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Research Article

Use of SCM in manufacturing the compressed brick for reducing embodied energy and carbon emission

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ABSTRACT

Brick is one of the most used building materials in masonry construction. Conventionally burnt clay bricks are used. These bricks are manufactured from clay and burnt in a kiln at a higher temperature. This results in a very high amount of CO_2 emission and has high embodied energy, which highly affects the environment. Compressed bricks are one of the sustainable solutions to overcome these issues of high CO_2 emission and embodied energy. Adopting sustainable alternatives, such as compressed bricks incorporating supplementary cementitious materials or environmentally friendly brick manufacturing processes, can help mitigate these issues and promote more sustainable construction practices. In this study, attempts have been made to manufacture and test the bricks with different proportions of the soil, i.e., the mix of locally available soil with sand, cement as the cementitious materials, and SCMs like fly ash & GGBS. The research methodology involves the formulation of different mixtures with varying proportions of SCMs. The specimens were then prepared using a compression molding technique and cured under controlled conditions. This research paper aims to investigate the effects of incorporating supplementary cementitious materials (SCMs) on the properties of compressed bricks. The study focuses on evaluating the density, compressive strength, water absorption, and efflorescence, as well as calculating the embodied energy and carbon dioxide emissions associated with the production of these bricks. Furthermore, the paper comprehensively analyzes the embodied energy and CO_2 emissions associated with producing compressed bricks. These calculations consider the energy consumed and CO_2 emitted in manufacturing, including raw material extraction, transportation, and brick fabrication. The study's results demonstrate the influence of SCMs on the properties of the compressed bricks. The analysis of embodied energy and CO_2 emissions provided valuable insights into the environmental sustainability of the brick production process.

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1. INTRODUCTION

"Brick" refers to a wide range of items made from clay mixed, prepared, and molded before being slowly dried and fired in an oven or kiln. Brick, the traditional material, is in rectangular shapes of baked clay and is used for many construction activities like building walls, pavements, canal lining, and many other masonry constructions. Brick is usually red or brown.

In India, the predominant construction method for buildings and houses involves cement blocks and burnt clay bricks due to their availability, affordability, and familiarity. However, this approach comes with several disadvantages. One significant drawback is its environmental impact. The production of these materials requires the extraction and processing of raw materials, resulting in substantial carbon dioxide emissions and contributing to climate change.

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Moreover, the depletion of natural resources poses environmental concerns—the high energy consumption associated with manufacturing cement blocks and burnt clay bricks. The kiln firing process for burnt clay bricks requires significant fuel, leading to increased energy demands and carbon emissions. However, exploring alternative construction materials that address these drawbacks can lead to greater sustainability in the long run.

In many nations experiencing significant economic growth, the requirement for brick clay is high, but it is valuable to farmers. It has become overly exploited, resulting in the devastation of agricultural areas. As a result, it is critical to identify alternate materials for replacing clay in bricks to minimize energy consumption caused by clay mining and the exploitation of non-renewable clay minerals. The construction sector has always been open to innovative research on materials [1, 2]. In brick manufacturing, research is being done on producing high-quality bricks using waste-based materials to replace clay as a viable strategy for developing environmentally friendly brick materials [3–6]. Concrete blocks, AAC blocks, and fly ash bricks have emerged as alternatives to traditional burnt clay bricks. But when compared to other construction materials, Compressed Stabilized Earth Blocks (CSEB) provide numerous benefits. It enhances the utilization of local resources, waste, and supplementary cementitious material (SCM), thereby reducing transportation costs. Additionally, constructing with local materials enables the employment of local individuals and fosters sustainability [7–9].

