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Research Article

Sustainable Stabilization of Earth Blocks Using Ground Flaxseed and Flax Fibers: A Bio-Based Alternative to Cement and Lime

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ABSTRACT

Earthen construction has re-emerged as a sustainable building method due to its local availability, excellent thermal performance, low energy requirements, and recyclability. However, traditional stabilized earth blocks (SEBs) often face limitations such as water sensitivity, shrinkage, and erosion. To mitigate these issues, various stabilizers—such as cement, lime, agro-industrial by-products, and natural fibers—have been investigated. While chemical stabilizers like cement and lime enhance the strength and durability of SEBs, they also significantly increase embodied energy and reduce overall eco-efficiency. This study explores ground flaxseed as a sustainable, bio-based alternative stabilizer, evaluating its performance at 2% of the soil's dry mass in comparison to conventional cement and lime stabilizers used at 10%. Additionally, the influence of flax fibers on SEB performance is assessed across five inclusion rates (0%, 0.25%, 0.5%, 0.75%, and 1%) to identify the optimal proportion for improving mechanical strength and thermal performance. The overarching goal is to develop an environmentally friendly SEB formulation that preserves or enhances structural integrity and thermal efficiency while minimizing environmental impact.

Keywords: stabilized earth blocks, ground flaxseed, flax fibers, strength and thermal performance.

INTRODUCTION

The excessive cost of building materials and the high energy consumption bill for heating and cooling, as well as the negative environmental impact resulting from the production of cement materials are the main source of CO2 emissions. In order to help reduce these problems pay researchers in most countries to find alternative building materials that are environmentally friendly and cheaper. Earth is one of the building materials used for thousands of years, about a third of the world's population still lives in earthen houses due to the numerous benefits associated with rammed earth constructions, such as availability of these materials and their proximity to the construction site, implementation and relatively easy and does not require energy for implementation, excellent thermal properties due to its mass and it provides excellent insulation and helps maintain a comfortable indoor temperature, staying cool in summer and warm in winter. having a pleasing aesthetic appearance and having a minimal need for maintenance and fully recyclable. Also it is neither cost-effective nor eco-friendly [1] [2] [3]. However, there are some disadvantages of stabilized earth concrete, such as poor stability, shrinkage and loss of strength due to high sensitivity to water, Also the risk of erosion due to exposure to wind or driving rain. to get around these problems a great deal of research has been allocated to developing earth concrete ,several possible solutions have been forwarded by past researchers in try to add strength and durability to earth raw material by using a chemical substance or bio-stabilizers that improves certain characteristics of soil, as well as the insertion of fibers and the reinforcement of additions helps to avoid the problems of this eco-concrete, ensuring stability and improving strength [4] [5] [6], where has been used cement and lime widely as chemical stabilizers for earthen construction [7] [8] . Several studies have been carried out on the using cement combined with other mineral additives, where they were the result of their use obtain high strength and durability [9] [10]. stabilization with lime prevents water attack and lowers density and thermal conductivity, and also use lime with white cement can meet both economic and sustainable requirements [11] [12]. However, cement and lime involve a substantial amount of energy, leading to an increase in the embodied energy of stabilized earth materials. Furthermore, numerous studies validate that lime and cement-based stabilization can alter the material's hydrothermal properties by reducing its vapor permeability and moisture retention [13], as well as the production of cement harm the environment which is considered a source of CO_2 emission, in the production of 1 ton of cement emits between 0.66 to 0.82 ton of CO_2 into the atmosphere [14]. Agro-wastes, such as sugar cane bagasse ash, rice husk ash, and sawdust ash, aggregates of cork also Groundnut shell ash, wheat straw have garnered significant attention as substitutes for cement in building materials. Existing literature demonstrates that construction materials incorporating agro-waste meet the minimum specifications recommended by local construction material standards. Given that a considerable amount of agro-wastes is currently underutilized, [15] [16] [17] [18] [19] [20] [21] [22]. Also, industrial wastes such as fly ash, copper slag, ceramic dust, grain storage dust, Nano-Silica, the core polystyrene beads.... etc. can improve stability of earth raw material, and the incorporation of construction wastes would contribute to mitigating environmental pollution, such as Crushed stone waste and crushed brick waste improved soil properties and increased porosity and water absorption, it improved insulation characteristics. as well as incorporating recycled brick waste such as crushed limestone and recycled brick, Slag waste has great potential to achieve economic and environmental requirements [23] [24] [25] [26] [27] [28]. Animal waste was also used to stabilize the soil and improve its properties, such as using waste eggshells and cow dung [29] [30]. Recently, the focus has been on using biological stabilizers to reduce carbon footprint and improve the characteristics of earthen structures, such as guar gum and xanthan gum commercially available, they contribute to the improvement of erosion resistance and durability, and gum Arabic was a positive result in improving strength for earth concrete [31] [32] [33].have proposed ecological solutions by using earth material reinforced with natural fibers, there are those who have used rice fibers to reinforce CEB led to improve thermal insulation and the insertion of date palm plant fibers resulted in increased the binder content and reduced swelling [33] [34]. as well as many other plant fibers used such as kenaf improved mechanical properties, sugarcane fibers allowed shrinkage reduction and improved strength. Flax fibers improved tensile strength and ductility [35] [36] [37] [38]. The main objective of This study is to investigate a sustainable and environmentally friendly alternative to chemical stabilizers (such as cement and lime) by incorporating ground flaxseeds into Stabilized Earth Blocks (SEB) at a relatively low percentage, comprising 2% of the soil's dry mass. Ground flaxseeds are included as a natural stabilizer for soil blocks. Cement and lime are used at a rate of 10% each for comparison purposes as the most commonly used stabilizers. In other words, incorporating ground flaxseed in SEB aims to produce eco-friendly material. The second objective of this study is to investigate the impact of flax fibers on the properties of these stabilized soil blocks. Five fiber ratios will be tested: 0%, 0.25%, 0.5%, 0.75%, and 1%. The study aims to determine the optimal ratio that enhances the performance of the stabilized soil blocks.

