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Optimising lightweight concrete and bricks using expanded polystyrene beads and silica fume: a sustainable approach to construction materials

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Abstract:
Construction components are in greater demand as a result of the rapid growth of the building sector. This study investigated the feasibility of using expanded polystyrene (EPS) beads in combination with silica fume to produce lightweight construction materials. The strength and weight properties were determined using different types of mixed samples consisting of bricks and concrete of the same grade. The results were compared with the standard samples and cast with EPS. EPS was used as a volumetric replacement of 0; 10; and 20 % of coarse and fine aggregate along with silica fume to increase the strength of concrete and bricks for the experiment. The results revealed that when using 10% and 20 % EPS, the unit weight of the concrete samples decreased by 9 and 16 %, whereas the compressive strength decreased by 25 and 43 %, respectively. For the bricks, the weight decreased by 10 and 19 %, whereas the strength decreased by 26 and 49 %, respectively. Cement was replaced with 7,5 and 12,5 % silica fume in various combinations with these EPS substitutes to mitigate the loss of strength. The results showed an increase in the strength of the EPS-mixed concrete increased by 9 % when pozzolanic material was used, and the strength of the brick increased by 6,5 % compared with normal samples. In the combined effectiveness analysis, the EPS used in bricks was more effective than in concrete samples. Therefore, based on the effectiveness analysis, EPS can be easily used in a moderate range of building materials.

Keywords:
expanded polystyrene; silica fume; sustainable infrastructure; concrete masonry brick; lightweight

1 Introduction

The demand for construction materials has increased worldwide owing to increasing developmental activities. Concrete and masonry bricks are widely used as building materials. The building business is considered a sector that utilises large amounts of raw resources and generates large amounts of waste [1]. Owing to the increasing demand for construction materials, substitute supplies must be used to ensure durability. Concrete is the most versatile building material. Global development and industrial expansion have led to increased pollution and resource scarcity [2]. The utilisation of large amounts of core items in the building sector requires substantial energy. Adopting materials with a significant amount of embodied energy requires an initial substantial level of energy consumption in the construction manufacturing phase but also dictates future energy consumption to satisfy heating, airflow, and air conditioning criteria [3]. The most common elements, cement, fine aggregate, and coarse aggregate, are combined to form concrete with an average density of 2300-2500 kg/m³. However, traditional concrete has the major disadvantage of high weight. Recently, the increasing use of waste materials in modern buildings has led to a growing demand for lightweight bricks and concrete. Because conventional concrete comprises approximately 60-75 % natural aggregates, developing lower-density alternatives can reduce the overall dead load. The primary motivation for lightweight concrete is the potential to reduce dead load and improve construction efficiency (e.g., easier handling and transportation); however, the extent to which member sizes and reinforcement can be reduced depends on the achieved strength and serviceability requirements. A possible solution is to incorporate expanded polystyrene (EPS) beads as a lightweight aggregate [4-6].

Lightweight aggregates may be divided into three categories: manufactured aggregates, naturally occurring aggregates, and aggregates made from scrap material. Slates, expanded clay, sintered shales, and expanded shales from rotary kilns are a few forms of treated aggregates. Among the ordinary aggregates are scoria, pumice, and perlite [5]. Because natural resources are limited, alternative, eco-friendly, low-cost, and locally available materials should be used. EPS is a bead-shaped polymer foam widely used in packaging and can be used as a partial replacement for natural aggregates in cementitious composites [7]. EPS consists of closed, air-filled, non-absorbent cells with a very low bulk density (about 18-25 kg/m³) [8-10]. When used as an ultra-lightweight aggregate, EPS can significantly lower the unit weight and improve thermal insulation; however, owing to its low stiffness and strength, increasing EPS content generally reduces the mechanical strength of the composite unless the paste–aggregate interface is improved [8-12].

Bricks remain common and highly demanded materials in many construction sectors, particularly in developing regions. Rapid urbanisation and population growth continue to increase brick demand, which can intensify the pressure on raw clay resources and energy consumption and may increase production costs over time [13-15]. From a sustainability perspective, the replacement of a portion of conventional brick and concrete constituents with recycled or lightweight materials is increasingly being explored to reduce resource depletion and waste accumulation [15-18]. The use of EPS beads in cement-based bricks and concrete offers a route to divert EPS packaging waste while reducing the consumption of non-renewable aggregate resources [16; 19-22].

Previous studies have consistently reported that increasing EPS volume fraction reduces density which leads to better thermal insulation properties. This process results in better insulation properties but limits the use of high-EPS mixtures as structural materials because their compressive strength decreases [21; 23-25]. To address strength reduction, the construction industry employs supplementary cementitious materials such as silica fume (SF), fly ash, and metakaolin to improve paste density and enhance the interfacial transition zone properties, which results in partial strength restoration [26; 27].

