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Strength and Durability of Adobe Brick with Natural Additives: The case of Hawassa and Ziway Town, Ethiopia

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Abstract

Construction materials are becoming scarce as a result of increase in population growth and urbanization. Adobe material with natural additives is sustainable, recyclable, eco-friendly, energy-efficient, incurring less cost of transportation and labor. As there is the abundant availability of adobe earth, and practices of adobe masonry to build rural structures in Ethiopia, the research focused on developing adobe bricks with improved properties using additives. Having found the soil ingredients percentage suitable for adobe making, compression and flexural strength tests and durability tests have been conducted. It was found that Hawassa soil adobe bricks performed best, showing a compressive strength of 8.06 MPa and satisfying durability criteria with 0.2% teff straw, 2% pumice fines, 4% pumice sand and 4% cactus resin, achieving a 23% increase in strength over the plain soil control specimen. The flexural strength of all the specimens tested has passed the minimum requirement as per the California Building Code (CBC) standards. The Ziway soil adobe bricks satisfy the minimum requirement of strength based on CBC standards. Hence, it is advocated to produce and use adobe bricks having control over water addition, adopting mechanization of pugging, volume batching and appropriate construction technology.

Keywords: adobe, cactus resin, compression strength, durability, pumice, teff straw

1. Introduction

The world experienced the use of crest soil in different facets through the civilizations. Primarily for agriculture, people plowed the land thereby the mineral content of the soil was utilized for plant growth. Clayey soils are used in ceramic works. Crest soil with the required amount of clay is widely used, even today, to make roof and floor tiles and burnt and un-burnt (adobe) bricks. In the twentieth century, buildings are being built involving the high cost of modern energy resources very intensely, while the natural energy through passive sources is not well been used. Use of crest soil as adobe brick can reduce wasting energy such as embodied energy in the production of cement and aggregates, the energy required for transporting these ingredients, and the energy required for construction.

The crest soil in many places in the world is suitable for adobe brick production which is based on the clay content in the soil. Brick is a word generally referring to burnt masonry unit made of soil; while 'adobe' or 'adobe brick' is a Spanish word implying un-burnt, sun-dried or air-dried masonry unit made of soil (Minke, 2007; Smith, 1981; Brown & Clifton, 1978). Clay, being a natural binder available in the soil, sets and hardens the soil mass upon evaporation of water in the soil mass. There are quite a large number of standards being followed to establish the suitability of the soil for adobe production based on clay content, which is either coded or not coded. According to Wilson Q (2019), of New Mexico college's adobe construction program, the optimum percentage of clay content in brick earth shall be around 30%, silt and sand together shall become the remaining 70%; according to Uniform Building Code of United States (1982), clay content shall be between 25% and 45%; according to VSBK-CESEF (2008), clay 20% to 35%, silt 25% to 45% and sand 20% to 45%; according to WikiHow (2016), both sand and clay content shall be greater than 33.33%.

Compression and flexural strength of adobe using additives have been tried by researchers of several parts of the world. Table 1 shows the summary of compression and flexural strength test results of adobe with various additives performed in different countries. Research conducted by Araya-Letelier et.al. On adobe bricks with pig hair of different lengths viz. 7 mm, 15 mm and 30 mm had shown a decrease in compressive and flexural strength on an average of 30%, due to the increase in length and percentages of pig hair when compared to the plain control specimen. It is also to be noted that some of the test results have not passed the minimum requirement of strength based on CBC standards.

The studies in Ethiopia related to the use of earth material have been conducted in the area of cement/lime stabilization in earth blocks, hydraform and burnt bricks. There is no visible work on adobe found by the authors while their exploration of the literature survey. The soil of Karamara near Jijiga in Ethiopia, when stabilized by the addition of 10 % cement, exhibited an average compressive strength of 4.633 MPa (Abdulkader, 2015). Asmamaw Tadege (2007) in Addis Ababa Institute of Technology, Ethiopia had experimented on cement stabilized compressed blocks to give a maximum of 5.03 MPa compressive strength at 56 days. Studies have been done by Altayework Tadesse (2013) on the effects of firing temperature of burnt clay bricks in which it has been shown that an increase in firing temperature increases the compressive strength. Arash Afkari (2010) has produced stabilized earth block by 8% cement and achieved an average compressive strength of 3.2 MPa. Cement and lime stabilization by 5% each in earth blocks yielded 4 MPa strength in the study conducted by Gobitu Tekle (2018). In cement stabilized earth blocks, with 5% replacement of cement Habtemariam Molla (2012) has obtained a maximum compressive strength of 5.43 MPa.