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Research Article

MATERIALS AND SPECIMENS PREPARATION

Soil

Red clay soil used is taken from Moudjebara area is located 25km southeast of djelfa city (Algeria), it is an abundant soil, this area is in operation for the supply of private brick factory. Before testing the soil, it is clipped to 2mm, the obtained resultants for the used soil showed that soil is permissible in the use of stabilized earth blocks according to XP-P13.901 standards. The standard recommends that the soil must have a minimum of plasticity index of 2.5-30% and the clay content of the soil should be between 5-20%. The physical and chemical composition of this soil are shown in Tables 1and 2 respectively.

Table 1. Physical properties of soil used.

Soil used	Particle(mm)					Atterberg limits(%)			Compactibility		density
	<2,5	<2	<0,08	<0,015	<0,002	Wl	Wp	Ip	γd	Wopm	KN/m3
	100%	99%	37%	8%	2%	35	22,7	12.3	2.23	14.06	23.3

Table 2. Chemical composition of soil used (%)

SiO2	Fe2O3	Al2O3	CaO	SO3	MgO	Na2O	K2O	Loss of fire
41.38	4.12	11.34	14.68	13.65	2.45	1.12	1.61	9.65

Sand

The alluvial crushed sand used in this study was sourced from the Laghouat River (Algeria). The physical characteristics of the sand, determined according to the ANFOR standards, are presented in Table 3. Many studies have shown that the most effective dosage of sand for stabilized earth blocks from 20 to 30%. So,30% of sand has been used in this study.

Table3. Physical and mechanical properties of sand.

property	(0/5)
Apparent volume mass (g/cm3)	1.324
Absolute density mass (g/cm3)	2.50
Degree of absorption (%)	0.31
Fineness modulus	2.09
Sand equivalent (%)	90.38

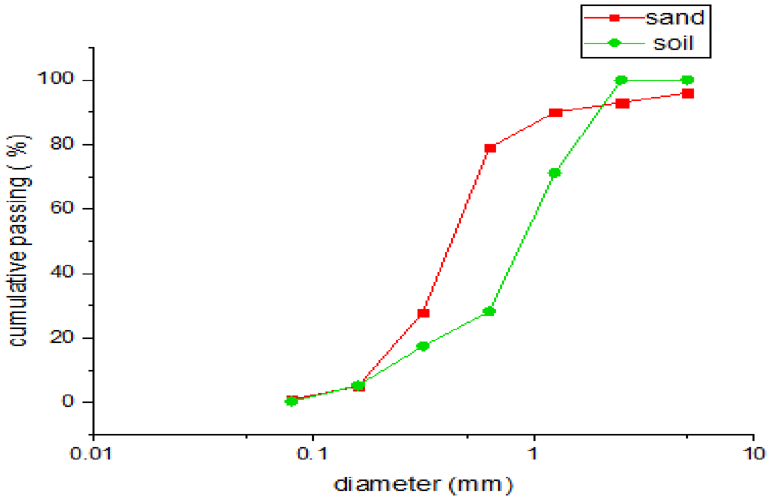

Figure 1. Granulometric analysis of soil and sand.

Cement

The cement used as stabilizer in this study is a Portland cement CEM II/B class 42.5 according to EN 197–1 [39], from Djelfa factory located in middle of Algeria. The physic-chemical and Mineralogical composition of this cement are shown in Tables 4,5 and 6 respectively. Many studies have indicated that the most effective dosage of cement for stabilizing earth blocks is between 5 and 12%. Therefore, 10% was adopted in this study.

Table 4. Physical and mechanical properties of cement

Properties	
Apparent density (kg/m3)	1100
Specific density (kg/m3)	3050
Fineness (cm2/g)	4091
Consistency (%)	29.18
Setting time (min)	150
End of taking (min)	210

Table 5. Chemical composition of cement (%)

SiO_2	Fe_2O_3	Al_2O_3	CaO	SO_3	MgO	Na_2O	LOI	K_2O
20.42	3.08	4.23	63.16	2.32	1.47	0.06	4.17	1.09

Table 6. Mineralogical composition of cement (%)

C_3S	C_2S	C_3A	C_4AF
63.41	15.50	8.17	12.92

Journal of Information Systems Engineering and Management
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Research Article

Figure 2. Materials used ; (A) soil used, (B) sand used,(C) flax fiber,(D) Ground flaxseed

Lime

The lime used as stabilizer in this study is a Natural hydraulic lime with minimum compressive strength of 3.5 MPa at 28 days, referred to as NHL 3.5 according to European standard EN 459-1:2015, The basic components of this lime are portandite, aluminates and reactive silicates formed during calcination from the reaction of crushed limestone containing clay or other impurities. Tables 7 and 8 show The physical and chemical composition of the lime used in the present study.

Table 7. physical properties of lime used.

Properties	
Free H2O (%)	0.7
Residual at 200 µm (%)	0.8
Residual at 90 µm (%)	5.7
Real density (kg/dm3)	2.5
Bulk density (kg/m3)	0.670
Blaine value (cm2/g)	8500
Setting time (min)	295
End of taking (min)	436

Journal of Information Systems Engineering and Management
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Research Article

Compressive strength at 28 days	4.8

Table 8. Chemical composition of lime (%)

SiO_2	Fe_2O_3	Al_2O_3	CaO	SO_3	MgO	Na_2O	LOI	K_2O
5.40	0.24	0.45	63.39	0.97	3.56	0.45	25.38	0.16

Ground flaxseed

Flaxseeds are the seeds of the flax plant, commercially available and widely used in various applications. In this study, commercially available ground flaxseed was chosen as biopolymer stabilizers for earth blocks. It was used at a concentration of 2% of the soil content. The Stabilization using biopolymers is achieved through "hydrogels" which are formed through the interaction of biopolymer, soil and water particles. In contrast, stabilization using cement occurs through hydration [39]. Tables 9 and 10 show Physical and Chemical composition of Ground flaxseed (%).

