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Article

Carbon Conscious Construction: Evaluating Compressed Stabilized Earth Blocks

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Abstract

The United Nations Environmental Programme and the Paris agreement emphasize the urgent need for net-zero embodied carbon in building materials by 2050. In line with the vision, this study investigates the production and performance of compressed cement-stabilized earth blocks (CSEBs) as sustainable alternative for wall construction. Soil samples from Kara, East of Addis Ababa, were analyzed for their suitability in block production, focusing on grading, plasticity, and chemical composition. Using Portland pozzolana cement (PPC) as a stabilizer, blocks were produced with varying cement contents and compaction pressure and tested for compressive strength and compaction pressure. Results show that blocks with as little as 6% cement content achieved compressive strengths exceeding 2 MPa at 56-day curing, meeting structural requirements. Higher cement content and compaction pressure further improved compressive strength and reduced water absorption. Importantly, the study demonstrates that CSEBs can reduce cement consumption by over 50% compared to conventional hollow concrete blocks, translating to significant embodied carbon savings, up to 2 tonnes of CO₂ per 100 m² of wall. These findings highlight the potential of CSEBs to contribute meaningfully to climate mitigation, while offering technically viable and resource-efficient solutions for sustainable and affordable construction.

Keywords: cement-stabilized earth block; compressive strength; compaction pressure; embodied carbon; low-carbon building materials; sustainable construction

1. Introduction

Selecting appropriate building materials is crucial for ensuring the strength, aesthetic quality, durability, and cost-effectiveness of construction projects while promoting sustainability and reducing negative environmental impacts. In the past, raw forms of natural materials such as stone, sand, earth, and wood were commonly utilized. Recent progress in construction technology, architectural design, and sustainable practices has led to notable changes in the types and properties of building materials [1]. Traditional materials have been refined or replaced by manufactured alternatives like bricks, cement, glass, and reinforced concrete. Further innovations have led to the development of advanced materials such as self-healing concrete, translucent wood, and other eco-friendly materials, driving rapid development in construction techniques.

While advancements in building materials have significantly improved construction techniques, they have also contributed to increased carbon emissions, making the built environment sector the largest emitter of greenhouse gases, responsible for at least 37% of global emissions [2]. This has brought increased attention to the embodied carbon construction materials, particularly cement, which alone account for approximately 8% of global CO₂ emissions [3]. Reducing cement use through alternative materials like compressed stabilized earth blocks (CSEBs) is therefore, critical to achieving net zero targets in the built environment.

Building materials also represent a significant portion of construction costs, with studies indicating that they account for approximately 50 to two-thirds of housing construction costs [4,5]. Traditional building materials, when improved with modern technology, can offer affordable and durable alternatives to expensive, imported materials. Furthermore, advancements in building

materials can be integrated with the United Nations Environment Programme's decarbonization goals, promoting the development of eco-friendly materials. This is particularly relevant in developing regions, where large-scale construction projects have significantly increased the cost of conventional materials like cement and steel, exacerbating the financial burden on middle and low-income groups.

The continued use of conventional building materials can contribute to ecological harm, including issues like deforestation and soil erosion. In addition, there is a lack of knowledge and access to modern, sustainable building materials and techniques that could improve the durability and efficiency of buildings. Tackling these challenges involves encouraging the adoption of innovative construction materials and methods that balance affordability with environmental responsibility.

Within this framework, interest in earth-based construction materials, especially compacted earth, is growing, largely due to the substantial energy demands and environmental consequences, such as elevated carbon emissions, linked to conventional building materials [6–8].

Soil has been a fundamental building material since ancient times, with communities traditionally constructing homes using locally available materials. This practice has resulted in a variety of earthen structures. Even today, raw earth remains the most widely used building material worldwide, especially in less developed areas [7]. According to UNESCO data, 40% to 50% of the global population resides in earthen houses [9], with higher percentages in developing regions such as Africa, Latin America, the Middle East, the Indian subcontinent and Asia. In some places, like Cameroon, over 95% of traditional housing is made from earth [10]. However, utilizing raw earth as a construction material comes with notable drawbacks, including a high absorption rate due to its considerable porosity, shrinkage during drying, and low resistance to moisture.

Compressed stabilized earth blocks (CSEBs) are a modern adaptation of Adobe, one of the earliest known building materials [4]. Despite their potential, the quality of CSEBs produced has been inconsistent, with a lack of standardized production procedures and scientific data on raw material compositions. Previous studies have demonstrated the potential of CSEBs [4,11–13]. Institutions such as Auroville (India), CRATerre (France) and Hydraform (South Africa) have contributed notably to the development and practical use of stabilized earth blocks. Although their work demonstrates the advantages of CSEBs – such as affordability, structural stability, aesthetic value, and environmental sustainability, additional research is needed to establish standardized production methods and refine material compositions for consistent performance.

Despite the promising results, the application of CSEBs in most developing countries has been limited due to inconsistent quality and lack of standardized production methods [4], and there is a need for further development and regulatory support [2]. Additionally, the rising costs of conventional building materials and the demand for environmentally sustainable local building materials in construction projects worldwide [14] further emphasize the need for CSEBs as an alternative solution with potential for improved sustainability and performance.

In addition to these technical considerations, the environmental implications of CSEBs, particularly their potential to reduce cement consumption and embodied carbon emission, have received limited empirical attention in the context of low-income housing and climate mitigation. The study addresses this gap by integrating technical performance evaluation with an environmental impact assessment.

The primary objective of this research is to evaluate the technical viability of CSEBs as a sustainable wall construction material. Specifically, the study aims to (i) determine the optimal proportions of soil and cement for stabilization, (ii) assess the effects of compaction pressure on the physical properties of CSEBs, and (iii) quantify the potential for cement savings and embodied carbon reduction compared to conventional masonry units. By integrating performance testing with environmental impact analysis, the study seeks to provide a comprehensive understanding of how CSEBs can contribute to sustainable and low-carbon construction practices. The investigation is guided by the following key questions:

What is the optimal soil-cement proportions for producing high-quality CSEBs?
How does compaction pressure affect the compressive strength and water absorption of CSEBs?
To what extent can the use of CSEBs reduce cement consumption and embodied carbon emissions compared to conventional masonry units?

2. Literature Review

2.1 Building Materials and Economic Development

The construction sector is responsible for approximately 40% of global raw material consumption and significantly contributes to environmental degradation. It is responsible for about 37% of total Co2 emissions [2,15], with a large share stemming from the production of building materials and products. This places immense pressure on the environment; therefore, it is essential to acknowledge the crucial role of building materials in global decarbonization efforts [16]. Despite this, the construction sector is a key driver of economic and social progress, stimulating demand for goods and services in related industries and generating millions of jobs annually across various economies [17]. Its activities are essential for achieving national socio-economic goals, such as providing housing, infrastructure, and employment opportunities.

