Available online at www.CivileJournal.org

Civil Engineering Journal

(E-ISSN: 2476-3055; ISSN: 2676-6957)

Vol. 11, No. 05, May, 2025

Sustainable Interlocking Blocks Containing Sugarcane Bagasse Ash: Structural Integrity, Cost Efficiency, and Environmental Benefits

Nitirach Sa-nguanduan [1], Kamol Amornfa [1*]

[1] *Faculty of Engineering at Kamphaeng Saen, Kasetsart University, Kamphaeng Saen, Nakhon Pathom 73140, Thailand.*

Received 10 February 2025; Revised 19 April 2025; Accepted 25 April 2025; Published 01 May 2025

Abstract

This study aimed to evaluate the potential use of sugarcane bagasse ash (SCBA) as a partial replacement for Portland cement in interlocking blocks to enhance sustainability, reduce costs, and mitigate environmental impacts. The research objectives included assessing the compressive strength, water absorption, durability, microstructural characteristics, cost-effectiveness, and carbon footprint of SCBA-modified interlocking blocks. Experiments followed established standards, using various SCBA replacement levels (5–30%), with performance evaluated through mechanical testing, SEM analysis, cost assessment, and life cycle carbon footprint calculation. The findings demonstrated that interlocking blocks with 20% SCBA substitution maintained structural integrity, achieving a compressive strength of over 7 MPa, with acceptable water absorption and excellent durability. Cost analysis showed savings of up to 7.53%, while environmental assessment revealed carbon emission reductions of 17.99%. Microstructural analysis confirmed the presence of calcium silicate hydrate, supporting strength development. The study also introduced the SCOPEC framework (Selection of materials, Composition and mix optimization, Operational performance, Production consistency, Economic feasibility, and Carbon reduction), offering practical guidance for SCBA utilization in sustainable block production. This research contributes a novel, scalable solution to reduce cement consumption, enhance resource efficiency, and promote eco-friendly construction materials for affordable housing projects.

Keywords: Sustainable Construction; Sugarcane Bagasse Ash; Interlocking Blocks; Cement Replacement; Pozzolanic Materials; Carbon Footprint Reduction; Cost-Effective Masonry.

1. Introduction

1.1. Background and Research Theory on Interlocking Blocks and SCBA

Interlocking blocks are becoming more popular in construction due to their cost-effectiveness and ease of assembly, requiring minimal mortar [1-3]. Typically, these blocks are produced using a mixture of lateritic soil, cement, and water that is compressed under high pressure to achieve structural integrity. Interlocking blocks have been widely studied for affordable housing and sustainable construction, with research highlighting their potential to reduce material costs while improving construction efficiency [4, 5].

In Thailand, the Thailand Institute of Scientific and Technological Research (TISTR) has been at the forefront of promoting interlocking blocks by utilizing locally available materials, contributing to both the sustainability and economic viability of housing projects. TISTR has made advancements in the size, weight, use of composite materials, and shape of these blocks to support a wider range of applications, thereby creating employment opportunities for local communities [6]. Figure 1 illustrates interlocking blocks and their assembly, as recommended by TISTR. In small-scale

* Corresponding author: fengkma@ku.ac.th

http://dx.doi.org/10.28991/CEJ-2025-011-05-024

production, manual tools and laborers, such as those unemployed from agriculture, can produce interlocking blocks during their free time for personal use, following TISTR's recommended proportions without complex inspections. Conversely, large-scale commercial production that utilizes hydraulic equipment requires appropriate quality control measures. However, the lack of a standardized block size in Thailand presents a challenge for large-scale manufacturing, as blocks from different manufacturers may not be compatible with each other.

Figure 1. Interlocking blocks and their assembly as recommended by TISTR

One promising avenue for enhancing the sustainability of interlocking blocks is the incorporation of sugarcane bagasse ash (SCBA), a by-product of the sugar industry. SCBA is rich in silica and exhibits pozzolanic properties, which allow it to partially replace cement in concrete, improving its environmental footprint and cost-effectiveness [7-9]. Recent studies have demonstrated that SCBA can enhance the mechanical properties and durability of cement-based materials, including improved compressive strength and resistance to water absorption [10-12]. Furthermore, the consistent chemical composition of SCBA across different batches ensures predictable performance, making it a reliable substitute for cement [4, 13]. However, while SCBA has been widely studied in conventional concrete applications, its use in interlocking blocks, particularly those made with tropical lateritic soils, remains underexplored [14].

1.2. Problem Statement and Objectives

The rising cost of Portland cement, coupled with its significant environmental impact—contributing nearly 8% of global CO_2 emissions—poses a major challenge for sustainable construction [9-11]. Alternative materials that can replace a portion of cement while maintaining or improving the structural properties of building materials are urgently needed. SCBA, as a waste by-product from the sugar industry, offers a dual benefit: reducing the cost of cement-based materials and minimizing environmental impacts through waste repurposing [15-17].

While previous research has highlighted SCBA's potential in conventional concrete, limited studies have focused on its role in improving the performance of interlocking blocks, particularly those made with tropical soils such as lateritic soils [2, 3, 8]. This study aimed to fill this gap by evaluating the feasibility of using SCBA in the production of interlocking blocks, focusing on their engineering properties, durability, and cost-effectiveness. The primary objectives of this study were:

- To evaluate the engineering properties (compressive strength, water absorption, and durability) of SCBA-modified interlocking blocks.
- To analyze the microstructural characteristics of the blocks using scanning electron microscopy (SEM).
- To assess the cost-effectiveness of SCBA- modified interlocking blocks compared to conventional blocks.
- To evaluate the environmental impact of SCBA- modified interlocking blocks by estimating the reduction in CO_2 emissions through a life cycle assessment (LCA).

To propose a structured framework (SCOPEC) for optimizing SCBA use in interlocking block production interlocking block production.

1.3. Novelty and Theoretical/Practical Impact

The novelty of this study lies in its comprehensive approach to investigating the potential of SCBA-incorporated interlocking blocks. Unlike previous research focused on conventional concrete or mortar [16, 18], this study explores SCBA's use in soil-cement interlocking blocks made from locally available materials, particularly lateritic soils. The findings will contribute to the growing body of knowledge on the optimal use of SCBA, with a particular emphasis on meeting the strength and durability requirements of interlocking blocks while promoting sustainable material use.

The theoretical contributions of this study include insights into the pozzolanic reaction kinetics between SCBA and soil-cement matrices, addressing gaps in understanding hydration behavior and microstructural formation [19-21]. Practically, the results are expected to influence the development of low-cost, eco-friendly building materials for affordable housing projects, particularly in developing regions. The incorporation of SCBA can improve the durability of interlocking blocks while reducing dependence on Portland cement, ultimately leading to cost savings and a reduction in environmental impacts associated with cement production.

This study also proposed the SCOPEC framework (Selection of materials, Composition and mix optimization, Operational performance, Production consistency, Economic feasibility, and Carbon reduction) as a practical guideline for using SCBA in interlocking blocks, focusing on key factors such as material selection, mix design, and production quality. The findings aimed to assist policymakers, engineers, and researchers in developing cost-effective and eco-friendly building materials, potentially leading to industry adoption and policy recommendations.

1.4. Structure of the Article

The remainder of this paper is organized as follows: Section 2 describes the materials and methods, including material selection, mix design, experimental setup, testing procedures, and analysis methods. Section 3 presents the results and discussion of the findings on engineering properties, microstructural analysis, cost efficiency, and environmental impact. Section 4 proposes the SCOPEC framework to guide the implementation of SCBA in interlocking block production. Finally, Section 5 provides the conclusions and recommendations for future research and practical applications.

2. Material and Methods

A clear step-by-step process was applied to examine the properties and performance of interlocking blocks with SCBA. Figure 2 illustrates the stepwise process undertaken, from raw material selection to the final evaluation of environmental impact.

