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Recycling of Industrial and Agricultural Wastes in Compressed Stabilized Earth Blocks for Sustainable Development

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ABSTRACT

This research aims at investigating the possibility of producing compressed stabilized earth blocks (CSEBs) using locally industrial and agricultural wastes for sustainable development. Two types of industrial wastes in Egypt (i.e., ceramic waste (Cr) and blast furnace slag (S)) were used as additional stabilizers to cement (C), while agricultural waste (i.e., flax fiber (f)) was used as reinforcement. The experimental work was all done in the laboratory of Cairo University, faculty of engineering. It was divided into three phases; the first phase was done to select the optimum conditions for the production of compressed earth cubes, the second was done to select the optimum mixes for each stabilizer, while the third included the investigation of the characteristics of CSEBs produced from the optimum mixes. The results indicate that ceramic powder and/or slag could be used as stabilizers with cement and their optimum percentage to use is 10 % by weight of soil and binders and using a blend of slag and ceramic powder is better than using any of them alone. CSEBs could be reinforced flax fibers and its optimum percentage is 1 % by volume of the mix.

Keywords: wastes; stabilizer; fibers; optimum-mix

1 INTRODUCTION

Earth as a construction material has been used for thousands of years by civilizations all over the world. Many different techniques have been developed such as rammed earth, wattle and daub, cop, or adobe. The methods used vary according to local climate and environment as well as local traditions and customs. As a modest estimate, it is thought that as many as 30% of the world's population lives in homes constructed with earth. These techniques are still spread all over the world, especially in developing countries [1]. The wattle is made by weaving thin branches between upright stakes. It could be used as loose panels, slotted between timbers framing to make infill panels, or it may be made in place to form the whole of a wall. The mixture consisting of binder, aggregates and reinforcement used in earth building is called daub while binders (i.e., clay, lime, chalk dust and limestone dust) hold the mix together; the aggregates (i.e., sand, crushed chalk and crushed stone) give the mix its bulk and dimensional stability and reinforcement is provided by straw, hair, hay or other fibrous materials. Cob technique depends mainly on mixing sand or small stones with clay and an organized material like straw. This technique can be used as load bearing walls up to two stories, but its minimum thickness is 41.0 cm with width to height ratio not exceeding 1:10. It is suitable for soil containing 30% or more clay [2].

Most of the Great Wall of China was built using rammed earth technique. In northern India area, thick sloping walls were found and building about seven stories of rammed earth was built in northern Europe [3, 4]. In yemen, Shibam which was known as "Manhattan of the desert" was considered to be the capital of Hadramawt Kingdom. This village was built using adobe blocks. Its fame comes from that some of its buildings are towers (up to 11 floors which approximately equals 30 meters). So, it was called the oldest skyscraper city in the world. Also in Saudi Arabia about 400 houses with small rooms were found in the Diriyah village where the adobe blocks was used for walls, and stone for columns and foundations.

In Egypt, there are two villages in Qurna, Luxor. The first one is known as the old Qurna, which was located about one hundred meter to the east of the Temple of Seti I, and the second was known as the new Qurna, built between 1946 and 1952 by Hassan Fathy. It is located in midway between the Colossi of Memnon and El-Gezira on the Nile on the main road to the Theban Necropolis to house the residents of the old Qurna. In the new Qurna, Hassan Fathy used earth as the main raw material in the design of planned village about of 55 Fadden. The mosque, market and a few houses still remain in new Qurna [5, 6]. While soil is a renewable material, the damaged walls were rebuilt using their damaged parts by separating the raw material and remaking blocks from them.

Earth construction is very cost effective, energy efficient (excellent thermal properties and low energy input required for production) and environmentally friendly process. In addition of the availability of soil, earth structures are completely recyclable [7, 8].

Due to the last increase in pollution and decrease in energy sources, earth buildings return into both developed and undeveloped countries. Methods derived from the traditional techniques are being developed to improve the quality of earth construction. Such methods include the stabilization and compaction of earth such as stabilized rammed earth and machine pressed compressed stabilized earth blocks [1]. Compressed stabilized earth blocks are widely used around the world in the last 30 years not only in the third world countries but also developed countries like USA, French, Canada and Australia. Recently, traditional earth construction technology has undergone considerable developments that enhance earth's durability and quality as a construction material for low-cost buildings [9]. The purpose of stabilization is to permanently improve soil, either by increasing its strength or by reducing the variations in cohesion and size caused by changes in moisture content, by reducing the erosive effect of water on the surface and enhancing soil resistance to the erosive effects of the local weather conditions, including variations in temperature, humidity and rainwater. The use and adoption of the right stabilization method can improve the compressive strength of a soil by as much as 400 to 500% and increase its resistance to erosion and mechanical damage. It should be mentioned that no single method of stabilization precludes the use of another. On the contrary, the most durable earth blocks result from a rational use of several stabilization methods. Soil may be stabilized by chemical, mechanical or physical methods. One method or more affects the properties of the soil [1, 7]. The most common stabilizers are cement and lime. However, others like chemicals, resins or natural products could be used as well. The selection of a stabilizer and its percentage depends upon number of factors including the quality of the soil and the requirements of the project, the property of the stabilized blocks which needs improvement (e.g. dry strength, wet strength, water erosion, abrasion resistance, surface protection), the level of required improvement, the cost and availability of the stabilizer. Cement is preferable for sandy soil to quickly achieve a higher strength. Lime is preferred for very clayey soil, but it will take a longer time to harden and give strong blocks [10].

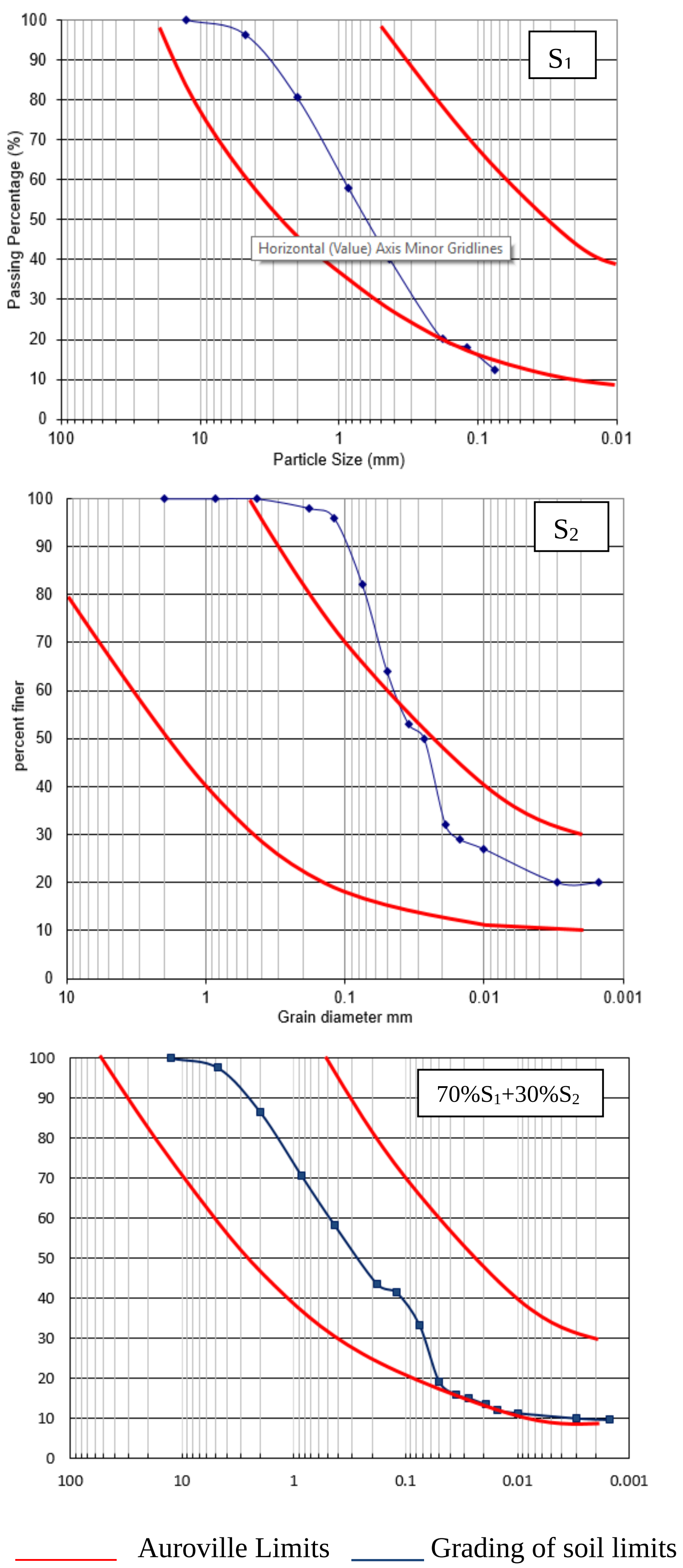
Many types of fibers are used in reinforcing CSEBs. Fibers are generally classified as natural and man-made fibers. Man-made fibers are varying from soft polymers to hard metals. Glass fiber, plastic fiber, carbon fiber, and boron are some examples of man-made fibers used as a reinforcement of CSEBs Natural fibers have high mechanical properties with low cost of manufacturing. There are different kinds of natural fibers used as a reinforcement with cement such as sisal, wood, bamboo, and flax fibers. Straw (wheat, rye, barley, etc) and plant fibers (sisal, hemp, elephant grass, coir and bagasse) are good fibers for soil with high clay content. Reinforcement of CSEB by fibers enhances the flexural strength and crack resistance compared with CSEB without fibers, however, excessive use of fibers should be avoided due to possibility of increased water absorption [11].

