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Compressed Stabilized Earth Block Incorporating Municipal Solid Waste Incinerator Bottom Ash as a Partial Replacement for Fine Aggregates

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Abstract: This research explores the potential of using municipal solid waste incinerator bottom ash (MSWIBA) as a partial replacement for fine aggregate and ordinary Portland cement (OPC) as a stabilizer in the production of compressed stabilized earth blocks (CSEBs). The study investigates the effect of varying levels of cement content (ranging from 0% to 10%) and MSWIBA content (ranging from 0% to 25%) on the strength and durability of CSEBs. The strength characteristics of CSEBs were evaluated through tests such as wet and dry compressive strength, flexural strength, water absorption, and stress–strain behavior, while durability was tested through wetting–drying cyclic tests. The results indicated that CSEB blocks made with 20% MSWIBA content and 10% cement were able to fulfill strength criteria. Additionally, using these blocks could result in cost savings of 8% during construction when compared to using fired clay bricks (FCB). Furthermore, varying the cement content while maintaining a constant proportion of MSWIBA showed a significant change in the stress–strain behavior and a cost analysis performed for CSEBs stabilized with the optimal quantity of MSWIBA-OPC combination showed that they can be a viable alternative to conventional earth blocks, providing an eco-friendly, sustainable, and cost-effective solution for construction initiatives.

Keywords: municipal solid waste incinerator bottom ash; sustainable cementitious material; compressed stabilized earth blocks; microstructure

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1. Introduction

Soil has been one of the primary construction elements for thousands of years. More than a third of the world's inhabitants are still living in soil dwellings. In the UK, around half a million earth houses were constructed before the 1900s and are still standing [1,2]. Nearly two-thirds of all homes in India are still constructed using soil [3,4]. Generally, in regions where the climate is hot and dry, and rain is scarce, earth has been utilized extensively for building houses [5]. Earth structures are becoming more popular nowadays because of their various environmental advantages, including low energy intensity, reduced CO_2 emissions, recycling capacity and the potential to serve as a buffer to manage humidity inside the house. Concrete blocks and burned clay bricks have been observed to emit 200 kg of CO_2 per ton and 143 kg of CO_2 per ton, respectively [6,7]. More importantly, cement manufacturing generates huge quantities of greenhouse gases, and an estimated quantity of 5% of annual production of carbon dioxide is because of cement production [8,9].

The usage of earth as a construction material is becoming more prevalent nowadays. Fired clay bricks are often used in masonry walls, but their high energy consumption and carbon dioxide emissions make them unsuitable, in addition to the growing energy cost and other associated environmental issues. Stabilized unfired clay bricks may be a sustainable solution for these issues. There are several techniques for making earth bricks, with adobe and compressed earth bricks (CEB) being the most common. Of these, CEB has proven to be particularly advantageous due to its low cost, durability, and eco-friendliness [3]. In this study, conventional earth blocks (CSB) were also considered. Compression is used to create sustainable bricks with good mechanical properties. However, not all soils are suitable for making CEB, and many researchers have resorted to modifying the soil by adding stabilizers, binders, or both [3]. This is necessary because the soil must meet specific requirements for CEB manufacturing, which may not be available in many cases. Stabilized earth seems to stand out among the environmentally friendly building materials [10]. Over the last fifty years, compressed stabilized earth blocks (CSEB) have been used for load-bearing masonry construction in various countries such as the USA, India, the UK, Brazil, Nigeria, etc. [11]. These blocks are made by pressing wet soil and an appropriate stabilizer into a high-density block with the aid of a manually operated press [12].

Environmentally friendly CSEBs possess high strength and durability with excellent thermal insulation capabilities [13]. When compared to CSEBs stabilized with lime, cement-stabilized CSEBs have better strength and durability [14]. At a cement content above 4%, CSEBs benefit from increased strength and durability [15]. At 10% cement, the strength has been observed to be twice that of 4% cement, and the quantity of cement varies with the nature of soil. A cement content above 15% has been considered uneconomical [16]. The increased cement content improves the stability, which in turn enhances the wet strength to dry strength ratio [17,18]. In the sand–clay matrix, there is the possibility that the smaller clay particles fill the voids of sand particles, resulting in an increase in density and decrease in void spaces as mentioned by Sekhar et al. (2018) [11]. Furthermore, in a study concerning the usage of crushed brick waste to produce CSEB presented by Kasinikota and Tripura (2021) [19], the CSH gel also fills up the void, making the structure impermeable and thereby increasing the rigidity of matrix [20,21].

The disposal of municipal solid waste (MSW) is a major environmental concern worldwide [22]. In 2012, around 1.3 billion tons of MSW were generated, which is estimated to become 2.2 billion tons by 2025 [23]. Incineration is often regarded as the most efficient method for recycling MSW because of its great volume reduction capability and the ability to recover energy [24]. Most of this refuse is discarded in landfills without any kind of retrieval or re-use, resulting in significant economic and environmental issues. The quantity of ash that is produced from MSW following the incineration process accounts for approximately 25% of the total weight of MSW. Landfill space is limited in countries with a high population density [25]. Recent developments show that solid waste materials may be turned into a valuable resource in a circular economy to improve resource efficiency. As the MSWIBA contains Ca, Si and Al, it may be a suitable candidate as a raw material for cement production [26]. Improved energy efficiency, compressive strength and thermal comfort may be achieved by using MSWIBA as an alternative building material.

The production process of Compressed Stabilized Earth Blocks (CSEBs) requires a significant amount of fine aggregates [27]. Using municipal solid waste incinerator bottom ash (MSWIBA) as a raw material in CSEB production could be a viable option for recycling MSWIBA and conserving clay, making it an environmentally friendly option for constructing earthen houses [11,28]. This study explores the potential of using MSWIBA as a partial replacement for fine aggregates in CSEBs and inv estigates its effects on the mechanical and durability properties of these blocks. The various tests were conducted on samples containing varying percentages of cement and MSWIBA, and the results were compared to those of conventional earth blocks. This research aims to contribute to the development of sustainable building materials that promote environmental responsibility and waste reduction. The tests conducted follow ASTM standards and Indian Standards Institution norms, including wet and dry compressive strength, flexural strength, water absorption, stress–strain behavior, and wetting and drying cycles [19]. The study provides an in-depth account of the use of MSWIBA and cement in producing CSEBs as an eco-friendly construction material commonly used in earthen construction.