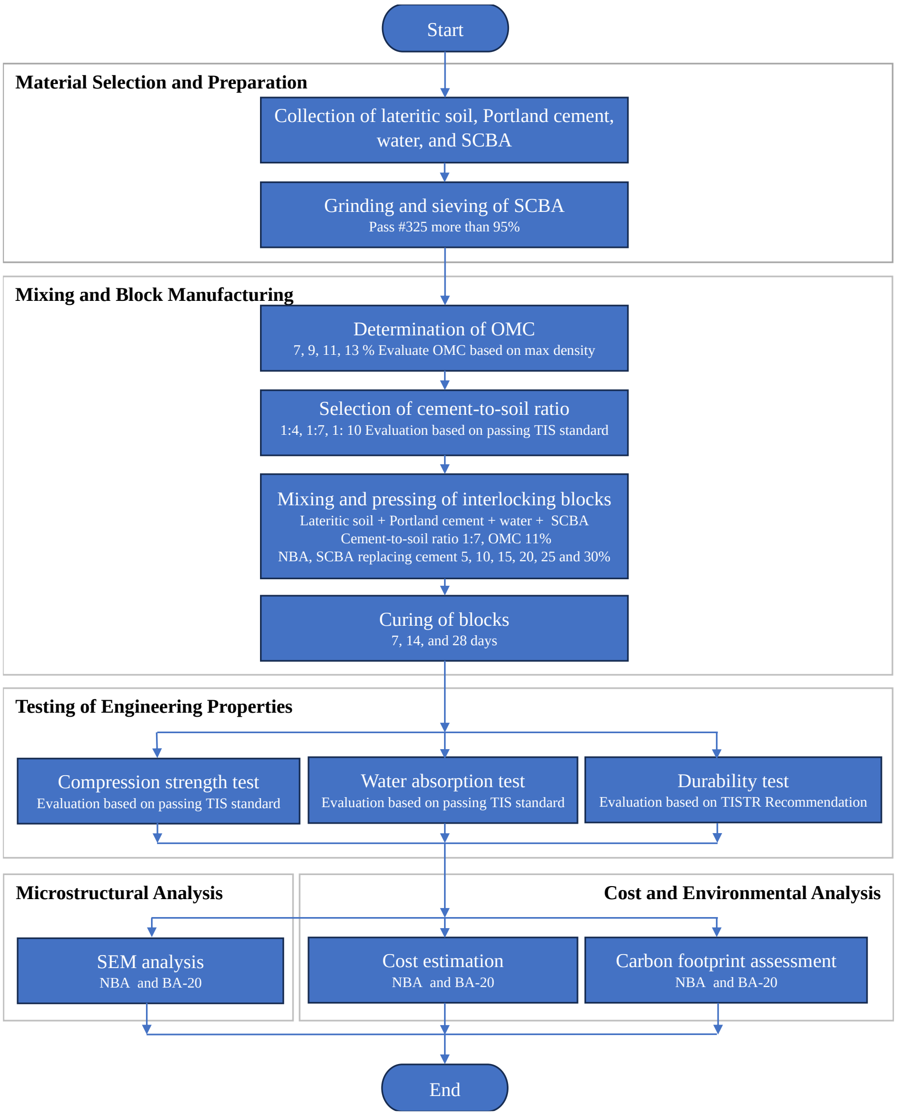

Figure 2. Research flowchart

2.1. Materials

The primary materials utilized were lateritic soil, Portland cement, SCBA, and water. The lateritic soil was selected based on its characteristic orange hue and was passed through a No. 4 sieve (4.75 mm). Any soil particles retained on the No. 4 sieve were pulverized until they were small enough to pass through the sieve. It is recommended that less than 35% of the soil should pass through a No. 200 sieve (0.075 mm) [6]. Amornfa [22] suggested an optimal range of 25–35% passing through the No. 200 sieve, as values below 25% may result in a coarse and unappealing block surface, while exceeding 35% could compromise strength. To achieve the desired particle size distribution, lateritic soil can be blended with sand or stone dust retained on the No. 200 sieve, ensuring 25–35% of the combined material passes through the No. 200 sieve. Prior to use, the soil mixture should be dried, either by sun exposure or in an oven. In this study, the sieved mixture was oven-dried. Portland cement Type I was used as the primary binder. The SCBA was procured from a single sugarcane mill to maintain consistency in its properties [13]. The SCBA underwent chemical composition analysis to confirm its pozzolanic potential. Subsequently, the SCBA was ground to achieve a fineness of >95% passing through a No. 325 sieve (45 µm) and oven-dried before utilization.

2.2. Testing Standards

All experimental procedures adhered to established testing standards to ensure reliability and reproducibility of results. The key standards referenced in this study were:

- Size and chemical composition of SCBA: ASTM C618-03 Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete [23].
- TIS 57-2533 (TIS 1990) or Thai Industrial Standard for Hollow Loadbearing Concrete Masonry Units [24], specifying the requirements for hollow loadbearing concrete blocks used in construction, including size, density, compressive strength, and water absorption. This standard has been made with reference to the ASTM C90-81 Standard Specification for Hollow Load-Bearing Concrete Masonry Units.
- Compression Test and Water Absorption Test: TIS 109-2517 (TIS 1974) or Thai Industrial Standard for Sampling and Testing Concrete Masonry Units [25]. This standard has been made with reference to the ASTM C140-70 Standard Methods of Sampling and Testing Concrete Masonry Units.
- Durability Test (Wet and Dry Process): ASTM D559-03 Standard Test Methods for Wetting and Drying Compacted Soil-Cement Mixtures [26].
- SEM analysis: ASTM E986-04 Standard Practice for Scanning Electron Microscope Beam Size Characterization [27].
- Carbon Footprint Assessment: ISO 14067 [28].

These standards provided a benchmark for evaluating the mechanical, physical, and environmental performance of the developed interlocking blocks.

2.3. Tests Performed

2.3.1. Determination of Optimum Moisture Content

The optimum moisture content for block production was determined by pressing blocks with varying moisture content, as shown in Figure 3. The moisture content corresponding to the maximum dry density was selected for block fabrication.

Figure 3. Interlocking block production

2.3.2. Selection of Cement-to-Soil Ratio

The optimal cement-to-soil ratio was determined based on the compressive strength criteria. Blocks were prepared with varying cement proportions (1:4, 1:7, 1:10), and the mix achieving a minimum compressive strength of 7 MPa (according to TIS 57-2533) was selected.

2.3.3. Compressive Strength Test

The compressive strength test was performed following TIS 109-2517, as shown in Figure 4. Interlocking blocks were tested at curing ages of 7, 14, and 28 days. The results were compared to the required strength threshold to assess the effect of SCBA replacement levels:

- Blocks without SCBA (control group, NBA);
- Blocks incorporating 5% SCBA replacement (BA-5);
- Blocks incorporating 10% SCBA replacement (BA-10);
- Blocks incorporating 15% SCBA replacement (BA-15);
- Blocks incorporating 20% SCBA replacement (BA-20);
- Blocks incorporating 25% SCBA replacement (BA-25);
- Blocks incorporating 30% SCBA replacement (BA-30).

Figure 4. Compressive strength testing of interlocking block

2.3.4. Water Absorption Test

Water absorption was measured to evaluate the porosity of the blocks after 28 days. After weighing, each specimen was oven-dried at 105°C, submerged in water for 24 hours, and then reweighed to determine the percentage of water uptake, in accordance with TIS 109-2517.

2.3.5. Durability Test (Wet and Dry Cycles)

The durability of the SCBA-modified blocks was assessed using the ASTM D559-03 wet and dry cycle test. Samples after 28 days were subjected to cyclic soaking and drying, followed by brushing to simulate weathering effects. The weight loss after 12 cycles was recorded.

2.4. Microstructural Analysis

SEM analysis was used to investigate the internal structure and bonding mechanism of the interlocking blocks. Two sets of specimens were prepared:

- Blocks without SCBA (control group, NBA);
- Blocks incorporating 20% SCBA replacement, BA-20).

Samples were cured for 7, 14, and 28 days before being analyzed under an electron microscope. The obtained micrographs were used to examine the degree of hydration, pore structure, and interface characteristics between soil particles and cementitious materials.

2.5. Cost Analysis

A comparative cost analysis, based on local pricing, was conducted to evaluate the economic feasibility of SCBA-modified interlocking blocks. The assessment considered:

- Fixed costs: machinery and equipment
- Variable costs: raw materials, labor, energy consumption
- Transportation costs: SCBA was assumed to be sourced from a sugarcane mill located 37 km from the production site

The cost per block was calculated for both small-scale manual production and large-scale hydraulic press production.

2.6. Environmental Impact Assessment

The environmental impact of SCBA incorporation was quantified based on a carbon footprint analysis, focusing on the raw material acquisition and manufacturing processes. The assessment followed the "Cradle-to-Gate" approach, considering CO_2 emissions from:

- Cement production
- SCBA processing and transportation
- Block manufacturing (pressing and curing)

The total CO_2 emissions per block were estimated using Equation 1:

$$CO_2\ emission = a \times b \tag{1}$$

where a is the activity data (energy consumption, material usage) and b is the CO_2 emission factor. The results provided insight into the environmental benefits of reducing the cement content through SCBA substitution.

3. Results and Discussion

3.1. Physical and Chemical Properties

3.1.1. Lateritic Soil

The lateritic soil utilized in this study was obtained from Kamphaeng Saen district, Nakhon Pathom province, Thailand. The soil had a specific gravity of 2.85, with 100% passing through a No. 4 sieve and 32.44% passing through a No. 200 sieve. Atterberg's Limit tests revealed that the soil was non-plastic. Based on the American Association of State Highway and Transportation Officials (AASHTO) classification, it was A-2-4 soil, while the Unified Soil Classification System (USCS) method categorized it as SM soil. The granular shape observed in the SEM analysis (Figure 5) suggests that these particles may facilitate the compaction and stabilization of the blocks, contributing to strength development through effective inter-particle bonding.

