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INVESTIGATION OF COMPRESSIVE STRENGTH OF STRAW REINFORCED UNFIRED CLAY BRICKS FOR SUSTAINABLE BUILDING CONSTRUCTION

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Abstract

The mud is considered as one of the oldest construction materials in Iraq and is still used in the country regions for farmer's houses or animal shelters. In Iraq, there are different types of mud constructions, including adobe, unfired bricks and cob. The presented study has focused on unfired clay brick where the clay is the main material. To ensure that the clay is pure and clean, it was excavated from the depth of 2 m below the natural ground level. Different types of unfired clay bricks produced by adding different materials to the clay to improve its properties and especially large deformation due to shrinkage. The added materials are classified into three concepts, the first additives are the natural fibers (straw, sawdust, and rice husk) and they are used to improve the tensile strength of brick and reduce the cracking due to shrinkage. The second additives included added the fine and coarse sand as a stabilizer to reduce the volumetric changes. The third additives are adding cement to increase the adhesive and cohesion of the mud matrix. The measurements included compressive strength of brick, mortar, and masonry and the flexural strength of bricks alone. The behaviour of unfired masonry prisms was also compared to the traditionally fired clay brick prisms. The results indicate that higher compressive strength of bricks was got for the mix that included clay, coarse sand and straw. The maximum flexural strength of bricks was got for the mix that included clay and sawdust, while for unfired masonry prism the higher compressive strength was obtained with a mix that included clay, coarse sand and straw. Finally, a proposed formula to obtain the compressive strength of unfired brick masonry from the compressive strength of brick and mortar is presented.

Keywords:

Straw;
Unfired clay bricks;
Masonry construction;
Sawdust;
Sustainable building.

1 Introduction

Clay bricks are commonly used in the low rise buildings in Iraq, especially as houses. Clay bricks have been used as the earliest building material since ancient times and are still in use today, where nearly 30 % of the world's current population still lives in nearby structures [1]. This is due to its simplicity, low cost, good thermal insulation, sound insulation properties, simple workability, and long life of the building. Clay material can be easily reused or resumed on the ground without any negative impact on the environment [2-3]. The Middle East has a rich history of unfired brick making structures, where the unfired bricks are generally made by combining clay and straw. Although the construction of adobe brick is often associated with Mexican peoples, it can also be found all over the world, including the countries of the Middle East, West Asia, and Africa [4-6]. The consumption of land-based materials such as clay, oil shale and sand in fired brick production has led to resource depletion, environmental degradation, and energy consumption. Environmental degradation accompanies these mining activities with air pollution and remains after the mines have stopped, leaving scars on the landscape. Much of the research has been concerned by enhancing the quality and properties of unfired clay

