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Termite Mound Soils for Sustainable Production of Bricks

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Abstract: The article presents the alternative use of termite mound soils (TMSs) as full replacement for clay soils in brick production. TMSs from two localities, Jawaj and Sene, in Ethiopia were investigated for bricks production. The TMSs samples contained high SiO_2 and Al_2O_3. The TMSs bricks were fired at different temperatures from 500 to 1,000°C. The obtained mean compressive strengths (σ), 18 and 14 MPa, were observed for bricks made from TMSs from Jawaj and Sene, respectively, at the optimum firing temperature of 700°C. The σ of TMSs bricks decreased as the firing temperature increased above 700°C, while for conventional clay soil brick, the σ increased with temperature beyond 700°C. The water absorptions and saturation coefficients of fired TMSs bricks decreased with increased firing temperature. The TMSs bricks meet the standard specification of dimension tolerance only along the height. All the TMSs bricks made from the two localities were not efflorescent. TMSs from Jawaj and Sene sites can be used as a raw material to replace the long-used clay soils for bricks production as a construction material for houses construction in rural and urban areas.

Keywords: compressive strengths; chemical composition; firing temperature; sustainable production; termite mound soil.

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1 Introduction

The history of brick making goes back to the earliest days of civilisation. It is claimed that bricks were made more than 10,000 years ago. Brick making is as ancient as human civilisation and the great architectural wonder, and the immortal monuments in the antique past had been built with bricks. Since man realised housing as one of the basic needs, bricks are being used as construction materials. The sundried and fired bricks are used from humble dwellings to the modern sky skyscrapers and complex structures. Thus, bricks are the most important building materials (James and William, 2004).

There is a need for affordable building materials in providing adequate housing for humankind in the world. The cost of conventional building materials has continued to increase. Therefore, as the majority of the population continues to fall below the poverty line, the cost of the conventional construction materials has become unfordable (United Nations, 2019). Thus, there is a need to search for local environmentally friendly materials as alternative and low-cost building materials, without compromising the quality in both rural and urban areas (Seghir, *et al.*, 2019).

The construction materials account for between 40 and 60 % of the total construction cost, and this is attributed to the fact that basic conventional building materials like cement and aggregates are becoming increasingly expensive due to high cost incurred in their processes, production and transportation (Alake and Akaninyene, 2014; Omofunmi and Oladipo, 2018). This led us to the utilisation of locally available materials like termite mound soil that can either reduce or replace the conventional materials. The characteristics of termite mound soil are suitable for construction material because they have binding properties as the mound is rich in silica and alumina (Omofunmi and Oladipo, 2018; Jouquet, *et al.*, 2007; Jouquet, *et al.*, 2020).

Housing is an asset that all family aspires to acquire and own in the world to feel secure. However, in many parts of the world, particularly in the developing countries, fulfilling housing requirement of the population remains challenging (Woetzel *et al.*, 2014). Therefore, majority of the population of developing countries are either homeless or live-in slums and sub-standard houses.

Similarly, the vast majority of Ethiopia live in poorly built, dilapidated and cramped houses, which lack even the basic facilities. In the urban areas, only 30% of the current housing stock in the country is in a fair condition, but the remaining 70% needs total replacement (Efrem, 2015). This inevitably has initiated the search for locally abundant available materials as alternative construction materials to clay soils for brick production.

Bricks manufactured from clay soils have environmental impacts such as land degradation due to extraction of the clay. They have led to the disfiguring of the landscape, cutting down the vegetation, water and air pollution, among the other impacts, thus affecting ecological diversity, animal habitats, drainage patterns and neighbouring local communities (Hartmann *et al.*, 2018).

A termite is an insect that builds nests from soil, causing a serious problem for local farmers' crops; chemical composition of termite mound reduces soil fertility. In the southern and western parts of Ethiopia, the average mound abundance was found to be 12 mound hills/ha, and the estimated termite mound soil mass is 58.9 t/ha (tonne/hectare) (Fufa, 2016). Termite mound soil is available everywhere (Miyagawa *et al.*, 2011; Eze *et al.*, 2020). According to Fuyane *et al.* (2013), extraction of clay for brick making causes land degradation because extensive and excessive clay removal from one place may affect human health by creating pools and still water, which provide a suitable environment for mosquitoes and malaria.

Therefore, a termite mound soil are earthen nests that are frequently found throughout the tropics and sub-tropics worldwide (Millogo *et al.*, 2011). According to Alabadan *et al.* (2016), termite hill soils contain clay, which consist of inorganic material minerals and water that makes them fire-resistant and incombustible. It is made of clay whose plasticity is further improved by the secretion from the termites while being used in building a termite mound (Assam *et al.*, 2016). It is, therefore, a better material than ordinary clay in terms of utilisation for moulding and soil stabilisation (Assam *et al.*, 2016) and in storage construction (Omobowale *et al.*, 2016).

Nowadays, using locally available alternative construction material are one of the most common methods for combating a lack affordable construction materials for a developing country. Termite mound soils (TMSs) are found all over the world. TMSs are usually made of clay whose plasticity has been further improved by the secretion from the termites while being used in building the mounds. TMSs are not significantly different in clay mineralogy (Millogo *et al.*, 2011). It is a better material than ordinary clay in terms of utilisation for moulding (Alake and Akaninyene, 2014). Globally, it is reported that mounds are clay-rich sites, and the composition of many chemical elements are greater than surrounding soils (Eze *et al.*, 2020).

The tradition of cutting a tree for construction purpose in a rural area is not recommended because of global warming. Therefore, the aim of this study was to investigate the performance of fired bricks made from TMSs as eco-friendly construction material to replace the long-used conventional clay soils.

2 Materials and Methods

2.1 Characterisation of Termite Mound Soils

TMSs were used in this study. TMSs are widely available in the eastern parts of Africa in the rift valley region that covers a wider area. In Ethiopia, TMSs are abundantly available in different localities, including the main Ethiopian rift valley. Representative samples of TMSs were collected from Jawaj and Sene localities located in Kiramu District, East Wollega Zone of Oromiya National Regional State and Benishangul Gumuz Regional State, Ethiopia, respectively (Figure 1). In addition, conventional clay soils samples were collected from traditional local brick production site from Bada Buna, Jimma Zone, Oromia region. The TMSs have different colours based on the source materials depending on the geological history of the deposit in the locality (Figure 2).

