Research Article

An engineered alternative brick masonry unit for the poor inhabitants at Hawassa village, Ethiopia

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Abstract
The southern rural regions of Hawassa village, Ethiopia customarily practices Chika-pet and adobe masonry houses. They use soil, wood and teff straw adobe bricks in house construction, due to its extreme poverty and unsophisticated manner of living. These houses are unsustainable and flimsy due to its inclusion of easily degradable raw materials, non-engineered construction practice, poor earthquake resistance and rapid climatic uncertainties. Moreover, the soil utilized for the adobe brick making is consumed from far away distant regions by ignoring their native Hawassa soil due to its unsuitable brick making characteristics. This impacts the economical expenditure of the poor income inhabitants. Therefore, this research is intended to facilitate the Hawassa village inhabitants by improving their native soil characteristics on adding lime and considers it for brick unit formation. In addition, an alternative reinforcement called pineapple leaf fibre is introduced for the adobe brick making which enriches compressive and tensile strength at a satisfactory rate according to the California Building Standard Code (CBC) requirement. The maximum compressive strength is recorded as 4.1 MPa which is 6 times greater than the conventional specimens and flexural strength is recorded at an improved rate of 0.78 Mpa. It ensures the standard requirement according to the CBC code. As a result, a sustained residual tensile load is recorded which indicates an efficient improvement in the ductility failure of brick. The bending test data is processed to estimate young's modulus in tension highlighting the bi-modularity of the earthen composite material. The experimental correlation between various mechanical properties is presented and modelling design equations are proposed in the engineered manner of design/assessment purposes. A comparative study and cost analysis of the existing and proposed approach is discussed to validate the superiority of the proposed concept.

Keywords
Rural development, House construction development, Brick masonry units, Adobe brick, Poor inhabitants, Economical construction materials.

1.Introduction
1.1Background of the study
The traditional house construction pattern in the southern rural regions of Ethiopia is preferably constructed by means of "Chika-pet", which is the mud and wood construction technique, due to the poverty and low annual income of the inhabitants. "Chika" is a composite mixture of clay, teff straw and water, that is used as a gap filling material between the wooden frames and finally as a plaster. Due to the climatic uncertainties, this mud wall construction pattern experiences severe shortcomings such as wide crack formation in the walls, shrinkage, strength weakening, and prone to be eroded by rain which deteriorates the durability.

Later on, to cope with these drawbacks the animal dung is used as a protective coating on the Chika-pet house walls. It further requires frequent maintenance and cost wise unaffordable by the inhabitants. Moreover, these houses require plenty of woods for the construction of walls and roofs which increases the cost and deforestation rate, hence these mud walls using soil is considered to be defective.

Recently, the advancement of house construction in the southern regions of Ethiopia is upgraded by using bricks as the construction material. In current practice, the brick masonry units are made of a composition of soil and teff straw fibre, wherein the soil is preferably collected from the far distance regions like Ziway, Alemtena and Meki. The negligence of their native southern region soil is due to its poor brick construction characteristics and hence this complicates

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the economical expenditure of the low-income inhabitants with increased rate of transportation cost.

The bricks in current practice are formed in larger size and this leads to increased heaviness with decreased strength [1]. Moreover, the durability and strength of the building is affected over years later due to the decomposition of teff straw present in the bricks which causes higher porosity [2]. This demerit the building structure by becoming more brittle and leads to poor performance during the seismic condition [3].

This research focus and address the major setbacks in the construction engineering such as uneconomic expenditure affecting poorly income people, increased rate of deforestation, reliance on Chika-pet, demerits of teff straw, rejection of native soil, weedy and non-engineered construction practices, unnecessary transportation expenditure, instability of the building during seismic situation, durability and eco friendliness of unfired mud brick houses need broad exploration.

The main objective of this study is to provide an economical, eco-friendly and sustainable brick masonry unity for the poor inhabitants of Hawassa village. To achieve this major objective, the compressive strength, tensile strength, residual load and durability test were conducted on the proposed masonry samples and compared with the conventional practice of masonry units. In addition, to calculate the mechanical properties and design the brick manually, experimental correlations between various mechanical properties were explored and modeling, design equations were proposed in the engineered manner of design/assessment purposes. A comparative study and cost analysis of the existing and proposed approach is discussed to validate the superiority of the proposed concept.

2.Literature review

Numerous researchers have reported different fibre compositions in the making of adobe bricks and its characteristics like compressive strength, flexural strength, modulus of elasticity, water absorption test, thermal conductivity etc. are tested and analysed for ensuring the efficacy of the fibre. Babé et al. (2020) addressed the influence of red millet fibres on the compressive and flexural strength of adobe mixes. The experimental test result of mechanical characteristics confirms that the inclusion of 2% millet fibres to the soil of adobe brick enhances the compressive and flexural strength at a rate of 38%. Also, incorporation of 2 to 4% addition of millet fibre to the soil of adobe

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brick shows more resistant composite while compared with the adobe brick made of pure matrix soil [1].

The mechanical properties with the addition of sea grass fibres to the soil of adobe brick was studied [2]. The experimental test result concludes that both the compressive and flexural strength of adobe brick is improved due to the addition of sea grass fibres. It is recorded that the maximum compressive and flexural strength of adobe brick is 2.672 MPa and 0.457 MPa, respectively corresponding to the addition of 1.5% of seagrass whose length is equal to 3cm.

Bertelsen et al. (2021) [3] reveals that the usage of synthetic waste fibres in adobe brick results in the formation of finer cracks as compared to the wider cracks generated on employing unreinforced specimen. On increasing the synthetic fibre content along the adobe brick the flexural strength increases, accordingly. It perceived that the addition of 5% synthetic fibre produces 75% superior flexural strength as compared to the conventional adobe brick. Similarly, the compressive strength increases 33% with respect to unreinforced specimen due to the addition of fibre content.

The influence of adding recycled pet fibres along with adobe bricks was investigated by literature [4] in terms of drying shrinkage and compressive strength effects. The experimental results ensure an encouraging effect on both properties while adding 0.25 to 0.5% fibres and a reduction of shrinkage is recorded up to 48%. Moreover, the highest compressive strength is reported corresponding to 0.5% of fibre with higher clay content.

Ige and Danso (2021) [5] focused on the solution to develop mechanical properties of adobe bricks with plantain pseudo-stem fibre. The experimental laboratory test was conducted on different ratio of fibres at 0, 0.25, 0.5, 0.75 and 1% in addition to adobe bricks. The average compressive strength is obtained as 1.76 MPa corresponding to 0.75% inclusion of fibre with 33% enhanced compressive strength over the pure matrix form of adobe brick. The 0.5% inclusion of plantain pseudo-stem fibre reinforced adobe brick attained maximum splitting tensile strength of 0.3 Mpa which is 53% enhanced strength over unreinforced brick.

Kafodyaab et al. (2019) [6] conducted an investigation by including sisal fibres as a reinforcing element for adobe masonry. A 25 mm length fibre is added at 0.75% and its experimental results reveal a 31%

increase of tensile strength and 25% increase of prism compressive strength as compared to the unreinforced mortar. Moreover, the sisal fibre wallets exhibit a two times enhancement in compressive strength and the reinforced wall panels records three times raise in shear strength.

The fonio straw is investigated on the mechanical properties of adobes and its laboratory experimentation was performed by Ouedraogo et al. (2019) [7]. The usage of small amount of fonio straw enhances the compressive strength, flexural strength and reduces the brittleness of the adobes. The maximum strength is attained corresponding to 0.2 to 0.4 % weight of fonio straw content. Besides, the thermal conductivity of adobes decreases during the addition of fonio straw due to the insulating nature of cellulose in the straw and the straw inclusion has a property to resist water erosion of adobe brick.

