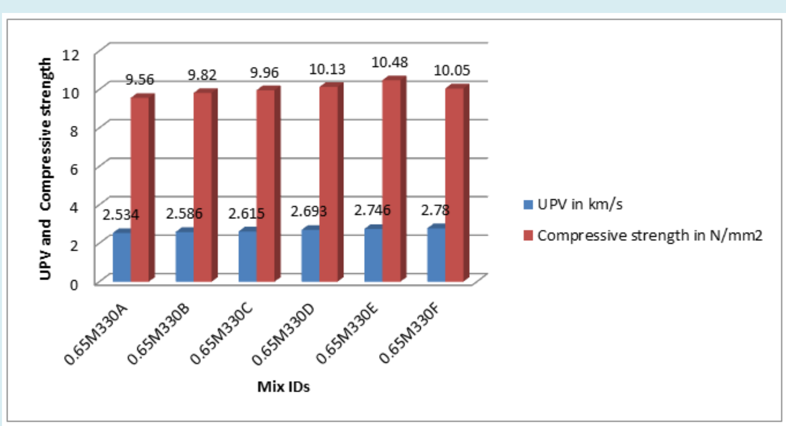


**Figure 1:** Variation of compressive strength and UPV for 1:3 mixes.

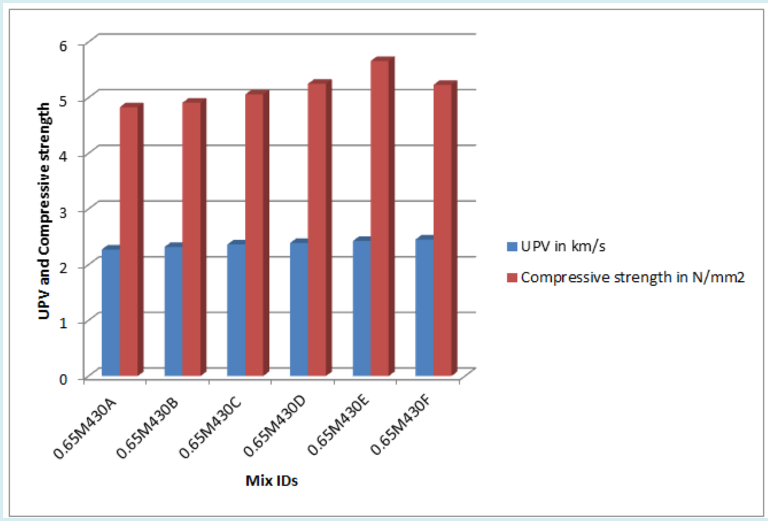


**Figure 2:** Variation of compressive strength and UPV for 1:4 mixes.

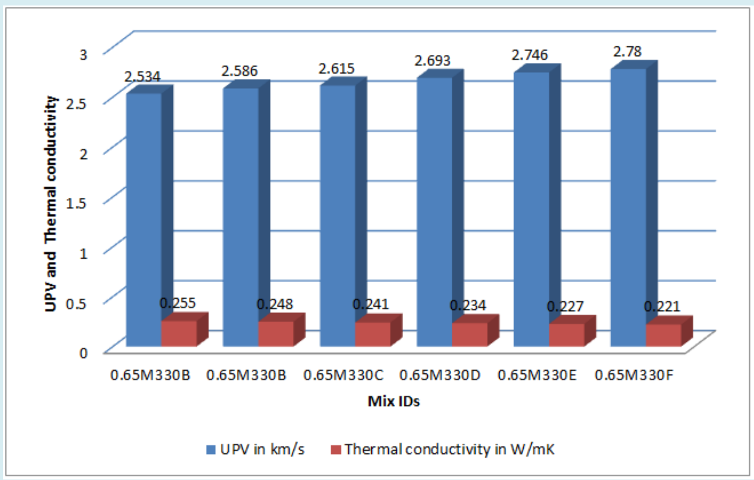


**Figure 3:** Variation of thermal conductivity and UPV for 1:3 mixes.

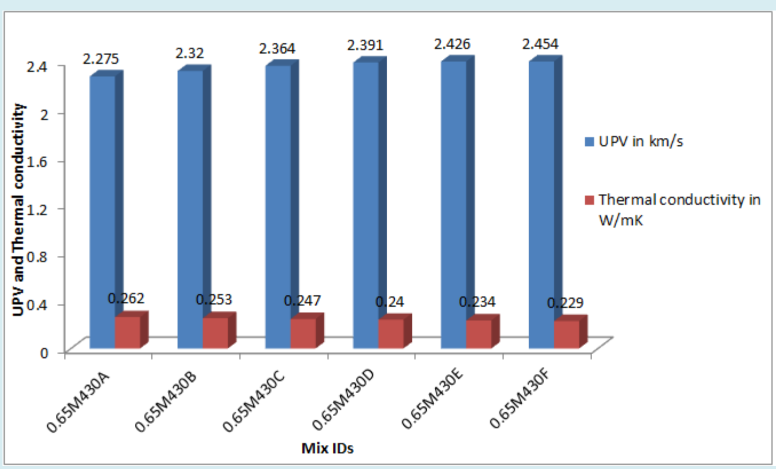


**Figure 4:** Variation of thermal conductivity and UPV for 1:4 mixes.

Due to the presence of finer particles of fly ash and GGBFS in cement, the bubbles are closely packed in foamed concrete, making it denser and allowing the wave to be transmitted at a faster rate just like through solid concrete compared to concrete with larger pore capillaries. The reduction in thermal conductivity (better heat insulation) could be due to the lower density and particle morphology of slag. Another possible reason may be related to the increase in fineness of cement by the utilization of very fine fly ash and GGBFS along with quarry fines, since the larger interface area would act as a thermal barrier decreasing the amount of heat transfer.

## Durability Studies on Foamed Concrete

Effect of industrial wastes on durability properties of foamed concrete is discussed in this section. Durability is an important factor that must be appreciable for any structure so that it is performing for the requirement for which it is built for. It is a time period requirement. Every structure irrespective of the material employed should gain this property.