This study conducted experimental tests to compare two construction materials, EPS-SF-modified concrete and cement-sand bricks, that were fabricated with identical replacement percentages of EPS at 0; 10; and 20 % of the total aggregate volume and SF at 0,0; 7,45; and

12,50 % of cement. The study assessed the mechanical properties by testing the compressive strength, split tensile strength, and flexural strength of concrete and the compressive strength of bricks. It measured the unit weight and conducted a basic benefit ratio assessment which calculated the weight reduction against strength reduction. The results of this study provide information regarding the materials and mix designs that were tested, which architects should use to build nonstructural elements and thermal-insulation materials.

2 Methodology

2.1 Materials

Portland composite cement (PCC), CEM-II, was obtained from the local market of Rajshahi and used for concrete preparation. Natural coarse aggregates with particle sizes between 19 and 4,75 mm, were used in this study, and their properties are listed in Table 1. Locally available river sand with FM = 2,93 and a specific gravity of 2,66 was used as a fine aggregate. The properties and particle gradations of the other aggregates are summarised in Tables 2 and 3. The mix included EPS aggregate with particle sizes ranging 4,75-12,50 mm. The EPS with a specific gravity of 0,0184 and unit weight of 18,4 kg/m³ (water absorption capacity of 0,0 %) was used. EPS grains employed in this study are shown in Figure 1.

SF, also known as micro-silica, is a fine, amorphous (noncrystalline) form of silicon dioxide. It consists of rough spherical particles with an average diameter of 150 nm. The characteristics of the SF used in this investigation are listed in Table 4.

Table 1. Properties of coarse aggregate

Properties	Value
app. sp. gravity	2,96
bulk sp. gravity	2,79
sp. gravity (SSD)	2,85
moisture content (%)	1,45
water absorption (%)	2,03
dry unit weight (loose) (kg/m³)	1431,94
dry unit weight (compacted) (kg/m³)	1637,8
fineness modulus	6,68

Table 2. Properties of fine aggregate

Properties	Value
app. sp. gravity	2,78
sp. gravity (SSD)	2,66
moisture content (%)	3,84
water absorption (%)	5,63
dry unit weight (kg/m³)	1548,60
fineness modulus	2,93

Table 3. Gradation of fine aggregate

Sieve size (mm)	Cumulative passing (%)	Limit of passing of ASTM C778-17
9,50	100,000	100
4,75	99,527	95-100
2,36	95,050	80-100
1,18	79,000	50-85
0,60	27,670	25-60
0,30	5,400	5-30
0,15	0,223	0-10

Table 4. Physical and chemical properties of silica fume

Physical properties		Chemical properties	
sp. gravity	2,20	SiO_2	85,00 %
average grain size	0,15 µm	MgO	0,20-0,80 %
sp. surface area	15 m^2/g	CaO	0,20-0,80 %
colour	Gray	Al_2O_3	1,15 %
N/A	N/A	Fe_2O_3	1,50 %
N/A	N/A	loss of ignition	2,00 %

Figure 1. Expanded polystyrene

2.2 Concrete mixtures

The concrete mixtures were designed following ACI 211.1-91 for an M30-grade concrete with a water-to-binder ratio (w/b) of 0,45 using a baseline proportion of 513:703:1015 kg/m³ (cement: fine aggregate (FA): coarse aggregate (CA)) [28]. SF replaced cement with masses of 0,00; 7,45 %; and 12,50 %, whereas EPS beads replaced 0; 10; and 20 % of the coarse aggregate volume. For the brick specimens, a cement-to-sand ratio of 1:3 and a w/b of 0,40 were adopted, with SF as a cement replacement and EPS as a partial replacement for fine aggregate (sand), were used. The variable sets are presented in Tables 5 and 6, and the corresponding calculated absolute quantities are summarised in Tables 7 and 8 for reproducibility.

Figure 2. Mixing and sample preparation

Table 5. Variable sets of replacement for concrete

Mix name	NC	NC-1	NC-2	NC-3	NC-4	C-1	C-2	C-3	C-4
Cement replaced by SF (%)	0,00	7,45	12,50	0,00	0,00	7,45	12,50	7,45	12,50
CA replaced by EPS (%)	0	0	0	10	20	10	10	20	20

Table 6. Variable sets of replacement for the brick

Mix name	NB	NB-1	NB-2	NB-3	NB-4	B-1	B-2	B-3	B-4
Cement replaced by SF (%)	0,00	7,45	12,50	0,00	0,00	7,45	12,50	7,45	12,50
FA replaced by EPS (%)	0	0	0	10	20	10	10	20	20

Table 7. Absolute mix proportions for concrete mixtures

Mix	**Cement** (kg/m³)	**Silica fume** (kg/m³)	**Water** (kg/m³)	**Fine agg.** (kg/m³)	**Natural CA** (kg/m³)	**EPS** (kg/m³)
NC	513,0	0,0	230,8	703,0	1015,0	0,000
NC-1	474,5	38,5	230,8	703,0	1015,0	0,000
NC-2	448,9	64,1	230,8	703,0	1015,0	0,000
NC-3	513,0	0,0	230,8	703,0	913,5	0,655
NC-4	513,0	0,0	230,8	703,0	812,0	1,311
C-1	474,5	38,5	230,8	703,0	913,5	0,655
C-2	448,9	64,1	230,8	703,0	913,5	0,655
C-3	474,5	38,5	230,8	703,0	812,0	1,311
C-4	448,9	64,1	230,8	703,0	812,0	1,311

