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Sustainable and Eco-Friendly Use of Clay Brick Waste as an Alumina-Silicate Base and Different Fillers for Geopolymer Brick Production

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ABSTRACT:

Brick is the most widely used construction material. Demolition of buildings and production of construction waste, including clay brick, are dramatically increasing in an alarming rate. The production of traditional bricks such as clay bricks has hazardous impacts on the environment, such as pollution and extensive use of natural resources. This study addressed the application of the geo-polymerization process as an environmental and sustainable method to produce new bricks from clay brick waste and different types of fillers. Accordingly, the powder and grains of clay brick waste, dune sand, washed sand, industrial sodium hydroxide, and water glass were utilized to prepare cubic and brick-shaped geopolymer samples with different mix designs and then cured at 70 °C. The samples' compressive strength, water absorption and SEM analysis were examined. According to the results, the highest compressive strength for cubic mortar samples was obtained in the case without filler; for these samples, with mass ratios of water glass to sodium hydroxide solution equal to 1 and 2, compressive strength was 18.45 and 22.15 MPa, respectively. In the brick samples, the highest compressive strength was obtained in the 28-day and 8 M geopolymer samples, which was equal to 25.38 MPa. On the other hand, the geopolymer samples made by sand filler had higher compressive strength and lower water absorption in comparison to other samples. Therefore, sustainable production of geopolymer bricks from clay brick waste and inexpensive materials as the filler can be a step toward mitigating the environmental impact of construction and demolition waste.

KEYWORDS:

Clay brick waste, Alumina-silicate, Filler, Eco-friendly, Sustainable.

1. Introduction

Construction and demolition waste or debris can be regarded as a type of solid waste that contains large and varied wastes, including concrete, brick, asphalt, wood, and plaster; these are obtained in the process of construction, reconstruction, and demolition of buildings, streets, bridges and dams (Quedou, Wirquin and Bokhoree, 2021, Sormunen and Kärki, 2019, Tam and Tam, 2006). Construction and demolition waste can be considered a global concern and therefore, should be managed throughout the construction cycle (Esa, Halog and Rigamonti, 2017, Mymrin, Aibuldinov, Alekseev, Avanci, Rolim, Catai and Carvalho, 2020). Due to the population growth in cities and the development of constructions, demolition of buildings and production of construction waste (including clay brick) has witnessed a dramatic increase. According to the Global Waste Management Outlook (GWMO),

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about 35% of the world's solid waste is related to construction and demolition waste; its recycling is an international concern. Most construction and demolition waste can be reused and recycled by adding better materials (Islam, Nazifa, Yuniarto, Uddin, Salmiati and Shahid, 2019, Silva, de Brito and Dhir, 2019, Tavira, Jiménez, Ayuso, López-Uceda and Ledesma, 2018, Wang, Yu, Shui, Song, Liu, Liu and Wu, 2019). Recycling these wastes through scientific methods helps to preserve natural resources and the environment but also confers economic benefits (Gavali, Bras and Ralegaonkar, 2021). Also, this recycling reduces carbon dioxide (CO_2) emissions and energy consumption (Akhtar and Sarmah, 2018, Liu, Zhang, Li, Zhou, Xiao, Li and Zhu, 2020, Mohajerani, Suter, Jeffrey-Bailey, Song, Arulrajah, Horpibulsuk and Law, 2019). According to Fig. 1. (Top), the demolishing of old buildings generates huge wastes, a major part of which is clay brick waste (CBW). Recycling CBW to produce new bricks (for rebuilding new constructions) is the first challenge of the present research. After concrete, brick is the most widely used construction material (Wong, Mo, Yap, Alengaram and Ling, 2018) and the most accessible and easy-to-use building material worldwide. Its clay type is prepared by baking dried mud brick, which is formed by methods such as extruding, pressure, etc.

With the remarkable progress of science, researchers have made bricks with new methods and materials to improve their properties; this is why bricks have entered the consumer market in various types and shapes (Ahmadi, Souri and Ebrahimi, 2020, Dai, Wu, Hu, Zhang and Mao, 2019, Limami, Manssouri, Cherkaoui and Khaldoun, 2020). Usually, it takes a great deal of energy and time to make clay bricks.

The production of traditional bricks, such as clay bricks, can lead to hazardous impacts on the environment in terms of pollution and immethodical use of natural clay resources. Reduction of the nature's irreversible destruction by quarries of natural raw materials like clay is one the most important environmental issues (Mymrin et al., 2020).

Therefore, adopting an environmentally friendly and sustainable method to produce new bricks from CBW (and not from the natural clay sources and via new eco-friendly technology) is the second challenge of our study.