Table 9. Physical properties of Ground flaxseed

Properties	
Apparent density (kg/m^3)	536.96
Specific density (kg/m^3)	2195
Fineness (cm^2/g)	5100
Water absorption rate (%)	1.23

Table 10. Chemical composition of Ground flaxseed (%)

Ca	Mg	P	K	Na	Zn	Cu	Fe	Mn
10.9	19.95	30.6	38.47	1.25	0.18	0.04	0.23	0.14

Flax fibers

flax fibers are Natural and commercially available fibers were clipped in 40mm in length, (80-0.4 mm) in diameter, flax fibers contain more than 60% in cellulose of their components. which makes them excellent tensile strength properties [40]. in this study, 0.5% of the total dry mass of all ingredients of flax fibers were used, and treated thermally, the hydrothermal treatment used to improve the surface properties of flax fibers by immersing in boiling water for 1heur after treatment, the fibers were dried and used, Table 9 shows The chemical composition of flax fiber used.

Table 11. Mechanical and physical properties of flax fibre used.

Items	(%)
density (g/cm^3)	1.2
Diameter (µm)	22-41

Journal of Information Systems Engineering and Management
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Research Article

Tensile strength (N/mm2)	885.9
Elastic modulus E (GPa)	41
Elongation ε (%)	2.5
Water absorption (%)	7.5

Table 12. chemical composition of flax fibre used.

Items	(%)
cellulose	69.21
Hemicelluloses	18.99
Lignin	8.50
pectins	2.35
Waxes and fats	0.95

Specimens Preparation

In order to prepare the stabilized samples, as a first step the optimum moisture content was determined using the Proctor test (ASTM D 698–07) for each mixture. After knowing the compaction characteristics. Dry components of the samples were mixed for two minutes in an electric mixer, then the water was gradually added, after mixing components well flax fibers has been added at different proportions 0,0.25,0.5,0.75 and 1% for various stabilizers cement, ground flaxseed and lime and they were mixed again manually to ensure good distribution of fiber and to get the formation of a homogeneous mix, then the mixture was placed in templates to compress using a hydraulic machine in a mold with 10*10*20 cm3 to reach the maximum dry density. The samples were wrapped with plastic cover to preserve moisture and other samples were exposed to normal weather conditions for 28 days.

Figure3. Some of the SEB specimens, with different stabilizers (cement, Ground flaxseed and lime) and fibers contents.

Journal of Information Systems Engineering and Management
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Research Article

RESULTS AND DISCUSSION

Density

Density plays a very important role in thermo-physical and mechanical properties, as well as in the workability of its use on various construction sites. It depends on a number of factors, such as soil composition, amount of water used, stabilizer content and compaction procedures. It is important to bear in mind that material density can influence other properties such as mechanical strength and thermal insulation. The figure 4 shows the variations in the dry density of the different specimens at 28 days of curing. as a function of changing the stabilizer and the percentage of the fibers content, in comparison with the specimen without curing, it is noted that the curing of the stabilized samples is increases the dry density. This means that the duration of wet curing leads to an increase in the density of the largest values by the addition of flax fibers. Indeed, the cement stabilizer samples have higher density values compared to other stabilizer samples of lime and ground flaxseed, this improvement in the density could be attributed to the incorporation of fine cement particles into the clayey soil, which has effectively reduced the void spaces within the soil mixture, as observed in other studies [46]. This means that the considerable decrease in dry density by increasing the percentage of flax fibers could be explained by an increase in porosity.

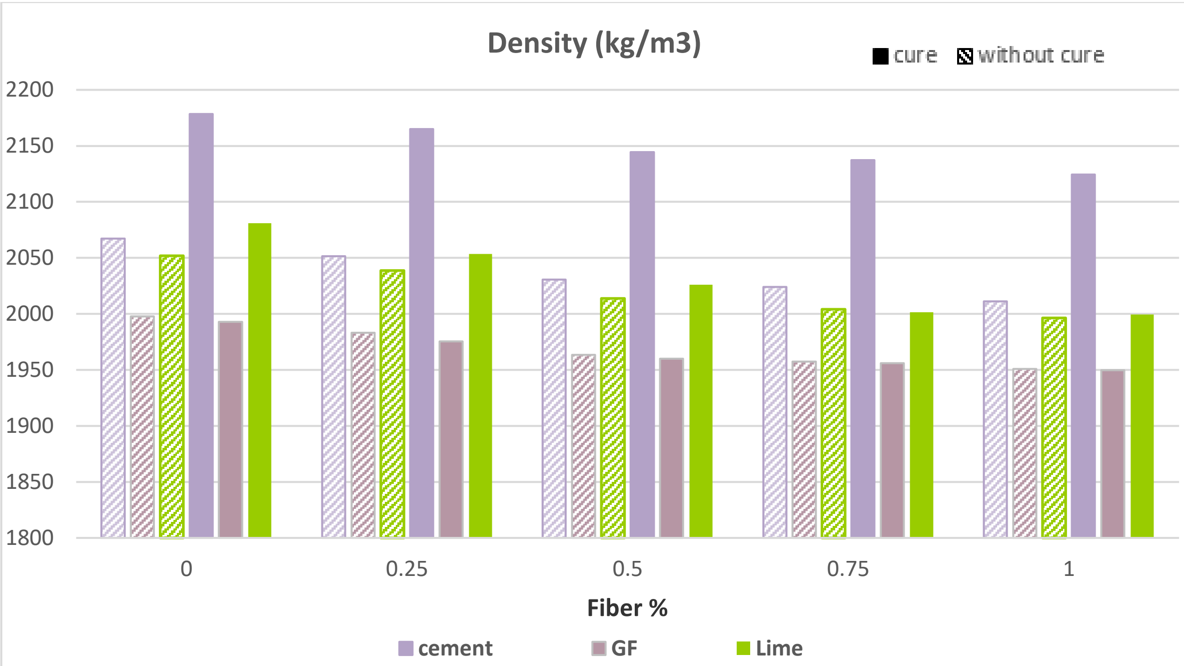

Figure4. Variation of density of SEB with fibers content, different stabilizers and the cure.