The mechanical properties of adobe brick composed of paper and pulp waste fibre were investigated [8]. The light weight adobes with lesser thermal conductivity and enhanced compressive strength are created by employing paper and pulp waste fibre. The compressive strength is superior up to 190%, while thermal conductivity diminishes 30% to 12.5% of fibre replacement.

Sudhir et al. (2020) [9] conducted a research on focusing the utilization of industrial waste fibre for the production of adobe bricks. Here, the compressive strength increases 40.10% maximum up to the addition of 60% industrial waste and beyond the compressive strength reduces. The researchers reported that the usage of red mud as a brick manufacturing material is economically feasible and cured bricks are eco-friendly as compared to conventional fired bricks.

Malkanthia et al. (2020) [10] states that the unfired adobe brick requires less energy than the fired bricks and the emission of CO_2 to the environment is 80% less as compared to the burnt bricks. This is evident from the *Figure 1* which graphically represents the increased rate of initial embodied energy and pollution emission per one cubic meter for various types of fire brick walls. CSEB indicates the Compressed Stabilized Earth Blocks. The cement is considered as the most admired stabilizer than the lime for earth block manufacturing. On comparing the production process of lime and cement, the emission rates of energy and CO_2 are recorded at higher values for the cement as compared to lime for a cubic meter of material quantity as mentioned in the *Figure 2*.

The existing literatures reveal that the authors significantly focus on the mechanical property investigation of the adobe bricks with the composition of variant type of fibres. However, the literatures fail to discover the relationship between the mechanical properties such as compressive strength, flexural strength, modulus of elasticity, etc. which facilitates the designer to design the bricks without conducting any laboratory testing. Furthermore, the reinforcement fibres like red millet, sea grass, industrial waste, synthetic waste, recycled pet, paper and pulp waste, plantain pseudo-stem, sisal, and fonio straw are employed for the brick making process, which lacks their easy and continuous availability in Ethiopia.
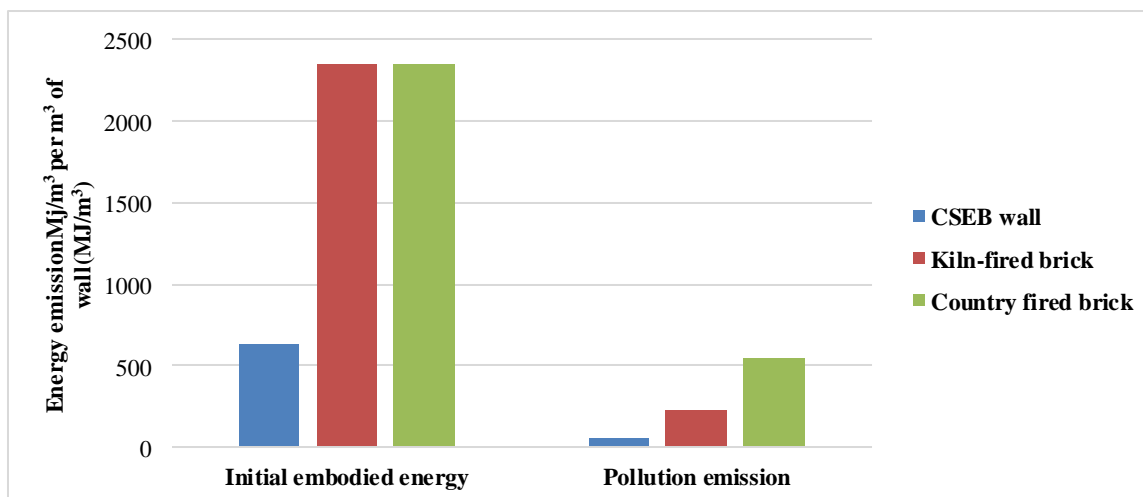

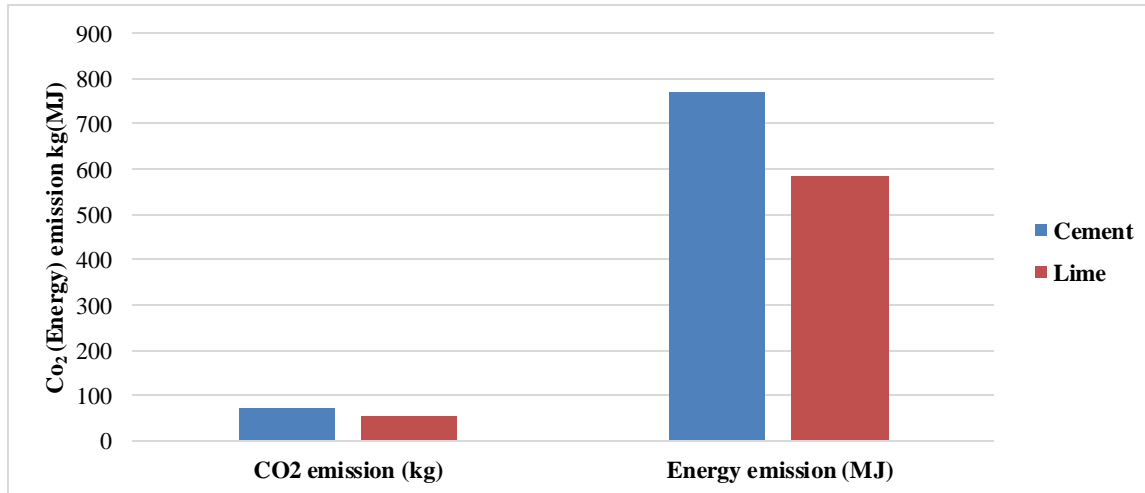**Figure 1** Initial embodied energy and pollution emission of wall [10]

Figure 2 Emission rates of CO_2 and energy during lime and cement blocks manufacturing [10]

This paper is highly intended to develop and propose the brick design equations based on the mechanical property relationships, which in turn simplifies the design engineer in the brick making process. This study not alone limited to the calculation of compressive strength, flexural strength, modulus of elasticity, but also explored the experimental correlation between various mechanical properties and modelling design equations are proposed in the engineered manner of design/assessment purposes. Correspondingly, these design equations help the designer to calculate the mechanical properties like compressive strength, flexural strength, modulus of elasticity etc. without conducting any laboratory experimentation. In addition, the economically feasible and easily available pineapple leaf fibre is used as a reinforced material for adobe brick making. Moreover, an eco-friendly binding agent called lime is used to improve the Hawassa soil property which requires lesser energy emission and is cheaper while compared with cement. A comparative study and cost analysis of the existing and proposed approach is discussed to validate the superiority of the proposed concept.

3.Materials
3.1Variables, availability and price of stabilizer and reinforcing material in Hawassa
The major variables considered in the experimental study include stabilizer called lime and reinforcing material called pineapple leaf fiber in total weight. Massive production resources of lime are found in Ethiopia and the lime is economically feasible at a rate around five Ethiopian Birr per one kilogram. This is afforded by the inhabitants as the requirement of lime for one masonry unit is in very small quantity. Around

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50 years ago, pineapple cultivation is established in the Ethiopian Sidama region (Hawassa) and it is the only region generates large quantities of pineapple fruits for local markets from the farm land due to its warm climatic condition as well as soil suitability [11]. From the mass production of pineapple leaf, lesser amount of leaf fibers is used as feedstock and employed for energy production, whereas the majority are wasted as residues from the agro based industries. Fortunately, these leaf fibers possess various beneficial features suitable for brick making [12], yet it is not used so far in un-burnt brick making process in Hawassa due to unawareness about its advantages. Therefore, this research proposes the pineapple leaf fiber as a reinforcing material for the brick manufacturing.