Table 8. Normalized mix proportions for brick mixtures (per 1,00 kg cementitious material)

Mix	**Cement** (kg)	**Silica fume** (kg)	**Water** (kg)	**Natural sand** (kg)	**EPS** (g)
NB	1,000	0,000	0,400	3,000	0,00
NB-1	0,925	0,075	0,400	3,000	0,00
NB-2	0,875	0,125	0,400	3,000	0,00
NB-3	1,000	0,000	0,400	2,700	2,08
NB-4	1,000	0,000	0,400	2,400	4,15
B-1	0,925	0,075	0,400	2,700	2,08
B-2	0,875	0,125	0,400	2,700	2,08
B-3	0,925	0,075	0,400	2,400	4,15
B-4	0,875	0,125	0,400	2,400	4,15

2.3 Fresh properties of concrete

The workability and consistency of fresh concrete were determined using a slump test according to ASTM C143 [29]. In this test, the slump cone was filled with three layers, and each layer was compacted using 25 strikes of the tamping rod. The vertical drop in the concrete after lifting the cone (slump) was recorded as an indicator of the mixture workability. Figure 3 shows the slump test procedure.

a) b)

Figure 3. Measuring slump value of the concrete mix: a) filling the slump cone; b) measuring the slump value after lifting the cone

2.4 Hardened concrete properties

2.4.1 Compressive Strength Test for Concrete

The concrete compressive strength was determined by applying axial pressure to cylindrical specimens (100 mm in diameter, 200 mm in height) in a compressive strength testing machine according to the ASTM C39/C39M guidelines [30]. The load was gradually applied until the specimen failed, and the maximum sustained load was used to compute the compressive strength. Figure 4 shows the compressive-strength test results obtained using the compressive-strength testing machine.

Figure 4. Specimen during compressive strength test

2.4.2 Split tensile strength test for concrete

As per ASTM C496/C496M-11 [31], the split tensile strength test was conducted on cylindrical specimens (150 mm diameter, 300 mm height). Specimen testing was performed with a compressive force applied along the vertical diameter of the specimen, creating tensile stress until fracture. The resulting fracture and maximum load recorded enabled the determination of the tensile strength. Figure 5 shows the specimen during the split tensile strength test under the UTM.

Figure 5. Specimen during split tensile strength test

2.4.3 Flexural strength test for concrete

The flexural strengths of the concrete beams (100 × 100 × 500 mm) were tested according to ASTM C293-02 [32]. This implementation focused on a single-point load applied at the midpoint of a simply supported beam to induce bending stress. The flexural strength was calculated from the maximum load that the beam could withstand before breaking. Figure 6 shows a sample obtained during the flexural strength test.

Figure 6. Sample during the flexural strength test

2.4.4 Unit weight measurement for concrete

To determine the unit weight of the concrete, ASTM C29/C29M-17a procedures were followed [33]. The concrete was placed in a container of a known volume and compacted into layers. The mass of the filled container was recorded, and the unit weight was derived by dividing the total mass by the volume of the container.

2.5 Brick test

2.5.1 Compressive strength test for brick

The compressive strengths of the bricks were assessed according to ASTM C67 [34]. Rectangular specimens (242 × 115 × 70 mm) were installed on the compression testing machine, and a gradually increasing load was applied until failure. The compressive strength of the bricks was calculated as the ratio of the ultimate load to the cross-sectional area. Figure 7 shows the compressive strength of the brick specimens, where the load was applied using a compressive strength testing machine.

Figure 7. Brick specimen during compressive strength

2.5.2 Unit weight of brick

All moisture was removed to determine the unit weight of the brick specimen. After curing, the brick was placed in an oven at 110 ± 5 °C for 24 h, as specified in ASTM C67, and dried thoroughly. When dry, the brick was allowed to cool in a desiccator to prevent it from absorbing moisture from the air. After the brick reached room temperature and stabilised, it was weighed using a balance with an accuracy of 0,1 g. Finally, the unit weight was calculated by dividing the mass of the sample (in grams) by its volume (in cubic centimetres).

2.5.3 Heat insulation test

The heat-insulation performance of the bricks was evaluated using a bench-scale comparative heating arrangement to obtain a qualitative indication of the effect of EPS incorporation. Each brick specimen was placed in a wooden frame over a heated steel plate; the plate temperature was maintained approximately between 110 and 120 °C, and the temperature on the exposed surface of the brick was recorded at regular intervals during a 2-h heating period. Because this setup did not fully eliminate heat losses (e.g., edge losses, convection, and radiation), the results were interpreted as comparative temperature-rise profiles rather than absolute thermal conductivity values. Figure 8 illustrates the experimental setup.