The soils were crashed to obtain the desired particle size for laboratory investigation. Samples of TMSs from two localities were mixed in a 1:1 ratio thoroughly for characterisation. The chemical compositions of the TMSs samples were determined using X-ray fluorescence (XRF) spectrometry at laboratory of Geological Survey of Ethiopia, Addis Ababa.

Laboratory tests of the Atterberg limits were conducted at the laboratory of Jimma Institute of Technology, Jimma University according to testing procedures, ASTM D 4318 (Dewangan *et al.*, 2016). The percentage of the soil samples that passed sieve 0.075 mm, No. 200 was conducted to determine the grain size of the soil as per the AASHTO Soil Classification System. The hydrometer analysis was conducted to determine the particle size distribution

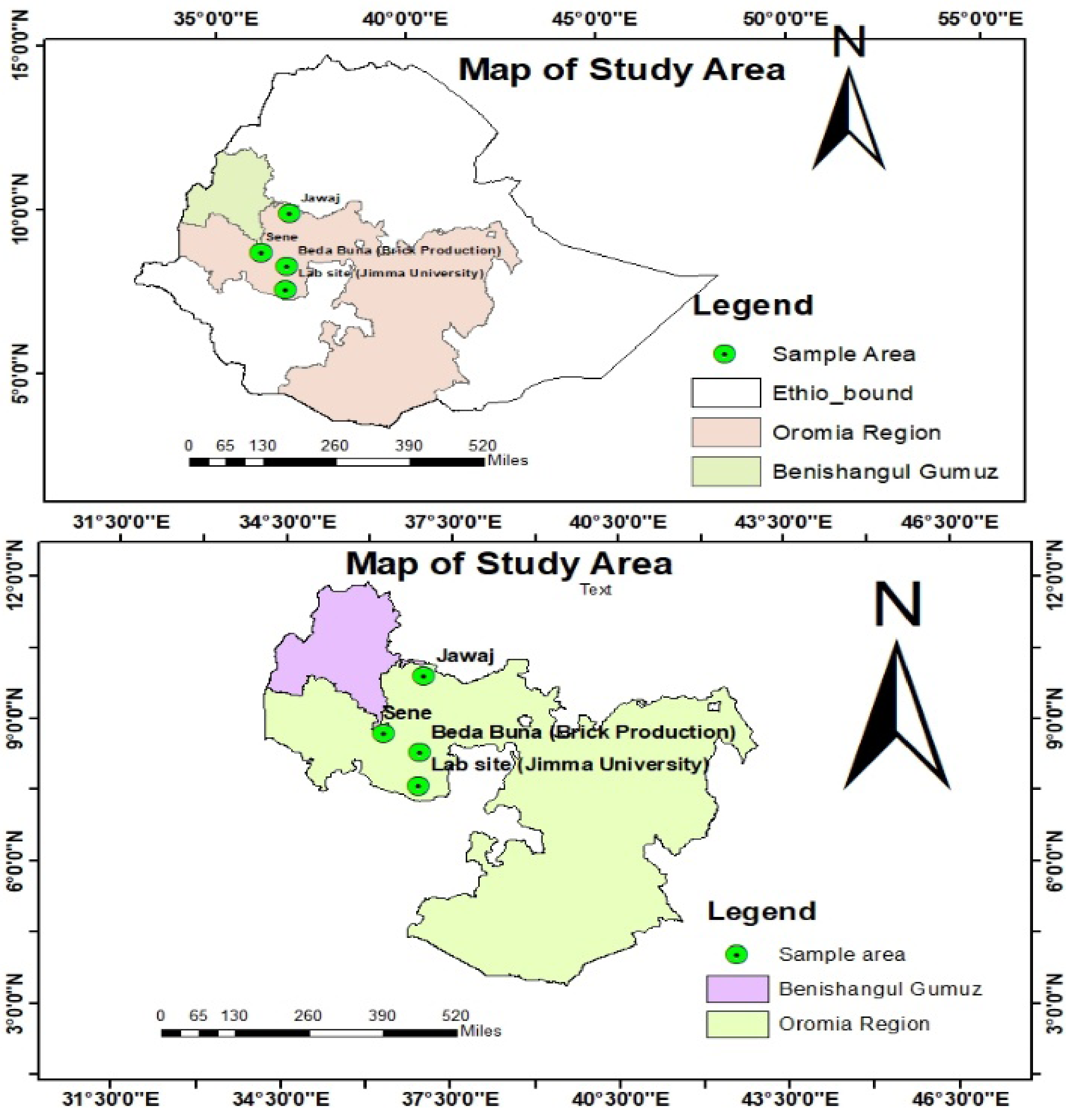

Figure 1: Point locations of Sene and Jawaj sampling sites.

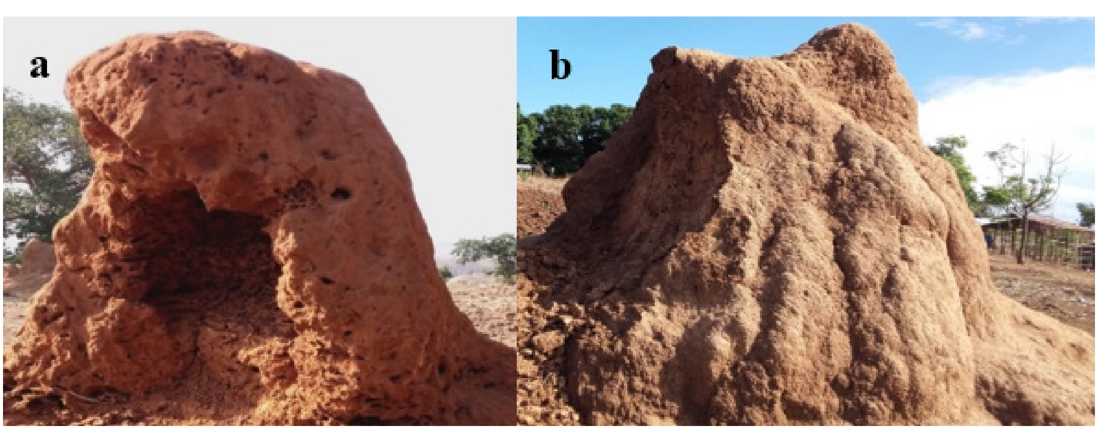

Figure 2: Colour of the termite mounds: (**a**) Jawaj (Red); (**b**) Sene (grey).

(percentage) of the samples and identify the silt, clay and colloids percentages in the TMSs samples.