The construction industry is vital for national prosperity, creating jobs through new projects, repurposing existing buildings, and refurbishment efforts across the entire economy. Its interconnectedness with other sectors highlights how economic growth and social equity are heavily reliant on the construction sector. In many developing nations, the construction sector accounts for an estimated 6% to 9% of gross domestic product, reflecting its significant role in economic development. With sustained economic growth over the past years, the sector has achieved an 8.2% growth rate, with the construction sector typically constituting about 40-60% of Gross Fixed Capital Formation (GFCF) in developing countries [18]. The industry's sensitivity to socio-economic conditions highlights the importance of clear policies and strategies to guide its development.

Research shows that construction impacts nearly every aspect of the economy, making it a crucial contributor to economic growth [19]. Therefore, the industry has significant potential to shift towards a circular economy by adopting strategies like using eco-friendly products and technologies, increasing the use of sustainable or recycled building materials, and reducing waste at various stages of the building lifecycle [20]. To address these environmental and economic challenges, the construction industry must adopt sustainable practices.

Ensuring the implementation of sustainable building practices can be achieved by utilizing sustainable components [21]. Investing significantly in the sustainable sourcing of materials is crucial for minimizing potential environmental damage. As environmental concerns continue to grow, selecting materials that support sustainability is no longer optional but necessary for construction organizations [22]. This approach aligns with global initiatives.

2.2. Key Features of Earth for Eco-Friendly Building

Earth is a versatile and sustainable building material with several advantages that make it suitable for environmentally conscious construction.

Low environmental impact: Earth blocks have a minimal environmental footprint [23–25]. It requires little energy for extraction and preparation, leading to lower embodied energy compared to other traditional materials like concrete and steel.

Strength: For instance, the New Mexico adobe code mandates a minimum strength of 2 MPa for traditional adobe blocks [26]. Earth blocks exhibit notable strength, durability, and longevity, often outlasting typical wood frame buildings, which have an average lifespan of 60-80 years [27]. Earthen structures, however, can endure for centuries. The advent of hydraulic press technology has further enhanced the durability, simplicity, and sustainability of earthen construction. This technology merges traditional materials with modern innovations, enhancing their structural performance and consistency.

Energy Efficiency: Earth blocks are made from readily available materials: sand, clay, silt, and water, combined with a small percentage of Portland cement. One of the most compelling advantages of earth block buildings is their exceptional energy efficiency. The thermal mass properties of earth blocks help regulate indoor temperatures, leading to significant energy savings for the building owner and benefiting the broader community. Compressed earth blocks require significantly less energy to produce compared to traditional fired bricks or concrete blocks, using only about 1/5 to 1/15 of the energy needed for fired bricks [28]. Additionally, the construction process itself is energy-efficient, as earth blocks are produced on-site, reducing transportation costs and fuel consumption. According to findings reported in [29], earth wall systems can reduce embodied energy by approximately 62% to 71% when compared to conventional wall construction methods. Research has shown that compressed earth blocks have a heat transfer coefficient of around $2.66 \text{ W}/(\text{m}^2\cdot\text{K})$ [30] indicating good thermal performance.

Acoustic Performance: Earth blocks are incredibly dense, providing excellent sound insulation. Their ability to dampen sound makes them particularly advantageous in acoustically sensitive settings, such as music production spaces. Interlocking compressed stabilized earth blocks (ICSEBs) have sound absorption coefficients ranging from 0.71 to 0.99 at frequencies of 500 Hz, 1000 Hz, 2000 Hz, and 4000 Hz [31]. This makes them viable alternatives to widely used materials such as fiberglass insulation batts and acoustic plasterboard. Earth block buildings create a serene interior environment, which many occupants find to be an added benefit.

Durability: Durability refers to the ability of earth blocks to maintain their strength, dimensional stability, and resistance to weathering over the lifespan of the structure [32]. Earth blocks must be durable and waterproof to withstand environmental factors such as rain, wind, and rising damp. The longevity of ancient earthen structures around the world attests to their durability. Earth blocks also offer good resistance to fire and pests [33]. Cement-stabilized earth blocks are defined as durable materials produced from natural or modified soil with sufficient fines to provide cohesion upon densification, allowing for unsupported handling or stack curing.

Aesthetic Appeal: Earth block buildings offer versatile design possibilities, allowing them to mimic any finished structure. Supporters of this building technique often appreciate this visual appeal of the blocks and the traditional adobe-style finish. In most cases, the outer surfaces are treated with protective coatings that shield against weathering, which may be tinted or retain the material's original appearance. Interior surfaces may be treated with different types of plaster or left bare to achieve a rustic aesthetic. Design elements like arches and rounded corners enhance flexibility and visual appeal, harmonizing seamlessly with the natural surroundings.

Thermal Properties: Building materials are assessed for thermal performance using R-values and U-values. The R-value serves as an indicator of a material's ability to resist heat flow; materials with greater R-values offer enhanced thermal insulation. To determine this value, the wall's thickness is divided by its thermal conductivity. The U-value, which is the inverse of the R-value, reflects how quickly heat passes through a material. Total R- and U-values for a wall are obtained by summing the values of each component, including insulation, sheathing, framing, and masonry [34]. For masonry-mass walls like adobe, heat capacity is crucial as it determines the time required to reach steady-state heat flow. Higher heat capacity means a longer time to reach this state. Due to ongoing temperature variations, achieving a truly stable state is uncommon. The flywheel effect describes how these walls absorb heat during the day and release it at night, ensuring consistent comfort [34].

3. Historical Background and Technical Foundations

Although earth-based construction has a long-standing history, the adoption of compressed stabilized earth blocks (CSEBs) represents a more modern innovation within this traditional building practice. The technique originated in the 1950s as part of a rural housing research program in Colombia, this method represents an improvement over traditional adobe production. In contrast to adobe, which is traditionally shaped manually using wooden molds, compressed earth blocks are produced by compacting damp soil under pressure within a steel mold or press. Originally, wooden

tamps were used to create the first compressed earth blocks [35]. This process results in blocks that are more uniform in size and shape and have greater density compared to hand-molded blocks.

