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Original Article

Sustainable Building Solutions: Testing Fiber-Stabilized Adobe Blocks as Wall Materials in Assosa, Ethiopia

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Abstract

In developing nations like Ethiopia, earth block construction is the most effective and sustainable solution to the housing shortage, particularly for low-cost dwellings, due to its minimum resource requirements. The research examines the fundamental engineering attributes of local soil material and fiber-reinforced adobe blocks as materials for wall construction. The widespread application of adobe blocks is supported by convenient accessibility to local soil, minimal energy requirements, and simplicity in production. The experiment entails adobe blocks of jute fiber-reinforced clay soil. The soil samples were collected from four locations in the Benishangul-Gumuz Regional State (Assosa Zone): Abrhamo, Assosa, Bambasi, and Homosha. Jute fiber was mixed in various percentages (0.5%, 1%, and 1.5% by weight of soil) and lengths (30 cm, 20 cm, and 10 cm). A set of experiments was conducted in an effort to examine the mechanical and physical behavior of unreinforced and fiber-reinforced adobe blocks. The results were found to possess a higher compressive strength with the addition of jute fiber. The highest compressive strength (5.98 MPa) was observed with 30 cm fiber length and 1.5% jute fiber addition in Assosa samples. These results demonstrate the potential of fiber-reinforced adobe blocks as a cost-efficient and durable building material for low-cost housing in Assosa.

Categories: Structural Analysis and Finite Element Analysis, Materials Engineering, Structural Engineering

Keywords: : assosa zone, jute fiber, reinforced adobe blocks, mechanical properties, compressive strength, low-cost housing

Introduction

Countries like Ethiopia are faced with significant socio-economic and environmental issues such as high population growth rates, deforestation, land degradation, and uncontrolled urbanization. Although high population growth can be a factor in the development of a nation due to an increased workforce and generational connections, it is also accompanied by significant socio-economic issues. These include a lack of economic capacity and poor productivity in the industrial sector, as well as an overwhelmed education system. Among the most immediate effects of the population explosion is the need for low-cost housing, which is further exacerbated by the rising costs of traditional building materials such as cement and steel. In rural settings, due to the unaffordability of industrial materials in terms of cost and logistics, traditional building methods are common. Wood is the most used material in the construction of walls, which are then coated with mud. This particular practice is one of the main causes of deforestation and land degradation, which is a serious problem in developing countries like the Benishangul-Gumz Regional State. In this region, conventional building practices add to environmental degradation, while inadequate shelter and sanitation facilities, especially in the case of displaced populations, are pressing concerns. To overcome these interrelated issues, the need for low-cost and sustainable construction solutions, particularly for low-income groups, is imperative. The substitution of conventional deforestation practices with effective alternatives has the potential to reduce environmental degradation while, at the same time, promoting the availability of affordable materials for housing. Adobe construction has many inherent benefits, such as being cost-effective, requiring low energy, fire-resistant, sound-absorbing, thermally insulating, and durable, while using locally sourced materials [1]. The advent of fiber-reinforced composites has brought about a technological shift in construction practices, with fiber-reinforced concrete (FRC) gaining widespread acceptance owing to its improved physical and mechanical properties [2]. The types of fibers employed in these composites can be classified into natural, regenerated, and synthetic types (Figure *1*). Jute fiber, the subject of this research, belongs to the natural fiber group and has the potential to serve as a biodegradable alternative.

In this regard, the current study aims to investigate the feasibility of jute fiber-reinforced adobe blocks as a sustainable building material for low-cost housing. The study was conducted in four districts of the Assosa Zone in Benishangul-Gumz (Assosa, Homosha, Abrhamo, and Bambasi) by laboratory testing of fiber-reinforced adobe samples. Jute fiber was uniformly mixed with soil of different lengths (10 cm, 20 cm, and 30 cm) and proportions (0.5%, 1.0%, and 1.5% by weight) to evaluate its reinforcement effectiveness. The general objective of this research study was to investigate the feasibility of fiber-reinforced adobe blocks as sustainable building materials for low-cost housing in the Assosa Zone. To accomplish this, the research study had the following specific objectives: (1) To evaluate the influence of varying jute fiber content (0.5%, 1.0%, and 1.5% by weight) and length (10 cm, 20 cm, and 30 cm) on the compressive strength of adobe blocks; (2) To determine the compressive capacity of adobe blocks reinforced with jute fiber, using soil sourced from four sites in the Assosa Zone (Abrhamo, Assosa, Bambasi, and Homosha), and (3) To observe the failure response of adobe blocks, both with and without jute fiber reinforcement, under ultimate compressive load.