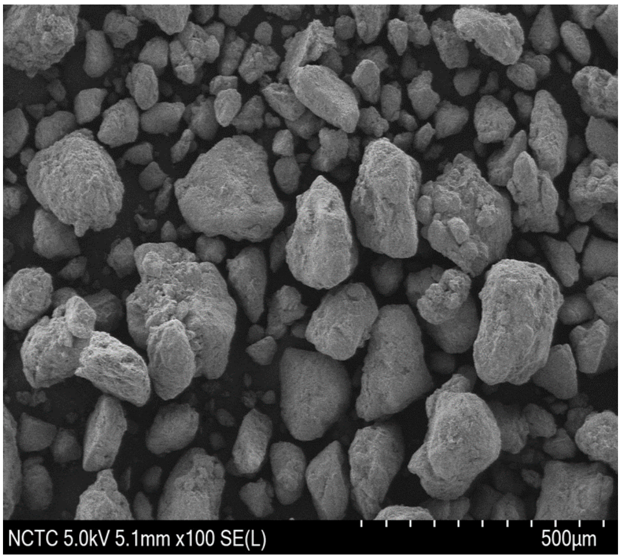

Figure 5. Scanning electron micrograph of lateritic soil

3.1.2. Portland Cement Type 1

Portland Cement Type 1, characterized by angular, irregular particles (Figure 6), provided superior bonding properties essential for the formation of strong, durable interlocking blocks. The irregular shapes of the cement particles improved the bonding with both the lateritic soil and SCBA, aiding the formation of a cohesive and robust matrix. This also enhanced the development of hydration products such as CSH, crucial for the material's compressive strength over time.

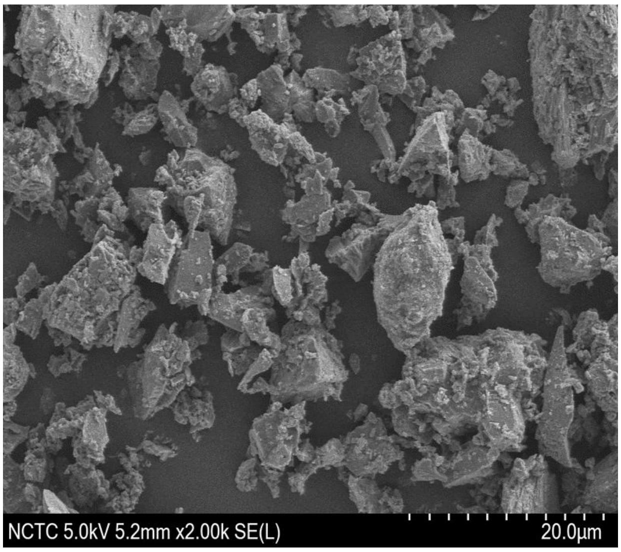

Figure 6. Scanning electron micrograph of cement

3.1.3. Sugarcane Bagasse Ash

The SCBA was sourced from a sugar factory in Tha Maka district, Kanchanaburi province, Thailand. The SCBA was finely ground using a Los Angeles machine, achieving a fineness where >95% passed through the No. 325 mesh sieve. This level of fineness considerably enhanced the strength of blocks when the SCBA replaced 20% of the cement for a cement-to-laterite ratio of 1:7, as depicted in Figure 7. Similar findings have been reported by Gudia et al. [8], where finely ground SCBA produced improved pozzolanic activity and contributed to strength enhancement in mortar formulations, particularly at replacement levels <20%.

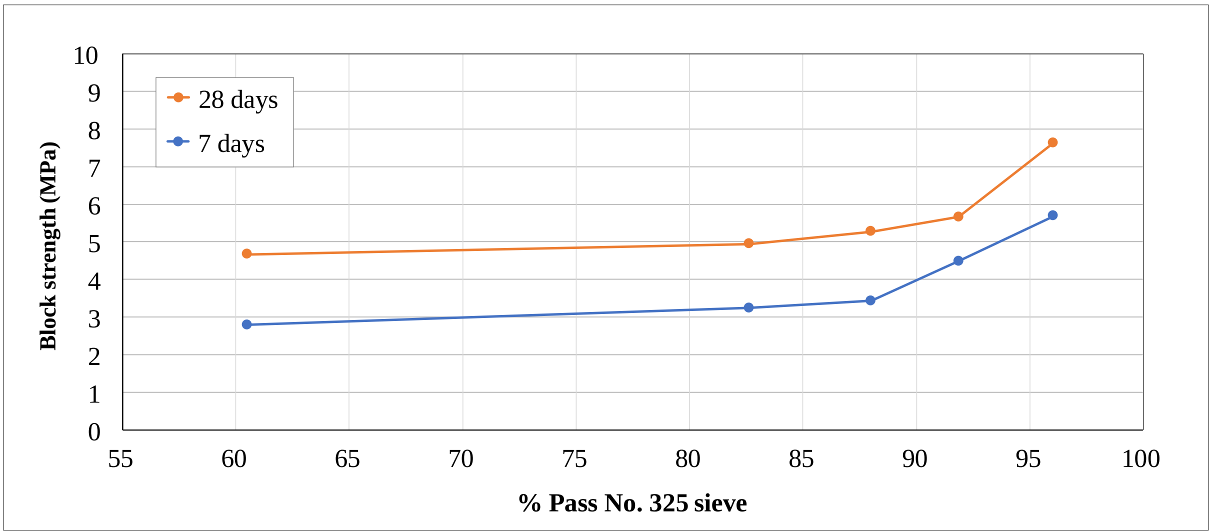

Figure 7. Effect of SCBA fineness (percentage passing through No. 325 sieve) on block strength

The SEM analysis of the SCBA (Figure 8) revealed porous and irregularly shaped particles that contributed to its pozzolanic activity due to its fine particle size, which facilitates the formation of additional CSH. The chemical composition of SCBA is detailed in Table 1, with SiO_2 accounting for 72.3%, Al_2O_3 for 8.6%, and Fe_2O_3 for 3.5%, making a total of 84.4% for the primary pozzolanic compounds ($SiO_2 + Al_2O_3 + Fe_2O_3$). This met the Class F pozzolan criteria outlined in ASTM C618-03, capable of enhancing the hydration reactions in cement-based systems. These chemical properties were consistent with the findings of Jahanzaib Khalil et al. [14], who reported a similar SiO_2 content in SCBA samples, emphasizing their suitability for use as a pozzolanic material in cement-based composites.

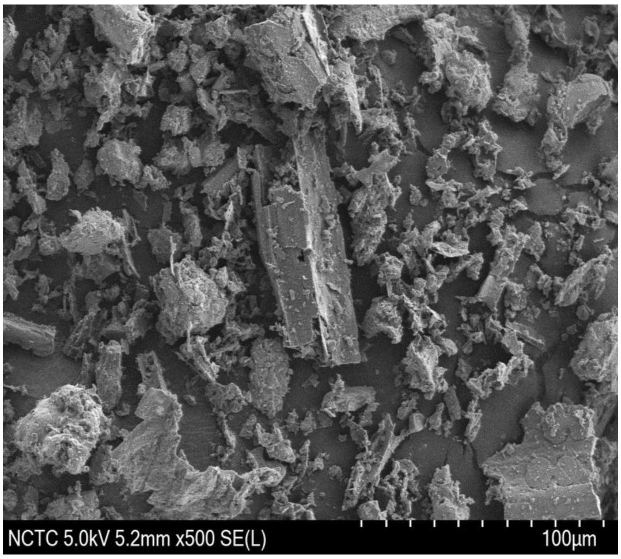

Figure 8. Scanning electron micrograph of SCBA

Table 1. Chemical composition of SCBA

Compound	Percentage
SiO_2	72.3
Al_2O_3	8.6
Fe_2O_3	3.5
CaO	5.2
Others	10.4

Furthermore, consistency in the SCBA chemical composition from this factory was reported by Sa-nguanduan et al. [13]. Their study examined SCBA from three production years at the same factory and found minimal variance in the SCBA chemical composition, with the SiO_2 content in the range of 67.00–73.20%, with an average of 71.54% (standard deviation 2.91, coefficient of variation 4.06%). The pozzolanic compounds ($SiO_2 + Al_2O_3 + Fe_2O_3$) were in the range of 80.94–85.13%, averaging 84.70% (standard deviation 3.91, coefficient of variation 4.61%). Based on their results, the strength tests of interlocking blocks produced using SCBA from different production cycles showed consistent performance at 7 and 28 days of curing.

3.2. Engineering Tests and Performance Evaluation

An in-depth analysis was carried out of the engineering tests used to evaluate the performance of the interlocking blocks made with SCBA as a partial replacement for cement.

3.2.1. Optimum Water Content for Block Compression

The effect of varying the water content on the dry density of interlocking blocks was investigated using a cement-to-soil ratio of 1:7. The results are summarized in Table 2.

Table 2. Effect of water content on dry density

Water content (%)	Dry density (kg/m³)
7	1,931
9	2,024
11	2,166
13	2,150

Based on these results, the dry density increased with water content up to an optimal value of 11%, beyond which it declined. This behavior was consistent with compaction theory, where sufficient moisture enhances particle packing by acting as a lubricant and reducing void spaces, with excess water introducing pores during evaporation and reducing the density.