Capillary water absorption test

Capillary water absorption test (**figure** 5) consists of placing the soil sample on a humid surface with voids, constantly water saturated, and measuring its weight after 24 hours. Absorption is evaluated in percentage of dry weight. The results illustrated in **figure** 6 show the values of water absorption measured after 24 hours of immersion at ambient temperature (28 ±2°C) for different specimens. It is observed that the curing has a positive impact on low absorption in different stabilizers used, this can be explained that the curing led to reduces the porosity by creating stronger links between soil particles and cement, ground flaxseed and lime. On the other side**,** the addition of flax fibers to stabilized earth blocks results in an increase in the amount of water absorbed. This increase in water absorption is further pronounced with higher rates of fiber addition, indicating the creation of significant porosity within the blocks. Despite the presence of fibers and the increased absorption coefficient, the blocks

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Research Article

remained structurally intact. This phenomenon can be attributed to the thermal treatment applied to the flax fibers, which altered their physical properties, reducing their hydrophilic nature and minimizing their tendency to absorb water. Additionally, the treatment likely enhanced the bonding between the fibers and the earth matrix, contributing to the blocks' structural integrity despite the increased water absorption. Prior research by Labiad et al [47] has also noted similar findings.

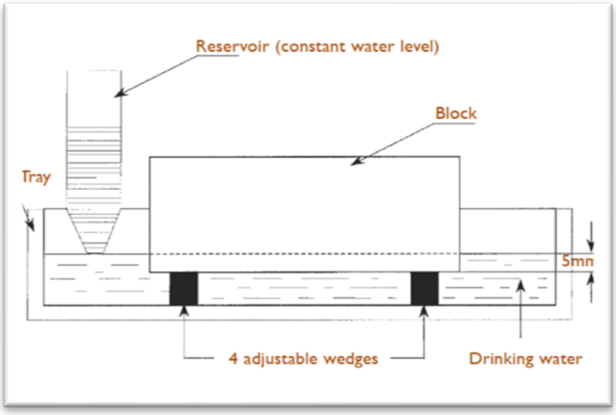

Figure5. Capillary water absorption test

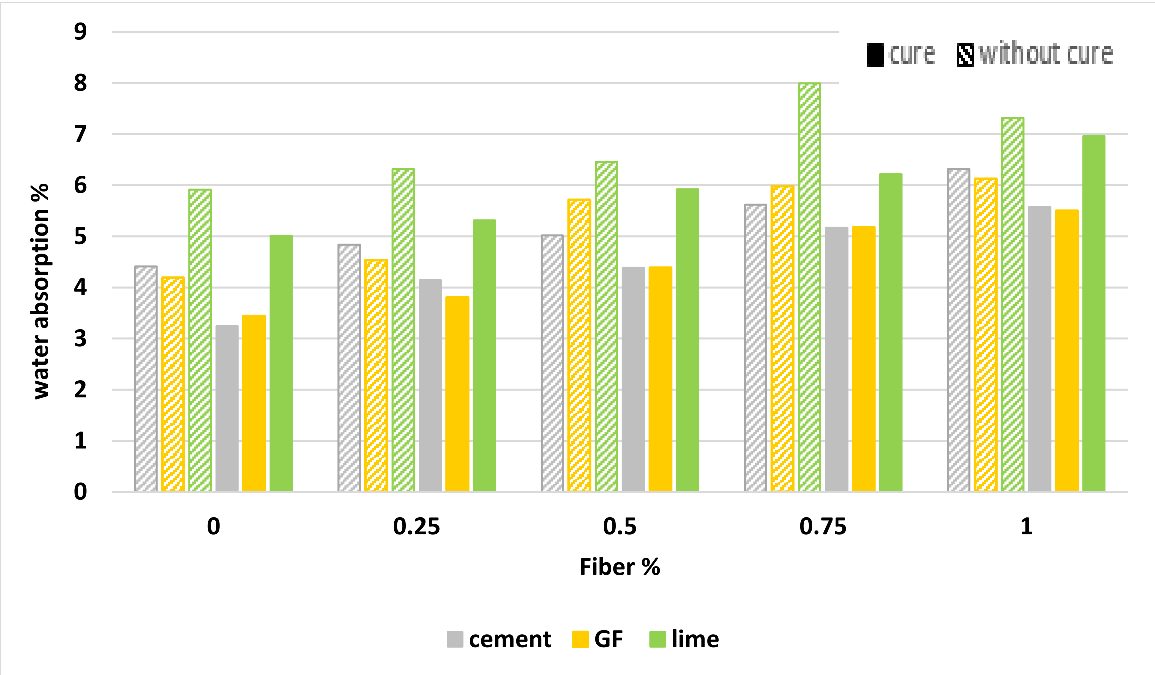

Figure 6. Variation of Water absorption of SEB with fibers content, different stabilizers and the cure.