Recently compressed stabilized earth blocks are widely used. In Saudi Arabia, Al Medy mosque in Riyadh, was built using compressed earth blocks stabilized with 8.3% cement. In Burkina Faso, Koudougou's central market was built using compressed earth blocks with traditional Nubian techniques of arch and vault construction. Also, in Egypt, Housing and Building National Research Center used CSEBs in a building consisted of two floors stabilized by 5% cement. Auram 3000 press was used in production by 400-600 press/day.

2 Materials and Methods

2.1 Methods

The used soil was combined of 70%S1+30%S2. Soil S1 was silty sand soil brought from al Haram area while soil S2 was clay brought from Alex. The grading curve for the used soil is shown in figure (1). The liquid limit, plastic limit, and plasticity index for the combined soil were 28%, 11%, 17% respectively. The used cement (C) was ordinary Portland cement CEM I 42.5N produced by National Cement Company. The used industrial wastes were ceramic powder (Cr) and slag (S). The first was obtained from local factory in Egypt, while the second was obtained from Iron and Steel Company, Egypt. They were ground to pass from sieve # 200. The specific gravity for soil, cement, ceramic powder, and slag was determined as 2.64, 3.15, 2.3, and 2.46 respectively. Table (1) shows the chemical composition of powders (soil, C, Cr, and S) determined by X-ray fluorescence (XRF). Flax fibers (f) which are considered a local agricultural waste were used as reinforcement in CSEBs to improve their tensile strength. Before use, they were left to dry in air for 2 days and cut to 10 mm length in case of being used in 50x50x50 mm cube, and 20 mm length in case of being used in 250x120x90 mm block. The density of flax fibers is 1.33 gm/cm3. Figure (2) shows the used materials.



(a) Grading of Soil S1 compared with Auroville

(b) Grading of Soil S2 compared with Auroville

(c) Grading of Soil mix of 70%S1+30%S2 compared with Auroville

Fig. 1: Grading curve

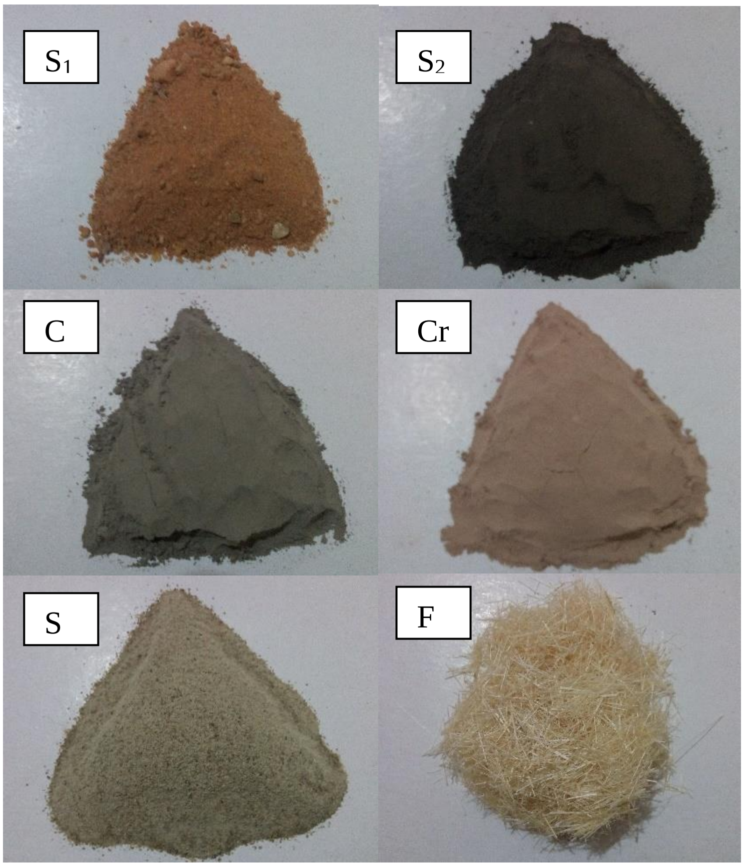


Fig 2: Materials

Table (1): Chemical composition of the used materials

%Component	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	MnO	K_2O	TiO_2	P_2O_5	Cl-	**L.O.I**
Soil	58.7	8.91	3.99	5.65	2.5	4	2.11	-	0.86	0.55	0.1	2.37	9.98
Ceramic (Cr)	65.34	19.1	5.09	2.65	0.71	<0.01	3.13	-	1.59	1.27	0.33	<0.01	0.33
Slag (S)	37.3	13.1	0.76	29.8	5.5	2.32	1.33	4	1.14	-	-	-	0.02

2.2 Methods

The experimental work was divided into three phases; the first phase was done to select the optimum conditions for the production of compressed earth cubes, the second one was done to select the optimum mixes for each stabilizer, while the third included the investigation of the characteristics of CSEBs produced from the optimum mixes.

Preliminary Investigation was done to select the optimum conditions for the production of compressed earth cubes. The investigated conditions were soil type, compaction method and curing method. The prepared cubes were tested in compression at 7 days. For soil type, two groups of compressed earth cubes stabilized with 8% cement were prepared. The first one included soil (S1), while the second one consisted of 70%S1+30%S2. It was found that combined soil provides higher compressive strength than soil (S1). For compaction method, three groups of compressed earth cubes from the same mix (soil 70%S1+30%S2, 8%C and water) were prepared. The first group was compacted manually in two layers as follows: each layer was compacted by 25 blows using standard rod. After the second layer, the compaction using a steel block of 48x48x48mm size was used for additional compaction of the upper layer. The second group was compacted using the compression machine only at pressure of 100 kg/cm². The third group was compacted manually and mechanically as follows: firstly, it was compacted by 25 blows using standard rod manually, secondly, it was compacted mechanically at 100 kg/cm² pressure using compression machine. It was found that the application of manual and mechanical compaction together gives the best results, while the worst result was obtained by using manual compaction only. However, for practical reasons, manual compaction was selected to be used in phase I. For curing method, two curing methods were investigated. The first one includes covering the cubes after 24 hour from casting with plastic sheet, while the second one includes covering with jute. It was found that covering with plastic sheet is better than covering with jute. So, it is recommended to cover the cubes with thick plastic sheet. Figure (3) shows both curing methods.

Fig. 3: Curing

In phase II, the effect of the content of each industrial and agricultural waste on the compressive strength of compressed stabilized earth cubes. Five groups of mixes were designed (i.e., groups A to E) shown in table (2). After sieving soil (S1) and (S2) on # 9mm sieve, they were mixed at 70%:30% and spread on the ground. The mixed powders were added to combined soil and dry mixing was carried out until obtaining homogenous color of the mix. In case of using fibers, it was added to the dry mix and intermixed until getting good distribution of fibers. Mixing water was added to the mix and wet mixing was carried out manually until obtaining well distribution of water. Drop test was carried out to check the consistency of the mix. Fresh mix was immediately cast in oiled cubes into two layers. Each layer was compacted by 25 blows using standard rod. After the second layer, the compaction of a steel block of 48x48x48mm size was used for additional compaction of the upper layer. The cubes were covered with thick plastic sheet to be protected from losing mixing water and they were cured for 28 days. Figure (4) shows the production of cubes in phase II.