The maximum dry density (MDD) and optimum moisture content (OMC) of TMSs were determined by the Standard Proctor Compaction Test following the test methods of ASTM D 698. The specific gravity of the soil was determined by following test procedure in ASTM D 854 (ASTM D 854, 2002).

2.2 TMSs Bricks Production and Characterisation

Wooden moulds of dimensions 240 mm x 120 mm x 60 mm (L x W x H) were used to make the bricks from the soils. The moulded bricks were left in a shed to be dried with air. The time of drying was dependent on the moisture content of the green bricks and the humidity of the production area. The TMSs brick production process is given in Figure 3.

Firing of the air-dried bricks was done using furnace for 4 h in Burqa Gibe Metal and Metals Manufacturing Plc, Jimma, Oromia, Ethiopia. The firing temperatures were 500, 600, 700, 800, 900 and 1,000°C.

The compressive strength, σ, water absorption, efflorescence, linear shrinkage (LS) and saturation coefficient of the fired TMSs bricks were characterised according to the Ethiopian Standard Specification of Solid Clay Bricks (ES 86: 2001) and the American Society for Testing and Materials; Standard Specification for Building Bricks (ASTM C 67).

The LS of the TMSs bricks was determined using British Standard, BS 3921(1985) Test 5. The standard specifies that standardised mould takes the shape of half cylinder of 12.5 mm diameter and 140 mm length. The LS in percent was determined using Eq. (1):

$$LS\ (\%) = 100\% * Ls/L \tag{1}$$

where L: initial length (the length of the mould); L_S: final length of the brick.

Then, the compressive strength, σ, of the bricks was calculated by dividing the maximum or failure load-by-load area of the sample bricks. The mean values of σ of the bricks under different firing temperature were determined using Eq. (2).

$$\text{Compressive strength} = \text{Failure load (N)}/\text{Area (mm}^2) \tag{2}$$

The water absorption test was conducted as per ASTM C 67 using five bricks dried in an oven for 24 h and the weight (W_1) of the samples measured carefully using a digital balance. The bricks were cooled to room temperature and submerged in water for 24 h. Then, the bricks were taken out from the water and wiped by damp cloth and weighted (W_2). The water absorption of the bricks was then determined employing Eq. (3).

$$\text{Water absorption (\%)} = (W_2\text{-}W_1) * 100/W_1 \tag{3}$$

The dimension tolerance test was conducted taking ten bricks and measuring their dimensions following the procedures of ASTM C 216. All the bricks were considered as FBS (brick for general use in masonry). Ten bricks from each type were taken, and the test was conducted by measuring the length, width and height of each of the bricks, and the dimension was checked if it is within the ASTM C 216 standard limit. The inside dimension of the mould used was 240 mm x 120 mm x 60 mm. The dimensions were measured along the length, width and height of the bricks. The average dimension reduced was compared with the ASTM standard.

The efflorescence of bricks was tested as per ASTM C-67. The ten bricks analysed for the dimension tolerance test were considered to determine the presence of salt on the bricks. The bricks were immersed in water for 7 d, and the rating was done by observing the surface of the bricks if there are white dots on the bricks. The bricks were rated as 'effloresced', or 'not effloresced' as stated in the standard ASTM C 67.

3 Results and Discussion

3.1 Chemical Composition of TMSs

The chemical compositions of the TMSs samples were given in (Table 1). Both Jawaj termite mound soils (JTMSs) and Sene termite mound soils (STMSs) had silica, SiO_2 > 60%. The alumina, Al_2O_3, contents for each of the TMSs from the two localities were > 17%. The sum of the percentage of SiO_2 and Al_2O_3 content are 80.59 and 79.86% for JTMSs and STMSs, respectively. According to the study conducted by Toure *et al.* (2017) on the mechanical and thermal characterisation of bricks, a combined percentage of SiO_2 and Al_2O_3 should be greater than 70% to be a good binder for the brick production. The combined percentage of SiO_2 and Al_2O_3 composition also meets the requirements of ASTM C-618 (ASTM C 618, 2010). Thus, TMSs can be considered as suitable raw materials for brick production. Alkali oxides (MgO, K_2O, Na_2O) compositions are 4.24 and 4.12 % for TMSs from Jawaj and Sene localities,

Figure 3: TMSs bricks production characterisation process: A = Sample collection; B = Preparation; C = Moulding; D = Firing; E = Fired bricks; and F = Compressive strength.

Table 1: Oxide compositions of TMS.

TMS	Chemical compositions (%)												
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	MnO	P_2O_5	TiO_2	H_2O	LOI	SO_3
JTMSs	63.00	17.59	5.34	0.60	1.00	1.14	2.10	0.02	0.04	0.26	1.75	8.19	0.34
STMSs	61.38	18.48	5.90	0.66	1.14	1.84	1.14	0.06	0.05	0.28	0.65	8.38	0.32

respectively. The alkali content is > 3% for JTMSs and STMSs. The results of the investigation made by (Attah, 2008) on the composition and physical properties of some clays of Cross River State, Nigeria, support the finding of this study. Thus, the TMSs results in low temperature vitrification and increases the firing shrinkage.

3.2 Particle Size Distribution

The sieve analysis results show that the percentage of soil passing sieve No. 200 were 60 and 67% for TMSs from Jawaj and Sene localities, respectively (Figure 4). These values are greater than 35% passing for both localities, indicating that soils were fine-grained (silt or clay (A4–A7)) material according to AASHTO Soil Classification System. Soils containing clay and silt contents 40–65% are suitable for brick making.

3.3 Atterberg Limits

The physical properties of the TMSs are presented in (Table 2). The liquid limits (LLs) were 38% for both JTMSs and STMSs. However, the LL for conventional clay soil was 34%. The plastic limits (PL) were 20, 23 and 19.27%, respectively, for JTMSs, STMSs and clay soil. The corresponding plasticity index (PI) values obtained were of 19, 16 and 14.7%, respectively, for JTMSs, STMSs and clay soils. The PI value greater than 17 for JTMSs is an indication that the TMSs from Jawaj were a highly plastic soil in character. The PI values for STMSs and clay soils ranged between 7 and 17%, indicating that the soils had a medium degree of plasticity property. Thus, the TMSs from both localities can be used as raw materials for brick production replacing clay soils.

