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Laboratory Study of High-Resistance Laterite-Based Geopolymer Bricks

Somayeh Mollaei[1*], Yaser Marabi[1], Ahmad Fahmi[1], Alireza Babaeian Amini[1]

[1]Department of Civil Engineering, Faculty of Engineering, University of Bonab, Bonab, East Azerbaijan, IRAN

*Corresponding Author

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Abstract: A high amount of energy is required to produce different types of clay and sand-lime bricks, and a huge amount of carbon dioxide is released into the atmosphere. Also, brick waste from the destruction of dilapidated buildings pollutes the environment. Application of pozzolanic sources containing aluminosilicate and alkaline activators can be beneficial in production of geopolymer bricks, which do not need to be baked in a furnace and can be recycled. A laterite-based geopolymer brick mix design was introduced in this study as an environmental-friendly material. This type of brick is produced using available and cheap raw materials without the need for high furnace heat. The raw materials included laterite soil as aluminosilicate, laterite aggregate filler passed through sieve No. 8 and an alkaline activating solution with different concentrations. The effect of laterite aggregate size on the compressive strength of these brick samples was investigated. The results showed that the compressive strength of the prepared bricks here was much higher than the recommended standards for construction bricks and was similar to those of high-resistance bricks. The size of laterite aggregate had a significant effect on the compressive strength of geopolymer brick samples. The percentage of water absorption of the bricks with different concentrations of alkali activating solution was also within the recommended range for construction bricks.

Keywords: Geopolymer bricks, laterite soil, aluminosilicate, compressive strength, water absorption

1. Introduction

High energy is required to produce different types of building bricks in the furnace, and a considerable amount of greenhouse gases are released into the atmosphere. Also, brick waste caused by the destruction of buildings is often unusable and causes environmental pollution worldwide. In this regard, using the pozzolanic sources containing aluminosilicate and alkaline activators in geopolymer bricks, which do not need to be baked in the furnace and can be recycled, is very useful in achieving the goals of sustainable development. A geopolymer mortar is obtained by reacting between aluminosilicate solids and alkaline activating solutions such as high concentration sodium hydroxide and sodium silicate. This mortar can be used to make a variety of environmentally friendly building materials. High mechanical strength, low shrinkage, high durability, high resistance in fire, and severe environmental conditions, as well as low thermal conductivity, are other advantages of geopolymer materials [1]-[3]. Geopolymerization technology is the chemical activation of an aluminosilicate or ferro- aluminosilicate materials with an activating solution at room or temperatures below 100 ºC in a short period of time [4]. In rock-based geopolymeric binders the part of Al atoms is substituted by Fe atoms [5]. In other words, alkali-activated binders (geopolymers) are formed by the mixing of aluminosilicate powders with alkaline solution at temperatures less than 100 ºC, through the geopolymerisation process or dissolution mechanisms [6].

Lateritic soils are composed of iron, silicon and aluminium oxides. Laterites is typically formed from the alteration of kaolinite by iron mineral phases such as goethite, lepidocrocite and hematite where a high proportion of aluminium, is substituted by iron [6]. Therefore, Laterite as an iron-rich aluminosilicate material can be a suitable choice for an

*Corresponding author: s.mollaei@ubonab.ac.ir

aluminosilicate base component used in the geopolymeric construction materials. Various studies have been conducted on the behavioral characteristics of different types of laterite-based geopolymer mortar and concrete [7]-[11]. Udawattha and Halwatura [12] used fly ash in the construction of concrete blocks containing mud. They utilized alkaline solutions of sodium hydroxide and sodium chloride at different concentrations and investigated the resulting geopolymer reactions under an electron microscope. Youssef et al. [13] used a new alkaline activator called Minealithe to make geopolymer bricks that did not require heat for curing and had the same compressive strength as conventional bricks. Kamseu et al. [14] showed that the presence of amorphous silica helped low temperatures polymerization of the laterite. They proposed a new method for brick producing [14]. Singh [15] compared the compressive strength and water absorption of laterite building bricks with local building materials. He also used percentages of fly ash and lubricant in his mix design and achieved acceptable strengths for masonry bricks [15]. Azeko et al. [16] investigated the physical and mechanical properties of laterite bricks reinforced with polyethylene waste. Shimol et al. [17] presented light and economic geopolymer bricks using fly ash and bentonite, which its other raw materials were made of waste materials except the alkaline activating solution. The production of bricks and other building materials following the indicators of sustainable development in Africa was reviewed by Oyelami and Van-Rooy [18], and successful laterite soil application in the manufacturing of load-bearing and non-load-bearing bricks was reported. Olutoge and Oladunmoye [19] tested water absorption properties of laterite bricks containing cement and wood ash. They showed that optimal ratios of wood ash and cement could effectively reduce the water absorption of bricks [19]. Tarighat and Moazzenchi [20] investigated the effects of different variables such as type of alkaline solution, presence of micro-silica, curing temperature (higher than 100 °C), and the laterite content in the mixture of laterite-based bricks. They achieved a water absorption range of 9-14% and maximum compressive strength of 21 MPa [20]. Awolusi et al. [21] utilized waste saw dust ash and laterite as SCM (supplementary cementitious material) and fine aggregate in concrete. They proposed some mix ratios for load-bearing bricks and blocks made of laterized concrete. In a similar study, Sojobi [22] introduced sawdust wastes and laterite mix designs for eco-friendly lightweight interlocking concrete paving units. Further investigations on ultra-lightweight green interlocking paving units were performed by Sojobi et al. [23]. They combined usage of sawdust and laterite as partial cement and fine aggregate replacements, respectively. For further information see the comprehensive review of different forms of green concrete made by innovative mixes of waste materials and unconventional alternative materials reported by Liew et al. [24].