3.2Hawassa soil sample
The southern regions of Ethiopia generally prefer the soil from Ziway, Alemtena and Meki regions for the construction purpose of brick masonry unit. The underlying fact of this soil preference is that, it complicates the economical expenditure of the low-income inhabitants of Hawassa village with increased rate of transportation charges. Due to the poor brick construction characteristics of Hawassa soil, it is generally not preferred for brick formation. Hence, this research facilitates the Hawassa inhabitants by improving their native soil quality with altered characteristics and considers it for brick unit formation. This alteration is performed by adding binder material called lime. The test sample soil is collected from the main campus of Hawassa University for the production of un-burnt brick as shown in the *Figure 3*. The characteristics of the collected soil sample are studied by performing Geotechnical analysis. Moreover, the physical

properties like Particle size distribution of the experimenting soil are tabulated in *Table 1*, optimum water content 15.40%, Liquid limit 30.6%, plastic limit 23.30% and plasticity index 7.30% are investigated and identified under laboratory testing as represented in the *Figure 3*. The test results ensure an adequate amount of plasticity for a uniform mix when added with other ingredients to the mixture.

Figure 3 Laboratory soil testing

Table 1 Particle size distribution of the experiment soil

Sieve opening (mm)	Percentage of passing
9.5	99.42
4.75	92.33
2.36	76.29
2	76.29
1.18	55.60
0.6	31.29
0.425	31.29
0.3	18.84
0.15	10.89
0.075	4.57
Pan	0.00

3.3 Reinforced composite-pineapple leaf fibre

Due to the excellent physical and mechanical characteristics of pineapple leaf fibre [11], it is used as a reinforcing composite matrix for the masonry units as pictured in *Figure 4*. It is considered as an efficient alternative for teff straw fibre [12]. The extraction process of fibres from the pineapple leaf is performed by the mechanical and retting method. The result of polymer composite pineapple leaf fibre confirms an excellent stiffness and strength as compared to other cellulose based compound materials [13]. The various dynamic features of pineapple leaf fibre include robust mechanical strength, good sound absorbent, thermal insulator, soft and glossy as silk, medium length fibre, high tensile strength, stiffness, softer exterior surface than other natural fibres and good colour maintenance [14]. The mechanical property of pineapple leaf fibres such as young's modulus varies from 34.5 to 82.51 $GN \cdot m^{-2}$, tensile strength varies from 413 to 1627 $MN \cdot m^{-2}$ and elongation at breakpoint varies from 0.8 to 1.6%. The physical and mechanical strength of pineapple leaf fibre is mentioned in the *Table 2*. The percentage weight of pineapple leaf fibre considered in this study varies from 0.1%, 0.2%, 0.3%, 0.4%, 0.5%, 0.6%, 0.7%, 0.8%, 0.9% and 1% in total weight of masonry units.

Table 2 Properties of pineapple fibre

Density (g/cm³)	Average diameter (µm)	Tensile strength (MPa)	Young's modulus (GPa)	Elongation at break (%)
1.35	61.87	227	52	2.42
1.4	63.2	238	53	2.52
1.3	58.6	221	49	2.34
1.5	67.5	254	56	2.69
1.45	67.2	243	53	2.58

Figure 4 Pineapple leaf fibres

3.4 Stabilizer–lime

Lime, an antique and economic material predominantly used as a soil stabilizer, which has its abundant natural resource in Ethiopia. On blending the lime content in the clay soil, the natural property of the soil gets improved due to the reaction of the calcium ion content in the lime with the clay soil. At this phenomenon, there is an exchange between metallic ion and cat ion which alters the electric charge density of the particles and tightly groups them in the form of flocks. The various percentage composition of lime weight considered are 1.5%, 3%, 4.5%, 6%, 7.5%, 9%, 10.5%, 12%, 13.5% and 15% in total weight of masonry units.

4. Methodology

The methodological schematic of this experimental investigation was presented in *Figure 5*, which includes sample collection, manufacturing of bricks, laboratory testing, analysis of test results and development of design equations. In order to develop an engineered customized design equation for adobe brick production. It is mandatory to perform laboratory experimentation for calculating the mechanical properties such as compressive test, flexural test, modulus of elasticity, etc. These test results facilitate in estimating the relationship or correlation between each mechanical property by performing a regression analysis. The design equations are structured based on the correlation

property of each parameter, which helps the design engineers in future in estimating the different mechanical properties without conducting any experimentation.

An efficient brick modeling with high durability is tested by considering various proportional ratios of the constructing ingredients as presented in the *Table 3* detailing three groups of masonry unit making process. The first group of masonry unit production includes the combination of soil and lime illustrated in *Figure 6(a),* whereas the second group includes the combination of soil and fibers as shown in *Figure 6(b).* The production process of these brick specimens includes grinding, mixing, manual molding and sun drying. Further the mechanical properties of group 1 and 2 adobe bricks are calculated using laboratory testing. Based on the test results of first and second group brick productions, the percentage ratio of mixing composition of third group specimen made of soil, lime and pineapple leaf fiber is identified and presented in *Figure 6(c).* Similarly, the group 3 specimen is treated under production process and laboratory testing, which finally concludes that group 2 and 3 are efficient and is considered as proposed 1 and 2 respectively. In current practice, the standard existing size of the brick measures 400×200×200 mm, whereas this investigation considers a brick size of 240×112×70 mm measurement which considerably reduces the heaviness as compared to the existing bricks and casting and drying process of brick

specimen is pictured in the *Figure 7*. The laboratory experimentation is performed to examine the compressive strength, tensile strength and durability testing on rain. In addition, the ductility nature of the brick specimen towards the seismic condition also studied using tensile load versus displacement curve. The experimental results obtained using the reinforcement pineapple leaf fiber is compared with the existing teff straw fiber composition.