Discussion: The observed optimal water content ensured maximum compaction, which is critical for achieving high compressive strength. This water content minimized voids and enhanced particle interlocking, especially as the blocks contained SCBA, where the pozzolanic reaction depends on moisture for effective chemical bonding.

3.2.2. Optimal Cement-to-Soil Ratio

To balance strength and cost, compressive strength was tested at varying cement-to-soil ratios. The results are shown in Table 3.

Table 3. Compressive strength of blocks at different cement-to-soil ratios

Cement-to-soil ratio	Compressive strength at 28 days (MPa)
1:4	11.37
1:7	10.03
1:10	4.20

While the 1:4 ratio produced the highest strength, the 1:7 ratio met the TIS 57-2533 standard of 7 MPa. Therefore, this latter ratio was selected for subsequent tests as it provided a balance between the strength and material cost, with a compressive strength of 10.03 MPa at 28 days. The lower ratio, 1:10, resulted in a drop in compressive strength, confirming that higher cement content is critical for strength but also increases material cost.

Discussion: Using a 1:7 ratio was consistent with sustainability goals by reducing cement consumption without compromising block performance. This is particularly relevant when incorporating SCBA, which further reduces reliance on cement, thereby lowering the environmental footprint.

3.2.3. Compressive Strength Tests

The compressive strength of the interlocking blocks was tested at 7, 14, and 28 days, with different proportions of SCBA replacing cement (5%, 10%, 15%, 20%, 25%, or 30%). The results are summarized in Figure 9. For comparison, the strength requirement of TIS 57-2533 for load-bearing blocks is 7 MPa.

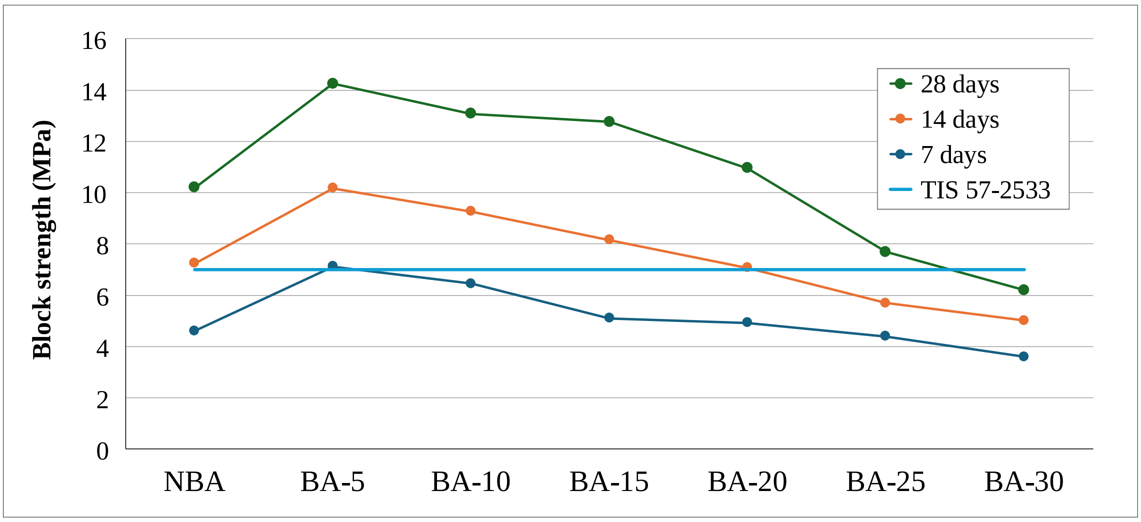

Figure 9. Compressive strength of blocks with SCBA replacement, where blue horizontal line is TIS 57-2533 strength requirement for load-bearing blocks

SCBA replacement at 5% resulted in the highest compressive strength, while strength values progressively declined beyond 10%, indicating an optimal threshold for maintaining structural integrity. Based on these results, BA-5 had the highest compressive strength at all curing ages, attributed to the pozzolanic reaction of the SCBA. However, beyond the 5% replacement level, the strength decreased, with BA-20 performing comparably to NBA at 28 days. Notably, BA-20 met the TIS 57-2533 standard while utilizing the highest SCBA proportion, optimizing the cost and environmental benefits without compromising the required strength for load-bearing applications. In this study, at 7 days, 5% SCBA replacement showed a compressive strength of 7.12 MPa, significantly higher than the control (NBA) at 4.61 MPa. At 14 days, the 5% SCBA showed a compressive strength of 10.03 MPa, and at 28 days, it reached 14.26 MPa, indicating significant strength improvement at lower SCBA replacement levels. These trends align with the findings from James et al. [29], who observed that incorporating SCBA into cement-stabilized soil blocks enhanced the compressive strength while still meeting standard requirements. However, as SCBA replacement levels increased (10%, 20%, 30%), the compressive strength progressively declined, consistent with the behavior observed in Hussien & Oan [1].

The effectiveness of SCBA as a partial replacement for cement in interlocking blocks lies primarily in its high amorphous silica content and pozzolanic properties, which promote the formation of additional calcium silicate hydrate (C-S-H), thereby enhancing the mechanical strength and durability of the blocks. The SCBA used in this study had an SiO_2 content of 72.3%, with combined pozzolanic compounds ($SiO_2 + Al_2O_3 + Fe_2O_3$) totaling 84.4%, meeting ASTM C618-03 criteria for Class F pozzolans. Additionally, SCBA's fine particle size and porous structure improve particle packing and reduce micro-cracking. However, there are some limitations. When the proportion of SCBA exceeds the optimal level (such as 20%), the amount of cement in the mixture becomes too low, leading to insufficient calcium hydroxide to fully react with the silica in SCBA. This limits the formation of strength-giving compounds and can result in reduced compressive strength. Although this study focused on substitution levels up to 30%, the data indicated that percentages beyond 20% significantly reduce strength, largely due to this dilution effect and reduced binder availability. While testing higher levels (such as 40%) could provide additional insight, the potential trade-offs would likely include a more pronounced loss of mechanical strength and durability, despite greater cost savings and marginal environmental benefits. Therefore, practical application must balance economic and environmental advantages with mechanical performance requirements, with 20% substitution emerging as the most effective compromise in this study.

Discussion: SCBA's pozzolanic activity contributed to strength development through the formation of calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH), enhancing particle binding. However, an excessive SCBA content reduced the block strength, likely due to a dilution effect and insufficient calcium ions from the cement for the pozzolanic reaction.

The use of SCBA at the 20% replacement ratio provided a balance between performance, economic feasibility, and sustainability. By reducing reliance on cement, BA-20 contributes to cost reduction and alleviates environmental issues, such as carbon emissions and industrial waste disposal. This demonstrated the potential of SCBA as an effective supplementary material in interlocking block production.

3.2.4. Water Absorption Test

The water absorption test was used to evaluate block porosity. The results are shown in Table 4.

Table 4. Water absorption of blocks

Block Code	Water Absorption (kg/m³)
NBA	183.6
BA-10	185.2
BA-20	188.0
BA-30	190.7

All blocks met the TIS 53-2533 standard (<208 kg/m³, with dry densities exceeding 2,000 kg/m³). BA-20 had slightly higher absorption due to the finer particle size and porous structure of the SCBA, which increased water retention.

Discussion: Although BA-20 had marginally higher water absorption, it was within acceptable limits (TIS 53-2533) confirming that the increase in absorption does not significantly impact the block's durability or suitability for construction purposes. Similar trends have been reported in other studies. For example, James et al. [29] and Jordan et al. [15] reported that while a higher SCBA content slightly increased water absorption, all their tested samples remained well within permissible limits. In this study, the water absorption at 10% SCBA was 185.2 kg/m³, 20% SCBA showed 188.0 kg/m³, and 30% SCBA resulted in 190.7 kg/m³, showing a slight increase in water absorption with higher SCBA content. This is in line with the findings from James et al. [29] and Jordan et al. [15], where the increase in water absorption remained within the acceptable range, indicating that even at higher SCBA replacement levels, the blocks' performance is still satisfactory for typical construction applications. Surface coatings could further enhance water resistance in practical applications.

3.2.5. Durability Evaluation

Durability was assessed using the wet-dry process (ASTM D559-03), with the results summarized in Table 5.

Table 5. Weight loss in durability tests

Block code	Weight loss (%)
NBA	1.032
BA-10	1.112
BA-20	1.251
BA-30	1.338

The durability tests revealed minimal weight loss across all block types, with all values being well below the 6% threshold recommended by the Thailand Institute of Scientific and Technological Research (TISTR) for interlocking blocks [6]. Similarly, the durability of blocks, measured through the wet and dry process (ASTM D559), showed a slight increase in weight loss as SCBA content increased. At NBA (control), the weight loss was 1.032%, which increased to 1.112% at 10% SCBA, 1.251% at 20% SCBA, and 1.338% at 30% SCBA. This trend is consistent with the durability findings in Jordan et al. [15], where the introduction of higher SCBA content resulted in marginally lower durability, but still met acceptable standards for use in construction.