2. Materials and Methods

2.1. Soil

Soil (containing a significant amount of clay) collected from a depth between 2 to 5 m below ground level in Auroville, Pondicherry (India), was selected as the raw material. The collected soil sample was air dried, crushed to remove clods and then sieved through a 4.75 mm mesh screen. According to the conventional procedures enumerated by SP-36 (Part1) 1987 [29], the physical characteristics including liquid limit, plastic limit, shrinkage limit, particle size distribution, specific gravity and free swell were determined Table 1 [9,19,30,31]. According to the Indian Soil Classification System, this soil can be classified as CH. For the manufacture of CEBs, AS HB 195 [32] and IS 1725 [33] recommended a sand proportion somewhere between 30% to 75% and 50% to 80%, which is more suitable for production of CEB. The sand mixture of 70% was selected to fabricate the CEB and an optimal soil–sand mixture 30:70 was determined according to [19].

Table 1. Characteristics of soil.

Property	Parameter	Soil
Atterberg limit	Liquid limit, LL	61.45%
	Plastic limit, PL	35.67%
	Plasticity Index, PI	25.78%
Grain size Distribution	Sand	51.78%
	Slit	25.55%
	Clay	22.67%
Proctor Test	Optimum moisture content (OMC)	19.67%
	Maximum dry density (MDD)	1820 kg/m^3
Shrinkage Limit		18.23%
IS Soil Classification		CH

2.2. Cement

Ordinary Portland Cement (OPC) Type I was used to produce CSEB. The chemical composition is shown in Table 2 [31]. Evaluation of the physical characteristics demonstrated that the specific gravity was 3.15, initial and ultimate setting times were, respectively, 145 and 309 min, the 28-day compressive strength was 49.1 MPa and its fineness was 326 m^2/kg Table 2.

Table 2. Chemical composition of municipal solid waste incinerator bottom ash and OPC.

Compound	Chemical Composition (%)	
	MSWIBA	OPC (Type I)
SiO_2	64.75	22.40
Al_2O_3	0.78	5.13
Fe_2O_3	0.38	3.98
CaO	14.85	61.64
MgO	0.74	1.26
K_2O	-	0.61
Na_2O	-	0.09

Table 2. *Cont.*

Compound	Chemical Composition (%)	
	MSWIBA	**OPC (Type I)**
SO_3	-	1.14
C	15.53	-
LOI	-	3.75

2.3. Municipal Solid Waste Incinerator Bottom Ash (MSWIBA)

The MSWIBA was collected from an incinerator plant located at Manali, North Chennai (India), where the MSWI bottom ash is produced at a rate of 2000 kg per day. The air-dried and pulverized MSWIBA, passing through a 4.75 mm sieve, was used to produce CSEBs [34]. The chemical composition of MSWIBA particles is shown in Table 2. The MSWIBA particles with a specific gravity of 2.30 were classified as Class F bottom ash.

2.4. Soil–Admixture Proportions

This study examined the impact of various soil and admixture combinations on the strength and durability of compressed earth blocks. MSWIBA was used to replace fine aggregates (sand) at a rate of 0% to 25%, depending on the mix. Based on the literature [26], blocks were prepared with varying cement contents (0%, 6%, 7%, 8%, 9%, and 10%). In evaluating the strength of the compressed stabilized earth blocks (CSEBs), a standard period of 28 days was adopted for all the casting blocks, irrespective of their mix ratios. This time period is widely accepted as it allows sufficient time for the stabilizer material to cure and hydrate, thereby achieving the desired strength and durability of the CSEBs. By adopting this testing period, this study was able to obtain valuable information about the engineering properties of the CSEBs, including their strength and durability, which are critical factors for evaluating the quality of the blocks and identifying their potential uses. Table 3 contains detailed information regarding the type of test performed, as well as the quantity of blocks utilized in each test for each mix ratio.

Table 3. Combination of cement and MSWIBA considered in this study.

Cement	MSWIBA	No of Samples	Testing
0%	0%, 5%, 10%, 15%, 20%, 25%	5	Dry compression strength
6%		5	Wet compression strength
7%		5	Flexural strength
8%		5	Water absorption
9%		3	Stress–strain behavior
10%		5	Wetting–drying test

2.5. Optimum Moisture Content (OMC)

The CSEB preparation test was administered in a proctored environment, but with some adjustments. According to the definition, the optimum moisture content (OMC) is the point at which the dry density of the mixture may be maximized for a given level of compaction. When determining the OMC, the same methods used by [7,27,35,36] were applied. Both stabilized and un-stabilized soils were tested for no more than 45 min following the addition of water. A technique for measuring the hardness of a mixed dry mix is presented by [27]. CSEBs produced with 10% cement show the dry-density OMC. An OMC of 12–16% and a maximum dry density of 1812–2154 kg/m^3 were observed for all the samples. The drop ball test, recommended by [27], was also carried out to assess the accuracy of water addition.

2.6. Optimum Fabrication of Compressed Stabilized Earth Block

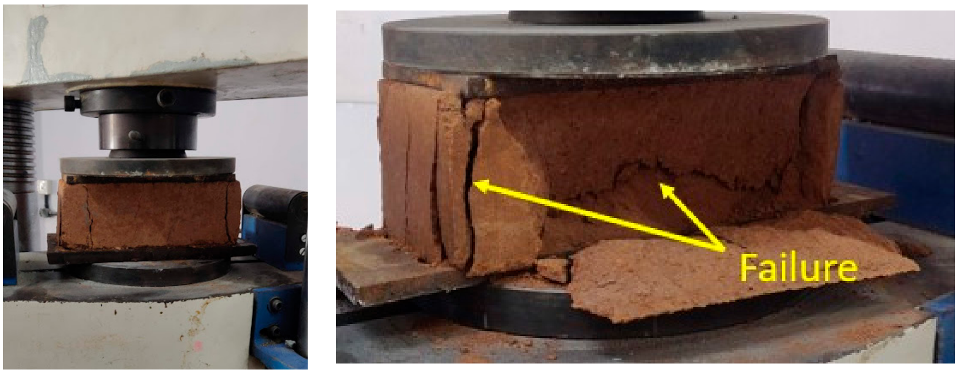
The dimensions of the blocks made using a block manufacturing machine were 240 mm × 115 mm × 90 mm in size. Figure 1 illustrates that the process of preparing blocks includes multiple stages, such as batching, mixing, placing the mix, compacting, and ejection of the blocks. The lumps of dried soil were manually crushed with a rammer and then sieved through a 1 mm mesh. In addition, the sand and MSWIBA were sieved through a 4.75 mm sieve. According to the calculations, the extent of air-dried materials, including soil, sand, MSWIBA and cement, were measured and combined [30].

Figure 1. Flowchart of production of CSEB.

