Performance of Controlled Flow Stabilized Adobe Utilizing Construction and Demolition Waste

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Abstract

Due to rapid urbanization and environmental degradation from construction and demolition waste (CDW), effective management, recycling, and reuse of CDW become a necessity. CDW can be appropriately utilized in the development of alternate masonry units, such as stabilized adobe blocks (SAB). However, challenges concerning production uniformity and consistency in the characteristics of SAB exist and require further investigation. To address these issues, this study aims to develop novel controlled flow-stabilized adobe (FSAB) incorporating CDW. This research involves collecting and processing CDW as a substitute for natural soil in the development of FSAB. An experimental study investigates physical, mechanical, and durability characteristics of FSAB as per Bureau of Indian Standards. CDW-based FSAB satisfied minimum block density, water absorption, and compressive strength requirements, confirming its suitability for Class 5 soil-based blocks. Sustainability analysis indicates the embodied energy and carbon equivalent of FSAB possess significant savings, equivalent to conventional masonry units. Environmental indicators such as embodied energy per unit strength, embodied carbon per unit strength, and structural efficiency highlight the potential of CDW-based FSAB as a sustainable alternative to conventional masonry units. These findings demonstrate pathways for waste valorization and reduced dependence on conventional materials while addressing environmental and structural performance challenges.

Keywords: Construction and Demolition Waste; Recycled Concrete; Recycled Brick Masonry; Embodied Energy and Carbon Equivalent.

1. Introduction

Adobe has been an energy-efficient construction material since the beginning of human civilization. Conventionally, it is an air-dried brick, comprising locally available materials such as natural soil, water, and sometimes organic fibers. Despite its energy-efficient characteristics, adobe has several limitations, such as lower resistance to moisture and poor mechanical and durability properties, which hinder its effective utilization. Advancements in adobe through stabilization techniques, such as the use of stabilizers such as cement, lime, marble dust, bagasse, rice husk ash, etc., have successfully overcome the limitations of conventional adobe [1–5]. Such stabilizer-based adobe is termed as "stabilized adobe blocks (SAB)." However, wider adoption and large-scale production of SAB face notable technical, environmental, and economic barriers that hinder its commercial viability. Conventionally, production of SAB relies on labor-intensive kneading or pugging operations, which hinders production speed and consistency in characteristics [6, 7]. This presents a critical need to develop an enhanced methodology, such as a flowable mixed approach, to mitigate these challenges.

In modern construction, the self-compacting or flowable earth approach has emerged as a promising alternative to conventional earthen technologies. The key advantage of this approach is the presence of clay-sized particles, which exhibit characteristics such as colloidal interaction and adhesive forces similar to those of cementitious materials. This approach facilitates novel production methods, enhanced mix design, and utilization of admixtures, thereby enhancing flowability, uniformity, and ease of handling. Furthermore, it offers various other benefits such as production uniformity for large-scale manufacturing and enhanced mechanical and durability characteristics. Recent research initiatives have focused on the use of flowable or self-compacting mixes in earthen construction, particularly in the context of rammed earth, mortar, and monolithic wall applications. Different researchers describe this concept with different terminologies such as self-compacting earth-based composites, poured earth, and flowable earth mixes, depending on specific applications [6, 8, 9]. In addition, the utilization of admixtures varies considerably, highlighting the use of polycarboxylate ester, sulfonated naphthalene, sodium hexametaphosphate, or only a higher water content to achieve a flowable earthen composite, ensuring quicker setting and improved mechanical and durability characteristics [10, 11].

Galabada et al. [12] explored the effects of chemical admixtures and soil gradation on the flowability of soil-concrete mixtures. The study recommended a cement dosage in the range of 16–18%, with fines, sand, and gravel fractions of 5–10%, 55–71%, and 24–40%, respectively. However, a higher dosage of cement has been reported to achieve the desired performance of flowable earth composites, posing environmental and economic challenges. Another study investigated the design criteria and performance characteristics of flowable earth-based composites using blended cement and limestone fillers, which resulted in enhanced compressive strength and electrical sensitivity [13]. This was attributed to the presence of secondary cementitious composites, which facilitated enhanced performance. Some studies have also explored the use of dispersion agents such as sodium hexametaphosphate to deflocculate the clay-sized particles, enhancing flowability, density, and strength characteristics [14]. Arooz & Halwatura [11] explored the development of self-compacting mud concrete without chemical admixture, indicating that higher water content added is sufficient for hydration of cement particles while maintaining a self-consolidating mix. These composites satisfied the durability standards of the Sri Lankan Standard SLC 1382. Gourav et al. [9] explored the use of flowable earth-mix concrete in the development of monolithic load-bearing walls. The study concluded that the type of soil and its constituents influence the properties of earth-based composites, indicating the suitability of clay-rich soils. Collectively, these studies emphasize the growing interest in the viability of flowable mixes in conventional earthen systems. The shift toward mechanized flowable formulations in earthen construction provides better control over material properties, homogeneity, and large-scale production. However, its utilization for the development of alternate masonry units, such as stabilized adobe blocks, remains scarce or unexplored.

Conversely, with modern construction practices, the construction industry faces significant environmental issues related to degradation through the generation of inorganic solid waste in the form of construction and demolition waste (CDW). The disposal of CDW fines reveals high contamination levels of heavy metals such as chromium, nickel, lead, and zinc, often exceeding the limiting values [15, 16]. Furthermore, due to rapid urbanization, the construction industry is expected to grow between 20-70 and 110-280 billion square meters for residential and non-residential buildings, respectively, by 2050. This results in huge demand for construction materials, of which more than 50% of conventional materials are extracted globally [17, 18]. This indicates a substantial increase in carbon emissions due to extraction of conventional construction materials and landfill operations [19, 20]. These concerns have steered the management of CDW through recycling and reuse. Studies have shown that recycled concrete aggregate (RCA), a byproduct of CDW, competitively performs in non-structural and structural applications with natural aggregates [21–26]. Its use in construction assemblies not only reduces the ecological footprint size but also conserves the resources of conventional materials, contributing to a circular economy in construction.

Nowadays, utilization of CDW in earthen construction, particularly SAB, has gained significant interest globally. Casapino-Espinoza et al. [19] found that incorporating crushed ceramic brick aggregates resulted in better compressive strength, flexural strength, and elastic modulus. Substitution of natural soil with 35% hydrated cement powder from RCA fines resulted in enhanced thermal resistance characteristics in lightweight blocks [27]. The incorporation of ceramic tile waste powder as a cement replacement in the range of 40–50% enhanced the strength characteristics of composites [28]. Roknuzzaman et al. [29] demonstrated that utilization of recycled brick aggregate with old mortar deteriorates the characteristics of composites, limiting it to 20% substitution. Another study highlighted the use of recycled aggregate powder as a stabilizer in earth-based composites. The pozzolanic activity of finely ground recycled aggregate in adobe mixes enhanced early strength gain, reduced water demand, and improved compressive strength and thermal insulation [30, 31].

Some studies have also demonstrated the adverse characteristics of utilizing full-scale (100%) CDW. Joshi et al. [20] explored the characteristics of stabilized adobe blocks using demolished brick masonry waste. The study showed better performance of SAB when the percentage substitution was in the range of 60–70%. Furthermore, a study highlighted that full-scale substitution of demolished brick masonry waste is challenging as specimens break during handling because of the non-cohesive nature of CDW. Another study demonstrated that the utilization of 100% recycled aggregate as a substitute for conventional aggregates results in a decrease in compressive strength and an increase in water absorption characteristics. However, bricks meet the minimum requirements for compressive strength, conforming to BS-6073 standards [14]. Similar observations were reported in the case of 100% CDW-based solid masonry concrete blocks, where a higher cement-to-aggregate ratio (1:6 to 1:18) was attempted to satisfy the limiting criteria suggested by the Indian Standard Code of Practice. This illustrates a growing belief in the suitability and associated challenges of CDW and its by-products in construction. However, the development of FSAB, particularly with the full-scale replacement of CDW, is scarce.

Considering these issues and the present need, the objective of this study was framed. This study aimed to develop a novel controlled flow stabilized adobe utilizing full-scale CDW as a substitute for natural soil. Specifically, this research aimed:

- To optimize CDW-based composites to achieve the desired flow characteristics

- To investigate the feasibility of FSAB utilizing CDW as substitute to natural soil

- To evaluate the physical, absorption, mechanical and durability characteristics of FSAB

- To assess the environmental impact of CDW-based FSAB compared to conventional masonry units

2. Research Significance

Previous studies have indicated that the utilization of higher water content, chemical admixtures, or secondary binder content can enhance the flowability of earth-based composites. These composites typically consist of gravel (24-40%), sand (55-71%), and fines (5-10%). Most studies have focused on self-compacting rammed earth, poured earth mortar, and gravel-based monolithic wall construction. However, the utilization of self-compacting or flowable earthen composites for the development of masonry units, such as stabilized adobe blocks, remains largely unexplored. This gap presents a substantial challenge for mechanized SAB production, as conventional methods are labor-intensive and inconsistent. Therefore, a controlled flow approach in stabilized adobe production presents benefits by eliminating kneading or pugging, thus minimizing performance inconsistencies. This approach also promotes mechanized production of stabilized adobe, enabling better quality control than the conventional manual approach. Thus, it creates a pathway towards industrialization and large-scale production. In addition, various studies have shown the potential of CDW as a partial substitute for soil in earth-based composites. However, limited studies have reported on full-scale substitution of CDW (100% substitution), indicating considerable challenges in dimensional stability and structural performance of adobe.

Thus, in the present study an attempt was made to develop controlled-flow stabilized adobe blocks as an alternative masonry unit utilizing CDW. Full-scale substitution of CDW was prioritized over optimized partial substitution, despite the higher porosity and absorption issues reported in earlier studies. This was mainly to maximize waste valorization and reduce dependence on conventional materials. Moreover, CDW poses control over gradation, which is essential because the inconsistent performance of soil-based construction is largely due to variability in gradation of natural soil.