Embodied Energy is the total energy consumed by a product or system during its entire life cycle. The energy is considered comprised or 'embodied' in the product or system [10]. It includes all energy inputs necessary to extract, process, manufacture, transport, and dispose. By considering the energy used during the whole life cycle of a product or system, including the extraction of raw materials, manufacture, usage, and disposal, it offers a comprehensive view of the environmental effect of a given product or system. However, manufacturing bricks, mainly using conventional techniques, may significantly impact carbon dioxide (CO_2) emissions and contribute to environmental problems. The embodied energy of a fired clay brick is nearly 3.75–5.60 MJ/brick [7, 11] or 0.54–3.14 MJ/kg [12]. While the estimated CO_2 emissions for fired clay brick range from 97 - 526 gm/kg of fired brick [13, 14].

According to reports, global fly ash (FA) production is around 1.143 billion tons annually. It is typically utilized at an average rate of 60% [15], while in developing nations such as India, the utilization rate of approximately 50%–60% for fly ash (FA) has been reported [16]. According to reports, the yearly global production of GGBS is around 530 million tonnes [17]. Currently, 65% of that amount is recycled [18]. Previous research has demonstrated that clay-based bricks incorporating FA can have desired properties equivalent to their traditional clay-based counterparts [19, 20]. A recent study on the behavior of clay-based bricks containing GGBS showed that 60% of GGBS content can improve the mechanical and durability properties superior to clay-based bricks without GGBS [21]. A few authors also investigated the manufacturing of bricks by GGBS, which is waste from the iron and steel industry [22, 23]. A study discovered that the bricks produced from the mixture of slag, lime, and sand are of good quality and obtained good wet compressive strength in the range of 80-150 kg/cm^2 after 28 days at ambient temperature in humid curing conditions. The production of slag-based bricks utilizes less energy than traditional burnt bricks [22]. However, the replacement of clay with such SCM has been little investigated in clay-based bricks.

This study investigates the innovative concept of replacing clay with a mixture of GGBS and FA in conventional clay-based bricks. This study evaluates the feasibility of developing SCM-based bricks using appropriate proportions of FA and GGBS. Various tests were performed on the brick samples to determine their water absorption, bulk density, and compressive strength. This study also presents a detailed account of embodied energy and CO_2 emissions to produce and deliver the bricks.

2. MATERIALS AND METHODS

The methodology for the present study, including procurement & properties of all the materials, mixing proportions, production, and curing, is discussed in this section.

2.1. Materials

2.1.1. Soil

A locally available soil sample collected from Chekhla Village of Sanand Taluka, Ahmedabad, Gujarat, India, was used for the study. The natural moisture content of the soil was found to be 22.05%, and the specific gravity was found to be 2.64. The soil contained 16.6% clay fraction, 48.2% silt content, and 35.2% sand as per IS 2720-part IV [24]. The soil used in this study had a 28% liquid limit and a 15% Plastic limit as per IS 2720-part V [25].

2.1.2. Sand

The sand was procured from Sabarmati River, Mahudi, Gandhinagar, Gujarat, India, which conforms to Grading zone II as per IS: 383:1970 [26] having a specific gravity of 2.68, fineness modulus of 2.4, and bulk density of 1610 kg/m^3 was used.

2.1.3. Cement

The Ordinary Portland cement (OPC) used for this study was procured from Nuvoco Vistas Corp. Ltd., India. The specific gravity and surface area were 3.15 and 2410 cm^2/gm, respectively [27].

2.1.4. Fly Ash

Fly ash used for this study was classified as Class F, which was procured from a fly ash pond, Torrent power, Pethapur, Gandhinagar, Gujarat, India. It has a light grey color and specific gravity of 2.3, conforming to IS 3812-2013 [28]. The chemical composition of fly ash provided by Torrent power is shown in Table 1.