Geopolymer binders have been widely used in the recent studies to alleviate the environmental impact of ordinary Portland cement. Producing one ton of Portland cement releases about one ton of carbon dioxide into the atmosphere (Abbas, Khereby, Ghorab and Elkhoshkhany, 2020, Shi, Jiménez and Palomo, 2011). As a new type of green material, geopolymer has good engineering technical properties (Yao, Qiu, He, Chen and Hao, 2021). Geopolymeric materials have received great attention due to their excellent mechanical properties, durability, fireresistance, high impact strength, and thermal stability (Chindaprasirt and Rattanasak, 2018, Fahmi, Babaeian Amini, Marabi and Majnouni-Toutakhane, 2021, Fahmi, Marabi, Zavaragh and Majnouni-Toutakhane, 2021, Liu, Zhu and Li, 2020, Mansourghanaei, Biklaryan and Mardookhpour, 2021, Parathi, Nagarajan and Pallikkara, 2021). Any source of aluminasilicate that can be soluble in alkaline activator solutions can be employed as a source of geopolymer production; so CBW may be utilized as a geo-polymeric material as well (Fig. 1 Top). In some studies, CBW powder has been used as an aluminasilicate base for the production of geo-polymeric bricks (Mahmoodi, Siad, Lachemi, Dadsetan and Sahmaran, 2020, Tang, Li, Tam and Xue, 2020, Tuyan, Andiç-Çakir and Ramyar, 2018, Yehualaw, Hwang, Vo and Koyenga, 2021).

Fig. 1. Demolishing waste containing CBW (Top), and CBW powder, alkaline solutions and CBW-based geopolymeric brick (Bot)

Due to the lack of experiments in relation to the construction of geopolymer bricks from CBW with or without fillers, this study examined the possibility of making geopolymer bricks from brick waste with filler. Herein, after crushing the CBW, the powder and grains of crushed clay bricks were separated by standard sieves. The powder was then used as an aluminasilicate base to make a geo-polymeric binder and the separated grains were utilized as the filler. In other tests, dune sand and washed sieved sand were also incorporated as the fillers. Evaluation of the effect of different fillers on the mechanical strength and water absorption of the produced geopolymer samples was another goal of this study. The sustainable production of geopolymer bricks from CBW and inexpensive materials such as dune sand can be a step toward mitigating the environmental impact of construction and demolition waste.

2. Materials and methods

2.1. Materials

Materials used in this research included CBW, dune sand, which was obtained from Jabalkandi region in the adjacency of Urmia Lake, washed sand (prepared from a sand crushing plant), industrial sodium hydroxide (NaOH) with 98% purity, industrial water glass (WG), 5×5×5-cm wooden cubic molds, 5×10×20-cm wooden brick molds, an oven, mechanical testing machines, etc. CBW prepared from a demolished building was separated from other construction wastes, including plaster and concrete. This CBW was crushed in several steps by a crusher. The powder passing through the standard sieve No. 30 (600μm) was selected as the source of aluminasilicate. Because CBW was crushed in several stages, the powder was poured into a container in different stages; after complete mixing, homogeneous materials were prepared to produce geopolymer samples (in all groups of samples, as described in the next part). The chemical composition of CBW powder was detected by X-ray fluorescence (XRF). XRD examinations of the CBW powder sample were also performed.

Regarding the used filler materials, the crushed CBW was passed through sieve No. 4 (4.75 mm) and the residue on sieve No. 8 (2.36 mm) was collected and used as a filler to make the first group of geo-polymeric samples. The dune sand of Jabalkandi was used as a filler to construct the second group of geo-polymeric samples (Katebi, Fahmi, Kafil and Bonab, 2018). According to Fig. 2, 92% of particles for this sand had a diameter of 75-250 micrometers. Washed sand was passed through sieve No. 4 (4.75 mm), and the residue on sieve No. 8 (2.36 mm) was employed as the filler to make the third group of geo-polymeric samples.

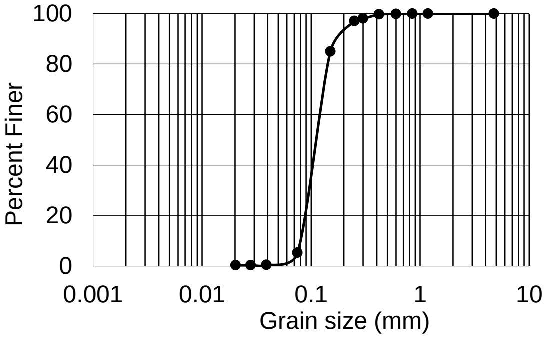


Fig. 2. Particle size distribution curve

The industrial-grade sodium hydroxide used in this research had the purity of 98%. The alkaline solution was formed by dissolving sodium hydroxide in water. Compared to other alkaline solutions, sodium hydroxide forms a stronger alkaline solution in water (Xu and Van Deventer, 2000). Because the sodium ion radius is larger and has less gravity on its OH- ion, it can be easily ionized in water to its constituent ions(Na+ and OH-) (Singh, Trigg, Burgar and Bastow, 2005). This chemical, when in contact with the skin, has a corrosive effect; so, safety principles must always be followed to prevent its irritating effects when used. The water glass (WG) used in this research was prepared from Silicat Sazan Alvand Co. The chemical compounds of this product are presented in Table 1.