Marginal changes in mix proportioning, increased stabilizer, and utilization of admixture might subside the drawbacks of full-scale utilization of CDW. This study aimed to utilize CDW such as recycled concrete and recycled brick masonry waste as a substitute for natural soil in the development of novel FSAB. This FSAB approach facilitates a flowable consistency of mix, leading to an increased production rate and uniformity of blocks. It also promotes the development of low-carbon materials and circularity in the construction industry. A detailed flow chart of the present study is shown in Figure 1.
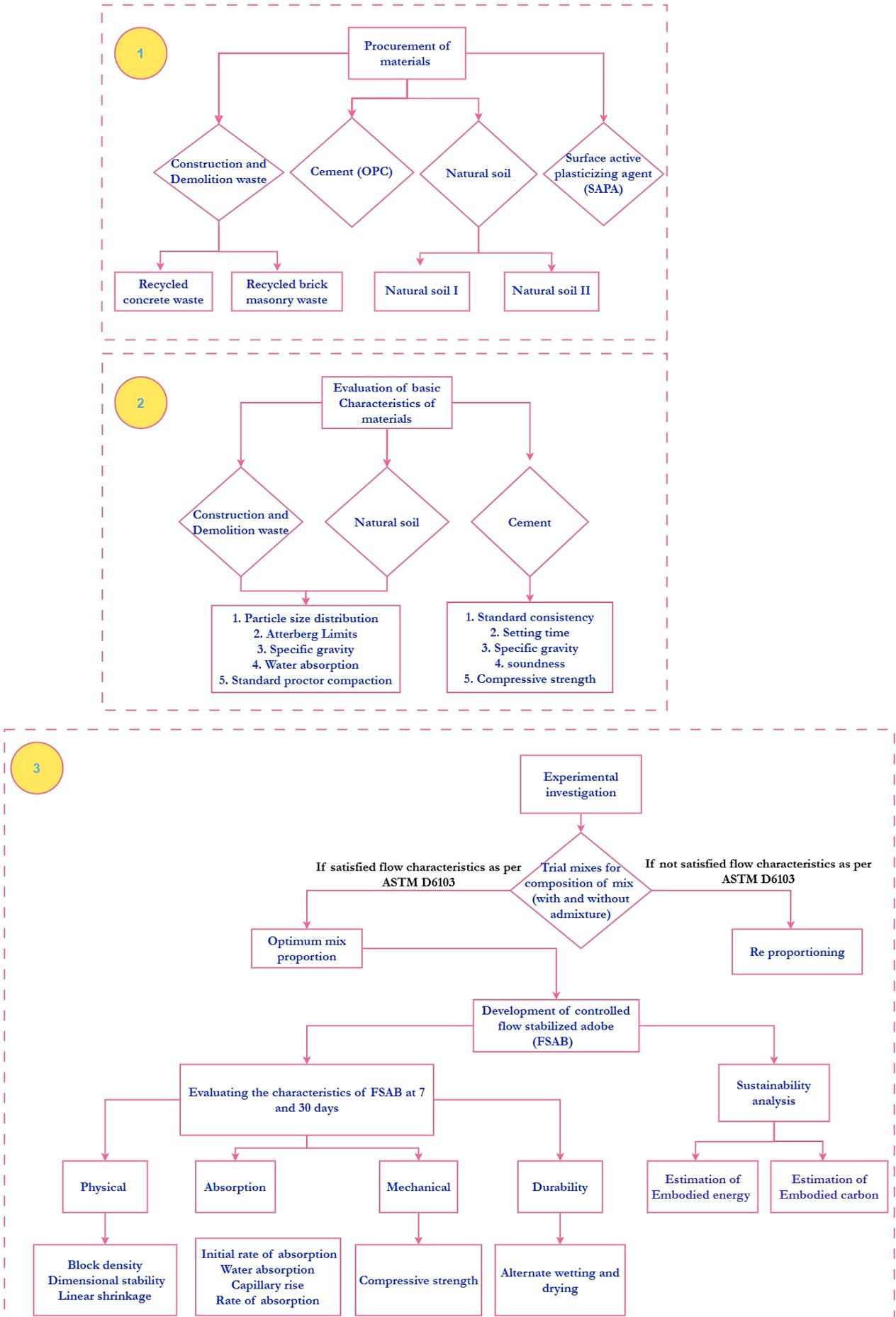
Figure 1. Flow chart of the present research work

3. Raw Materials

The materials used in the development of FSAB include locally available soil, CDW—recycled concrete (RC) and recycled brick masonry (RBM), cement, and surface-active plasticizing agents (SAPA). The CDW was procured from a nearby demolition site and crushed using a jaw crusher available in the laboratory. Similarly, natural soil (NS) was procured from two sources: NS I and NS II. The constituent materials used in the development of FSAB were sieved through an Indian Standard sieve of size 4.75 mm. Ordinary Portland cement (OPC) of grade 53, conforming to Indian Standard 12269, 2013, was used as a stabilizer in the current study. The detailed characteristics of the materials were evaluated in accordance with the Indian standard code of practice and are presented in Table 1. The particle size distribution curves of various materials used are presented in Figure 2.

Table 1. Characteristics of materials used in the development of FSAB

Physical Characteristics		Materials				Reference
		RBM	**RC**	**NS-I**	**NS-II**	
Particle size distribution	Clay (%)	2.00	1.06	47.00	3.00	[32]
	Silt (%)	6.53		24.00	27.53	
	Sand (%)	91.47	98.94	29.00	69.47	
Atterberg Limits	LL (%)	---NP---	---NP---	47.20	34.11	[33]
	PL (%)	---NP---	---NP---	28.79	22.79	
Specific gravity		2.22	2.30	2.65	2.69	[34]
Water absorption (%)		25.00	30.2	17.51	19.42	[35]
Standard proctor compaction	OMC (%)	13.10	-	16.00	14.67	[36]
	MDD (g/cc)	1.65	-	1.89	1.80	

* LL-Liquid limit, PL-Plastic limit, NP: Non-plastics, OMC- Optimum moisture content, MDD- Maximum dry density
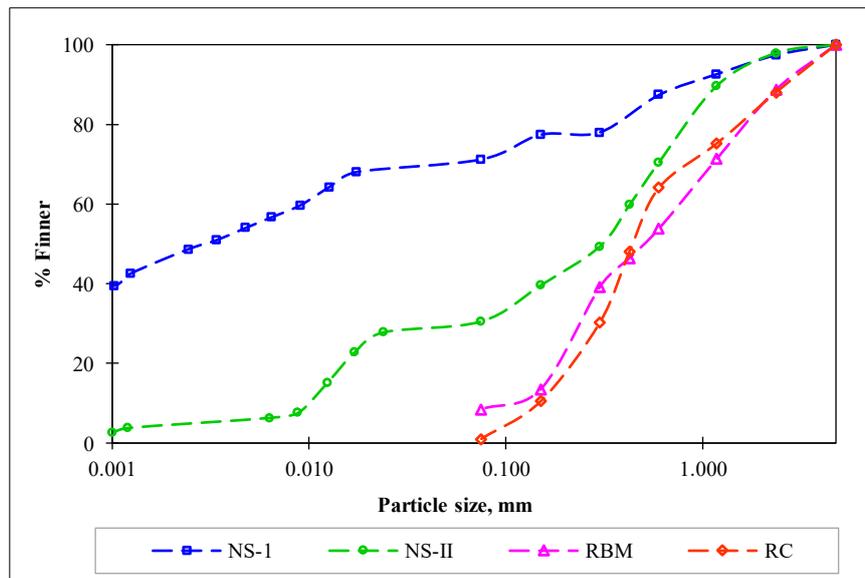

Figure 2. Particle size distribution curve of soil, RC and RBM

4. Methodology

In the present study, FSAB was produced in two phases. In phase-1, FSAB-1 was produced using RBM, RC, and NS. Whereas in phase-2, along with basic constituents, a chemical admixture, namely a surface-active plasticizing agent (SAPA), was used and termed as FSAB-2. Similar to conventional SAB, a non-modular size of a 230 × 150 × 100 mm mold was used to produce FSAB. The following sections discuss the selection of mix proportions and the detailed experimental evaluation of FSAB.

4.1. Selection of Mix Proportion

Trials were conducted to optimize the mix proportions using NS, RC, RBM, cement, and water based on flow characteristics. The optimum flow considered was in the range of 110 to 145% for all mixes and was measured as per Indian Standard 5512, 1983 [37]. These flow values are within the recommended range as suggested by ASTM D6103,

2017 [38], which facilitates workability and consolidating characteristics of the mix when poured into molds, eliminating the necessity of pugging the flowable cementitious matrix. In addition, this flow value aligns with those reported in earlier investigations, highlighting it as an adequate criterion for achieving self-consolidating earthen mixes without segregation and bleeding [39]. Conventionally, a cement content between 6 to 12% is sufficient to achieve the compressive strength of SAB for load-bearing masonry, as recommended by the Indian standard code of practice [40, 41]. In the present study, a total of six mix proportions were investigated with 12% cement by weight of FSAB mix. The utilization of SAPA in flowable mixes improves the flow characteristics, achieving the specified flow at a lower water content. The percentage reduction in water content ranged from 4.58 to 7.08%. The optimized mix proportions considered in this study are listed in Table 2. The variations in flow characteristics obtained during the trial studies are presented in Figures 3 to 5.