The PI values for the TMSs from the two localities were 20 and 23%. According to the results of the percentage

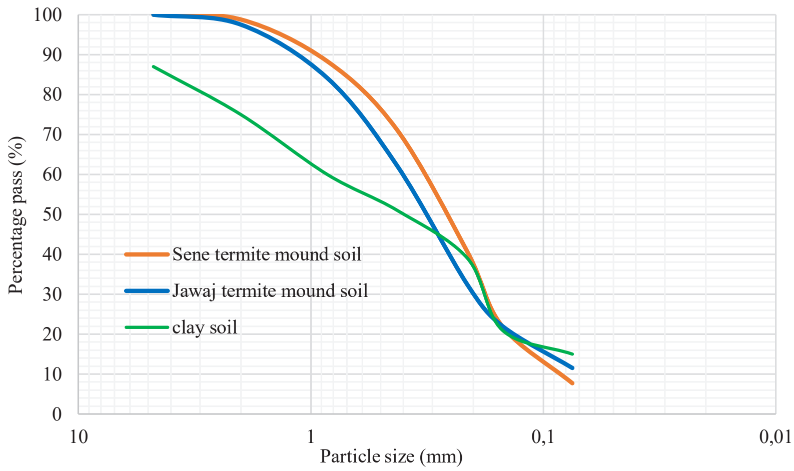

Figure 4: Particle size distribution curve.

Table 2: Physical properties of TMSs samples and clay soils.

Index properties	JTMSs	STMSs	Clay soils
Specific gravity	2.55	2.66	2.68
LL (%)	38	38	33.94
PL (%)	20	23	19.27
PI (%)	19	16	14.7
MDD* (kg/m^3)	1,684	1,614	1,870
OMC* (%)	18	19	14.6
AASHTO class	A6	A6	A6

*MDD = Maximum dry density; MOC = optimum moisture content

Table 3: AASHTO classification for fine-grained soils (Brajam, 2002).

Soil type (1)	Passing No. 200 sieve (2)	Liquid limit (3)	Plastic index (4)	Material type (5)
A4	36 min	36 min	10 min	Silty soil
A5	36 min	41 min	10 min	Silty soil
A6	36 min	40 min	11 min	Clayey soil
A7	36 min	41 min	11 min & PI ≤ LL-30	Clayey soil
	36 min	41 min	11 min & PI > LL-30	Clayey soil

passing the No. 200 sieve and LL, the soil was either A4 or A6. The AASHTO Soil Classification PI for A4 is 10 max, and for A6, it is 11 min. The PI were 19 and 16 for JTMSs and STMSs, respectively. Hence, based on their respective PI values, both JTMSs and STMSs are categorised under A6, which are clay soils. Thus, TMSs can substitute clay soils as raw materials for brick production to deter environmental degradation due to excessive use of clay soils.

3.3.1 Liquid limit

The value at 25 blows from the LL flow curve for JTMSs and STMSs was 39% for both of them. Table 3 presents the AASHTO Soil Classification depending on LL. The soil type was categorised based on percentage pass by sieve number 200 (0.075 mm). The LL results of JTMSs and STMSs summarised in Table 3. As PI of JTMSs and STMSs was greater than 11 min, and they fall under A-6, clayey soil type. Figure 5 presents the LL of TMSs and clay soils.

3.3.2 Linear shrinkage

Bricks will shrink when drying, so the mould size must be larger than the intended finished brick (Riza and Rahman, 2017). The LS results were 7.28 and 8.0% for JTMSs and STMSs bricks, respectively. According to Toure *et al.* (2017), clay soils with LS less than 5% are non-critical, 5 to 8% are marginal and LSs greater than 8% are critical. Higher LS is not desirable in brick making, as this may create cracks on final products. The TMSs used in this study were suitable for brick making as the LS values were, respectively, 7.28 and 8.0% for bricks made from JTMSs and STMSs. The value fall between 5 and 8%, which is the marginal range.

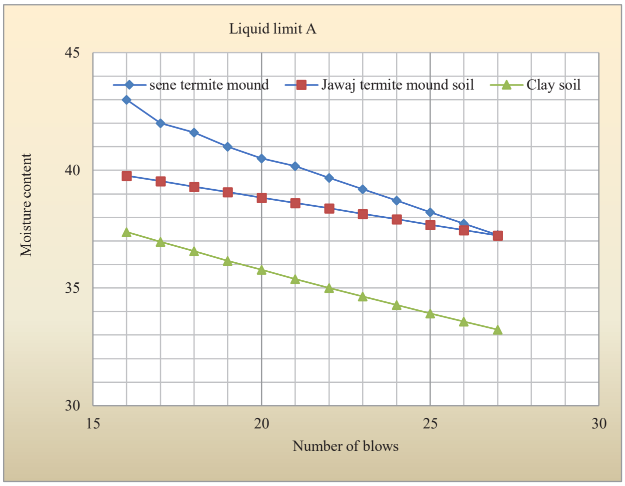

Figure 5: LL of JTMSs, STMSs and clay soils.

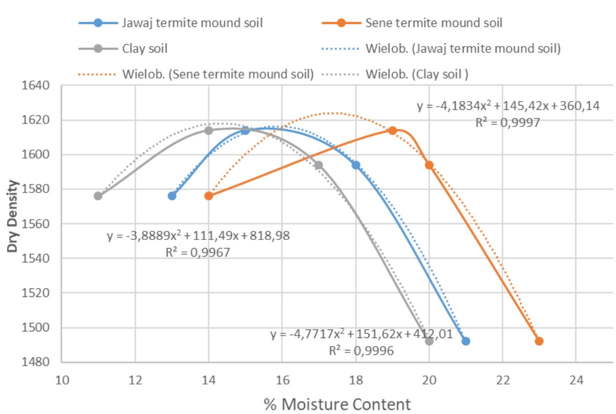

Figure 6: Standard compaction curve for TMSs and clay soil (*fourth-order polynomial was used to give better results than the tangent line approximation*).

Table 4: Specific gravities ranges for various soil types (Das & Sawicki, 2001).

Soil type	Specific gravity
Sand	2.63–2.67
Silt	2.65–2.7
Clay and silty clay	2.67–2.9
Organic soil	< 2

3.4 Soil Compaction

The graph of OMC and MDD is given in Figure 6. The pick point of the graph shows the MDD and the moisture content corresponding to the MDD, which is the OMC. Thus, the values of MDD for JTMSs and STMSs were 1,684 and 1,614 kg/m^3, respectively. The OMC determined from the curve are 18 and 19% for JTMSs and STMSs, respectively. According to Arora (2019), the OMC of the TMSs from the two localities is between 14 and 20%, which is in the range of OMC for clay soils. The OMC for sand ranges from 6–10%, from 8–12% for silty sand, from 12–16% for silt and from 14–20% for clay soils.