bricks by mixing clay with various recycled waste such as dried sand, granite waste, port deposits, perlite, fly ash, clay waste, final boron waste, sewage sludge, glass waste from the wall and structural and other miscellaneous waste [7-8]. Other authors [9-13], used Lower Oxford Clay (*LOC*), two different types of lime *L1* and *L2*, *GGBS*, and Portland cement (*PC*) in production unfired clay bricks. They found that the performance of using lime-activated GGBS for both laboratory and industrial-scale unfired clay masonry brick production is better than that of the PC-activated *GGBS* bricks. Maheri, R.M. et al. [14], investigate the effects of crusher dust and clay contents on the strength and durability. They found that addition of 10 % crusher dust, corresponding to a reduction of approximately 5 % in clay content, improves the compressive strength by 26 %, and when the crusher dust content increases to 20 % and higher, resulting in a reduction in clay content beyond 40 %, a marked reduction in the strength of the plaster. Miqueleiz, L. et al. [15], investigated the using of alumina filler wastes and coal ash waste for unfired brick production. They concluded that the compressive strength resistance of the unfired bricks reduced as the clay replacement level increased. Also, the unfired brick test specimens made with the blended mixtures containing coal ash waste and lime tended to achieve higher strength values when compared with the coal ash waste and Portland cement blends. Al-Ajmi, F. et al. [16], studied the use of earth construction as energy-efficient housing. They showed that the increase of cement ratio, as an ingredient to certain limits, can lead to an optimum compressive strength of the brick. El-Mahllawy, M.S. et al. [17], evaluated the feasibility of stabilizing clay bricks with marble cutting waste (MCW). They demonstrate high potential usage of MCW based additives up to 15 % incorporating HL. Also, the used paint could be an effective treatment way for the use of stabilized bricks in a wet environment. Bhanulatha, N. et al. [18] pointed out the durability of brick influenced by low water absorption and high strength. Chan, C.M. [19], has been found that the cement is added for the baked and non-baked bricks that influenced on the strength of specimens positively. Ymxd, A. et al. [20], investigated the improvement of mud bricks stabilized with cement characteristics by rice husk ashes as additives. Using the rice husk leads to an increase in the compressive strength of bricks. Besides, the density is decreased with the rice husk is increased. Bahobail, M.A. [21], presented higher insulation for the mud-brick by adding some additives such as plant oil, ash, soap, and cow duns. Shariful, M.I. et al. [22], carried out adding the natural fibers such as jute for adobe block and using cement materials such as cement or gypsum had been produced improvement the earthquake resistance of adobe structures, i.e. more ductility of structures. Habib, A. et al. [23], investigated that the effect of stone dust with cement-based on the mechanical properties of the adobe, they had been got the best performance of these materials. Njau, H.G. and Park, E. [24], found that the compressive strength of unfired compressed clay brick increased when using natural fibers such as sisal and coir to make the brick units. Abdeldjebar, R. et al. [25], investigated that the earth blocks have better mechanical properties when the percentage of cement and lime is 5 % for each one. The impermeable clay material provides a sustainable and healthy alternative as a substitute for traditional building materials, such as burnt clay and concrete block, both non-load bearing and low-rise applications. Unprofitable clay materials provide potential health benefits for indoor built environments, primarily through passive regulation of relative humidity. Although traditional clay building materials, such as adobe bricks, clay blocks, and blocks, as well as newly developed compact floor blocks, have been used successfully in various projects, more and more interest has been shown in the use of unrefused clay bricks produced in large size brick manufacturers industries. Teslík, J. et al. [26], studied the effect of adding straw bales to the peripheral non-load-bearing wall. The straw wall was remodeled in combinations with various materials which included; without plasters, with a wet clay plaster from one side, with dry clay plaster from one side, and with a double-sided clay plaster. The study was implemented in actual straw houses. They found that, the use of straw bales on higher density and thickness enhance the acoustic parameters. Saraswathy, R. et al. [27], examined used the crushed glass as an additive replacement in the cement stabilized fly ash bricks. The percentage of the replacement instead of the fine aggregate were 10 % to 40 % by crushed glass. While the replacement of the sand was 100 % by crushed glass. The study detects that the increasing of crushed glass to the brick mix produced an increase in compressive strength of the bricks. Pericleanu, B.D. and Pericleanu, M. [28], carried out a specific study of the buildings in the southeast of Romania. The study focused on constituent materials and techniques of the traditional building. Which were; natural stone, clay, a smooth paste of earth mixed with chaff and/or chopped straw, the kneading earth mixed with straw and water, Cane/reed, wood, brick. They found that traditional materials are most suitable for the environment and climate. Also, less costly for people in rural areas. James, J. and Saraswathy, R. [29], studied the durability performance of various combinations of lime and fly ash stabilized local lateritic soil blocks subjected to conditions of alternate wetting and drying.

The examination of these compounds shows that the ability of producing stabilized blocks meeting the standard requirements of Indian codes in terms of compressive strength, water absorption, and efflorescence.

2 Experimental program

The objective of this study was to investigate the compressive strength of straw reinforced unfired clay bricks to produce different types of Unfired Clay Bricks (UCB) with regular size using different materials like soil, straw, sawdust, rice husk, cement, etc…

2.1 Materials

The materials used in this work were commercially available materials, which include soil, cement, sand, and water. The soil was used from the south Amarah City, from a depth of 2 m below natural ground level, which has been used by most local factories in the production of fired brick, was used in the investigation. The liquid limit of this soil was 37 %, and the plastic limit was 21 %. While, the Ordinary Portland cement type I was used in this investigation. And the retained sand on sieve No. 4 was added to the mix to increase the compressive strength of the unfired brick units as coarse sand. Also, fine sand which passes through sieve No. 4 and retained on sieve No. 19 was used to increase the compressive strength and homogeneity of the mixture as well.