Table 3 Group and specimen composition of adobe brick

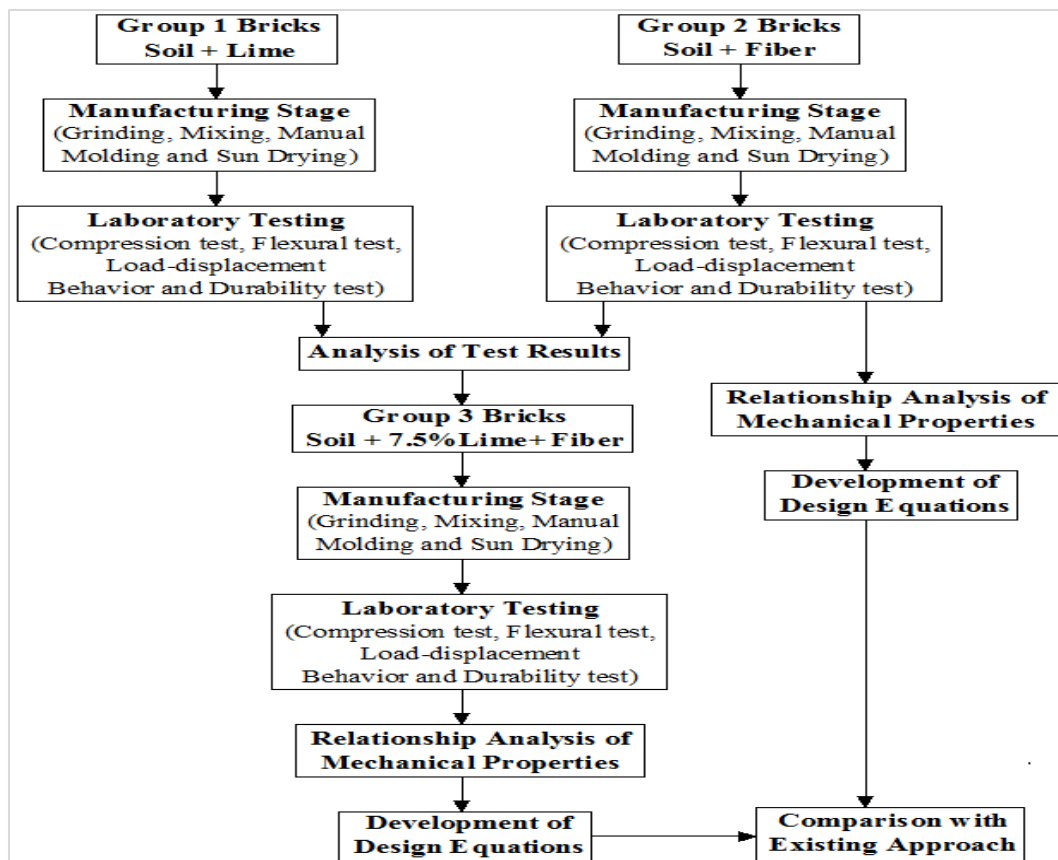| Group-1			Group-2			Group-3		
Brick specimen	Lime (%)	Fibre (%)	Brick specimen	Lime (%)	Fibre (%)	Brick specimen	Lime (%)	Fibre (%)
L1	1.5		F1	-	0.1	L5F1	0.9	0.1
L2	3	-	F2	-	0.2	L5F2	0.9	0.2
L3	4.5		F3	-	0.3	L5F3	0.9	0.3
L4	6	-	F4	-	0.4	L5F4	0.9	0.4
L5	7.5		F5	-	0.5	L5F5	0.9	0.5
L6	9	-	F6	-	0.6	L5F6	0.9	0.6
L7	10.5		F7	-	0.7	L5F7	0.9	0.7
L8	12	-	F8	-	0.8	L5F8	0.9	0.8
L9	13.5		F9	-	0.9	L5F9	0.9	0.9
L10	15	-	F10	-	1	L5F10	0.9	1

Figure 5 Methodological schematic flowchart

Figure 6 Various group of composition of adobe brick specimen

Figure 7 Making process of brick specimen

4.1 Uniaxial compression tests

The mechanical behaviour of un-burnt bricks in uniaxial compression are distinguished using the displacement controlled uniaxial testing machine as per the European standard [15]. The brick specimen of size 240×112×70 mm is located between stiff rigid steel plates on the testing machine. The loading process includes two initial cycles of loading, which follows by a displacement- controlled monotonic loading at a displacement rate of 0.01 mm/s and the load measurements are straightforwardly applied by the test machine in digital form. Correspondingly, the axial deformation of adobe brick specimens is observed and measured by using four linear variable differential transducers which are fixed on the corner of the rigid end plates of the machine. It is noted that Linear Variable Differential Transducers (LVDT) readings provide the same average displacements of the specimen. The uniaxial compression test is conducted in three stages of brick specimen as mentioned in the *Table 3*, from which the stress strain curves are drawn to reveal the significance of compressive stress variation. Moreover, the elastic modulus, peak compressive strength and axial strain at peak compressive stress are calculated.

4.2 Modulus of rupture (Three-Point Bending test)

The Modulus of Rupture (MOR) is the transverse rupture strength and is generally referred as the ability to resist bending stress. The mechanical behaviour of pineapple leaf fibre reinforced adobe brick in tension is examined by means of three-point flexural test. MOR testing is conducted on stage 1 and 2 specimens of size 240×112×70 mm according to European standard EN 1015-11. The universal compression testing machine is used to perform the bending strength test of all specimens and each specimen is positioned upon the steel prop-up to attain the clear span of 220 mm, in which a point load is applied gradually in the mid span section of the specimen. As similar to compression test, the load-deflection curves are drawn by performing displacement-controlled monotonic loading at a displacement rate of 0.01 mm/s and the digital indication of the applied load in test

machine is noted. According to EN 1015-11 [16], the flexural strength of masonry units can be calculated using the Euler–Bernoulli beam theory of uniaxial bending as shown in *Equation 1*.

$$f_t = \frac{3PL}{2wd^3} \qquad (1)$$

Where, P - the maximum load indicated by the machine, L - the span length between the supports, w and d - the width and depth of the transverse section of the specimen at failure.

The code standard [16] permits to neglect the arching action of the specimen during testing due to the short span to depth ratio. Nevertheless, currently there is no regular guideline rules are available for the conversion of deflection to tensile strain which is measured at the bottom of the testing specimen. According to the study [17], it is assumed that the pineapple leaf fibre reinforced earth brick specimen has two different elastic modulus values under uniaxial bending test, wherein one is on the compression and another one at the tension. This assumption is based on the most materials experience different strain values at compression and tension zone of the specimen under uniaxial bending test. The tensile modulus of brick specimen is calculated using *Equation 2*.

$$E_t = \frac{PL^3}{4\delta wd^3} \qquad (2)$$

Where δ is the maximum deflection at the mid span of the specimen. The ratio of tensile elastic modulus to the compressive elastic modulus is symbolize by n as shown in Equation 3.

$$n = \frac{E_t}{E_c} \qquad (3)$$

5.Experimental results
5.1Effect of fibre and lime content on the compressive strength
The compressive test is conducted for three groups of brick specimens as shown in *Figure 8(a), (b)* and *(c)*. The first group of specimen consists of soil and lime, wherein the percentage composition of lime is considered as variable in a range of 1.5% to 15%. The second group comprises of soil and fibre, in which the fibre varies from 0.1% to 1%. The third group is a combination of soil, lime and fibre, here the percentage variation of lime and fibre depends on the test result of the first two groups. Three tests are conducted for each component of specimen group. The applied vertical force and resulting deformation is recorded up to the failure stage of the brick. This is observed based on the appearance of vertical cracks

near the brick corners and in the middle of vertical surface.

The *Figure 9(a)* represents the compressive strength, performance of the first group specimens L1 to L10 comprising soil and lime. Here, the specimen demolition occurs instantly and the load carrying capacity gets affected after the occurrence of several cracks on the corners as presented in *Figure 8(a)*. It is inferred that the compressive strength increases gradually up to a range of 6% addition of lime; on further addition of lime there is a rapid increase in compressive strength and reaches a maximum value of 1.59 N/mm² corresponding to 9% lime composition of specimen L6. Lower compressive strength values are recorded on the corners due to high load concentration and early dryness in the specimen corners. Beyond 9% composition, the compressive strength decreases gradually with respect to addition of lime content.

The specimens with pineapple fibres (F1 to F10) are subjected to compressive test as shown in *Figure 9 (b)*. The compressive strength increases rapidly up to 0.4% addition of fibre content that corresponds to a maximum value of 3.52 N/mm². Beyond 0.4%, specimen failure occurs due to the formation of vertical cracks at the corners. These cracks are propagated to the middle vertical plane of the specimen as shown in *Figure 8(b)*. This phenomenon occurs due to the homogeneousness of the fibres in the specimen that gradually prolong the vertical cracks to the middle portion. The homogeneity of the specimen depends on the percentage content of fibres, and hence the increased rate of pineapple fibre content leads to more homogeneity and higher the dispersion of compressive stress. This inference correlates with the concept reported in literature [18] states that the addition of 5% straw and palm fibres tends to higher homogeneous effect which increases the compressive stress distribution.

In specimens L1 to L10, the entire corners get crushed immediately and the cracks never prolong towards the centre due to the lack of linking medium fibre as shown in *Figure 8(a)*. This leads to lesser compressive strength capacity. Therefore, the soil particles and lime certainly not impact on crack extension, whereas the fibre composition greatly impacts. The inclusion of pineapple fibres prevents crack opening by shear force transmission through link to the composition parts. According to literature [19], the compressive strength was reduced with respect to the addition of fibre content beyond its nominal range, which in turn weakens the connection and friction between soil

particles. Correspondingly, it is observed in this study that there is a reduction in compressive strength due to increased fibre content beyond 0.4% inclusion of pineapple fibre.