3.5 Specific Gravity

The values of the specific gravity of the TMSs samples for Jawaj and Sene are 2.55 and 2.66, respectively (Table 4). The specific gravity of the JTMSs was between that of clay and organic soils. Whereas the specific gravity of the STMSs samples fell in the range of sand. The specific gravity of the clay soils from Jimma town was 2.68.

3.6 Compressive Strength

The mean compressive strengths, σ, of JTMSs bricks produced at different firing temperatures are presented in Figure 7. The σ of brick was remarkably improved by firing at higher temperature. With the increase in the firing temperature from 500 to 700^{0}C, the σ increased from 11 to 18 MPa. The increase in the σ can be due to the decrease in porosity and increase in bulk density as the firing temperature increases (Tsega *et al.*, 2017; Johari *et al.*, 2010; Okunade, 2008; Glaydson *et al.*, 2020; Karaman *et al.*, 2006). As the firing temperature increased from 800 to 1,000^{0}C, the σ of the brick decreased. The JTMSs bricks demonstrated a bit greater σ when compared with the σ of STMSs bricks (Figure 7). This could be because of the higher silica content of JTMSs.

Keeping the firing temperature in the range from 500 to 1,000 ^{0}C and increasing the firing time from 120 to 480 min resulted in a small increase in the σ. Therefore, increasing the firing time did not improve the quality of the bricks. So, prolongation of firing time is wasting of energy and time.

It was observed that the TMSs bricks demonstrated highest σ at about 700^{0}C firing temperature, which was taken as the optimum firing temperature for brick production from JTMSs and STMSs. However, the σ of bricks produced from clay soils required greater than 700^{0}C firing temperature. The finding of this study is in line with the observation made by Tsega *et al.* (2017). The σ of the bricks made from JTMSs, STMSs, the mixture of JTMSs and STMSs and the conventional clay soils were given in Table 5.

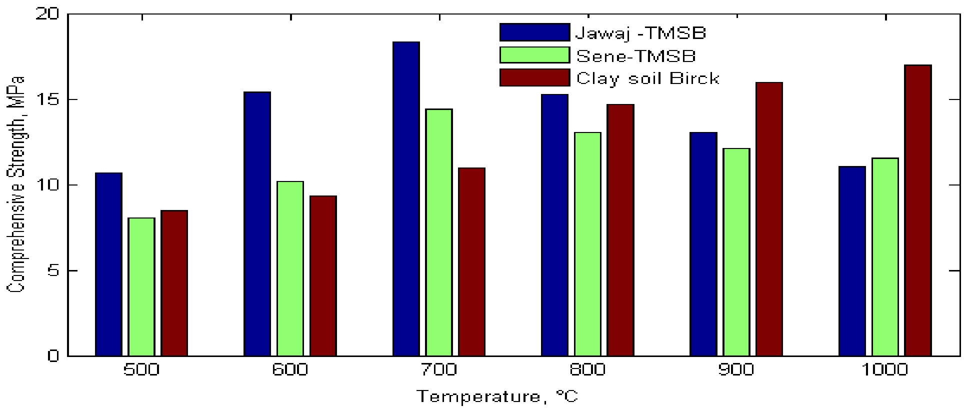

Figure 7: Compressive strength of TMSs bricks and clay soils bricks at different firing temperatures.

Table 5: Mean compressive strength of five bricks and their classifications.

Bricks	Description		Firing temperature (ºC)					
			500	600	700	800	900	1,000
JTMSs bricks	Mean compressive strength of 5 bricks (MPa)		11	15	18	15	13	11
	Classification	ES 86:2001	C	B	B	B	C	C
		ASTM C 62-97a	NW	NW	MW	MW	NW	NW
STMSs bricks	Mean compressive strength of 5 bricks		8	10	14	13	12	12
	Classification	ES 86:2001	D	C	C	C	C	C
		ASTM C 62-97a	-	NW	NW	NW	NW	NW
JTMSs and STMSs bricks	Mean compressive strength of 5 bricks		9.4	12.8	16.4	14.1	12.6	11.3
	Classification	ES 86:2001	D	B	B	B	B	C
		ASTM C 62-97a	D	C	C	C	C	C
Clay soil bricks	Mean compressive strength of 5 bricks		8.10	8.58	10.8	13.02	15.25	17.36
	Classification	ES 86:2001	D	D	C	C	B	B
		ASTM C 62-97a	-	-	NW	NW	MW	MW

The physical property requirements of fired clay bricks are different in different standard specifications. Different countries have different physical property requirements of fired clay bricks in their specifications. For instance, lower values of water absorption are required in BS 3921(1985), Standard Specification for classifying clay bricks when compared with ASTM standard specifications.

The bricks produced from the JTMSs firing at 700ºC are classified as class B, C and D based on their mean compressive strength, mean water absorption and mean saturation coefficient, respectively. This classification is according to the requirements of ES 86:2001 (Ethiopian Standards Agency, 2015). However, according to the ASTM standard, the bricks categorised as moderate weathering (MW) consider the σ, which was 18 MPa. The σ of the bricks is greater than 17.2 MPa, so JTMSs bricks produced at the firing temperature 700ºC meet the ASTM standard specification. However, the σ of bricks produced from conventional clay soils increased as the temperature increased beyond 700ºC. This shows bricks produced from TMSs demonstrated maximum σ strength at low temperature. According to Okunade (2008), σ of brick range between 15 and 18 MPa.

3.7 Water Absorption

The water absorptions and saturation coefficient of the bricks made from for JTMSs and STMSs at different firing temperatures are given (Table 6). The observed mean water

Table 6: Average water absorption and saturation coefficient of TMSs and clay soils bricks and their classification.