On the other hand, the natural fibers used in this study included:

2.1.1 Straw

Straw is the main part of adobe or unfired bricks, traditionally used in the south of Iraq. Straw fibres length ranges between 2–6 cm, therefore they are considered as the main part in the presented study. Straw used in this work was collected from local farms in Maysan province as shown in Fig. 1. The major contribution of the straw admixture is the reduction in the dry density and increasing the tensile strength.

2.1.2 Sawdust

The coarse sawdust used in the presented experimental study had a maximum size of 12 mm. Sawdust was collected from the carpentry shops scattered throughout the region as shown in Fig. 2.

2.1.3 Rice husk

The rice husk shown in Fig. 3, also called rice hull, is the coating on a seed or grain of rice. It consists of hard materials, including silica and lignin. In the presented study, sawdust is passing from sieve No. 4.75 mm used as an alternative to straw in the mix.



Fig. 1: Straw.



Fig. 2: Sawdust.



Fig. 3: Rice husk.

2.2 Raw materials proportions

The mix proportions of different mixtures are listed in Tables 1 to 3. Table 1 shows the mix proportions for clay unfired bricks with different binder's fibers namely straw, sawdust, and husk rice. Table 2 shows the traditional mix proportions in the south of Iraq which consisted of clay and straw by modified with different percentages of sand, while Table 3 shows mixes included cement and sand.

Table 1: Mix proportions of clay only and different types of fibers.

Group	Clay [%]	Straw [%]	Sawdust [%]	Rice husk [%]	Water [%]
G1	100	-	-	-	27
G2	95	5	-	-	28
G3	95	-	5	-	28
G4	95	-	-	5	27

Table 2: Mix proportions of clay with sand.

Group	Soil [%]	Fine sand [%]	Coarse sand [%]	Straw [%]	Water [%]
G5	87.5	10	-	2.5	28
G6	82.5	15	-	2.5	28
G7	87.5	-	10	2.5	29
G8	82.5	-	15	2.5	27

Table 3: Mix proportions of clay with cement.

Group	Soil [%]	Cement [%]	Sand [%]	Straw [%]	W.C [%] for cement [%]	Water [%]
G9	90	10	-	-	50	26
G10	80	10	10	-	50	26
G11	77.5	10	10	2.5	50	26

3 Method of mixing

3.1 First method (Traditional method)

The procedure of the traditional work method used by local Iraqi builders for adobe construction with natural fibers begins with the preparation mixing area which includes soil fermentation as it is shown in Fig. 4. Where included:

- Weighing a quantity of the soil, using a water ratio of 25 % from the dry weight of soil and leaving for 24 hours,
- Then other materials were added according to the ratios in Table 1 until the homogenization matrix was obtained as shown in Fig. 5,
- Preparing the brick mold with dimensions 240 ×110 × 75 mm by cleaning it and grease from the inside as shown in Fig. 6,
- Fill the mold on three layers with compaction as shown in Fig. 7,
- After that, settle and lift the mold and then clean it and paint it and return the process, and
- After 24 of casting the bricks, samples are taken and placed in the oven at 65°C for drying purposes due to poor natural temperature in the winter season and also leaving samples to dry naturally as shown in Fig. 8.



Fig. 4: Soil fermentation



Fig. 5: Mixed mud with one of the materials.



Fig. 6: The molds used in the study.


Fig. 7: Fill the mold.


Fig. 8: Bricks after casting.

3.2 Second method (Mix included cement)

Because the cement granules are very fine and difficult to mix with the clay, also the cement hardening speed, another method to mix was used. The steps of this method are:

- Grinding dry soil using grinding machines to get fine soil as shown in Fig. 9,
- Weighing a quantity of grinding soil, cement, and sand according to the mixing percentages in Table 1,
- Water ratio of 25 % of dry soil plus 50 % of cement was gradually added to the mixture until obtaining a homogeneous mix as shown in Fig. 10,
- Fill the 240×110×75 mm brick molds in three layers with compaction, and
- Then left for solar curing as shown in Fig. 11.


Fig. 9: Soil grinding.


Fig. 10: Mixing of materials.


Fig. 11: Mud with mold.