Table 1. Compression and flexural strength of adobe with different additives

Year	Author	Country	Additives	Percentage	Compressive Strength (MPa)	Flexural strength (MPa)
2015	Correa et.al.	Brazil	Bamboo particles	6	1.14	
2016	Serrano et. al.	Spain	Straw	3	2.908	0.271
"	"	"	Corn Plant	3	3.253	0.347
"	"	"	Olive Stone	5	1.619	0.16
"	"	"	Rubber Crumbs	5	2.521	0.105
"	"	"	Polyurethane	5	2.627	0.104
2018	Araya-Letelier et. al.	Chile	Pig hair	0.5	1.9	0.47
2018	Jové-Sandoval et al.	Spain	Pine needle	33% by vol.	3.3	0.22
2015	Calatan et al	Romania	Hemp fiber	9 to 10	2.62	0.3
2011	Lertwattanaruk et. al.	Thailand	Bagasse	6	3.217	
"	"	"	Rice husk	3	2.235	

The brick size specimens are suitable to obtain greater compressive strength compared to block size specimens as used in some places in southern Ethiopia because, the platen shear will not cause splitting failure at the mid height part of the brick as the brick is of less thick (Chandrasekar et al., 2019, Shetty, 2005). The size of burnt bricks used in different countries are little different from each other; such as in USA, 203 × 102 × 57 mm, in South Africa, 222 x 106 x 73mm, in Australia, 230 x 110 x 76mm, in UK, 215x102.5x65mm, in India, 190 x 90 x 90mm, and in China, 230mmx114mmx65mm. The size of adobe bricks used for the present research was chosen, having the understanding of standard brick sizes in different other countries.

In Ethiopia, rural houses built by adobe masonry are quite seen in many places, remarkably in the south, around Adama, Adami Tulu and Ziway. The usual practice of adobe production is found to be of block size with teff straw as the only additive. From the researchers' point of view, the block size masonry unit is heavy, weighing around 12 kg to 14 kg, which proves difficulty in handling while laying the courses of masonry. Also, edges and corners of blocks are easily able to be damaged during the construction of the wall, as the weight is greater. Generally, the strength and durability performances of the adobe can be improved when appropriate additives are selected and used. The compressive strength of block size adobe specimens was less when compared to the brick size specimens (Chandrasekar et. al., 2019), hence, in the present research trials have been attempted with brick size specimens and with natural additives such as teff straw, pumice of three different particle size ranges and cactus resin and to compare and assess the cost of adobe with its conventional counterpart, HCB.

The general objective of this research was to produce a new engineered construction material i.e. adobe bricks with additives such as teff straw, pumice materials and cactus resin that economizes and improves the present day's rural construction practices and also could be used to some extent in urban and sub-urban sectors as a substitute for HCB material.

2. Materials and Methods

2.1 Study area description

The study is conducted on soils from Hawassa and Ziway town, which are both located in the rift valley of Ethiopia on the way from Addis Ababa to Moyale Road at 275 km and 163 km respectively. In the nearby areas of these two towns adobe block constructions are being practiced traditionally for the construction of Houses.

2.2 Trend of use of Adobe brick

The people in the areas used soil as lathing material for rural houses, and visual examinations of the sample proved good to use as building materials. Even in the urban areas there are a number of houses built of locally made unburnt brick (adobe brick). The housing patterns of the rural kebeles and even some of the newly included urban areas of both Hawassa and Ziway area are traditional wattle and daub structures; circular chikka (Mud) houses and adobe block walled houses

2.3 Additive materials

Certainly, additives impart improvement in mechanical properties of adobe units. Three additive materials (Teff straw, Pumice and Opuntia (cactus) resin) were used in different proportions. All the additives selected are available in and around the study area in plenty (Fig.1). Adobe brick production in any part of the world uses either straw or grain husk to minimize shrinkage cracks which may appear up on drying. As *teff* is the major crop in Ethiopia, it has been used by the rural community where adobe is in practice. Pumice when used as coarse aggregate of size between 4.75mm and 12mm, minute surface shrinkage cracks were observed in bricks casted out of clayey soils (Tariku et. al. 2017). By reducing the grain size of quartz in the lime-clayey adobe bricks strength was found to be improved (Millogo et al., 2008). This indirectly infers that inert fines can aid to develop strength in clayey mixes. With this idea, later it was tried with two more sizes such as, pumice fines (particle size < 0.75mm) and pumice sand (particle size between 0.75mm and 2.36mm) along with coarse aggregate size (particle size between 4.75mm and 12mm.

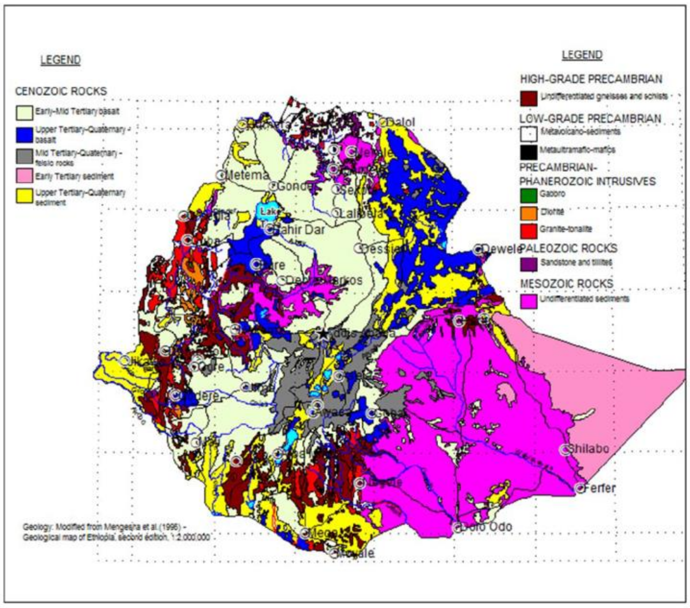


Figure 1. Geological map of Ethiopia-Mid tertiary and quaternary felsic rocks (Source: GSE, 2011)

On exploring the possibility of including additional natural binders in adobe, it was attempted to use the resinous pulp of cactus thorny leaves. Cactus with botanical name Opuntia Ficus Indica is found all along the rift valley, in the arid and semi-arid areas of Lake Hawassa, Langano, Ziway and Awash. It can be grown for the purpose of additive in adobe production in any other areas nearby too. The resin from cactus (Fig.2) was used as additional binder due to its sticky nature.