Table 1. Chemical properties of water glass

Ratio	2.4±0.05
Na_2O%	13.00-13.89
SiO_2%	32.59-34.64
Density at 25 ºC	52±1
Specific gravity (g/cm3)	1.543-1.576
Viscosity (CPS)	600-1500

2.2. Methods

In the first step of constructing brick samples, the required alkaline solution should be prepared. The solution was prepared at three concentrations of 2 M, 4 M and 8 M of NaOH with two mass ratios of water glass to sodium hydroxide solution (1 and 2). After preparing the sodium hydroxide solution with specified molarity, to prepare the alkaline solution with a mass ratio of WG/NaOH=1, the sodium hydroxide solution was first weighed; then the same mass of water glass was added to the solution. The same procedure was adopted to prepare a solution of WG/NaOH=2, with the difference that the mass of water glass was twice that of the sodium hydroxide solution. To investigate the characteristics and strength of geopolymer bricks, samples of geopolymer (Fig. 1-Bot & Fig. 3) were cast in 200×100×50-mm wooden brick molds and 50×50×50-mm wooden cubic molds. The mixing scheme for constructing the samples was similar in both types of molds; the only difference was in the mass of the materials. Two mass ratios of WG/NaOH =1 & 2 were adopted to make cubic geopolymer samples, and the single weight ratio WG/NaOH=2 was chosen to construct geopolymer brick samples. The mix design of geopolymer samples is according to Table 2. The liquid-to-binder ratio (L/B) is the weight ratio of the prepared alkaline solution to CBW powder; it was equal to 0.45 or 0.5 in the samples. The temperature of 70 °C was selected as the curing temperature (based on the results of the preliminary tests). Initially, the specimens were poured into molds and kept in the oven for 24 hours to be hardened.