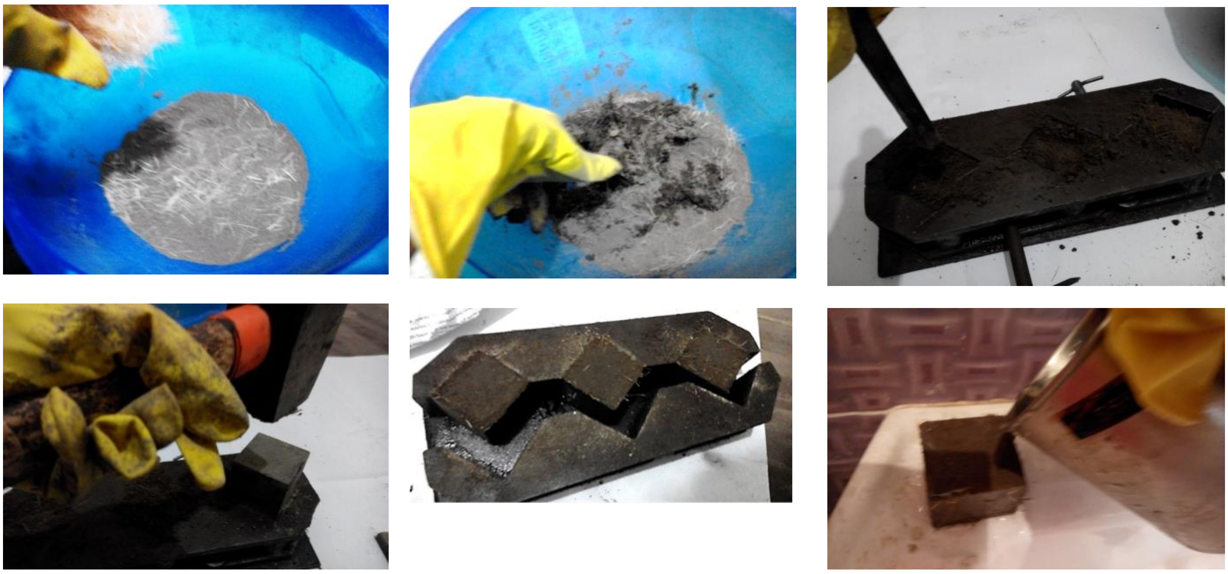


Fig. 4: Production in Phase II

Table (2): Mixes of phase II (kg/m³)

Group	Mix No.	Identification of the mix	Soil		Stabilizers			Fiber	Water
			S_1	S_2	OPC	Cr	S	F	
A	1	soil only	1566	671	0	0	0	0	240
B	2	soil+6% OPC	1472	631	134	0	0	0	267
	3	soil+8% OPC	1441	617	179	0	0	0	267
	4	soil+10%OPC	1410	604	224	0	0	0	293
	5	soil+12%OPC	1378	591	268	0	0	0	293
C	6	soil+8% OPC+6%Cr	1347	577	179	134	0	0	267
	7	soil+8% OPC+8%Cr	1316	564	179	179	0	0	280
	8	soil+8% OPC+10%Cr	1284	550	179	223	0	0	293
	9	soil+8% OPC+12%Cr	1253	537	179	268	0	0	307
D	10	soil+8% OPC+6%S	1347	577	179	0	134	0	267
	11	soil+8% OPC+8%S	1316	564	179	0	179	0	280
	12	soil+8% OPC+10%S	1284	550	179	0	223	0	293
	13	soil+8% OPC+12%S	1253	537	179	0	268	0	307
E	14	soil+8% OPC+0.5%F	1441	617	179	0	0	6.7	267
	15	soil+8% OPC+1%F	1441	617	179	0	0	13.3	258
	16	soil+8% OPC+1.5%F	1441	617	179	0	0	20	249
	17	soil+8% OPC+2%F	1441	617	179	0	0	26.6	240
F	18	soil+8%OPC+10%Cr+10%S	1128	483	179	224	224	0	320
	19	soil+8% OPC+10%Cr+1%F	1284	634	179	224	0	13.3	302
	20	soil+8% OPC+10%S+1%F	1284	634	179	0	224	13.3	302
	21	soil+8%OPC+10%Cr+10%S+1%F	1128	544	179	224	224	13.3	311

In phase III, seven optimum mixes were selected from phase II to be used. The effect of using stabilizers and reinforcement on dry compressive strength, wet compressive strength, water absorption, will be investigated in this phase. Table (3) shows the identification of mixes and their proportions. All contents were calculated by weight of soil and binders except sisal fibers content was calculated as a percentage of mix volume. The stabilizer was spread on the soil. Mixing was done by moving the pile two times so as to get a homogenous dry mix. Mixing water was added to the mix and wet mixing was carried manually until obtaining well distribution of water. The wet mix was filled into the press molds and leveled with a ripper and then compacted using Auram 3000 press. The blocks were removed immediately after compaction and compaction was checked with a pocket penetrometer. The blocks were stacked in long piles in the open air and covered with plastic sheet. Afterward, the blocks were sprinkled with water once per day for 28 days for curing. Figure (5) shows the production of blocks in phase III.

Fig. 5: Production in Phase III

Table (3): Mixes of phase III (kg/m³)

Group/mix No	Identification of the mix	Soil		Stabilizers			Fiber	Water
		S_1	S_2	C	Cr	S	F	
B-2	soil+8%OPC	1441	617	179	0	0	0	254
C-7	soil+8% OPC+10%Cr	1284	550	179	224	0	0	261
D-11	soil+8% OPC+10%S	1284	550	179	0	224	0	261
F-17	soil+8%OPC+10%Cr+10%S	1128	483	179	224	224		268
F-18	soil+8%OPC+10%Cr+1%F	1284	550	179	224	0		254
F-19	soil+8% OPC+10%S+1%F	1284	550	179	0	224		254
F-20	soil+8%OPC+10%Cr+10%S+1%F	1128	483	179	224	224		264

The Standard proctor test was used to determine the required amount of mixing water for mixes in group A (phase I). The obtained values were used for the remaining mixes in addition to the drop test. The test was conducted according to ASTM D698-07 [12(2017)]. Drop and Penetration tests were carried out on the fresh mix to check the amount of water required for each mix during casting according to the code of practice – Auroville Earth Institute, code of practice [13,(2017)]. Figure (6-a) shows drop test while figure (6-b) shows penetration test.

Compression test was conducted on soil cubes and compressed stabilized earth blocks. The cubes (50×50×50 mm) were tested after 7, 28 and 90 days from casting to obtain their compressive strength. Compressed stabilized earth blocks were tested in compression in both dry and wet conditions at ages 28 and 90 days. The specimens were tested according to the code of practice – Auroville Earth Institute, code of practice [13, (2017)]. In the dry state, the specimens were oven-dried at a temperature of 90 ºC for 24 hours until their weight became constant. They were left to cool before testing. For specimens to be tested under wet conditions, they were immersed in water at a temperature of 27 °C for 24 hours. Then the specimens were wiped with a wet cloth before testing to remove any water on their surface. During testing, plywood sheets of 3 mm thick were laid on the cube faces in contact with loading plates. Water absorption at saturation test was conducted on compressed stabilized earth blocks after 28 days from manufacture according to the code of practice - Auroville Earth Institute, code of practice [13]. The specimens were oven-dried at a temperature of 105 ºC for 24 hours, and left to cool and their weight was checked immediately after removing from the oven. Then they were submerged in water at ~27 ºC for 24 hours. They were allowed to drain for not more than 1 minute and re-weighed to get the weight of the wet specimen.

Fig. 6-a: Drop Test

Fig. 6-b: Penetration Test

Fig. 6: Tests for fresh mixes

3 Results and Discussion

Figure (7) shows the effect of using cement as a stabilizer on the compressive strength of earth cubes. In general, the compressive strength increased with curing age. The compressive strength increased from 7 to 28 days by 42%, 43.7%, 36.5%, and 25.2% for mixes containing 6, 8, 10 and 12% cement content, respectively. It also increased from 28 to 90 days by 34%, 20.4%, 16.3% and 17%, for mixes containing 6, 8, 10 and 12% cement content, respectively, regardless of curing. Similar findings were reported by Abdel Aziz et. Al [14,(2010)] that the compressive strength of stabilized soil cubes increases with increasing curing time and the rate of increase is high from 7 to 28 days thereafter the strength slightly increases.