According to the review of previous studies in this field, it is necessary to perform the feasibility study of making geopolymer bricks using raw materials that are quickly and cheaply available in our neighborhood. Controlling the amount of carbon dioxide and natural soil using in industry, especially in construction industry, is a significant indicator of sustainable development to developed and developing countries. Therefore, the main focus of the current study is on the construction materials which do not need to be baked in a furnace and can be recycled. Here, the application of laterite-based geopolymeric materials in producing of the high-resistance bricks at a low curing temperature (85 °C) without the need for pressing was investigated. Introduce a laterite-based mix design for high-resistance construction material and its laboratory investigation are the most significant objectives of the current study. For this regard, an alkaline solution containing sodium hydroxide as well as the industrial sodium silicate were utilized, and the effect of laterite soil particle size (passing through sieves No. 30 and 100), as well as the concentration of the alkaline solution on the compressive strength and water absorption of the bricks, have been evaluated. In the introduced design mix ratios here, an attempt was made to use cheap and available raw materials and a simple process for molding and curing the bricks. The main goals here were achieving high compressive strength and reasonable water absorption.

2. Materials and Methods

The aluminosilicate material used to make the geopolymer bricks in this study is the laterite soil, collected from "Qaryaghdi" laterite quarry in Miandoab town, East Azerbaijan. Alkaline activation of the aluminosilicate to produce the geopolymer binder allows a good cohesion between different constituents of the material. Based on the results of X-ray Fluorescence (XRF) analysis, the chemical composition of the laterite soil (displayed in Table 1) indicates its rich sources of iron oxide aluminosilicate. Sodium silicate with a ratio of 2:4 and sodium hydroxide (99% caustic soda flakes) were used to prepare the alkaline activating solution. The alkaline solution of sodium hydroxide was made of drinking water. The tools and equipment used in this research include a pan mixer, a 5×20×10 cm wooden mold, an oven, and a compressive strength testing machine, available at the soil mechanics laboratory of the Department of Civil Engineering, Faculty of Engineering, University of Bonab. The X-ray diffraction analysis (XRD) test results related to the laterite soil sample are demonstrated in Fig. 1. According to Fig. 1, the laterite is composed of kaolinite (Aluminum Hydroxide Silicate), hematite (Iron Oxide), and cristobalite (Silicon Oxide) minerals.

Table 1 - Chemical content of laterite soil (weight percentage) with XRF analysis.

SO3	P2O5	CaO	MgO	TiO2	Fe_2O_3	SiO_2	Al_2O_3
0.1	0.1	0.54	1.87	3.29	37.37	19.03	37.03

