Investigation on Mechanical Strength of Cellular Concrete in Presence of Silica Fume

G M Fani¹, S Singla²*, R Garg², and R Garg³

¹Department of Civil Engineering, RIMT University, Mandi Gobindgarh, India
²Department of Civil Engineering, Galgotias College of Engineering and Technology, Greater Noida, India
³Department of Chemistry, Rayat Bahra University, Mohali, India
*Corresponding author: drsandeepsinglaz@gmail.com

Abstract. Over the past decade, Cellular Lightweight concrete has gained popularity in the construction industry. Despite its advantageous low weight, thermal insulating, and fire-resistant nature, its comparatively low strength is a matter of concern. To develop the strength of this type of concrete, a thorough characterization of its main characteristics must be studied thereafter in addition to supportive cementitious materials. The effect of polyurethane on density and strength of cellular concrete subjected to varying curing conditions have been investigated in this report. Besides, Silica Fume has been used as a partial substituent of cement and as supportive cementitious material. The cellular concrete has been obtained by varying silica fume (0-20% by weight of cement) and polyurethane (0-20% by volume) at 7, 28, 56, and 90 days of curing. Density, compressive strength, split tensile strength and flexural strength have been investigated for all the specimens. The findings revealed a decrease in density and strength of cellular concrete in the absence of SF and the presence of polyurethane. The introduction of silica fume resulted in higher density and strength revealing the beneficial use of this pozzolanic material.

Keywords: Cellular concrete, Silica fume, Polyurethane, Compressive Strength, Split tensile strength.

1. Introduction

Concrete is currently the most common and most frequently used building material in different structural forms because of its strength and durability. Concrete is an acceptable building material and has some excellent properties, such as being rigid, low cost, and manufacturing ease [1]. Nevertheless, concrete has been commonly used for many years, it has undergone numerous improvements and enhancements during this time. Nowadays, concrete is not just a three-component mineral composite consisting of cement, aggregates, and water. Instead, it also includes mineral additives and chemical admixtures [2]. Many techniques have been used for enhancing the physical and mechanical properties of concrete by using auxiliary substances, including the incorporation of admixtures, supportive cement material (SCM), or other specific types of aggregates such as polycarboxylate polymer-based superplasticizers and varying water binder ratios [3]. The ecological effects of cement production can be minimized by the use of auxiliary substances, as a partial substituent of cement. The decreased use of cement as a binder in the concrete mixture has a positive influence on reducing...
CO₂ emissions and reduces energy usage in the Portland cement production process [4]. Also, in the current scenario of large modern structures, the intrinsic weight needs to be reduced. Lightweight concrete is an innovative tool in this concern and has gained more publicity in recent years [5].

The use of lightweight concrete further boosts the building’s structural capacity and reduces transportation and maintenance costs [6]. In general, lightweight aggregate concrete is obtained by mixing regular and lightweight aggregates which reduces the density of the aggregate. These aggregates include foamed slag, expanded shale, slag, vermiculite, expanded clay, pumice, perlite, or expanded polystyrene [7]. However, the manufacturing cost of lightweight aggregate concrete is more due to the involvement of a high-temperature sintering process. Also, the unequal distribution of aggregates renders the practical use of lightweight aggregate concrete. Aerated concrete is also known as foamed lightweight concrete, porous concrete or cellular concrete emerged as the modern construction material [8]. It has a relatively homogeneous and cellular structure as no coarse aggregates are used during its production. The cellular structure is because of the formation of air voids during the mixing process due to the introduction of a foaming agent. The materials used to manufacture the cellular concrete are the same as those used for traditional concrete, except the quartz aggregate and chemicals that produce the air voids [9]. Thus, the aerated concrete is a modification of normal concrete and the difference between them is in density and not quality. It exhibits properties like ordinary concrete with dense weight in most aspects, such as curing. The amount of air that can be included in aerated concrete precast or cast on-site varies from 20-50 per cent in volume in structural practices but may occupy 51 to 80 percent in concrete used for only thermal insulation, packaging, or filler purposes [10].