In general, the compressive strength enhances by using of cement as a stabilizer. Using 6%, 8%, 10% and 12% cement as a stabilizer increased the compressive strength at 7 days by 258%, 372%, 685%, and 907%, respectively compared with the control mix (i.e., without stabilizer), while it increased by 115%, 186.4%, 352%, and 432.6%, respectively at 28 days, and the increase in the compressive strength at 90 days was 150%, 200%, 357.6%, and 442%, respectively. The enhanced compressive strength by using cement is due to the hydration of cement when water is added and the formation of a cementitious gel. This gel is made up of calcium silicate hydrates; calcium aluminate hydrates and hydrated lime. The first two compounds form the main bulk of the cementitious gel, whereas the lime is deposited as a separate crystalline solid phase. The cementation process results in deposition between soil particles of an insoluble binder capable of embedding soil particles in a matrix of cementitious gel [7,(2001)].

Ceramic powder was used as an additional stabilizer with cement. Figure (7) shows the effect of using 6%, 8%, 10% and 12 % of Cr as an addition to 8% cement on the compressive strength of stabilized earth cubes. It can be seen that the compressive strength increased with curing age. The improvement in the compressive strength by increasing the curing age from 7 to 28 days was 22.7%, 28%, 29.7% and 32.3% for 6%, 8%, 10% and 12% Cr content, respectively. It also increased from 28 to 90 days by 17%, 15%, 23% and 14%, for mixes containing 6%, 8%, 10% and 12% Cr content, respectively, regardless of no curing. The compressive strength of stabilized earth cubes improved by adding ceramic powder to 8% cement. At 7 days, the compressive strength increased by 30.2% ,36.8%, 55.8% and 37.2%, respectively by adding 6%, 8%, 10% and 12 % of Cr to 8% cement, while at 28 days, the compressive strength increased by 11.1%, 21.7%, 40% and 26.3%, respectively. At 90 days, the compressive strength increased by 7.6%, 16.3%, 43.5% and 19.7%, respectively by adding 6%, 8%, 10% and 12 % of Cr to 8% cement. The improvement in compressive strength is due to the filler effect of ceramic powder as well as its pozzolanic reaction. Samadi [15], found that the amount of calcium silicate hydrated (C-S-H) increases in cement mortar by increasing ceramic powder content due to its pozzolanic reaction between silicon oxide (SiO2) in ceramic powder and calcium hydroxide Ca(OH)2 from hydration process.

Slag was used as an additional stabilizer with cement. Figure (7) shows the effect of using 6%, 8%, 10% and 12 % slag as an addition to 8% cement content on the compressive strength of stabilized earth cubes. It can be found that there is an enhancement in the compressive strength with curing age. The improvement in the compressive strength by increasing the curing age from 7 to 28 days was 73.6%, 91.4%, 80.4% and 85.2% for 6%, 8%, 10% and 12% slag, respectively. Similarly, it increased from 28 to 90 days by 21.5%, 13.5%, 22.4% and 20.1% for 6%, 8%, 10% and 12% slag, respectively, regardless of no curing. The compressive strength of stabilized earth cubes increased by adding slag to 8% cement. At 7 days, the compressive strength increased by 6%, 15.4%, 43.6% and 30%, respectively, by adding 6%, 8%, 10% and 12 % slag to 8% cement, while at 28 days the compressive strength increased by 27.8%, 53.6%, 80.2% and 67.7%, respectively. At 90 days the compressive strength increased by 29%, 44.8%, 83% and 67%, respectively, by adding 6%, 8%, 10% and 12 % of ceramic powder to 8% cement. The improvement in compressive strength by using slag is due to the filler and pozzolanic effect of slag. When slag is used, it reacts with Portland cement through the pozzolanic reaction to form a finely dispersed gel (calcium silicate hydrates), which fills the larger pores. The result is a hardened cement paste, which contains far fewer calcium hydroxide crystals and therefore has fewer large capillary pores. The additional C-S-H densifies the concrete matrix thereby enhancing strength [16]. Furthermore, according to Lee and Wang [17(2014)-18(2015)], as the amount of slag increases, the late-age compressive strength of concrete mixtures increases in indicating the slow reaction between slag and cement.

Figure (7) shows the effect of using 0.5%, 1%, 1.5% and 2 % fiber on the compressive strength of stabilized earth cubes. It can be found compressive strength increased with curing age. The improvement in the compressive strength by increasing the curing age from 7 to 28 days was 37.7%, 35.8%, 37.7% and 33.1% for 0.5%, 1%, 1.5% and 2% flax fiber, respectively. It also increased from 28 to 90 days by 62.6%, 69%, 44.5%, and 58.8% for 0.5%, 1%, 1.5%, and 2% fiber, respectively.

At 7 and 28 days, the compressive strength of stabilized earth cubes decreased by adding flax fibers to 8% cement. At 7 days, the compressive strength decreased by 17.9%, 19.7%, 30.2% and 38.6%, respectively, by adding 0.5%, 1%, 1.5% and 2% fiber to 8% cement, while at 28 days the compressive strength decreased by 17.1%, 17.9%, 28.6% and 39.3%, respectively. At 90 days the compressive strength increased by 3.9% and 8.9% by adding 0.5% and 1% fiber, respectively, while it was decreased by 19.7% and 25% by adding 1.5% and 2% fiber, respectively compared with the control mix with 8% cement only. Similar findings were reported by Taallah [18, (2008)], that using in palm fibers compressed earth blocks and decreases their compressive strength, but compared with 8% cement only, 0.05% fibers percentage increases the dry compressive strength by 6% compared to the non-filled blocks.

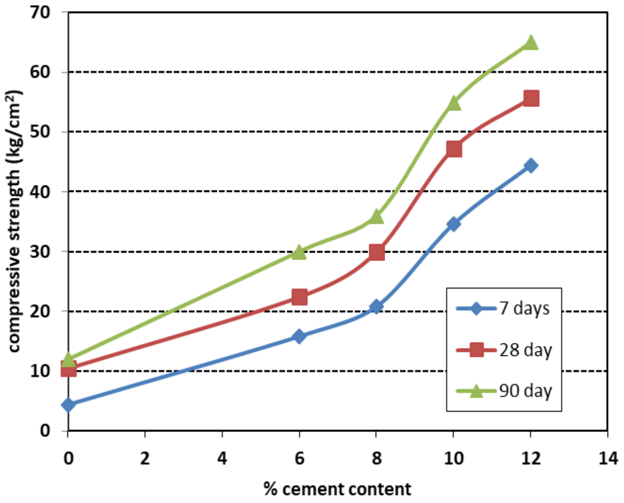


Fig. 7a: Cement content versus compressive strength at different curing age

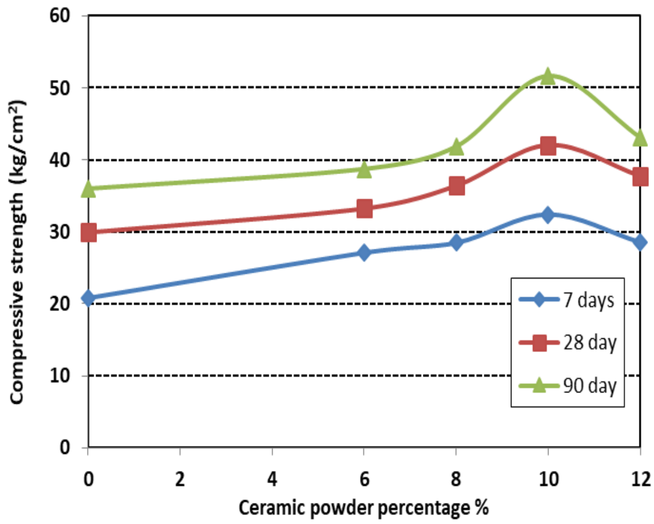


Fig. 7b: Compressive strength versus ceramic powder percentage as an addition to8% cement at different curing age

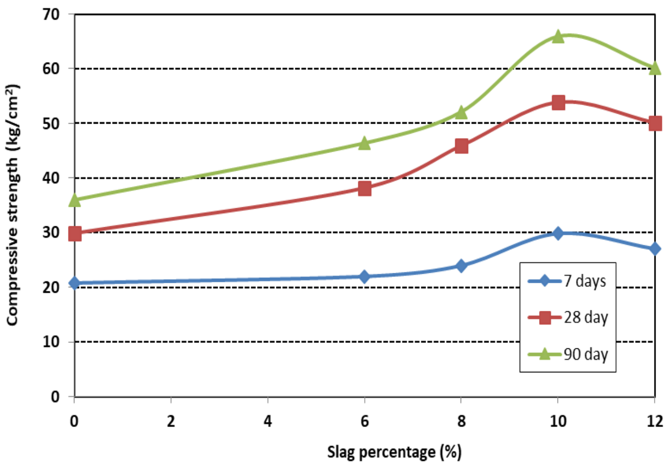


Fig. 7c: Compressive strength versus slag percentage as an addition to 8% cement at different curing age