Since its inception in the 1950s, compressed earth block (CEB) technology has steadily advanced, demonstrating both scientific and technical value in construction applications [35]. Compressed earth blocks have supported multi-story residential and recreational construction globally. Despite their functional advantages, the technique has seen limited application in many parts of the world. However, there is a growing revival of this traditional building material, driven by its cost-effectiveness, natural aesthetic appeal, environmental friendliness, and energy conservation benefits. Research centers such as Auroville (India), CRA Terre (France), and Hydraform (South Africa) have played significant roles in advancing CEB technology. Their intensive research, experimentation, and architectural innovations have led to the development of technical documentation and academic curricula supporting its use. Efforts are now being made to establish norms and standards for compressed earth blocks, which will help legitimize the technique and promote its wider adoption in both developing and developed countries [4,6].

3.1. Characteristics of soil for Compressed Cement Stabilized Earth Blocks

Accurate identification of soil characteristics and an understanding of the ambient climatic conditions are essential prerequisites for producing stabilized soil blocks. Soil properties exhibit significant variability depending on the prevailing climate, whether it be dry, temperate, rainy, or tropical. The physical properties of the soil are particularly critical in the manufacture of compressed stabilized soil blocks, as they influence key factors such as mixing, forming, de-molding, porosity, permeability, shrinkage, dry strength, and apparent bulk density.

CSEB manufacturing demands soil with minimal silt and clay content to ensure structural integrity. For best results, the fine particle should make up about 25% of the soil, with clay accounting for at least 10% of that portion. An ideal particle size distribution generally includes 40 -75 % sand or fine gravel, 10- 30% silt, and 15 -30% clay [36].

3.2. Soil Stabilization Using Cement

A range of soil stabilization methods is used worldwide to improve the structural and mechanical characteristics of soil. These include approaches such as mechanical compaction, and chemical treatments using materials like cement, lime, bitumen, gypsum, and pozzolana. In this research, cement stabilization was selected, which involves adding different percentages of cement to moist soil samples and mechanically pressing them.

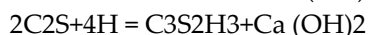
Cement is primarily composed of lime (CaO) and silica (SiO₂), which react with each other and other components in the mix in the presence of water to form calcium silicate hydrates [37]. The resulting chemical reactions form a network of interlocking crystalline structures that bind to inert aggregate, such as sand, enhancing both compressive strength and overall stability. Due to its strong chemical binding capability, positive test results from prior studies, and availability in the market, cement was selected as the binding agent for this study. Lime and lime-pozzolan stabilization are also gaining popularity as they can be produced at a lower cost using small-scale batching kilns.

3.3. Production of CSEB

The production process begins by dry mixing suitable soil with a specific amount of cement and then remixing the product with a precise quantity of water. The resulting damp soil is compressed in a mold, ejected, and subsequently wet-cured for 3-4 days, followed by damp curing for twenty-eight days before being used for building purposes. The quantity of cement needed to stabilize a block varies depending on factors such as soil composition, compaction level, and the intended use of the blocks. Typically, efforts are made to keep the cement content below 10% to optimize material efficiency. When conditions are favorable, it is possible to manufacture blocks using little as 3% cement.

Standard Portland cement typically contains around 54% tricalcium silicate (C3S) and approximately 16.6% dicalcium silicate (C2S, which are key components influencing its strength and setting behavior [37]. The exact mechanism by which a small amount of cement can stabilize a large mass of soil is not fully understood. In moist soil environments, the primary cement compounds – tricalcium silicate (C3S) and dicalcium silicate (C2S) react to form calcium silicate hydrate gels, which contribute to the stabilization process.

These reactions can be simplified as follows [37]:



The free lime, $Ca(OH)_2$ undergoes a pozzolanic reaction with the clay fraction, extracting silica from the clay minerals and generating additional calcium silicate gel. Over time, this gel crystallizes and forms a dense, interlocking matrix within the soil pores, effectively binding the particles together. This matrix is insoluble, providing a strength mechanism that restrains the softening and swelling of the unaffected soil, thereby significantly reducing the weakening effect of water. The interlocking calcium silicate fibers can be observed under an electron microscope in a cured soil-cement sample [38].

4. Methodology

4.1. Study Area

The study was carried out in Addis Ababa. Soil samples were obtained from Kara; a location situated roughly 20 km to the east of Addis Ababa. This area was selected because local people use the soil for adobe block production.

4.2. Study Design

This experimental study focused on assessing the characteristics and performance of Compresses Stabilized Earth Blocks (CSEBs). The study followed a systematic approach beginning with the assessment of the suitability of materials – soil, cement, and water. Soil samples were collected and prepared by pulverizing and sieving them to the appropriate size. The physical and chemical properties of the soil were determined through laboratory tests, including sieve analysis and Atterberg limit tests. The soil sample was characterized in two main ways: by particle size distribution analysis and by plasticity index. The soil sample was separated into distinct particle size fractions using a combination of sieving and hydrometer tests, which revealed its grading characteristics. This particle size analysis offered insights into the soil's compaction potential and the proportion of fine particles (silt and clay), while the plasticity index provided an indication of the cohesive nature of these fines.

The procedures for determining plastic and liquid limits adhered to ASTM D2216 [39]. The linear shrinkage test, which measures the soil's contraction on drying and provides a combined measure of the soil's particle grading, plasticity, and clay type, was conducted based on BS 1377-2 [40]. The test provided insight into the soil's characteristics and its potential for stabilization. Addis Ababa municipal water was used throughout the procedure. Portland pozzolana cement, sourced from the Mughher cement factory, was used as the stabilizer. Information about the chemical composition of the Portland cement used in the study was obtained from [41].

Following these initial assessments, a Standard Proctor Compaction Test was performed to determine the optimum moisture content (OMC) and maximum dry density (MDD) of the soil. The test, conducted using ASTM D 698 Method A, revealed an MDD of 1,610 kg/m³ and an OMC of 19%. The compaction effort, using an M7 E380 Hydraform machine at 10 MPa system pressure, showed that the ideal block length required a moisture content of 24%.

After conducting suitability tests for the materials, the mix design and specimen preparation commenced. The mix proportions were based on literature recommendations, with varying cement contents (4%, 6%, 8%, 10%, and 12% by weight of soil) and a constant water content of 24%. The soil-

cement mixtures were compacted using a hydraulic press at different pressures (4 MPa, 6 MPa, 8 MPa, and 10 MPa) to form the blocks. Post-production, the blocks were cured in controlled settings and tested for strength and water absorption at intervals of 7, 14, 28, and 56 days.

All laboratory investigations on materials were carried out at the Addis Ababa University, Faculty of Technology Construction Materials and Soil Mechanics Laboratory, Selam Technical and Vocational Center, and the Geological Survey of Ethiopia Geochemical Laboratory.