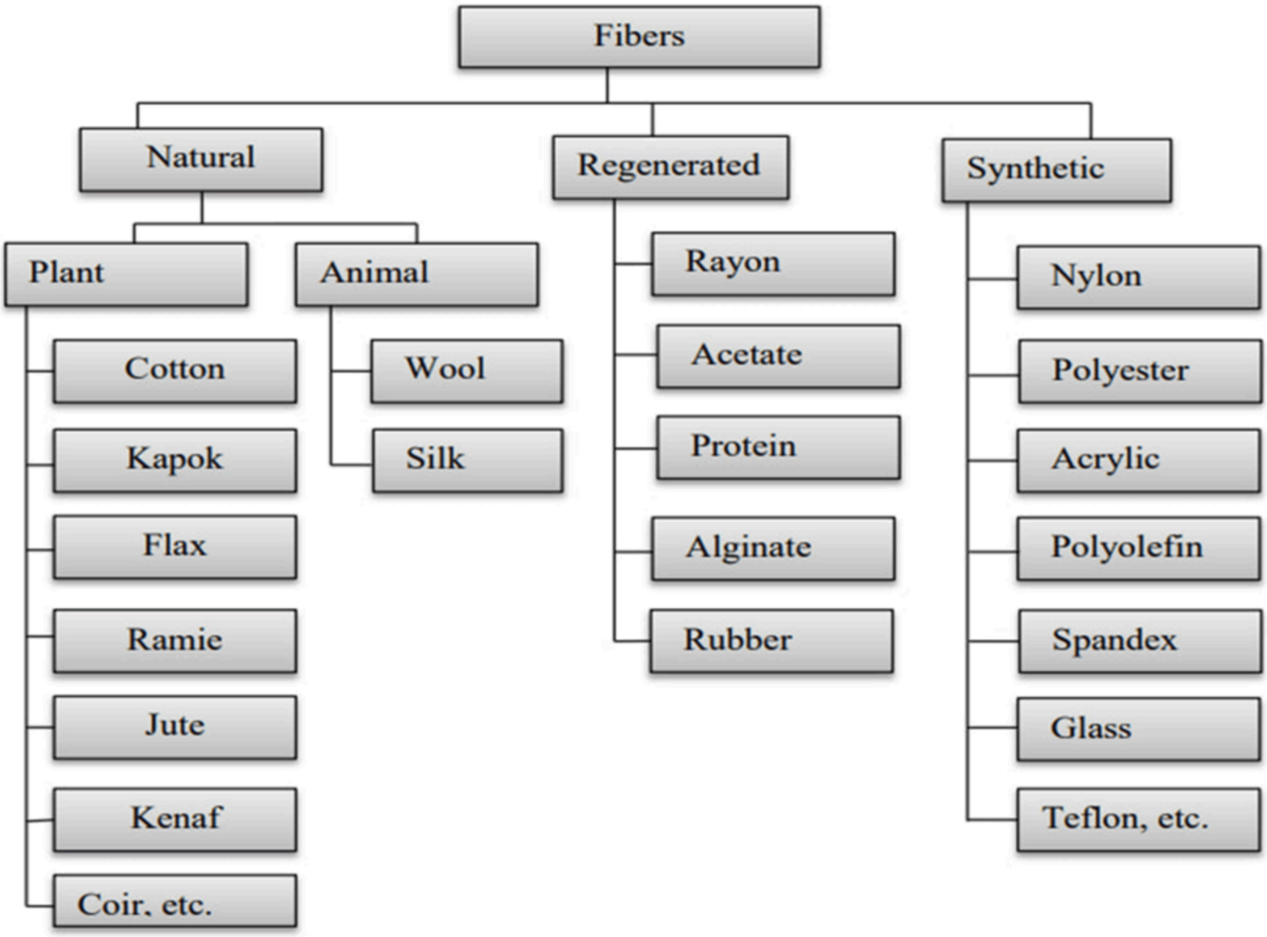

FIGURE 1: Classification of fibers

Literature reviews

Adobe is an old building technique that consists of the use of soil, a combination of clay, sand, and water, along with stabilizers and binders to form sun-dried blocks [3]. Though adobe blocks are made up of one of the most basic building elements, their subtle virtues and prevalence are concealed in plain sight. All soils are not amenable for block manufacturing; sandy soil and clay soil are the best. Organic soil, for instance, is not suitable for constructing adobe and is not sustainable in the long term [4]. To enhance water resistance and durability, fibrous components such as straw or grass are added to the mix with it. Cow dung, lime, and termite mound soil serve as stabilizers [5]. The fibers also help withstand cracking as the blocks set in the sun by distributing tension caused by shrinking clay across the material. The straw acts as tiny channels, allowing moisture to be released more easily. Research indicates that fibers can increase the compressive strength of set adobe blocks by a minimum of 15% [6]. The traditional Ethiopian construction practices dependent on wood are not viable due to high population growth rates and the destructive behavior of termites on materials [1]. Although concrete is normally introduced as an alternative, its high cement content makes it unsustainable. Moreover, its cost excludes its use by low-income families, highlighting the need to reduce dependency on cement-reliant materials. While conventional views show Ethiopia's construction systems as natural in their approach, they have gigantic environmental and social drawbacks, and solving these problems requires a new remedy that guarantees sustainable, affordable shelter [7]. Several foreign aid schemes and international organizations have introduced low-cost

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housing schemes in Ethiopia with varying degrees of success. One of the first adobe-block structures was constructed by the Swedish Lutheran Mission in eastern Ethiopia. Likewise, the German Hermannsburg Mission has advocated adobe technology in western Ethiopia for almost twenty years, where it has been universally accepted by rural communities. Efforts to establish Compressed Stabilized Soil Blocks have also been undertaken, although the product has largely been utilized in well-funded schemes in contrast to large-scale low-cost housing [1]. The Swedish Lutheran Mission first tested low-cost housing construction in Ethiopia's Kambaata region, and later a broader research project was initiated in 2002 by Professor Bengt Hjort of Halmstad University and two other researchers. The project originally had five components: pioneer survey, research and experimentation with new construction methods, construction of demonstration buildings, analysis of locals' attitudes towards new methods of construction, and manufacturing of implementation manuals, though progress was slowed down by poor funding, which prevented strict adherence to the original plan [7]. The first two field surveys in 2002-2003, conducted by Halmstad University students of civil engineering for their degree projects, confirmed the suitability of Durame's soil to make adobe blocks. The minimum composition of adobe blocks is simple: soil, binder, and water - the ideal mix is predominantly sand and clay. Surface organic soil should be removed, since good construction soil is typically located beneath the surface organic horizon. Such subsurface soils are often found in mixed rather than segregated layers. Suitability of the soil can be tested through simple, inexpensive tests. Field tests conducted in 2003 and documented by [7] confirmed the presence of suitable soil in Durame through simple bottle tests. Most soils require binders like fiber or straw from grass in order to find application as construction materials [7]. Chopped jute fiber was utilized as the binder for [7] research because it was readily available and low-cost. The fermentation causes the ingredients to stick together more easily, and, in this manner, the structural properties of the completed block are improved. After a week the fermented mud was typically ready to be molded into blocks. The only necessary equipment for this production was simple mold made of wood or metal. The stiff mud was pressed into the mold and subsequently removed to cure and slow dry. Drying of blocks is a critical aspect so that cracks do not form, care has to be taken to dry the blocks slowly and not expose them to direct sunlight. Sun protection can be simply provided by sheets or plastic leaves. Drying would typically take one month. Blocks may be made to any size desired but if made too large, they will be uncontrollable. A block was constructed using the size of the mold of size 14 × 20 × 40 cm and weighing about 15 kg when dry [7].

Justification for fiber content and length in soil reinforcement

Influence of Fiber Content

The choice of suitable fiber content and length is an important consideration in the design of fiber-reinforced earth composites, as these factors have a direct bearing on the workability, strength, and failure behavior of the resulting material. The choice of the ranges considered in this study (0.5% to 1.5% fiber content by weight, and 10 cm to 30 cm fiber length) is well supported by the existing literature on natural fiber reinforcement in soil-based construction materials. Many studies have shown that the amount of fiber added to the soil matrix significantly affects the mechanical properties. The first thing that needs to be considered is the presence of an optimal amount; if it is below that, there will be no improvement, and beyond that, there might be a deterioration. Studies have shown that a certain level of fiber content is required, below which the amount of reinforcement is insufficient to make a significant difference in the material properties. For example, in a study involving *Hibiscus cannabinus* fibers in pressed adobe blocks, the fiber content was as low as 0.2%, and while it was shown that improvement was possible, the maximum impact was seen at higher percentages in their range [8]. Similarly, by [9] involving sisal fiber-reinforced soil, the range started at 0.25% to account for the initial impact of reinforcement, suggesting that values below this are of little use. There is a consensus among various studies that beyond a certain level of fiber content, beyond 1.5% to 2% by weight, there are diminishing or even negative returns due to various practical and mechanical reasons such as lack of workability because of the difficulty in preparing a homogeneous mixture, fiber balling, and poor compaction, as well as lower strength due to the inhibiting effect of excessive fiber content on soil-to-soil contact, as seen in the study of [8], which found that beyond a certain level of fiber content in adobe mixtures, the compressive and tensile strengths may decrease. Bouhicha et al. [10], in their study of barley straw-reinforced soil, also systematically investigated the effect of fiber fraction on compressive and flexural strength, finding an optimal level beyond which performance plateaued or decreased. Excess fibers can lead to higher porosity, which may affect the material's durability and water resistance [8]. The range of 0.5% to 1.5% chosen for this investigation is therefore intended to examine this critical phase, recognizing the transition from a position of limited reinforcement (0.5%), through a possibly intermediate fiber content (1.0%), to a point at the maximum fiber content of (1.5%).

Influence of Fiber Length

The role of fiber length in earthen composites is based on a critical trade-off between mechanical properties and workability: while the shorter fibers, like the 10 mm to 25 mm sisal fibers investigated in [10], are more easily mixed in and have a better micro-reinforcement role in terms of shrinkage crack control and interparticle bonding, they are also more prone to pull-out without much energy absorption, thus being less effective in the post-peak regime, whereas longer fibers have better pull-out resistance and are more effective in micro-reinforcing larger cracks to improve post-cracking ductility and energy absorption capacity, as discussed with wool fibers in [8] and with sisal and coconut fibers in [11]; yet, these latter mechanical advantages are in turn limited by the mixing difficulties, as fibers that are too long, like the 60 mm *Hibiscus cannabinus* fibers used in [8], tend to entangle and form "fiber balls" during manual mixing, thus leading to non-uniform distribution and weak points that may ultimately cause a reduction in compressive strength [12]. The choice of 10 cm, 20 cm, and 30 cm fibers in this study is deliberate. The 10 cm length is a short fiber for micro-reinforcement, the 30 cm length is a long fiber for possible macro-crack bridging, and the 20 cm length is an intermediate length. This was a deliberate selection that enabled the study of the effect of fiber length on the mechanical properties of adobe blocks while still being within the limits of manufacturability for hand-made adobe blocks in the Assosa Zone.