Table 1. Chemical composition of fly ash

Sr. No.	Details	Test results	Requirement as per IS: 3812–2013 [28]
1	Specific surface area	416.4 m^2/kg	>200 m^2/kg
2	Loss of ignition	1.10%	<7.0% by mass
3	$SiO_2+Al_2O_3+Fe_2O_3$	93.00%	>70.00% by mass
4	SiO_2	61.40%	>35.00% by mass
5	Reactive silica	34.70%	>20.00% by mass
6	MgO	1.40%	<5.0% by mass
7	Na_2O	0.60%	<1.5% by mass
8	Retention on 45 µ sieve	21.10%	<50.0% by mass

Table 2. Chemical composition of GGBS

Sr. No.	Details	Test results	Requirement as per IS: 16714–2018 [29]
1	Specific surface area	364 m^2/kg	>275 m^2/kg
2	Loss of ignition	0.60%	<3.0% by mass
3	Magnesium oxide (MgO)	6.07%	<17.00%
4	Manganese oxide (MnO)	0.32%	<5.50%
5	Sulphide sulphur	0.57%	<2.0%
6	Sulphate (as SO3)	0.29%	<3.0%
7	Insoluble residue (IR)	0.21%	<3.0%
8	Chloride content (CI)	0.008%	<0.1%
9	Glass content	92.50%	>85.00%
10	Retention on 45 µ sieve	11.00%	--

2.1.5. GGBS

GGBS used for this study was collected from Suyog Elements India Pvt. Ltd., Bharuch, Gujarat, India. It was white and had a specific gravity of 2.89. The chemical composition of GGBS provided by the firm conforming to IS 16714 – 2018 [29] is shown in Table 2.

2.2. Mix Proportions

The mix adopted for manufacturing bricks was 3:3:1 (Sand: Clay: SCM), and SCM included FA, GGBS, and cement. The proportion of sand and clay used in the mix was taken as given in IS 1725: 2013, and it has been shown that the content of clay should be 5% to 18%, silt content should be 10% to 40%, and sand content should be 50% to 80%. The different SCM mixes considered for the present study are given in Table 3. In all mixtures, the total weight of SCM content was kept constant. The brick with mix label M0 is considered a reference mix to compare all other mixes. In mix label M0 (3:3:1), the amount of soil and sand was kept equal, i.e., 12kg, and instead of using fly ash and GGBS, only cement was used, which has a proportion of 4 kg.

Table 3. Proportions of dry mix

Mix label	Mix proportions (kg)				
	Soil	Sand	Fly ash	GGBS	Cement
M0	12	12	0	0	4
M1	12	12	3	0	1
SM2	12	12	0	3	1
M3	12	12	1.5	1.5	1
M4	12	12	1.75	1.75	0.5
M5	12	12	3.5	0	0.5
M6	12	12	0	3.5	0.5
M7	12	12	2	2	0

2.3. Manufacturing of Bricks

In the present investigation, rectangular brick specimens of 230 mm x 105 mm cross-section with a height of 70 mm were produced using a hydraulic brick-making machine. The mix adopted for brick manufacturing was 3:3:1 (Sand: Soil: SCM) with SCM of different proportions, as shown in Table 3. A total of 8 different ratios were produced, and 15 bricks were manufactured for each proportion. Firstly, the soil and sand were mixed in the dry state in the mixer for 5 minutes. Then, FA, GGBS, and cement were added during mixing and continued for 5 minutes. One liter of water was added into the mix consisting of 12 kg of soil, 12 kg of sand, and 4 kg of cement or SCM. Subse-