The presence of air voids in the cellular concrete imparts unique properties particularly, low density and lightweight. Cellular concrete provides the thermal and acoustic insulation properties depending on the density as the thermal conductivity increases linearly with the moisture content [11]. Cellular concrete has very low water absorption due to greater air content and high fire resistance. Its environmental friendliness, durability, and versatility increase the aesthetic value of buildings [12]. These distinctive properties of cellular concrete along with its easy production, high flow, and self-compacting nature result in its widespread use in numerous areas of civil and structural engineering such as the manufacture of pre-cast blocks and panel, shock-absorbing structures, road sub-base, and soil stabilization [13]. Its use in construction at regions under the threat of earthquakes and hurricanes is highly desirable. The physical and mechanical characteristics of cellular concrete are largely affected by the pore structure and porosity. The effect of foam content on the microstructure cement-based clay has been analyzed and an increase of permeability was obtained [14]. The curing duration and heat treatment have been found to significantly impact the pore structure and the performance of the silica fume based aerated concrete. The bulk density was also found to be dependent upon the content of the foaming agent [15]. The improvement in compressive strength has been observed with decreasing porosity in the presence of slag and an optimal water/binder ratio [16]. The pore distribution in the microstructure also affects the strength and durability of cellular concrete. The presence of large content of pores decreases the compressive strength but improves the thermal insulation and hygroscopic property as observed for foam concrete in the presence of silica fume and quick lime [17].

Foaming agents are used to lower the density of cellular concrete by generating and maintaining the air bubbles inside the cement paste [12]. The quality and quantity of the foaming agent pointedly affect the fresh and hardened properties of the cellular concrete. Various commonly used foaming agents include natural saponins and synthetic surfactants in addition to protein or resin-based polymeric compounds. The synthetic foaming agents have been found to provide more expansion with lesser density while the natural foaming agents provide a stable pore network structure [18]. The quality of foam is affected by various factors including water-binder ratio, the concentration of the foaming agent, mixing method, time of mixing, and curing type. The strength and rigidity of the resulting cellular concrete are strongly dependent upon the foam quality. The excessive use of the foaming agent has been reported to lead to a decrease in flow and compressive strength [19].
Prolonged mixing time reduces the air content and thereby increases the flow. The chemical admixtures with water reduction property have also been reported to lead to the destruction of the air network. The use of low content of foaming agents at a high water-binder ratio has been observed to decrease the consistency with increasing density of foamed concrete. On the contrary, the addition of superplasticizers has been found to increase flow [20]. The water-cement ratio has been found to significantly affect the microstructure and compressive strength of the cellular concrete [13].

The low mechanical strength of cellular concrete is a matter of concern and is usually dealt with by the incorporation of supportive cementitious materials (SCM) such as pozzolans [21]. It has been detected that the ultimate strength of foamed concrete is attained at a later age in the presence of high content of SCM [22]. These are siliceous substances with the composition of silico-aluminous or a combination of both. Most pozzolan materials are production residues of industrial or agricultural processes such as the burning of wastes left after agricultural production. These substances increase the density and impermeability, lower heat of hydration, and inhibit or counteract the expansions of cement matrix caused by the presence of free lime and free magnesia. The optimal incorporation of SCM has been found to result in intensification of the strength of cellular concrete. A significant impact of the alkali-activated fly ash has been observed on the heat resistance of cellular concrete [23]. The addition of an optimal amount of fly ash has been observed to improve the wetting strength, fluidity, and durability of cellular concrete [24]. These materials can replace between 15% and 40% of cement, without significantly reducing the strength and long-term durability of concrete. The most common materials used are fly ash, activated clays, foundry slag, and silica fume. The addition of carbon nanotubes has been found to enhance the uniform pore distribution and minimize the incurring strength loss [25]. Silica fume is another pozzolan that is generally used by replacing 5 to 10% Portland cement, and has the effect of reducing the average pore size of the capillaries in concrete; reduce its permeability; increase its resistance to chemical attack, and increase its compressive strength. Its role is two-fold, firstly it acts as an effective filler because of its fineness and, secondly chemically consumes the calcium hydroxide produced in the cement hydration to additionally produce calcium silicate hydrates (CSH gel). The effect of incorporation of foam in the presence of fly ash and silica fume has been observed on the physical and mechanical properties of cellular concrete at varying curing conditions [26]. The introduction of silica fume has been found to improve the microstructure and porosity of cellular concrete leading to enhanced strength [27].

Although literature reports many studies on fly ash based cellular concrete using various foaming agents, little data is available on the silica fume-based cellular concrete in the presence of polyurethane as a foaming agent. Hence, this study is aimed to obtain lightweight cellular concrete using polyurethane as a foaming agent at an optimum water-binder ratio in the presence of silica fume as supportive cementitious material. The effect of variation of percentage of polyurethane and silica fume for the cellular concrete has been studied. The study has been planned to explore the effects on the compressive strength, split tensile strength, and flexural strength at 7, 28, 56 & 90 days of curing ages of cellular concrete.