Discussion: BA-20 demonstrated excellent durability, comparable to NBA, confirming the long-term stability of the SCBA-modified blocks under cyclic wetting and drying and making them suitable for diverse environmental conditions.

3.3. SEM Analysis

Two different sets of interlocking block samples were prepared for analysis. The first set (NBA) used no replacement of the cement with SCBA, while the second set (BA-20) replaced 20% of the cement with SCBA, based on results presented in the previous section regarding strength equivalence and compliance with TIS 57-2533. Both sets were compacted and cured for 7, 14, or 28 days. After curing, the compressive strength of the NBA samples was tested, while the BA-20 samples were examined using SEM to investigate internal structures and compare consistency.

3.3.1. SEM Observations

3.3.1.1. After 7 Days of Curing

The NBA SEM images (Figure 10) revealed the presence of ettringite in the form of long, slender rods distributed throughout the matrix. CSH, a product of the hydration reaction, was observed as small fibers scattered across the structure. Numerous pores were identified, indicating the early stage of hydration, which suggests the material is still in the process of developing its full strength.

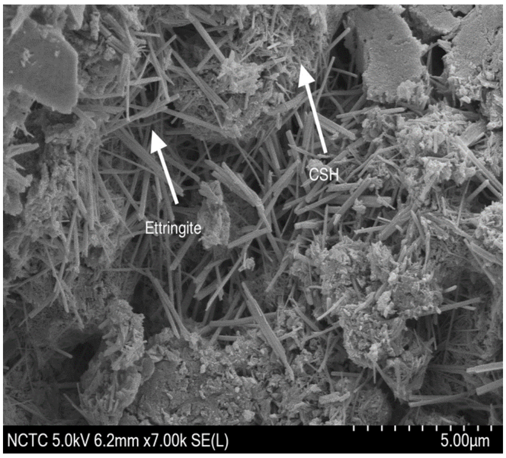

Figure 10. Scanning electron micrograph of interlocking block NBA after 7 days

The BA-20 SEM images (Figure 11) were similar to those of NBA, with ettringite and CSH both present. However, the replacement of cement with SCBA at a 20% replacement ratio did not greatly alter the initial microstructure, with both hydration products and pores still visible. This suggests that the early hydration process in the BA-20 mix proceeds similarly to NBA, with moderate compressive strength at this curing age.

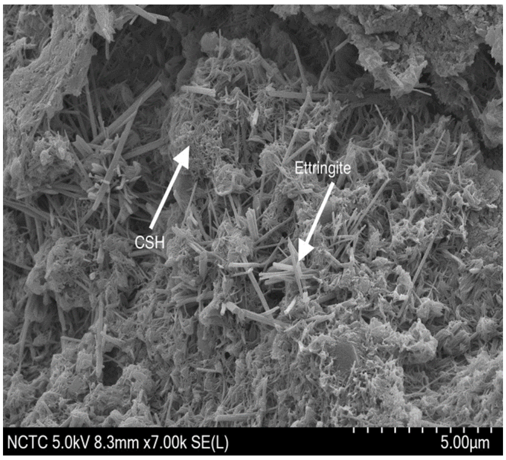

Figure 11. Scanning electron micrograph of interlocking block BA-20 after 7 days

3.3.1.2. After 14 Days of Curing

The NBA SEM image (Figure 12) showed the ettringite has stretched further within the pores, and the CSH fibers have begun to form a denser network around the ettringite crystals. These fibers were interconnected, creating a dense layer, reducing voids, and enhancing strength.

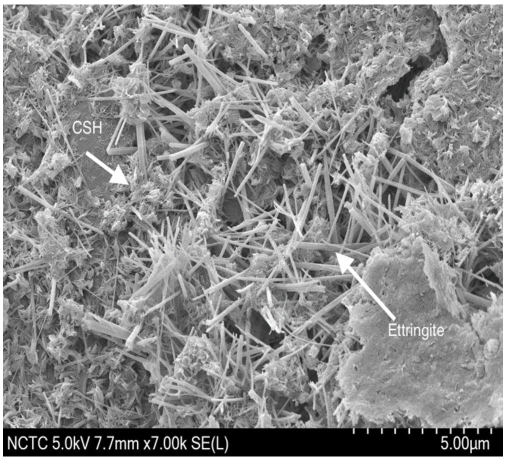

Figure 12. Scanning electron micrograph of interlocking block NBA after 14 days

The BA-20 SEM image (Figure 13) showed similar structural characteristics to NBA, with CSH fibers forming a dense, interconnected network that reduces internal voids. The structural consistency between the NBA and BA-20 samples at this curing age aligned with their comparable compressive strength results, indicating that SCBA does not negatively affect the hydration process at this stage.

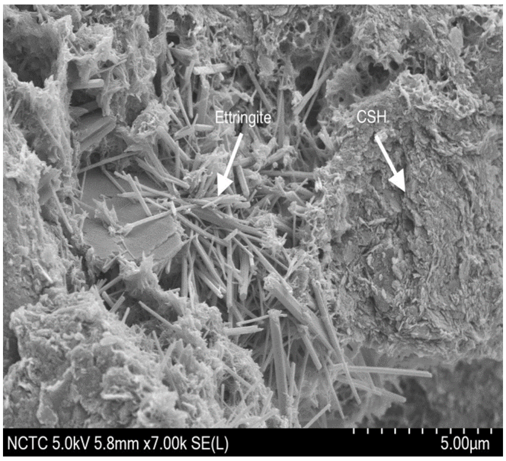

Figure 13. Scanning electron micrograph of interlocking block BA-20 after 14 days

3.3.1.3. After 28 Days of Curing

The NBA SEM image (Figure 14) showed that the pores within the structure were greatly reduced, with the remaining ettringite being less prominent due to the dense packing of hydration products that resulted in improved strength. This final structure indicated a mature state of hydration, contributing to the strength development observed in NBA blocks.

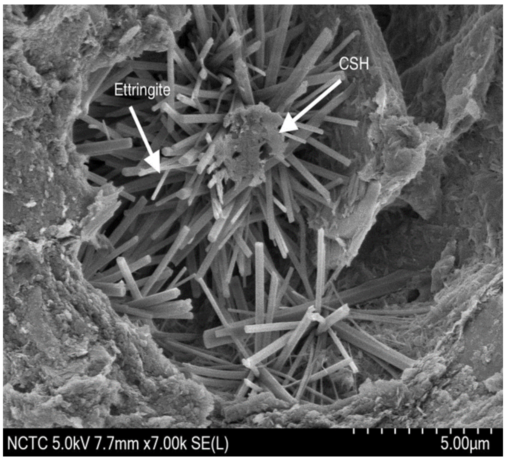

Figure 14. Scanning electron micrograph of interlocking block NBA after 28 days

The BA-20 SEM image (Figure 15) showed a comparable reduction in voids to NBA. The ettringite appeared larger and more uniformly distributed. The dense CSH matrix minimized internal spaces, contributing to the development of strength similar to NBA. The microstructure at this stage supports the conclusion that SCBA incorporation did not compromise hydration or strength development in the long term.

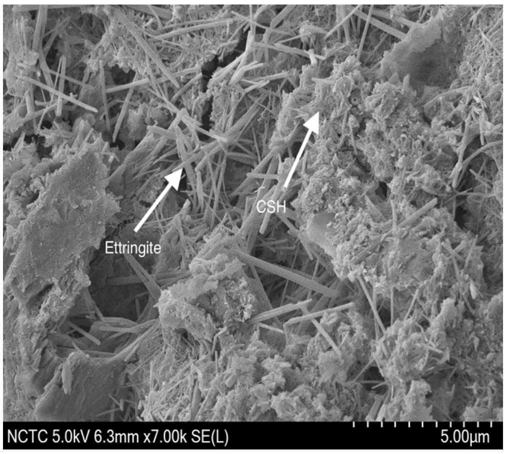

Figure 15. Scanning electron micrograph of interlocking block BA-20 after 28 days

3.3.2. Analysis and Conclusion Based on SEM observations

The SEM observations indicated similar internal structural characteristics for the NBA and BA-20 samples across all curing ages. After 28 days, both samples had reduced porosity and well-developed hydration products, leading to comparable compressive strength values. The incorporation of SCBA at 20% replacement did not adversely affect the microstructure, confirming its potential as a sustainable alternative to cement in interlocking blocks. Microstructural analysis from other research supported this observation, with the SCBA effectively filling micro-pores in cementitious materials, enhancing bonding, and reducing crack propagation [9].

The incorporation of SCBA also influenced the porosity and microstructural development of interlocking blocks at different curing ages. SEM observations confirmed that at early ages (7 days), SCBA contributed to the formation of ettringite and CSH but with visible pores. By 28 days, these pores were significantly reduced, and the denser CSH matrix indicated progressive hydration and pore refinement. This reduction in porosity contributed to enhanced compressive strength and durability over time. Although the current study focused on 7, 14, and 28 days, future work could extend to 56 days to assess long-term microstructural evolution.