Type	Description		Firing temperature (^{0}C)					
			500	600	700	800	900	1,000
Jawaj	Mean W of 5 bricks (%)		12.26	14.72	15.72	15.98	11.17	9.88
	Classification	ES 86:2001	A	A	A	A	A	A
		ASTM C 62-97a	SW	SW	SW	SW	SW	SW
	Mean saturation coefficients of 5 bricks %		0.85	0.84	0.78	0.70	0.39	0.37
	Classification	ES 86:2001	A	A	A	A	A	A
		ASTM C 62-97a	SW	SW	SW	SW	SW	SW
Sene	Mean W of 5 bricks (%)		17.48	19.12	21.07	18.60	17.43	21.38
	Classification	ES 86:2001	A	A	A	A	A	A
		ASTM C 62-97a	SW	SW	SW	SW	SW	SW
	Mean saturation coefficients of 5 bricks (%)		0.84	0.82	0.81	0.78	0.73	0.57
	Classification	ES 86:2001	B	B	B	A	A	A
		ASTM C 62-97a	MW	MW	MW	SW	SW	SW
Clay soil	Mean W* of 5 bricks %		12.98	12.04	11.86	10.67	9.48	8.88
	Classification	(ES 86:2001)	A	A	A	A	A	A
		ASTM C 62-97a	SW	SW	SW	SW	SW	SW
	Mean saturation coefficients of 5 bricks (%)		0.87	0.84	0.82	0.69	0.68	0.65
	Classification	(ES 86:2001)	B	B	B	A	A	A
		ASTM C 62-97a	MW	MW	MW	SW	SW	SW

*W = water absorption

absorption values of bricks made from TMSs increased as the firing temperature increased by 100^{0}C, whereas the saturation coefficients of the bricks reduced when the firing temperature increased. On the contrary, the water absorptions and saturation coefficients decreased for bricks produced from clay soils as the firing temperature increased. The findings of this study are consistent with the observations made by Matysek *et al.* (2016).

Based on the mean water absorption, clay bricks are classified as class A according to ES 86:2001 (Ethiopian Standards Agency, 2015), are also classified as MW according to the ASTM standard specification. This shows that classification of fired bricks is different based on different standards.

3.8 Dimension Tolerance of Fired TMSs Bricks

Figure 8 presents the dimension tolerance of fired TMSs bricks along the length of 240 mm. The dimension tolerance of the of TMSs bricks of the two localities did not fulfil the ASTM (ASTM C62/C62M-12, 2012) permissible dimension variation along the length. This was due to the shrinkage of TMSs bricks during sun drying and firing. The amount of water added during mixing of the TMSs for workability was lost during firing, causing reduction in the dimensions of the bricks. Firing temperature is one of the key factors to modulate the physical properties of bricks. The dimensions of the bricks decreased as the firing temperature increased. This finding was similar with the results of the study conducted by Karaman *et al.* (2006) on the clay bricks in Turkey.

The change in dimension along the width of the bricks produced at the firing temperature of 600^{o}C fulfilled the ASTM requirements (ASTM C62/C62M-12, 2012). Size reductions of the bricks along the width are presented in Figure 9 (in this figure, a fourth-order polynomial was used to give better results than the tangent line approximation). The dimension reduction of JTMSs bricks did not fulfil the ASTM (ASTM C62/C62M-12, 2012) permissible dimension tolerance along the width. The findings of this study are different from the observations made by Kabtamu

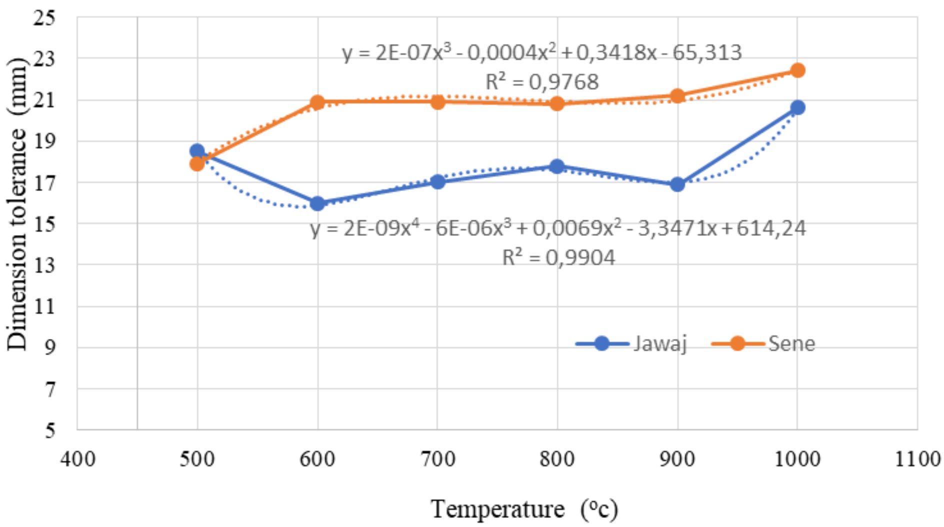

Figure 8: Average dimension tolerance test results along the length 240 mm.

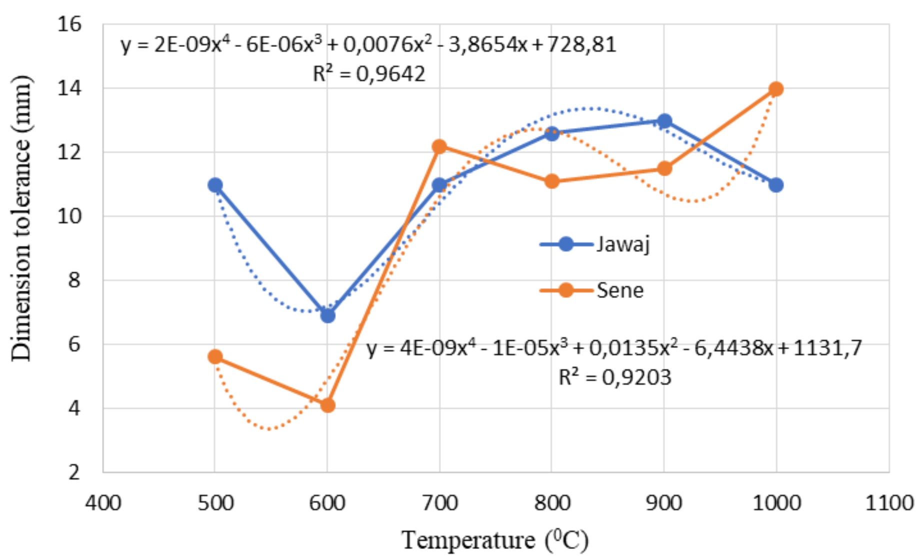

Figure 9: Average dimension tolerance test results along the width 120 mm.

and Alemu, (2017) on the clay soils bricks quality and suitability. This could be because of the materials used from brick production are different in their composition and formation.