2. Materials and Methods
Ordinary Portland cement (43 Grade) was used. Silica fume was used as pozzolan and polyurethane was used as a foaming agent. These were obtained from the local supplier and were used as such without any modification. The Chemical composition of the binder materials have been given in Table 1. Natural sand conformed to IS: 383-1970 and a specific surface area of 256 m²/kg was used as fine aggregates. The physical properties of SF have been given in Table 2. Polyurethane (PU) percentage was varied from 0-20% by volume while silica fume was mixed from 0-20% by weight of cement at a water-binder ratio of 0.35. The mix proportion has been given in Table 3. The components were mechanically mixed and moulded as per method given in literature [28]. The specimens were kept to set for 24 hours and then positioned in a water tank for curing at standard temperature. The strength analysis of the fully cured, surface dried concrete specimens was performed with a compression
testing machine at 7, 28, 56 and 90 days as per IS 516-1959. Testing was carried out with three specimens for each mix and the average value was considered [29].

Table 1. Chemical Composition of Binder Materials

| Oxides          | SiO₂ | Al₂O₃ | Fe₂O₃ | CaO  | MgO  | K₂O  | Na₂O | TiO₂ | SO₃ | Cl | LOI |
|-----------------|------|-------|-------|------|------|------|------|------|-----|----|-----|
| OPC (% by mass) | 19.46| 4.22  | 3.56  | 65.92| 1.08 | 0.67 | 0.21 | 0.24 | 2.6 | 0.01| 0.96 |
| SF (% by mass)  | 98   | 0.03  | 0.02  | 0.3  | 0.2  | 0.3  | 0.3  | -    | -   | -   | 0.8  |

Table 2. Physical Properties of SF

| Property                  | Value                  |
|---------------------------|------------------------|
| Size of Particle          | <1.0 µm                |
| Specific Gravity          | 2.23                   |
| Solid Bulk density        | 130–480 kg/m³          |
| Slurry Bulk density       | 1,450–1,600 kg/m³      |
| Densified Bulk density    | 560–720 kg/m³          |
| Specific Surface Area     | 13,200–26,500 m²/kg    |

Table 3. Mix proportion of Specimens per m³

| Designation | Cement (kg) | SF (kg) | Water (litre) | PU (%) | Sand (kg) |
|-------------|-------------|---------|---------------|--------|-----------|
| CM          | 435         | 0       | 152.25        | 0      | 938       |
| CC1         | 435         | 0       | 152.25        | 10     | 938       |
| CC2         | 435         | 0       | 152.25        | 20     | 938       |
| CCSF0       | 391.5       | 43.5    | 152.25        | 0      | 938       |
| CCSF1       | 391.5       | 43.5    | 152.25        | 10     | 938       |
| CCSF2       | 391.5       | 43.5    | 152.25        | 20     | 938       |
| CCSF3       | 348         | 87      | 152.25        | 0      | 938       |
| CCSF4       | 348         | 87      | 152.25        | 10     | 938       |
| CCSF5       | 348         | 87      | 152.25        | 20     | 938       |

3. Results and Discussions

3.1. Density

Figure 1 illustrates the outcomes of the density determination of the concrete specimens. It can be observed that the density of the specimens decreases with the incorporation of PU, both in the absence of SF (CC1 and CC2) and presence of SF (CCSF0, CCSF1, CCSF2, CCSF3, CCSF4 and CCSF5). However, the decrease is small in the case of SF-based cellular concrete. Literature reports a decrease in the density of cellular concrete as related to conventional concrete due to the inclusion of air voids [15]. The comparative account of densities of control mix (CM) and SF-based cellular concrete reveals no significant impact on density in the absence of PU.
Figure 1. Density of Concrete Specimens