According to the testing methodology, the soil was then mixed with the required quantity of cement–MSWIBA. For the fabrication of CSEBs, 0–10% of cement and six proportions of MSWIBA (0%, 5%, 10%, 15%, 20% and 25%) were employed. Over-integrating MSWIBA by more than 25% would have led to block failure because of the soil's low clay concentration. The prepared wet mixture was scooped into the press mold, and any overage was afterwards removed. After the mixture was compacted using static compaction, the block was gently removed from the compactor and placed on a level surface to cure [37]. Blocks that had been pushed out of the mold were measured for weight and cured for 28 days in a moistened tow sack. When the block was ejected, the weight and date of preparation were recorded, and an appropriate identification number (for the series used) was assigned for future reference.

2.7. Test Methods

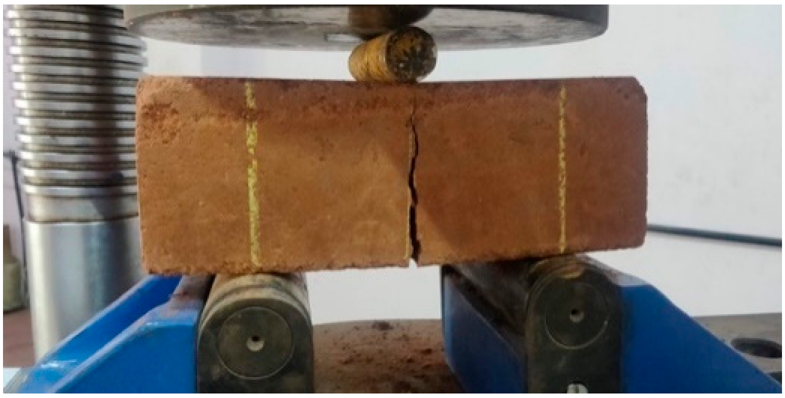
The compressive strength of the stabilized earth blocks was measured using a 100-ton compression testing equipment as per IS 3495 (Part 1): 1992 [38]. The combination of wet and dry compressive strength was measured since wet strength may be advantageous in the worst-case scenario. According to IS: 5454-1978 [39], a total of five samples were tested for each variation. The average value of the five samples was then used to represent the compressive strength of all the mixtures tested. Figure 2a,b shows a test set up for compressive strength and observed sample failure. The minimum acceptable compressive strength for the stabilized earth block is 3.5 MPa, according to IS: 1725-2013 [33]. The specimen was prepared before subjecting it to the compression testing machine. The unevenness in the bed faces removed by grinding, resulting in two smooth and parallel surfaces. Cement mortar was used to fill up the frog and any other holes in the bed. Then it was placed under moist jute bags for one day before being immersed in water for 3 days to complete the process. To determine the wet compressive strength, the blocks were soaked for 48 h in clean water, then were surface cleaned and tested using a universal testing machine [40].



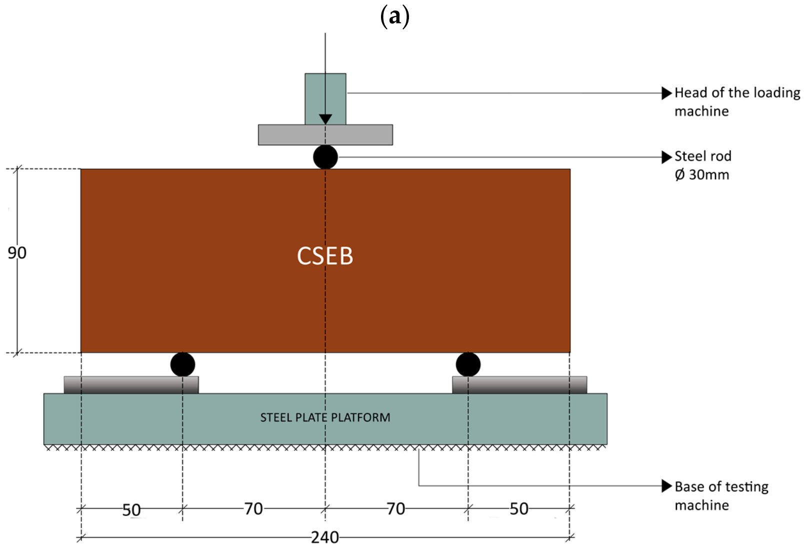
(**a**) (**b**)

Figure 2. (**a**) Test set up for compressive strength and (**b**) observed crack pattern of the sample.

The flexural tensile strength in terms of modulus of rupture was determined by subjecting specimens to a three-point bending flexural test, as specified in Indonesian Standard SNI 03-6458-2000 [19], similar to the specifications in ASTM C67-02c [41]. The specimen was loaded until failure, at a constant rate of 2.5 kN/min for 240 mm in a span using a universal testing equipment with a capacity of 200 kN. Figure 3a,b shows the arrangement of the samples for flexural strength test.



(**a**)



(**b**)

Figure 3. (**a**,**b**) Flexural test setup for CSEB.

The water absorption (WA) test according to IS 3495 (Part 1): 1992 [38] was performed on five samples (for each variation), as per IS: 5454 1978 [39]. con The initial weight was measured after the specimen was cooled to room temperature (M1). The specimen was then immersed in potable water for 24 h. The final weight was taken after surface drying for three minutes. Figure 4 shows the water immersion, surface drying of block and final weight for the waste absorption test. The specimen was weighed 3 min after it was taken out of water (M2), as shown in Figure 4. According to IS: 1725-2013 [33], the average water absorption should not exceed 15% of the weight of the material.

Figure 4. Flowchart of water absorption test.

The alternate wetting and drying tests were carried out in accordance with IS: 1725-2013 [33], which is comparable to that mentioned in ASTM D559-03 [42]. Three specimens from each series were dried in a ventilated oven at 60 °C until their weight was constant. The air-cooled blocks were immersed in water at room temperature for 5 h, and then dried in an oven at 70 °C for an additional 42 h. The dried blocks were scraped on all six sides twice using a wire scratch brush, using a force of 1.5 kg for each stroke The method used to scrape the dried blocks involved using a wire scratch brush to scrape with a force of 1.5 kg for each stroke. To ensure the accuracy of the pressure applied by the brush stroke, we clamped the wider face of the specimen on one corner of a platform scale and set the scale to zero and then placed a standard weight of 1.5 kg on the brush to measure the pressure as shown in Figure 5. The blocks were subjected to twelve similar cycles. The samples were then oven-dried and their final weights were recorded. After 12 rounds of wetting and drying, the blocks were evaluated for their dry compressive strength and flexural strength to determine the performance.

Figure 5. Measurement of pressure applied by wire scratch brush on the specimen.

The weight of the block is measured immediately after demolding to determine how much moisture is present in the block. As the block dries, it loses moisture and its weight reduces. After the block was demolded, it was placed in a curing chamber or covered with a moist cloth to prevent the moisture from escaping too quickly. Curing is the process of keeping the block moist so that it can continue to gain strength and harden. The block is typically cured for 28 days, after which it reaches its maximum strength. Therefore, Figure 6 shows that the weight of the block was measured after demolding and after 28 days of curing to determine how much weight loss had occurred during the curing process. The weight loss is an indication of the moisture loss and the strength gain of the block.