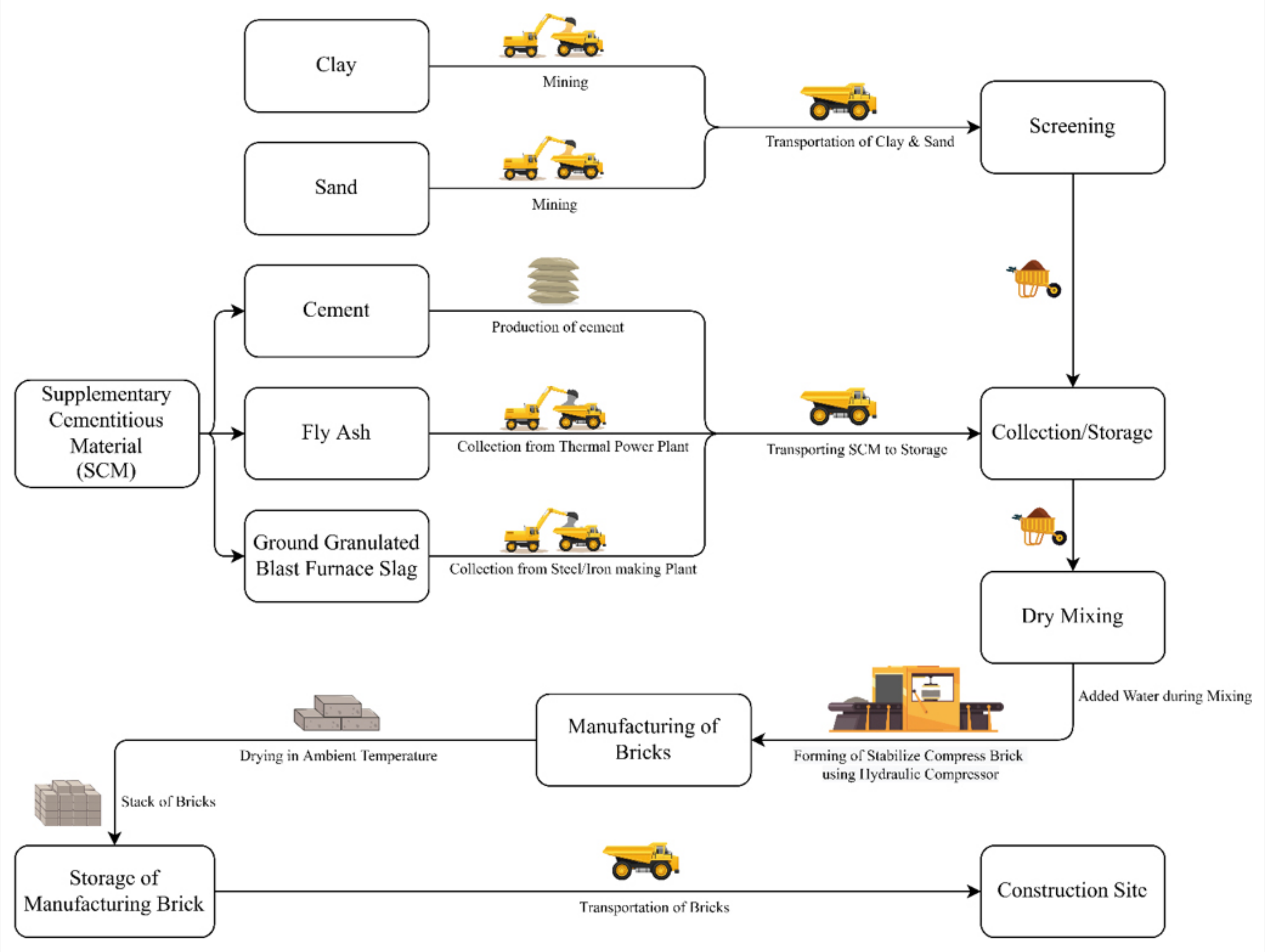

Figure 1. Flowchart for manufacturing of brick.