4.3. Material Suitability Analysis

4.3.1. Soil Physical Properties

The soil's suitability was assessed based on its particle size distribution, plasticity, and chemical composition—key properties influencing its strength and durability [42].

To this end, the soil properties were tested at the Material Testing Laboratory of the Civil Engineering Department at Addis Ababa University (AAU). Concurrently, the soil's chemical composition was determined at the Geochemical Laboratory of the Geological Survey of Ethiopia. The test results indicated that the particle size distribution and plasticity of the soil were within acceptable ranges. An overview of the soil's physical traits and chemical makeup is provided in Tables 1 and 2.

Table 1. Physical properties of the soil.

NO	Physical Properties	Values
1	Specific gravity (gm/cc)	2.61
2	Natural moisture content (%)	14.87
3	Optimum moisture content (%)	19
4	Maximum dry density (kg/m ³)	1610
5	Silt content (%)	16.25
6	Clay content (%)	13.75
7	Sand content (%)	70
8	Linear shrinkage (%)	7.14
9	Liquid limit (%)	31.91
10	Plastic limit (%)	25.75
11	Plasticity index (%)	6.16

Table 2. Overview of soil chemistry.

Chemical oxides of the soil and their chemical Composition														
SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	Na ₂ O	K ₂ O	MnO	H ₂ O	LOI	TiO ₂	P ₂ O ₅	SO ₃	Cl ⁻	pH
65.32	15.27	7.68	<0.01	0.18	1.59	4.08	0.17	0.19	4.06	0.4	<0.01	0.07	<0.01	6.75

4.3.2. Particle Size Distribution

The combined sieving and hydrometer tests separated the different size fractions of the soil sample into discrete parts, thereby revealing the soil's particle grading. Figure 1 illustrates the outcomes of the compressive strength and water absorption tests conducted at various curing stages.

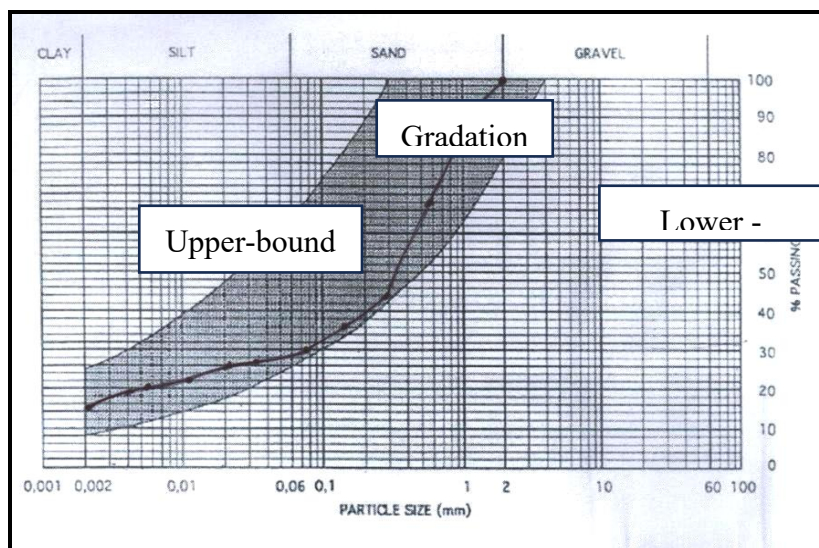


Figure 1. Particle size distribution

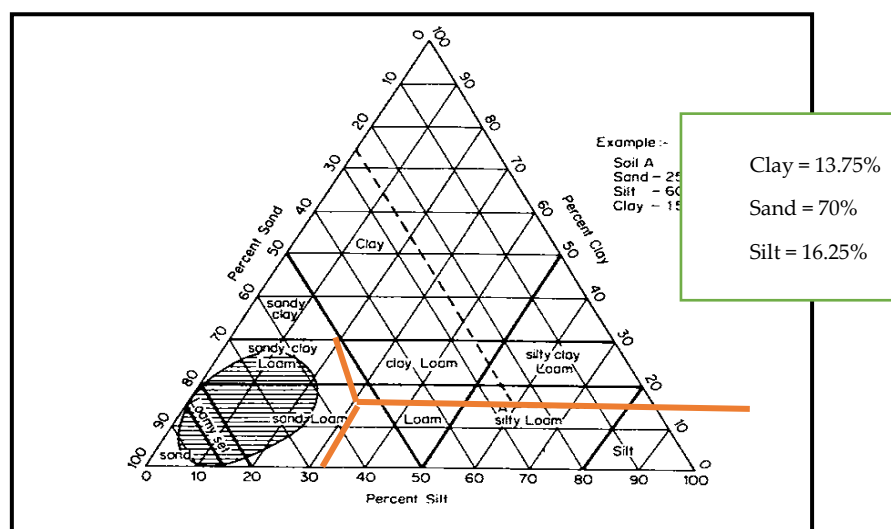


Figure 2. Soil particle size distribution presented in triangular diagram [38].

The shaded area in Figure 2 indicates soils most suitable for stabilization. Soil sample which has a composition of 70% sand, 16.25% silt and 13.75% clay as plotted "1" in Figure 2 falls within the shaded area, indicating the soil's suitability for soil cement block production.

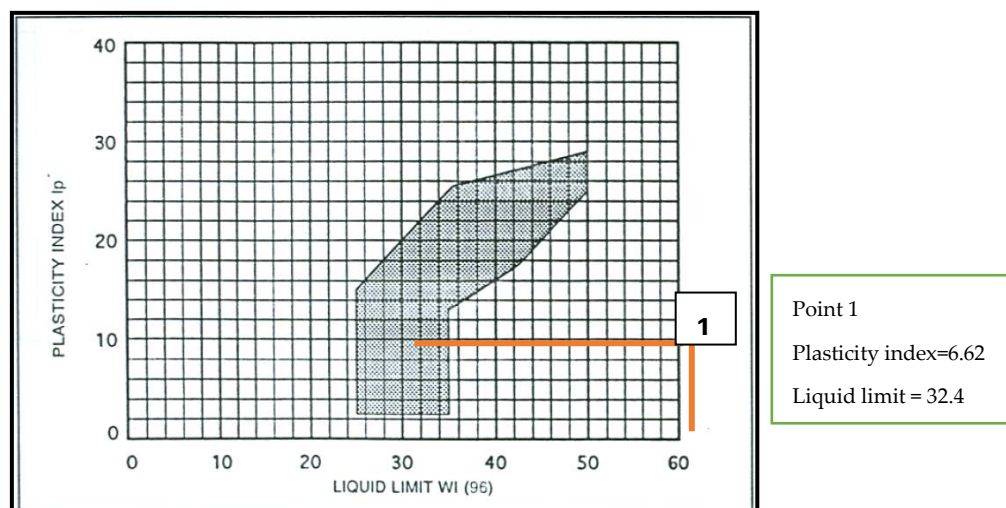
4.3.3. Soil Plasticity

The Atterberg or plasticity tests define the moisture content at which the soil transitions from a liquid state to plastic state, and from plastic state to a solid state; these boundary points are the liquid limit and plastic limits, respectively [43]. The Atterberg limits allow the soil plasticity characteristics to be related to the suitable soil selection criteria. The plastic limit and liquid limit tests were conducted by using ASTM D2216 method. The linear shrinkage test, which measures the soil's contraction upon drying and believed to provide a combined measure of the soils' particle grading, plasticity, and clay type, was performed according to BS 1377-2. It gives an overall idea of the soil's behavior and suitability for stabilization. The Atterberg limit test results of the soil sample are summarized in Table 3.