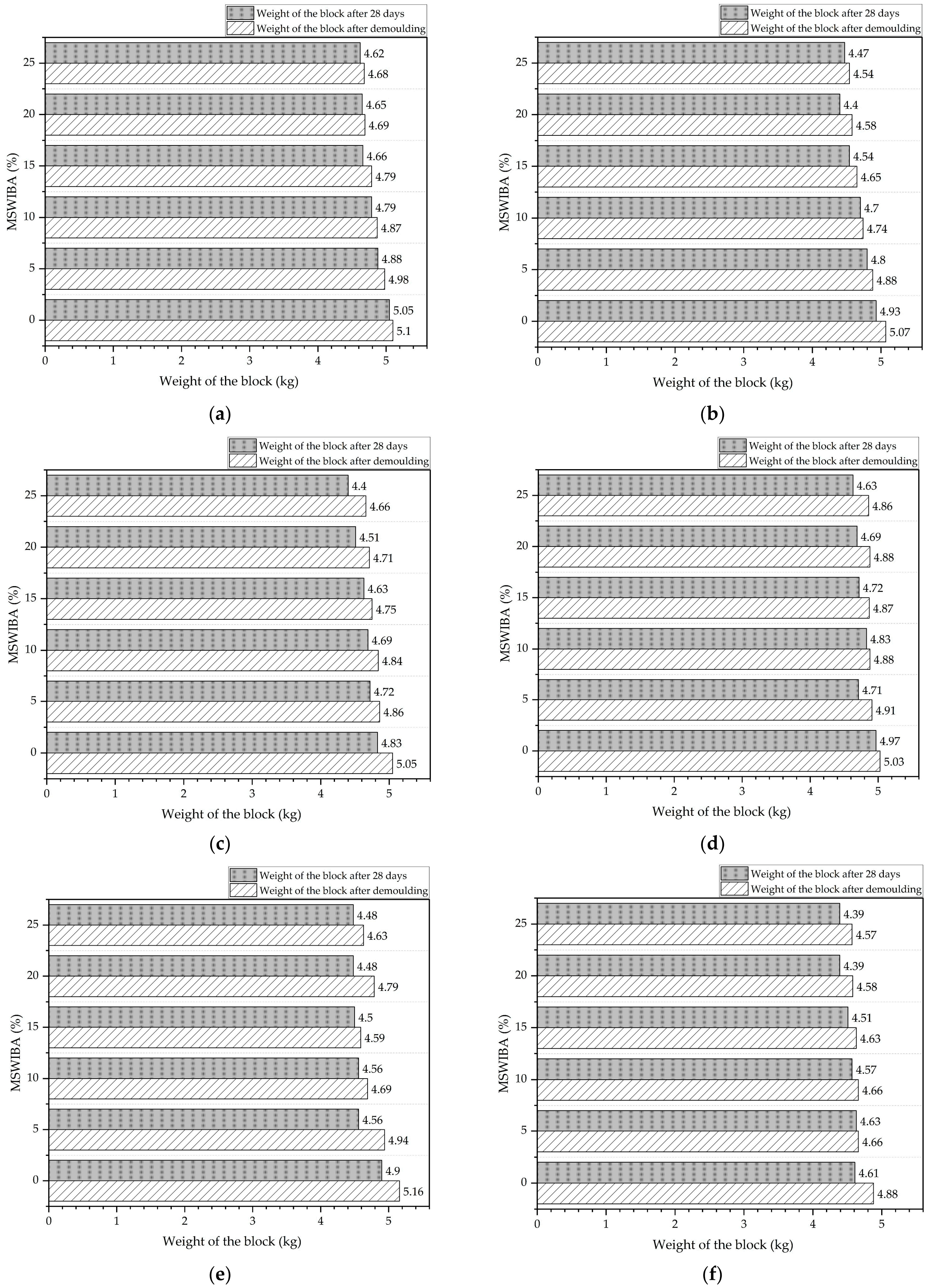


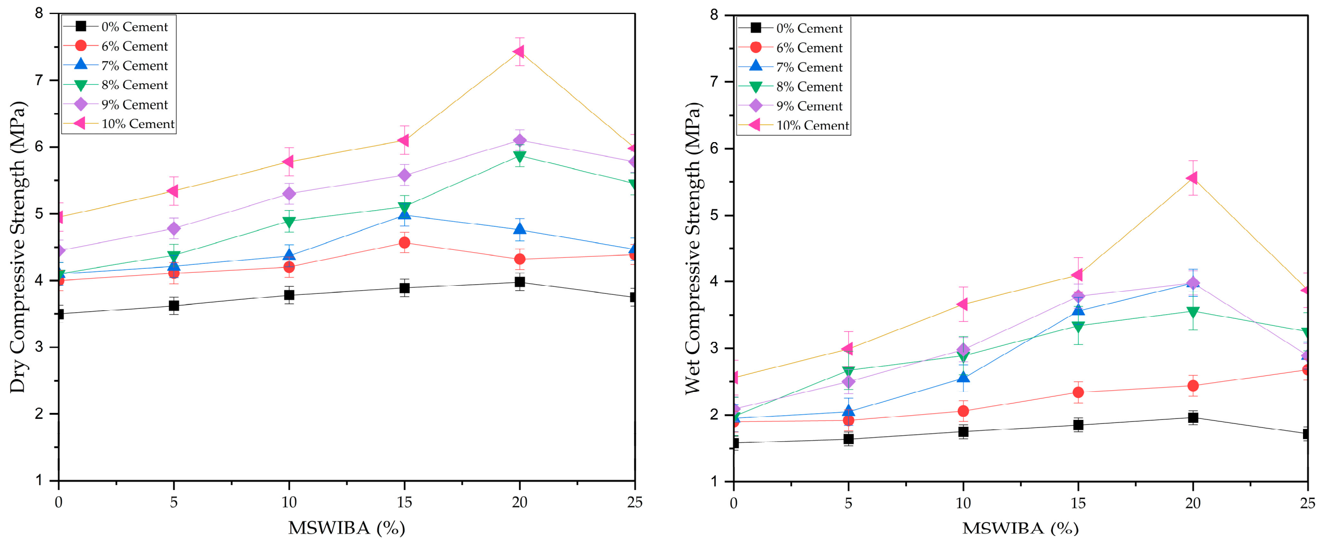
Figure 6. Weight of block with various % of cement content (**a**) 0% cement, (**b**) 6% cement, (**c**) 7% cement, (**d**) 8% cement, (**e**) 9% cement, (**f**) 10% cement.