Tensile strength

Tensile strength of stabilized earth blocks SEB that were cured for 28 days and uncured are demonstrated in Figure 7. In curing the samples inside the plastic cover led to a noticeable improvement in flexural strength. This improvement can be attributed to the role of stabilizers, such as cement, lime, and ground flaxseed, in enhancing the mechanical properties of the soil. Stabilizers react with the soil particles to form chemical bonds, thereby increasing cohesion and reducing porosity. In turn, this leads to a more compact and structurally sound material, resulting in higher flexural strength. Comparatively,

Journal of Information Systems Engineering and Management
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https://www.jisem-journal.com/
Research Article

the samples that were not cured exhibited lower flexural strength, indicating the importance of proper curing in achieving optimal material performance.

These results indicate that fiber reinforcements in both cured and uncured samples, may prove highly beneficial in improving the flexural behavior of rammed earth blocks .On the other hand, it is evident that as the flax fiber content increased, the tensile strength consistently rose for both cement, ground flaxseed and lime-stabilized. the flexural strength of fiber-reinforced SEB increased with the increase in fiber content. It changed from 0.44 to 1.1 MPa when fibers were added at a rate of 0.5%, which indicated an improvement of 107.2% in comparison with the unreinforced sample. In addition, researchers indicated that the fibers subjected to tensile stresses enhance adhesion between fibers and the matrix [45] [36]. Another research demonstrated that the incorporation of 1% flax fibers improved the tensile strength of fiber-reinforced blocks [37]. Additionally, during testing it was observed that two pieces of fiber-reinforced SEB specimens remained connected upon failure, whereas unreinforced SEB specimens completely separated. This indicates that fiber incorporation increases the ductility and enhances energy absorption capacity of the material compared to unreinforced SEB. These observations are consistent with previous research [45].

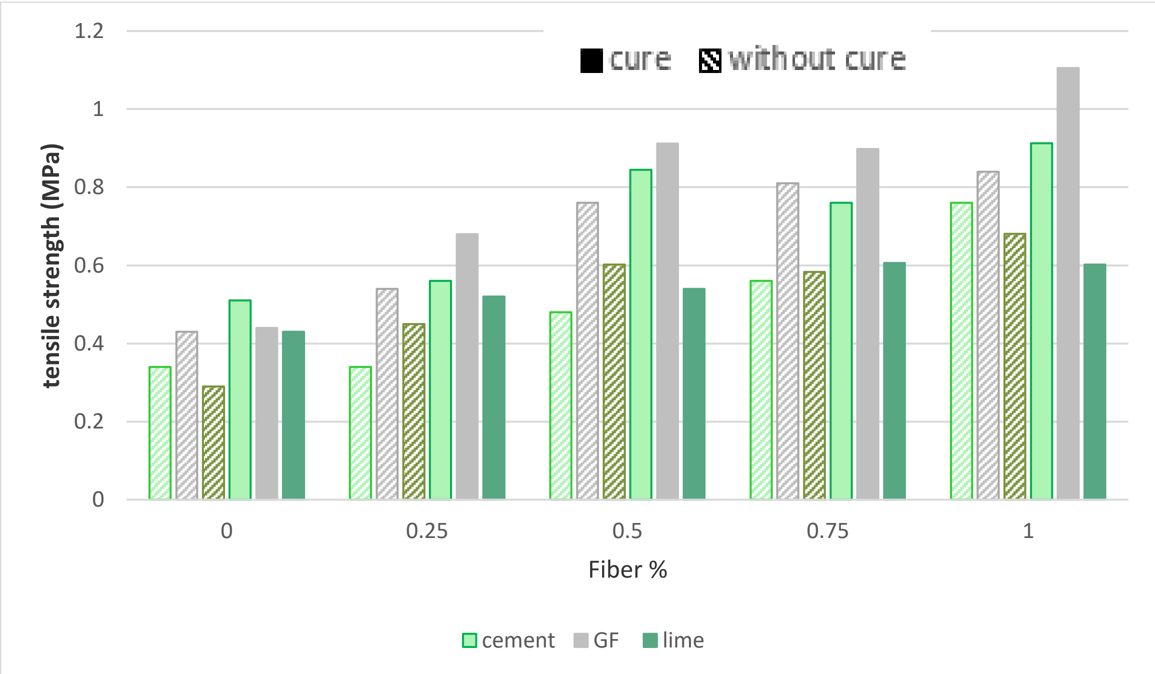

Figure 7. Variation of Tensile strength of the SEB with fibers content, different stabilizers and the cure.

Compressive strength

Figure 8 summarizes the compressive strength results of different blocks produced, Firstly, it is evident that the cure has a significantly positive effect on the compressive strength, as indicated by the obtained results. This can be attributed to hydration leading to pore closure and the formation of bonds between clay particles. After 28 days of curing, an increase in compressive strength is observed irrespective of the type of stabilizer or fiber content. In addition, it can be observed that the addition of cement, lime, and ground flaxseed leads to the formation of strong chemical bonds by reacting with soil particles. These bonds work to fill the voids within the mass, resulting in reduced porosity. As a result, the strength of the concrete has improved. Similar observations were stated that compressive strength of earth brick samples is highly dependent on the density by Zak et al [47].

On the other hand, adding of flax fibers to the stabilized earth concrete can impact its strength. It appears that an increase in the fiber content may enhance the strength in some cases, but it may decrease the strength in other cases if a certain percentage is exceeded. The compressive strength increased by 17.32% for cement, 50.41% for lime and 61.60% for flaxseed, at a fiber content of 0.5%, indicating that adding a content not exceeding 0.5% resulted in an improvement in compressive strength. However, when the fiber content reached 1, a decrease in concrete strength was observed, this leads to its easy deterioration. Several studies have indicated that an increase in compressive strength is correlated with fiber quantity up to a maximum limit, beyond which the opposite effect occurs [8] [46] [47] [45]. The use of plant fibers in high percentages (>0.5 weight %) does not enhance the compressive strength of stabilized earth concrete. Furthermore, the Poor distribution of fibers within the matrix can lead to an increase in void volume, thereby reducing the density and strength of the concrete. Similar results were obtained in previous investigations [46].