Table 3. Atterberg limit test results of soil sample.

Atterberg limits	Value
Plastic limit	25.78
Liquid limit	32.4
Plasticity index	6.62
Shrinkage limit	7.15

Based on these results, the soil sample was evaluated for suitability in the plasticity chart as shown in Figure 3, by applying the Atterberg limit values from Table 3. The plasticity index of 6.62 and liquid limit of 32.4 falls at point “1” in the plasticity chart (Figure 3). Point “1” is in the shaded area, which indicates the suitability of the soil for CSEB production.

**Figure 3.** Plasticity chart.

Based on the laboratory results, the suitability of this soil for soil-cement block production was evaluated using compressed earth blocks standards criteria prepared by CDI and CRATerre-AEG [44]. The soil's particle grading and plasticity met the acceptable ranges for both criteria, allowing it to pass for further investigation.

4.3.4. Cement

In this study, Mughher Portland pozzolana cement was used as the binding material. The chemical composition of this cement is provided in a separate source [41]

4.3.5. Water

During the investigation, tap water provided by the Addis Ababa water system was used, in accordance with the recommendations of the African Standard, Compressed Stabilized Earth Blocks-Requirements, Production and Construction (WD-ARS 1333:2018) [45]. This standard specifies that water used in the production and curing of CSEBs must be clean and free from harmful substances. The use of potable tap water, as applied in this study, meets the criteria and is therefore considered suitable for both mixing and curing processes in CSEBs production.

4.4. Mix proportion

The following test programs were designed based on recommendations from relevant literature.

1. The first series of mixes (5 in total) was prepared to study the variation in compressive strength values with age of the blocks produced using Mugher Portland pozzolana cement. These mixes were made with a constant water content of 24% and varying cement contents of 4%, 6%, 8%, 10% and 12% by weight of the soil. The Mix proportions are summarized in Table 4.

Table 4. Materials mix design for the first series.

Mix code	Cement (kg)	Water (%)	Soil (kg)
MUG-4	4	24	100.45
MUG-6	6	24	100.45
MUG-8	8	24	100.45
MUG-10	10	24	100.45
MUG-12	12	24	100.45

2. The second series of mixes (4 in total) was conducted to evaluate the effect of moulding pressure on the compressive strength of the blocks and the effectiveness of the cement stabilizer. These mixes were produced using moulding pressures of 4MPa, 6MPa, 8MPa and 10MP, with cement contents of 6%, 8%, 10% and 12% by weight of soil. The mix proportions are presented in Table 5.

Table 5 Materials mix design for the second series

Mix code	Cement (Kg)	Mould pressure (MPa)
C6P4	6	4
C6P6	6	6
C6P8	6	8
C6P10	6	10
C8P4	8	4
C8P6	8	6
C8P8	8	8
C8P10	8	10
C10P4	10	4
C10P6	10	6
C10P8	10	8
C10P10	10	10
C12P4	12	4
C12P6	12	6
C12P8	12	8
C12P10	12	10

4.5 Specimen Preparation

A pre-installed M7 E380 block-making machine, designed on the quasi-static compression principle, was used to produce all block samples. To facilitate demoulding, the mould lining was lightly lubricated with used engine oil prior to each compression cycle. The soil— pre-weighed, packed, and sealed in light transparent plastic bags— was carefully poured into the mould. After each addition, the soil was leveled within the mould to ensure uniform compaction. The M7 E380 machine was operated strictly in accordance with its operational manual.

Compaction was performed using a side-mounted pump applying a pressure of 10 MPa. Hydraulic pressure was then released using the flow valve screw, causing the hand pump to slacken the top ram of the mould was lifted to reveal the freshly formed block, which was then carefully removed from the mould. The green blocks were carefully removed, placed on base plates, and immediately sealed in plastic bags to cure in the shade. The dimensions and weights of the green blocks were recorded. To maintain uniformity in production, all test specimens were prepared at the Selam Technical and Vocational Center in Addis Ababa.

4.6 Tests on blocks

4.6.1 Compressive strength test

The main aim of the compressive strength tests was to assess the block's performance under wet conditions. These tests were conducted in accordance with ASTM standards, Volume 04.08 - Soil and Rock [39]. The blocks underwent wet curing for 7, 14, 28, and 56 days, after which their dimensions and weights were recorded. A 100 KN testing machine, certified and calibrated by Hydraform, was used throughout the testing process..

For each mix proportion, three test samples were produced, and the mean value of the three results was used to represent the specific mix. The sample mould measured 22×22×11 cm. Prior to testing, all specimens were immersed in tap water for a duration of 24 hours. After soaking, the samples were allowed to rest for 30 minutes to enable excess surface water to drain. The samples were then carefully positioned within the marking pins of the compression-testing machine and prepared for loading. The load was applied steadily at a rate of 3.5 MPa per minute until the block failed. Compressive strength under wet conditions was obtained by applying the peak load-to-area ratio.

4.6.2 Water Absorption Test

The block samples were first weighed in their dry state (W_d), then submerged in water for 24 hours, and subsequently reweighed (W_w). An electronic weighing machine with an accuracy of 0.05g was used for all measurements.

Water absorption by weight was determined using the following formula:

$$M_c = ((W_w - W_d) / W_d) \times 100 (\%)$$

Where:

M_c = Moisture absorption (%)

W_w = Wet sample mass (g)

W_d = Dry sample mass (g)

The acceptable range for water absorption in CSEBs, as per the guidelines, is between 15% and 20% [32].