Table 2. Optimized mix proportion of constituent materials for FSAB used in the present study

Phase	Block type	Free w/c ratio	C (kg/m³)	FA (kg/m³)	W (kg/m³)	SAPA (kg/m³)
I (FSAB-1)	FSAB - RBM	1.56	235	1335	371	
	FSAB - RC	1.48	237	1363	352	-
	FSAB - NS (I)	1.91	225	1200	450	
II (FSAB-2)	FSAB – RBM*	1.43	236	1415	354	3.53
	FSAB – RC*	1.33	235	1412	333	3.54
	FSAB - NS (II)*	1.80	219	1200	418	3.27

| Flow (%) = 24 | Flow (%) = 48 | Flow (%) = 145 |
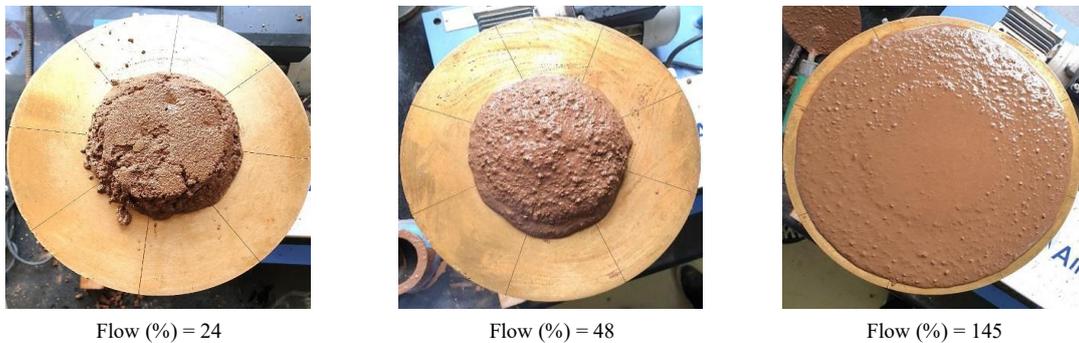
Figure 3. Flow variation of flowable mixes using RBM as per IS: 5512 – 1983

| Flow (%) = 29 | Flow (%) = 55 | Flow (%) = 140 |
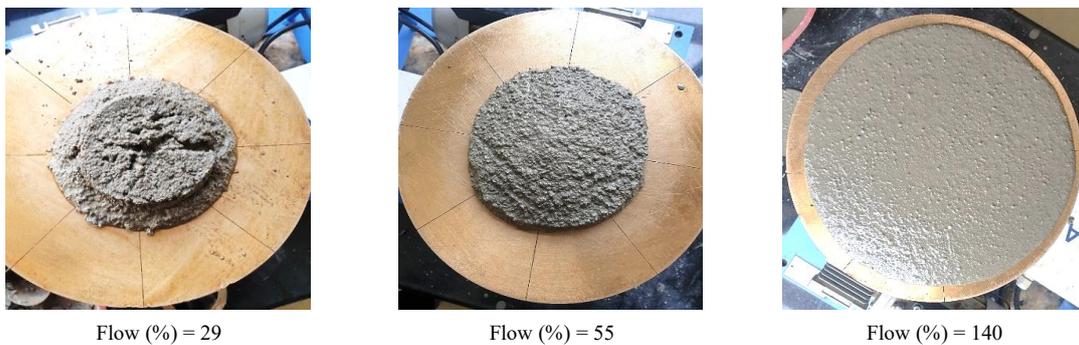
Figure 4. Flow variation of flowable mixes using RC as per IS: 5512 – 1983

| Flow (%) = 5 | Flow (%) = 45 | Flow (%) = 125 |

Figure 5. Flow variation of flowable mixes using NS-I as per IS: 5512 – 1983

4.2. Production of Controlled Flow Stabilized Adobe

The stepwise procedure adopted for the production of FSAB is shown in Figure 6.

Figure 6. Sequence of process in the Production of FSAB

4.3. Experimental Evaluation

The developed FSAB was assessed for its physical, absorption, mechanical, and durability characteristics. Physical characteristics evaluated include block density, dimensional stability, and linear shrinkage. Initial rate of absorption (IRA), rate of absorption, water absorption (WA), and capillary rise tests were conducted to determine the absorption characteristics of FSAB. Mechanical characteristics, viz., compressive strength, were determined in accordance with Indian Standard 3495, 2019 [42]. Alternate wetting and drying test were performed to evaluate durability characteristics of FSAB. A set of three specimens was cast for each mix and test. The experimental investigation was carried out as per the procedures specified by the Indian standard code of practice.

Density

The density of FSAB was tested as per Indian Standard 1725, 2023 [41] under two conditions, namely saturated and dry. The blocks after the respective curing periods were immersed in water for about 24 hours and weighed to measure the saturated density of FSAB. Whereas dry density was noted after 24 hours of drying of FSAB in a thermostatically controlled oven.

Dimensionality

Dimensional stability of the FSAB was evaluated following the guidelines mentioned in the Indian standard code of practice [41, 43]. The dimensions were measured in all three directions (length × width × depth), and the mean dimensions were precisely recorded to confirm the dimensional stability of FSAB.

Initial Rate of Absorption (IRA)

IRA was carried out as per ASTM C67 [44]. The IRA of the blocks was evaluated by immersing them in a tray filled with water to a film depth of 3 mm for a period of one minute. Blocks were weighed to determine the initial rate of absorption of FSAB and expressed in kg/m²/min. The IRA of the FSAB samples is shown in Figure 7.

Rate of Absorption & Water Absorption

The rate of absorption signifies the saturation of blocks required to achieve adequate bonding with mortar during masonry construction [45]. To determine the rate of absorption, the oven-dry FSAB was submerged in water for various time intervals: 1, 2, 5, 10, 15, 30, 45, 60, 120, 240, and 1440 minutes. The maximum absorption corresponding to complete saturation was measured after 24 hours of immersion. The water absorption test was conducted following Indian Standard 3495, 2019 [42].

Capillary Rise

The capillary rise within the blocks was assessed by placing the specimens in a tray with a 2.5 cm depth of water. The rise in moisture level in blocks was measured at different locations on each side at 1, 5, 10, 20, and 30 minutes. Figure 8 shows the maximum capillary rise of the FSAB.

Saturated Compressive Strength

Compressive strength was conducted in accordance with Indian Standard 3495, 2019 [42]. The FSAB was immersed for a duration of 24 hours to ensure complete saturation before testing. An axial load was applied at a constant loading rate of 14 MPa/min. Figure 9 illustrates the failure pattern of FSAB.

Alternate Wetting and Drying

Durability characteristics, such as alternate wetting and drying tests, were conducted on FSAB to determine the loss of mass and dimensional stability for 12 successive cycles of saturation and drying. Specimens were soaked in water for 24 hours and dried in a thermostatically controlled oven for 24 hours. The mean dimensions and weights of the blocks were recorded after each cycle. The percentage of weight loss and variations in dimensions were recorded after every cycle. This test was conducted in accordance with Indian Standard 1725, 2023 [41].
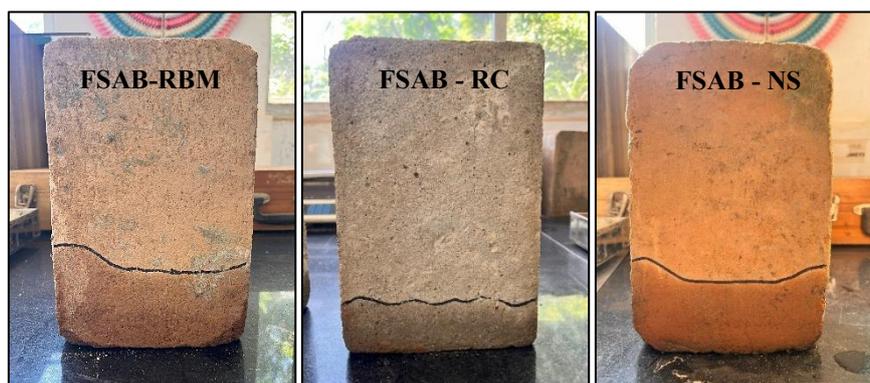

Figure 7. Initial absorption level of FSAB

Figure 8. Capillary rise of FSAB

Figure 9. Failure pattern of FSAB prepared with RC-based composite

5. Results and Discussion

The characteristics of FSAB were evaluated at the age of 7 and 28 days. The experimental results of FSAB are discussed in the following subsections.

5.1. Physical Characteristics

Block Density

The density of FSAB was measured under saturated and dry conditions. The densities of FSAB-1 exhibited values ranging from 1872 to 1975 kg/m³ (saturated) and 1604 to 1796 kg/m³ (dry) at 28 days of aging period. In contrast, block density incorporating SAPA (FSAB-2) ranged from 1818 to 1965 kg/m³ (saturated) and 1652 to 1828 kg/m³ (dry). A slight increase in density was noted with the utilization of the admixture (for FSAB-2), which might be due to better cohesion or plasticization, facilitating denser, proper particle distribution with reduced air voids. Additionally, a pore space factor, 'χ,' was identified, viz., a ratio of the difference in densities (saturated-dry) to its dry density. Compared to FSAB-1, a reduction in a factor by 27.6% (RBM), 27.0% (RC), and 39.85% (NS) was observed for SAPA-based FSAB, highlighting a reduction in water-accessible pore space with utilization of the admixture and lowered water content in the composites. The dry density of FSAB made with RC and RBM meets the minimum density criteria of soil-cement blocks as recommended by Indian Standard 1725, 2023 [41], indicating adequate structural integrity. However, FSAB made with natural soil was less than the recommended value (< 1750 kg/m³). The lower density of NS-based FSAB might be due to the presence of fine-sized particles and an increased w/c ratio influencing packing density and interparticle interaction within the mix. The densities of both FSAB obtained in the current investigation were similar to those of SAB prepared using the conventional method [46, 47]. Figures 10a and 10b show the dry densities of FSAB for different age periods and variations in accessible pore space of FSAB.
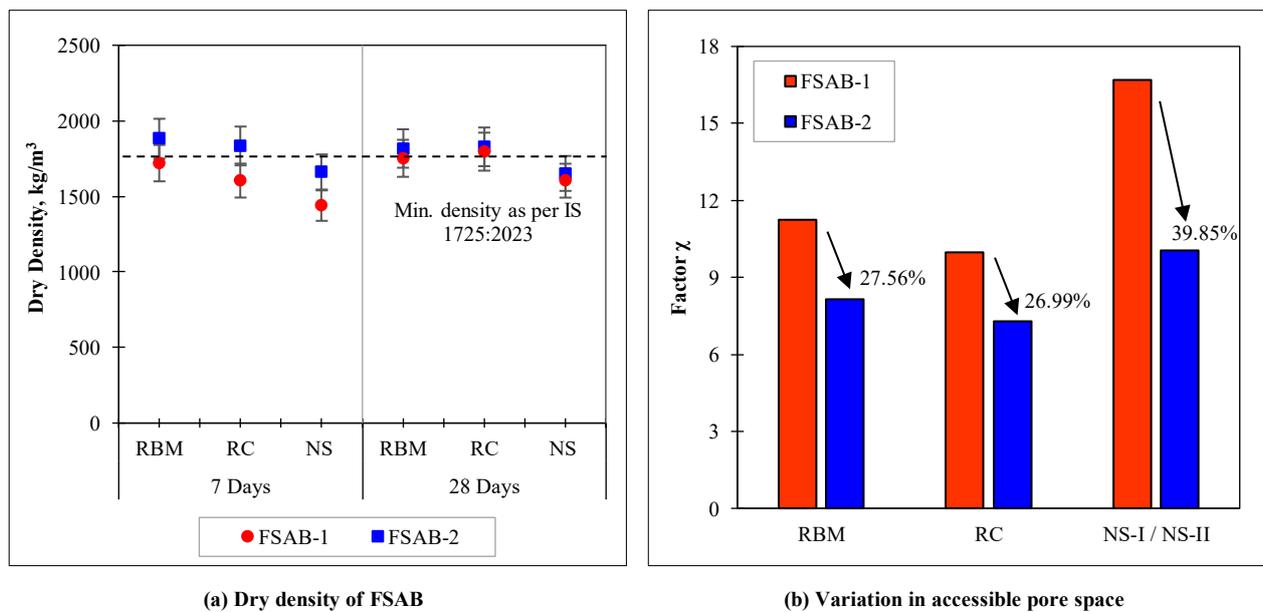