4 Results and discussions

The effect of added materials on the compressive strength of unfired clay bricks was classified into three groups in addition to the control of the mix of clay only bricks. The first group included the natural fibers additives (straw, sawdust, and rice husk) to improve the tensile strength of brick and reduce the cracking due to shrinkage. The second group included the adding of fine and coarse sand as a stabilizer to reduce the volumetric changes. The third group included the adding of the cement to the clay to increase the adhesive and cohesion of the mud matrix.

4.1 Control mix: Clay only

When only soil is used to produce mud bricks, it is noticed that during the drying period, cracking on the surface and sides of the bricks occurs due to tensile stresses developed by shrinkage. The weak tensile strength of mud as weak brittle material and also the absence of an additive that helps to increase the cohesion of the matrix led to the early failure of these samples. The average cracked compressive strength is 1.1 MPa.

4.2 Effect of natural fibers

4.2.1 Clay with straw

Using straw as an admixture for the mud mix increased the performance of clay bricks compared with samples including clay only. The straw worked as links or natural fibers which led to increase of the resistance to shrinkage of the samples and to prevention the cracks due to tensile stresses, which was clear during the drying period where no cracks appeared in the resulting bricks, which happened in the control mix (clay only). The addition of straw also increased the compressive strength of the bricks as well as its compressibility. Despite the deformations, the cracks did not appear even after the brick depth pressed to about half of the centimeter, after increasing the

compression force, the sides of the block were crushed and there were no longitudinal or transverse cracks, as shown in Fig. 12. The average cracked compressive strength is 2.4 MPa. There is no clear failure load due to the brick still compressed and not failed. Therefore, the so-called cracked compressive strength is considered for comparison as a suitable indication of brick strength in service.

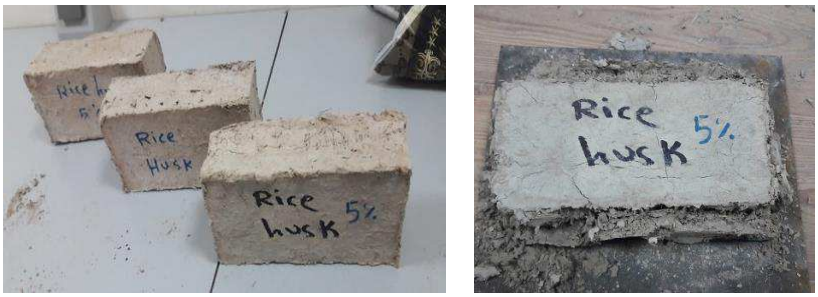


Brick before test Brick after test

Fig. 12: Unfired brick with clay and straw.

4.2.2 Clay with rice husk

As a result of the small size of rice husk compared to the straw, the compressibility was lower than that of bricks included straw. The rice husk added an extra compressive force in the bricks, preventing severe deformation of the brick (the thickness of the brick and the lack of significant descent) which obtained in the straw mix with the clay. However, rice husk has increased the stability of the brick and reduced its compressibility under loading and led to the appearance of cracks along the surface of the brick, as shown in Fig. 13. The average cracked compressive strength is 2.4 MPa and the compressive strength at failure is 2.64 MPa.



Brick before test Brick after test

Fig. 13: Unfired brick with clay and rice husk.

4.2.3 Clay with sawdust

The sawdust was the best additive for the bricks due to the sawdust was not as hollow as in the straw and it were longer than the rice husk. It was also more flexible than straw and lighter as well. These differences were evident during its use in the mixture. The mixing process was easier and the shrinkage was less than in the rest of the mixtures. The test showed that the compressive strength was higher than the previous mixtures and also the deformations were significantly lower. When the compressive strength increased, the failure appeared in the form of hair cracks on the surface of the brick as well as a collapse on its sides, as shown in Fig. 14. The average cracked compressive strength is 2.85 MPa and the compressive strength at failure is 3.9 MPa.



Brick before test Brick after test

Fig. 14: Unfired brick with clay and sawdust.

4.3 Comparison among of the effect of different materials

4.3.1 Effect of straw, rice husk, and sawdust fibers

Table 4 and Fig. 15, show that the comparison of the average test specimens of the three natural fibers on the compressive strength of unfired clay brick, in which straw fibers are considered as reference brick due to straw is the traditional fibers in unfired clay brick in the south of Iraq. The sawdust fibers yielded an average compressive strength about 62.5 % larger than straw fibers, also rice husk presented higher average compressive strength than straw fiber, by about 10 %.