The blending of pineapple fibres with the soil-lime composition (L6F1 to L6F10) represented in *Figure 9(c)* is revealed as significant up to some extent and further, the strength gets denied. The compressive strength profile of the composite represented in *Figure 9(c)* exhibits almost similar performance with the *Figure 9(b)*. However, there is a considerable improvement in the compressive strength due to the inclusion of 9% lime content. The increase in compressive strength from 0.1% to 0.4% fibre content is because of the increased frictional resistance between soil-lime particles and the fibres. The distribution of cracks is prevented by the union of soil-lime and fibres which link across the cracks [20]. The maximum compressive strength attained is 4.1 Mpa that corresponds to 0.4% fibre and 9% lime content. Once peak strength is achieved, the fibres start to overlay each other which result in poor cohesion with the soil ensuing in the weakening strength of the composites [21]. The addition of lime also plays a significant role in the bond strength development of the composites and sealing the pores. Constituents such as silica, calcium oxide and alumina produce a gel that interlinks with the soil particles and seal the pores to achieve enhanced strength [22].

The experimental association between the compressive strength and modulus of rupture is illustrated in *Figure 10*. The robust regression analysis is performed to present the linear correlation between compressive strength and bending strength. The compressive and bending strength of the three groups of specimen model increases mutually, which exhibits significant correlation and the coefficient of determination $R^2=0.921$ for the specimens L1 to L10, 0.941 for F1 to F10 and 0.979 for the specimens L6F1 to L6F10 as mentioned in *Figures 10 (a), (b)* and *(c)* respectively.

As the determination coefficient R^2 is close to 1, this signifies an average 94% rate of strong bond relationship between the modulus of elasticity and compressive stress. Therefore, modulus of elasticity can easily be determined from the compressive stress factor as mentioned in the proposed simple linear *Equations 4, 5 and 6*.

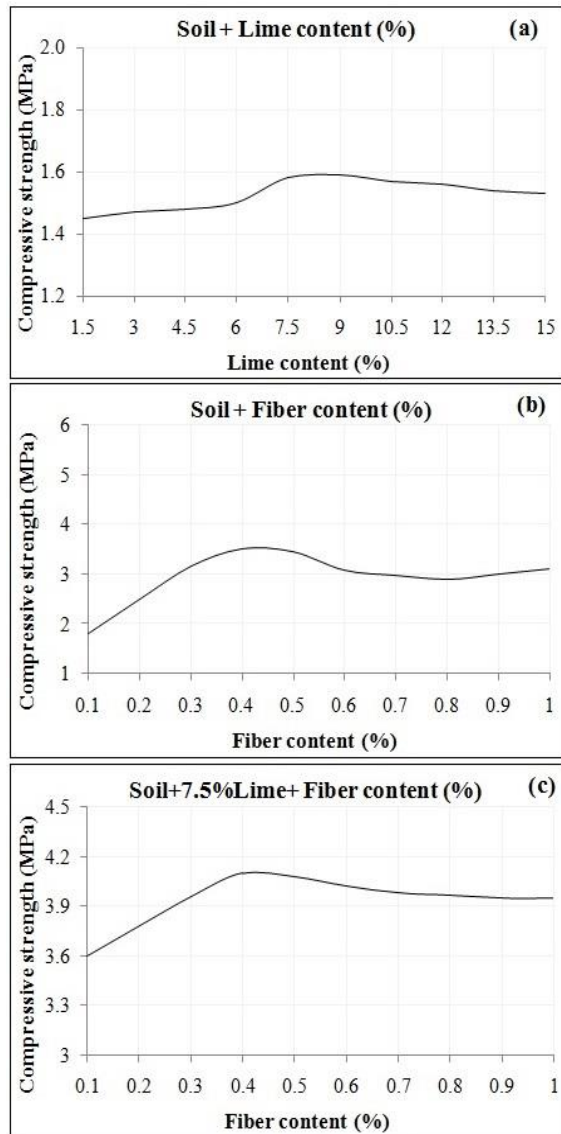**Figure 8** Compressive strength test and failure pattern of brick specimen

Figure 9 Compressive strength performances of various compositions

$$E_c = 165.7f_c - 230.7; \text{ Soil + Lime composition} \quad (4)$$
$$E_c = 20.39f_c - 28.41; \text{ Soil + Fiber composition} \quad (5)$$
$$E_c = 54.71f_c - 162.6; \text{ Soil + Lime +} \text{ Fiber composition} \quad (6)$$

5.2 Effect of fibre and lime content on the tensile strength

Mechanical behaviour of reinforced and unreinforced adobe brick in tension is examined by conducting three point bending test on all three specimen groups. In *Figure 11*, the curve illustrates the flexural strength of the specimens corresponding to different percentages of compositions. The *Figure 11(a)* represents the specimens without fibre content (L1 to L10), which records a maximum tensile strength as 0.111 N/mm² corresponding to specimen L6 9% lime composition. This value is similar to the compressive strength of concrete of same specimen and is observed that the tensile strength depends on the bond between the soil particles through lime paste along the failure plane. In general, tensile strength of soil relies on the cohesion of the soil, whereas in the case of saturated soil, the cohesion is mostly characteristic to electrostatic attraction and bonds between particles. The cohesion of unsaturated soils corresponds with suction. The approximate average tensile strength of brick specimen is a 0.58 times cohesion value which is slightly higher than the empirical value reported by [23], due to the lime content on the specimen.

The specimen with fibre content (F1 to F10) as shown in *Figure 11(b)* improves the tensile strength of the brick specimen. The flexural strength increases rapidly with the addition of fibre content up to the range of 0.4% and the maximum value is recorded as 0.51 N/mm² corresponding to 0.4% fibre content. This is mostly due to the sliding of fibres in the soil matrix controlled by the interfacial mechanical interactions between fibre surface and soil particles. Accordingly, fibres exhibit the potentiality to distribute the tensile load to the soil matrix of brick and hence intensify tensile strength. Therefore, the pineapple fibre reinforcement combined with Hawassa soil offers a noticeable tensile strength enhancement.

The specimen tensile strength of pineapple fibre and lime composition (L6F1 to L6F10) as shown in *Figure 11 (c)* is similar to the compressive strength and hence the compressive strength increasing and decreasing attributes are same as that of tensile strength. The maximum tensile strength recorded is 0.780 N/mm² corresponding to 9% addition of lime and 0.4% pineapple fibre composition due to the increased frictional resistance between soil-lime particles and the fibres. Another significant factor responsible for the increase of tensile strength is the addition of fibres to the soil lime content that enhances the interface between soil matrix and fibres for better resistance against splitting. On further addition of pineapple fibre the flexural strength gradually reduces due to the overlay of fibres each other which result in poor cohesion with the soil ensuing in the weakening strength of the composites [21]. Duan and Zhang [22] reported that there is a delay in the extension of crack due to the linking of the soil matrix by the fibres. In addition, the tensile failure of the specimen is more gradual with the increased fibres content with soil lime

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matrix and hence more ductile behaviour is also reported in earlier studies [24].

To analyse the regression robustness between the tensile modulus and tensile strength, the polynomial correlation was performed as represented in *Figure 12*. It is inferred that the tensile strength and tensile modulus increases mutually and possess a better correlation at an average rate of 86.7%. The coefficient of determination, R2 is equal to 0.910 for the specimens L1 to L10, 0.806 for F1 to F10 and 0.888 for the specimens L6F1 to L6F10 as mentioned in *Figures 12(a), (b)* and *(c)* respectively. This indicates the strengthened robustness between the tensile modulus and tensile strength factors, and hence the tensile modulus is calculated effortlessly from the tensile strength by using the proposed simple polynomial *Equations 7,8 and 9* as shown below.