| (a) Dry density of FSAB | (b) Variation in accessible pore space |

Figure 10. Dry density and variation in accessible pore space of FSAB

Dimensional Stability & Linear shrinkage

Dimensional variations of FSAB made with RC, RBM, and NS was found to be less than ±2% along the length, breadth, and thickness. These variations were well within the permissible limits suggested by Indian Standard 1725, 2023 [41].

Linear shrinkage was assessed by measuring the variation in thickness of FSAB in fresh and hardened states. The mean linear shrinkage was 0.32 to 1% and 0.18 to 0.54% for FSAB-1 and FSAB-2, respectively. The maximum value of linear shrinkage was observed for NS-based FSAB due to the presence of clay-sized particles. The obtained shrinkage values were well within the permissible limits (< 10 %) reported in the literature [48, 49].

5.2. Absorption Characteristics

Initial Rate of Absorption

CDW (RC & RBM) based FSAB showed the lowest absorption rate at different curing periods, indicating a denser mix. Compared to NS-based mixes, the reduction in IRA ranged from 41.50 to 49.71% with RBM-based mixes and 61.00 to 61.14% for RC-based mixes at 7- and 28-day curing periods. This reduction in IRA is due to increased density and pore packing in the block. These values are consistent with the use of admixture (FSAB-2), indicating improved cohesiveness in the fresh state (indicated by a lower water requirement) and hydration reaction upon aging, which tends to reduce the pathway for capillaries, thereby enhancing pore connectivity in the composites. On the other hand, NS-based FSAB (both types) exhibited the highest initial rate of absorption (IRA), ranging from 1.59 to 1.87 kg/m²/min. This is attributed to the presence of higher plasticity characteristics in NS-based FSAB, revealing a higher demand for mixing water and increased capillary pathways upon drying. These observations are consistent with the density characteristics reported previously, indicating that lower-density composites could enhance capillary action in the composites [50]. However, the IRA obtained for FSAB was within the permissible values reported in literature [45, 51]. Figure 11 shows the variation in IRA of FSAB.
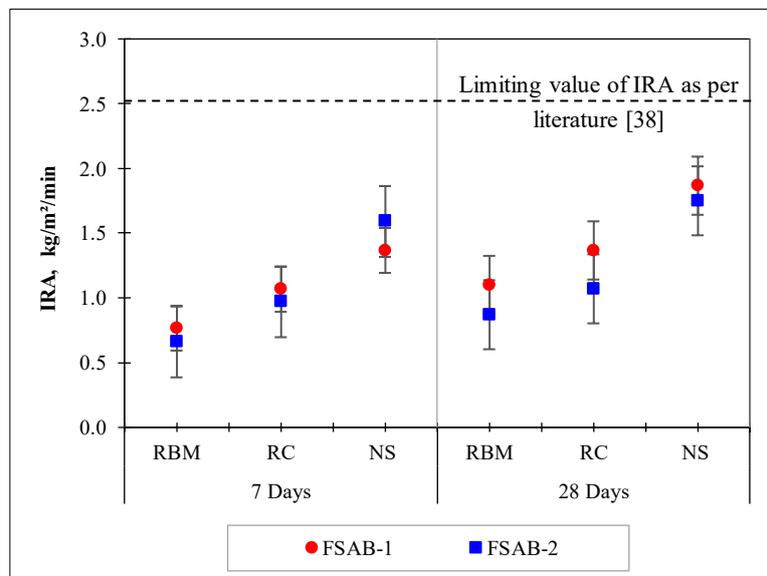

Figure 11. Initial rate of absorption of FSAB

Water Absorption

The water absorption (WA) characteristics of FSAB are within the permissible limits as suggested by Indian Standard 1725, 2023 [41]. The maximum WA values were noted for NS-based composites with 16.71% (FSAB-1) and 10.03% (FSAB-2). This decrease in WA is predominantly governed by changes in soil composition, affecting packing density and pore connectivity rather than the effectiveness of admixture alone. This aligns with the previous studies, which indicates that deviations in optimal composition adversely affect the characteristics of soil-based blocks [6, 52]. On the other hand, utilization of CDW (RBM and RC) for FSAB resulted in 26 to 44% reduction in WA compared to NS-based composites. A variation of 12 to 32% was observed in WA of FSAB made with RC and RBM. This indicates that, despite higher water absorption characteristics associated with recycled CDW, better control of hardened capillary network restricting the pathway for moisture movement was noted for CDW-based FSAB. These results are in good agreement with those reported by Kumar et al. [53], indicating that utilization of CDW satisfied the acceptable absorption criteria. It is interesting to note that CDW-based FSAB follows a positive trend representing improved packing density (indicated by enhanced dry density) and pore connectivity (indicated by reduced IRA) resulting in lower WA characteristics. Figure 12 shows the variation in water absorption of FSAB.
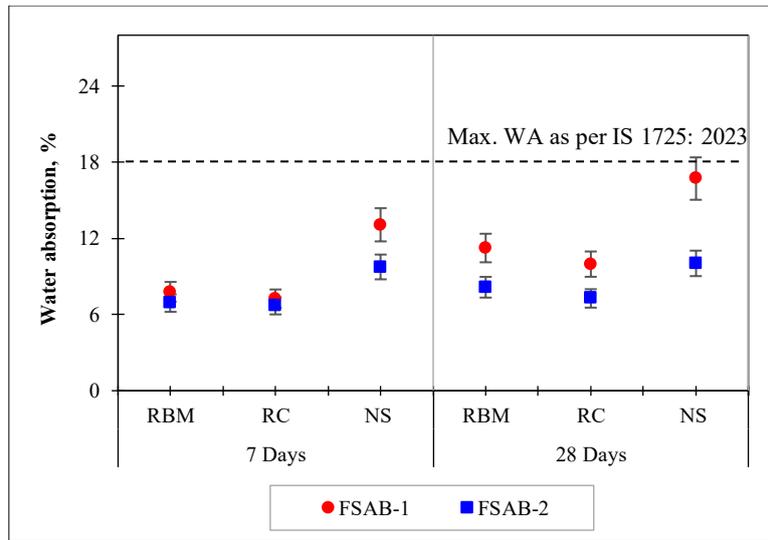
Figure 12. Water absorption of FSAB

Capillary Rise

The phenomena of capillary rise in FSAB indicates the upward movement of water in blocks when immersed in a tray with a consistent water level of 2.5 cm. The behavior of capillary rise in FSAB is influenced by various parameters, such as the block density, pore structure, grain size distribution, stabilizer content, and environmental exposure. The capillary rise in FSAB (both types) was lower than that in conventional masonry units, namely burnt-clay bricks, indicating a less porous structure, block homogeneity, and dense matrix. The maximum capillary rise was measured on a burnt clay brick sample approximately 7.36 cm after 60 minutes of immersion. On the other hand, the FSAB measured capillary rise in the range of 1.60 to 4.77 cm, 1.45 to 3.55 cm, and 2.00 to 5.27 cm for RBM, RC, and NS-based mixes (FSAB-1 and FSAB-2), respectively. The percentage reduction in capillary rise of various mixes compared to burnt clay bricks ranged from 46.41% to 80.29% (FSAB-1) and 15.76% to 51.766% (FSAB-2). This improved performance of FSAB is due to its higher density. NS-based FSAB exhibited a noticeable increase, followed by conventional burnt-clay brick. This increase in capillary rise is attributed to the low density of blocks, which represents a more porous structure. However, the capillary rise observed in FSAB is in good agreement with the results reported by Joshi [47]. Figure 13 shows the capillary rise of FSAB with various mixes.
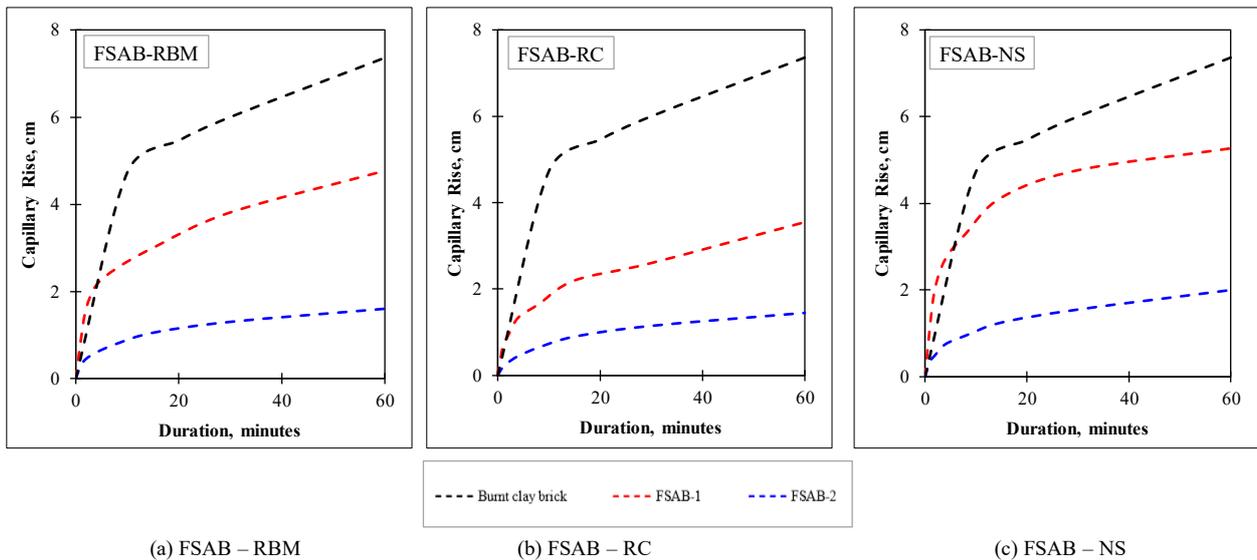