Figure 2. Mashed pasty resin of cactus

2.4 Study design

2.4.1 Soil sample collection

Soil samples were collected from the respective study sites selected. The top or surface soil 20 to 30 cm was removed and for sufficient soil samples to be made six quintals were collected from each site.

2.4.2 Soil suitability and characterization tests

Basic field tests and Laboratory tests on soil were done to check the suitability and characterization of soil for adobe brick production. The field tests performed were, dry strength, adhesion and roll tests. In all of which the samples selected were performing to the satisfactory extent. Laboratory tests done on soil were; Sedimentation, Atterberg's limits, Sieve analysis, Hydrometer and Shrinkage test , with all of which soils were characterized and suitability was ascertained. Moreover, proctor compaction test was performed to find optimum moisture content to get maximum density and to avoid lateral bulging of specimens after removal of mold.

2.4.3 Brick casting and tests on cast brick specimens

The size of wooden mold used to cast test specimens was the standard brick size of 23 cm*12 cm*7.5 cm (Fig.3). The mold used was open at both top and bottom so that immediately after casting the bricks, the mold could be removed. The specimens were prepared with the fixed proportion as detailed in the research design and casted in larger trays. Subsequently, after two or three days of drying, they were transferred to smooth floor for further drying (Fig.4).

Figure 3. Mold used for casting adobe bricks

Figure 4. Adobe brick specimens under air curing

2.4.4 Experimental design

For each soil sample from respective locations, the variables constitute the percentage dosages of teff straw, pumice fines (fines passing through 0.75mm sieve), pumice sand (particles passing through 2.36mm sieve and that retained in 0.75mm sieve), pumice coarse aggregate (aggregates passing through 12mm sieve and that retained in 4.75mm sieve) and cactus resin. Water content was made constant which was fixed as a workable quantity as explained in the following sub section. The dosage of different variables used is as follows:

- Teff straw: 0.1%, 0.3%, 0.5%, 0.7%, 0.9%, 1.1% and 1.3% (if optimum teff straw percentage was found at lower values, higher percentage dosages were not used).
- Pumice fines: 2%, 4%, 6% and 8%,
- Pumice sand and coarse aggregate: 2%, 4% and 6% each,
- Cactus resin: 4%, 8% and 12%

Additives proportion in adobe usually is based on trial and error (Mohammed, 2011). In this study, dosages of teff straw were decided based on past work (Chandrasekar et. al., 2019). Inert pumice materials replace the percentage of clay for the clay should not shrink more leaving surface cracks and sometimes deeper cracks even. Hence, it could be understood that based on the binding property of clay in a soil sample, if the clay content is between 20% to 40%, nearly 10% by weight of pumice replacement may be necessary so that strength improvement and as well as crack prevention may be effected. By this rough judgement the maximum percentage dosage of pumice fines was taken up to 8%, and that of pumice sand and aggregate size were taken up to 6% each, increased in step of 2%. Cactus resin can be considered as replacement of water. Based on the consistency levels of soils from different locations, the cactus resin dosages were decided to be up to a maximum of 12%, increased in step of 4%.

2.4.4.1 Specimen size

The optimum dosage of every variable was found and finally a mix containing optimum dosage of all the variables was used to check whether strength improvement was possible. While doing so, the performance of combined effect of pumice fines, sand and coarse aggregate was considered for final mix (Table 2). Plain soil mixed with workable water content and without any additives was considered as control mix.

Table 2. Specimen size summary

Location of soil	Number of compression test specimens	Number of flexural test specimens	Number of durability test specimens
Hawassa	81	81	12
Ziway	72	72	12

After full drying of the casted specimen for different combinations the brick specimens were subjected to, Dry compressive strength test, Flexural strength test, Durability testes; erosion test, wet and dry appraisal tests.

2.5 Data analysis

The results obtained were direct measurements of quantities. They were physically compared to the standards and or controls, so as to find out the optimum properties of the new material. Descriptive statistics like percentages and tables/charts were used to present the findings of optimum test values.

3. Results

3.1 Field Test

Field examinations such as dry strength test, roll test and adhesion test were successful for all the samples produced from both places such as Hawassa and Ziway.As per the procedure for dry strength test (IAEE, 2004), for samples from each location, three small balls of 20 mm in diameter, dried for 48 hours, were produced and tried to crush between the forefingers and thumb. All samples passed the criteria of not being crushed and so have enough clay content to produce adobe brick. Based on the approach suggested by Adam and Agib (2001), Houben H and Guillaud H (1994), when the prepared balls of moist soil from all sites were subjected to spatula penetration, it was found that all samples were resistive to penetrate, meaning, they possess sufficient clay content to produce adobe bricks.

From the roll test based on the procedure and standard set (Adam and Agib, 2001, Houben H and Guillaud H, 1994), the Hawassa soil samples showed a ribbon length of 26 cm and 27 cm which lies in the range of 25 to 30 cm length. This proved that Hawassa soil has high clay content, while the Ziway sample showed a length of 12 cm indicating that it was of relatively low clay content. Hence, the soils at respective sites were passed the required field tests to be used for the adobe brick production.