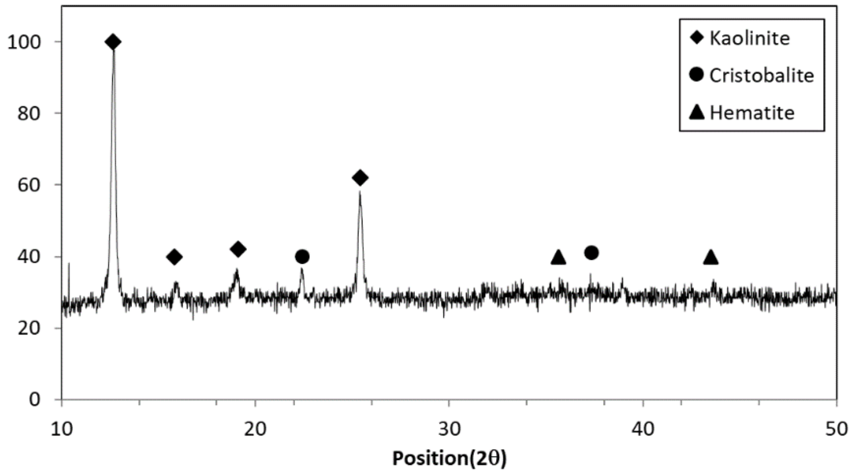


Fig. 1 - XRD analysis of laterite soil

Sodium hydroxide solution with a concentration of 8, 10, 14, and 18 M was used to make geopolymer brick samples. The mass ratios of sodium silicate to sodium hydroxide equal to 1 and 2 were selected to prepare the alkaline activating solutions. For example, the sample naming "G14-2" of geopolymer mortar indicates the use of 14 M sodium hydroxide solution and a mass ratio of sodium silicate to sodium hydroxide solution of 2. The laterite soil passed through sieves No. 30 and 100, and the laterite aggregate filler remaining on the sieve No. 8 were selected as the aluminosilicate base material and the filler aggregates, respectively. Then, the laterite powder and the laterite aggregates were poured into a plastic container, and the alkaline activator was gently added and mixed. Then, the mixture was poured into a pan mixer and after 5 minutes of complete mixing, casted into the wooden molds having a size of 10×20×5 cm and vibrated on a vibrating device. Also, for all the mix proportions in Table 2, several perforated brick samples were prepared and tested which are named in the table with suffix "P". Pictures of raw materials and molded brick samples were displayed in Fig. 2.

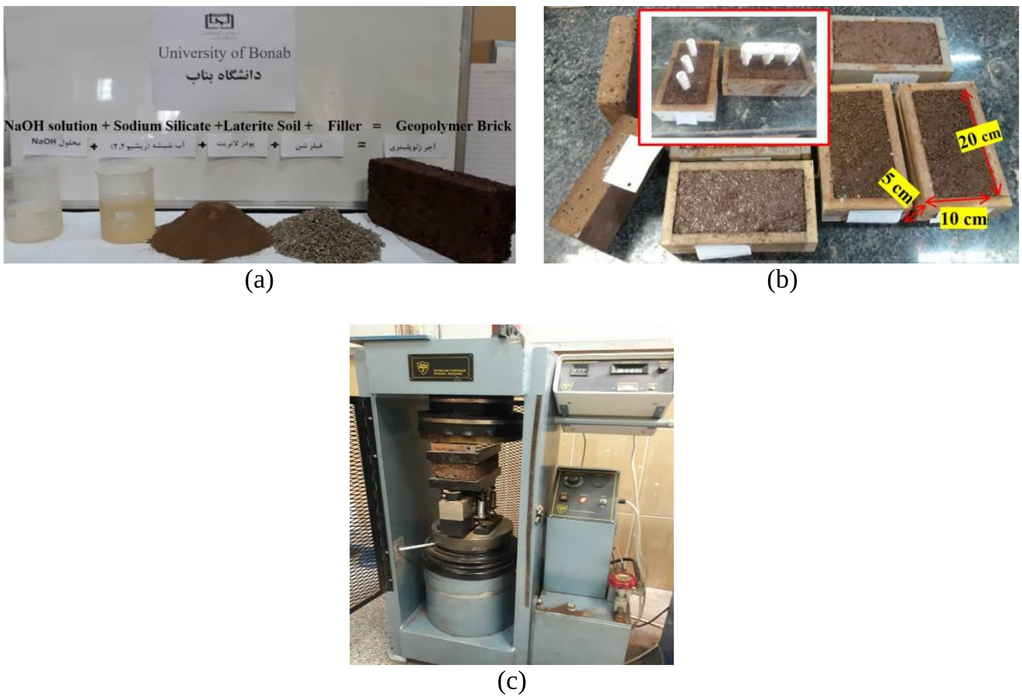


Fig. 2 - Samples preparation (a) Raw materials; (b) Molding ordinary and perforated samples; (c) Compressive strength testing machine

The molded brick samples here were oven drying at a relatively low temperature (85 °C) for three days, and compressive strength was measured 7 and 28 days after leaving the oven. The curing Process is defined in an Iranian national patent [25]. The average compressive strength of every three samples of each design mix ratio was calculated. The water absorption percentage of each design mix with specific molarity was also determined at 7 and 28 days ages.

To measure the water absorption percentage, requirements of ASTM-C67–03a standard [26] (in accordance with Iranian National Standard ISIRI-7 [27]) for the method of boiling for 5 hours at a temperature range of 110-115 °C was used. The water absorption capacity of the brick is then obtained by Eq. (1).

$$\text{Water absorption (\%)} = 100(W_2 - W_1)/W_1 \tag{1}$$

where, W_1 is dry weight, and W_2 is wet weight of the sample.

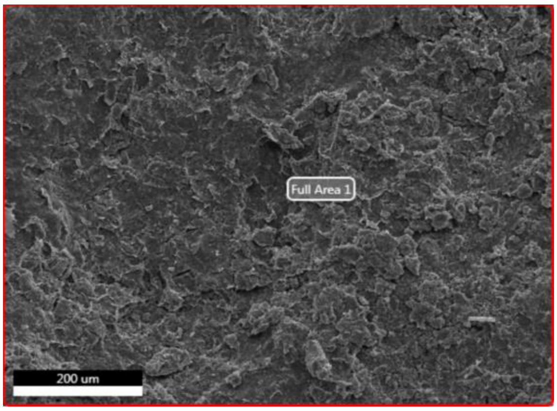
The testing program and mix proportion of geopolymer brick samples are according to Table 2. Several conventional clay bricks were also purchased from the market and have been subjected to compressive strength tests, and measurement of water absorption (mixing: clay, silica sand and water with baking in a kiln at 1000 °C temperature). It should be noted that for each sample ratio in Table 2, 6 perforated brick samples were also prepared and subjected to compressive strength tests at the ages of 7 and 28 days which are named in the table with suffix "P".