**Acid attack tests:** Concrete is susceptible to acid attack because of its alkaline nature. The components of the cement paste break down during contact with acids as a process of disintegration. Most pronounced reaction is the dissolution of calcium hydroxide which occurs according to the following reaction.

$$HX + Ca(OH)_2 \text{ -> } CaX_2 + 2\ H_2O$$

In the above equation, X represents the negative ion of the acid. A more aggressive and destructive case of acid attack occurs when concrete is exposed to sulphuric acid. The calcium salt produced by the reaction of the sulphuric acid and calcium hydroxide is calcium sulphate, which in turn causes an increased degradation due to sulphate attack. This process is illustrated below. Calcium sulphate is responsible for the sulphate attack.

$$H_2SO_4 + Ca(OH)_2 \Rightarrow Ca(SO)_4 + 2H_2O$$

In order to determine the effect of acid attack, the prepared specimens were subjected to surface erosion by immersing them in 3% sulphuric acid solution and 3% hydrochloric acid solution. It has been noted that there was no discolouration to the specimens immersed in sulphuric acid solution even after 90 days. But, there was slight discolouration to the specimens immersed in hydrochloric acid solution after 90 days. Figure 5 shows the specimens after immersing them in acid solutions for 90 days.


Specimens subjected to sulphate attack

Specimens subjected to chloride attack

**Figure 5:** Specimens after immersing in acid solutions for 90 days.

The percentage loss of weights of the specimens after immersing them in sulphuric acid solution and hydro chloric acid solution are presented in Tables 5 & 6.