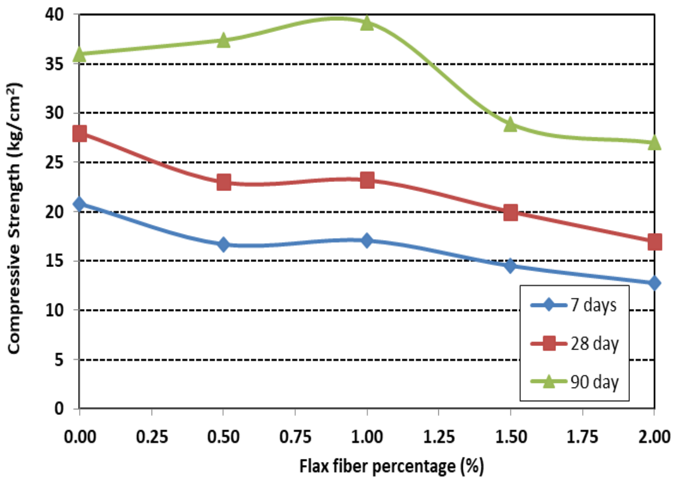


Fig. 7d: compressive strength versus fiber percentage as an addition to 8% cement at different curing age

Fig. 7: Compressive strength at different curing age

Four mixes which included the optimum percentage of each stabilizer and reinforcement of stabilized earth cubes were tested for compressive strength. The improvement in the compressive strength by increasing the curing age from 7 to 28 days was 120% for mix contenting 8% C+ 10% Cr +10% S, 32% for mix contents 8% C+ 10% Cr +1% F, 84% for mix contenting 8% C+ 10% S +1% F, and 122.7% for mix contenting 8% C+ 10% Cr +10% S+1% F. It also increased from 28 to 90 days by 23.7% for mix containing 8% C+ 10% Cr +10% S, 210% for mix contenting %8% C+ 10% Cr +1% F, 183.2% for mix contents 8% C+ 10% S +1% F, and 107.8% for mix contenting 8% C+ 10% Cr +10% S+1% F. The significant increase in the compressive strength of stabilized earth cubes from 28 to 90 days compared with that from 7 to 28 days by using flax fibers may be due to that agricultural fibers lose their stiffness by exposure to water from wet curing as the cubes were cured by sprinkling water up to 28 days, while after 28 days the cubes were not exposed to curing. The compressive strength of stabilized earth cubes from mix (8% C+ 10% Cr +10% S) was significantly higher than that of 8% cement, regardless of cubes age. It increased by 70%, 160.2% and 167% at 7, 28, and 90 days, respectively. This indicates the positive effect of using slag and ceramic powder simultaneously on the strength of compressed earth cubes. On the other hand, using flax fibers in combination with ceramic/slag or both of them increases compressive strength of stabilized earth cubes compared with control mix with cement only at all ages. The compressive strength of mix containing 8% C+ 10% Cr +1% F, was higher than that of the control mix with 8% cement by 46%, 34% and 245% at 7, 28, and 90 days, respectively, while the compressive strength of mix containing 8% C+ 10% S +1% F, was higher than that made from the control mix with 8% cement by 34%, 71.5% and 303% at 7, 28, and 90 days, respectively. The compressive strength of mix containing 8% C+ 10%Cr+10% S +1% F, was higher than that of the control mix with 8% cement by 60%, 147.8% and 327% at 7, 28, and 90 days, respectively.

Figure (8) shows the effect of stabilizer type on the compressive strength of earth cubes, it is clear from the figure that the compressive strength of earth cubes stabilized with 12% cement is higher than that of 8% cement mix, regardless of age. The compressive strength increased by 113.5%, 86% and 80.6% at 7, 28 and 90 days, respectively. The compressive strength of earth cubes stabilized with 8% C+ 10% Cr is higher than that of 8% cement mix and lower than that of 12% cement mix, regardless of age. The compressive strength was higher than that made from the 8% cement mix by 55.8%, 40.6%, and 43.5% at 7, 28 and 90 days, respectively, while it was lower than 12% cement mix by 37%, 38.8% and 25.9% at 7, 28 and 90 days, respectively. On the other hand, the compressive strength of earth cubes stabilized with 8% C+ 10% S is higher than that of 8% cement mix and lower than that of 12% cement mix at 7 days, with comparable values at 28 and 90 days. The compressive strength was higher than 8% cement mix by 43.6%, 80.2%, and 83.1% at 7, 28 and 90 days, respectively, while it was lower than 12% cement mix by 48.7% and 3.2% at 7, 28 respectively and was closely equals to 12%C mix at the age of 90 days. The compressive strength of earth cubes stabilized with 8%C+10%Cr+10%S is significantly higher than that of 8% cement mix and higher than that of 12% cement mix (at age 28 and 90 days). The compressive strength was higher than that made from the 8%

cement mix by 70%, 160.2%, and 167.4% at 7, 28 and 90 days, respectively. It was lower than that of 12% cement mix by 25.6% at age 7 days, while it was higher than 12% cement mix by 28.5% and 32.5% at 28 and 90 days, respectively.

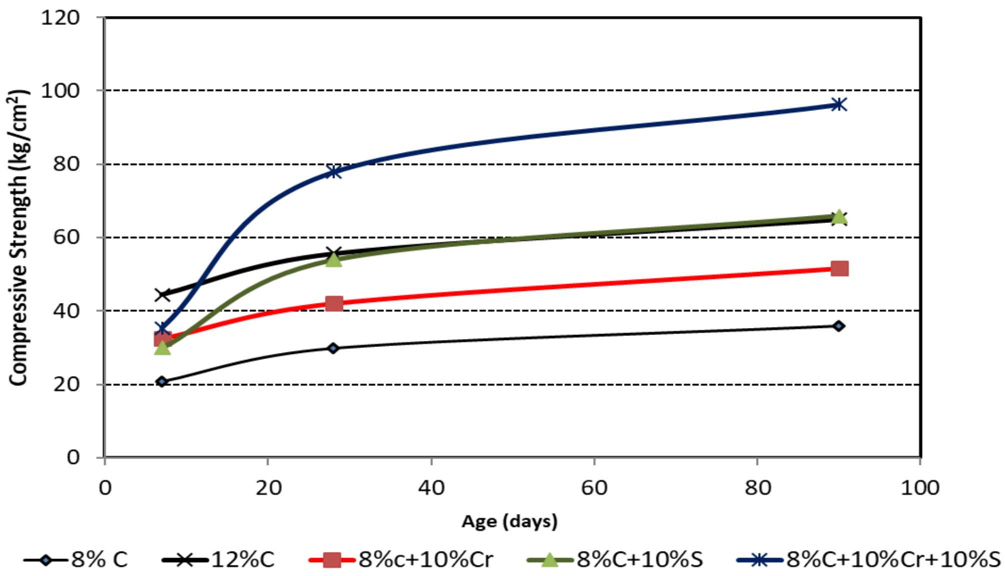


Fig. 8: Compressive strength versus curing age for optimum mixes containing different types of stabilizers

Figure (9) shows a comparison between the compressive strength of stabilized earth cubes with/without flax fibers. It is clear from the figure that using flax fibers decreases the compressive strength of earth cubes at 7 and 28 days compared with similar cubes without flax fibers due to the curing of earth cubes at this period by sprinkling water, which reduces the stiffness of flax fibers and consequently reduces the compressive strength of the cubes. At 90 days, the compressive strength of earth cubes containing flax fibers is significantly higher than that of similar cubes without flax fibers. This is due to stopping the curing by sprinkling water, thus, flax fibers recover their stiffness. The compressive strength of earth cubes containing 8%C+10%Cr+1%F was lower than that of cubes containing 8%C+10%Cr by 6.3% and 4.8% at 7 and 28 days, respectively, and higher than it by 140.5% at 90 days. The compressive strength of earth cubes containing 8%C+10%S+1%F was lower than that of cubes containing 8%C+10%S by 6.7% and 4.7% at 7 and 28 days, respectively, and higher than it by 120.3% at 90 days. The compressive strength of earth cubes containing 8%C+10%Cr+10%S+1%F was lower than that of cubes containing 8%C+10%Cr +10%S by 5.9% and 7.8% at 7 and 28 days, respectively, and higher than it by 60% at 90 days.