Table 4: Results of effect of natural fibers.

Group	Description	Average compressive strength [MPa]		As % of clay - straw
		Cracked	Failure	
G1	Clay only	-	1.1	45.8
G2	Clay and straw	2.4	-	100
G3	Clay and sawdust	2.85	3.9	162.5
G4	Clay and rice husk	2.4	2.64	110

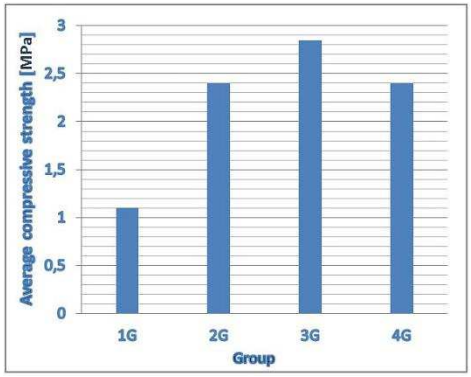


Fig. 15: The compressive strength of natural fiber.

4.3.2 Effect of sand

The traditional mud matrix that consisted of straw and clay is modified by adding sand. The addition of sand to the mud matrix serves as stabilizer to reduce the volumetric change of unfired bricks. Both fine and coarse sands are used in the mud matrix that consisted of both clay and straw.

4.3.2.1 Soil, fine sand and straw

The fine sand increased the compressive strength of the brick and the straw increased stiffness as well as the bond strength and reduced the cracks during the drying period. The increased compression strength of the brick is due to the sand resistance to the compressibility. The reducing of straw proportion in the mixture led to reduce of the brick deformation during the test. It was noticed that the increasing of sand proportion in the mixture to some extent improves the properties of the resulting bricks, such as its resistance to pressure, as well as its stiffness, as shown in Fig. 16. The average cracked compressive strength was 2.75 MPa and the average compressive strength at failure is obtained for clay only bricks is 5.2 MPa.

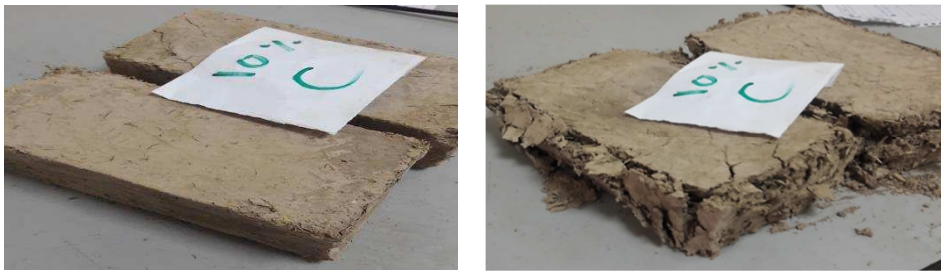


Brick before test Brick after test

Fig. 16: Unfired brick with clay and straw with 10 % fine sand.

4.3.2.2 Soil, coarse sand and straw

The addition of coarse sand instead of fine sand was increased the compressive strength of the unfired brick, as shown in Fig. 17. The average cracked compressive strength is 2.87 MPa and the average compressive strength at failure is obtained for clay only bricks is 4.1 MPa.



Brick before test Brick after test

Fig. 17: Unfired brick with clay and straw with 10 % coarse sand.

4.3.2.3 Comparison among fine and coarse sand

Table 5 and Fig. 18 show the average comparison among the fine and coarse sand on the compressive strength for unfired clay brick in included straw fibers as reference brick. The fine sand yielded the average compressive strength about 12.5 % larger than straw fibers, also coarse sand presented higher compressive strength than straw fiber by about 20 %.

Table 5: Result of effect of sand.