| Sl No. | Mix ID | Percentage reduction in weight after | | | | |
|---|---|---|---|---|---|---|
| | | 7 days | 14 days | 28 days | 56 days | 90 days |
| 1 | $0.65M_330A$ | 0.85 | 1.05 | 1.33 | 1.74 | 2.02 |
| 2 | $0.65M_330B$ | 0.76 | 0.93 | 1.24 | 1.62 | 1.87 |
| 3 | $0.65M_330C$ | 0.65 | 0.87 | 1.11 | 1.51 | 1.81 |
| 4 | $0.65M_330D$ | 0.56 | 0.78 | 1.02 | 1.40 | 1.70 |
| 5 | $0.65M_330E$ | 0.49 | 0.70 | 0.91 | 1.31 | 1.68 |
| 6 | $0.65M_330F$ | 0.42 | 0.63 | 0.82 | 1.19 | 1.53 |
| 7 | $0.65M_430A$ | 1.05 | 1.32 | 1.54 | 1.96 | 2.35 |
| 8 | $0.65M_430B$ | 0.96 | 1.24 | 1.41 | 1.82 | 2.24 |
| 9 | $0.65M_430C$ | 0.85 | 1.15 | 1.32 | 1.74 | 2.13 |
| 10 | $0.65M_430D$ | 0.73 | 1.03 | 1.21 | 1.62 | 2.01 |
| 11 | $0.65M_430E$ | 0.64 | 0.91 | 1.13 | 1.50 | 1.92 |
| 12 | $0.65M_430F$ | 0.55 | 0.83 | 1.02 | 1.41 | 1.83 |

**Table 5:** Percentage loss of weight due to sulphate attack.

| Sl No. | Mix ID | Percentage reduction in weight after | | | | |
|---|---|---|---|---|---|---|
| | | 7 days | 14 days | 28 days | 56 days | 90 days |
| 1 | $0.65M_330A$ | 1.20 | 1.65 | 1.97 | 2.23 | 2.54 |
| 2 | $0.65M_330B$ | 1.12 | 1.51 | 1.91 | 2.08 | 2.42 |
| 3 | $0.65M_330C$ | 1.01 | 1.42 | 1.80 | 1.92 | 2.33 |
| 4 | $0.65M_330D$ | 0.93 | 1.34 | 1.72 | 1.79 | 2.21 |
| 5 | $0.65M_330E$ | 0.86 | 1.26 | 1.63 | 1.65 | 2.13 |
| 6 | $0.65M_330F$ | 0.80 | 1.16 | 1.53 | 1.53 | 2.04 |
| 7 | $0.65M_430A$ | 1.53 | 1.87 | 2.25 | 2.58 | 2.93 |
| 8 | $0.65M_430B$ | 1.41 | 1.80 | 2.12 | 2.46 | 2.84 |
| 9 | $0.65M_430C$ | 1.32 | 1.72 | 2.01 | 2.37 | 2.76 |
| 10 | $0.65M_430D$ | 1.25 | 1.61 | 1.93 | 2.30 | 2.62 |
| 11 | $0.65M_430E$ | 1.13 | 1.50 | 1.82 | 2.21 | 2.51 |
| 12 | $0.65M_430F$ | 1.01 | 1.42 | 1.71 | 2.08 | 2.40 |

**Table 6:** Percentage loss of weight due to chloride attack.

From the above tables, it is clear that, the percentage loss of weight is less than 3%. It can be observed that the intensity of acid attack both chloride and sulphate are reduced by the increased addition of substitutes for cement (fly ash and GGBFS) in foamed concrete.

**Rapid chloride permeability Test:** Rapid chloride permeability test **(**RCPT) has been carried out to quickly test the rate of flow of chloride ions in concrete. Concrete disc specimens of size 100 mm diameter and 50 mm thick were used for testing the chloride ion permeability. The cathode compartment for the test set up was filled with 3% sodium chloride solution and anode compartment was filled with 0.3 Normal sodium hydroxide solution. Then the concrete specimen was subjected to rapid chloride permeability by connecting 60 volts current from a DC power supply. The chloride permeability was calculated in terms of charge passed in Coulombs (Q) using the relation given by eq. 1 (as per ASTMC 1202-12) [13].

$$Q= 900(I_0+I_{360}+2(I_{30}+I_{60}+I_{90}+I_{120}+\dots\dots\dots +I_{330}) \quad (1)$$

where,
Q = Charge passed in Coulombs
$I_0$ = Current passed in amperes immediately after voltage is applied
$I_t$ = Current passed at t minutes after voltage is applied