| (a) FSAB – RBM | (b) FSAB – RC | (c) FSAB – NS |

Figure 13. Capillary rise of FSAB

Rate of Absorption

The rate of absorption was conducted to determine the rate at which the FSAB absorbs water when immersed completely, and measurements were taken at definite time intervals. Figure 14 illustrates the rate of absorption of FSAB with various mixes. The percentage absorption of blocks prepared with RBM and RC-based mixes (both types of FSAB) was more than 60% when the range of immersion period was between 45 and 60 minutes. For NS-based mixes (FSAB-1), the first 10 to 15 minutes of immersion resulted in 60% block saturation. This is due to the presence of clay-sized

particles and a lower density of blocks, resulting in increased permeability and absorption rates. After an immersion period of 240 min, the saturation of FSAB prepared with various flowable mixes was approximately 90% across different age periods.
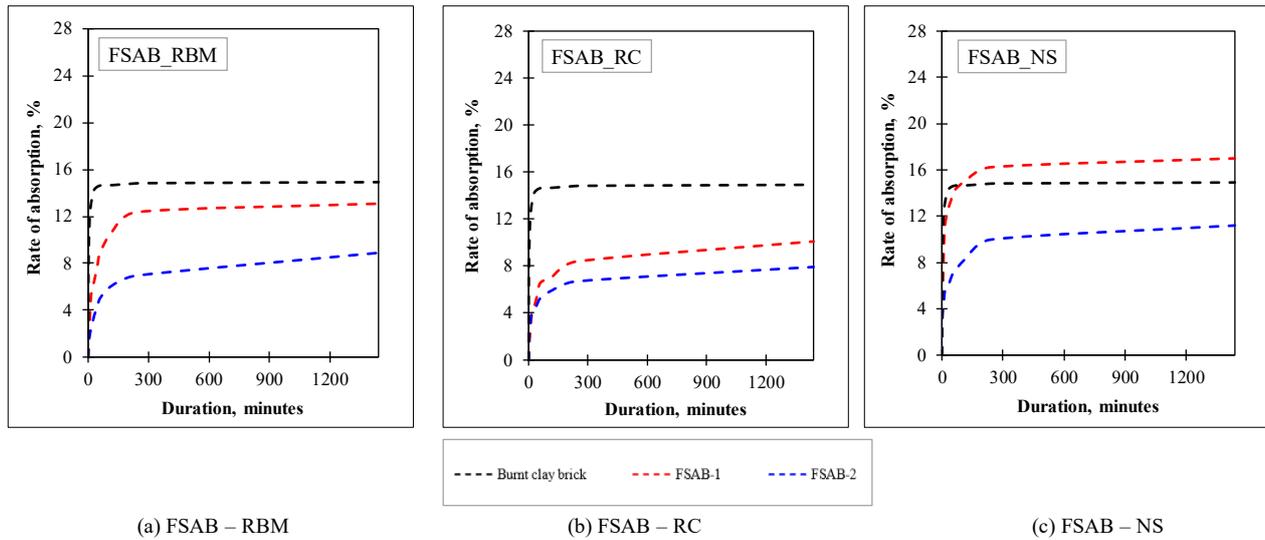

(a) FSAB – RBM   (b) FSAB – RC   (c) FSAB – NS

Figure 14. Rate of absorption of FSAB

5.3. Mechanical Characteristics

Saturated Compressive Strength

An FSAB with dimensions of 230 x 150 x 100 mm was tested to evaluate saturated compressive strength (SCS) at 7 and 28 days of curing. The 28-day SCS of RC, RBM, and NS-based FSAB-1 was 8.41, 7.74, and 4.34 MPa, respectively. FSAB-2 resulted in SCS of 10.22, 8.27, and 6.13 MPa for RC, RBM, and NS-based composites, respectively. FSAB attained 50 to 77% strength after 7 days of curing. The maximum wet compressive strength was observed for the RC-based FSAB. The percentage increase in compressive strength of RC-based FSAB ranged from 66.76 to 93.73% compared to NS-based FSAB. Similarly, an increase in the order of 35 to 78.43% was observed for RBM-based FSAB. The lowest value of SCS was found for NS-based FSAB-1. This lowered strength was due to increased clay fraction and water content. Nevertheless, blocks with NS-based FSAB-2 (incorporating SAPA) satisfied the minimum strength criteria of Class 3.5 soil-based blocks as suggested by Indian Standard 1725, 2023 [41]. These observations are consistent with those of soil-based blocks, where soil with higher plasticity characteristics exhibits lower strength gain but is enhanced significantly with adequate optimized gradation, curing, and stabilization techniques [6]. In contrast, RBM and RC-based FSAB (both types) meet the minimum strength criteria of Class 5 soil-based blocks. The results obtained are higher than those obtained by the conventional method of SAB, i.e., 3.04 to 5.37 MPa for the attainment of maximum strength [20, 46]. Figure 15 shows the variation in SCS of FSAB for various age periods.
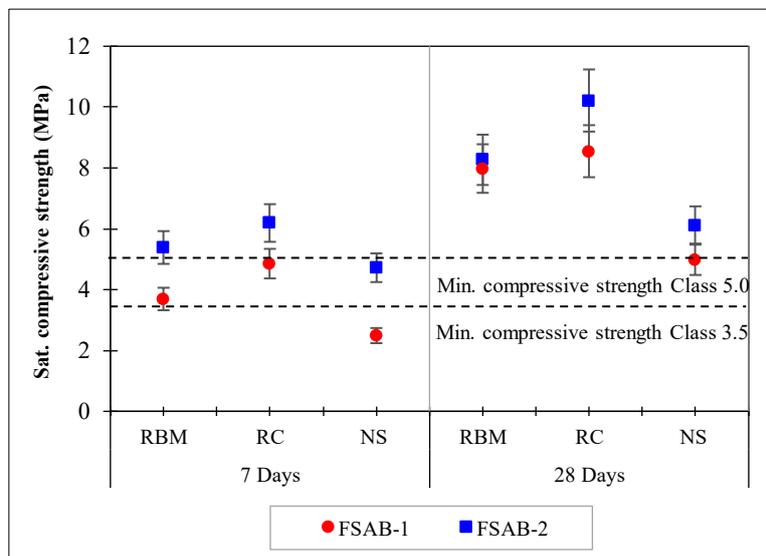

Figure 15. Saturated compressive strength of FSAB

5.4. Durability Characteristics

Alternate Wetting and Drying

FSAB was subjected to extreme saturation conditions for 12 cycles by alternate wetting and drying to measure the effect of mass loss. It was observed that, among the various mixes, blocks prepared with NS-based mixes exhibited a maximum loss of mass in the order of 2.99% (FSAB-1) and 2.68% (FSAB-2). This might be due to the presence of higher clay fractions, resulting in higher water demand and low density along with porous structure. A minimum mass loss in the order of 1.86% was noted for RC-based FSAB. The experimental results obtained were within the permissible limits specified by the Indian standard code of practice [41]. Figure 16 illustrates the percentage mass loss of FSAB.
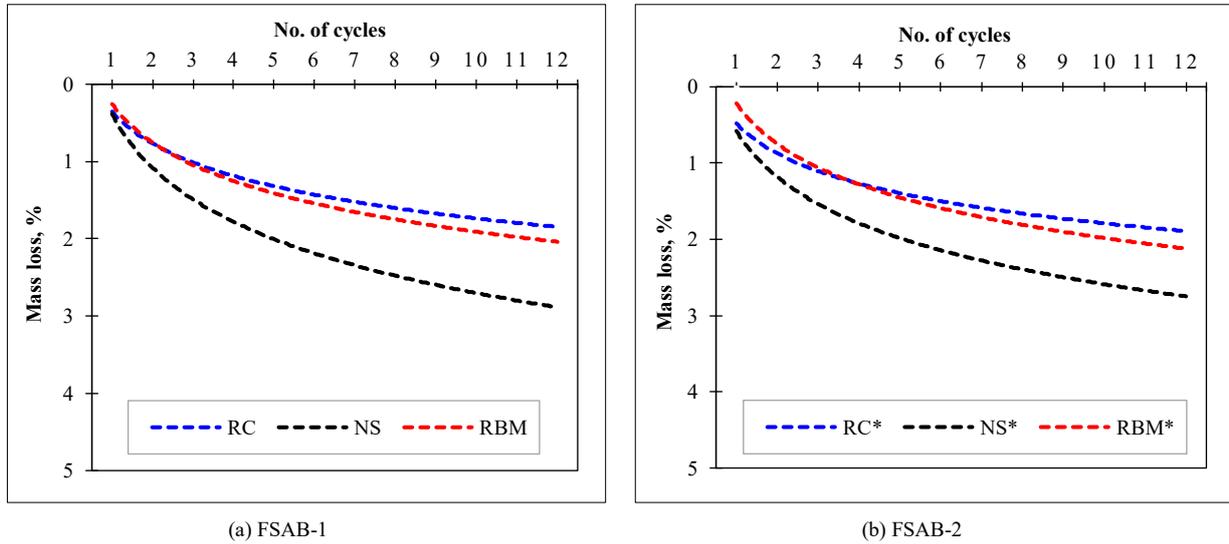