Moreover, the addition of SCBA has potential implications for other durability aspects, such as resistance to abrasion and chemical attack, which are critical for infrastructure and pavement applications. While this study did not specifically test these properties, the denser microstructure and refined pore network observed with SCBA use suggested improved resistance to aggressive environments. However, these benefits may diminish at higher SCBA levels where incomplete hydration or excess porosity could compromise long-term durability. Further studies are recommended to evaluate abrasion resistance and chemical durability in detail.

3.4. Cost Comparison

Cost analysis is a critical factor in assessing the feasibility of incorporating SCBA into interlocking block production. Cement is a primary cost component in block manufacturing, so reducing its consumption could lead to major cost savings. This study compared the cost of producing interlocking blocks using manual press (non-electric) and hydraulic press (electric) methods, evaluating the economic impact of SCBA replacement at different levels (5%, 10%, 15%, or 20%).

3.4.1. Cost Comparison Data

Tables 6 and 7 present the comparison of cost per block for four different SCBA replacement levels using two types of manufacturing systems: a manually operated press (300 blocks/day) and a hydraulic press (1,500 blocks/day). USD 1 = THB 34 as at March 2025.

Table 6. Cost comparison (THB/block) of blocks made using manual press

Block code	Lateritic soil	Cement	Water	SCBA transport	Electricity	Labor	Variable cost	Fixed cost	Total cost	Cost Reduction (%)
NBA	0.91	2.18	7.85E-3	0	0	4.41	7.51	0.21	7.72	0
BA-5	0.91	2.07	7.85E-3	1.60E-3	4.00E-4	4.41	7.40	0.24	7.65	0.91
BA-10	0.91	1.96	7.85E-3	3.30E-3	8.00E-4	4.41	7.30	0.24	7.54	2.30
BA-15	0.91	1.85	7.85E-3	4.90E-3	1.20E-3	4.41	7.19	0.24	7.43	3.69
BA-20	0.91	1.74	7.85E-3	6.50E-3	1.60E-3	4.41	7.08	0.24	7.32	5.07

Table 7. Cost comparison (THB/block) of blocks made using hydraulic press

Block code	Lateritic soil	Cement	Water	SCBA transport	Electricity	Labor	Variable cost	Fixed cost	Total cost	Cost Reduction (%)
NBA	0.91	2.18	7.85E-3	0	1.29E-1	1.32	4.55	1.04	5.59	0
BA-5	0.91	2.07	7.85E-3	1.60E-3	1.30E-1	1.32	4.44	1.05	5.49	1.78
BA-10	0.91	1.96	7.85E-3	3.30E-3	1.30E-1	1.32	4.34	1.05	5.38	3.70
BA-15	0.91	1.85	7.85E-3	4.90E-3	1.31E-1	1.32	4.23	1.05	5.27	5.61
BA-20	0.91	1.74	7.85E-3	6.50E-3	1.31E-1	1.32	4.12	1.05	5.17	7.53

3.4.2. Cost Reduction Trends

The cost per block for the conventional mix (NBA) was THB 7.72 using the manual press and THB 5.59 using the hydraulic press. These costs were used as the baseline for comparisons with adding SCBA. The cost progressively decreased as the SCBA content increased, with BA-20 having the highest cost reductions of 5.07% (manual press) and 7.53% (hydraulic press), primarily due to the decrease in cement consumption, which more than offsets the minor increases in SCBA transportation and electricity costs.

3.4.3. Impact of Production Method

A key finding from this study was that there was a considerable cost reduction associated with the hydraulic press, which produced five times more blocks per day than the manual press. While using the hydraulic press increased the electricity costs, labor costs were greatly reduced (THB 1.32/block) compared to using the manual press (THB 4.41/block), resulting in an overall lower total cost per block compared to the manual press. Scaling up production with hydraulic presses further enhances cost reductions due to increased efficiency and lower labor costs.

3.4.4. Economic Feasibility

The economic viability of SCBA replacement was clearly evident, as even at the 5% replacement level, there were cost reductions. Similar trends were reported in other studies, where SCBA replacement contributed to cost savings due to reduced cement consumption [8, 9]. The dual benefits of economic viability and environmental sustainability make SCBA an attractive alternative for construction applications. Given that cement represents the largest cost component, replacing it with SCBA would lead to substantial long-term savings. The adoption of SCBA would also be consistent with the move to more sustainable construction by reducing dependency on cement, which is associated with high carbon emissions.

3.4.5. Energy Consumption Considerations

Although the hydraulic press consumes more electricity, its higher production efficiency offsets the additional cost, with the results from this study confirming that the total cost per block was lower than from manual production. This would reinforce the cost-effectiveness of mechanized production when considering large-scale implementation.

3.4.6. Concluding Remarks on Cost Optimization

The incorporation of SCBA as a partial cement replacement not only enhanced cost efficiency but also supported sustainable construction. Furthermore, using the hydraulic-electric press optimized costs by increasing production efficiency and reducing labor expenses. These findings suggested that SCBA-modified interlocking blocks would be an economically viable and environmentally sustainable alternative for construction applications.

3.5. Environmental Impact

3.5.1. Activities Considered in Assessment

The environmental impact assessment applied the LCA approach, focusing on the carbon footprint of interlocking block production. The boundary was set as a “Cradle-to-Gate” analysis, covering raw material acquisition and the manufacturing process, without considering distribution, usage, or end-of-life disposal.

3.5.1.1. Raw Material Acquisition

The raw materials consisted of lateritic soil, Portland cement, water, and SCBA. Notably, each material contributed differently to carbon emissions based on its extraction, processing, and chemical composition. The transportation emissions for the lateritic soil, Portland cement, and SCBA from their sources to the manufacturing site were considered, with the distance and mode of transportation influencing the overall footprint. The SCBA preparation costs considered the energy consumption and emissions from grinding the SCBA into a fine powder.

3.5.1.2. Interlocking Block Manufacturing Process

The mixing of the raw materials involved energy usage in the blending of the ingredients to ensure uniformity in block composition. The pressing of the interlocking blocks, using either the mechanical or hydraulic press machinery, contributed to emissions, depending on the energy source used.

3.5.2. Carbon Emission Factors of Raw Materials

Table 8 summarizes the carbon emission factors for the raw materials.

Table 8. Carbon emission factors of raw materials

Material	Emission factor	Unit	Source
Lateritic Soil	0.0037	kg. CO_2 eq./kg	TGO [30]
Portland Cement	0.375	kg. CO_2 eq./kg	TGO [30]
SCBA	0	kg. CO_2 eq./kg	Fairbairn et al. [10]
Water	0.0003238	kg. CO_2 eq./L	Ministry of Industry [31]
Diesel	2.7446	kg. CO_2 eq./L	Ministry of Industry [31]
Electricity	0.6933	kg. CO_2 eq./kW	MTEC [32]

3.5.3. Comparative Carbon Footprint Analysis

Tables 9 and 10 present the carbon emissions per interlocking block for the different SCBA replacement levels studied using two types of manufacturing systems: a manually operated press (300 blocks/day) and a hydraulic press (1,500 blocks/day).

Table 9. Carbon emissions for manually operated press operation (kg CO_2 eq./block)

Block code	Raw material acquisition	Transportation	SCBA preparation	Mixing	Pressing	Total emission	Reduction (%)
NBA	0.31245	0.00728	0	0	0	0.31973	0
BA-5	0.29785	0.00760	0.00008	0	0	0.30553	4.44
BA-10	0.28325	0.00755	0.00017	0	0	0.29097	9.00
BA-15	0.26865	0.00786	0.00025	0	0	0.27676	13.44
BA-20	0.25405	0.00780	0.00034	0	0	0.26220	17.99

Table 10. Carbon emissions for hydraulic press operation (kg CO_2 eq./block)

Block code	Raw material acquisition	Transportation	SCBA preparation	Mixing	Pressing	Total emission	Reduction (%)
NBA	0.31245	0.00720	0	0.01379	0.01379	0.34723	0
BA-5	0.29785	0.00737	0.00008	0.01379	0.01379	0.33289	4.13
BA-10	0.28325	0.00748	0.00017	0.01379	0.01379	0.31847	8.28
BA-15	0.26865	0.00764	0.00025	0.01379	0.01379	0.30413	12.41
BA-20	0.25405	0.00774	0.00034	0.01379	0.01379	0.28971	16.57

3.5.4. In-Depth Analysis

Incorporating SCBA as a partial cement replacement in construction materials offers notable environmental benefits. Due to SCBA's minimal emission factor, substituting cement with SCBA greatly reduces carbon emissions. For example, a 5% SCBA replacement resulted in a carbon footprint reduction of 4.44% when using a manual press and of 4.13% with a hydraulic press. Increasing the replacement to 20% led to emission reductions of 17.99% and 16.57% for the manual and hydraulic presses, respectively. These results were consistent with other studies that highlighted SCBA's role in lowering carbon footprints by reducing clinker demand and utilizing industrial waste [9, 14].