Table 2 - Mix proportion of geopolymer brick samples with laterite aggregate filler

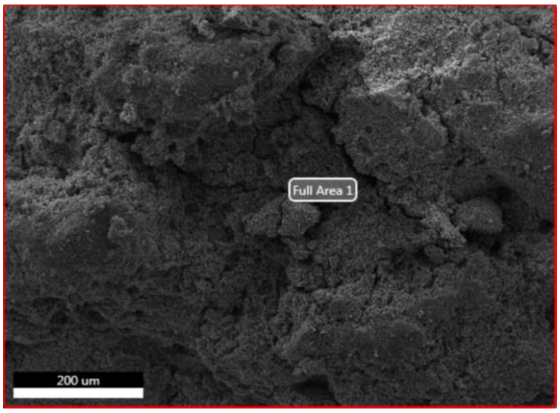
No.	Composition	Activator/Pozzolan ratio	Laterite Soil (gr)	Laterite aggregate filler (gr)	NaOH solution (ml)	Na_2SiO_3 (ml)	Number of samples
1	G-F 8-1 P-G-F 8-1	0.33	900	900	148.5	148.5	4×3
2	G-F 8-2 P-G-F 8-2	0.33	900	900	99	198	4×3
3	G-F 10-1 P-G-F 10-1	0.33	900	900	148.5	148.5	4×3
4	G-F 10-2 P-G-F 10-2	0.33	900	900	99	198	4×3
5	G-F 14-1 P-G-F 14-1	0.33	900	900	148.5	148.5	4×3
6	G-F 14-2 P-G-F 14-2	0.33	900	900	99	198	4×3
7	G-F 18-1 P-G-F 18-1	0.33	900	900	148.5	148.5	4×3
8	G-F 18-2 P-G-F 18-2	0.33	900	900	99	198	4×3

3. Results and Discussion

The specific weight of traditional clay bricks in Iran is about 1700 kg/m3, and the weight of each brick is about 2 kg that gives a number of approximately 450-500 of bricks per ton weight. The laterite-based geopolymer bricks introduced in this study had similar weight characteristics, and the perforated samples were about 300 g lighter than normal samples. In this study, some of the geopolymer brick samples with different molarity were selected for electron scanning by an SEM device to investigate their microstructural aspects. The results of SEM imaging, along with energy-dispersive X-ray spectroscopy EDAX analysis on the laterite and 10 M laterite-based geopolymer samples containing laterite aggregates are presented in Fig. 3. The increase in sodium ion peak in the geopolymer sample (Fig. 3 (d)) comparing to the original laterite particles (Fig. 3 (c)) indicates the chemical reactions between the activating solution (containing sodium hydroxide and sodium silicate) and the laterite powder as an aluminosilicate source.



(a)



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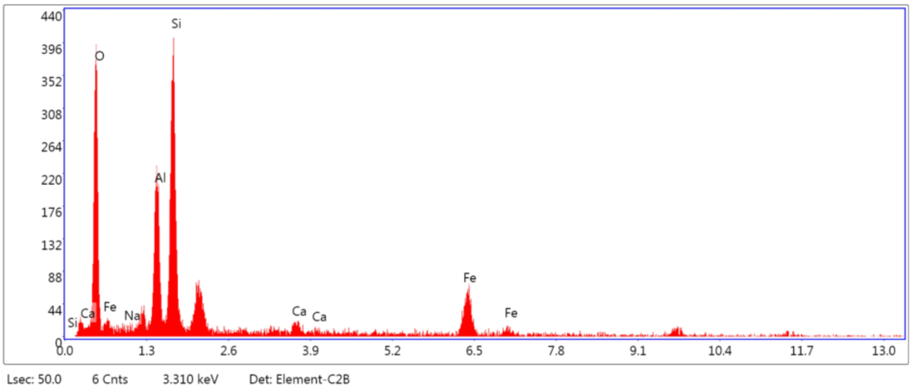

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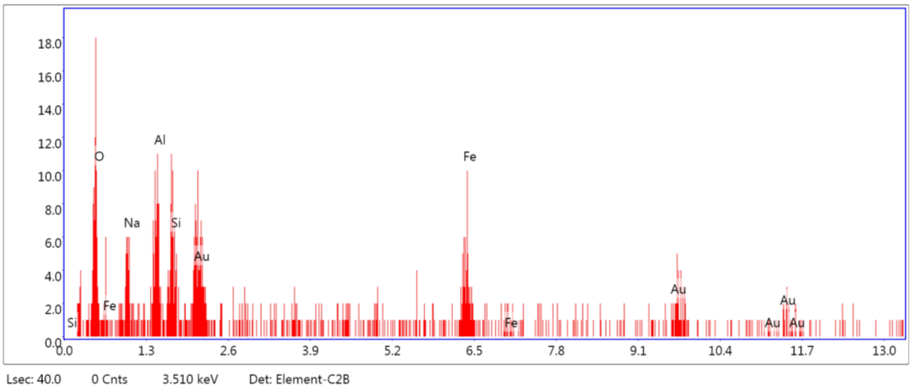