Group	Description	Average compressive strength [MPa]		As % of clay - straw
		Cracked	Failure	
G5	Clay +10 % Fine Sand + Straw	2.75	5.2	112.5
G6	Clay +15 % Fine Sand + Straw	2.75	5.5	114.6
G7	Clay +10 % Coarse sand + Straw	2.87	4.1	120
G8	Clay + 5 % Coarse Sand + Straw	2.42	4.22	100

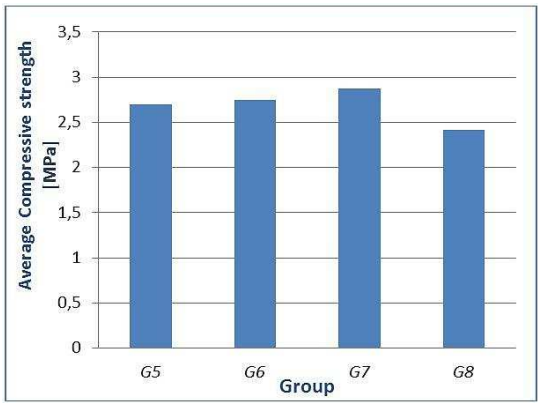


Fig. 18: Effect of sand on the compressive strength of unfired bricks.

4.3.3 Effect of cement

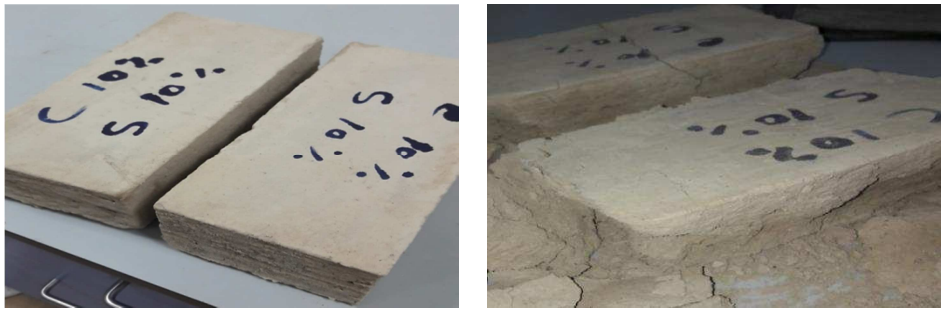
The effect of cement on unfired clay brick was investigated. Firstly, the cement is added to the clay only. Secondly, cement is added to clay and sand mix. And finally, cement is added to the mix that included clay, straw and sand.

4.3.3.1 Soil and cement

When cement is added to the soil alone, it makes the bricks fragile, brittle, and weak. The average cracked compressive strength is 0.9 MPa.

4.3.3.2 Soil, sand, and cement

When the sand was used with cement as a clay additive, it was not noticed a change in the properties of the brick, where it remained fragile and weak as shown in Fig. 19. The average cracked compressive strength is 1.1 MPa.



Brick before test Brick after test

Fig. 19: Unfired brick with clay, sand and cement.

4.3.3.3 Soil, sand, straw and cement

The addition of straw, along with the presence of sand and cement to the clay mix, increased the strength of the bonding between the mixing elements, and also increased the bearing of the bricks for compressing. The presence of straw has increased the stiffness of the brick and the lack of cracks as shown in Fig. 20. The average cracked compressive strength is 2.4 MPa, while the average compressive strength at failure is 2.9 MPa.



Brick before test Brick after test

Fig. 20: Unfired brick with clay, sand, cement and straw.

4.3.3.4 Comparison among mixes incorporating cement

Table 6 and Fig. 21 displayed a comparison between the sand and cement on the compressive strength of unfired clay brick, in which brick with straw fibers are considered as reference brick. The cement and sand with clay bricks yielded the average compressive strength, namely 37.9 % of straw and clay bricks with cement. Unfired bricks with cement only presented average compressive strength about 31 % of straw and clay bricks with cement.

Table 6: Result of effect of cement.

Group	Description	Average compressive strength [MPa]		Comparison per straw [%]
		Cracked	Failure	
G 9	Soil + Cement	0.9	-	31.0
G10	Soil + Cement + Sand	1.1	-	37.9
G11	Soil + Cement + Sand +Straw	2.4	2.9	100

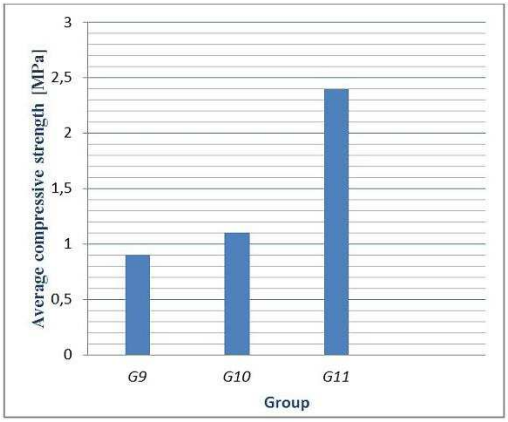


Fig. 21: The compressive strength effect of cement.