Compared to a manual press, using a hydraulic press inherently has a higher initial carbon footprint—0.34723 kg CO_2 equivalent per block—primarily due to electricity consumption. In contrast, the manual presses had a lower carbon footprint—0.31973 kg CO_2 equivalent per block. Despite the higher energy usage associated with the hydraulic press, the integration of SCBA still resulted in substantial emission reductions, albeit slightly less pronounced than with manual presses.

Additional factors, such as transportation and SCBA preparation, contributed minimally to the overall emissions. Transportation accounted for approximately 2.2% of total emissions, underscoring its relatively minor impact compared to cement production. However, further reducing transportation-related emissions could be achieved by sourcing SCBA from locations closer to construction sites or optimizing transport logistics. The grinding process required to prepare SCBA added a negligible emission factor of up to 0.00034 kg CO_2 equivalent per block. These findings highlighted the environmental advantages of incorporating SCBA into construction materials, as it effectively reduces carbon emissions while making use of agricultural waste products.

3.5.5. Conclusion on Environmental Impact

The integration of SCBA as a partial cement replacement effectively reduced the carbon footprint of interlocking block production. Fairbairn et al. [10] reported that SCBA-based cement resulted in substantial reductions in CO_2 emissions, supporting its use in sustainable construction. In this study, the highest reductions of 17.99% (manual press) and 16.57% (hydraulic press) were achieved with 20% SCBA replacement. While the hydraulic press option had a higher initial carbon footprint than the manual option, due to electricity consumption, both manufacturing systems benefited from SCBA substitution. These findings emphasize the potential of SCBA in promoting sustainable construction materials while maintaining production efficiency.

3.6. Criteria for Sustainable Interlocking Block Production Using SCBA (SCOPEC Framework)

A structured framework is required to ensure the successful incorporation of SCBA as a cement replacement in interlocking blocks. Therefore, this study proposed the SCOPEC criteria—a practical guideline to optimizing material selection, mix proportions, performance evaluation, production methods, cost efficiency, and environmental impact reduction. The SCOPEC framework consists of six key aspects:

3.6.1. Selection of Materials and Preparation (S)

Choosing the right materials and preparing them correctly helps improve the consistency and quality of interlocking blocks. The lateritic soil used must be well-graded and free of organic matter, while the SCBA should be properly processed, ground, and tested for pozzolanic activity. Additionally, as the chemical properties of SCBA vary depending on its source and combustion process, periodic characterization is necessary to maintain uniformity. When sourcing SCBA from different locations, retesting is required to optimize its reactivity and ensure compatibility with the binder matrix.

3.6.2. Composition and Mix Optimization (C)

The right balance of cement, SCBA, and lateritic soil affects how strong, durable, and easy to work with the blocks will be. Based on these results, a cement-to-soil ratio of 1:7 with 20% SCBA replacement provided an optimal balance between compressive strength and cost efficiency. However, since mix optimization depends on the chemical properties of all constituent materials, adjustments must be made when material sources change. In addition, the mix design must align with the intended application, as non-commercial or self-use production may not require full adherence to all engineering criteria.

3.6.3. Operational Performance and Strength Criteria (O)

The strength and durability of SCBA-modified blocks are important to ensure they can be safely used in construction applications. Key performance parameters include:

- Compressive Strength: Must meet or exceed the 7 MPa requirement for load-bearing applications, according to TIS 57-2533, although this threshold can be adjusted based on project needs.
- Water Absorption: Should remain within an acceptable range to prevent excessive moisture uptake, which affects long-term durability.
- Durability under Wet-Dry Cycles: There should be minimal weight loss in blocks subjected to ASTM D559-03 durability testing to support resistance to weathering.

3.6.4. Production Consistency and Quality Control (P)

Keeping production consistent and ensuring quality control is especially important for large-scale manufacturing. The following measures should be considered:

- Standardization of Block Dimensions: Since Thailand lacks universal size regulations for interlocking blocks, consistent mold calibration should be applied to achieve proper alignment during assembly.
- Quality Control in Small-Scale Production: Manual block pressing requires careful moisture content control to achieve optimal compaction. In non-commercial applications, strict adherence to all standards may not be necessary.
- Hydraulic Press Optimization for Large-Scale Production: Mechanical presses should be calibrated regularly to maintain uniform compaction pressure and minimize defects.

3.6.5. Economic Feasibility and Cost Efficiency (E)

Using SCBA in interlocking blocks helps lower costs by reducing the amount of cement used while still keeping the blocks strong. Based on these results, using 20% SCBA replacement led to cost savings of 5.07% (manual press) and 7.53% (hydraulic press). Additionally, the availability of SCBA as an agricultural waste by-product makes it an affordable alternative to cement, particularly in regions with abundant sugarcane waste from industrial processing. Cost efficiency varies with the production scale. Thus, while small-scale manual production incurs lower initial investment, large-scale hydraulic pressing improves long-term economic viability.

3.6.6. Carbon Reduction and Environmental Sustainability (C)

Using SCBA instead of some cement helps cut carbon emissions from cement production, supporting more sustainable construction. Based on the LCA calculations in this study, SCBA substitution at 20% reduced the CO_2 emissions by up to 17.99% (manual press) and 16.57% (hydraulic press), highlighting its potential as a low-carbon building material. Compared to conventional cement-based blocks, SCBA-modified blocks could effectively repurpose agricultural waste, thus reducing landfill accumulation and contributing to circular economy practices. While hydraulic press production has higher initial emissions due to electricity consumption, it remains more energy-efficient for large-scale manufacturing.

3.6.7. Conclusion on SCOPEC Framework

The SCOPEC framework offers practical steps for making interlocking blocks with SCBA in a sustainable way. By integrating material selection, optimized mix design, engineering performance criteria, quality control, economic feasibility, and environmental sustainability, the SCOPEC approach ensures practical implementation while allowing flexibility based on local materials and project needs. This study highlighted the importance of adapting mix proportions, performance benchmarks, and cost considerations to specific conditions, thereby demonstrating SCBA as a viable, cost-effective, and eco-friendly cement alternative in interlocking block construction.

4. Conclusion

The feasibility of using sugarcane bagasse ash (SCBA) as a partial cement replacement in interlocking blocks was examined. The research established SCBA as a viable supplementary material for sustainable construction, based on comprehensive experimental analyses, using mechanical, microstructural, economic, and environmental assessments.

Replacing 20% of the cement with SCBA maintained block strength while lowering the costs and reducing the associated environmental impact. Blocks with 20% SCBA substitution (BA-20) had comparable compressive strength to conventional cement-based interlocking blocks (NBA) while meeting the strength requirements specified by Thai Industrial Standards (TIS 57-2533). The microstructural analysis confirmed that SCBA contributed to hydration reactions, improving the formation of calcium silicate hydrate and reducing porosity over time. Additionally, durability tests indicated that SCBA-modified blocks had minimal weight loss under cyclic wet-dry conditions, ensuring long-term stability in diverse environmental settings.

From an economic perspective, the integration of SCBA substantially reduced material costs, achieving a cost reduction of up to 5.07% in manual press production and 7.53% in hydraulic press production. These cost savings highlighted the potential for SCBA-modified interlocking blocks to serve as a cost-effective alternative for affordable housing projects. Furthermore, the environmental assessment confirmed that SCBA replacement led to a reduction in carbon emissions, with a maximum CO_2 reduction of 17.99% for manual press production and 16.57% for hydraulic press production. These findings were aligned with global sustainability goals, supporting the adoption of SCBA in construction to mitigate the carbon footprint of cement-based materials.

The proposed SCOPEC framework (Selection of materials, Composition and mix optimization, Operational performance, Production consistency, Economic feasibility, and Carbon reduction) offers guidelines for effectively using SCBA utilization in interlocking block production. This framework ensures a systematic implementation pathway for sustainable masonry construction by addressing material selection, performance criteria, production quality, economic viability, and environmental impact.

Overall, this study has contributed to advancing knowledge of sustainable material applications by demonstrating the technical, economic, and environmental feasibility of SCBA-modified interlocking blocks. The findings provided valuable insights for policymakers, engineers, and researchers, paving the way for broader adoption of eco-friendly building materials in the construction industry. Future research should focus on large-scale field applications, long-term durability studies under varying climatic conditions, and policy recommendations for promoting SCBA-based masonry materials. Notably, this study showed that SCBA could partially replace cement in interlocking blocks and thus reducing costs and adverse environmental impacts while maintaining strength.

5. Declarations

5.1. Author Contributions

Conceptualization, N.S. and K.A.; methodology, N.S. and K.A.; formal analysis, N.S. and K.A.; investigation, K.A.; writing—original draft preparation, N.S.; writing—review and editing, K.A.; project administration, K.A.; funding acquisition, N.S. and K.A. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available in the article.

5.3. Funding

This research was supported by a grant from the Faculty of Engineering at Kamphaeng Saen, Kasetsart University. The authors gratefully acknowledge the staff and students from the Soil Mechanics Laboratory in the Department of Civil Engineering, Faculty of Engineering at Kamphaeng Saen, Kasetsart University.