(d)

Fig. 3 - SEM images and AEDX spectra of: (a) and (c) for laterite particle; (b) and (d) for 10 M geopolymer samples, respectively

3.1 Compressive Strength Test

The average compressive strength of the geopolymer brick samples at 7 and 28 days are presented in Fig. 4 and Fig. 5 for bricks made of laterite soil passing through the sieve No. 30 and 100, respectively. The composition named "Com. Brick" at the following diagrams refers to the control clay bricks chosen from the popular commercial bricks in Iran. It can be seen that the compressive strength at 7 and 28 days of all samples cured in the oven is higher than 23 MPa, which is much higher than the resistance of traditional clay brick samples, and it is near to the expected strength of engineering (high-resistance) bricks. It is noteworthy that this high strength is achieved even at an early age. Also, the highest resistance was obtained in the concentration of 14 M sodium hydroxide solution, and the mass ratio of sodium silicate to sodium hydroxide solution of 1 (37.5 MPa) for the case of No. 30 sieve screening of the laterite soil. And, for this case, the lowest resistance was obtained in the concentration of 8 M sodium hydroxide solution (24.5 MPa). For the case of using a sieve No. 100, similarly, the highest compressive strength (45 MPa) was obtained at a concentration of 14 M sodium hydroxide solution and a mass ratio of sodium silicate to sodium hydroxide solution of 1 and the lowest compressive strength (30.8 MPa) at the sodium hydroxide solution concentration of 8 M. Compressive strength of bricks made with an alkaline solution containing 10 M sodium hydroxide is not significantly different from bricks made with an alkaline solution containing 8 M sodium hydroxide. Therefore, to produce bricks with a lower cost and adequate compressive strength, it is recommended to use an alkaline solution containing 8 M sodium hydroxide, and a mass ratio of sodium silicate to sodium hydroxide solution of 1.

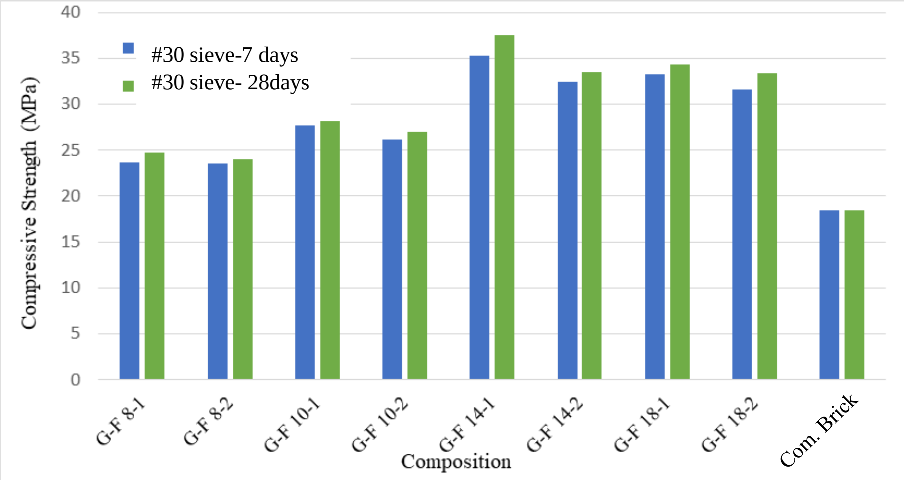

Fig. 4 - Average compressive strength of the laterite-based geopolymer bricks at 7 and 28 d (sieve No. 30) containing laterate aggregates as filler

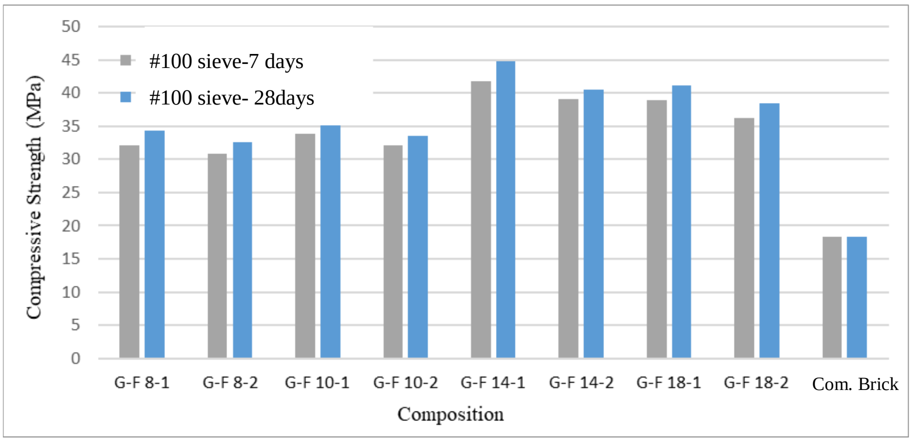

Fig. 5 - Average compressive strength of the laterite-based geopolymer brick samples at 7 and 28 d (sieve No. 100) containing laterite aggregate filler

From the above-mentioned results, it is clear that the obtained strengths are comparable to the minimum standards for high-strength engineering clay bricks proposed by the Iranian and international standards [27], [28] and are far higher than the strength of common construction bricks in the market. The similarity of the 3-day resistance to thoes of 28-day indicates that most of the geopolymerization reactions took place at a very early age.