5. Results and Discussions

This section presents the findings from the experimental evaluation of compressed stabilized earth blocks (CSEBs), followed by a detailed interpretation of their implications. The analysis focuses

on key performance indicators such as compressive strength and water absorption, which are essential for evaluating the block's structural integrity and long-term durability. Water absorption was assessed through controlled drying and soaking procedures, allowing for the evaluation of moisture resistance across varying cement stabilization levels. In addition to reporting the measured values, the discussion explores underlying trends, compares the findings with theoretical expectations and existing literature, and examines the implications of any observed deviations. This comprehensive approach supports a deeper understanding of CSEB behavior and informs strategies for improving their design, production, and application in sustainable construction.

5.1 Compressive Strength

The compressive strength of CSEBs is influenced by several manufacturing variables, including soil type, cement content, compaction pressure, moisture content, and curing methods. In this study, only the cement content was varied, while all other parameters were kept constant. This approach is supported by existing literature, which identifies stabilizer content as a key factor in enhancing strength, dimensional stability, and durability of soil-based construction materials.

5.1.1. Relationship Between Cement Proportion and Compressive Strength in Stabilized Soil Units

Table 6 and Figure 4 display the outcomes of the compressive strength evaluations. The data reveal a consistent pattern: compressive strength improves with increased cement content and extended curing durations. Blocks containing 6% or more cement content consistently met or exceeded the 28-day compressive strength threshold of 2 MPa, which is the minimum standard for class C hollow concrete blocks as specified in the ES [46]. Additionally, blocks containing 6% cement and evaluated after 56 days were found to comply with the required standards.

These findings suggest that, when properly manufactured, CSEBs can offer a competitive alternative to conventional hollow concrete blocks. Moreover, with higher cement content, these blocks can achieve superior performance compared to the hollow concrete blocks commonly available in the local market, which often do not meet standard specifications.

Table 6. Compressive strength trends of PPC- stabilized soil blocks.

Mix code	Mean compressive strength [MPa]			
	7 days	14 days	28 days	56 days
MUG-4	0.3	0.6	1	1.25
MUG-6	0.6	1.3	1.5	2.23
MUG-8	1.1	1.8	2.1	3.2
MUG-10	1.4	2.1	2.6	4.03
MUG-12	1.5	2.5	3.5	5.03

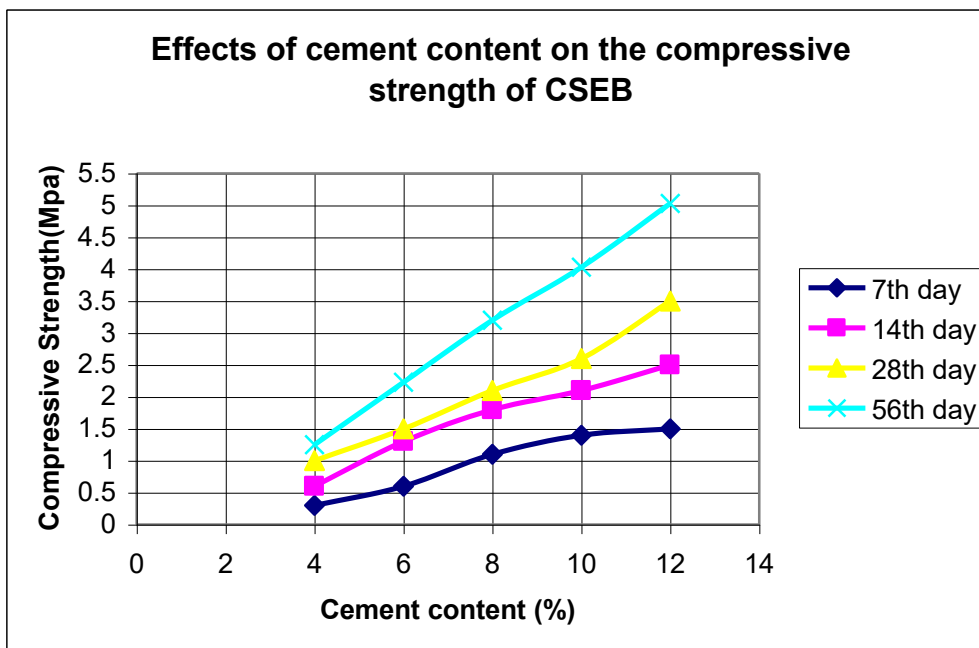


Figure 4. Impact of cement proportion on the compressive strength of stabilized soil blocks.

The results reveal both general and localized trends. Under constant compaction pressure, increasing cement content leads to higher compressive strength. Higher cement content enhances the bonding between soil particles through the development of cementitious compounds, leading to improved structural integrity. This mechanism is analogous to the hydration process in concrete - making process, where the chemical reaction between cement and water forms a matrix of interlocking crystals. The matrix envelops any inert filler, resulting in a high compressive strength and stability [37].

The results indicate that blocks produced with varying cement contents, from 4% to 12% in 2% increments at a constant compaction pressure of 10 MPa, exhibit 28-day wet compressive strength values that exceed most recommended minimum values for structural applications, except for blocks with 4% cement. Literature suggests various minimum values for 28-day wet compressive strength, all above 1.0 MPa. However, all block surpassed these minimum values at the 56-days.

The graphical data in Figures 4 illustrate the rate of strength development. While the absolute strength increases steadily, the rate of increase is more pronounced at higher cement contents. For instance, doubling the cement content from 4% to 8% at constant compaction pressure results in a 110% increase in compressive strength. Further doubling the cement content from 6% to 12% is projected to yield up to a 135% increase in wet compressive strength.

5.1.2. Effects of Compaction Pressure on the Compressive Strength Development

The data shown in Table 7 and Figure 5 reveal a clear trend: compressive strength increases as compaction pressure rises. For example, increasing the compaction pressure from 4 MPa to 10 MPa results in an almost twofold improvement in compressive strength. Based on these findings, a compaction pressure of 8-10 MPa is recommended to produce high-quality blocks.

While the stabilizer content is essential for binding and stabilizing the soil matrix, compaction pressure plays a critical role in densifying the material and reducing internal voids. This densification improves the effectiveness of the stabilizer, enhances strength and impact resistance, and reduces the potential for shrinkage, swelling, cracking and provides a waterproofing film. The benefits of stabilization are significantly amplified when the soil is adequately compacted.

All specimens in this investigation were compacted at 10 MPa before undergoing the curing process – a level considered sufficient for producing high-quality blocks. However, in practice,

many CSEB producers, including Selam Technical and Vocational Center, use compaction pressures much lower than 10 MPa.

To evaluate the combined effects of cement content and compaction pressure, additional tests were conducted using the mix proportions outlined in Table 5. The results, shown in Table 7 and Figure 5, confirm that compressive strength increases with compaction pressure across all cement content levels (4% to 12%).