3. Results and Discussion

3.1. Mechanical Properties of Compressed Stabilized Earth Block

3.1.1. Dry and Wet Compressive Strength of Compressed Stabilized Earth Blocks

The compressive strengths of CSEBs with and without MSWIBA were compared (dry and wet values taken after 28 days of curing, presented in Figure 7a,b). The dry and wet compressive strengths for the conventional earth blocks were, respectively, 3.50 and 1.68 MPa. In line with results from the literature, it was noted that the introduction of MSWIBA leads to a significant enhancement in compressive strength when compared to the conventional earth block. The highest compressive strength was observed in the samples containing 10% cement, whereas the lowest compressive strength was noted in samples without cement. Compressive strength improves with the cement content because of the stronger inter-particle connections from the cement hydration with the formation of calcium silicate hydrate (CSH) gels [43], binding the soil particles and filling the pores within the soil matrix. In addition, calcium aluminate silicate was formed when calcium hydroxide, a by-product of the crystallization of cement, reacts with the added MSWIBA [44]. In the CSEBs without cement content, the incorporation of MSWIBA does not have the same impact, and the strength of the system was not significantly improved. An appropriate quantity of MSWIBA must be added to the mixture in order to react with the hydrated product of cement crystallization. If the quantity of MSWIBA exceeds the required amount, the unreacted MSWIBA particles remain in the mixture, preventing the creation of strong interconnecting bonds with soil, thereby reducing the strength of the blocks.



(**a**) (**b**)

Figure 7. (**a**) Dry compression strength and (**b**) wet compression strength varies with MSWIBA concentration.

From the results, it was observed that the dry compressive strength values varied from 3.5 to 7.43 MPa and wet compressive strengths varied from 1.68 to 5.56 MPa, corresponding to 0–25% MSWIBA concentrations. The pozzolanic action and superior particle size distribution of MSWIBA may be attributed to this increase as reported by [44,45]. According to the standards, the wet strength should be over and above 0.7 MPa. The dry compressive strength of the mixture containing 10% cement, and 15, 20 and 25% of MSWIBA were, respectively, 6.10, 7.43 and 5.98 MPa, while the wet compressive strengths were, respectively, 4.10, 5.56 and 3.87 MPa. Superior strength was noted in the mixtures incorporating 10% cement and 20% MSWIBA. Figure 8 shows the wet-to-dry strength ratios for different cement–MSWIBA combinations. It can be noted that the addition of an optimal quantity of MSWIBA to cement increases the wet-to-dry strength ratio, proving the need for stabilization.

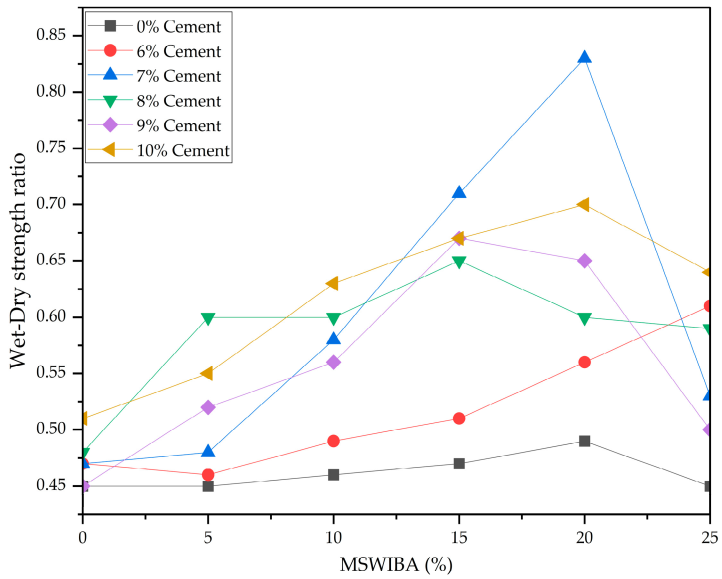


Figure 8. Wet-to-dry strength ratio.

3.1.2. Flexural Strength of Compressed Stabilized Earth Block

Figure 3 depicts the experimental setup for the flexural test of CSEB and the results are shown in Figure 9. The conventional earth block exhibited a flexural strength of 0.48 MPa. A progressive improvement in the flexural strength may be noted with an increase in the MSWIBA and cement content. The formation of cement hydration products and the reaction with the MSWIBA help to improve the hydration cycle. Consequently, a greater degree of bending resistance is provided by the soil matrix, which got tightly interconnected. The New Mexico [46] earthen building materials code recommends a minimum flexural strength (in saturation) as 0.35 MPa, whereas the New Zealand Standard [47] and the Sri Lankan Standard [48] require stabilized earth bricks to have a flexural strength above 0.25 and 0.5 MPa, respectively [9].

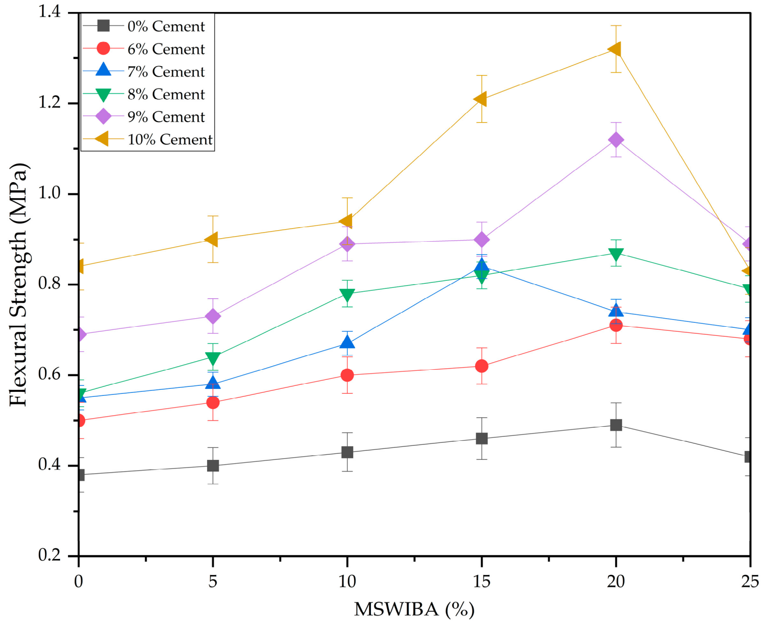


Figure 9. Effect of MSWIBA on the flexural strength.

From the results, the flexural strength of blocks comprising MSWIBA was higher than that of the conventional earth block. On average, the blocks had a flexural strength of 26%

to 28% of their compressive strength. The flexural strengths of the mixture incorporating 10% cement, and 15, 20 and 25% of MSWIBA were, respectively, 1.21, 1.32 and 0.83 MPa, as shown in Figure 9. Increasing MSWIBA from 10% to 20% increases the flexural strength, on account of the pozzolanic activity and more uniform particle size distribution. The shape and roughness of MSWIBA, in addition to its pozzolanic action, are important factors in the development of strength. MSWIBA also acted as a connecting link between the cement–soil matrix, improving the performance.