To better investigations, the compressive strength of all samples at 7 and 28 days is shown in Fig. 6 and Fig. 7, respectively. It can be seen that in the case of using laterite soil passing through a sieve No. 100, the compressive strength of the brick is generally higher than in the case of using the sieve No. 30 (14-39% differences). This phenomenon is due to the smaller size of the laterite powder grains and their higher specific surface area, which improves the geopolymerization reactions. Finer the laterite aggregate size, higher the compressive strength of the material; But this needs to be investigated more pricelessly.

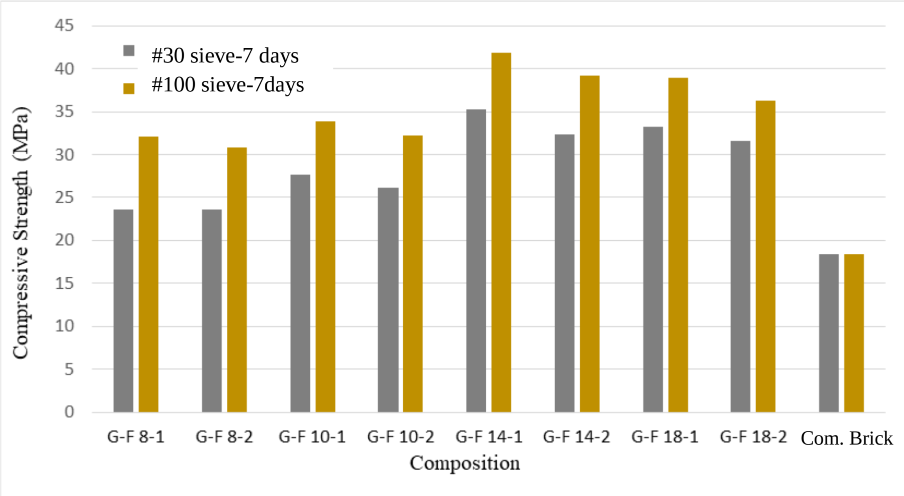

Fig. 6 - Average compressive strength of the geopolymeric brick samples at 7 d with laterite screened through sieve No. 30 and 100

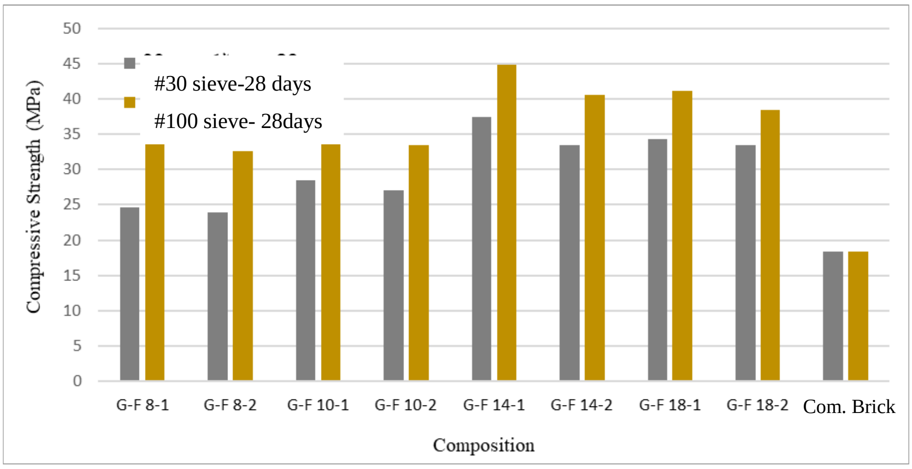

Fig. 7 - Average compressive strength of the geopolymeric brick samples at 28 d with laterite screened through sieve No. 30 and 100

The average compressive strength of the geopolymer perforated brick samples at 7 and 28 days are presented in Fig.s 8 and 9 for bricks made of laterite soil passing through sieves No. 100 and 30, respectively. It can be seen that despite the lower mass of perforated bricks compared to normal ones, the compressive strength of all perforated brick samples at 7 and 28 days is still in a high range and does not decrease significantly (more than 28 MPa and 22 MPa for sieves No. 100 and 30, respectively).