$E_t = -21810 f_t^2 + 4864 f_t - 254.1$; Soil + Lime composition (7)

$E_t = -88.11 f_t^2 + 102.6 f_t + 33.55$; Soil + Fiber composition (8)

$E_t = -575.5 f_t^2 + 929.1 f_t - 311.4$; Soil + Lime + Fiber composition (9)

The compressive and tensile strength model of specimen increases mutually as shown in the *Figure 12*. It infers a significant association between each composition and the coefficient of determination, R2=0.985 for the specimens L1 to L10, 0.886 for F1 to F10 and 0.964 for the specimens L6F1 to L6F10 as mentioned in *Figures 13(a), (b)* and *(c)* respectively.

This represents a compressively strong brick also enables a strong tension and hence the compressive testing effectively facilitates to predict the tensile strength, which is in perfect harmony with the existing literature [20]. As an averaged statistic, the flexural strength equals 6.9%, 14.5% and 19% of the compressive strength of the specimens L1 to L10, F1 to F10 and L6F1 to L6F10 respectively. The proposed linear *Equations 10, 11 and 12* mentioned below are used to calculate the flexural strength of brick for various compositions using compressive strength test result data.

$f_t = 0.069 f_c$; Soil + Lime composition (10)

$f_t = 0.124 f_c + 0.059$; Soil + Fiber composition (11)

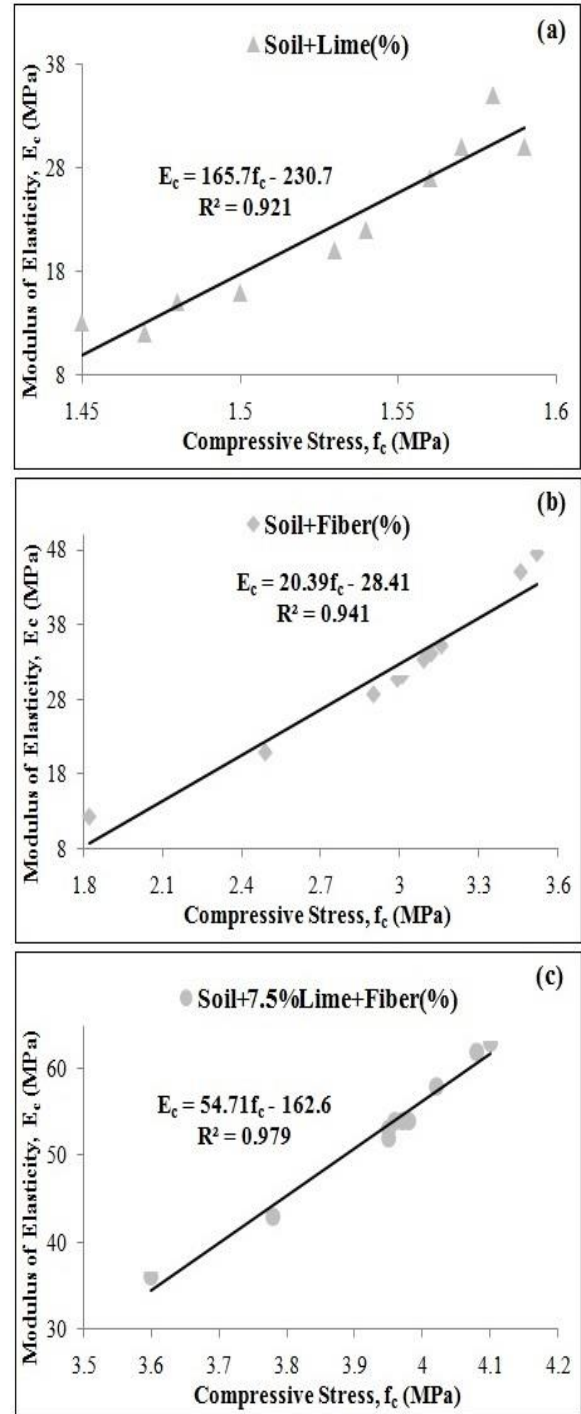$f_t = 0.161 f_c + 0.115$; Soil + Lime + Fiber composition (12)

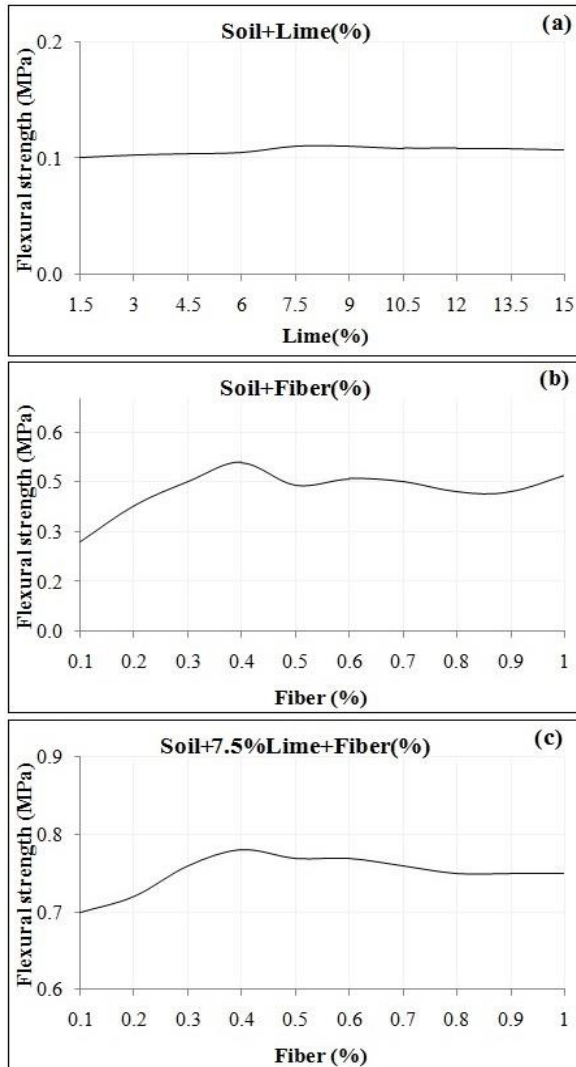**Figure 10** Regression analyses of compressive strength and modulus elasticity

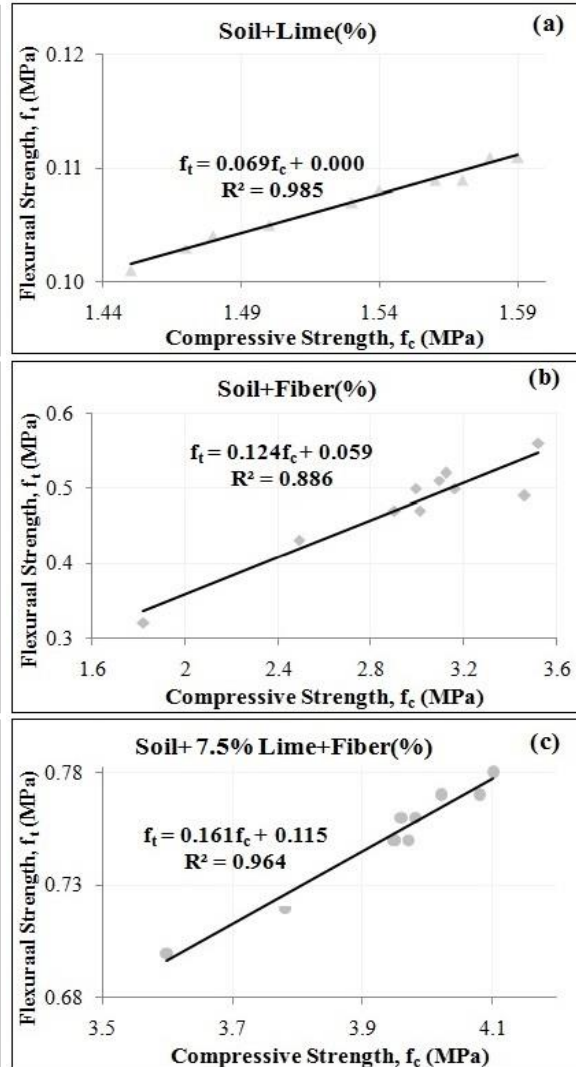**Figure 11** Flexural strength performances of various compositions