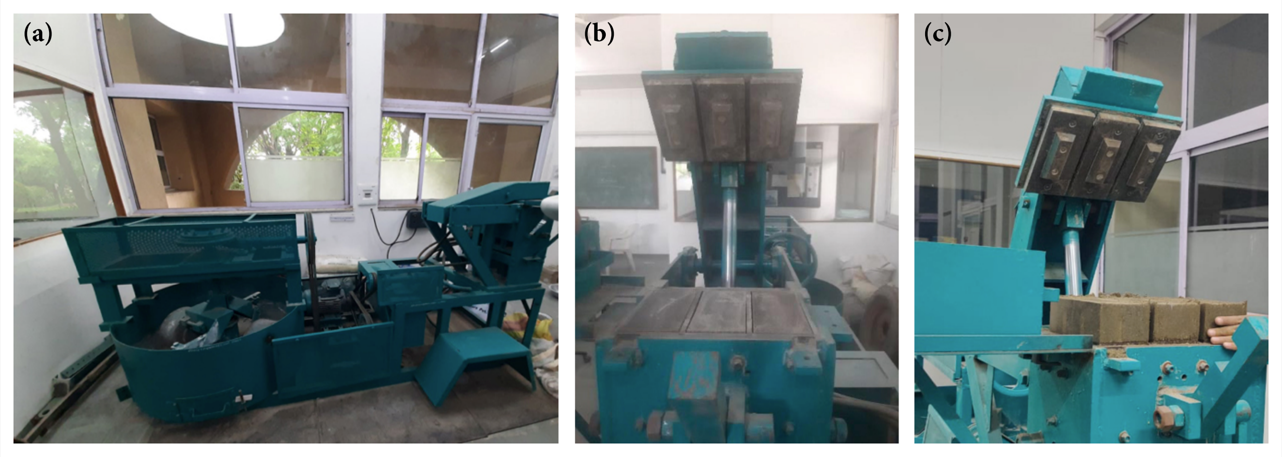

Figure 2. **(a)** Hydraulic brick-making machine. **(a)** Hydraulic compressor. **(c)** Production of brick.

quently, the mixing continued for another 5 minutes. Water was then added, and the blending was for another 5 minutes. The fresh mixture of all these materials was poured into the brick mold of a hydraulic brick-making machine. The freshly poured mixture was hydraulically stressed from above and below so that the height of the brick sample was obtained as required. After demoulding the brick samples, they were transferred for curing purposes. The whole process of manufacturing brick is illustrated in Figure 1. A hydraulic brick-making machine was used to produce brick, and the raw material and water were mixed and compressed in this machine, as shown in Figure 2a–c.

2.4. Curing

The consistency of water content remained uniform across all brick mixes. After demoulding, the brick

Table 4. Properties of bricks with different proportions

Name of test	Mix label							
	M0	M1	M2	M3	M4	M5	M6	M7
Density (kg/m^3)	1804	1775	1769	1769	1781	1757	1763	1727
Compressive strength (MPa) - B	4.23	3.57	3.50	3.60	4.21	3.61	3.56	3.77
Water absorption (%)	5.59	6.71	6.40	6.73	6.35	7.46	7.43	7.24
Efflorescence	No	No	No	No	No	No	No	No

Table 5. Dimension tolerance test results

Dimensions	Mix label								Limits as per IS 1725:2013	Remarks
	M0	M1	M2	M3	M4	M5	M6	M7		
Length	4599	4598	4600	4598	4601	4600	4599	4600	4520 mm to 4680 mm	Within the limit
Width	2098	2099	2100	2099	2099	2100	2098	2099	2160 mm to 2240 mm	Within the limit
Height	1403	1394	1402	1401	1400	1401	1396	1401	1360 mm to 1440 mm	Within the limit

samples were kept for drying at a controlled temperature of 27°C±1°C for one day. Then, the brick samples were cured at an ambient temperature of 22°C–24°C for 28 days.

3. RESULTS AND DISCUSSION

The comprehensive test outcomes are detailed in Table 4. It delineates the properties of the bricks, encompassing density, dimensional tolerance, compressive strength, water absorption, and efflorescence.