These findings indicate that the stabilized earth blocks achieved the maximum resistance of compressive strength when the blocks were reinforced with 0.5 wt.% SEBF**.**

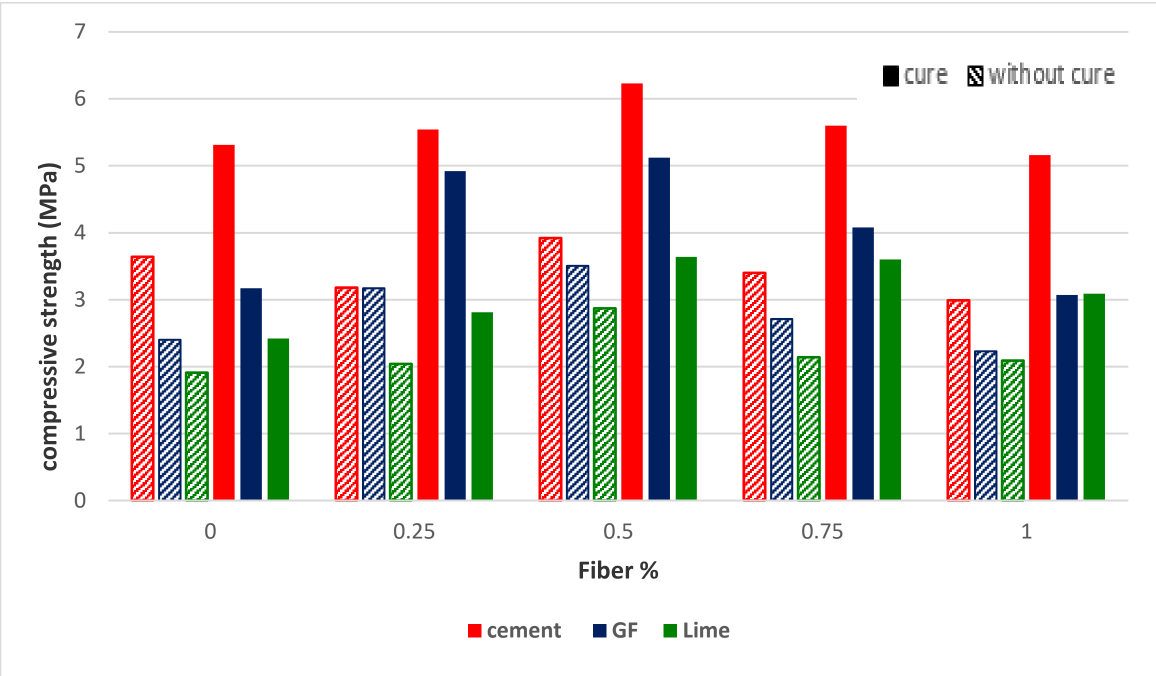

Figure 8. Variation of compressive strength of the SEB with fibers content, different stabilizers and the cure.

Ultrasonic pulse velocity (UPV)

The Ultrasonic Pulse Velocity (UPV) is a non-destructive testing method used for measuring the speed of sound waves propagating through materials. It involves transmitting ultrasonic pulses through the material and measuring the time taken for them to travel from the transmitter to the receiver. The use of UPV as a tool for inspecting structures without causing damage is crucial for evaluating material quality and detecting potential defects, thus contributing to the preservation of the safety and sustainability of various buildings and structures.

Figure 9 illustrates the evolution of Ultrasonic Pulse Velocity (UPV) for different specimens. The results demonstrate that UPV was influenced by the curing regimen. Specimens cured for 28 days exhibited an increase in UPV with age, regardless of the stabilizers used, whether cement, ground flaxseed or lime.

Journal of Information Systems Engineering and Management
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This increase can be attributed to the positive effect of curing, which allows for the hydration process facilitated by the vehicles and minerals present in clay or through the interaction of organic materials from ground flaxseed with soil particles. This resulted in a reduction in voids and the formation of strong bonds. On the other side**,** Ultrasonic Pulse Velocity was observed to be affected by the addition ratio of **flax** fibers, with the addition of fibers at ratios of 0%,0.25%, 0.5%,0.75% and 1% respectively resulting in velocities of 1600, 1612.9, 1693.34, 1612.9, and 1587.31 m/s, sequentially, regarding the samples stabilized with cement, and 1600,1639.34,1666.6,1612.3 and1562.5 m/s regarding the ground flaxseed. for the lime, the speeds are 1000,1245.4,1540.61,1279.06 and 1157.89 m/s respectively. these results indicate that the addition of fiber in stabilizers earth blocks is an increasing function up to 0.5% of flax fiber content (optimum), and beyond that, it becomes decreasing. This means that the use of fibers with high percentages (>0.5 weight %) does not improve the UPV of SEB**.**