3.1.3. Water Absorption of Compressed Stabilized Earth Block

The stabilized earth blocks become less porous with age. After 28 days of curing, there was a notable reduction in water absorption across the board for all the blocks incorporating 7–10% of cement. The chemical reaction of the cement with the alumino silicates in the soil generates cementitious products that bind soil particles together and solidify over time, minimizing void interconnectivity [14]. The water absorption of the conventional earth block was 14.4%. All the blocks exhibit water absorption varying between 10.2% to 14.4% at the end of the 28-day ageing period. With extended ageing, the water absorption values reduce considerably, as most of the specimens exhibited a water absorption far below the 15% maximum limit indicated by IS: 1725-2013 [33]. As shown in Figure 10, the water absorption of blocks improves with the increase in the quantity of cement and the MSWIBA. The water absorption of the mixture containing 10% cement, and 15, 20 and 25% of MSWIBA were, respectively, 12.4, 11.6 and 10.4%. The water absorption of the specimen containing 7% cement was also comparable. These values were 12.8, 12.4 and 12.1%, respectively, at the MSWIBA content of 15, 20, and 25%.

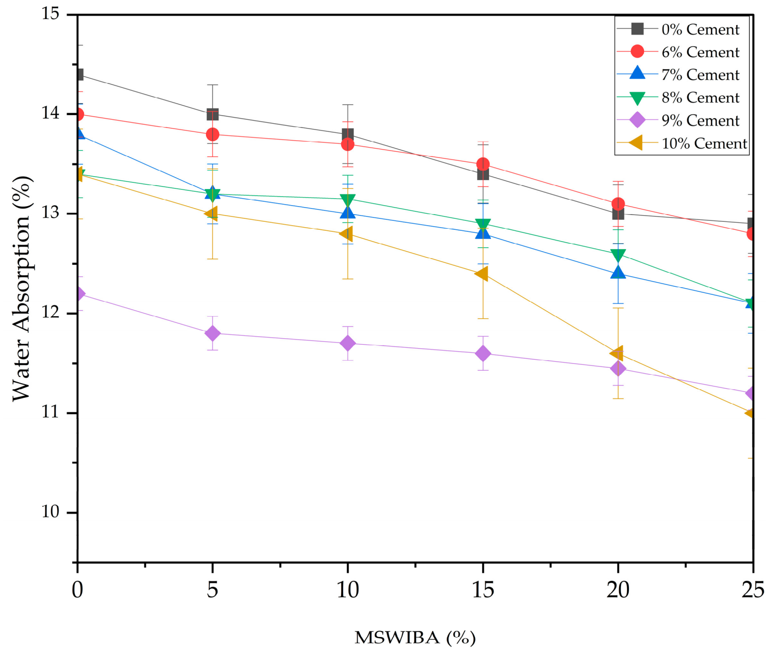


Figure 10. Effect of MSWIBA on the water absorption.

3.2. Alternate Wetting–Drying

The dry compressive strength of the mixture (at normal curing) containing 10% cement and 15, 20 and 25% of MSWIBA were, respectively, 6.10, 7.43 and 5.98 MPa, while strengths were, respectively, 7.54, 7.98 and 6.43 MPa after the wetting and drying cycles. A slight reduction in the compressive strength and flexural strength was noted for the conventional earth block, following the wetting–drying test, while an improvement in the strength may be noted for the specimen containing cement and MSWIBA. The gain in strength for the blocks containing 0% to 25% MSWIBA was in the range of 12–27% which is mentioned in Figure 11. Supplementary calcium silicate hydrate (CSH) gel was formed during the faster hydration of the cement due to the pozzolanic reaction with MSWIBA at 70 °C, which further enhanced the stiffness of the matrix [49]. Figure 12 shows the improvement in flexural strength of blocks after a series of wetting–drying cycles. There was a notable improvement in the flexural strength for the samples incorporating 10% cement and 10–25% MSWIBA.

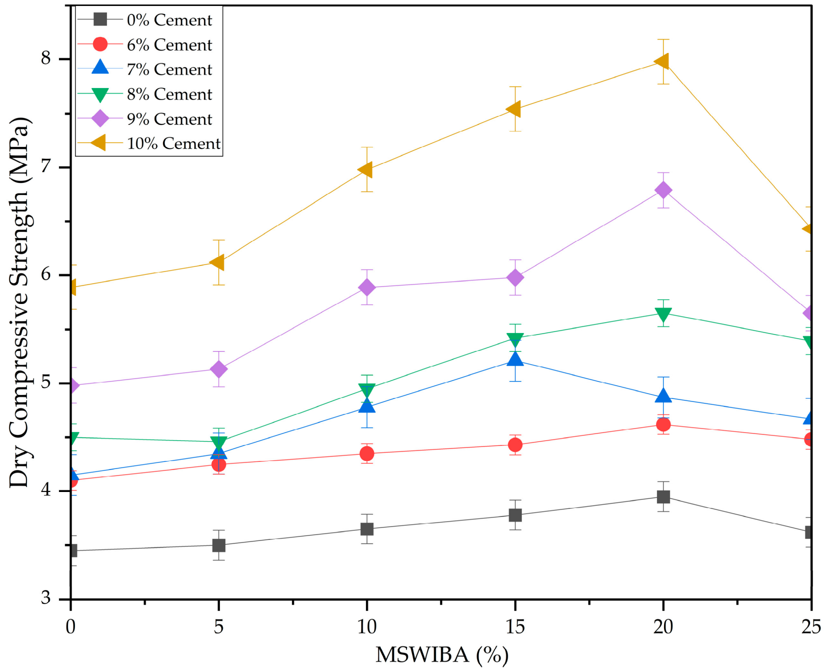


Figure 11. Dry compression strength of CSEB after alternate wetting and drying.