Figure 8. Heat insulation test of brick

2.6 Benefit ratio

This factor is the ratio of the percentage weight variation to percentage strength with a standard value. This term is used to compare the concrete and brick specimens at the same level of EPS to determine their effectiveness [35]. Equation 1 represents the expression of the benefit ratio:

$$\text{Benefit ratio} = \frac{percentage\ of\ weight\ varies}{percentage\ of\ strength\ varies} \tag{1}$$

3 Results

3.1 Workability test

Figure 9 shows the effects of SF and EPS on the workability of fresh concrete mixes. Relative to the control mix (NC), introducing SF (NC-1 and NC-2) reduced the slump by approximately 5 and 13 %, respectively, which was consistent with the high specific surface area of SF and its associated increase in water demand [36; 37]. In contrast, when EPS replaced a part of the coarse aggregate (NC-3 and NC-4), the slump increased by approximately 3-5 %. This improvement in workability can be attributed to reduced inter-particle friction and smoother, more spherical EPS particles compared with angular natural aggregates [11]. For example, the 20 % EPS mix (NC-4) exhibited the highest slump among all EPS-only mixes. Similar trends have been reported for EPS-based lightweight concretes, where a higher EPS content increases the slump or flow owing to the lower internal friction [11; 25; 38]. The combined C-series mixes showed that EPS improves workability, whereas SF decreases workability, resulting in net slump values that remain within a narrower range, demonstrating the practical balance between cohesion and ease of placement.

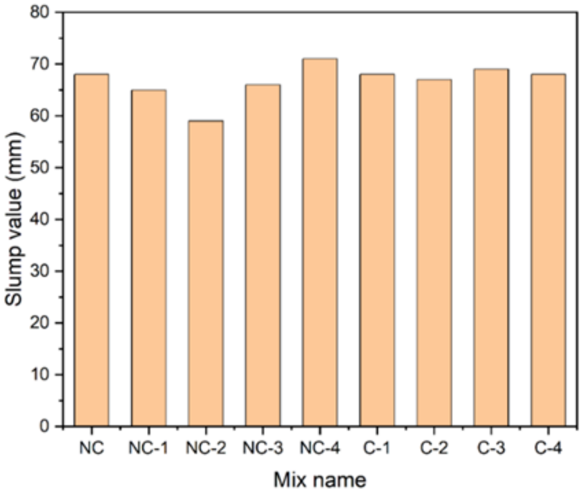

Figure 9. Workability of various concrete mixes

3.2 Compressive strength of concrete

Figure 10 illustrates the development of compressive strength in various concrete mixes over curing periods of 7, 14, and 28 days, highlighting the influence of SF and EPS on strength gain and loss. The compressive strength results indicated that when SF was used as a partial cement replacement in NC-1 and NC-2, the compressive strength improved because of the fine particle size of SF, which promoted better dispersion of EPS within the cement paste and strengthened the interfacial bond between the EPS and cement matrix [39]. Notably, NC-2, with 12,50 % SF replacement, showed approximately 13,95 % higher strength at 28 days compared with NC, proving its effectiveness in improving concrete performance.

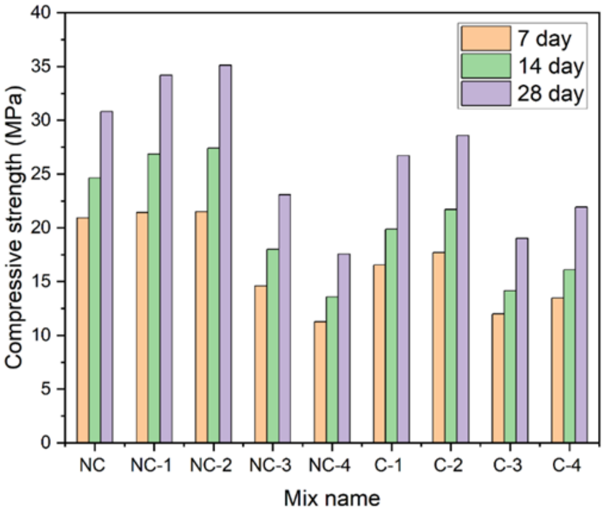

Figure 10. Average compressive strength of different types of concrete for 7,14, and 28 days of curing

In contrast, mixes incorporating EPS (NC-3, NC-4, C-3, and C-4) experienced a significant strength reduction. Numerous studies have demonstrated that incorporating EPS particles into cementitious composites reduces their strengths [2; 35; 39; 40]. This is attributed to the fact that EPS particles are of low density and are only weakly bonded to the cement paste, resulting in a highly porous structure. In particular, NC-4, which contained the highest EPS content (20 %), showed a 43,04 % decrease in strength compared with NC at 28 days. In the hybrid mixes where both SF and EPS were combined (C-1 to C-4), a partial recovery in strength was observed. The combined effect indicates that SF improves the strength by refining the matrix, although at higher EPS content, its influence has reduced. C-2 (12,5 % SF, 10,0 % EPS) showed a better performance than C-3 (7,45 % SF, 20,00 % EPS), highlighting that beyond 10 % EPS, the strength loss became more dominant than the benefits of SF. Therefore, the amount of EPS must be balanced with that of SF to achieve maximum strength.