3.2 Laboratory Tests

Laboratory tests conducted could be grouped under two heads, one the soil suitability and characterization tests, and the other, tests on cast brick specimens. Apart from the field examinations as suitability tests, at the laboratory it is essential to check the percentage contents of ingredients such as clay silt and sand to adjudge suitability of soil for adobe brick production.

3.2.1 Soil suitability and characterization tests

3.2.1.1 Sedimentation tests

Soil characterization by sedimentation test was conducted for both the soil samples from two different locations. The samples from Hawassa did not show clear response as the soil particles did not settle to exhibit distinct layers of clay, silt and sand, even after a week's time. Hence hydrometer analysis was preferred to characterize these soils. Ziway sample responded well in sedimentation test by displaying clear boundaries of clay, silt and sand layers. By sedimentation test, Ziway sample was observed to have 15% clay, 35% silt and 50% sand. Even though Ziway sample shows a little low value of clay content, as the soil is being used for adobe block production in rural construction practice, this has also been considered for the research examinations.

3.2.1.2 Atterberg's limits (ASTM D 4318-5) and wet sieving

To classify the soil samples by ASTM unified soil classification procedure, firstly index properties such as liquid limit, plastic limit and plasticity index were found. Table 3 shows the Atterberg's limit parameters (index properties) and percentage passing through 75-micron sieve by wet sieving for different soil samples.

Table 3. Atterberg's limits and percentage passing through 75-µ sieve

Sample	Liquid limit (LL)	Plastic Limit (PL)	Plasticity Index (PI)	% passing through 75-µ sieve
Hawassa	44.7	25	19.7	54
Ziway	30.88	28.125	2.755	51

The soil classification based on ASTM unified classification chart (ASTM D 2487-98) for all the samples are shown in table 4.

Table 4. ASTM unified soil classification of selected samples

Sample	Liquid limit (LL)	Plasticity Index (PI)	% retained in 75-µ sieve& gravel %	ASTM soil classification
Hawassa	< 50	> 7	> 30, < 15% gravel	Sandy lean clay
Ziway	< 50	< 4	> 30, < 15% gravel	Sandy silt

3.2.1.3 Hydrometer analysis

To ascertain the percentage of clay, silt and sand contents, hydrometer test was conducted for the clayey samples and sedimentation test result was used for Ziway sample. The ingredient contents of soil determined out of hydrometer analysis indicated that the ASTM D 422-63 classification affirmed was true. As it is shown in table 5, it is evident that the ASTM classification matches with the percentage ingredients found by hydrometer analysis. For explain, for Hawassa soil being classified as sandy lean clay sand percentage is 46 which is greater than clay percentage which is 20. The clay content in Ziway soil is found to be a little bit insufficient.

Table 5. Percentage of soil ingredients by hydrometer analysis (Hawassa) and sedimentation test (Ziway)

Sample	Clay %	Silt %	Sand %	ASTM soil classification
Hawassa	20	34	46	Sandy lean clay

Ziway	15	35	50	Sandy silt

The ingredients proportion of Hawassa soil is considered optimum for adobe production due to the better cohesive property of clay present in Hawassa soil.

3.2.1.4 Shrinkage test

A wooden mold of 4 cm * 4 cm * 60 cm was used where the wet sample was hand compacted and allowed to dry for seven days. The shrinkage length after 7-day drying was measured, which should not exceed 10% of the length of mold to satisfy the standard (UN-HABITAT, 2009, Adam and Agib, 2001, Houben H and Guillaud H, 1994). The test results showed that the Hawassa and Ziway samples showed shrinkage of 3.5 cm (5.83%) and 2.5 cm (4.17%) respectively, which shows both samples satisfy the requirement of less than 10% shrinkage.

3.2.1.5 Proctor compaction test (ASTM D 698-00)

The water content to be used to cast the brick specimens was fixed based on three criteria of optimum moisture content (OMC) for maximum density, a workable water content needed for production and the upper limit of water content that could cause lateral bulging of wet brick specimens up on removal of the mold. Hence, standard Proctor compaction tests were conducted on samples collected from both the sites (Table 6).

Table 6. OMC and workable water content used for brick production

Sample	OMC %	Water used %
Hawassa	23.4	25
Ziway	23	25

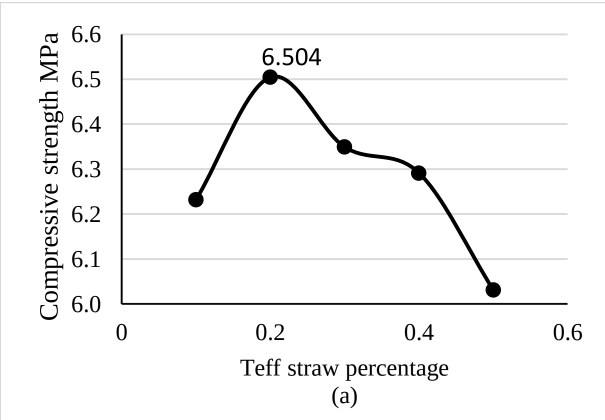
As a final remark on soil suitability and characterization tests conducted, it was found that the soils study area were suitable for adobe brick production as some adjustment in clay content can be executed during the inclusion of additive proportions.