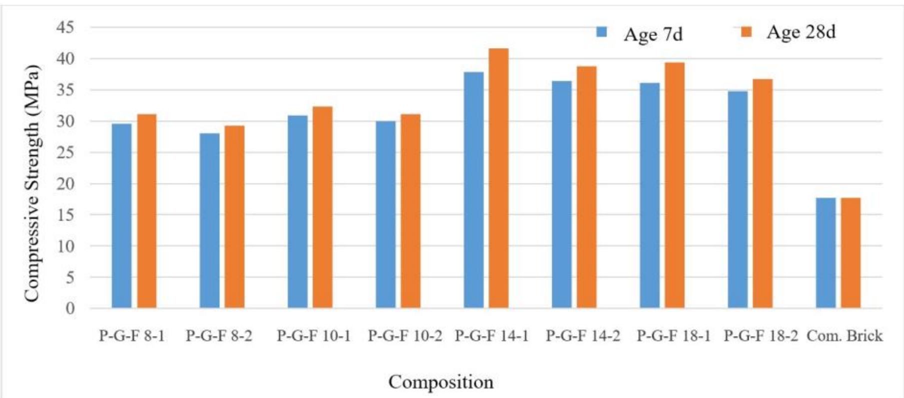

Fig. 8 - Average compressive strength of the perforated geopolymer bricks at 7 and 28 d with laterite (passing sieve No. 100) and laterite aggregate filler

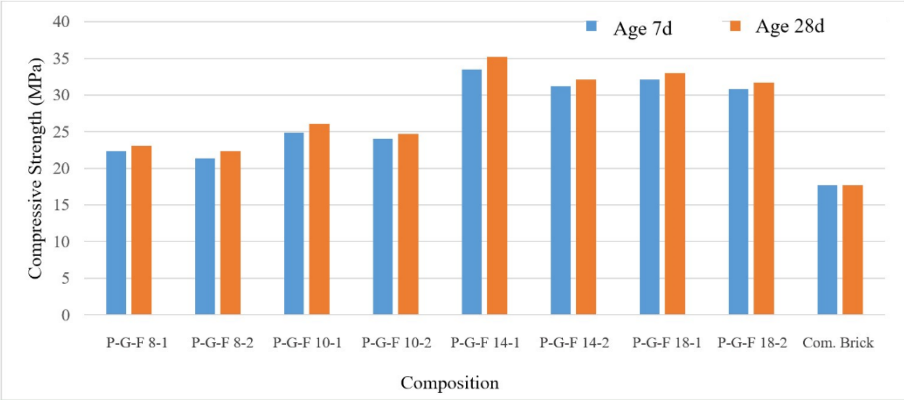

Fig. 9 - Average compressive strength of the perforated geopolymer bricks at 7 and 28 d with laterite (passing sieve No. 30) and laterite aggregate filler

3.2 Water Absorption Test

Fig. 10 shows the water absorption capacity of the samples. It can be seen that with increasing the sodium hydroxide solution content and the mass ratio of sodium silicate to sodium hydroxide solution, the water absorption of geopolymer bricks has also increased. In general, the water absorption of geopolymer bricks introduced here is 17 to 51% lower than conventional control clay bricks. At the same time, it provides the requirements for the minimum water absorption necessary for adhesion to the mortar.

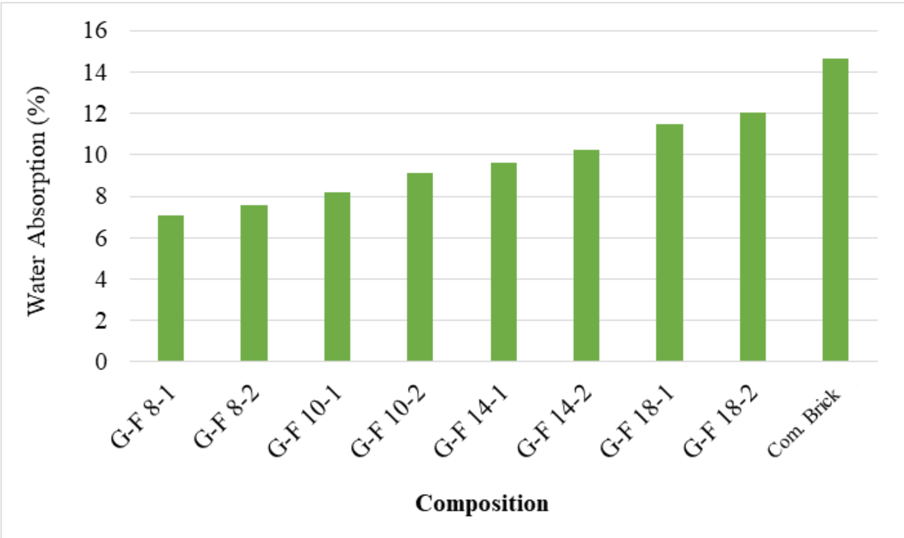

Fig. 10 - Water absorption capacity of geopolymer brick samples with laterite aggregate filler

Gradually increase in water absorption due to increase in sodium hydroxide density and a higher ratio of sodium silicate to sodium hydroxide solution is evident in Fig. 10. This might be happening because of the increased porosity of the material arising from higher viscosity of the alkaline solution comparing to the less concentration solutions. However, this phenomenon requires further experimental investigations.