| (a) FSAB-1 | (b) FSAB-2 |

Figure 16. Mass loss of FSAB

5.5. Correlation between FSAB Characteristics & Reliability Analysis

Dry Density versus Saturated Compressive Strength

A correlation between dry density and saturated compressive strength was conducted to determine the densification of the mix contributing to the mechanical characteristics of FSAB mixes as shown in Figure 17. Similar to conventional adobe, an increase in the density of FSAB resulted in higher compressive strengths. The maximum density and compressive strength characteristics were observed for the RC-based composites. A ratio was identified to arrive at optimal characteristics with dry density to saturated compressive strength and was found to be in the range of 179 to 197. On the other hand, Figure 17b represents the variation of FSAB density and SCS. A positive incremental rate of SCS values with increasing density was noted for both types of FSAB. FSAB-1 and FSAB-2 showed R^2 values of 0.99 and 0.82, respectively. Every 5% increase in dry density resulted in a 0.85 to 0.87 times increase in the SCS of FSABs.
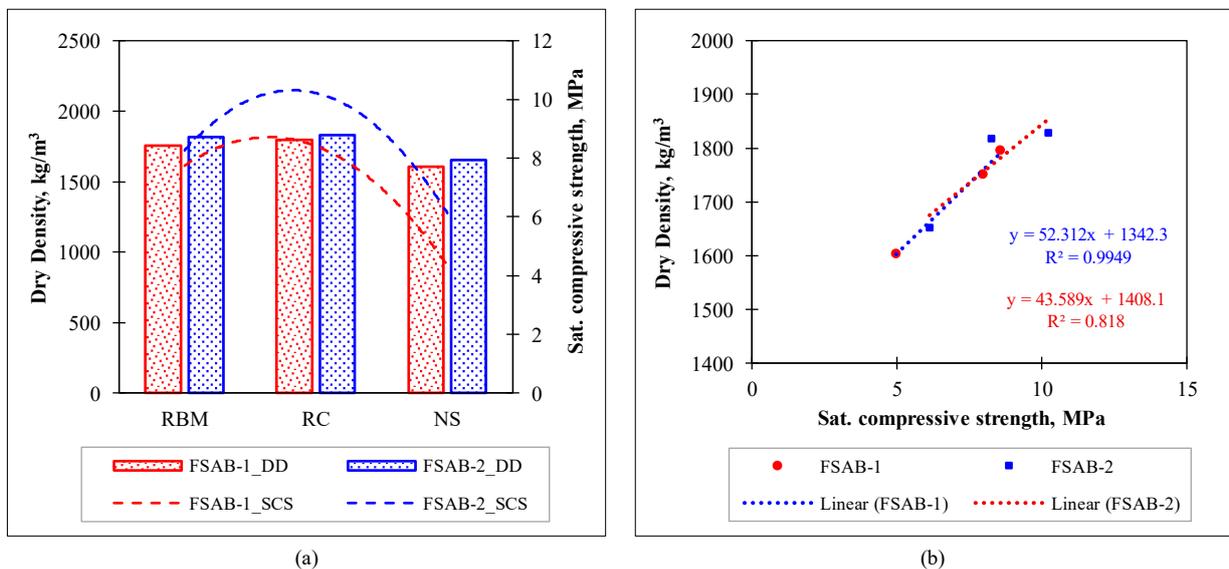

| (a) | (b) |

Figure 17. Relation between Dry density and SCS of FSAB

Dry Density versus Water Absorption

It was noted that higher densities of FSAB resulted in lower water absorption characteristics, as presented in Figure 18. The lowest water absorption was observed for the RC-based composites. The results obtained within the limiting values specified by Indian Standard 1725, 2023 [41]. From Figure 18b, it was observed that every 5% decrement in dry density resulted in a 0.96 to 1.05 times increment in water absorption for FSABs. A linear relationship of dry density and water absorption revealed R^2 values ranging between 0.93 to 0.99 for both types of FSAB.
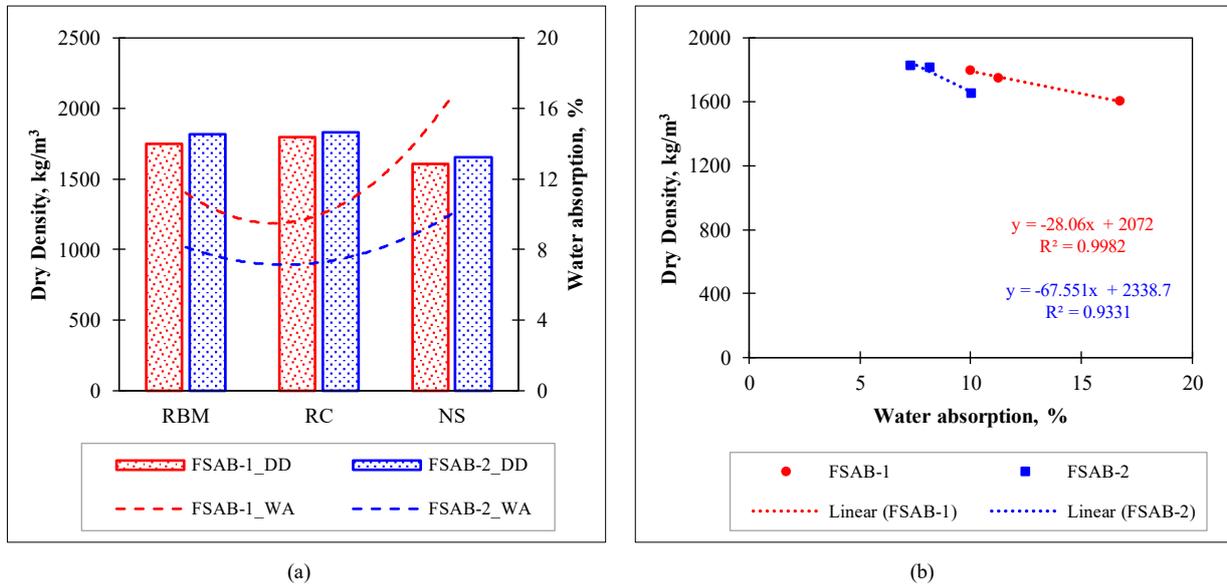

(a)

(b)

Figure 18. Relation between dry density and water absorption of FSAB

Other Influencing Factors

A correlation between the saturated compressive strength, water-cement ratio (W/C), water-fine aggregate ratio (W/Fa), and cement-fine aggregate ratio (C/Fa) of FSAB is illustrated in Figures 19a, 19b, and 19c. RC-based composites exhibited maximum strength, achieving 10.22 MPa (FSAB-2) and 8.41 MPa (FSAB-1). It is evident from Figure 19a that the higher W/C ratio resulted in lowered SCS. Recycled aggregate composites, such as RBM and RC, exhibited W/C ratios ranging between 1.33 and 1.56, whereas NS-based composites exhibited a higher W/C ratio of the order of 1.8 to 2.0. This may be attributed to the presence of clay, which requires a higher W/C ratio to achieve the required flow. Similar observations were made for W/FA and C/FA ratios of FSAB mixes. Recycled aggregate-based FSAB resulted in SCS greater than 5.5 MPa when W/FA and C/FA were 0.26±5% and 0.17±3%, respectively.

(a)

(b)
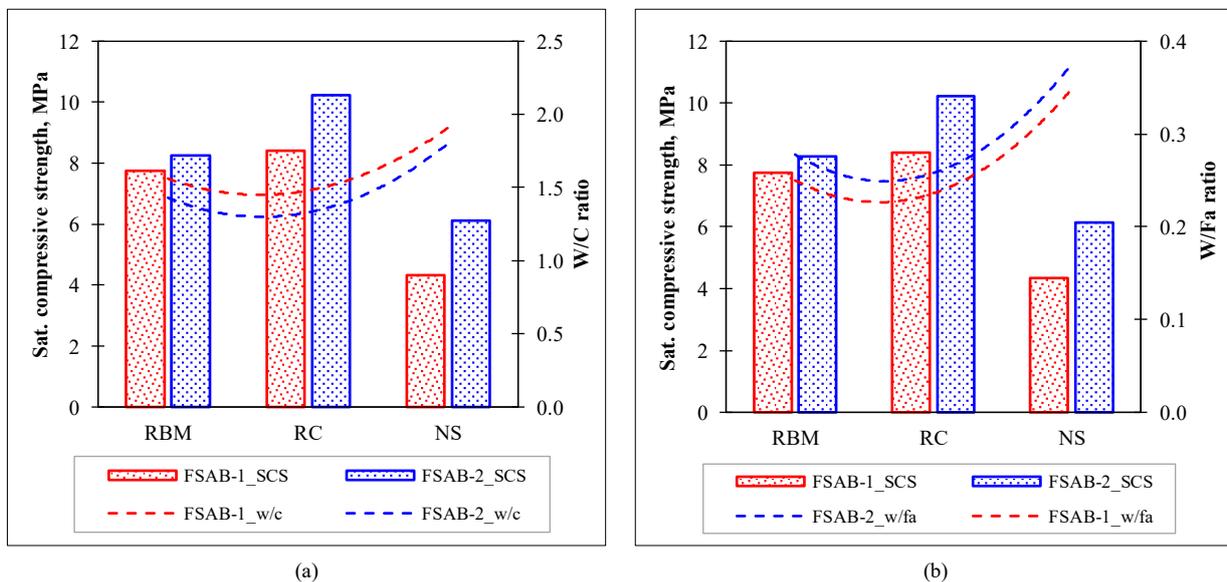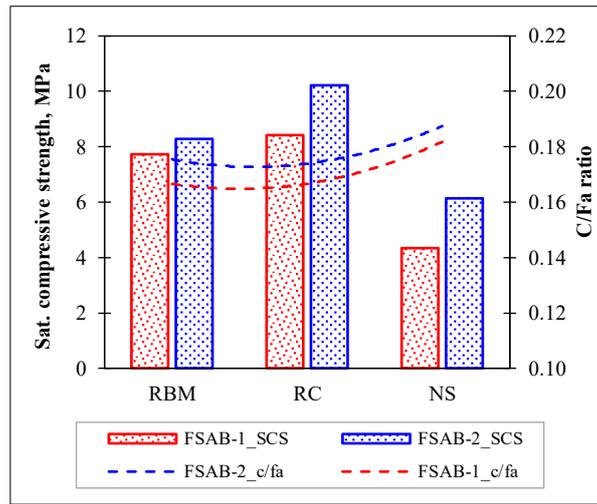
(c)