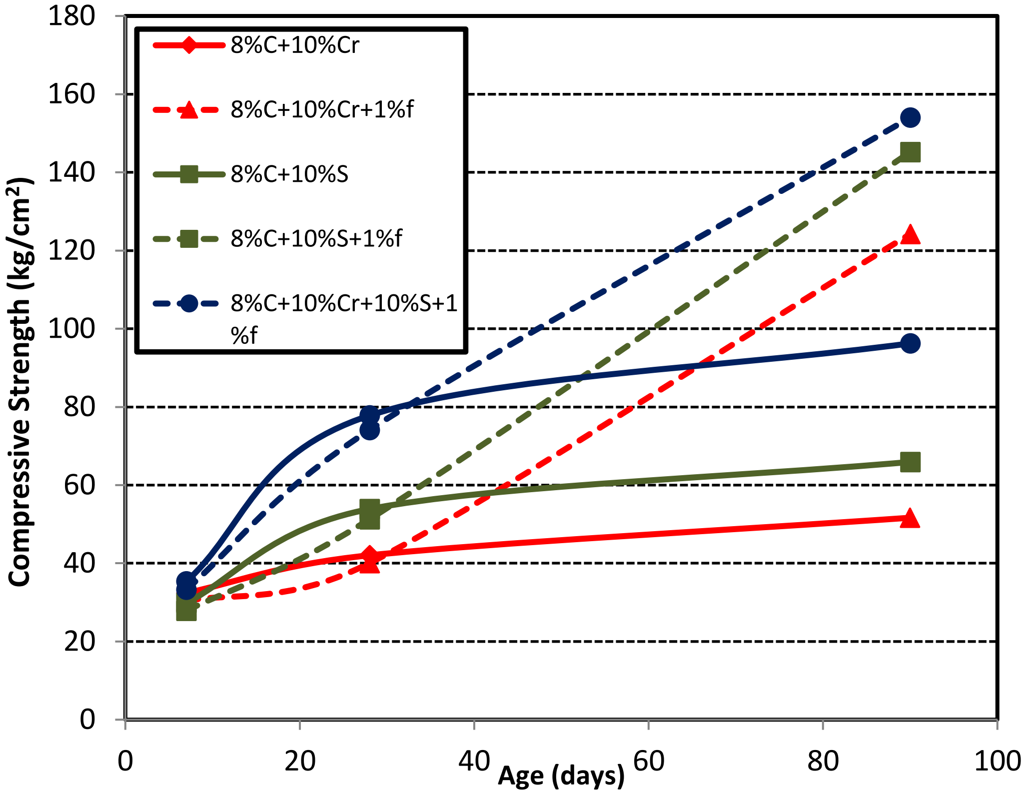


Fig. 9: Comparison between compressive strength of mixes with/without fibers

Figure (10) shows the percentage of water absorption at saturation for each mix and its class according to Auroville Earth Institute, code of practice [13] which classifies CSEBs to classes A, B and C as shown in table (7). It can be found that the addition of ceramic powder/slag or both of them to 8% cement decreases the water absorption of CSEBs compared with those made with 8% cement only. The percentage of water absorption of CSEBs containing 8%C+10%Cr, 8%C+10%S and 8%C+10%Cr+10%S was lower than that of CSEBs containing 8% cement only by 11.60%, 22.3% and 25.9%, respectively. On the other hand, using flax fibers increases the water absorption of CSEBs compared with those without flax fibers. The percentage of water absorption of CSEBs containing 8%C+10%Cr+1%F, 8%C+10%S+1%F and 8%C+10%Cr+10%S+1%F was higher than that of CSEBs made with the control mix (8% cement) only by 26.8%, 11.2% and 5.4%, respectively, while it was higher than that of CSEBs containing 8%C+10%Cr, 8%C+10%S and 8%C+10%Cr+10%S by 43.4%, 43.1% and 42.2%, respectively. Similar finding were reported by Ugwuishiwh [19](2013), found said that blocks with palm kernel fibers have a slightly higher water permeability and absorption than fibreless blocks [19] (2013). In general, using of 10% slag is more efficient in reducing water absorption of CSEBs than the use of 10% ceramic powder. The percentage of water absorption of CSEBs containing 8%C+10%S was lower than that of CSEBs containing 8%C+10%Cr by 12.1%, while the percentage of water absorption of CSEBs containing 8%C+10%S+1%F was lower than that of 8%C+10%Cr+1%F by 12.3%.While, using a blend of slag and ceramic powder is better than using any of them alone. The percentage of water absorption of CSEBs containing 8%C+10%Cr+10%S was lower than that of CSEBs containing 8%C+10%Cr and 8%C+10%S by 16.2% and 4.6%, respectively, while the percentage of water absorption of CSEBs containing 8%C+10%Cr+10%S+1%F was lower than that of 8%C+10%Cr+1%F and 8%C+10%S+1%F by 16.9% and 5.2%, respectively. Compressed earth blocks stabilized with 8%C+10%Cr+10%S showed the lowest percentage of water absorption while CSEBs stabilized with 8%C+10%Cr+1%F showed the highest one.

Table (7): Limits of code of practice-Auroville Earth Institute [13]

Class	A	B	C
Percentage of water absorption	8-10%	10-12%	12-15%
The required 28 days dry compressive strength (kg/cm²)	50-70	40-60	30-50
The required 28 days wet compressive strength (kg/cm²)	30-40	20-30	15-20