Figure 2 represents the effect of curing age with PU incorporation on the percentage decrease in densities of the cellular concrete specimens as related to the control mix. At 7 days of curing, the addition of PU decreased the density of CC1 by 29% and that of CC2 by 49% confirming that an increase in foaming agent decreases the density of cellular concrete. The results are consistent with earlier studies as literature reports the densities of cellular concrete varying from 770-1800 kg/m³ [29]. Further, it has also been reported that the incorporation of pozzolans such as FA and SF improves the density of cellular concrete [5,17]. Also, the density is strongly affected by the fineness of the supportive cementitious materials. The fine silica particles form a coating over the air bubbles and prevent their flocculation resulting in uniform void structure. In the case of CCSF1 and CCSF2, the decrease in density was 18% and 36% respectively. Likewise, in the case of CCSF4 and CCSF5, a percentage decrease of 14% and 20% respectively was observed. However, as the curing age progressed, a slight increase in density was observed. The percentage decrease in density for CC1, CC2, CCSF1, CCSF2, CCSF4 and CCSF5 at 28 days was 26%, 49%, 11%, 28%, 5% and 17% respectively as compared to CM. The results were again consistent with earlier reported studies confirming the development of density with an increase in curing age [26].
Figure 2. Variation in density of Concrete Specimens

3.2. Compression Strength

The outcomes of the compressive strength analysis of the concrete specimens have been represented in figure 3. The results reveal the significant impact of foaming agent on the compressive strength of cellular concrete. In comparison to CM, for CC1 and CC2, a decrease of 46% and 66% respectively was observed at 7 days of curing age, while a decrease of 44% and 64% was observed at 28 days. However, it is already reported that blends of foaming agents and pozzolans with finer material can improve the compressive strength of cellular concrete due to improved and uniform pore structure [5]. Better strength of limestone-based cellular concrete has been observed in the presence of a synthetic foaming agent [7]. Likewise, the incorporation of fly ash has resulted in better development of strength in cellular concrete [12]. Literature also reports similar observations in the presence of SF, where the introduction of SF progressed the compressive strength of cellular concrete significantly. The effect was pronounced at the optimal percentage of SF [26].

Figure 3. Compressive Strength of Concrete Specimens
A similar effect has been observed in the case of CCSF1 and CCSF2, where an increase of 19% and 32% respectively at 7 days and 28% and 47% increase at 28 days has been observed at the same content of PU as compared to CC1 and CC2. Further, the increase in SF content was observed to develop the compressive strength of the specimens. This effect is attributed to the amendment of pore structure leading to increased density and homogeneity of the matrix [18]. Hence, an increase of 6% and 67% for CCSF4 and 16% and 56% for CCSF5 respectively has been observed at 7 and 28 days. Since the introduction of SF results in the development of long-term strength of concrete, hence, the effect was more pronounced at later stages of curing. Thus, the decline in compressive strength due to decreased density of concrete in the presence of foaming agents can be managed by the addition of pozzolans such as SF. The pozzolanic action and filler effect of SF are primarily responsible for the strength development of concrete due to its participation in CSH gel formation [17].

![Figure 4. Effect of PU content on Compressive Strength of Concrete Specimens at 28 days](image)

### 3.3. Split Tensile Strength

The outcomes of split tensile strength analysis were similar in pattern to that observed in the case of compressive strength analysis. Here also, a decrease in split tensile strength was observed with the incorporation of the foaming agent. Further, a decline in split tensile strength was observed with decreasing compressive strength of the specimen. Earlier studies on lightweight concrete also indicate similar behaviour and a correlation between split tensile and compressive strength [30]. Figure 5 illustrates the effect of incorporation of PU on the split tensile strength of concrete specimens in the presence and absence of SF at the varying volume of PU. In the case of CC1 and CC2, the strength decreased by 40% and 51% at 7 days and 43% and 55% at 28 days, respectively. Further, with an increase in the curing age of 7 to 90 days, a remarkable growth in split tensile strength was observed for all the specimens as illustrated in Figure 6.
The results indicate the increase in volume content of PU resulted in an increased porosity of the matrix leading to interfacial defects and load failure [8]. However, as the cement was partially substituted by SF, an increase in split tensile strength was observed. Thus, the % decrease for 20% SF was least as observed in figure. In the case of CCSF1 and CCSF2, an increase of 22% and 41% at 7 days and 14% and 44% at 28 days was observed. The effect was pronounced with an increasing SF percentage. The 7-day strength for CCSF4 and CCSF5 was higher by 5% and 8% respectively than the control mix specimen. The decrease at 28 days for CCSF4 and CCSF5 was observed as 2% and 4% respectively. The increase in splitting tensile strength is ascribed to the filler effect and pozzolanic activity of fine silica microparticles of SF that bring the better and refined distribution of pore structure [18]. Thus, a significant impact of the incorporation of SF on the splitting tensile strength of cellular concrete has been observed.