Materials And Methods

The research was carried out in Assosa Zone, in the Benishangul-Gumuz Regional State of Ethiopia, where there is a huge problem of sustainable housing due to deforestation, the cost of construction, and the use of traditional timber-based construction. The four districts of Assosa, Bambasi, Abrhamo, and Homosha were selected for soil sampling based on geographical and demographic significance to affordable housing. The research used available geographic materials in order to ensure cost-effectiveness and sustainability. Soil samples were collected from four research sites (Assosa, Bambasi, Abrhamo, and Homosha) after removing the organic topsoil to obtain construction-grade soil. Jute fiber was the main reinforcement material of choice, whose tensile strength, local availability, and environmental advantages made it more preferable. The choice of jute fiber is supported by recent studies showing that jute is one of the most extensively produced vegetal fibers globally and has been effectively utilized to improve properties such as cracking resistance, flexural strength, and water erosion resistance in adobe mixtures [13]. Water and hand-mixing equipment were the only stabilizers used, without the use of chemical additives to retain the natural composition of adobe blocks. The experimental study was conducted using a systematic approach to examine the impact of jute fiber reinforcement on compressive strength. The three variables under investigation are the amount of fiber (0.5%, 1.0%, and 1.5% by weight of the soil), the length of the fiber (10 cm, 20 cm, and 30 cm), and the geographical location of the soil samples. These values are consistent with other studies, where the amount of jute fiber (0.5% to 2.0%) and the length of the fibers (7 mm to 30 mm) have been examined for their impact on adobe structures [13]. The control samples were made of plain adobe without any fiber. Soil analysis was done before the production of blocks, i.e., grain size distribution analysis (ASTM D422) and Atterberg limits (ASTM D4318) for plasticity tests. Block production was done as per normal procedures: after pulverization and water correction, soil was mixed with jute fibers and then manually compacted in 400 × 200 × 150 mm molds. A total of 120 blocks were prepared (for each of all the variable combinations at four locations, including controls). The sample size and experimental design are in line with the methodological approaches in fiber-reinforced adobe studies, where several replications are used to capture the natural variability of earthen materials [14]. Curing conditions included drying: initially in shade for 14 days, then under ambient conditions (25-35°C) for 28 days. Test procedures in the materials lab at Assosa University included test-retest measurement of compressive strength by specific equipment, and each set of variables was tested in triplicate. Such testing procedures have been used in other research studies on the mechanical performance of jute fiber-reinforced adobe [15]. The results were compared systematically among all the variables and referred to the Ethiopian Standard Code specification requirements for concrete blocks (Class A: 4.2 MPa; Class C: 2.0 MPa). The systematic method ensured valid data collection, although it remains relevant to the needs of low-cost housing construction in the Benishangul-Gumuz Region. The experimental design, including site selection by data analysis, is graphically represented in Figure *2*.

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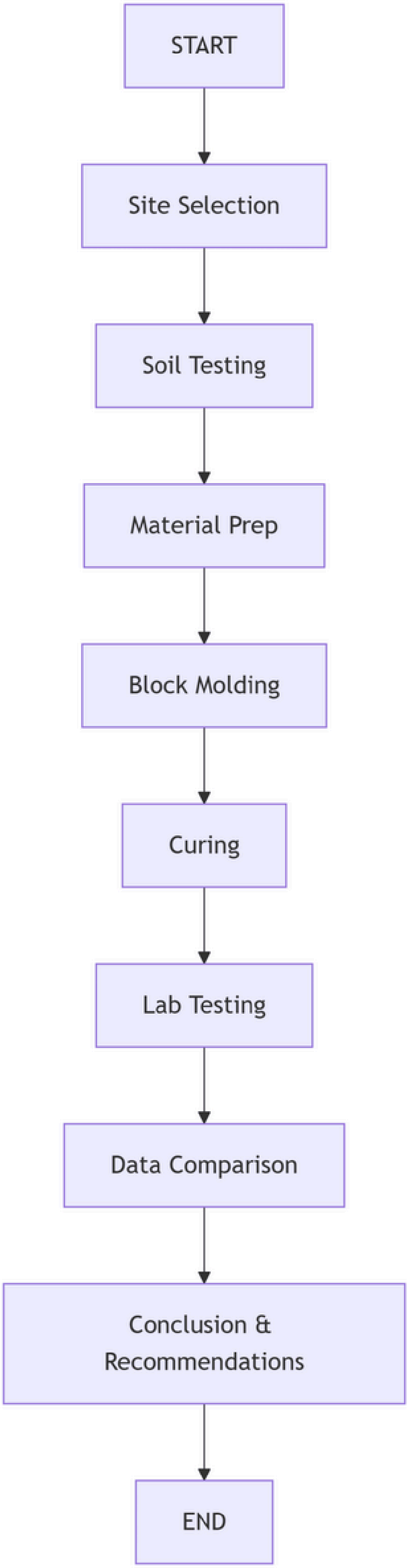

START
Site Selection
Soil Testing
Material Prep
Block Molding
Curing
Lab Testing
Data Comparison
Conclusion & Recommendations
END

FIGURE 2: Methodology flow

Thirty adobe blocks in total (three samples for each variable) of 400 × 200 × 150 mm were prepared. Jute fiber was utilized as reinforcement in mixed proportions of 0.5%, 1%, and 1.5% by weight of the soil, with fiber lengths of 10 cm, 20 cm, and 30 cm. Preparation began with the removal of the topsoil up to 10 cm depth (Figure *3*(a)) for obtaining quality clay soil, and then excavation up to 5 cm depth, as depicted in Figure *3*(b) below.

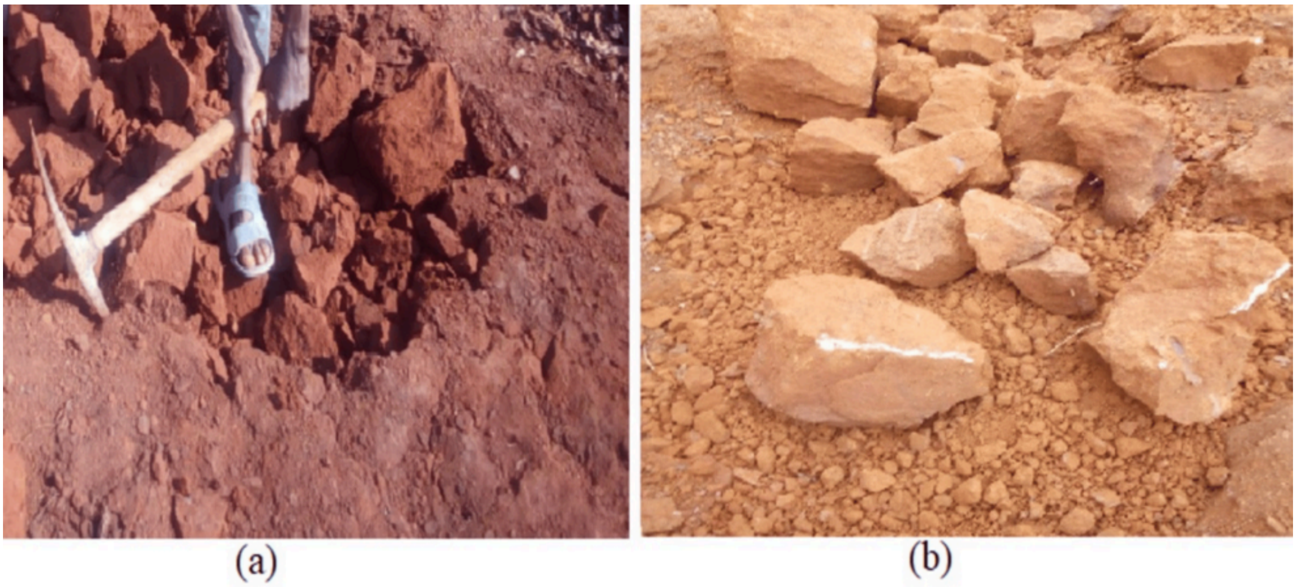
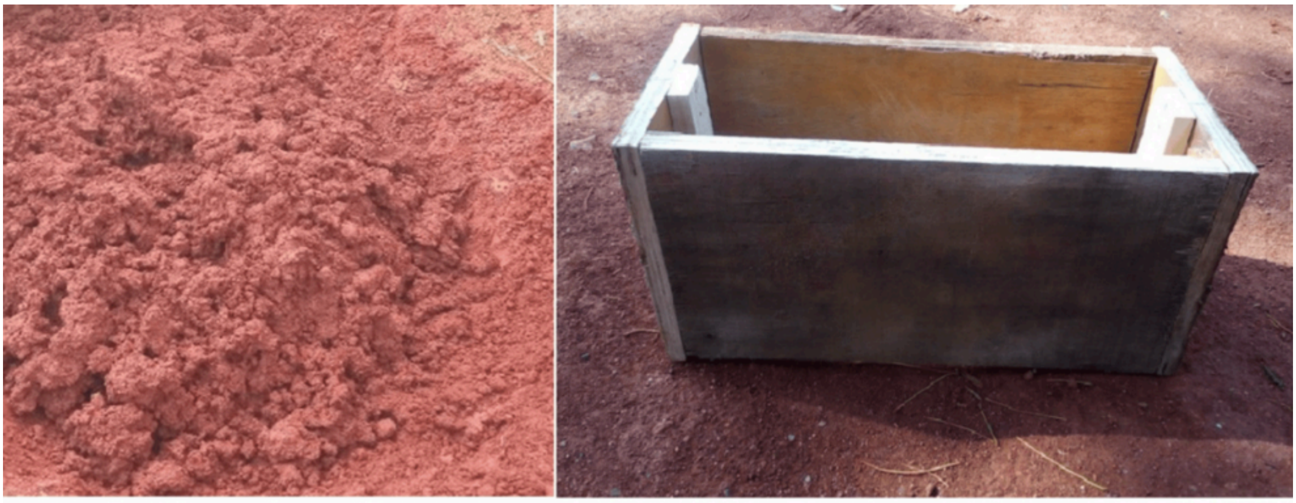


FIGURE 3: Initial soil resource preparations by digging and removing top soil (a), excavation up to 5 cm depth (b)

Since the soil was highly compacted and difficult to make manually, digging and crushing was difficult. To address this, water was added to moisten the soil, followed by crushing using a hammer, an effective solution to soften the hardened material. Once the soil was sufficiently crushed into a fine powder, fiber and water were added in appropriate amounts, and the mixture was uniformly blended using a shovel. The mixed mud was compacted by foot and ready for molding, as illustrated in Figure *4*(a). Following this, a mold was prepared using plywood to shape the adobe blocks. The mold design is shown in Figure *4*(b) below.