The average dimension reduction of TMSs bricks along the height is shown in Figure 10. TMSs bricks from Jawaj and Sene do not fulfil the ASTM C216 (ASTM-C216-16, 2013) maximum permissible variation. The reason of this phenomenon is high loss of ignition (LOI) in TMSs from Jawaj and Sene, which was about 8.38%-dimension tolerance along the length. According to ASTM C216 (ASTM-C216-16, 2013), the size variation occurred due to the production method of bricks. These size variations occurred due to the shrinkage during drying and firing of the bricks (Brick Development Association, 2006). Therefore, variations in dimensions are compensated by providing a mould size considering the expected change in the dimensions. For example, for JTMSs bricks, at firing temperature of 500°C reduced dimension along the length, width and height were, respectively, 18.5, 11 and 7.4 mm. As a result, to obtain brick the same as with 240 mm x 120 mm x 110 mm, the moulding box should have the internal dimension of 259 mm x 231 mm x 118 mm to get desired brick dimensions.

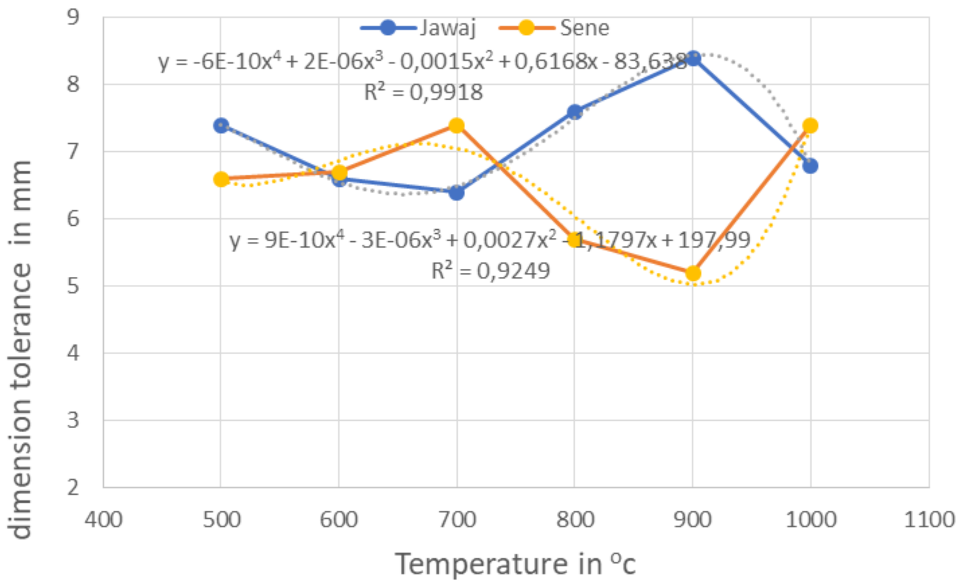

Figure 10: Average dimension tolerance test results along the width 60 mm.

3.9 Efflorescence Tests

The efflorescence test for both JTMSs and a STMSs bricks was conducted according to ASTM C67 (ASTM C67-19, 2019). The test was followed after the dimension tolerance test was accomplished (Drive, 2007; Chin and Behie, 2010). The results of the efflorescence test on TMS bricks show that all the bricks were not effloresced.

4 Conclusion

Based on the results of this study, the following conclusions are drawn:

– The chemical compositions of JTMSs and STMSs show the combined percentage of silica (SiO_2) and alumina (Al_2O_3) are, respectively, 80.59 and 79.86%. This indicates that TMSs from the two localities meet the criteria of good-quality brick-making materials. Therefore, TMSs can be used as alternative materials for the production of bricks.
– JTMSs and STMSs are classified as A6 according to the AASHTO Classification System. The TMSs maintain shape after moulding because of the plasticity characteristics and clay contents in the soils.
– The optimum firing temperature for the brick production of JTMSs and STMSs is 700°C. The increase in the firing temperature of TMSs bricks from 500 to 700°C causes the increase of σ from 9.4 to 16.4 MPa. On the other hand, the increase in temperature from 800 to 1,000°C results in the decrease in σ from 14.1 to 11.3 MPa. The W of the TMSs bricks decreases as the firing temperature increases. This verifies that firing temperature significantly affects the physical requirements of fired bricks.
– Physical properties of fired TMSs bricks fired at different firing temperatures satisfy the Ethiopian Standard Specification for Solid Clay Bricks (ES 86: 2001).
– In general, the research findings concluded that TMSs can be used as a raw material for brick production, as the TMSs are mainly available in nature.

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References

[1] Alabadan, B. A., Adekola, K. A., & Esumobi, T. J. (2016). Compressive strength of rice husk stabilized termite hill soil. *Agricultural Engineering International: CIGR Journal*.

[2] Alake and Akaninyene,(2014) "Influence of curing media on the compressive strength of termite mound-lime blended cement mortar g media on the compressive strength of termite mound-lime blended cement mortar," https://doi.org/10.11113/mjce.v26.15896

[3] Assam, S., Okafor, F., & Umoh, U. (2016). Potentials of Processed Termite as a Stabilizing Agent in Clay Soil. *IOSR Journal of Mechanical and Civil Engineering*. https://doi.org/10.9790/1684-1304014050

[4] ASTM-C216-16. (2013). Standard Specification for Hollow Brick (Hollow Masonry Units Made From Clay or. *American Society for Testing Material*. https://doi.org/10.1520/C0652-12A.

[5] ASTM C 618. (2010). Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use. *Annual Book of ASTM Standards*.

[6] ASTM C62/C62M-12. (2012). Standard Specification for Building Brick (Solid Masonry Units Made From Clay or Shale). *ASTM International*. https://doi.org/10.1520/C0062-10

[7] ASTM C67-19. (2019). Standard Test Methods for Sampling and Testing Brick and Structural Clay Tile. *ASTM International*. https://doi.org/10.1520/C0067

[8] ASTM D 854. (2002). ASTM D854 Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer. *ASTM International*.