3.1. Density

Brick density is significant since it affects the material's durability and strength. It directly affects the structural stability and weight of a structure. While ensuring stability and efficiency in construction, the optimal brick density impacts significant parts of a building's operation. The details regarding the density of bricks are illustrated in Figure 3. Analysis of the test outcomes indicates a consistent density range between 1757–1781 kg/m^3 for bricks incorporating FA, GGBS, and cement. Notably, this range exceeds the minimum density requirement of 1750 kg/m^3 as outlined in the IS 1725: 2013 standard [30].

3.2. Dimensional Tolerance

Brick dimensional tolerance is essential for guaranteeing consistency and accuracy in building. It ensures that bricks follow prescribed size variations, making precise alignment and assembly easier while constructing. Accurate dimensional tolerance helps preserve structural integrity and aesthetic appearance by preventing wall thickness and alignment variations. Table 5 provides a comprehensive overview of the results of the dimensional tolerance of 20 bricks. However, every brick satisfies the requirements listed in IS 1725: 2013 [30].

3.3. Compressive Strength

The compressive strength of bricks is crucial as it signifies their ability to withstand significant loads without deformation or failure. It determines the capacity of brick to bear vertical loads, ensuring structural stability in buildings and other constructions. A higher compressive strength indicates resilience against external forces, ensuring durability and safety in various structures. The compressive strength test of brick was performed on a universal testing machine shown in Figure 4. The compressive strength of bricks for all eight mixes is shown in Figure 5. This assessment was conducted after a 28-day curing period. The reference mix, M0, exhibited a compressive strength of 4.23 MPa. Across all eight mixtures tested, the compressive strength ranged from 3.50 to 4.21 MPa. Notably, the compressive strength of all mixes surpasses the minimum requirement specified for Class 3.5, as outlined in IS 1725: 2013, ensuring compliance with these standards [30].

3.4. Water Absorption

The average value of water absorption for the individual mix is shown in Figure. 6. Notably, the reference mix, M0, demonstrated the lowest water absorption at 5.59%. In contrast, the remaining mixes exhibited a water absorption range between 6.35% and 7.46%. These values comply with the stipulated IS 1725: 2013 standard, which specifies that water absorption should not surpass 20% of the brick's weight. Additionally, it's worth noting that no efflorescence was observed on the surface of any of the bricks.

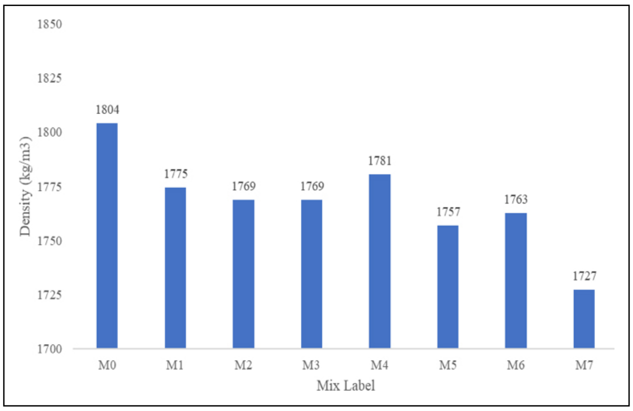

Figure 3. Density.

Figure 4. Universal testing machine.

3.5. Embodied Energy

The energy used for excavation and transportation of raw materials is determined using the gathered field data. The field data of all raw materials, i.e., soil, sand, GGBS, fly ash, and cement, are assessed based on travel distance, time, capacity, and primary energy use. This work's sustainability aspects are limited to energy use and emissions. The calculation of energy use per unit amount of excavation and transportation demonstrates the influence of technological and operational parameters. Several data have been considered for calculating embodied energy regarding the raw material, equipment, and transportation of brick.