(a) (b)

FIGURE 4: Mixed mud (a) and typical molding formwork (b) for adobe block preparation

The moisture content for the preparation of the blocks was determined in accordance with traditional methods and workability, namely the amount of water that would cause the soil-fiber mixture to hold together when hand-compacted, without being too dry (resulting in crumbling) or too wet (resulting in stickiness or excessive shrinkage). With respect to the distribution of the fibers, to ensure an even distribution of the fibers within the soil matrix, a step-by-step hand mixing process was followed. The dry soil was first evenly spread on a clean mixing surface. The jute fibers, cut into predetermined lengths of either 10 cm, 20 cm, or 30 cm, were gradually sprinkled over the soil while manually turning the mixture to ensure that the fibers do not clump together. The mixture was then gradually wetted with water while mixing until the mixture was workable enough for hand compaction. The mixing process took about 10-15 minutes for each batch until the mixture had an even appearance, with the fibers well dispersed and randomly distributed within the soil matrix. After molding, the blocks underwent a 28-day sun drying at average temperatures ranging from 25°C to 35°C. To prevent undue loss of moisture during hot weather, the freshly molded blocks were initially kept in the shade for the first 14 days. After the initial curing, the blocks were fully exposed to ambient environmental conditions like sunlight and natural airflow while being protected from direct rain. The controlled drying permitted the development of strength and prevented cracking.

FIGURE 5: Sixty grams of packed jute fiber (a) and chopped jute fiber (b) before mixing

The experimental process, illustrated in Figure *5*, involved chopping the jute fibers to three different lengths (10 cm, 20 cm, and 30 cm) (Figure *5*(b)) and packing them in 60-gram batches (Figure *5*(a)) in plastic wrap. Four methods of mixing were utilized in the research: control samples with three simple blocks of mud without fiber reinforcement; low fiber content with 60 grams (a single batch) for three samples; medium fiber content with 120 grams (two batches) for the same amount of mud; and high fiber content with 180 grams (three batches) for the same amount of mud. During the mixing process, it was noticed that the longer fibers (20 cm and 30 cm) tended to clump together, making it more difficult to mix them evenly compared to the 10 cm fibers. To counter this effect, extra care was taken during the mixing process for the longer fiber lengths. The fibers were poured more slowly into the dry soil, and the mixing process was prolonged by turning and kneading the mixture manually to mix the fibers as evenly as possible. On the other hand, 10 cm shorter fibers were much easier to process, exhibiting better mixability and integration into the soil. Fiber mixing (Figure *6*(a)), molded blocks, and controlled curing of adobe specimens (Figure *6*(b)) are shown below.

FIGURE 6: Fiber mixing (a), molding and curing (b) of adobe blocks

After the 28 days of curing at room temperature, the specimens of the adobe blocks were subjected to compressive strength tests. The evaluation was conducted using a compression testing machine, whereas the experimental setup is portrayed in Figure 7. The structural strength and load-carrying capacity of the fiber-reinforced adobe blocks were the objectives that were sought to be measured through this testing method. The compression tests yielded vital information for assessing the impact of varying fiber lengths and proportions of the fiber mixture on improving the mechanical properties of the blocks.

FIGURE 7: Adobe sample testing using a compression machine

Results And Discussion

This research study was conducted on 120 Solid Adobe Blocks (SAB), with 30 samples from each of the four locations (Assosa, Bambasi, Abrhamo, and Homosha) and tested in the laboratory at Assosa University. All samples were given a standard curing process for 28 days to develop compressive strength similar to that of concrete blocks. The study scientifically evaluated three critical factors: jute fiber content (0.5%, 1.0%, and 1.5% of the soil weight), fiber length (10 cm, 20 cm, and 30 cm), and differences in soil type based on geographical location. The result of the enhanced compressive strength at 1.5% fiber content is in line with the experimental results of the evaluation of adobe mixtures reinforced with jute fibers, where different amounts (0.5% and 2.0%) and sizes (7 mm, 15 mm, and 30 mm) were considered [13]. The maximum compressive strength of 5.98 MPa obtained in this study is better compared to the results of other recent studies where jute fiber reinforcement resulted in the enhancement of the compressive strength of cement-stabilized raw earth mortar by 12%, with the strength improving from 5.64 MPa to 6.31 MPa [16]. The persistent superiority of the Assosa samples indicates that the soil from this location has desirable geotechnical properties that improve fiber-matrix interaction, since studies have shown that the efficiency of fiber reinforcement is highly dependent on the compatibility between the fibers and the soil matrix [13]. These findings confirm the sustainability and efficiency of fiber-reinforced adobe as a viable alternative to traditional building materials, thus adding to the existing literature that supports natural fiber reinforcement in earthen construction [13,16].

Ultimate compression load of jute fiber reinforced adobe blocks and plain adobe blocks

This study conducted a comparative assessment of compressive strength between Jute Fiber-Reinforced Adobe Blocks and regular adobe blocks using ultimate load capacity tests, which indicated that fiber reinforcement has a significant impact on increasing average compressive strength performance. On the basis of Ethiopian Standard Code D3.301 requirements, plain blocks as well as the least reinforced variants (0.5% fiber at a length of 10 cm) were not able to achieve the 2.0 MPa required for Class C standards, whereas moderately reinforced samples (1% fiber content or 0.5% at the length range of 20-30 cm) exceeded Class C standards. The highest performing blocks, with 1.5% jute fiber in all lengths tested (10 cm, 20 cm, and 30 cm), not only outperformed the 4.2 MPa Class A requirement but showed exceptional strength characteristics, with the top performing 30 cm fiber compound showing maximum compressive strength of 5.98 MPa. This translates into a whopping 147.8% gain in strength over unreinforced Assosa sample blocks and a 42% conservatism over class A minimums, conclusively establishing that properly engineered fiber-reinforced adobe blocks (particularly at 1.5% fiber content) can be technically viable and sustainable alternatives to standard class A concrete blocks, with complete strength development data provided in Table *1* and Figure *8* below. The grain size distribution, liquid limit, and plastic limit for the Assosa site soil are presented in Table *2*.