3.3 Split tensile strength of concrete

Figure 11 presents the variation in the split tensile strength for different concrete compositions, showing how the inclusion of SF enhances the bonding strength, whereas EPS negatively affects the tensile resistance. In the split tensile test, the trend mirrors that of the compressive strength, with NC-2 (12,5 % SF) showing the maximum split tensile strength, which is approximately 18,68 % greater than that of NC. This increase was due to the enhanced bond strength between the particles, resulting from the densification effect of the SF. However, when EPS was introduced, the tensile strength decreased significantly. This decrease in strength can be attributed to the hydrophobicity of EPS particles. As the quantity of EPS increased, the cohesiveness of the material decreased, resulting in weakened structural integrity and potential shearing at elevated dosages [38]. This leads to early crack formation under tensile stress, resulting in lower tensile strength. NC-4 (20 % EPS) showed a decrease of nearly 35% in tensile strength compared to NC, highlighting the negative impact of excessive EPS. Interestingly, when SF was combined with EPS (C-1 to C-4), a partial improvement in the tensile strength was observed compared with NC-3 and NC-4. This suggests that although SF can enhance the tensile properties by improving particle packing and ITZ strength, the structural integrity is still weakened by excessive EPS replacement.

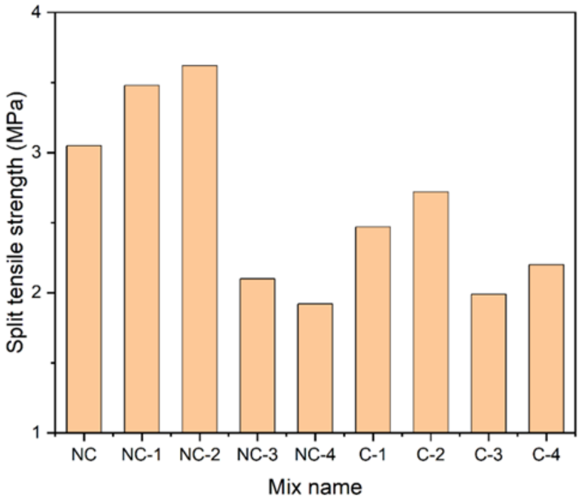

Figure 11. Split tensile strength of different types of concrete for 28 days curing

3.4 Flexural strength of concrete

Figure 12 shows the variation in flexural strength among the different concrete mixes when subjected to bending forces. These results were consistent with the trends observed in the compressive and tensile strengths. NC-2 (12,5 % SF) showed the highest flexural strength, with an increase of approximately 10 % over NC, indicating the positive effect of SF on the load distribution in the composite and the strength of the matrix. The incorporation of EPS into concrete reduces the modulus of rupture primarily because of the decreased density of the composite [40]. The flexural capacity declined by 30 % for NC-4 (20 % EPS) compared with that of NC. Because EPS does not provide significant resistance to bending, concrete mixes with higher EPS contents become more susceptible to flexural failure. The flexural performance of the SF and EPS combined mixes (C-1 to C-4) indicates that SF can counteract some strength loss by improving bonding within the cementitious matrix. However, beyond 10 % EPS, the loss in stiffness outweighs its benefits. C-2 (12,5 % SF, 10,0 % EPS) showed the best flexural performance among EPS-containing mixes, highlighting that a controlled balance of these materials is key to maintaining strength. On the other hand, C-3 and C-4, with an increase in the EPS content, show a sharp drop, indicating that more EPS reduced the modulus of rupture. Overall, while SF enhanced the microstructure, EPS compromised the load-bearing capacity, making it necessary to balance both materials carefully for optimal results.