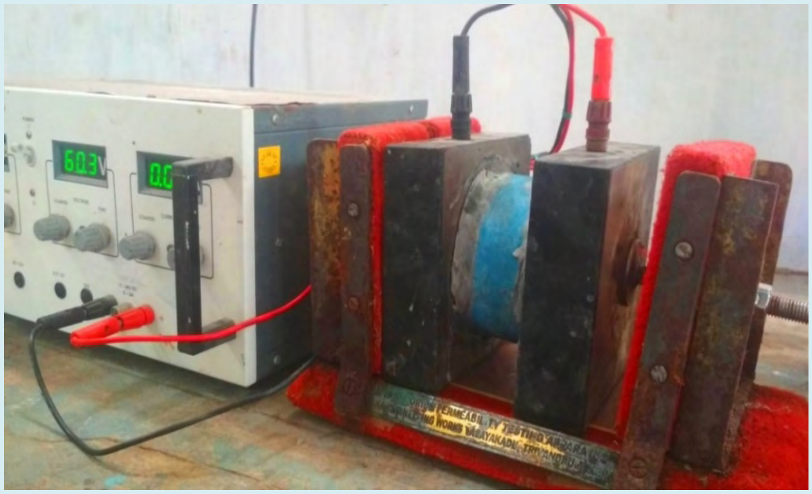

**Figure 6:** RCPT Test Set up.

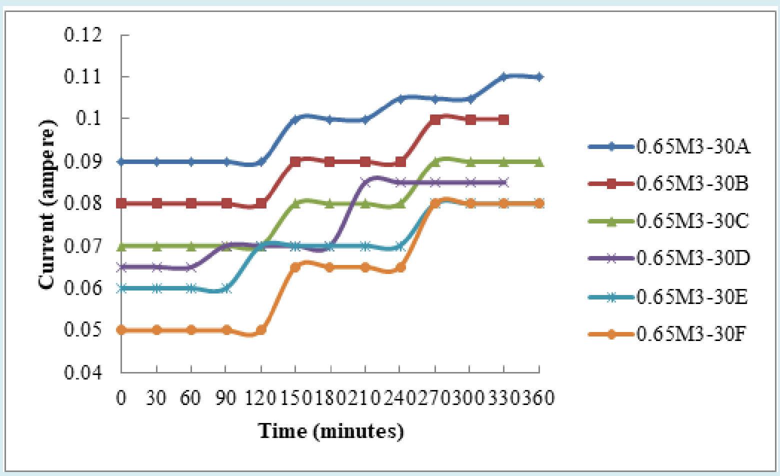


**Figure 7:** Current passed through FC with time.

The test set up for conducting RCPT is shown in Figure 6.

The variation of current with time is shown in Figure 7.

| Charge passed (Coulombs) | Chloride ion penetrability |
|---|---|
| › 4000 | High |
| 2000-4000 | Moderate |
| 100-2000 | Very low |
| 1-100 | Negligible |

**Table 7:** Chloride ion penetrability based on charge passed as per ASTMC 1202-12.

| Sl. No. | Mix ID | Charge passed (Coulombs) | Chloride ion penetrability |
|---|---|---|---|
| 1 | $0.65M_3 30A$ | 2133 | Moderate |
| 2 | $0.65M_3 30B$ | 1926 | Very low |
| 3 | $0.65M_3 30C$ | 1710 | Very low |
| 4 | $0.65M_3 30D$ | 1643 | Very low |
| 5 | $0.65M_3 30E$ | 1512 | Very low |
| 6 | $0.65M_3 30F$ | 1377 | Very low |

**Table 8:** Chloride ion penetrability of foamed concrete with the addition of industrial wastes.

From the Table 8, it can be noted that the chloride ion permeability is reduced with increase in industrial wastes. This may be due to the formation denser matrix of foamed concrete in the presence of finer industrial wastes including quarry fines. The results show that foamed concrete with industrial waste materials can sustain the chloride ion penetrability very effectively.