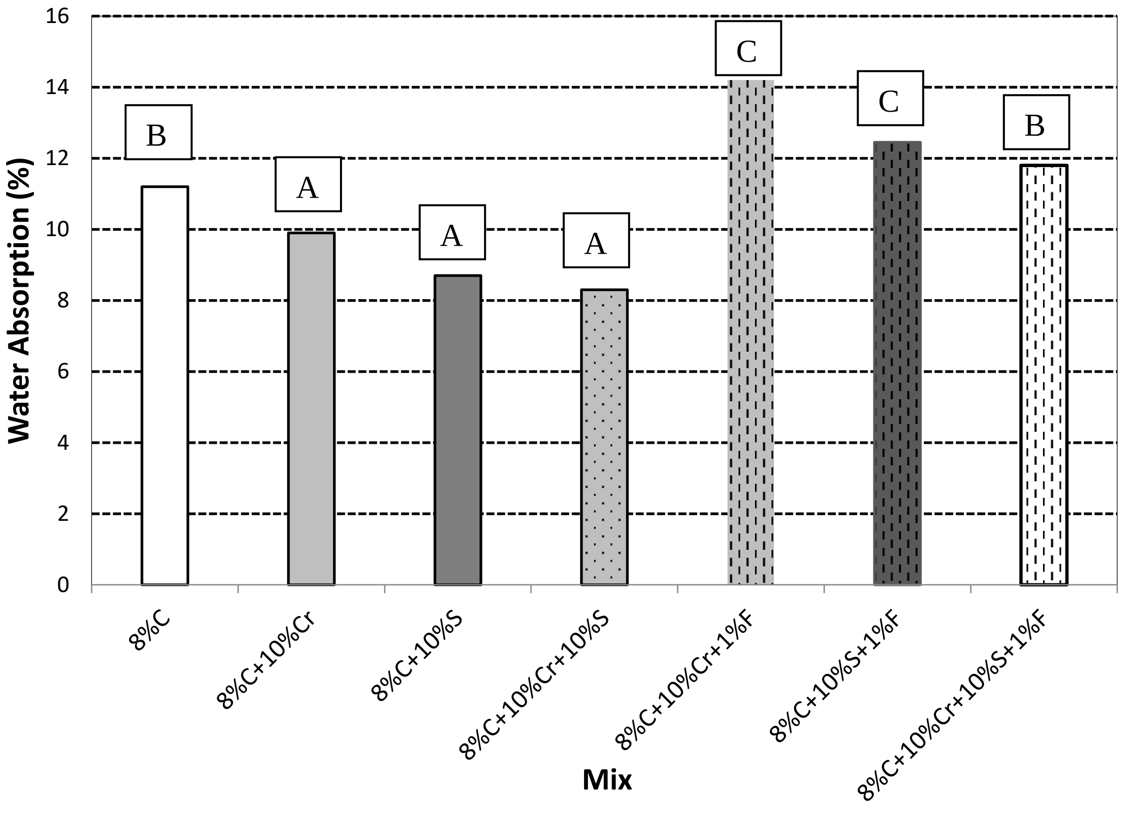


Fig.10: Percentage of water absorption at saturation of CSEBs

Figure (11) shows the dry compressive strength of compressed stabilized earth blocks. It can be observed from the figure that the compressive strength increased with curing age. The dry compressive strength increased from 28 to 90 days by 19.8%, 33%, 34%, and 18.6%, for mixes containing 8%C, 8%C+10%Cr, 8%C+10%S and 8%C+10%Cr+10%S respectively. It also increased by 47%, 66.3%, and 45.6%, for mixes containing 8%C+10%Cr+1%F, 8%C+10%S+1%F, and 8%C+10%Cr+10%S+1%F, respectively. The addition of ceramic powder/slag or both of them to 8% cement increases the dry compressive strength of CSEBs compared with those made with 8% cement only. The 28 days dry compressive strength of CSEBs containing 8%C+10%Cr, 8%C+10%S and 8%C+10%Cr+10%S was higher than that of CSEBs containing 8% cement only by 18.2%, 29.5% and 65.9%, respectively, while the 90 days dry compressive strength of CSEBs containing 8%C+10%Cr, 8%C+10%S and 8%C+10%Cr+10%S was higher than that of CSEBs containing 8% cement only by 31.2%, 45% and 64.3%, respectively. On the other hand, using flax fibers decreases the 28 days dry compressive strength of CSEBs compared with those without flax fibers, while it gives comparable values at 90 days. The 28 days dry compressive strength of CSEBs containing 8%C+10%Cr+1%F, 8%C+10%S+1%F and 8%C+10%Cr+10%S+1%F was higher than that of CSEBs made with the control mix (8% cement) only by 10.2%, 15.9% and 50%, respectively, and it was lower than that of CSEBs containing 8%C+10%Cr, 8%C+10%S and 8%C+10%Cr+10%S by 6.7%, 10.5% and 9.6%, respectively. The 90 days dry compressive strength of CSEBs containing 8%C+10%Cr+1%F, 8%C+10%S+1%F and 8%C+10%Cr+10%S+1%F was higher than that of CSEBs control mix (8% cement) only by 35.3%, 60.9% and 82.4%, respectively, while it was higher than that of CSEBs containing 8%C+10%Cr, 8%C+10%S and 8%C+10%Cr+10%S by 3.1%, 11% and 11%, respectively. In general, using of 10% slag is more efficient in increasing the dry compressive strength of CSEBs compared with the use of 10% ceramic powder. The 28 days dry compressive strength of CSEBs containing 8%C+10%S was higher than that of CSEBs containing 8%C+10%Cr by 9.6%, while the 28 days dry compressive strength of CSEBs containing 8%C+10%S+1%F was higher than that of 8%C+10%Cr+1%F by 5.2%. The 90 days dry compressive strength of CSEBs containing 8%C+10%S was higher than that of CSEBs containing 8%C+10%Cr by 10.5%, while the 90 days dry compressive strength of CSEBs containing 8%C+10%S+1%F was higher than that of 8%C+10%Cr+1%F by 18.9%. While using a blend of slag and ceramic powder is better than using any of them alone. The 28 days dry compressive strength of CSEBs containing 8%C+10%Cr+10%S was higher than that of CSEBs containing 8%C+10%Cr and 8%C+10%S by 40.4% and 28.1%, respectively, while the 28 days dry compressive strength of CSEBs containing 8%C+10%Cr+10%S+1%F was higher than that of 8%C+10%Cr+1%F and 8%C+10%S+1%F by 36.2% and 29.4%, respectively. The 90 days dry compressive strength of CSEBs containing 8%C+10%Cr+10%S was higher than that of CSEBs containing 8%C+10%Cr and 8%C+10%S by 25.3% and 13.4%, respectively, while the 90 days dry compressive strength of CSEBs containing 8%C+10%Cr+10%S+1%F was higher than that of 8%C+10%Cr+1%F and 8%C+10%S+1%F by 34.8% and 13.3%, respectively. Compressed earth blocks stabilized with 8%C+10%Cr+10%S showed the highest value of 28 days dry compressive strength while CSEBs stabilized with 8%C+10%Cr+10%S+1%F showed the highest value at 90 days. One the other hand, CSEBs stabilized with 8%C only showed the lowest value of 28 and 90 days dry compressive strength. According to code of practice-Auroville Earth Institute [13] and Egyptian code of earth building (under publication), each class of CSEBs classified based on its water absorption should satisfy the required range of 28 days dry compressive strength as shown in table (7). It is clear that all mixes satisfied the requirement of code of practice-Auroville Earth Institute code of practice [13] with respect to dry compressive strength.

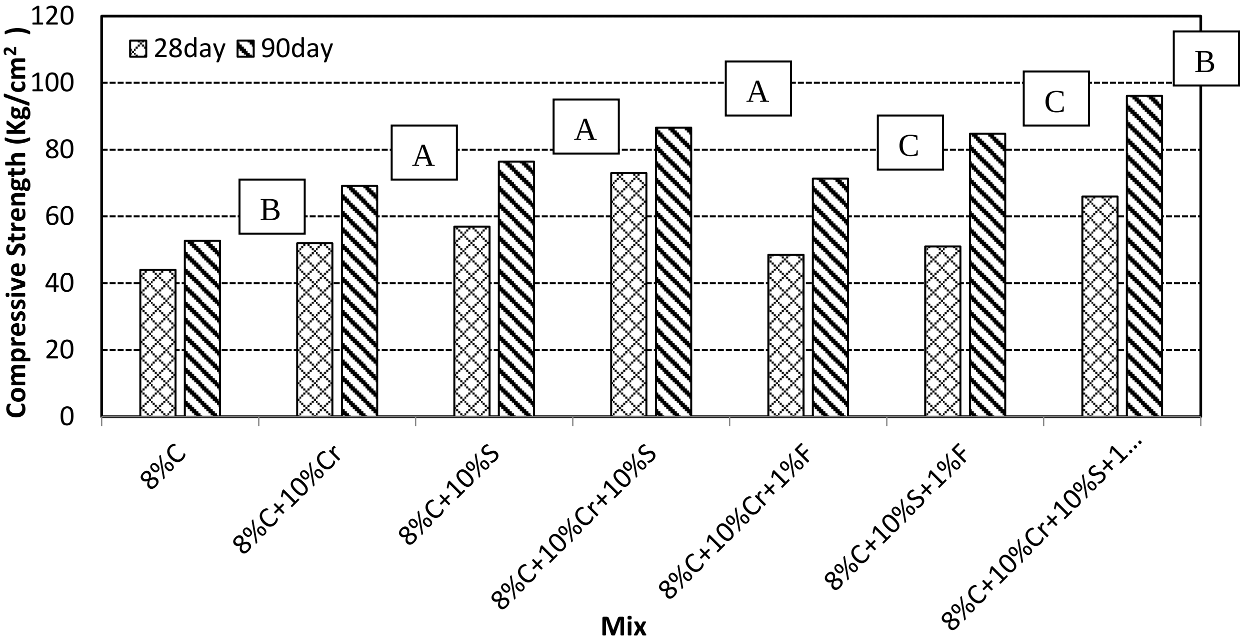


Fig. 11: Dry compressive strength of CSEBs

Figure (12) shows the wet compressive strength of CSEBs at the age of 28 days. It can be found that the addition of ceramic powder/slag or both of them to 8% cement increases the wet compressive strength of CSEBs compared with those made with 8% cement only. The 28 days wet compressive strength of CSEBs containing 8%C+10%Cr, 8%C+10%S and 8%C+10%Cr+10%S was higher than that of CSEBs containing 8% cement only by 32.4%, 47.1% and 94.1%, respectively. On the other hand, using flax fibers decreases the wet compressive strength of CSEBs compared with those without flax fibers. The 28 days wet compressive strength of CSEBs containing 8%C+10%Cr+1%F, 8%C+10%S+1%F and 8%C+10%Cr+10%S+1%F was lower than that of CSEBs containing 8%C+10%Cr, 8%C+10%S and 8%C+10%Cr+10%S by 34.4%, 30% and 31.8%, respectively. In general, using of 10% slag is more efficient in increasing wet compressive strength of CSEBs compared with the use of 10% ceramic powder. The 28 days wet compressive strength of CSEBs containing 8%C+10%S was higher than that of CSEBs containing 8%C+10%Cr by 11.1%, while the 28 days wet compressive strength of CSEBs containing 8%C+10%S+1%F was higher than that of 8%C+10%Cr+1%F by 18.6%. In general, using a blend of slag and ceramic powder is better than using any of them alone. The 28 days wet compressive strength of CSEBs containing 8%C+10%Cr+10%S was higher than that of CSEBs containing 8%C+10%Cr and 8%C+10%S by 46.7% and 32%, respectively, while the 28 days wet compressive strength of CSEBs containing 8%C+10%Cr+10%S+1%F was higher than that of 8%C+10%Cr+1%F and 8%C+10%S+1%F by 52.5% and 28.6%, respectively. According to code of practice-Auroville Earth Institute [13] and Egyptian code of earth building, each class of CSEBs classified based on its water absorption should satisfy the required range of 28 days wet compressive strength as shown in table (7). It is clear that all mixes satisfied the requirement of code of practice-Auroville Earth Institute [13] with respect to wet compressive strength.