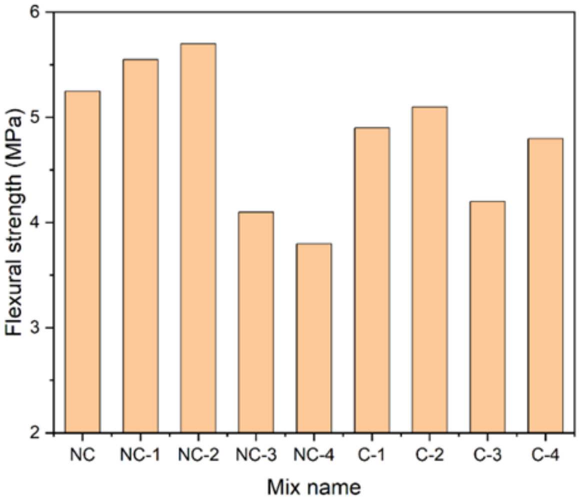

Figure 12. Flexural strength of different types of concrete for 28 days curing

3.5 Unit weight of concrete

The variation in the unit weight of concrete resulting from the inclusion of SF and EPS as replacement materials is illustrated in Figure 13. The overall trend shows that, while SF slightly increased the density owing to better particle packing, EPS significantly reduced it, making the concrete lighter but less compact. When SF was added to replace cement (NC-1, NC-2), the density increased slightly by approximately 2 % because the fine particles of SF filled the gaps in the concrete matrix, improving the overall packing. This densification effect made the mixture more compact without drastically altering its weight. However, under the partial replacement of coarse aggregates with EPS (NC-3, NC-4), the unit weight was significantly lower by 8,16 % and 15,81 % for 10,00 % and 20,00 % EPS, respectively, and the larger the EPS content, the higher the reduction rate. Previous studies have found that the incorporation of WPFs into lightweight concrete (LWC) reduces the density of the mixtures [25; 41-43], resulting in a lightweight structure. This phenomenon was attributed to the tendency of EPS particles to cluster together, absorb water, and dry the mixture [41]. The introduction of EPS results in a specific gravity of less than 1 [44; 45], leading to a more porous and less compacted concrete mix, because it reduces the density of the concrete. In the hybrid mixes (C-1 to C-4) containing SF and EPS, the unit weight exhibited an intermediate trend. This mix, with a high percentage of SF but moderate EPS content, retained 90 % of its original density. However, with increasing EPS content, the density decreased by more than 12 % when EPS comprised more than 10 % of the total composition, suggesting that, at a specific ratio, the lightweight nature of EPS superseded the densification effect of SF. Overall, the results confirm that SF slightly enhances density, whereas EPS significantly reduces it. A balance must be maintained to achieve weight reduction without compromising the concrete integrity.

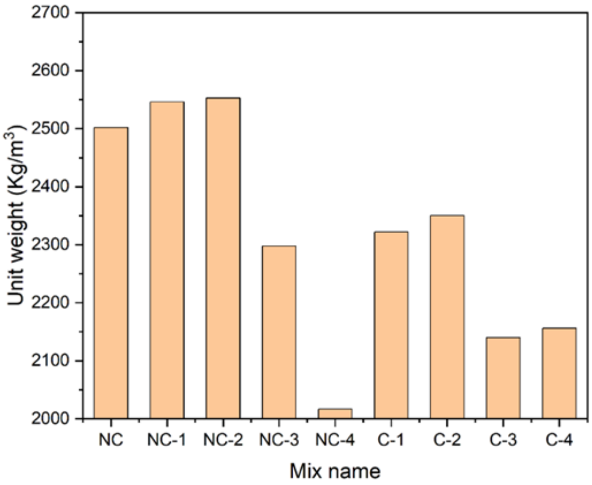

Figure 13. Unit weight of cylindrical concrete specimen at 28 days of curing

3.6 Compressive strength of bricks

Figure 14 showcases how EPS and SF impact the compressive strength of bricks, emphasizing how their combination alters mechanical performance. The strength of the bricks follows a clear trend across the different mixes. As EPS is introduced, the strength gradually decreases. For mixes without EPS replacement (NB, NB-1, NB-2), there is a progressive increase in compressive strength. NB-1 shows a modest rise, while NB-2 demonstrates the highest strength, indicating that a 12,5 % replacement of cementitious material (CIM) with SF (SF) enhances strength due to its pozzolanic effect.

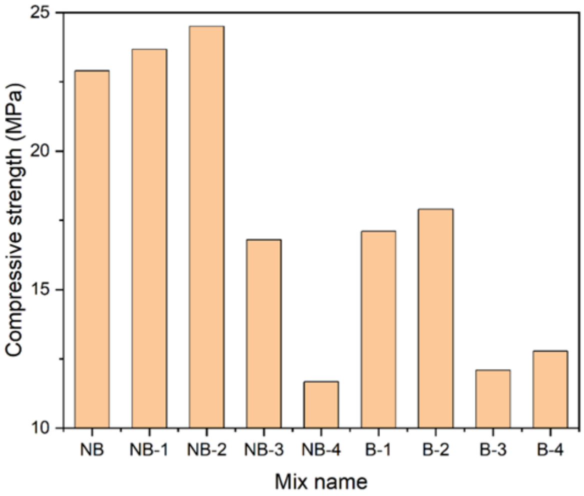

Figure 14. Compressive strength of brick

SF improves the strength by reacting with calcium hydroxide to form additional calcium silicate hydrate (C-S-H), which enhances the density and bonding in the mortar matrix. Compared with the base mix (NB), NB-2 showed an approximate 7 % increase in strength. However, when EPS were introduced (NB-3 and NB-4), the strength decreased significantly. NB-3, with 10 % EPS, experienced more than 25 % reduction compared to NB, whereas NB-4, which contained 20 % EPS, showed an even steeper decline, losing almost 50 % of its strength. This reduction was attributed to the characteristics of EPS particles, which created large voids of negligible strength within the relatively strong cement and sand paste, resulting in a significant reduction in the compressive strength of the composites [46]. EPS particles can be considered as air voids, and composite EPS mortar can be regarded as cellular concrete [6]. A similar pattern was observed for the B-series mixes. B-1 and B-2, which contained both EPS and SF, performed slightly better than NB-3 and NB-4 because SF helped mitigate strength loss by refining the microstructure and reducing porosity.