4.4 Masonry

Generally, the masonry units represent the units that consisted of bricks and mortars. The behavior of masonry units is different from the behavior of bricks or mortar alone. The compressive strength of masonry is less than the compressive strength of bricks and mortar due to weak bonding between them which failed before reaching the strength of bricks or mortars.

In the presented study, the prisms of masonry are investigated, which consisted of three unfired bricks and mortars from similar materials used to manufacture the unfired bricks. Also, the presented study incorporated the testing of traditionally fired clay bricks masonry to compare the behavior of fired bricks with unfired bricks masonry.

4.4.1 Unfired bricks used for masonry prisms

Six types of unfired bricks are considered for masonry assemblage: clay and straw, clay and sawdust, clay with 10 % fine sand and straw, clay with 10 % coarse sand and straw, clay with cement and sand, and clay with cement and sand in addition to straw. The compressive strength of each type of unfired bricks was listed in Table 7.

Table 7: Compressive strength for unfired bricks used for masonry prisms.

Group	Description	Compressive strength [MPa]
G2	Clay + Straw	2.4
G3	Clay + Sawdust	2.85
G5	Clay + 10 % Fine sand + Straw	2.7
G7	Clay + 10 % Coarse sand + Straw	2.87
G10	Clay + Cement + Sand	1.1
G11	Clay + Cement + Sand + Straw	2.4

4.4.2 Mud mortar

The mortar used for unfired masonry brick was produced by mixing clay and 5 % straw with water content was equal to 40 % from the dry weight of clay. The mortar compressive strength was 1.5 MPa which was used by testing a cube with dimensions of 10×10×10 cm as shown in Fig. 22.



Cube during test Cube after test

Fig. 22: Cube mud mortar.

4.4.3 Unfired masonry

The unfired masonry behavior is studied by using prisms consisted of three bricks and mortar. Six mixes were considered: clay and straw, clay and sawdust, clay with 10 % fine sand and straw, clay with 10 % coarse sand and straw, clay with cement and sand, and clay with cement and sand in addition to straw. The compressive strength of each mix was listed in Table 8. Figs. 23 to 27 show the masonry brick with the types of mixes before and after the compressive test.

Table 8: The compressive strength for unfired masonry.

Group	Description	Compressive strength [MPa]
G2	Clay + Straw	1.6
G3	Clay + Sawdust	1.65
G5	Clay + 10 % Fine sand + Straw	1.3
G7	Clay + 10 % Coarse sand + Straw	1.9
G10	Clay + Cement + Sand	1.5
G11	Clay + Cement + Sand + Straw	1.2



Fig. 23: Masonry brick (Clay + Straw).



Fig. 24: Masonry brick (Clay + Sawdust).

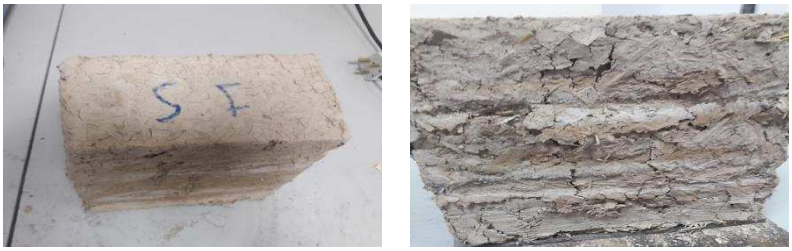


Fig. 25: Masonry brick (Clay + Fine sand + Straw).



Fig. 26: Masonry brick (Clay + Coarse sand + Straw).



Fig. 27: Masonry brick (Clay + Cement + Sand + Straw).

4.4.4 Traditional fired brick masonry

The compressive strength of fired clay brick was 10 MPa and the compressive strength of mortar with a mixing ratio of 1:3 was 20 MPa. The masonry compressive strength was 4.5 MPa. The compressive strength of masonry fired brick was lower than the compressive strength of fired brick and mortar, i.e. less than masonry fired brick by 45 % and less than mortar by 22.5 %. The cause of decreasing of compressive strength of masonry was because of the difference in thermal expansion coefficient between the fired clay brick and the mortar.