No	Code	Average failure force (kN)	Average failure pressure (Mpa)
1	SAB (control)	53.86	0.90
2	10SAB(0.5)	114.04	1.90
3	10SAB(1)	139.07	2.32
4	10ASB(1.5)	308.43	5.14
5	20SAB(0.5)	123.13	2.05
6	20SAB(1)	151.94	2.53
7	20SAB(1.5)	340.55	5.68
8	30SAB(0.5)	127.96	2.13
9	30SAB(1)	181.62	3.03
10	30SAB(1.5)	358.87	5.98

TABLE 1: Average crushing load of adobe blocks at Assosa site

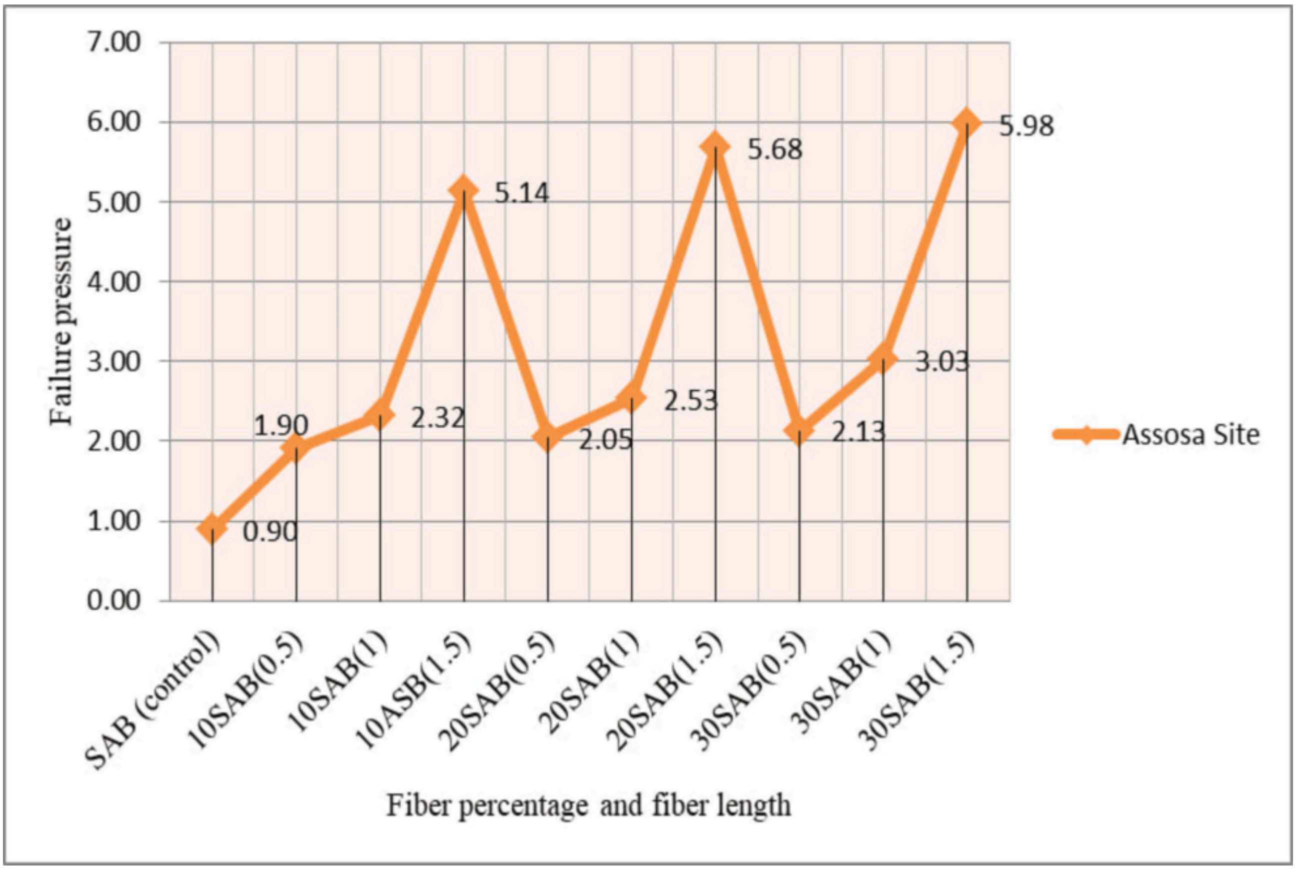


FIGURE 8: Average crushing load by fiber content and length for Assosa site

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Type of testing: Grain size analysis (ASTM D-421)								
Wt. of sample: (g): 1000 g								
Sample location: Assosa site								
Grain size distribution								
Sieve size (mm)	Mass of retain on each sieve (g)	Percentage of retained soil	Percentage of cumulative retained soil	Percentage of passing soil particle				
9.5	374	37.4	37.4	62.6				
4.75	191	19.1	56.5	43.5				
2	155	15.5	72	28				
1.18	51	5.1	77.1	22.9				
0.3	125	12.5	89.6	10.4				
0.075	76	7.6	97.2	2.8				
Pan	25	2.5	99.7	0.3				
Sum	997							
Liquid Limit (D-4318)								

Number of blows	Can code	Wt. of container, (g)	Wt. of container + wet soil, (g)	Wt. of container + dry soil, (g)	Wt. of water, (g)	Wt. of dry soil, (g)	Moisture container, (%)	
28	A	18.29	45.44	35.62	9.82	17.33	56.66	
20	B	16.83	51.65	39	12.65	22.17	57.06	
17	C	18.37	48.41	37.4	11.01	19.03	57.86	
Plastic Limit (D-4318)								
Can code	Wt. of container, (g)	Wt. of container + wet soil, (g)	Wt. of container + dry soil, (g)	Wt. of water, (g)	Wt. of dry soil, (g)	Moisture container, (%)		
B	18.35	23.09	21.7	1.39	3.35	41.9		
D	16.5	21.26	19.9	1.36	3.4	39		
Average 40.45								

TABLE 2: The grain size distribution, liquid limit, and plastic limit for the Assosa site soil

Experimental findings conclusively establish that the jute fiber-reinforced adobe blocks possess greater compressive strength compared to the unreinforced blocks, since all the tested fiber lengths (10-30 cm) and percentages (0.5-1.5%) showed consistent increases in load-carrying capacity without a decrease in performance. The positive trend noticed up to the maximum tested values (1.5% fiber content and 30 cm length) indicates that, within the context of this research, the compressive strength will continue to increase with an increase in fiber content and length. Although the highest strength was noticed at 1.5% and 30 cm, the continuous positive trend indicates that there is a need to investigate beyond these values. Comparative testing of samples from Homosha site supported the Assosa results, wherein fiber-reinforced blocks consistently outperformed plain adobe in compressive strength. Plain blocks as well as marginally reinforced samples (0.5% fiber at 10 cm length) were less than Class C level of 2.0 MPa, but moderately reinforced blocks (coded 10SAB (1), 20SAB (0.5), 20SAB (1), 30SAB (0.5), and 30SAB

(1)) fully complied with Class C requirements. As shown in Table 3 and Figure 9 below, the growing strength gains observed with increasing fiber content from 0.5% to 1.5% are strong evidence for the effectiveness of jute fiber as a reinforcement material for adobe construction. The grain size distribution, liquid limit, and plastic limit for the Homosha site soil are presented in Table 4.

No	Code	Average failure force (kN)	Average failure pressure (Mpa)
1	SAB (control)	53.67	0.89
2	10SAB(0.5)	113.91	1.90
3	10SAB(1)	138.86	2.31
4	10ASB(1.5)	307.57	5.13
5	20SAB(0.5)	120.47	2.01
6	20SAB(1)	150.92	2.52
7	20SAB(1.5)	339.19	5.65
8	30SAB(0.5)	126.56	2.11
9	30SAB(1)	178.16	2.97
10	30SAB(1.5)	355.50	5.93