3.2.2 Compression strength

Compression strength test could be considered as one of the major tests which determine the use of adobe brick as an alternative wall material. In this study the standard used to compare the mechanical strength of adobe bricks tested, was California Building Code (CBC, 2013). Based on CBC section 2109, the minimum compressive strength required for an adobe brick is 2.06 MPa. According to CBC, the brick size specimens casted can be tested directly in a compression testing machine. The optimum dosage of every variable was found and finally a mix containing optimum dosage of all the variables was used to check whether strength improvement was possible. While doing so, the performance of combined effect of pumice fines, sand and coarse aggregate was considered for final mix.

3.2.2.1 Optimum percentage of teff straw content

The trials of adobe casting and testing for compression strength were started with soil from Hawassa University campus. At that first stage of work, teff straw dosages were considered from 0.1% to 0.5% in increments of 0.1%. With such tests, the optimum teff straw percentage was found to be 0.2%, yielding compressive strength of 6.5 MPa. Figure 5 shows the detail test results of the teff straw percentage verses compressive strength of the adobe specimen. The optimum teff straw percentage maintained constant while the other ingredients (pumice fractions and cactus resin) were varied for the different specimen designations casted and tested.



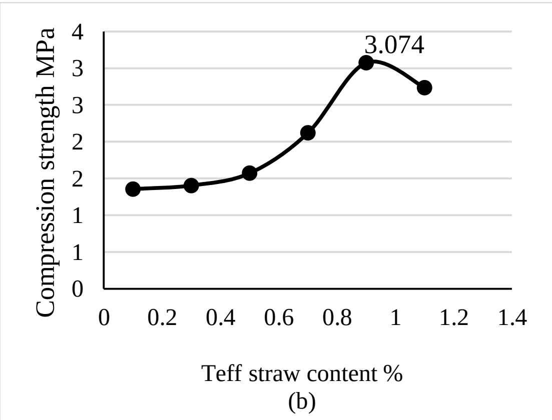


Figure 5. Variation of compression strength with teff straw percentage – Hawassa (a) and Ziway (b)

However, the teff straw percentage with the optimal compression strength for Ziway sites was found different from that of Hawassa soil. It is obvious that the soils were different in nature or in their particle size distribution so that the optimum straw content was also different. Hence the increments were taken in steps of 0.2%, starting from 0.1%. It was depicted in figure 5 that there is a variation in strength with the increase in teff straw content. Ziway adobe bricks, initially an increasing trend was shown with increase in teff straw content. It presented also a definite optimum teff straw content of 0.9% giving a maximum strength of 3.074 MPa.

3.2.2.2 Compressive strength tests on Hawassa adobe brick specimens

With the second stage exploration of different percentage dosages of ingredient of nine mixes having an optimal percentage of teff straw were analyzed and the results of those tests are shown in Table 7. The plain control specimen(PH) showed a greater strength. There may be a possibility of increase in strength with the increase in pumice coarse aggregate percentage (H1, H2 & H3). Optimum cactus resin percentage can be 4% (H5 & H6). Increase in pumice sand percentage increases the strength (H7, H8 & H4). All the mixes did not contain pumice fines. A set of specimens with 0.2% percentage of pumice fines and 0.2% pumice sand showed an increase in strength. It sparked the idea to use fines as one of the variables (Table 7). With the results of the second stage exploration of ingredients dosages, the final experimental program having different mix ratios were fixed.

Table 7. Compression strength of Hawassa adobe bricks in second stage mix proportions

Designation	Percentage of additives by weight of soil taken						Average compressive Strength (MPa)	standard deviation (coefficient of variation)
	Straw	Pumice Fines	Pumice Sand	Pumice Coarse	Cactus Resin	Water		
PH	xxx	xxx	xxx	xxx	xxx	25	6.55	0.105(0.016)
H1	0.2	xxx	2	4	xxx	25	6.3	0.350(0.056)
H3	0.2	xxx	4	2	xxx	25	5.7	0.196(0.034)
H4	0.2	xxx	6	xxx	xxx	25	5.74	0.077(0.013)
H5	xxx	xxx	xxx	xxx	4	21	5.47	0.379(0.069)
H6	xxx	xxx	xxx	xxx	8	17	4.55	0.178(0.039)
H7	0.2	xxx	2	xxx	xxx	25	4.89	0.125(0.026)
H8	0.2	xxx	4	xxx	xxx	25	5.72	0.408(0.071)
H9	0.2	2	4	xxx	xxx	25	5.94	0.310(0.052)

Note: xxx: mean additive not used

As to the result analysis of compression strength test for Hawassa adobe specimens, the maximum compression strength was found to be more than 6 MPa for H1 and PH mix. The other trial is considering no straw to see the net effect of the resin; the maximum compression strength found was little less than the strength found for plain specimen. Moreover it was found that the resin percentage increment had a negative impact on the compression strength for Hawassa soil (Table 7).