The range of water absorption of laterite bricks introduced here (in most samples) is within limits recommended in Iranian National Standard No. 7 [27] and Part 5 of the Iranian national building code [29]. Table 3 lists the required specifications of bricks for severe, moderate, and mild weathering conditions (S, M, and N, respectively) according to ASTM-C standard. C-62 series clay bricks are suitable for construction work, and C-902 series bricks are desired for pavement applications under light traffic conditions. The requirements of clay bricks according to the Iranian national building code (Part 5) are shown in Table 4. Considering Tables 3 and 4, it can be inferred that in terms of resistance properties and water absorption, most samples made and tested in this study are in the range of high-strength (engineering) load-bearing bricks and can even be used in pavement applications.

Table 3 - Standard specifications of clay bricks according to ASTM-C [28], [30]

Brick Class		Minimum Compressive Strength psi (MPa)		Maximum Cold Water Absorption, %	
		Average of 5 brick	Individual	Average of 5 brick	Individual
C 62 Grade	SW	3000 (20.7)	2500 (17.2)	-	-
	MW	2500 (17.2)	2200 (15.2)	-	-
	NW	1500 (10.3)	1250 (8.6)	-	-
C 902 Class	SX	4000 (27.6)	3500 (24.1)	16.0	18.0
	MX	3000 (20.7)	2500 (17.2)	14.0	17.0
	NX	3000 (20.7)	2500 (17.2)	No limit	No limit

Table 4 - Performance specifications of clay bricks according to Iranian national building code- Part 5 [29]

Brick Class		Minimum Compressive Strength, (MPa)		Maximum Water Absorption*, %	
		Average	Individual	Average	Individual
Engineering brick	Class-1	35	30	12	15
	Class-2	25	20		
Facing brick	Class-1	14	11	18	20
	Class-2	12	9		
Building brick	Load bearing	8	6	-	-
	Non-loadbearing	4	3		

* Minimum Water Absorption: 8%

4. Conclusion

In this paper, a mix design for recyclable and eco-friendly geopolymer bricks was presented. Laterite soil was utilized here as a pozzolanic solid component with a laterite aggregate filler in combination with an alkaline activating solution of sodium silicate and NaOH. These bricks are cured in the oven with a temperature below 100 °C and gained high compressive strength at an early age. The bricks introduced here were molded without the need for pressing force and in a simple curing process. The compressive strength of the introduced bricks was much higher compared to the conventional clay bricks, and their water absorption capacity was in a reasonable range. Therefore, laterite based geopolymer bricks introduced here can be very suitable constructions materials for load-bearing applications (with a minimum compressive strength of 24 MPa). Also, the results showed that in the case of using laterite powder passing through a sieve No. 100, the compressive strength of the bricks was always be higher than the case of using laterite passing the sieve No. 30. From the economic point of view, the production of perforated geopolymer bricks using an alkaline solution containing 8 M sodium hydroxide solution was more cost-effective than other samples and had adequate mechanical strength.

Cost comparison of geopolymer bricks commercial clay bricks in Iran was done as shown in Table 5. Cost benefits analysis was implemented using the method described by Sojobi & Liew [31]. Perforated geopolymer brick proposed here obtained the highest ranking with strength to cost of MPa/US$ 132 followed by the solid geopolymer brick in this study with MPa/US$ 120 while the strength to cost of MPa/US$ 50 was obtained by the solid commercial clay brick.

Table 5 - Ranking of solid and perforated geopolymer bricks and commercial clay bricks

Brick Sample	Cost per brick (US$)	Compressive strength (MPa)	Strength/cost (MPa/US$)	Ranking in terms of Strength/cost
Solid geopolymer bricks	0.2	24	120	2
Perforated geopolymer bricks	0.167	22	132	1
Solid commercial clay bricks	0.22	11	50	4
Perforated commercial clay bricks	0.252	17	67.5	3

Initial price analysis in this study showed approximately 5,000 Rials (about 0.2 US$) were required for each laterite-based geopolymer brick sample under the laboratory conditions, which can compete with conventional building bricks in the market. It should be noted that in a practical factory environment, due to the existence of mass production facilities, these costs can be reduced significantly. As a result, these bricks will be an excellent alternative to the conventional clay bricks, which is also very desirable in savings clay consumption (which is essential for agricultural applications).

We can also recommend the high-strength bricks introduced here for façade and pavement applications. Therefore, to continue the studies, abrasion, and durability tests against freeze-thaw cycles should be implemented. According to the experience of the authors, the laterite-based geopolymer bricks introduced here will show high resistance to fire, freezing, and thawing and abrasion. Also, it is predicted that if the curing temperature increases, the strength of the resulting bricks would increase significantly. So that by further increasing the compressive strength of the laterite bricks, it is possible to produce the bricks for paving purposes that meet the requirements of the Iranian National Standard ISIRI-20185 [32].

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