TABLE 3: Average crushing force of adobe blocks at Homosha site

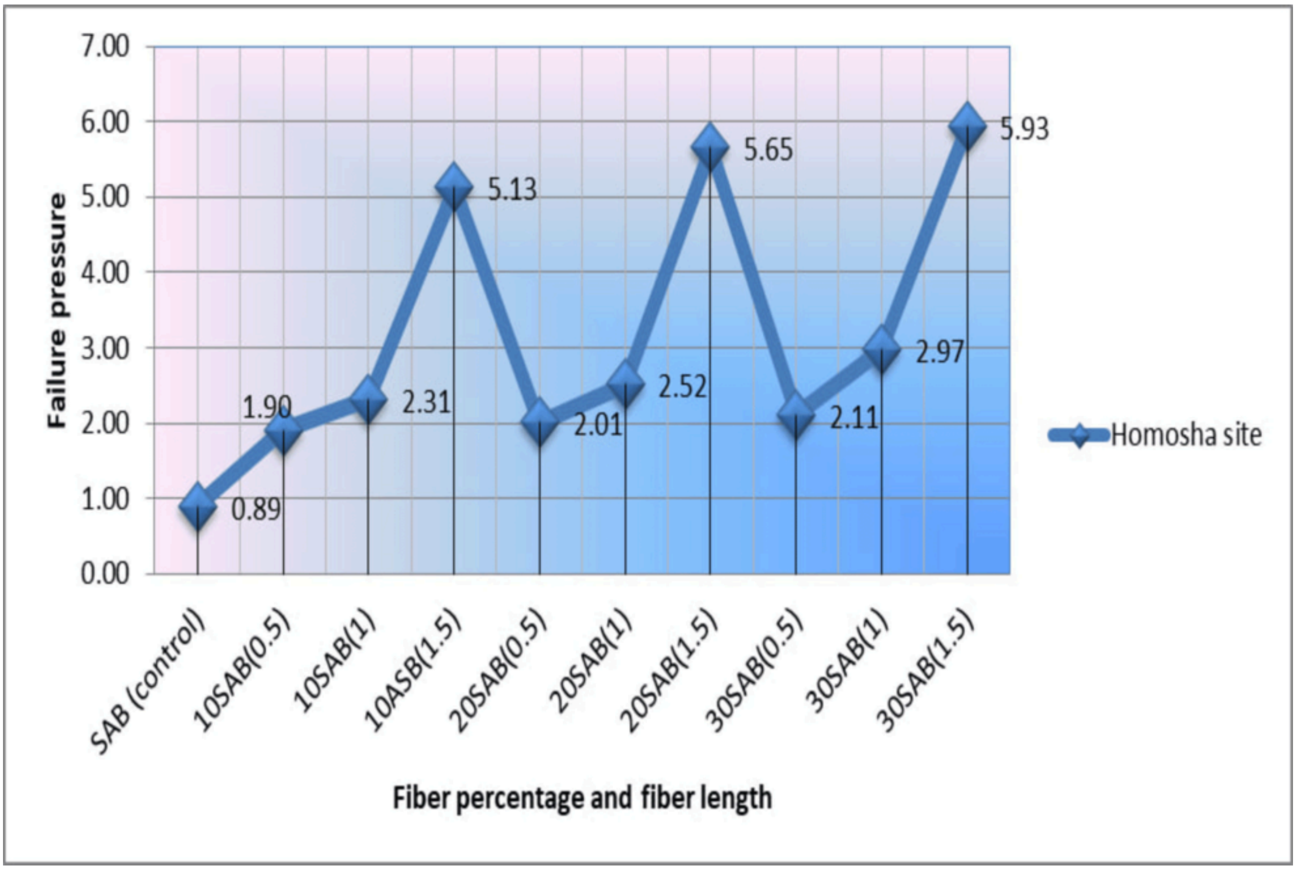

FIGURE 9: Graphical representation of crushing load for Homosha site lab result

Type of Testing: Grain Size Analysis (ASTM D-421)							
Wt. of Sample: (g): 1000 g							
Sample Location: Homosha site							
Sieve size (mm)	Mass of retain on each sieve (g)	Percentage of retained soil	Percentage of cumulative retained soil	Percentage of passing soil particle			
9.5	189	18.9	6.8	93.2			
4.75	293	29.3	36.1	63.9			
2	361	36.1	72.2	27.8			
1.18	68	6.8	79	21			
0.425	138	13.8	92.8	7.2			
0.3	33	3.3	96.1	3.9			
0.075	29	2.9	99	1			
Pan	7	0.7	99.7	0.3			
Sum	980						
Liquid Limit (D4318)							
Number of blows	Can code	Wt. of container, (g)	Wt. of container + wet soil, (g)	Wt. of container + dry soil, (g)	Wt. of water, (g)	Wt. of dry soil, (g)	Moisture container, (%)
33	A	17.1	61.82	46.88	14.94	29.78	50.17
22	B	17.51	70	51.86	18.14	34.35	52.81
18	C	18.25	64.78	48.36	16.42	30.11	54.53

Plastic Limit (D-4318)							
Can code	Wt. of container, (g)	Wt. of container + wet soil, (g)	Wt. of container + dry soil, (g)	Wt. of water, (g)	Wt. of dry soil, (g)	Moisture container, (%)	
B	17.23	21.56	20.32	1.24	3.09	40.13	
D	16.8	25.95	23.32	2.63	6.52	40.34	
Average 40.23							

TABLE 4: The grain size distribution, liquid limit, and plastic limit for the Homosha site soil

It was established from the research that samples with additional fiber reinforcement (named 10SAB(1.5), 20SAB(1.5), and 30SAB(1.5)) all met the Class A block requirements (minimum 4.2 MPa), indicating that adobe blocks reinforced with 1.5% jute fiber content (for all the considered lengths of 10 cm, 20 cm, and 30 cm) can be effectively utilized instead of normal Class A concrete blocks. The 30SAB(1.5) mixture achieved good performance with a maximum crushing load of 5.93 MPa for a notable enhancement compared to normal adobe blocks. Quantitative analysis showed 140.57%, 145.35%, and 147.53% increases in strength in 10 cm, 20 cm, and 30 cm fiber lengths, respectively, for Homosha site samples. These findings were also supported by the same tests at the Abrhamo site, which is indicated by Table *5* and Figure *10* below, where jute fiber-reinforced adobe blocks once again demonstrated significantly greater compressive strength than their unreinforced equivalents, continuing the consistent performance trend at all the test locations. The grain size distribution, liquid limit, and plastic limit for the Abrhamo site soil are presented in Table *6*.

No.	Code	Average failure force (kN)	Average failure pressure (Mpa)
1	SAB (Control)	52.41	0.87
2	10SAB(0.5)	112.92	1.88
3	10SAB(1)	137.32	2.29
4	10SAB(1.5)	305.05	5.08
5	20SAB(0.5)	119.32	1.99
6	20SAB(1)	149.47	2.49
7	20SAB(1.5)	335.55	5.59
8	30SAB(0.5)	124.35	2.07
9	30SAB(1)	176.35	2.94
10	30SAB(1.5)	352.37	5.87