The optimum dosage of sand pumice (4%) and fine pumice (2%) with an optimal straw and resin percentage of 2% fines and 4% (H91), was found to give the maximum strength of 7.934 MPa. It achieved 22% increase in strength as compared to the control specimen (6.55 MPa). Having the optimum values of all additives, final sample was made in the following proportion: 0.2% straw: 2% fines: 4% sand: 4% cactus resin (H23) which had given a maximum compressive strength of 8.06 MPa achieving 23% increase in strength over the control specimen (Table 8). Further specimens with different percentage ingredients as shown in table 8 were casted and tested. The variation in percentage was effected considering one variable i.e. pumice fines firstly and then adding one by one the other variables such as pumice sand and pumice coarse aggregate.

Table 8. Compressive strength of Hawassa adobe bricks in final stage mix proportions

Designation	Percentage of additives by weight of soil taken						Mean value (MPa)	standard deviation (coefficient of variation)
	Straw	Pumice Fines	Pumice Sand	Pumice Coarse	Cactus Resin	Water		
H41	0.2	2	xxx	xxx	xxx	25	7.371	0.136(0.018)
H51	0.2	4	xxx	xxx	xxx	25	7.01	0.754(0.108)
H61	0.2	6	xxx	xxx	xxx	25	6.591	0.624(0.095)
H71	0.2	8	xxx	xxx	xxx	25	7.068	0.597(0.084)
H81	0.2	2	2	xxx	xxx	25	6.499	0.037(0.006)
H91	0.2	2	4	xxx	xxx	25	7.934	0.355(0.045)
H10	0.2	2	6	xxx	xxx	25	7.478	0.255(0.034)
H11	0.2	4	2	xxx	xxx	25	7.749	0.327(0.042)

H12	0.2	4	4	xxx	xxx	25	7.529	0.213(0.028)
H13	0.2	4	6	xxx	xxx	25	7.006	0.326(0.047)
H14	0.2	6	2	xxx	xxx	25	7.279	0.672(0.092)
H15	0.2	6	4	xxx	xxx	25	6.826	0.114(0.017)
H16	0.2	2	2	2	xxx	25	7.682	0.439(0.057)
H17	0.2	2	2	4	xxx	25	7.13	0.588(0.082)
H18	0.2	2	2	6	xxx	25	7.265	0.425(0.058)
H19	0.2	2	4	6	xxx	25	7.148	0.615(0.086)
H20	0.2	4	4	6	xxx	25	6.81	0.717(0.105)
H23	0.2	2	4	xxx	4	21	8.048	0.068(0.009)

Note: xxx: Additive not used.

3.2.2.3 Compression strength tests on Ziway adobe brick specimens

Being a sandy silt soil, with very low clay content, Ziway adobe bricks performed very poor when compared to the adobes out of Hawassa soils. At the first stage of works, to find the optimum teff straw percentage, specimens were cast with teff straw percentages from 0.1% through 0.5% in increments of 0.1%. It was an increasing trend in strength observed. Hence further specimens with higher percentages of teff straw were casted and tested (Table 9).

Table 9. Compressive strength of Ziway adobe bricks specimens

Designation	**Percentage of additives by weight of soil taken**						**Average compressive Strength (MPa)**	**standard deviation (coefficient of variation)**
	Straw	**Pumice Fines**	**Pumice Sand**	**Pumice Coarse**	**Cactus Resin**	**Water**		
PZ	xxx	xxx	xxx	xxx	xxx	25	2.051	0.046(0.022)
Z1	0.7	xxx	xxx	xxx	xxx	25	2.122	0.039(0.018)
Z2	0.9	xxx	xxx	xxx	xxx	25	3.074	0.222(0.072)
Z3	1.1	xxx	xxx	xxx	xxx	25	2.736	0.156(0.057)
Z4	0.9	2	xxx	xxx	xxx	25	2.851	0.150(0.052)
Z5	0.9	4	xxx	xxx	xxx	25	2.436	0.062(0.025)
Z6	0.9	6	xxx	xxx	xxx	25	2.252	0.198(0.088)
Z7	0.9	8	xxx	xxx	xxx	25	2.553	0.1450.057)
Z8	0.9	2	2	xxx	xxx	25	2.702	0.082(0.030)
Z9	0.9	2	4	xxx	xxx	25	2.204	0.086(0.039)
Z10	0.9	2	6	xxx	xxx	25	2.152	0.001(0.005)
Z11	0.9	4	2	xxx	xxx	25	2.162	0.140(0.064)
Z12	0.9	4	4	xxx	xxx	25	2.114	0.199(0.094)
Z13	0.9	4	6	xxx	xxx	25	2.524	0.026(0.010)
Z14	0.9	6	2	xxx	xxx	25	2.278	0.034(0.015)
Z15	0.9	6	4	xxx	xxx	25	2.343	0.141(0.060)
Z16	0.9	2	2	2	xxx	25	2.187	0.147(0.067)
Z17	0.9	2	2	4	xxx	25	2.473	0.094(0.038)
Z18	0.9	2	2	6	xxx	25	2.503	0.144(0.057)
Z19	0.9	xxx	xxx	xxx	4	21	2.389	0.027(0.011)
Z20	0.9	xxx	xxx	xxx	8	17	2.786	0.049(0.018)
Z21	0.9	xxx	xxx	xxx	12	13	2.257	0.078(0.035)
Z23	0.9	2	xxx	xxx	8	17	2.91	0.039(0.013)

Note: xxx: Additive not used

The results shown in table 9 could depict that, optimum straw dosage was found to be 0.9%, which yields strength value of 3.07 MPa (Z2). While the lower strengths were found to be as low as 2.114 MPa in specimens where there was an addition of fine sand and pumice sand and pumice course additives.