Table 7. Effects of compaction pressure on the 28 days compressive strength of concrete.

Cement content (%)	Compaction pressure Mpa			
	4	6	8	10
	Compressive strength of CSEB (MPa)			
6	0.1	0.9	1.2	1.7
8	1.3	1.65	2.1	2.6
10	1.4	2.2	2.6	2.75
12	1.8	2.4	2.95	3.4

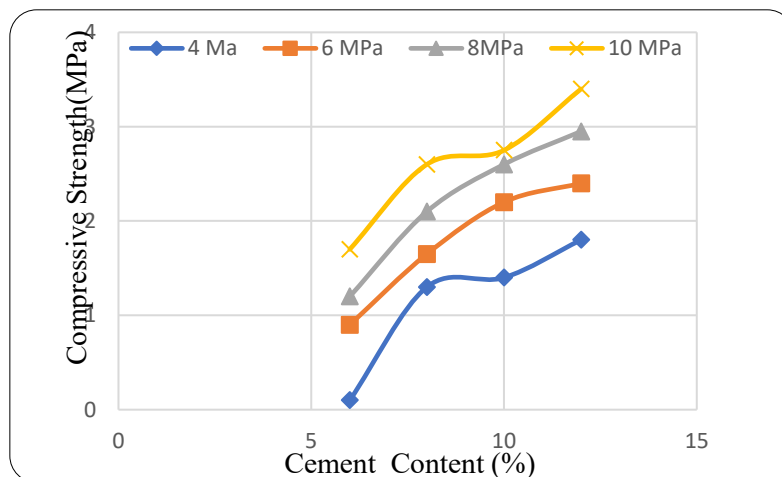


Figure 5. Influence of compaction pressure on compressive strength of CSSB units.

Table 7 presents the compressive strength outcomes for CSEB samples prepared with cement contents between 4% and 12 %, subjected to compaction pressure from 4 MPa TO 10 MPa at 2 MPa increments. The results demonstrate that compaction pressure significantly affects the compressive strength of soil-cement blocks. Specifically, higher compaction pressures result in greater compressive strength. For instance, when the compaction pressure is doubled from 4 MPa to 8 MPa at constant cement contents of 8%, 10%, and 12%, the compressive strength increases by 62%, 86%, and 64%, respectively. The findings highlight the importance of optimizing compaction pressure in the production of CSEBs to ensure both structural and performance and material efficiency.

In addition to their mechanical performance, CSEBs contribute meaningfully to climate mitigation efforts by offering a significantly lower embodied carbon footprint compared to conventional concrete blocks. This is primarily due to their use of locally sourced soil and reduced reliance on energy-intensive materials like Portland cement. According to the UNEP report Building Materials and the Climate: Constructing a new future [2], shifting to regenerative materials such as stabilized earth blocks is essential for achieving net-zero emissions in the built environment by 2050. Supporting this, a comparative analysis of two real-world projects in Bangalore, India found that the whole life embodied carbon of a CSEB building (Mud Decisions project) was only 192 kg Co₂ e/m²,

compared to 747 kg Co₂ e/m² for a conventional concrete structure (SUVI project) [47]. The findings underscore the potential of CESBs as technically viable and environmentally responsible alternative for sustainable construction. construction.

5.2 Water Absorption

As shown in figure 6, water absorption decreases with increasing cement content in the blocks. The results show a clear inverse relationship: as cement content increases, water absorption decreases. Average water absorption decreases from 15.81% at 4% cement content to 9.8% at 12%, indicating improved density and reduced porosity. Even at lowest cement content, the absorption remains within the acceptable limit of 15% recommended by Kerali [32].

Notably, there is minimum variations in absorption between 6% and 10% cement content, suggesting that 6% cement content may be sufficient to meet sorptivity requirements under standard conditions. Doubling the cement content from 4% to 8% results in a 10% reduction in mean water absorption, while increasing it from 6% to 12% yields a 30% reduction. These findings confirm that higher cement content enhances the block's resistance to moisture ingress.

Moisture ingress into the block can occur in liquid form, such as via precipitation or capillary rise, or in vapor form through processes like condensation or adsorption. However, moisture typically exits the block through evaporation. Therefore, the water content of the wall should be determined not only by its contact with water sources but also by its water vapor balance, i.e., evaporation minus condensation and adsorption. Seasonal variations significantly influence moisture content, with elevated levels observed during the rainy season and reduced levels in dry periods. These fluctuations add complexity to moisture behavior and should be factored into durability evaluations and design planning. Moreover, the role of moisture transport mechanisms and seasonal impacts has been extensively studies in relation to the hydraulic performance of stabilized earth blocks, highlighting their relevance in assessing long-term durability [48].

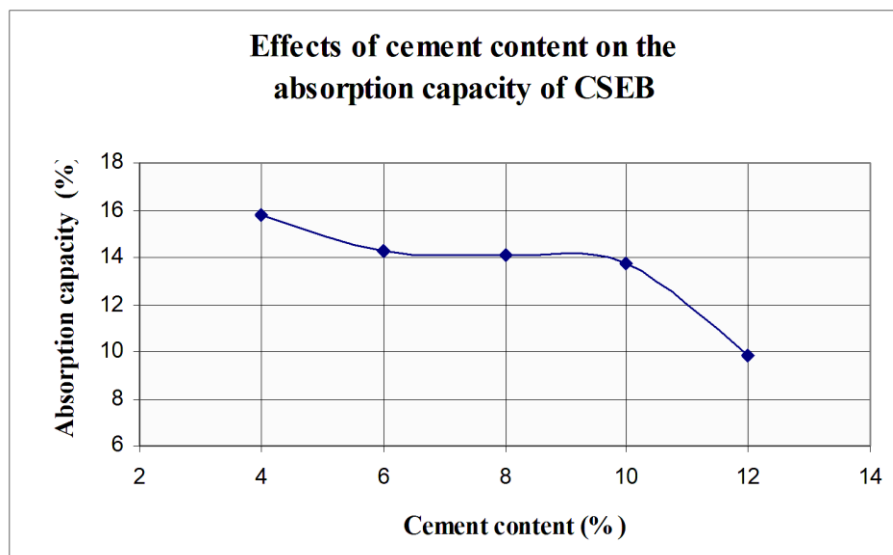


Figure 6. Influence of cement proportion on water absorption in soil cement blocks.