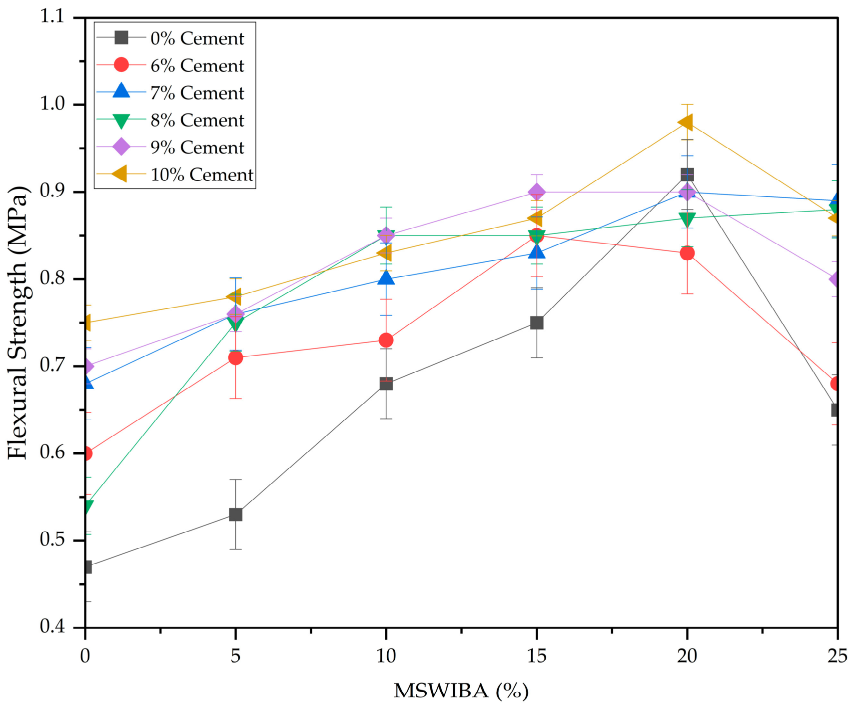
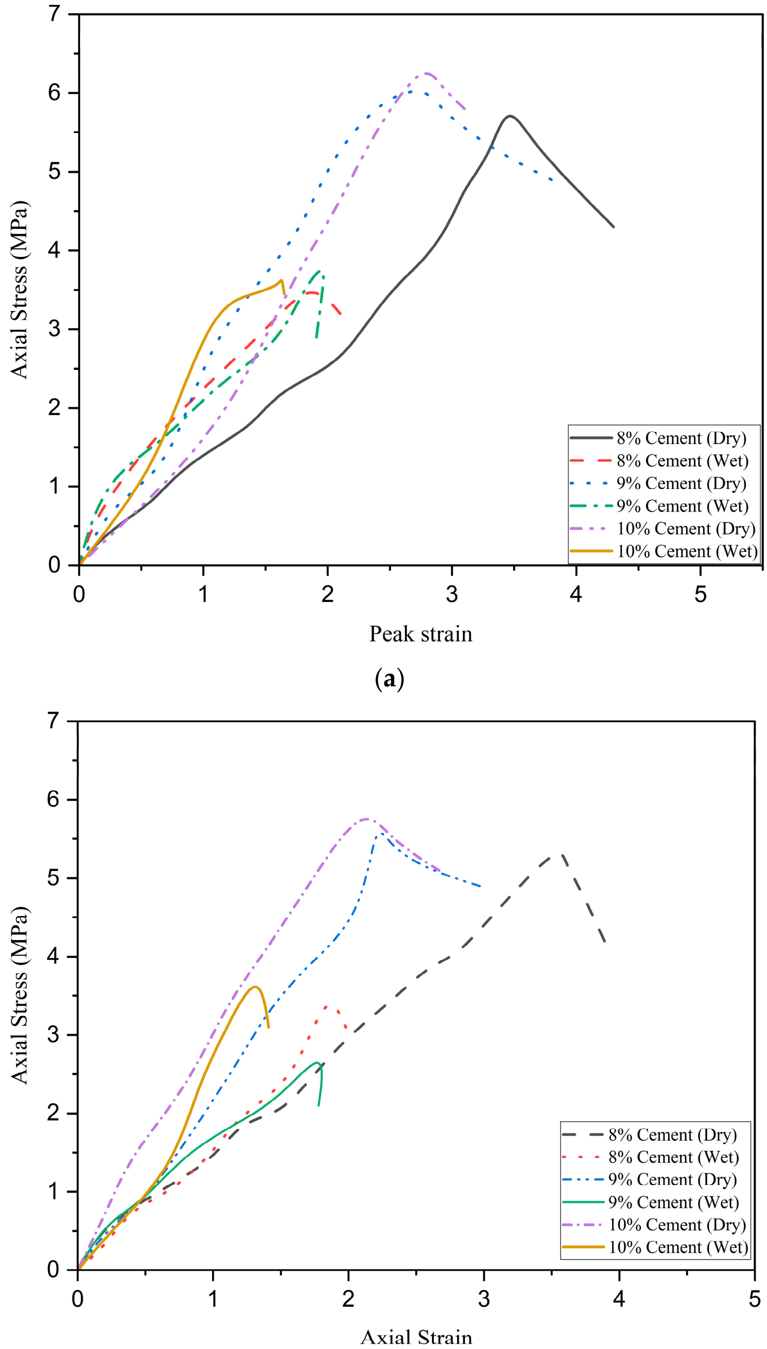


Figure 12. Flexural strength of CSEB after alternate wetting and drying.

3.3. Stress–Strain Behavior of CSEB

Dry and wet stress–strain behavior of CSEB specimens containing 20% and 25% MSWIBA, and 8%, 9%, and 10% of cement, exhibited superior strength and durability. More straining was seen at lower stresses in the beginning for all CSEB samples. As strain increases past the peak, the stress drops, and the CSEB specimens eventually fail. The strain values observed for the CSEB specimens containing 20% and 25% MSWIBA, and 8%, 9%, and 10% of cement in the wet condition ranged between 0.02% and 0.18%. In contrast, for the dry state, the strain values were found to be higher, ranging between 0.24% and 1.10%. All the specimens showed a reduction in peak strain with time, with cement content and failure strain varying between 2.5% and 3.4%. An increase in cementitious material–soil connections may lead to a stiff axial response and a steep slope of axial stress–axial strain response. In Figure 13, peak stress and failure strain are greater for dry than wet samples. Stress–strain graphs are used to determine the initial tangent modulus (ITM). The addition of various proportions of cement and MSWIBA resulted in a 40–50% rise in ITM, with a maximum value of 2.89 GPa.



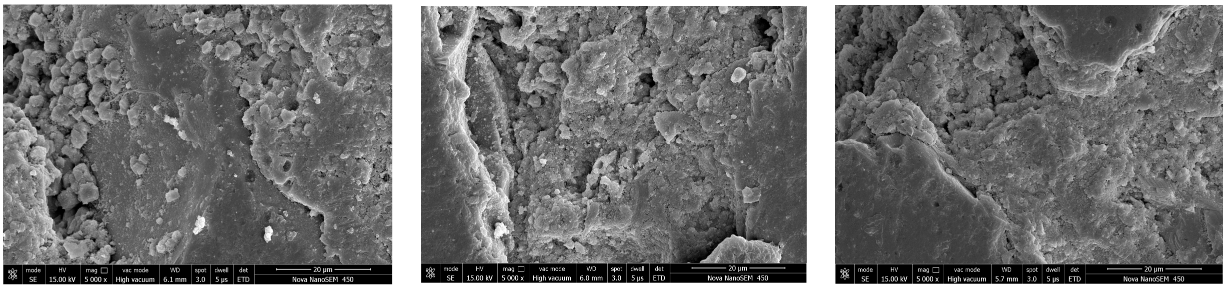
(**b**)

Figure 13. Stress–strain response of CSEB sample (**a**) 20% MSWIBA and (**b**) 25% MSWIBA.