3.7 Unit weight of bricks

The impact of EPS and SF on the unit weight of the bricks, along with the effect of their interaction on the density and structural integrity, is illustrated in Figure 15. In the NB-series, the unit weight remained relatively consistent in NB, NB-1, and NB-2, with only a slight increase (~0,5 %) owing to the densification effect of the SF. SF contributed to weight retention by improving particle packing and reducing voids, thereby rendering the structure denser. However, when EPS was added (NB-3 and NB-4), a significant decrease in unit weight was observed. NB-3 (10 % EPS) showed a 9,11 % decrease compared with NB, whereas NB-4 (20 % EPS) experienced more than 18 % reduction, demonstrating how EPS lowers the density. One study found that the addition of EPS reduced the weight of bricks by approximately 27,78 % while maintaining their overall effectiveness [14]. B-series followed a similar pattern. B-1 and B-2, a combination of 10 % EPS with 7,45% and 12,5% SF, respectively, maintained a slightly higher weight, with weight losses remaining within an 8-10 % range compared with NB. The inclusion of SF helps retain some density by filling voids and reducing large pores, thus mitigating the weight reduction caused by EPS. However, as EPS content increased to 20 % in B-3 and B-4, it experienced a 17,96 % and 17,29 % reduction, respectively, confirming the dominant influence of EPS in reducing unit weight. The combined effect of EPS and SF suggests that, while SF densifies the structure, the lightweight nature of EPS overrides this effect when its proportion is increased.

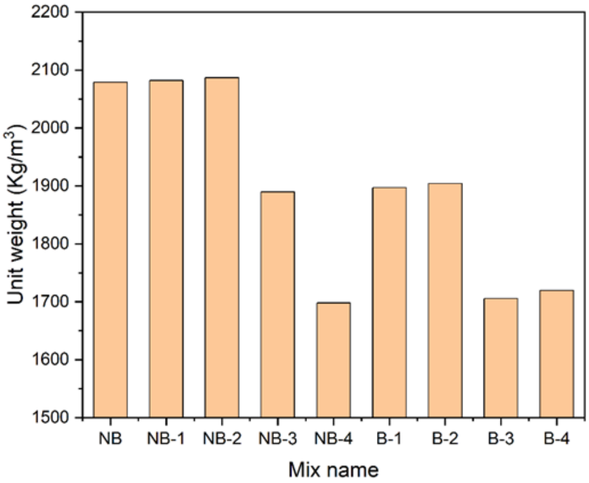

Figure 15. Unit weight of brick for various types of mix

3.8 Heat insulation

The research evaluated the temperature and time graphs, which showed four different materials and operational conditions, by testing their performances using the same bench-scale heating method. The temperature of the specimens increased steadily throughout the experiments. The control clay brick (FCB) achieved its maximum surface temperature after 120 min when it reaches approximately 52 °C, whereas the nominal cement–sand brick (NB) followed with a surface temperature of approximately 48 °C. The EPS-containing bricks (NBH-1 with 10 % EPS and NBH-2 with 20 % EPS) exhibited reduced surface temperature increases, demonstrating their superior heat-insulation capabilities during testing. The NBH-2 brick had the lowest surface temperature throughout the entire heating process, which demonstrated that decreasing EPS content resulted in better insulation performance, as shown in Figure 16.

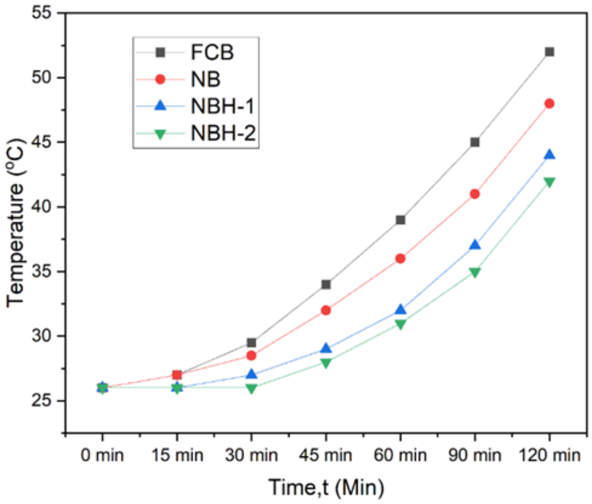

Figure 16. Surface temperature rise during the 2-h bench-scale heat-insulation test for brick mixes

3.9 Benefit ratio

The benefit ratios of various concrete and brick samples are shown through visual evidence in Figures 17 and 18. The benefit ratio was calculated using Equation 1 and is defined as the percentage reduction in unit weight divided by the percentage reduction in strength, thereby enabling a standardised comparison across mixtures. The study defines a benefit ratio above 0,5 as an optimum weight reduction to strength retention ratio, whereas performance values between 0,4 and 0,5 demonstrate borderline results.

Figure 17 shows the benefit ratios of various concrete specimens, including nominal concrete (NC) and EPS-modified concrete. For instance, NC-3, in which EPS replaced 10 % of the coarse aggregate (CA), showed a lower benefit ratio (0,32), indicating a weaker balance between weight reduction and strength retention. Similarly, NC-4 with 20 % EPS replacement in CA achieved a slightly higher ratio of 0,37. In contrast, C-1, which includes 7,45 % SF (SF) and 10 % EPS in CA, achieved a benefit ratio of 0,54, demonstrating a more favourable performance. Notably, C-2, in which replaces 12,5 % SF and 10,0 % EPS, attained the highest benefit ratio (0,83), making it the most efficient concrete mixture. Conversely, C-3, incorporating 7,45 % SF and 20,00 % EPS, resulted in a lower benefit ratio (0,34), suggesting that excessive EPS replacement may significantly affect strength. C-4, which combined 12,5 % SF with 20 % EPS, maintained a moderate benefit ratio of 0,48, which was within an acceptable range.