**Figure 5.** Split Tensile Strength of Concrete Specimens

**Figure 6.** Effect of PU content on Split Tensile Strength of Concrete Specimens at 28 days
3.4. Flexural Strength

Figure 7 represents the behaviour of the flexural strength of the concrete specimens with the incorporation of foaming agent. Previous studies reveal a direct correspondence between compressive and flexural strength [9,10]. The flexural strength of cellular concrete specimens in the absence of SF was found to be lower as compared to the control mix. Hence, a decrease of 42% and 61% at 7 days along with a decrease of 37% and 53% was observed in flexural strength of CC1 and CC2 at 28 days respectively.

Figure 7. Flexural Strength of Concrete Specimens

The partial substitution of cement by SF increased the flexural strength of the specimens. In the case of CCSF1 and CCSF2, a decrease of 25% and 42% at 7 days, and 26% and 44% at 28 days was observed. The effect was more pronounced at increased content of SF. Thus, the flexural strength of CCSF4 and CCSF5 decreased by 2% and 17% at 7 days and 2% and 11% at 28 days, respectively. The test results show that at 20% content of SF and 10% of PU, the similar values of flexural strength were obtained for CCSF4 and CCSF5 as that of CM. Hence, the presence of pozzolanic SF provides a supportive impact on the matrix by improving the pore structure of cellular concrete [31,32].
3.5. Correlation Analysis

Various researchers have reported correlation equations for the relationship between split tensile strength and compressive strength at various curing ages [7,18,30,32,33]. A correlation was obtained on a similar basis for concrete specimens with varying volume % of PU from 0-20% namely, CC (with the absence of SF), CCSF10 (with the presence of 10% SF), and CCSF20 (with the presence of 20% SF). The proposed model has been represented by equation 1.

\[ f_s = a f_c^b \]  \hspace{1cm} (Equation 1)

Where, \( f_s \) and \( f_c \) represent the split tensile strength and compressive strength respectively, while \( a \) and \( b \) are the model parameters. The values of the model parameters and correlation coefficient \( (R^2) \) have been listed in Table 3. The relationship between \( f_s \) and \( f_c \) has been represented in figure 8-10.

|       | 7 days    | 28 days   | 56 days   | 90 days   |
|-------|-----------|-----------|-----------|-----------|
| \( a \) | 0.2035    | 0.104     | 0.1843    | 0.0564    |
| \( b \) | 0.6754    | 0.8013    | 0.9763    | 0.9983    |
| \( R^2 \) | 0.9754    | 0.9763    | 0.1843    | 0.9983    |
| \( a \) | 0.0231    | 0.0254    | 0.0325    | 0.0123    |
| \( b \) | 1.3914    | 1.2485    | 1.1927    | 1.4253    |
| \( R^2 \) | 0.9993    | 0.9996    | 0.9944    | 0.9975    |
| \( a \) | 0.0508    | 0.0646    | 0.0118    | 0.0098    |
| \( b \) | 1.155     | 0.96      | 1.4197    | 1.4713    |
| \( R^2 \) | 0.9618    | 0.9955    | 0.9876    | 0.9537    |
Figure 9. Correlation between Split Tensile Strength and Compressive Strength at 7 Days

Figure 10. Correlation between Split Tensile Strength and Compressive Strength at 28 Days
Figure 11. Correlation between Split Tensile Strength and Compressive Strength at 56 Days

Figure 12. Correlation between Split Tensile Strength and Compressive Strength at 90 Days

4. Conclusion
Based on the above investigations, the resulting conclusions can be listed out:

1. The incorporation of foaming agents results in a significant decrease in density of the cellular concrete and the effect is pronounced with an increase in the content of the foaming agent. However, the inclusion of SF as a partial substituent of cement increased the density of the cellular concrete at the particular volume % of the foaming agent. The maximum increase was found for 10% inclusion of SF.

2. There was a comparative decrease in the compressive strength of the cellular concrete as compared to the control mix. The use of SF resulted in the enhancement of compressive strength due to its pozzolanic action as well as the ability to introduce homogeneity in the pore
structure. Similar effects were observed in the case of split tensile strength and flexural strength analysis.

3. There was a good correlation observed between split tensile strength and compressive strength for the studied days of treatment. Hence, SF can be used to improve the performance of cellular concrete for further use in various construction purposes.

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