## Cost Analysis

An analysis is carried out to compare the cost of foamed concrete block with the industrial by-products studied and conventional concrete blocks commercially available in the construction industry. It is understood that the production cost of foamed concrete is comparatively less than that of conventional concrete, the reduction in cost of production being 21.18% (Table 9). The cost of production can be expected to be reduced further on large scale production.

| Sl No | Description | Foamed concrete with Fly ash, GGBFS, Quarry dust and manufactured sand | | | Conventional concrete | | |
|---|---|---|---|---|---|---|---|
| | | Quantity | Rate (Rs) | Amount (Rs) | Quantity | Rate (Rs) | Amount (Rs) |
| 1 | Cement | 98.25 kg | 8 | 786 | 153.60 kg | 8 | 1228.8 |
| 2 | Manufactured Sand | 393.01 kg | 1.54 | 605.24 | 578.20 kg | 1.54 | 890.43 |
| 3 | Fly ash | 131.00 kg | 1.7 | 222.7 | | | |
| 4 | GGBFS | 98.25 kg | 2.9 | 284.93 | ------------ | -------- | ------------ |
| 5 | Quarry dust | 589.52 kg | 1.03 | 607.21 | | | |
| 6 | 6 mm aggregates | | | ---------- | 1164.80 kg | 1 | 1164.8 |
| 7 | Foaming agent | 0.30 liter | 100 | 30 | ------------ | -------- | ----------- |
| 8 | Labour | 0.25 nos. | 1000 | 250 | 0.25 nos. | 750 | 250 |
| 9 | Total cost/m$^3$ | ----------- | -------- | 2786.08 | ------------ | | 3534.03 |
| 10 | Cost of one block of dimension 400x200x200 mm | | | 44.22 | | | 56.1 |

**Table 9:** Cost analysis per cubic meter of concrete.

## Conclusion

A detailed study on the combined effect of fly ash and GGBFS as substitute for cement and quarry dust as replacement for manufactured sand in foamed concrete has been carried out and the results are analysed in detail. It has been identified that foamed concrete blocks can be produced economically by using 30% cement, 30% GGBFS, 40% fly ash, 40% manufactured sand, 60% quarry dust and required quantity of stable foam. Thus the cement consumption can be reduced by 70% and the consumption of manufactured sand can be reduced by 60%. UPV tests and durability tests are also conducted on the specimens and are reported. The summary and findings from the study are as follows.

- The maximum compressive strength of foamed concrete, with 30% cement, 40% fly ash, 30% GGBFS, 60% quarry dust and 40% manufactured sand, with 30% foam volume and w/p ratio 0.65 is 10.48 N/mm$^2$ with a density of 1587 kg/m$^3$.
- The thermal conductivity of foamed concrete is reduced with inclusion of all the industrial by-products. The maximum reduction in thermal conductivity is observed to be 13.33% for 0.65M$_3$30F, i.e, mix with 20% cement, 40% fly ash 40% GGBFS, 40% manufactured sand and 60% quarry dust for 1:3 proportion with water powder ratio 0.65.
- The ultrasonic pulse velocity test indicates that the quality of foamed concrete is comparatively good as the velocity is less than 3 kmph.
- The low values of percentage loss of weight indicates that the foamed concrete specimens prepared are durable and can withstand the acid attack, both chloride and sulphate, very effectively.
- Rapid chloride permeability test results show that the chloride ion permeability is very low. Hence, it can be inferred that the foamed concrete specimens are durable and resistant to chloride ion penetration.
- The cost analysis shows that the copiously available industrial by-products, being very cheap, can be effectively utilized for reducing the production cost of foamed concrete considerably. The reduction in cost is 21.18% for the proportion studied.

- Since the cement consumption in the proposed foamed concrete is very less in comparison with that of conventional concrete, it will lead to a substantial decrement in carbon footprint.
- By using such lightweight blocks as infills in framed structures, the wall load over the beams can be reduced considerably, so that cross sections of beams and columns can be made thinner for the design of framed structures. Hence, the foundations also can be designed accordingly. This will lead to savings of materials viz; cement, steel and other finishing materials, labour and material charges including formwork etc. Thus, the total construction cost can be reduced.

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## Declaration of Interest

The authors hereby declare that they have no specific conflict of interest.

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