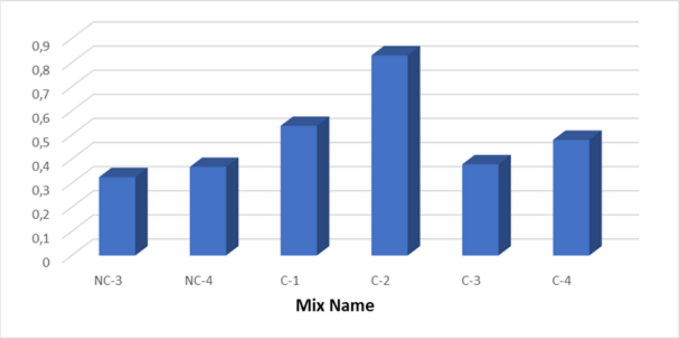

Figure 17. Benefit ratio of concrete specimens

The benefit ratios of various brick specimens are shown in Figure 18, which includes both nominal bricks (NB-series) and EPS–SF modified bricks (B-series). The brick mixes exhibited weight loss with strength changes when EPS replaced fine aggregates (sand) at 10 % and 20 % by volume. The benefit ratio for NB-3 (10 % EPS replacement in FA) was 0,88, whereas NB-4 (20 % EPS replacement in FA) produces a slightly lower ratio of 0,66.

Furthermore, the modified brick specimens incorporating SF along with EPS demonstrated even better performance. For example, B-1, which contained 10,00 % EPS and 7,45 % SF, achieved a high benefit ratio of 0,91. Among all the brick specimens, B-2, which included 10% EPS and 12,5 % SF, exhibited the highest benefit ratio of 1,05, making it the most effective mix for balancing weight reduction and strength retention. Meanwhile, B-3 and B-4, which incorporated 20 % EPS with 7,45 % and 12,50 % SF, respectively, maintained benefit ratios of 0,66 and 0,70, respectively, which were within an acceptable range.

Overall, Figures 17 and 18 demonstrate that EPS incorporation influenced the concrete and brick specimens differently. While some concrete specimens, such as NC-3 and C-3, struggled to meet the balance condition, all brick specimens performed satisfactorily. Among these, B-2 and C-2 emerged as the most efficient mixes for achieving a desirable balance between weight reduction and strength retention.

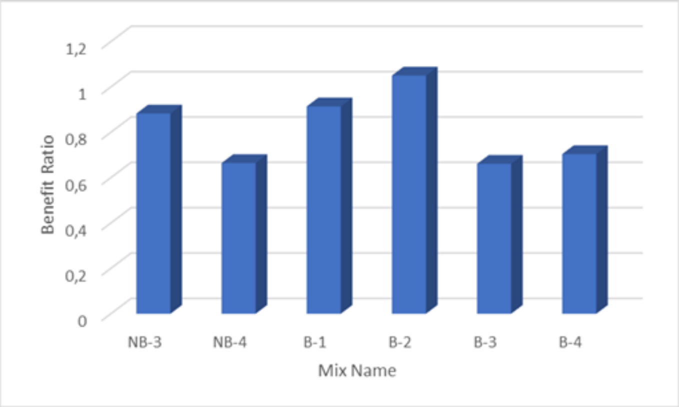

Figure 18. Benefit ratio of brick specimens

4 Conclusions

This paper presents the possibility of using sustainable lightweight construction materials by incorporating EPS beads and silica fume. It establishes that EPS bead incorporation reduces the concrete and brick densities to a large extent while satisfying reasonable levels of mechanical properties, which makes these materials suitable for nonstructural applications. Silica fumes aid in strengthening and durability by refining the microstructure of composite materials.

The results imply that this approach could be an environmentally friendly substitute for traditional construction materials, incentivising waste utilisation in construction, and reducing environmental impacts. Future work should focus on optimising mix proportions, evaluating long-term durability, and field applications to confirm the practical benefits of these materials.

This study investigated materials together with two distinct mix designs: M30 concrete with a water-to-binder ratio of 0,45 and cement-sand bricks at a water-to-binder ratio of 0,40, EPS replacement levels between 0 and 20 %, and silica fume replacement 0,0-12,5 %. The research conducted only short-term mechanical tests using a bench-scale setup to assess thermal insulation, rather than performing standard thermal conductivity tests. The results represent an experimental comparison within the studied range because further testing is needed to establish long-term durability and measure thermal properties using standardised techniques.

Thus, this study showed that EPS is effective for use in lightweight construction materials when combined with silica fume to maintain structural integrity. The results offer a solution to environmental sustainability by minimising the impact of construction materials while maintaining suitable mechanical properties, as well as highly valuable possibilities for engineers and researchers in the sustainable construction paradigm.

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