4.4.5 Unfired brick masonry

The highest decrease in the resistance of masonry bricks was equal to 52 % comparing it with the compressive strength of unfired clay brick and mortar, which recorded the highest decrease of about 30 %. This decrease of the compression strength was low comparing it with the decreasing of the compression strength in masonry fired brick. The close results of the compressive strength between the unfired masonry brick and the unfired bricks were because the bricks and mortar were made of the same material and have the same Poisson ratio.

4.4.5.1 Proposed formula for compressive strength of unfired clay bricks

Due to difficulty and time consuming of measuring the compressive strength of masonry units, which is needed for numerical analysis or design calculations, the codes of practice presented a different formula to obtain the compressive strength of masonry units from the compressive strength of mortar and bricks which could be obtained easily.

The three compressive strengths of mortar, bricks and masonry can be conveniently related as done in Eurocode [30]:

$$f'_M = K\, f_b^{\alpha}\, f_m^{\beta}\ , \tag{1}$$

where: f'_M is compressive prism strength of masonry in MPa, K is a constant depending upon brick properties and brick-mortar joint configuration, f_b is compressive strength of bricks in MPa, f_m is compressive strength of mortar in MPa, α and β are the constants representing contribution of bricks and mortar compressive strengths on f'_M.

According to the results of bricks compressive strength and masonry compressive strength, the following equations are proposed to estimate the masonry prism compressive strength from the compressive strengths of unfired bricks and mortar obtained experimentally.

1) Soil with straw: $f'_M = 0.685\, f_b^{0.75}\, f_m^{0.55}$, (2)

2) Soil with sawdust: $f'_M = 0.66\, f_b^{0.65}\, f_m^{0.5}$, (3)

3) Soil, fine sand and straw: $f'_M = 0.69\, f_b^{0.5}\, f_m^{0.35}$, (4)

4) Soil, coarse sand and straw: $f'_M = 0.761\, f_b^{0.68}\, f_m^{0.49}$, (5)

5) Clay, cement and sand: $f'_M = 0.96\, f_b^{0.87}\, f_m^{0.74}$, (6)

6) Clay, cement, sand and straw: $f'_M = 0.57\, f_b^{0.66}\, f_m^{0.42}$, (7)

5 Conclusions

From the results achieved from this study on the mechanical properties or investigation of compressive strength of straw reinforced unfired clay bricks for sustainable building construction, the following conclusions were obtained:

1) The use of clay alone is not appropriate as a masonry unit due to its a brittle and fast-cracking material. Additional materials should be added to the mix to increase its strength and flexibility of the brick. The maximum compressive strength for this mixture was 1.1 MPa.

2) Adding straw increased the strength and plasticity of the brick. Increased plasticity of the bricks by adding straw was an important thing. Despite the great deformations that have to happen to it, the cracks were not shown on its surface as well as not get collapse. It can benefit from this property in areas where earthquakes get. The maximum compressive strength for this mixture was 2.4 MPa.

3) Adding rice husk somewhat increased the strength of the bricks but its small size did not give a high bonding strength to the bricks. The maximum compressive strength for this mixture was 2.4 MPa.

4) Sawdust is considered one of the best additive materials that was used in this research. It is thick, long, and not hollow as in straw increased brick compressive and bonding strength when adding it to the mix. Also, it decreases the cracks that occurred during the drying period. The maximum compressive strength for this mixture was 2.85 MPa.

5) Using the sand in the production of bricks was considered a good addition. Whether the sand is fine or coarse, it increased its strength and decreased the deformation that occurred to it during the test. The maximum compressive strength for this mixture was 2.87 MPa.

6) Using the cement in the production of bricks was considered as a bad addition because the cement made the mixture brittle, weak, and fast-cracking material. The maximum compressive strength for this mixture was 0.9 MPa.

7) The maximum compressive strength of masonry unfired brick was 1.9 MPa which was made of clay, coarse sand, and straw. The compressive strength of masonry bricks was close to the compressive strength of unfired bricks and mortar. This was because the bricks and mortar were made of the same material and have the same Poisson ratio.

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