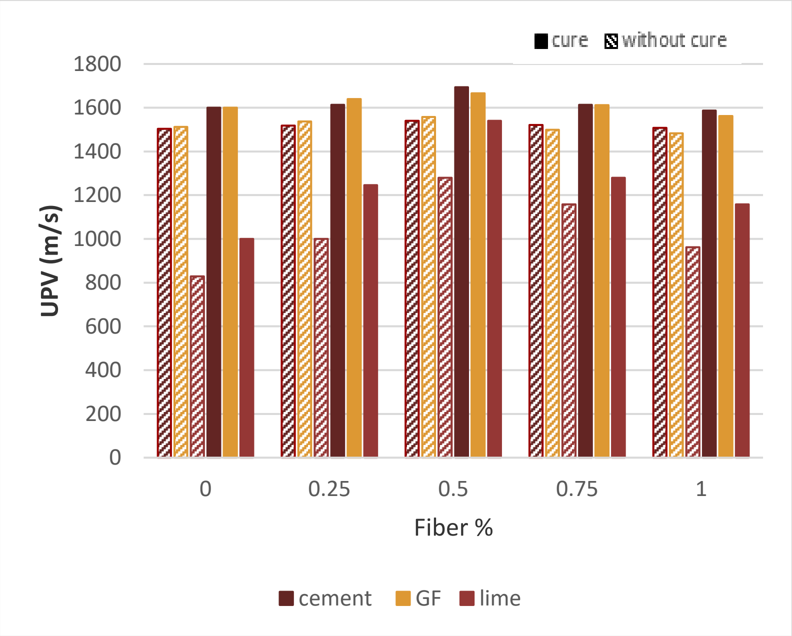

Figure 9. Variation of Ultrasonic Pulse Velocity of the SEB with fibers content, different stabilizers and the cure.

Thermal conductivity

Figure 10 displays the results of a thermal conductivity test conducted on various formulations under study. The results indicate that the thermal conductivity decreases in both cured and uncured samples with the addition of flax fibers in all stabilizers (cement, ground flaxseed, and lime). It is observed that curing has a positive effect on thermal conductivity, with higher values appearing in cured samples. This increase in thermal conductivity is primarily attributed to the hydration process between cement or lime and soil minerals, which creates stronger bonds. Additionally, biological stabilizers such as ground flaxseed react with soil particles to form chemical bonds, thereby reducing voids in the matrix. Furthermore, the incorporation of fibers in the soil-cement mixture results in a reduction in thermal conductivity. For example, in the case of cement-stabilized samples reinforced with 1% fiber, the thermal conductivity was 0.786 W/m.K for cured samples and 0.645 W/m.K for uncured samples. Conversely, samples without fiber exhibited thermal conductivities of 0.889 W/m.K and 0.713 W/m.K for cured and uncured samples, respectively. However, the thermal behavior decreased with an increase in fiber content, which can be attributed to the formation of voids in the matrix, thus increasing porosity. As some studies have [48] [49].

Journal of Information Systems Engineering and Management
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Research Article

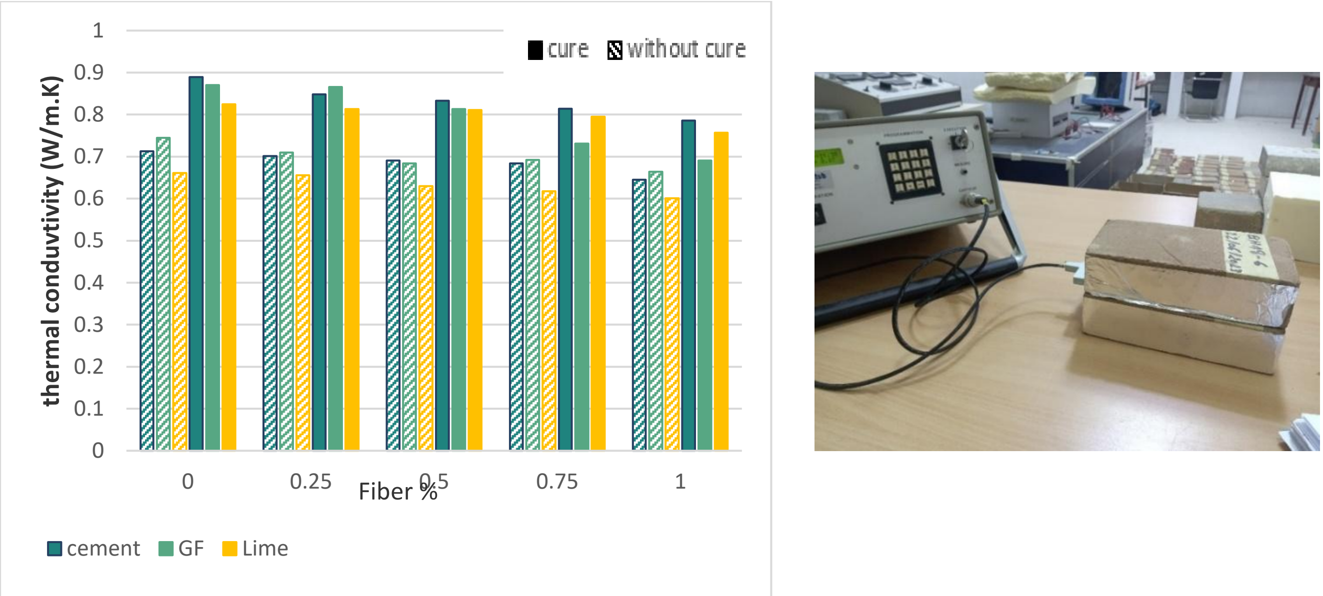

Figure 10. Variation of Thermal conductivity of the SEB with fibers content, different stabilizers and the cure.

These results showed that the thermal conductivity of SEB related on the porosity of the material. the porosity of the material increases leads to decrease in thermal conductivity as reported by Labiad and al [45]and Colbert B and al [50], Similar observations were stated by Toufigh et al [51] and Anh Phung [52]

Abrasion test

The abrasion test (figure 11) is a critical measure of the properties of SEB (Stabilized Earth Blocks), indicating their resistance to abrasive stress. This test method involves measuring the mass loss resulting from frictional forces, with the results typically depicted in Figure 12. The abrasion coefficient of SEB decreases as the fiber content increases up to 0.5%. The reduction coefficients for cement, ground flaxseed, and lime are recorded as 54.32%, 50.02%, and 46.35% respectively, for samples reinforced with 0.5% fiber compared to unreinforced samples. This reduction suggests that the inclusion of fibers enhances cohesion and adhesion between soil particles. However, with a higher fiber content exceeding 0.75% up to 1%, a slight increase in the abrasion coefficient is observed. This behavior could be attributed to inadequate adhesion and non-uniform fiber distribution. The improved abrasion resistance observed with the inclusion of fibers at 0.5% is due to enhanced cohesion between soil particles. Similar findings have been reported in various studies [45] [50] [49] [53] [54] [55].