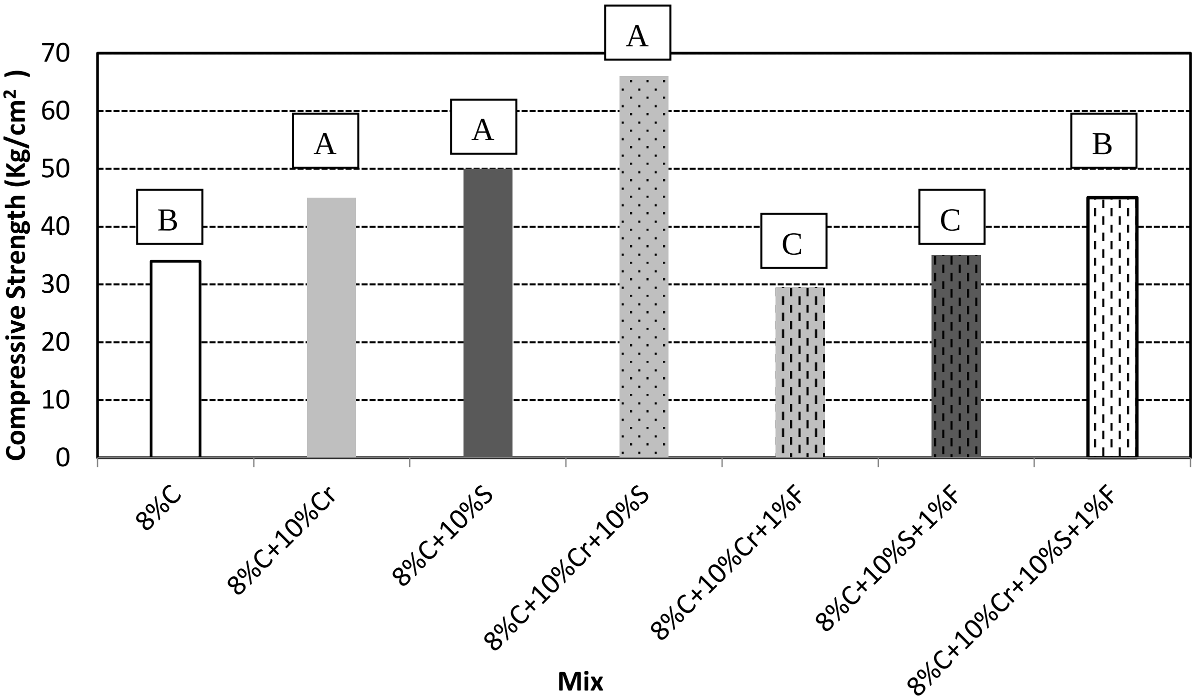


Fig. 12: Wet compressive strength of CSEBs

4 Conclusions

This research investigated the possibility of producing compressed stabilized earth blocks (CSEBs) using ceramic waste and blast furnace slag as additional stabilizers to cement, and flax fiber as reinforcement. The main conclusions can be summarized as follows:

- Well graded soil is preferable to be used in the production of CSEBs.
- The compressive strength of earth cubes increases with cement content.
- The compressive strength of CSEBs increased with curing age.
- Ceramic powder and/or slag could be used as stabilizers with cement and their optimum percentage to use is 10 % by weight of soil and binders and using a blend of slag and ceramic powder is better than using any of them alone. It increases the compressive strength of CSEBs compared with those made with 8% cement only.
- CSEBs could be reinforced flax fibers and its optimum percentage is 1 % by volume of the mix.
- It is preferred to cure CSEBs by sprinkling water and covering it with plastic sheet.
- The addition of ceramic powder/slag or both of them to 8% cement decreases the percentage water absorption at saturation of CSEBs compared with those made with 8% cement only.
- Using flax fibers increases the percentage of water absorption at saturation of CSEBs compared with those without flax fibers.
- The compressive strength of earth cubes stabilized with 8% C+ 10% Cr is higher than that of 8% cement mix and lower than that of 12% cement mix. While, for the compressive strength of earth cubes stabilized with 8% C+ 10% S is higher than that of 8% cement mix, lower than that of 12% cement mix at 7 days, but showed comparable values at 28 and 90 days.
- The compressive strength of earth cubes stabilized with 8%C+10%Cr+10%S is higher than that of 12% cement mix (at age 28 and 90 days).
- Using flax fibers decreases the compressive strength of earth cubes at 7 and 28 days compared with similar cubes without flax fibers. However, at 90 days, the compressive strength of earth cubes containing flax fibers is significantly higher than that of similar cubes without flax fibers.
- Compressed stabilized earth blocks stabilized with 8%C+10%Cr+10%S showed the highest value of compressive strength while CSEBs stabilized with 8%C only showed the lowest value.

REFERENCES

[1] Houben, H., Guillaud, H., 1994, Earth Construction: A Comprehensive Guide. Intermediate Technology Publications, London,

[2] TERIPress, Sustainable Building – Design Manual Vol 1, ISBN 978-81-7993-053-3, Retrieved 2014-04-26

[3] Walker, P. Keable, R. Martin, J. and Maniatidis, V. (2005). Rammed earth: Design and Construction Guidelines. BRE Bookshop, Zimbabwe.

[4] Fleming, John; Honour, Hugh; Pevsner, Nikolaus (1966). The Penguin dictionary of architecture. drawings by David Etherton. London, England ; New York, N.Y., USA: Penguin Books. ISBN 978-0-14-051241-0. OCLC 638962596.

[5] HASAN FATHY, ARCHITECTURE FOR THE POOR, published 1969, p.106-112

[6] A sightseeing to Qurna Village, visited in March 2017

[7] E.A.Adam, "Compressed Stabilised Earth Block Manufacture in Sudan", Printed by Graphoprint for the United Nations Educational, Scientific and Cultural Organization, France, Paris, July 2001.

[8] Rigassi, V.,1995, Compressed Earth Blocks Volume I: Manual of Production. CRATerre, Aus der Arbeit von GATE, Friedr. Vieweg&Sohn, Braunschweig/Wiesbaden,

[9] Yaser Khaled Abdulrahman Al-Sakkaf, 2009 , "Durability properties of stabilized earth blocks", Doctor of Philosophy, UniversitiSains Malaysia,

[10]"Earthen Architecture for Sustainable Habitat- Auroville's Case Study", http://www.earth-auroville.com.

[11] Saul SitatiNamango, 2006, "Development of Cost-Effective Earthen Building Material for Housing Wall Construction:Investigations into the Properties of Compressed Earth Blocks Stabilized with Sisal Vegetable Fibers, Cassava Powder and Cement Compositions", A Doctoral thesis, Faculty of Environmental Science and Process Engineering, Brandenburg Technical University, Cottbus, Kenya.

[12] ASTM International- Standards https://www.astm.org

[13] Production and use of compressed stabilized earth blocks, code of practice ,2011, Auroville Earth Institute, http://www.earth-auroville.com.

[14] E.M.Abdel Aziz, A.K.Altohamy, and A.R.Tawfeek, 2010, "physical and chemical properties for stabilized sand using cement kiln dust" journal of engineering scinces, Assiut University, Vol 38, No3, pp.655-669.

[15] Mostafa Samadi, 2015, Properties Of Mortar Containing Ceramic Powder Waste As Cement Replacement, Research gate, https://www.researchgate.net/publication/286920915

[16] Moinul, Paper of "Strength Behavior of Mortar Using Slag as Partial Replacement of Cement" Department of Civil Engineering, Chittagong University of Engineering and Technology

[17] Reshma, 2014, "Partial Replacement of Cement by Ground Granulated Blast furnace Slag In Concrete", Journal of Emerging Trends in Engineering and Applied Sciences (JETEAS) 5(5): 340-343.

[18] Lee and Wang, 2015, "Analysis of the Optimum Usage of Slag for the Compressive Strength of Concrete", www.mdpi.com/journal/materials

[19] Ugwuishiwh,2013,"Effects of Natural Fiber Reinforcement on Water Absorption of Compressed Stabilized Earth Blocks", International Journal of Scientific Research