Figure 12 Tensile strength verses tensile modulus

5.3 Effect of lime and fibre content on the tensile load verses displacement behaviour

The influence of the lime and pineapple fibres on the tensile load verses displacement behaviour is shown in the *Figure 14*. It is found that the tensile load increases with increasing displacement rapidly up to the ultimate value where the tensile cracks are formed. Henceforth in the specimens without fibre content (L1 to L10), the tensile load falls to zero rapidly, this signifies the inelastic nature of the specimen for failure. In case of specimens reinforced with fibres (F1 to F10) the behaviour is similar up to the ultimate tensile load, beyond there is a reduction in the applied load due to the total displacement of specimen focused on the bond slipping of the fibres in either side of the crack. However, due to the availability of fibres, a residual tensile load is sustained after the ultimate load. This declares that the addition of reinforced fibres in the Hawassa soil is efficient in enhancing ductility failure of brick. The specimen composition with both lime and fibres F4L1 to F4L10 also experience similar behaviour, up to ultimate tensile load, further there is a sudden reduction in the tensile load and maintain the enhanced residual load, which is a more improved behaviour than the soil with fibre compositions. This is due to the inclusion of lime content which improves the bond strength and diminishes the bond slipping between the soil particles and fibres. Hence the inclusion of lime and fibres on Hawassa soil brick enhances the ductility and sudden collapse of the structure during seismic.
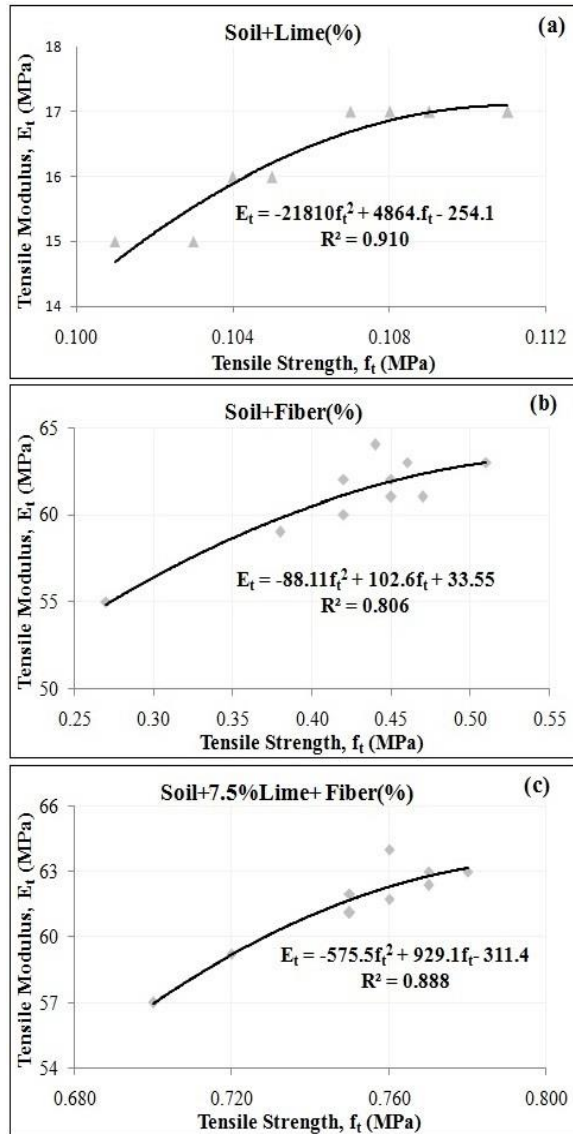
Figure 13 Experimental relationships between brick compressive and flexural strength

5.4 Durability test on rain

The durability testing based on water absorption is not essential in case of plastered un-burnt brick masonry [24]. Even though, the durability property of the un-burnt brick is tested by immersing it in the water for 30 minutes and is observed that there is no disintegration in the brick specimen of group 2 and 3 as shown in *Figure 15(a)*. Moreover, this study conducts the direct field test to check the durability by exposing the three groups of brick specimen towards rain for one month and its corresponding effect of erosion is studied. Fortunately, the rain exposed testing locality experiences rainfall for at least one hour per day. On completion of testing after one month

duration, the erosion rate recorded in the first group of specimens is very high due to its edges and corners gets faded away and hence this specimen composition is unsatisfactory. Whereas, the second and third groups of brick specimens experience a negligible deterioration rate less than 8 mm and 5 mm, respectively, due to its mixed composition with fibre as shown in *Figure 15(b)*. If plastering is applied on the bricks the abrasive effect of water on adobe brick is completely negligible.
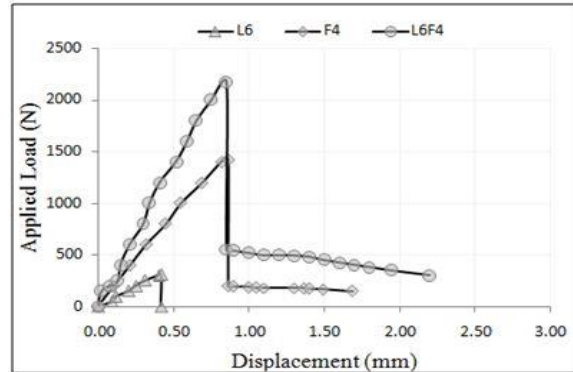

Figure 14 Tensile load verses displacement behavior

(a) Water immersion test   (b) Rain test

Figure 15 Durability test

6. Discussion

From the experimental results, it is inferred that the adobe bricks made of lime ingredient get collapsed suddenly due to the formation of cracks. The entire corners get cracked rapidly and there is no possibility to propagate these cracks towards the middle of the specimen because of the lack of linking element in the adobe bricks. Hence this kind of adobe bricks exhibits smaller load carrying capacity, poor load sustainability and the failure occurrence is sudden. This motivates this research to incorporate a suitable linking element. For this purpose, laboratory testing was conducted for various natural fibres and finally the pineapple leaf fibre is selected due to its superior tensile capacity.

The beneficial aspect of this composite is improved cohesion property between the soil particles due to the presence of lime content. Accordingly, the second group of specimens is made of pineapple leaf fibre without any addition of lime content. Under this condition, the load carrying capacity is improved and the failure is occurring due to corner crack. These corner cracks are propagated towards the middle of the specimen due to the linking element called pineapple leaf fibre. Here, the sudden occurrence of failure is avoided with an added advantage of enhanced load carrying capacity. Moreover, the inclusion of pineapple leaf fibre prevents crack opening by shear force transmission through the link to the composite parts. Therefore, this composite is proved as robust, sustainable and durable and is considered as proposed 1 adobe brick. It is found that the higher rate of pineapple leaf fibre content inclusion leads to a reduction in the strength, because the pineapple leaf fibre weakens the connection and friction between the soil particles [19]. The third group includes composites of pineapple leaf fibre and lime which comprises the advantageous feature as enhanced strength of adobe brick. Here, the distribution of crack is prevented by the union of soil – lime and fibres which link across the cracks [20]. The inclusion of lime plays a significant role in improving the bond strength between the pineapple leaf fibre and soil [22].