In both the dry and wet phases, it is important to notice that the elastic modulus increased significantly with an increase in cement percentage from 8% to 9%. Upon adding 8–10% of cement, the elastic modulus in the wet blocks increased between 19% and 42% compared to 15% and 20% for dry CSEB specimens. Similar reactions were obtained for 15% and 20% MSWIBA, emphasizing the necessity to utilize 9% cement rather than 10% cement when producing CSEB using MSWIBA. Overall structural ductility may be assured by using cement-stabilized blocks with strong mortar joints between them and by increasing the integration between the block and the mortar.

3.4. Microstructural Analysis

The scanning electron microscopy (SEM) images given on Figure 14 confirm the performance of cement and MSWIBA materials. SEM was conducted on polished and gold-coated brick chips samples at a magnification of 5000×. Micrographs were captured using backscattered electrons and were viewed. An increase in the compressive strength of blocks with MSWIBA was observed on account of the better filling when compared to the conventional earth block. The internal phase of the compressed stabilized earth block containing 10% cement with 20% MSWIBA exhibits a higher density and fewer voids in comparison to the compressed stabilized earth block containing 10% cement with 15% and 25% MSWIBA, as depicted in Figure 14. The C-S-H gel formation in transition zone appears to be superior in the specimen incorporating 10% of cement with 20% of MSWIBA, and it had a maximum compressive strength of 7.43 MPa.

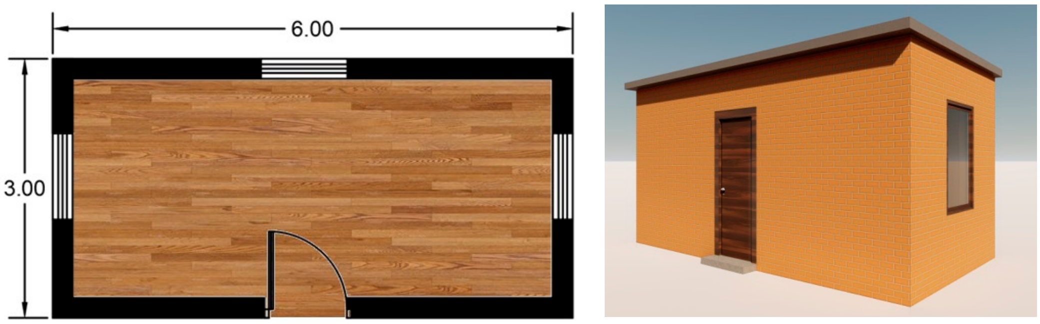


(**a**) (**b**) (**c**)

Figure 14. SEM analysis, (**a**) 10% of cement with 15% of MSWIBA, (**b**) 10% of cement with 25% of MSWIBA, (**c**) 10% of cement with 20% of MSWIBA.

3.5. Cost Analysis

The cost to construct a typical room, measuring 6 m× 3 m× 3 m, is calculated. In the design, a wall thickness of 0.3 m is considered, with three windows measuring 1.2 m × 1.2 m, and one door with dimension 1.2 m × 2.1 m. Figure 15 illustrates the structure as seen from the plan view perspective. The CSEB blocks have dimensions of 240 mm × 115 mm × 90 mm (MSWIBA–cement) and 240 mm × 120 mm × 90 mm (sand–cement), and an approximate unit weight of 1850 kg/m^3. To manufacture 3900 earthen blocks, the estimated quantity of cement is 1300 kg and MSWIBA is 2900 kg. The Indian standard rates were utilized for all the costs of materials in this investigation, and the projected cost is estimated as USD 750. Modern construction practices employ CSEBs in the form of interlocking blocks, which significantly minimizes the need for mortar and the associated cost. In addition, due to the added transportation expenses, the total cost of the CSEB was significantly greater than the typical concrete block. For building an identical room using fired clay bricks (FCBs), the total cost may be computed as USD 809 [27], while the overall construction cost for sand–cement-stabilized CSEBs is projected to be USD 862 [27]. The cost comparison reveals that utilizing CSEBs stabilized with MSWIBA might reduce the total construction costs by 8% compared to the price of FCBs and by 13% when compared to the price of CSEBs stabilized with cement and sand. MSWIBA and cement-stabilized CSEBs are therefore a cost-efficient option.



(a) (b)

Figure 15. Cost analysis. (**a**) Plan and (**b**) perspective view.

4. Conclusions

This study evaluated the application of municipal solid waste incinerator bottom ash (MSWIBA) to partially replace fine aggregate and ordinary Portland cement (OPC) as stabilizers in compressed earth blocks (CEBs). The amount of cement binder added to the mix varied from 0% to 10%. Additionally, a portion of the sand was replaced with MSWIBA in varying amounts ranging from 0% to 25%. This replacement of sand with MSWIBA resulted in a corresponding decrease in the sand content, which varied from 70% to 45% depending on the specific amount of MSWIBA added to the mix. An assessment was conducted to determine the strength and durability of compressed stabilized earth blocks (CSEBs). This included evaluating the compressive strength in dry and wet conditions, flexural strength, water absorption, and analyzing their behavior during alternate wetting and drying, as well as their stress–strain behavior and microstructure. Based on the findings of this investigation, the addition of cement increases the mechanical and durability characteristics of the compressed earth blocks. The optimal quantity of MSWIBA was noted as 15% for 6–7% cement and 20% for 10% cement content, while the optimal mix proportion may vary depending on the type of cement and MSWIBA. If the cement and MSWIBA content exceeds the optimal level, there could be a marginal reduction in strength and a rise in water absorption. The cost of CSEBs stabilized with cement and MSWIBA was reduced by 8–13% when compared with the earthen blocks stabilized with a cement–sand combination, demonstrating the economic advantage of cement–MSWIBA-stabilized CSEBs.

The utilization of bottom ash obtained from municipal solid waste incinerators in the production of compressed stabilized earth blocks has the potential to maintain the mechanical and durability properties of the blocks. Nevertheless, further research is necessary to analyze the long-term performance, such as ageing tests, and field studies should be conducted to evaluate the performance of MSWIBA-stabilized CSEBs in different climatic conditions and soil types.

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