TABLE 5: Average crushing load of adobe blocks at Abrhamo site

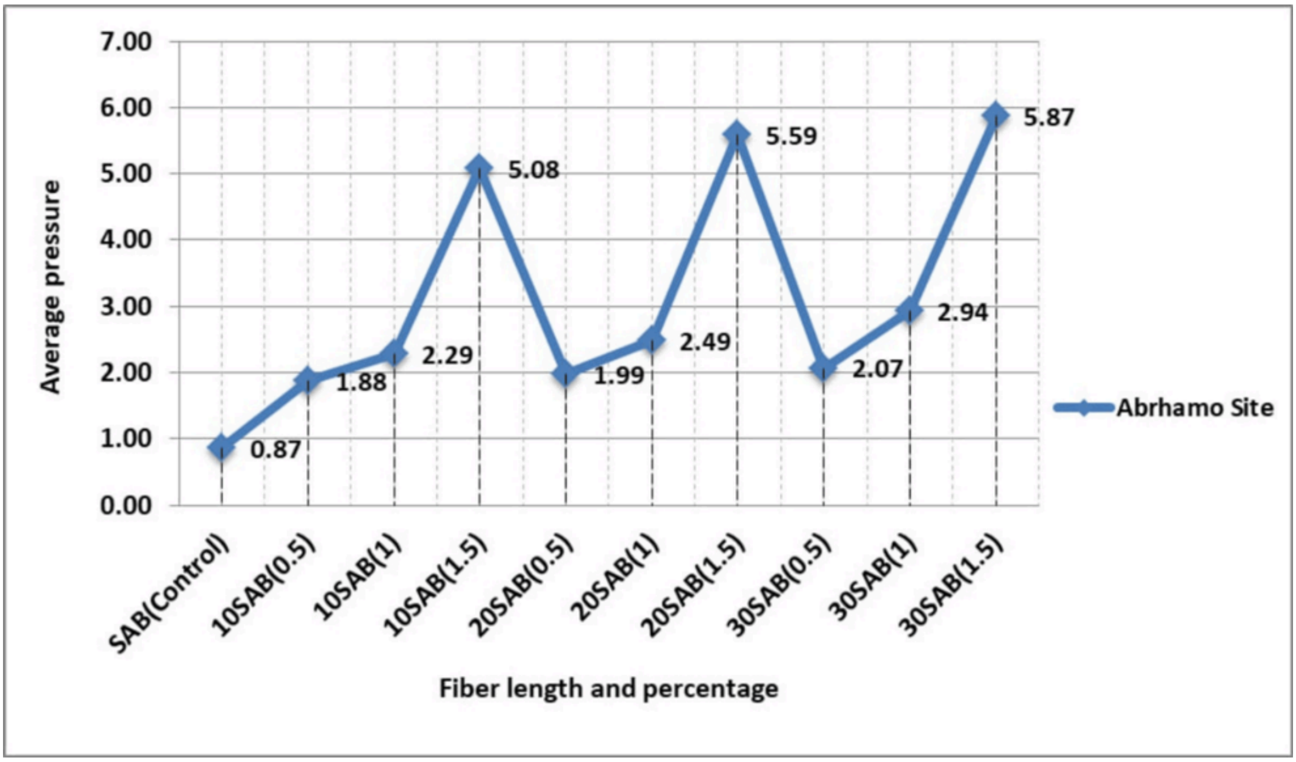

FIGURE 10: Graphical representation of average crushing load for Abrhamo site

Type of Testing Grain Size Analysis (ASTM D-421)							
Wt. of Sample: (g) 1000 g							
Sample Location: Abrhamo							
Sieve size (mm)	Mass of Retain on Each Sieve (g)	Percentage of Retained Soil	Percentage of cumulative Retained Soil	Percentage of Passing Soil Particle			
9.5	40	4	4	96			
4.75	88	8.8	12.8	87.2			
2	130	13	25.8	74.2			
1.18	182	18.2	44	56			
0.425	102	10.2	54.2	45.8			
0.3	130	13	67.2	32.8			
0.075	98	9.8	77	23			
pan	229	22.9	99.9	0.1			
sum	999						
Liquid Limit (D-4318)							
Number of blows	Can code	Wt. of container, (g)	Wt. of container + wet soil, (g)	Wt. of container + dry soil, (g)	Wt. of water, (g)	Wt. of dry soil, (g)	Moisture container, (%)
28	A	18.29	42.46	38.24	4.22	19.95	21.15
20	B	16.83	49.21	42.55	6.66	25.72	25.89
17	C	18.37	44.66	38.71	5.95	20.34	29.25

Plastic Limit (D-4318)							
Can code	Wt. of container, (g)	Wt. of container + wet soil, (g)	Wt. of container + dry soil, (g)	Wt. of water, (g)	Wt. of dry soil, (g)	Moisture container, (%)	
B	18.35	23.09	21.7	1.39	3.35	41.49	
D	16.5	21.26	19.9	1.36	3.4	40	
Average 40.75							

TABLE 6: The grain size distribution, liquid limit, and plastic limit for the Abrhamo site soil

The studies found that plain adobe blocks and 0.5% jute fiber-reinforced blocks of 10 cm length were less than the minimum expected load for Class C adobe blocks. Those samples designated as 10SAB(1), 20SAB(0.5), 20SAB(1), 30SAB(0.5), and 30SAB(1) achieved the minimum level of strength for Class C blocks. Apart from that, 1.5% jute fiber reinforced specimens (10SAB(1.5), 20SAB(1.5), and 30SAB(1.5)) surpassed the class strength limit of Class A concrete blocks and thus proved their compatibility as a green building material. Among the samples considered, 30SAB(1.5) recorded the maximum crushing load of 5.87 MPa. The addition of 1.5% jute fiber to the adobe blocks yielded spectacular strength increases over non-fiber blocks, with increases of 145.21% (10 cm fiber), 149.54% (20 cm fiber), and 151.40% (30 cm fiber). These findings for the Bambasi site, presented in Table *7* and Figure *11*, indicate that jute fiber reinforcement has a significant influence on adobe block performance and that jute fiber-reinforced adobe is an appropriate substitute for conventional concrete blocks in some contexts. The grain size distribution, liquid limit, and plastic limit for the Assosa site soil are presented in Table *8*.

No.	Code	Average failure force (kN)	Average failure pressure (Mpa)
1	SAB (Control)	47.83	0.80
2	10SAB(0.5)	108.87	1.81
3	10SAB(1)	135.25	2.25
4	10SAB(1.5)	301.32	5.02
5	20SAB(0.5)	117.16	1.95
6	20SAB(1)	145.04	2.42
7	20SAB(1.5)	331.29	5.52
8	30SAB(0.5)	123.05	2.05
9	30SAB(1)	168.31	2.81
10	30SAB(1.5)	345.77	5.76

TABLE 7: Average crushing force of adobe blocks at Bambasi site

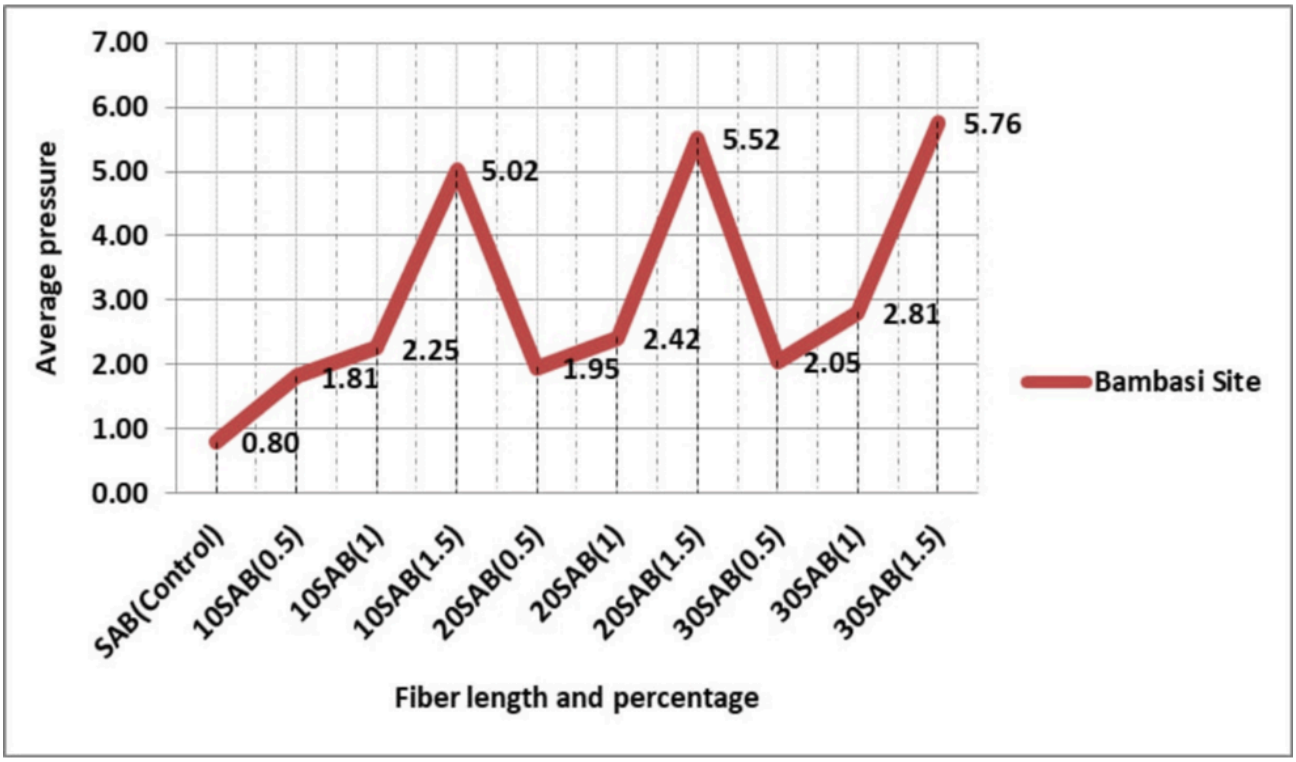

FIGURE 11: Graphical representation of Average crushing load for Bambasi site

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Type of Testing: Grain Size Analysis (ASTM D-421)							
Wt. of Sample: (g): 1000 g							
Sample Location: Bambasi							
Grain Size Distribution							
Sieve size (mm)	Mass of retain on each sieve (g)	Percentage of retained soil	Percentage of cumulative retained soil	Percentage of passing soil particle			
9.5	189	18.9	6.8	93.2			
4.75	293	29.3	36.1	63.9			
2	361	36.1	72.2	27.8			
1.18	68	6.8	79	21			
0.425	138	13.8	92.8	7.2			
0.3	33	3.3	96.1	3.9			
0.075	29	2.9	99	1			
pan	7	0.7	99.7	0.3			
sum	980						
Liquid Limit (D-4318)							

Number of blows	Can code	Wt. of container, (g)	Wt. of container + wet soil, (g)	Wt. of container + dry soil, (g)	Wt. of water, (g)	Wt. of dry soil, (g)	Moisture container, (%)
33	A	17.1	61.82	46.88	14.94	29.78	50.17
22	B	17.51	70	51.86	18.14	34.35	52.81
18	C	18.25	64.78	48.36	16.42	30.11	54.53
Plastic Limit (D-4318)							
can code	Wt. of container, (g)	Wt. of container + wet soil, (g)	Wt. of container + dry soil, (g)	Wt. of water, (g)	Wt. of dry soil, (g)	Moisture container, (%)	
B	17.23	21.56	20.32	1.24	3.09	40.3	
D	16.8	25.95	23.32	2.63	6.52	40.4	
Average 40.35							

TABLE 8: The grain size distribution, liquid limit, and plastic limit for the Bambasi site

Atterberg limits

Analysis of the data shows that the plasticity of Assosa soil is moderate (PI = 12%), which is sufficient for adobe construction, especially when reinforced with jute fibers. The plasticity of Homosha soil (PI = 6%) and Bambasi soil (PI = 2%) is low to very low, indicating that they have low to very low cohesive properties, which can be improved by fiber reinforcement. Abrhamo soil has non-plastic properties (NP), indicating that it is silt or silty sand, which depends on compaction and fiber reinforcement for strength. Table 9 presents the Atterberg's limits of soil from the four study sites, determined in accordance with ASTM D4318.