Figure 19. Relation between SCS, W/C, W/Fa and C/Fa ratio of FSAB

Reliability Analysis

The reliability analysis of FSAB was performed using statistical indicators such as mean (M), standard deviation (SD), and coefficient of variance (CoV) for the crucial physical (dry density), absorption (water absorption), and mechanical (compressive strength) characteristics. Table 3 provides statistical indicators for various characteristics of FSAB (both types) tested at 28 days of aging period. It is noted that the dry density of FSAB exhibits high uniformity among all mixes with CoV ranging from 0.33 to 0.97%, indicating consistency in mixing, casting, and pourability of mixes. On the other hand, utilization of CDW (RBM and RC) for FSAB showed variability in absorption characteristics, with CoV ranging from 8.44 to 11.58%. However, the results obtained were within the permissible limits [41]. The compressive strength of FSAB indicates notable improvement with the use of an admixture ranging from 8.55 to 10.22 MPa, although a slight increase in CoV was also noted. However, the observed CoV was less than 10%, indicating acceptable experimental consistency. Among all, CDW-based FSAB-2 showed better control over the reliability profile, consolidating better compressive strength with low variability in dry density and controlled variability associated with absorption characteristics. These results highlight the potential of CDW-based FSAB associated with consistent and enhanced structural characteristics.

Table 3. Statistical indicators for various characteristics of FSAB

Composition		Statistical indicators	Dry density (kg/m³)	Water absorption (%)	Compressive strength (MPa)
FSAB-1	RBM	Mean	1752.00	11.24	7.98
		Standard Deviation (SD)	11.14	1.13	0.13
		Coefficient of Variation (CV, %)	0.64	10.08	1.57
	RC	Mean	1796.00	9.97	8.55
		Standard Deviation (SD)	17.35	0.84	0.22
		Coefficient of Variation (CV, %)	0.97	8.44	2.60
	NS-I	Mean	1604.00	16.70	4.98
		Standard Deviation (SD)	10.44	0.66	0.38
		Coefficient of Variation (CV, %)	0.65	3.96	7.61
FSAB-2	RBM	Mean	1817.68	8.15	8.27
		Standard Deviation (SD)	15.38	0.94	0.75
		Coefficient of Variation (CV, %)	0.85	11.58	9.02
	RC	Mean	1828.89	7.27	10.22
		Standard Deviation (SD)	9.26	0.63	0.55
		Coefficient of Variation (CV, %)	0.51	8.70	5.40
	NS-II	Mean	1652.46	10.03	6.13
		Standard Deviation (SD)	5.52	0.28	0.36
		Coefficient of Variation (CV, %)	0.33	2.78	5.86

6. Sustainability Analysis of FSAB

A cradle-to-gate assessment focusing on the embodied energy (EE) and embodied carbon equivalent (EC) of FSAB was explored. The EE and EC associated with FSAB were calculated for the two phases.

Phase 1: Raw material production and transportation

This phase includes the EE and EC associated with the production and transportation of raw materials, such as cement (C), recycled concrete (RC), recycled brick masonry (RBM), natural soil (NS), and water used in the FSAB.

Phase 2: Manufacturing

This phase includes the EE and EC associated with the manufacturing process, such as mixing, casting, and curing. The EE and EC assessments were based on widely used relationships, as shown in Equations 1a and 1b [54].

Embodied energy = ($Ø_{Ei}$) × Quantity of material consumption (Q_i) (1a)

Embodied carbon=Carbon emission co-efficient ($Ø_{Ci}$) × Quantity of material consumption (Q_i) (1b)

The energy and carbon coefficients for conventional materials, such as natural soil, cement, and water, were obtained from a database corresponding to the Indian context [55, 56]. For recycling construction and demolition waste (RC and RBM), a laboratory-based jaw crusher with a capacity of 1 HP and a crushing rate of 10 to 500 kg per hour was considered. The transportation distance from the demolition site to the laboratory was 15 km. The EE and EC coefficients considered in this study are presented in Table 4. For the mixing process in the manufacturing phase, a 5 HP pan mixer with a mixing capacity of 150 to 300 kg was used. The mixing duration for the raw materials was fixed at 10 min. The total EE and EC are the cumulative EE and EC yielded per phase per type of FSAB, respectively.

Table 4. Energy and Carbon coefficients of materials used in the present study

Raw materials	$Ø_{Ei}$ (MJ/kg)	$Ø_{Ci}$ (kgCO$_2$/kg)	Reference
Natural soil	0.022	0.00165	Maini & Thautam (2013) [55]
Recycled concrete	0.054	0.0018	Current study
Recycled brick masonry	0.038	0.0014	Current study
Cement	4.60	0.83	Maini & Thautam (2013) [55]
Water	0.01	0.001	-

* Øei and Øci tabulated considers a transportation distance of 20km, 15km, and 150km for NS, RC/RBM and Cement respectively

The EE and EC of FSAB were in the range of 4.11 to 4.57 (MJ/block) and 0.72 to 0.80 kgCO₂e/block, respectively. The embodied energy and embodied carbon of various masonry units are shown in Figure 20. It should be noted that FSAB prepared with flowable mixes exhibited higher EE and EC values than those of conventional SAB. This is attributed to the increase in stabilizer content (up to 12%); however, these values were lower than those of burnt clay and country-fired bricks, which are widely used as masonry units. The net savings in EE and EC with respect to the brick equivalent are shown in Figure 21.
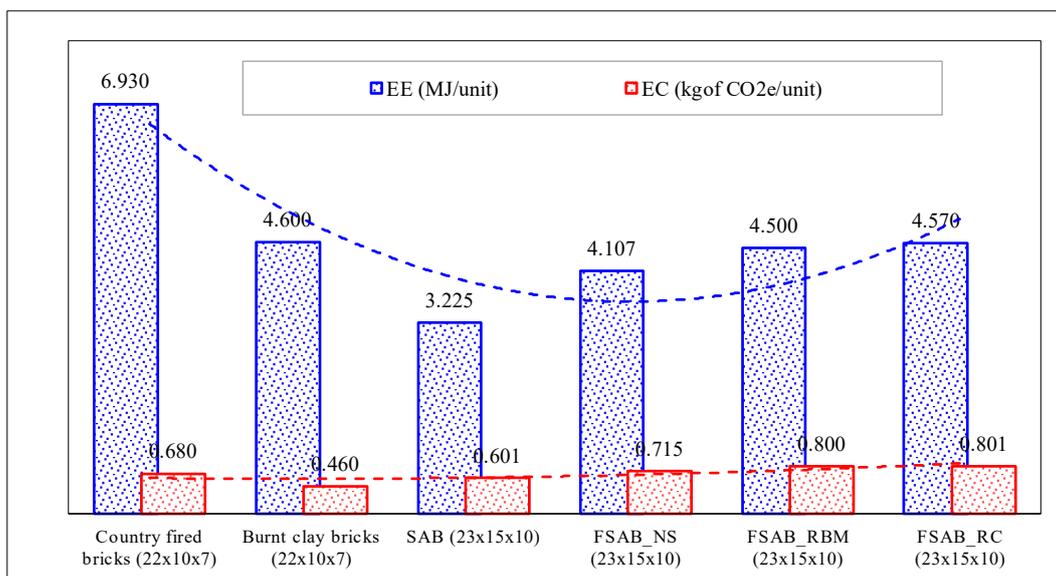

Figure 20. Embodied energy and embodied carbon of FSAB and other conventional masonry units

(a) Embodied energy   (b) Embodied carbon equivalent
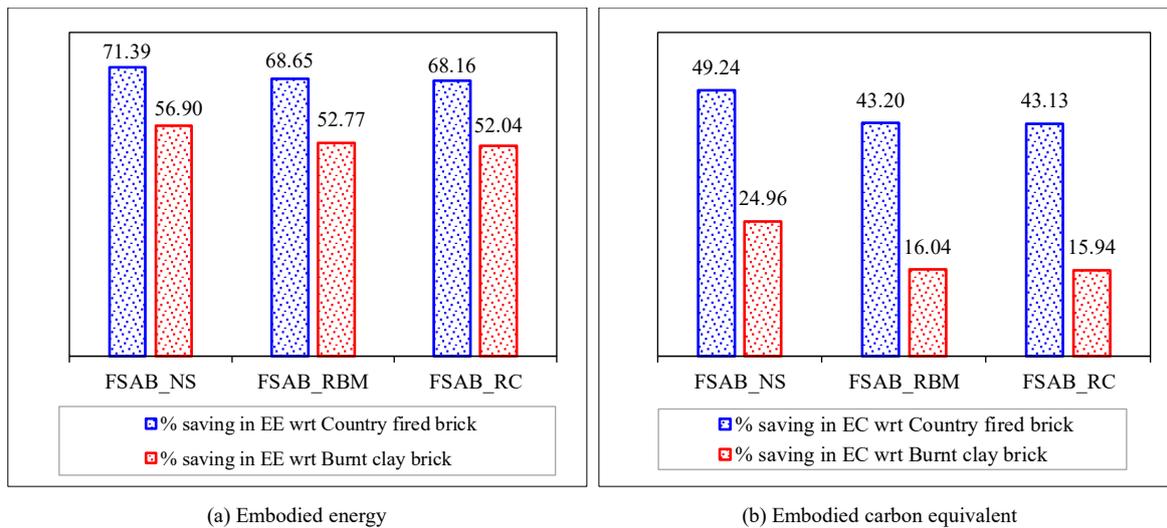
Figure 21. Net saving in EE and EC with respect to Brick equivalent (Country fired and Burnt clay brick)