6.1 Comparative study of conventional and proposed method

An existing practice of adobe brick making is reported in a recent literature [25] is referred as a conventional method throughout this paper. The comparative analysis between the conventional method and the proposed concepts are tabulated in *Table 4* by enlightening the imperfection in the conventional method and remedial actions taken in the proposed methods by conducting laboratory investigation. A critical analysis between the conventional and proposed methods in terms of ingredients, the optimum percentage of ingredients, easy to handle, compressive strength, tensile strength, residual load and cost analysis were conducted.

As far as the brick making ingredients are concerned the conventional method uses the teff straw as a reinforcing agent at an optimum ratio of 0.1% and is to be noted that teff straw is easily degradable which complicates the robustness of the brick. Hence the proposed strategy utilizes pineapple leaf fibre at an optimum ratio of 0.4% as the reinforcing element which possesses high tensile strength capability. The laboratory results show that the compressive strength of the conventional method varies from 0.447 to 0.708 Mpa, whereas the proposed 1 and 2 method adobe brick groups are 3.52 MPa and 4.1 MPa respectively. Similarly, the tensile strength of the proposed 1 and 2 methods is 0.51 MPa and 0.78 MPa, respectively and the conventional method value varies from 0.05 to 0.065 Mpa. The test results infers that the proposed 1 and 2 concepts satisfy the minimum requirement as per the CBC code [26] and the conventional method fails to attain the minimum requirement. This shows the superiority of the proposed 1 and 2 concepts as compared to the conventional brick in terms of mechanical property investigation. In case of conventional method, the soil sample is collected from far distance regions which unnecessarily increase the transportation cost and hence the proposed methods employ soil from the native regions in favour of reducing the transportation charge. Consequently, the unit cost of proposed 1 and 2 method bricks rates economical as 0.78 and 0.83 Birr respectively, this is greatly reduced as compared to the conventional brick cost rate of 4 Birr. The brick production cost is estimated based on the present market rate of raw materials required and manpower as given in *Table 5*. Furthermore, in the proposed 1 and 2 methods an enhanced residual tensile load is recorded which makes the masonry more ductile and earthquake resistant. Complete list of abbreviations is shown in Appendix I.

Limitation of the study

The inclusion of fibre content beyond the nominal range leads to a reduction in the load carrying capacity, which deteriorates the connection and friction between the soil particles. The property of the soil may vary slightly within Hawassa, which may cause minor variation in the strength property of the masonry units. Moreover, the strength outcome of the masonry units depends on the water and soil lime ratio adopted by the construction engineer. Besides, the calculated cost of brick masonry unit was obtained based on the current market price at Hawassa and this may get varied.

Table 4 Comparison of conventional and proposed approaches

No.	Parameters	Conventional [26]	Proposed-1	Proposed-2
1	Type	Adobe Block	Adobe Brick	Adobe Brick
2	Size	400×200×200mm	240×112×70mm	240×112×70mm

No.	Parameters	Conventional [26]	Proposed-1	Proposed-2
3	Soil Preferred	Far distance soil	Native soil	Native soil
4	Ingredients	Teff straw	Pineapple fiber	Lime + Pineapple fiber
5	Optimum ingredients %	0.1% average	0.40%	7.5%+0.4%
6	Average weight per unit	>15kg	2.5kg	2.5kg
7	Ease of handling	Hard as it is heavier	Simple as it is lighter	Simple as it is lighter
8	Compressive strength	0.447 to 0.708 Mpa	Attained from optimal proportion of additives 3.52 Mpa	Attained from the optimal proportion of additives 4.1 Mpa
9	Tensile strength	0.05 to 0.065 Mpa	Attained from the optimal proportion of additives 0.51 Mpa	Attained from the optimal proportion of additives 0.78 Mpa
10	Compressive strength according to CBC code [25]	Unsatisfactory	The minimum required is 2.06 Mpa Gained 3.52 Mpa-Satisfactory	The minimum required is 2.06 Mpa Gained 4.1 Mpa-Satisfactory
11	Compressive strength according to CBC code [25]	Unsatisfactory	The minimum required is 0.35 Mpa Gained 0.51 Mpa-Satisfactory	The minimum required is 0.35 Mpa Gained 0.78 Mpa-Satisfactory
12	Residual load	Not conducted	The residual tensile load is sustained	The enhanced residual tensile load is sustained
13	Durability test on rain	Not conducted	deterioration rate less than 8mm	deterioration rate less than 5mm
14	Unit cost	4 Birr	0.78 Birr	0.83 Birr

Table 5 Estimation of brick production cost

Details	Proposed-1	Proposed-2
Volume of one brick (m^3)	0.002	0.002
Cost of soil for unit brick (Birr)	Free of cost	Free of cost
Weight of one brick (kg)	2.5	2.5
Weight of 7.5% lime	-	0.1875
Weight of 0.4 % Pineapple fiber	0.010	0.010
Cost of 1kg of lime (Birr)	-	5
Cost of lime for unit brick (Birr)	-	0.05
Cost of 1kg of pineapple fiber (Birr)	20	20
Cost of Pineapple fiber for unit brick (Birr)	0.08	0.08
Labor cost per unit brick (Birr)	0.7	0.7
Total cost of one unit brick (Birr)	0.78	0.83

7.Conclusion and future work

An engineered and economically feasible brick construction method was proposed for the poor inhabitants of Hawassa village and adobe brick design modelling equations are presented. Amongst the three groups of brick test specimens, the optimum strength is recorded for the composites belongs to group 2 having 0.4% pineapple fibre with Hawassa soil and group 3 possessing 7.5% lime and 0.4% pineapple fibre. The maximum compressive strength is recorded as 3.52 MPa and 4.1 MPa for the groups 2 and 3 respectively, which is 5 and 6 times respectively greater than the conventional specimens. Moreover, the optimal flexural strength is recorded at an improved rate of 0.51 Mpa and 0.78 Mpa for the groups 2 and 3 respectively. These improved strength
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recording rates ensure the standard requirement according to the CBC code. The test results confirms that a residual tensile load sustains beyond the ultimate load, which reveals the addition of reinforced fibres on the Hawassa soil is efficient in enhancing ductility failure of brick. The durability of the specimens belongs to group 2 and 3 experiences a negligible deterioration rate less than 8mm and 5mm respectively. Cost estimation analysis evidences the estimated cost as 0.83 birr per brick including labour cost, which is 72% lesser as compared to conventional bricks. Hence it is considered as reasonable expenditure for the low-income community. The future extension of the study is to investigate the seismic behaviour and performance of same masonry unit wall under seismic loading.

Acknowledgment
None.

Conflicts of interest
The authors have no conflicts of interest to declare.

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Appendix I

S.No.	Abbreviation	Description
1	CBC	California Building Standard Code
2	CSEB	Compressed Stabilized Earth Blocks
3	d	Depth of the transverse section of specimen
4	E_c	Compressive modulus of brick specimen
5	E_t	Tensile modulus of brick specimen
6	f_c	Compressive Strength
7	f_t	Flexural Strength
8	L	Span length between the supports
9	LVDT	Linear Variable Differential Transducers
10	MOR	Modulus of Rupture
11	n	Ratio of tensile elastic modulus to the compressive elastic modulus
12	P	Maximum load indicated by the machine
13	R^2	Coefficient of determination
14	w	Width of the transverse section of specimen