3.2.3 Flexural strength tests

Flexural strength tests were performed by applying center point loading on the adobe brick specimens supported over a simple span leaving 2 cm offset at either edges of adobe bricks adopted as in CBC (2013). The minimum average flexural strength required as per CBC is 0.345 MPa. The test results of all the specimens passed the minimum required strength as per CBC (Table 10).

Table 10. Flexural Strength Results Hawassa and Ziway adobe bricks specimens

Hawassa specimens		Ziway specimens	
Designation	**Average Modulus of rupture (MPa)**	**Designation**	**Average Modulus of rupture (MPa)**
PH	3.03	PZ	0.74
HSt 0.4	3.58	Z1	0.74
HSt 0.6	3.3	Z2	1.14
H5	3.35	Z3	0.96
H6	3.11	Z4	1.03
H41	3.39	Z5	0.9
H51	3.34	Z6	0.82
H61	3.35	Z7	0.89
H71	3.48	Z8	0.95
H81	3.27	Z9	0.78
H91	3.37	Z10	0.8
H10	3.44	Z11	0.81
H11	3.33	Z12	0.76
H12	3.31	Z13	0.88
H13	3.35	Z14	0.81
H14	3.28	Z15	0.86
H15	3.39	Z16	0.79
H16	3.37	Z17	0.87
H17	3.3	Z18	0.88
H18	3.23	Z19	0.86
H19	3.17	Z20	0.99
H20	3.18	Z21	0.83
H21	3.32	Z23	1.09
H23	3.43		

As the values of flexural strength had very marginal differences between one mix proportion to the next higher or lower mix proportion, no particular inference with respect to additives inclusion were able to be derived. Generally flexural strength of adobe is governed by an irregular weaker plane which could be inclined in multiple angles irregularly. Such weaker planes could form based on factors such as additives dispersion, level and evenness of compaction and basically the clay content available in the soil (Fig.6).

Figure 6. Irregular failure planes of flexural strength test of Hawassa adobe

3.2.4 Durability tests

After an intense search in literatures, durability tests such as erosion test (Geelong method) and wet and dry appraisal test were found suitable from New Zealand code, NZS 4298:1998. These tests incorporate also the acceptable limits of moisture penetration in to the adobe bricks.

3.2.4.1 Erosion test (Geelong method)

Erosion test was conducted by allowing 100 ml of water to fall over the inclined surface of brick from a height of 400mm, drop by drop. The time for 100 ml of water to drop over the specimen was set as 40 minutes.

Every test specimen was cut immediately after the test and the depth of penetration of water was measured and it was found that all the specimens pass the test (Table 11).

Table 11. Erosion test results

Site location	Depth of erosion result mm	Erodibility index result	Depth of penetration of water result mm	Limiting Depth of penetration of water mm	Pass/fail Acceptability in index & penetration
Hawassa	0.5	2	9	120	Pass
Ziway	0.5	2	22	120	Pass

The specimens from the soil of both Hawassa, and Ziway were indexed 2 which are of the same durability, though the Hawassa specimen show a little better. The depth of penetration of water after the erosion test was observed to be very less with maximum depth of penetration value being 27 mm for Ziway soil specimen while the limiting value is 120mm.

3.2.4.2 Wet and dry appraisal test

In this test, as suggested in NZS 4298:1998, one face of the adobe brick was soaked in to water for a depth of 10mm with bottom surface set at a gap of 2mm above the surface of container used for water bath. The final specimens with cactus resin from the study sites were indexed as 2 in the present research. Hence the duration of soaking based on the erodibility index of the adobe, was 2 minutes for both study sites (Hawassa, and Ziway) specimens. After soaking in water, the adobe specimens were kept under air curing until the color and appearance of the tested adobe face matches that of the reference brick face (opposite face) indicating that drying is complete. The dried specimens were checked for the presence of the following defective conditions.

The specimens of both study sites were not possessing any of the defective conditions (Crazing type crack patterns, Star type crack patterns, Local swelling, Local pitting in at least 5 locations, Local/general Fretting, (loss of layers), Water penetration > 70% width, Loss of fragments > 50mm Surface efflorescence (white patches) and Disintegration during soaking time) according to the test method stated above. The test was repeated for 6 cycles and then also no defective conditions occurred in any specimens from Hawassa, and Ziway. Hence the adobes from Hawassa, and Ziway have passed the durability tests.

4. Discussion

The final stage mix proportions of Hawassa adobe specimens and corresponding average compressive strength obtained for each mix proportions were given in table 8. Optimum dosage of pumice fines was found to be 2% (comparing H41, H51, H61 & H71). With optimum pumice fines percentage and pumice sand of 4%, maximum compression strength of 7.93 MPa (H91) was found. It achieved 22% increase in strength as compared to the control specimen (6.55 MPa).For a total of 6% pumice materials in combination the performance was better (H91, H11 & H16); if the total pumice percentage exceeds 6%, the performance became poorer (H10<H91, H12, H13<H11, H17,H18,H19,H20<H16). Having the optimum values of all additives, final sample was made in the following proportion: 0.2% straw: 2% fines: 4% sand: 4% cactus resin (H23) which had given a maximum compressive strength of 8.06 MPa achieving 23% increase in strength over the control specimen (Table 8).