The present study also highlights the influence of parameters, such as embodied energy per unit strength (E_f), embodied carbon per unit strength (C_f), and structural efficiency (SE), on the environmental impact corresponding to their strength characteristics [57, 58]. The ratio of compressive strength to dry density of units is defined as structural efficiency (SE). It is noted that FSAB prepared with recycled aggregate-based mixes exhibited the least E_f and C_f values, ranging from 0.45 to 0.54 and 0.08 to 0.10, respectively. Correspondingly, the conventional blocks, namely SAB and burnt clay brick, exhibited values ranging from 0.6 to 1.16 and 0.11 to 0.12, respectively. In contrast, the structural efficiency factor for FSAB prepared with recycled aggregate-based mixes showed a maximum value ranging from 4.22E-03 to 5.60E-03. This indicates the potential of RC/RBM-based FSAB as a substitute for conventional masonry units with enhanced structural performance. The variation in these values highlights the broad range of possibilities for FSAB incorporating recycled aggregate mixes as an efficient masonry unit. Figure 22 shows the variations in E_f, C_f, and SEE of FSAB and other conventional masonry units.
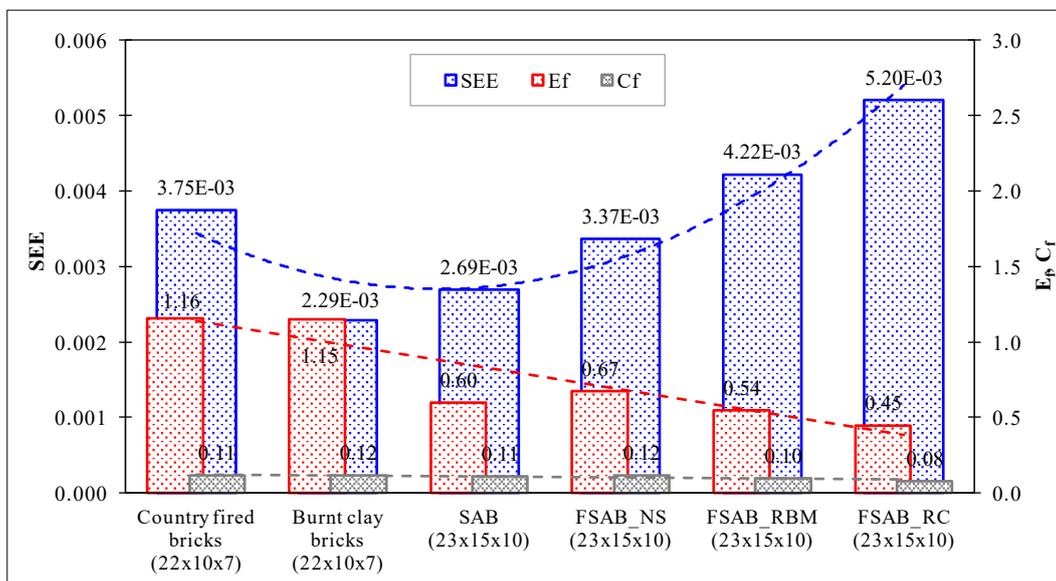

Figure 22. Variation of SEE, E_f, and C_f various masonry units

7. Comparison of FSAB by Conventional SAB

The characteristics of SAB produced using conventional methods, that is, by incorporating a kneading or pugging process, have been widely explored. In the present study, FSAB was produced by incorporating CDW, that is, recycled concrete and brick masonry waste, and locally available soil as a fine aggregate, and its strength characteristics were compared with those of conventional SAB. Table 5 presents the compressive strength of SAB produced by the conventional method with the range of constituents and cement content explored by various researchers. It was noted that an increase in the clay content resulted in a decrease in the compressive strength of SAB. A similar observation was noted for FSAB prepared with a combination of mixes. Despite the variations in the optimum soil gradation suggested by various researchers for soil–cement blocks, FSAB prepared with flowable mixes achieved higher compressive strength (>3.5 MPa) for all mixes. The increment in strength may be due to the increased cement content, utilization of

recycled aggregate, and chemical admixture. The incorporation of recycled aggregate in FSAB exhibited increased packing density, a more uniform and denser microstructure, and enhanced strength characteristics of FSAB.

Table 5. Comparison of compressive strength of conventional SAB prepared with various soil compositions and cement contents with FSAB

Block type	Sand (%)	Fines (%)	Clay (%)	Cement (%)	Compressive strength (MPa)	References
SAB	61.60	38.40	21.70	4-8%	0.99-4.42	Reddy et al. (2007) [59]
	68.30	31.70	16.30		3.14-5.73	
	76.00	24.00	10.90		2.77-4.99	
	83.70	16.30	5.40		2.64-4.54	
SAB	41.51	58.49	19.50	9%	3.04	Joshi et al. (2019) [20]
	54.56	45.44	14.20		3.36	
	61.78	38.22	8.00		4.34	
	68.18	31.82	6.00		5.23	
	69.08	30.92	6.00		5.37	
	72.56	27.44	5.00		5.15	
	80.96	19.04	2.00		3.80	
SAB	71.00	29.00	10.00	10%	7.48	Bharadwaj (2017) [60]
	61.00	39.00	15.00		5.47	
	50.58	49.42	20.00		3.62	
	71.00	29.00	10.00		6.33	
	61.00	39.00	15.00		4.79	
	50.58	49.42	20.00		3.67	
	91.47	8.53	2.00		7.98	
	29.00	71.00	47.00		4.98	
FSAB	98.94	1.06	-	12%	10.22	Current study
	91.47	8.53	2.00		8.27	
	69.47	30.53	3.00		6.13	

8. Conclusions

This study provides a detailed experimental investigation of novel controlled flow stabilized adobe using CDW, such as recycled concrete and recycled brick masonry waste, as a full-scale substitute for natural soil. In addition, the influence of surface-active plasticizing agents on characteristics of FSAB was explored. Based on the investigation conducted, the following conclusions were drawn.

- The physical characteristics of CDW, such as recycled concrete and recycled brick masonry waste, indicate its potential as a full-scale substitute for natural soil in the development of FSAB. Block density, dimensional stability, and linear shrinkage were well within the permissible limits.

- The absorption characteristics of FSAB indicated a homogeneous structure with enhanced pore packing density, except for those prepared with NS-based composites. Incorporation of surface-active plasticizing agent enhanced the absorption characteristics of FSAB.

- The mechanical characteristics of FSAB, viz., saturated compressive strength, prepared with CDW byproducts, meet the minimum strength criteria of Class 5 soil-based blocks as suggested by IS 1725:2023. Blocks with NS-based FSAB (with SAPA) satisfied the minimum strength criteria for Class 3.5 soil-based blocks.

- The durability characteristics of FSAB indicated no substantial visible damage or loss in mass for the blocks prepared with CDW. However, maximum loss of mass in the order of 2.99% (FSAB-1) and 2.68% (FSAB-2) was noted for NS-based FSAB.

- Influencing factors such as W/FA and C/FA of order 0.26±5% and 0.17±3%, respectively, resulted in saturated compressive strength greater than 5.5 MPa.

- The EE and EC of FSAB were in the range of 4.11 to 4.57 (MJ/block) and 0.72 to 0.80 $kgCO_2e$/block, respectively. This exhibits significant savings in EE (52.04 to 71.39%) and reduction in EC (15.94 to 49.24%) compared to conventional masonry units.

- Environmental indicators such as E_f, C_f, and SEE indicate the potential of CDW-based FSAB as a substitute for conventional masonry units with enhanced structural performance.

9. Abbreviations and Symbols

CDW	Construction and demolition waste	C	Cement
FSAB	Controlled flow stabilized adobe	FA	Fine aggregate
EE	Embodied energy	W	Water
EC	Embodied carbon	IRA	Initial rate of absorption
SAB	Stabilized adobe blocks	WA	Water absorption
RCA	Recycled concrete aggregates	SCS	Saturated compressive strength
RA	Recycled aggregates	W/C	water-cement ratio
RC	Recycled concrete	W/Fa	water – fine aggregate ratio
RBM	Recycled brick masonry	C/Fa	cement-fine aggregate ratio
NS	Natural soil	$\emptyset_{Ei}$	Energy co-efficient
NS-I	Natural soil from source-1	$\emptyset_{Ci}$	Carbon emission co-efficient
NS-II	Natural soil from source-2	Q_i	Quantity of material consumption
OPC	Ordinary Portland cement	E_f	Embodied energy per unit strength
SAPA	Surface active plasticizing agent	C_f	Embodied carbon per unit strength
LL	Liquid limit	SE	Structural efficiency
PL	Plastic limit	OMC	Optimum moisture content
NP	Non-plastic	MDD	Maximum dry density
χ	Pore space factor	SD	Standard deviation
M	Mean	CoV	Coefficient of variance

10. Declarations

10.1. Author Contributions

Conceptualization, M.V.R. and A.M.J.; methodology, M.I.A.; validation, A.M.J. and S.M.B.; formal analysis, M.I.A.; investigation, M.I.A.; resources, M.I.A. and A.M.J.; data curation, M.I.A.; writing—original draft preparation, M.I.A.; writing—review and editing, S.M.B.; visualization, A.M.J. and S.M.B.; supervision, M.V.R., A.M.J., and S.M.B. All authors have read and agreed to the published version of the manuscript.

10.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

10.5. Conflicts of Interest

The authors declare no conflict of interest.

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