5.3. Cement Savings, Decarbonization Impact, and Global Implications

The experimental results confirmed that blocks stabilized with 6% cement content meet the minimum structural strength requirements for wall construction, making this the optimal mix for technical and environmental performance. Each block (22 cm × 22 cm × 10 cm) requires approximately 0.502 kg of cement. With 21 blocks per m², the cement consumption per square meter is: 21×0.502≈10.54 kg (plus 1.5 kg for pointing) ≈ 12.04 kg/m².

For a 100 m² wall, this equals 1,204 kg (\approx 1.2 tonnes). In comparison, Hollow Concrete Blocks (HCBs), including plastering and mortar, consume:

- HCB Class C: 29.8 kg/m² \rightarrow 2,980 kg per 100 m²
- HCB Class B: 36.8 kg/m² \rightarrow 3,680 kg per 100 m²

This represents cement savings of:

- 1,776 kg compared to HCB Class C
- 2,476 kg compared to HCB Class B

Given that each tonne of cement emits approximately 0.8 tonnes of CO₂ [49], these savings correspond to 1.4 – 2.0 tonnes of CO₂ emissions avoided per 100 m² wall.

Global projection: Low-income housing and decarbonization potential

According to UN-Habitat, an estimated 9, 6000 new homes need to be built daily, approximately 35 million affordable homes annually to close the global housing gap by 2030 [50].

Assuming an average house size of 50 m² and wall area of 50 m²:

- HCB Class C: 1,490 kg per house \rightarrow 52.15 million tonnes/year
- CSEB (6%): 630 kg per house \rightarrow 22.05 million tonnes/year
- Annual savings: \sim 30 million tonnes of cement
- CO₂ avoided: \sim 24 million tonnes/year.

These projections underscore the transformative potential of CSEBs in achieving Paris Agreement targets and advancing SDG 1, 11, 12, and 13. Scaling up CSEB adoption globally could significantly reduce embodied carbon while addressing housing affordability and social equity. The confirmation of 6% cement content as optimal aligns with the theory of decarbonization, which emphasizes reducing embodied carbon in building materials. Cement production accounts for 8% of global CO₂ emissions [3], making material substitution critical for climate mitigation. By reducing cement consumption by over 50%, CSEBs offer a practical solution for low-carbon construction.

This performance supports:

- Paris Agreement and UNEP's Net-Zero Roadmap: Advocating regenerative, locally sourced materials.
- SDG 1 (No Poverty): Lower costs and local production enable affordable housing and create employment opportunities.
- SDG 11 (Sustainable Cities and Communities): Promotes resilient, resource-efficient building practices adaptable to local contexts.
- SDG 12 (Responsible Consumption and Production): Encourages circular economy principles by using natural and industrial by-products.
- SDG 13 (Climate Action): Reduces embodied and operational carbon, contributing to global climate mitigation targets.

6. Conclusions and Recommendations

This study investigated the performance of compressed stabilized earth blocks (CSEBs) using Portland pozzolana cement (PPC) as a stabilizer, with a focus on mechanical strength, water absorption, and environmental sustainability. The findings demonstrate that CSEBs, when properly designed and produced, can meet structural and durability requirements while offering significant environmental advantages over conventional masonry units.

6.1. Technical Performance

Experimental results confirmed that increasing cement content significantly enhances the compressive strength and durability of CSEBs. At a constant compaction pressure of 10 MPa, increasing cement content from 4% to 8% resulted in a 110% increase in compressive strength. While compaction pressure contributes to strength development, cement content had a more pronounced effect. Water absorption decreased with higher cement content, with blocks containing 6% or more cement meeting recommended thresholds for moisture resistance.

The ideal soil composition for CSEBs was found to be approximately 75% sand and 25% silt and clay, with a minimum of 10% clay to ensure cohesion and workability. Soil sourced from the Kara area of Addis Ababa (70% sand, 16.25% silt, 13.75% clay) proved suitable for block production, underscoring the importance of site-specific soil testing and mix optimization.

6.2. Environmental Implications

The findings of this study underscore the significant environmental benefits of using Compressed Stabilized Earth Blocks (CSEBs) as a sustainable alternative to conventional masonry units. By utilizing locally available soil and incorporating Portland Pozzolana Cement (PPC) at an optimal 6% content, CSEBs achieve the necessary structural performance while substantially reducing cement consumption. For a standard 100 m² wall, CSEBs require approximately 1.2 tonnes of cement, compared to 2.98–3.68 tonnes for conventional Hollow Concrete Blocks (HCBs), resulting in cement savings of 1.8–2.5 tonnes. Given that each tonne of cement emits approximately 0.8 tonnes of CO₂, this translates to a reduction of 1.4–2.0 tonnes of CO₂ emissions per 100 m² wall.

When scaled to meet global affordable housing needs—estimated at 35 million homes annually—CSEBs could reduce cement demand by approximately 30 million tonnes per year, avoiding up to 24 million tonnes of CO₂ emissions. These results demonstrate that CSEBs not only meet technical and durability standards but also align with global decarbonization goals, including the Paris Agreement and the UNEP's Net-Zero Roadmap. Furthermore, the use of PPC, which incorporates industrial by-products, enhances the environmental performance of CSEBs by further lowering embodied carbon. Thus, CSEBs represent a practical and scalable solution for reducing the carbon footprint of the built environment, particularly in low- and middle-income contexts where sustainable and affordable housing is urgently needed.

6.3. Practical Considerations

Effective quality control is essential for ensuring consistent block performance. Key factors include soil selection, moisture content, compaction pressure, and curing practices. For enhanced durability, it is recommended to plaster the first two courses of walls and design roof overhangs to minimize moisture exposure. In small-scale or rural contexts, simple field tests and trial block production can serve as cost-effective quality assurance measures.

6.4. Social and Policy Dimensions

Despite their technical and environmental merits, CSEBs often face social resistance due to perceptions of earth construction as inferior or “low-cost.” Addressing this requires coordinated efforts from architects, engineers, policymakers, and educators to promote awareness and acceptance. Integrating CSEBs into affordable housing initiatives can simultaneously address housing shortages and advance sustainable development goals.

6.5. Future Research

To enhance the versatility of CSEBs, it is advisable to pursue further investigations in the following domains:

- Development of long-term durability models under varying climatic conditions
- Performance evaluation of CSEBs made from diverse soil types, including clay-rich and marginal soils
- Investigation of chemical and organic soil components that inhibit cement hydration
- Exploration of alternative or supplementary stabilizers to enhance performance and reduce costs

These findings affirm that CSEBs stabilized with Portland pozzolana cement represent a technically viable and environmentally responsible solution for sustainable construction. With appropriate design, quality control, and policy support, they can play a pivotal role in reducing the

carbon footprint of the built environment while addressing critical housing needs in a resource-efficient and socially inclusive manner.

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