Properties	Assosa	Abrhamo	Homosha	Bambasi
Liquid Limit, LL (%)	31	21.7	28	20
Plastic Limit, PL (%)	19	23	22	18
Plasticity Index, PI (%)	12	-1.3*	6	2

TABLE 9: Atterberg's limits of soil as per ASTM D4318

Comparative performance of adobe blocks between sites

Based on the findings acquired in this research, adobe blocks produced at the Assosa site exhibited good compressive strength, relative to the other sites. The performance ranking of the samples in descending order after Assosa was Homosha (second), Abrhamo (third), and Bambasi (fourth). Despite these variations, all the samples tested exhibited significantly improved and relatively consistent strength, particularly with 1% and 1.5% reinforcement of jute fiber for all fiber lengths. This suggests their great potential as promising substitutes for conventional concrete blocks.

Comparison of failure behavior of plain and jute fiber-reinforced adobe blocks

Failure analysis revealed noticeable differences between plain and reinforced adobe blocks. All plain adobe blocks in the four test locations failed brittly, collapsing abruptly under very slight load. The failure for plain adobe blocks at ultimate load is shown in Figure 12(a). In contrast, jute fiber-reinforced samples exhibited progressive failure behavior. As the fiber content increased, specimens maintained structural integrity (Figure 12(b)) for extended durations, and load-bearing capacity decreased gradually after reaching peak compressive strength. The highest duration of time was observed in 1.5% jute fiber samples for all the tested lengths (10 cm, 20 cm, and 30 cm). Notably, the 1.5% reinforcement sample with 30 cm fibers from Assosa site presented the maximum resistance time before failure. These findings confirm that jute fiber reinforcement significantly enhances load-bearing capacity as well as structural resilience.

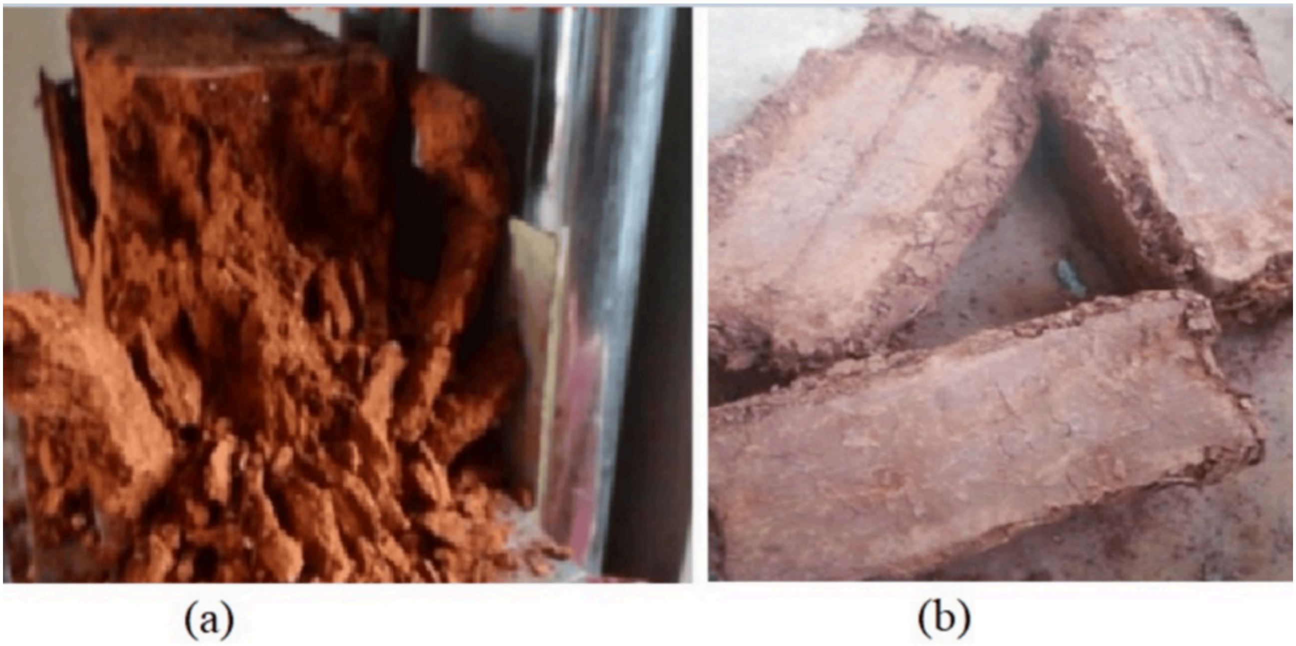

FIGURE 12: Sample failure at ultimate load: plain adobe (a) and jute fiber-reinforced adobe (b)

Conclusions

The research objectives of this study have been successfully met by performing the compressive strength test on 120 jute fiber-reinforced adobe block samples collected from four sites in the Assosa Zone of Ethiopia, which showed that the adobe blocks reinforced with 1.5% jute fiber (10 cm, 20 cm, and 30 cm long) satisfied the minimum requirements for certain concrete block classes, with the highest strength of 5.98 MPa recorded for the Assosa samples containing 1.5% 30 cm fiber, whereas the normal and 0.5% fiber samples did not satisfy the requirements of Class C concrete block. All the samples developed cracks within 24 hours of sample formation, which emphasizes the importance of moisture management, and failure analysis indicated that although all samples failed in a brittle fashion, the fiber-reinforced samples possessed better post-failure properties due to the bridging effect. While these compressive strength values are encouraging and verify the potential of jute fiber-reinforced adobe blocks as a low-cost, sustainable walling solution for non-structural applications or low-rise structures in the Assosa Zone.

Recommendations for future study

Although the impact of jute fiber reinforcement on 15 cm thick adobe units has been successfully analyzed in this study, there are a few aspects that need to be explored further to develop this material further for use in practical applications.

Determination of Optimum Fiber Content

The fiber content of up to 1.5% and lengths of up to 30 cm were considered in this study, and the results indicated an increase in the compressive strength at higher values of both parameters. Further studies should focus on fiber contents above 1.5% and lengths above 30 cm to determine the limit at which the strength increases, and the workability starts to reduce.

Variation in Block Thickness

The blocks used in this study had a thickness of 15 cm. Future research should consider the effect of different block sizes on the structural performance of blocks, with a comparison of 10 cm and 20 cm thick blocks.

Optimization of the Mixing Process

The mixing process adopted in this research work involved the use of freshly mixed mud-fiber composites. Future research work should focus on the effect of pre-hydration of the soil (e.g., soaking it for a period of one week or more before adding the fibers) on the fiber-matrix interface, crack resistance, and compressive strength. Optimization of the mixing process may result in remarkable improvements in the performance of the material. By addressing these issues through specialized testing, a complete understanding of jute-reinforced adobe blocks can be gained, and they can be considered as a viable alternative to concrete blocks in low-cost housing.

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

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Disclosures

Human subjects: All authors have confirmed that this study did not involve human participants or tissue. **Animal subjects:** All authors have confirmed that this study did not involve animal subjects or tissue. **Conflicts of interest:** In compliance with the ICMJE uniform disclosure form, all authors declare the following: **Payment/services info:** All authors have declared that no financial support was received from any organization for the submitted work. **Financial relationships:** All authors have declared that they have no financial relationships at present or within the previous three years with any organizations that might have an interest in the submitted work. **Other relationships:** All authors have declared that there are no other relationships or activities that could appear to have influenced the submitted work.

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