[9] Attah, L. E. (2008). The Composition and Physical Properties of Some Clays of Cross River State, Nigeria. *African Research Review*. https://doi.org/10.4314/afrrev.v2i1.41026

[10] Brick: a world history. (2004). *Choice Reviews Online*. https://doi.org/10.5860/choice.41-3863

[11] Brick Development Association, T. (2006). BDA Guide to Successful Brickwork. In *BDA Guide to Successful Brickwork* (Third Edit). https://doi.org/10.4324/9780080456287

[12] BS 3921(1985) Specification for clay bricks. *British Standards Institution https://infostore.saiglobal.com/en-us/Standards/BS-3921-1985-1985 196932_SAIG_BSI_BSI_469615/*

[13] Chin, I. R., & Behie, B. (2010). Efflorescence: Evaluation of published test methods for brick and efforts to develop a Masonry assembly test method. *Journal of ASTM International*. https://doi.org/10.1520/JAI102744

[14] Dalkılıç, N., & Nabikoğlu, A. (2017). Traditional manufacturing of clay brick used in the historical buildings of Diyarbakir (Turkey). *Frontiers of Architectural Research*. https://doi.org/10.1016/j.foar.2017.06.003

[15] Das, B., & Sawicki, A. (2001). Fundamentals of Geotechnical Engineering. In *Applied Mechanics Reviews* (Third). Chris Carson. https://doi.org/10.1115/1.1421116

[16] Dos Reis, G. S., Cazacliu, B. G., Cothenet, A., Poullain, P., Wilhelm, M., Sampaio, C. H., Lima, E. C., Ambros, W., & Torrenti, J. M. (2020). Fabrication, microstructure, and properties of fired clay bricks using construction and demolition waste sludge as the main additive. *Journal of Cleaner Production*. https://doi.org/10.1016/j.jclepro.2020.120733

[17] Dr.k. Arora, Soil mechanics and foundation engineering,. 7th Edition print 2019 Edition Delhi. 2019

[18] Drive, C. P. (2007). Specifications for and Classification of Brick. *Technical Notes on Brick Construction*.

[19] Efrem Wakjira Hode. (2015). Study of Compressed Earth Blocks as an Alternative Wall Building Material. *International Journal of Engineering Research and Technology (IJERT)*.

[20] Ethiopian Standards Agency. (2015). *Catalogue 2015 Catalogue 2015*. Ethiopian Standards Agency. http://www.ethiostandards.org/other files/2015 catalogue.pdf

[21] Eze, P. N., Kokwe, A., & Eze, J. U. (2020). Advances in Nanoscale Study of Organomineral Complexes of Termite Mounds and Associated Soils: A Systematic Review. In *Applied and Environmental Soil Science*. https://doi.org/10.1155/2020/8087273

[22] Fufa, F. (2016). Experimental Evaluation of Activated Termite Mound for Fluoride Adsorption. *IOSR Journal of Environmental Science, Toxicology and Food Technology*. https://doi.org/10.9790/2402-100802119132

[23] Getachew, K., & Mosisa, A. (2017). Laboratory Investigation of Locally Produced Clay Brick Quality and Suitability for Load Bearing Element in Jimma Area, Ethiopia Alemu Mosisa. *International Journal of Engineering Research & Technology*.

[24] Glaydson Simõesdos Reisab Bogdan Grigore Cazacliub Alexis Cothenetb Philippe Poullainc Michaela Wilhelmd Carlos Hoffmann Sampaioae Eder Claudio Limaah Weslei Ambrosf Jean and Michel Torrentig "Fabrication, microstructure, and properties of fired clay bricks using construction and demolition waste sludge as the main additive," J. Clean. Prod., 2020, doi: 10.1016/j.jclepro.2020.120733.

[25] Hartmann, K., Krishnan, R., Merz, R., Neplotnik, G., Prinz, F. B., Schultz, L., Terk, M., & Weiss, L. E. (2018). Robot-assisted shape deposition manufacturing. In *Proceedings - IEEE International Conference on Robotics and Automation* (Vol. 1). https://doi.org/10.1109/robot.1994.350900

[26] Impact Analysis Of Informal Brick Production On The Environment: Gaborone Dam Area, Botswana. (2013). *International Journal of Scientific & Technology Research*.

[27] James W. P. Campbell and William Pryce,"Brick: a world history," *Choice Rev. Online*, 2004, doi: 10.5860/choice.41-3863.

[28] Johari, I., Said, S., Hisham, B., Bakar, A., & Ahmad, Z. A. (2010). Effect of the change of firing temperature on microstructure and physical properties of clay bricks from beruas (Malaysia). *Science of Sintering*. https://doi.org/10.2298/SOS1002245J

[29] Karaman, S., Ersahin, S., & Gunal, H. (2006). Firing temperature and firing time influence on mechanical and physical properties of clay bricks. *Journal of Scientific and Industrial Research*.

[30] Matysek, P., Stryszewska, T., Kańka, S., & Witkowski, M. (2016). The influence of water saturation on mechanical properties of ceramic bricks – tests on 19th- century and contemporary bricks. *Materiales de Construcción*. https://doi.org/10.3989/mc.2016.07315

[31] Millogo, Y., Hajjaji, M., & Morel, J. C. (2011). Physical properties, microstructure and mineralogy of termite mound material considered as construction materials. *Applied Clay Science*. https://doi.org/10.1016/j.clay.2011.02.016

[32] Miyagawa, S., Koyama, Y., Kokubo, M., Matsushita, Y., Adachi, Y., Sivilay, S., Kawakubo, N., & Oba, S. (2011). Indigenous

utilization of termite mounds and their sustainability in a rice growing village of the central plain of Laos. *Journal of Ethnobiology and Ethnomedicine*. https://doi.org/10.1186/1746-4269-7-24
[33] Okunade, E. A. (2008). Engineering properties of locally manufactured burnt brick pavers for agrarian and rural Earth roads. *American Journal of Applied Sciences*. https://doi.org/10.3844/ajassp.2008.1348.1351
[34] Omobowale, M. O., Armstrong, P. R., Mijinyawa, Y., Igbeka, J. C., & Maghirang, E. B. (2016). Maize storage in termite mound clay, concrete, and steel silos in the humid tropics: Comparison and effect on bacterial and fungal counts. *Transactions of the ASABE*. https://doi.org/10.13031/trans.59.11437
[35] Toure, P. M., Sambou, V., Faye, M., & Thiam, A. (2017). Mechanical and thermal characterization of stabilized earth bricks. *Energy Procedia*. https://doi.org/10.1016/j.egypro.2017.11.271
[36] Eshetu Tsega, Alemu M. Legese and Fekadu F. Feyissa (2017). Effects of Firing Time and Temperature on Physical Properties of Fired Clay Bricks. *American Journal of Civil Engineering*. https://doi.org/10.11648/j.ajce.20170501.14
[37] United Nations. (2019). The sustainable development goals report 2019. In *United Nations publication issued by the Department of Economic and Social Affairs*.
[38] Woetzel, J., Ram, S., Mischke, J., Garemo, N., & Sankhe, S. (2014). A blueprint for addressing the global affordable housing challenge. In *McKinsey Global Institute*.