5.4. Conflicts of Interest

The authors declare no conflict of interest.

6. References

[1] Hussien, N. T., & Oan, A. F. (2022). The use of sugarcane wastes in concrete. Journal of Engineering and Applied Science, 69(1), 31. doi:10.1186/s44147-022-00076-6.

[2] Kumar, N., & Barbato, M. (2022). Effects of sugarcane bagasse fibers on the properties of compressed and stabilized earth blocks. Construction and Building Materials, 315, 125552. doi:10.1016/j.conbuildmat.2021.125552.

[3] Thennarasan Latha, A., & Murugesan, B. (2024). Compressed stabilised earth block synergistically valorising municipal solid waste incinerator bottom ash and sisal fiber: Strength, durability and life cycle analysis. Construction and Building Materials, 441, 137514. doi:10.1016/j.conbuildmat.2024.137514.

[4] James, J., & Pandian, P. K. (2017). A Short Review on the Valorisation of Sugarcane Bagasse Ash in the Manufacture of Stabilized/Sintered Earth Blocks and Tiles. Advances in Materials Science and Engineering, 2017, 1706893. doi:10.1155/2017/1706893.

[5] Abbas, S., Hameed, R., Baig, M. A., Kashif, M., & Shaukat, S. (2024). Mechanical performance of coal ash based interlocking bricks wall panel: A sustainable and viable solution. Journal of Building Engineering, 95, 110288. doi:10.1016/j.jobe.2024.110288.

[6] TISTR. (2025). Technology of Interlocking Blocks. Thailand Institute of Scientific and Technological Research (TISTR), Bangkok, Thailand. (In Thai).

[7] A Sunardi, S., Ariawan, D., Surojo, E., Prabowo, A. R., Ghanbari-Ghazijahani, T., Wibowo, C. H., & Akbar, H. I. (2024). Tribological Performance of Polymer Composite Modified with Calcined Eggshell Particles Post High-Temperature Exposure. Emerging Science Journal, 8(4), 1280-1292. doi:10.28991/ESJ-2024-08-04-03.

[8] Gudia, S. E. L., Go, A. W., Giduquio, M. B., Juanir, R. G., Jamora, J. B., Gunarto, C., & Tabañag, I. D. F. (2023). Sugarcane bagasse ash as a partial replacement for cement in paste and mortar formulation – A case in the Philippines. Journal of Building Engineering, 76, 107221. doi:10.1016/j.jobe.2023.107221.

[9] Yarra, A., Nakkeeran, G., Roy, D., & Alaneme, G. U. (2025). Evaluation of SCBA-replaced cement for carbon credits and reduction in CO_2 emissions. Discover Applied Sciences, 7(2), 114. doi:10.1007/s42452-025-06487-3.

[10] Fairbairn, E. M. R., Americano, B. B., Cordeiro, G. C., Paula, T. P., Toledo Filho, R. D., & Silvoso, M. M. (2010). Cement replacement by sugar cane bagasse ash: CO2 emissions reduction and potential for carbon credits. Journal of Environmental Management, 91(9), 1864–1871. doi:10.1016/j.jenvman.2010.04.008.

[11] Ainomugisha, S., Kibwami, N., Racheal, W., Adubango, E. N., J Matovu, M., & Manga, M. (2025). Effect of sugarcane bagasse ash on eco-friendly blended cement production: Physicochemical, mechanical, and microstructure properties. Case Studies in Construction Materials, 22, 4141. doi:10.1016/j.cscm.2024.e04141.

[12] Khan, M. A., Zhang, B., Ahmad, M., Niekurzak, M., Khan, M. S., Sabri Sabri, M. M., & Chen, W. (2025). Optimizing concrete sustainability with bagasse ash and stone dust and its impact on mechanical properties and durability. Scientific Reports, 15(1), 1385. doi:10.1038/s41598-025-85363-x.

[13] Sa-nguanduan, N., Amornfa, K., & Dechkrong, P. (2024). Consistency of Chemical Composition of Bagasse Ash and Application in Interlocking Blocks. Journal of Science and Technology Kasetsart University, 13(1), 48-60.

[14] Jahanzaib Khalil, M., Aslam, M., & Ahmad, S. (2021). Utilization of sugarcane bagasse ash as cement replacement for the production of sustainable concrete – A review. Construction and Building Materials, 270, 121371. doi:10.1016/j.conbuildmat.2020.121371.

[15] Jordan, R. A., Da Costa, M. V., Martins, E. A. S., Rosa, M. A., & Petrauski, A. (2019). Manufacture of soil-cement bricks with the addition of sugarcane bagasse ash. Engenharia Agricola, 39(1), 26–31. doi:10.1590/1809-4430-Eng.Agric.v39n1p26-31/2019.

[16] Alvarenga, K. P., & Cordeiro, G. C. (2024). Evaluating sugarcane bagasse fly ash as a sustainable cement replacement for enhanced performance. Cleaner Engineering and Technology, 20, 100751. doi:10.1016/j.clet.2024.100751.

[17] Subedi, S., Arce, G. A., Hassan, M. M., Barbato, M., Gutierrez-Wing, M. T., & Kumar, N. (2024). Louisiana's Sugarcane Bagasse Ash Utilization for Partial Cement Replacement in Concrete for Transportation Infrastructure Applications. International Journal of Pavement Research and Technology, 17(3), 595–614. doi:10.1007/s42947-022-00258-8.

[18] Rihan, M. A. M., Onchiri, R. O., Gathimba, N., & Sabuni, B. (2024). Mechanical and Microstructural Properties of Geopolymer Concrete Containing Fly Ash and Sugarcane Bagasse Ash. Civil Engineering Journal (Iran), 10(4), 1292–1309. doi:10.28991/CEJ-2024-010-04-018.

[19] Onsongo, S. K., Olukuru, J., Munyao, O. M., & Mwabonje, O. (2025). The role of agricultural ashes (rice husk ash, coffee husk ash, sugarcane bagasse ash, palm oil fuel ash) in cement production for sustainable development in Africa. Discover Sustainability, 6(1), 62. doi:10.1007/s43621-025-00841-6.

[20] Akila, D., Pal, S., Sarkar, B., Jayalaksshmi, S., Muthaiyah, S., & Anbananthen, K. S. M. (2024). Multi-Criteria Decision-Making Model to Achieve Sustainable Developmental Goals in Industry 4.0 for Smart City Infrastructure. HighTech and Innovation Journal, 5(4), 1135-1153. doi:10.28991/HIJ-2024-05-04-018.

[21] Aouf, G., Alhakim, G., & Jaber, L. (2024). Utilizing Recycled Rubber and Municipal Waste Incineration Fly Ash in Cement-Stabilized Clayey Soils. Civil Engineering Journal, 10(11), 3721-3737. doi:10.28991/CEJ-2024-010-11-017.

[22] Amornfa, K. (2016). Engineering Properties Improvement of Interlocking Block by Mixing with Sand. Naresuan University Engineering Journal, 11(1), 67–74.

[23] ASTM C618-03. (2017). Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete. ASTM International, Pennsylvania, United States. doi:10.1520/C0618-03.

[24] TIS-57. (1990). Hollow Load-Bearing Concrete Masonry Units. Thailand Industrial Standards Institute (TISI), Bangkok, Thailand. (In Thai).

[25] TIS-109. (1974). Sampling and Testing Concrete Masonry Units. Thailand Industrial Standards Institute (TISI), Bangkok, Thailand. (In Thai).

[26] ASTM D559-03. (2012). Standard Test Methods for Wetting and Drying Compacted Soil-Cement Mixtures (Withdrawn 2012). ASTM International, Pennsylvania, United States. doi:10.1520/D0559-03.

[27] ASTM E986-04(2017). (2024). Standard Practice for Scanning Electron Microscope Beam Size Characterization. ASTM International, Pennsylvania, United States. doi:10.1520/E0986-04R17.

[28] ISO 14067:2018. (2018). Greenhouse gases — Carbon footprint of products — Requirements and guidelines for quantification. International Organization for Standardization (ISO), Geneva, Switzerland.

[29] James, J., Pandian, P. K., Deepika, K., Manikanda Venkatesh, J., Manikandan, V., & Manikumaran, P. (2016). Cement stabilized soil blocks admixed with sugarcane bagasse ash. Journal of Engineering (United Kingdom), 2016(1), 7940239. doi:10.1155/2016/7940239.

[30] TGO. (2019). Thailand Greenhouse Gas Emission Factor Report. Thailand Greenhouse Gas Management Organization (TGO), Bangkok, Thailand. (In Thai).

[31] MOI. (2019). Industrial Greenhouse Gas Emission Report. Ministry of Industry (MOI), Bangkok, Thailand. (In Thai).

[32] MTEC. (2019). National Greenhouse Gas Emission Data. National Metal and Materials Technology Center (MTEC), Bangkok, Thailand. (In Thai).