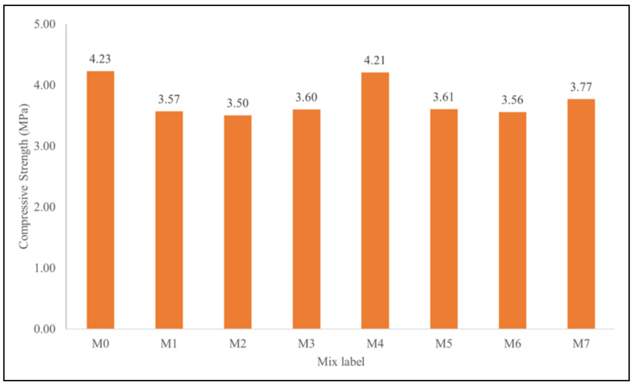

Figure 5. Compressive strength.

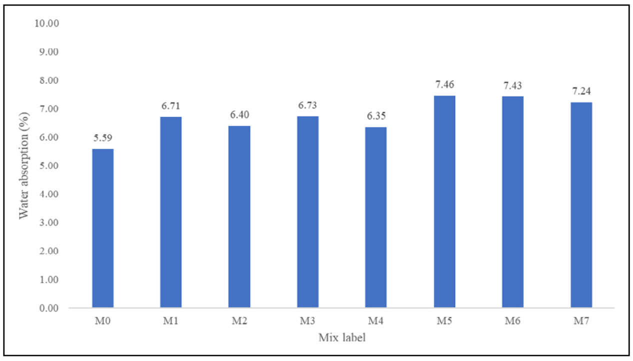

Figure 6. Water absorption.

The lorry transports a volume of 10 m^3 in a single trip. The actual distance was considered for the transportation of the raw materials. The fuel consumption for the excavation of soil and sand was considered as per field data, which was about 0.35 lire per 1 m^3 excavation [31]. The fuel consumption of a lorry for transporting materials was 5 km per 1 liter of fuel [31], and for energy calculation, both the trips (up trip and down trip) are considered. For all the activities of excavation and transportation, diesel was used as fuel, and it has an energy of 8.7 MJ per 1 liter of diesel [31]. The embodied energy is 3.6 MJ for 1 kg of cement production [31]. The brick-making machine was used to mix the raw materials and compress the brick; it consumes 7.5 kW. The capacity per day of the brick-making machine was 1000 bricks, for which working time was 10 hours per day. The amount of coal used is 0.7 kg for producing 1kWh of electricity, and coal has embodied energy of 20 MJ per 1 kg [31].

The calculated embodied energy for the production, excavation, and transportation of different raw materials, brick-making equipment, and transportation of bricks are enlisted in Table 6.

3.6. Carbon Dioxide Emissions

The CO_2 emission during excavation and transportation of raw materials is determined. Moreover, CO_2 emission during manufacturing and transporting bricks

Table 6. Calculated embodied energy for production and transportation

	Energy (MJ/Cu. m.)	
	Production	**Transportation**
Raw materials		
Soil	13.55	46.44
Sand	13.55	77.40
GGBS	–	928.80
Fly ash	–	46.44
Cement	5142.86	47.39
Manufacturing process		
Mixing & Compression	525	–
Transportation of bricks	–	77.40

Table 7. Calculated CO_2 emission for production and transportation

	CO_2 Emission (kg/Cu. m.)	
	Production	**Transportation**
Raw materials		
Soil	0.89	3.05
Sand	0.89	5.08
GGBS	-	60.96
Fly ash	-	3.05
Cement	1142.86	3.11
Manufacturing process		
Mixing & Compression	51.45	–
Transportation of bricks		
Bricks	–	5.08

Table 8. Comparison of various properties of different mixes

Mix label	Compressive strength (MPa)	Water absorption (%)	Embodied energy (MJ/Cu. m.)	CO_2 emissio (kg/Cu. m.)
M0	4.23	5.59	806.15	167.96
M1	3.57	6.71	255.03	45.50
M2	3.50	6.40	283.22	47.35
M3	3.60	6.73	269.12	46.42
M4	4.21	6.35	179.62	26.17
M5	3.61	7.46	163.17	25.09
M6	3.56	7.43	196.07	27.25
M7	3.77	7.24	90.12	5.91

is also determined. The data for all raw materials, i.e., soil, sand, GGBS, fly ash, and cement, during the manufacturing transportation of brick, is assessed based on travel distance, time, and capacity.