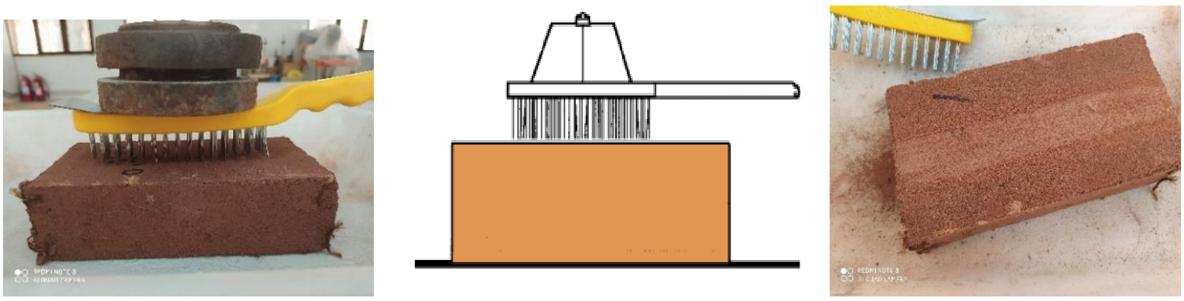

Figure 11. Abrasion test

Journal of Information Systems Engineering and Management
2025, 10(4)
e-ISSN: 2468-4376
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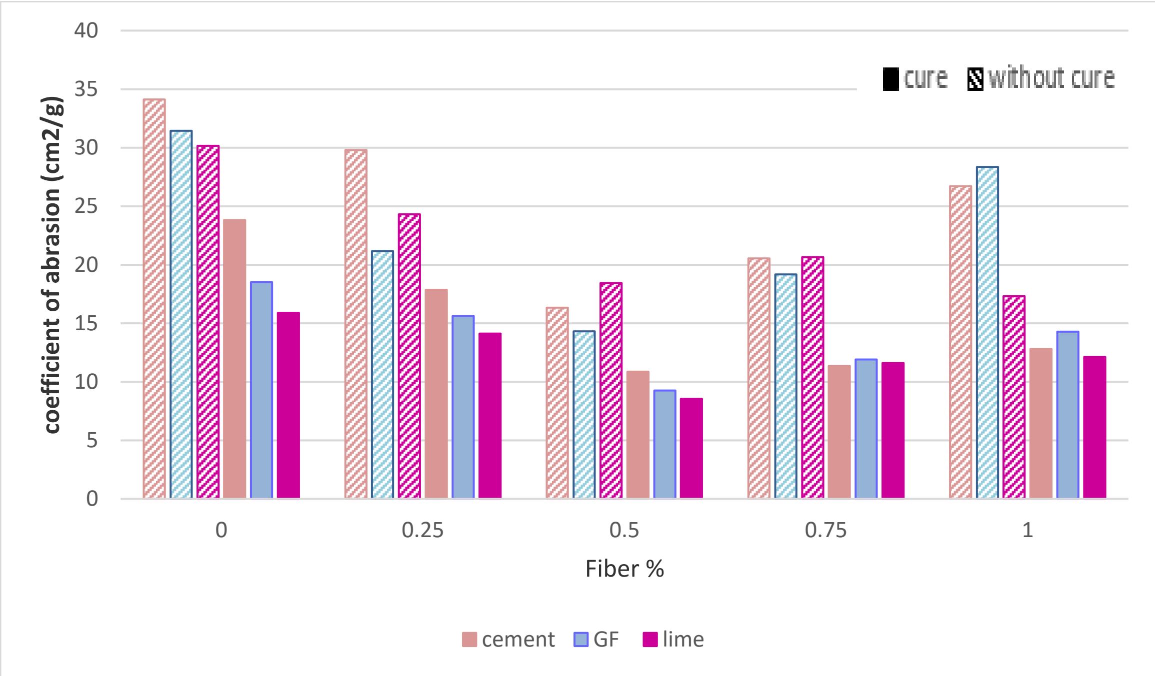

Figure 12. Variation of Abrasion coefficients of the SEB with fibers content, different stabilizers and the cure.

CONCLUSION

This study highlights the effectiveness of ground flaxseed as a sustainable, bio-based stabilizer for stabilized earth blocks (SEBs), offering a promising alternative to traditional cement and lime.

The compressive strength results revealed a 17.32% increase with cement, 50.41% with lime, and a remarkable 61.60% with flaxseed at a flax fiber content of 0.5%. These findings indicate that fiber reinforcement enhances mechanical strength up to an optimal threshold of 0.5%, beyond which performance begins to decline. This trend suggests that flax fiber addition is beneficial in moderation, with 0.5% identified as the optimal content for maximizing strength.

Thermal conductivity tests further revealed that curing has a positive effect, with increased conductivity observed in cured samples. This improvement is attributed to the hydration reactions between stabilizers (cement/lime) and soil minerals, which densify the matrix. Ground flaxseed also contributes by forming chemical bonds with soil particles, reducing voids and thereby enhancing thermal transfer. In contrast, the incorporation of flax fibers reduced thermal conductivity, likely due to the increased porosity introduced by the fibrous material.

Overall, the use of ground flaxseed—both as a stabilizer and in combination with flax fibers—offers a viable, eco-efficient alternative to conventional stabilizers. It enhances the structural and thermal properties of SEBs while significantly lowering the environmental impact, aligning with the principles of sustainable construction.

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