In Ziway specimens' trials, optimum pumice fines dosage was found to be 2% which offered a strength value of 2.85 MPa (Z4). Optimum pumice sand dosage along with fines was found to be 2% which produced strength of 2.7 MPa (Z8). Optimum cactus resin dosage was observed to be 8% yielding strength of 2.786 MPa (Z20). With a total pumice material percentage of around 8% to 10%, compressive strength of around 2.5 MPa was able to be obtained (Z7, Z13 & Z18); whereas with some other similar total percentage of pumice material dosage it did not hold good. Hence a final combination of 0.9% Straw: 2% fines: 8% cactus resin was produced and tested, which showed a strength of 2.9 MPa. This value is somehow close to strength offered by optimum straw dosage. Final combination produced 41.9 % increase in strength over plain specimen.

All the specimens passed the minimum required compressive strength of 2.06 MPa as per CBC (2013). The performance of Hawassa soil was the best among the locations selected with a maximum strength of 8.06 MPa. The clay content in Hawassa soil is very conducive to offer greater strength when compared to low clayey soil of Ziway highly. As a whole, clay soils of Hawassa, required more stabilization with pumice, while less clay soil of Ziway required less stabilization with pumice. Improvement in strength had been found in Ziway soil with the increase in teff straw content as it acted as a better binder than other additives such as pumice and cactus resin. The addition of cactus resin added better texture and firm edges of adobe bricks when compared to specimens without cactus resin. By the addition of cactus resin improvement in compressive strength was found very meager in Hawassa specimens but it was little reduction in compressive strength in the case of the Ziway sample.

For an adobe without cement or lime stabilization and with natural additives such as fibers, vegetable materials and animal excreta, the strengths achieved by researches as sited were all less than 3.3 MPa. Brazil average compressive strength 1.14 MPa with bamboo particle additives (Correa et.al., 2015), Spain average compressive strength 3.3 MPa with Pine needle additives (Jové-Sandoval et al.,2018). Romania average compressive strength 2.62 MPa with hemp fiber (Correa et.al., 2015), Thailand average compressive strength 3.217 MPa with bagasse additive (Lertwattanaruk et. al.,2011). Whereas in the present research, the compressive strengths achieved are more than 100% increase with regard to Hawassa (8.05 MPa), Ziway (3.07 MPa) adobes performed a little less but the minimum requirement as per CBC code was satisfied.

Flexural strength of adobe bricks was comparatively of higher values because the span between the simple supports was smaller value due to which the behavior as a bending member was less exhibited while, compression behavior influenced the strength value. Hawassa and Ziway samples achieve minimum average flexural strength required as per CBC is 0.345 MPa. It was found that the maximum flexural strengths obtained from adobes with the final mix ratio containing optimum additives dosage along with a comparison between the flexural strengths of adobe, with additives other than cementitious ones, exhibited 3.43 Mpa for Hawassa and 1.09 MPa for Ziway. This shows that it is better than that of 0.3 and 0.35 MPa which were found in Romania (Calatan et al., 2015), Spain (Serrano et. al., 2016) respectively. To put in a shell nut, Hawassa and Ziway sample shows better performance compared to CBC standards in compressive strength, flexural strength and durability. Based on the durability tests performed, it was found that the adobe bricks from Hawassa and Ziway soils are appreciably durable against water contact. However, construction technology by adopting sufficient overhanging of roof covering and sloping mud envelop around the adobe brick wall can help avoid water contact with adobe brick masonry.

5. Conclusion

In the present research, the performance improvement of adobe bricks using natural additives that are available around the study area was analyzed. The natural additives used were teff straw, pumice fines, pumice sand, pumice coarse aggregate and cactus resin. Soils from two locations (Hawassa and Ziway) were selected. Tests were conducted for their suitability to produce adobe and further characterized the soil type. Strength and durability tests were performed and test results were analyzed to draw the following conclusions.

- Soil samples from both study sites were found to be suitable for adobe masonry unit production based on the required percentages of ingredients which were examined in suitability and characterization tests.
- Specimens from all the locations passed the minimum required strength criteria based on CBC (2013) standards.
- Addition of cactus resin supplemented to obtain better size, shape and texture of adobe than the one without cactus resin while strength increment was very marginal with the inclusion of cactus resin in almost all the specimens.
- Hawassa specimen with 0.2% teff straw, 6% in total of pumice fines and sand content and 4% cactus resin performed better yielding a compressive strength of 8.06 MPa achieving 23% increase in strength over the control specimen.
- With Ziway soil, the final combination of 0.9% Straw: 2% fines: 8% cactus resin was yielding strength of 2.91 MPa. However, the maximum compressive strength for Ziway soil was found under 0.9 % straw with no other additives inclusion, which showed nearly 33.27 % increase in strength over the plain specimen. Hence, it could be good to use adobe with straw alone which has better strength.
- In the flexural strength test, the strength values were higher enough because the specimen size offered comparatively low value of span length between the supports which had resulted in the compressive behavior of the loaded specimen. However, all the specimens have passed the requirement based on CBC (2013) standard. Moreover, adobes from Hawassa, Ziway have proved good in durability tests.
- Adobes from Hawassa and Ziway have proved good in durability tests.

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