As explained earlier, the data for CO_2 emission is the same as embodied energy. Some changed data is also considered; diesel produces 2.54 kg CO_2 per liter [31]. The CO_2 emission was 0.8 kg for 1 kg of cement production [31]. The coal has produced CO_2 of 1.96 kg per 1 kg coal [31]. The calculation of CO_2 emission for the output, excavation, and transportation of different raw materials, brick-making equipment, and transportation of bricks are enlisted in Table 7.

3.7. Comparison

Different mixes are employed in manufacturing bricks, each offering unique properties and characteristics. These mixes are carefully formulated to ensure optimal brick quality and performance. A comprehensive analysis of various brick mixes reveals a range of distinctive properties. The identified properties have been enlisted in Table 8, allowing for easy comparison and informed decision-making in brick manufacturing processes. The embodied energy and calculated CO_2 emission for different raw materials, processing, and transportation computed for the bricks manufactured for different mixes are tabulated in Table 8. The calculation for embodied energy and CO_2 emission is calculated for 1 Cu. m. which approximates 500 nos. of bricks.

These properties include compressive strength, water absorption, embodied energy, and CO_2 emission. After comparing all the data, mix M7 shows a reduction in embodied energy by 88.82% and a reduction in CO_2 emission by 96.48%. Also, it was found that the compressive strength of all mixes satisfies the minimum compressive strength specified for Class 3.5 designated as per IS 1725: 2013 [30]; hence, it can be used for structural members.

4. CONCLUSIONS

The investigation was conceived to adopt a sustainable alternative to the conventional bricks, attempting to reduce the Embodied energy and CO_2 emissions. Based on the experimental studies conducted to evaluate the optimal mix for manufacturing bricks using fly ash (FA), ground granulated blast furnace slag (GGBS), and cement, the following significant conclusions have been drawn:

- All the stabilized compressed earth brick samples with different mixes meet the criteria for density, dimensional tolerance, compressive strength, and water absorption. This indicates that these mixes are suitable for brick production and exhibit satisfactory performance in essential properties.
- Mix M7 demonstrates the lowest embodied energy, measuring 90.12 MJ/m^3 among the various tested mixes. This value is 88.82% lower than the reference mix (M0), with the highest embodied energy of 806.15 MJ/m^3. The significantly lower embodied energy of Mix M7 signifies its superior sustainability in terms of energy consumption during the production process.
- Mix M7, which does not contain cement, exhibits the lowest CO_2 emissions of 5.91 kg/m^3. This value is 96.48% lower than the reference mix (M0), with the highest CO_2 emissions of 167.96 kg/m^3. The substantial reduction in CO_2 emissions achieved by Mix M7 highlights its superior environmental performance, contributing to lower carbon dioxide emissions during brick production.

In summary, the experimental study reveals that the stabilized compressed earth brick mixes, including the recommended Mix M7, i.e., without the use of cement and using only SCMs, meet the required standards for essential properties such as density, dimensional tolerance, compressive strength, and water absorption. Furthermore, Mix M7 stands out as a more sustainable option due to its significantly lower embodied energy and CO_2 emissions than the reference mix. These findings underscore the importance of alternative mixes using fly ash, ground granulated blast furnace slag, and reduced cement content to promote environmentally friendly and energy-efficient brick manufacturing practices.

Furthermore, with a comprehensive understanding of the environmental impact, future research should consider conducting a comparative analysis of additional parameters such as water usage, waste generation, and potential pollutants associated with different brick mixes.

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ETHICS

There are no ethical issues with the publication of this manuscript.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

FINANCIAL DISCLOSURE

The authors declared that this study has received no financial support.

PEER-REVIEW

Externally peer-reviewed.

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