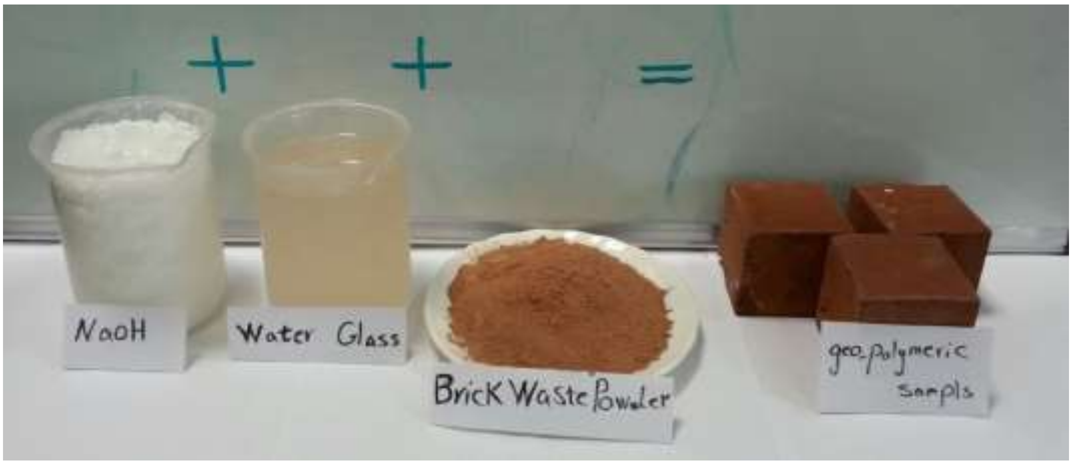


Fig. 3. Cubic geopolymeric 50×50×50-mm samples

Table 2. The mix design of CBW powder-based geopolymer samples

No.	Name	NaOH solution (molarity)	WG/NaOH	Filler	Filler replacement %	L/B	Mold dimension
1	N-2-1	2	1	None	-	0.45	5×5×5 cm
2	N-4-1	4	1		-	0.45	
3	N-8-1	8	1		-	0.45	
4	BW-2-1	2	1	Brick Waste	50	0.5	5×5×5 cm
5	BW-4-1	4	1		50	0.5	
6	BW-8-1	8	1		50	0.5	
7	WS-2-1	2	1	Dune sand	50	0.45	5×5×5 cm
8	WS-4-1	4	1		50	0.45	
9	WS-8-1	8	1		50	0.45	
10	WSS-2-1	2	1	Washed Sieved Sand	50	0.45	5×5×5 cm
11	WSS-4-1	4	1		50	0.45	
12	WSS-8-1	8	1		50	0.45	
13	N-2-2	2	2	None	-	0.45	5×5×5 cm & 20×10×5 cm
14	N-4-2	4	2		-	0.45	
15	N-8-2	8	2		-	0.45	
16	BW-2-2	2	2	Brick Waste	50	0.5	5×5×5 cm & 20×10×5 cm
17	BW-4-2	4	2		50	0.5	
18	BW-8-2	8	2		50	0.5	
19	WS-2-2	2	2	Dune Sand	50	0.45	5×5×5 cm & 20×10×5 cm
20	WS-4-2	4	2		50	0.45	
21	WS-8-2	8	2		50	0.45	
22	WSS-2-2	2	2	Washed Sieved Sand	50	0.45	5×5×5 cm & 20×10×5 cm
23	WSS-4-2	4	2		50	0.45	
24	WSS-8-2	8	2		50	0.45	

The molds were then removed and the specimens were kept in the oven for further 48 hours. Subsequently, they were taken out of the oven and kept at room temperature (25°C) until mechanical strength measurement at the ages of 3, 7 and 28 days. The compressive strength of geopolymer bricks is a component indicating their quality; it can be compared with that of non-geopolymer bricks. So, compressive strength tests were performed at the age of 3, 7 and 28 days according to the ASTM C62 standard. Water absorption is another characteristic that must be determined to assess the quality of bricks. In this research, the water absorption test was conducted at the age of 28 days, according to the ASTM C62. FESEM-Edax and XRD examinations for geopolymer sample (made with an 8 M NaOH solution and the weight ratio WG/NaOH=2) were also carried out. Several days before the FESEM-EDAX examination, the geopolymer sample was immersed in water to eliminate the possible residual non-reacted alkaline solution in the produced matrix and; oven drying, it was sent for examination.

3. Results and discussion

3.1. CBW examination

The chemical composition of the CBW powder was detected by X-ray fluorescence (XRF). The results are presented in Table 3. It was found that alumina silicate materials (Al_2O_3 and SiO_2) constituted 76% of the CBW composition. According to the XRD examination (Fig. 4), for the CBW powder, most of the peaks were related to augite [(Ca, Mg, Al) $(Si,Al)_2O_6$], alpha-quartz (SiO_2), and anorthite ($CaAl_2Si_2O_8$). Augite, which is a pyroxene serving as a desirable mineral phase in ceramic bodies, can enhance sintering and improve abrasion resistance and mechanical strength (Dagounaki, Sikalidis, Kassoli-Fournaraki and Tsirambides, 2008). The crystallization of the anorthite phase can significantly enhance the properties of ceramics (Tabit, Hajjou, Waqif and Saâdi, 2020).

Table 3. Chemical composition of the CBW powder (XRF examination)

Composition	% by weight	Composition	% by weight
SiO_2	58.8	Na_2O	2.52
Al_2O_3	17.88	K_2O	2.27
Al_2O_3	8.62	TiO_2	0.53
MgO	4.52	SO_3	0.38
Fe_2O_3	4.12	LOI	0.33

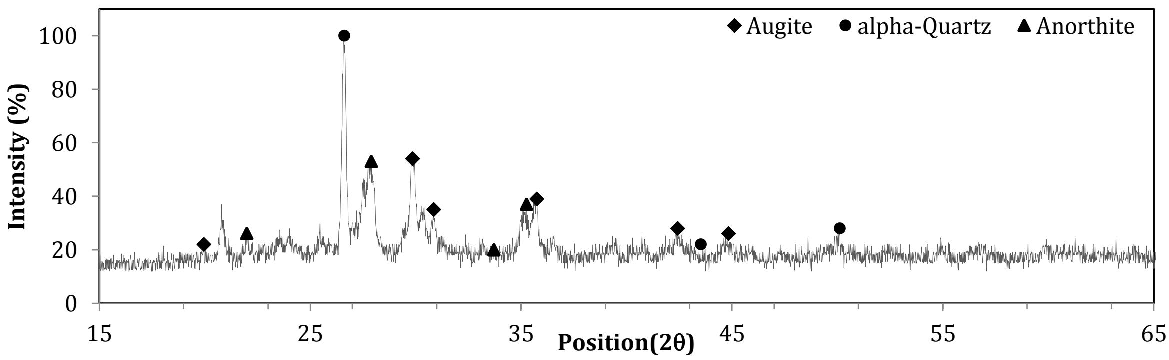


Fig. 4. XRD examination of CBW powder

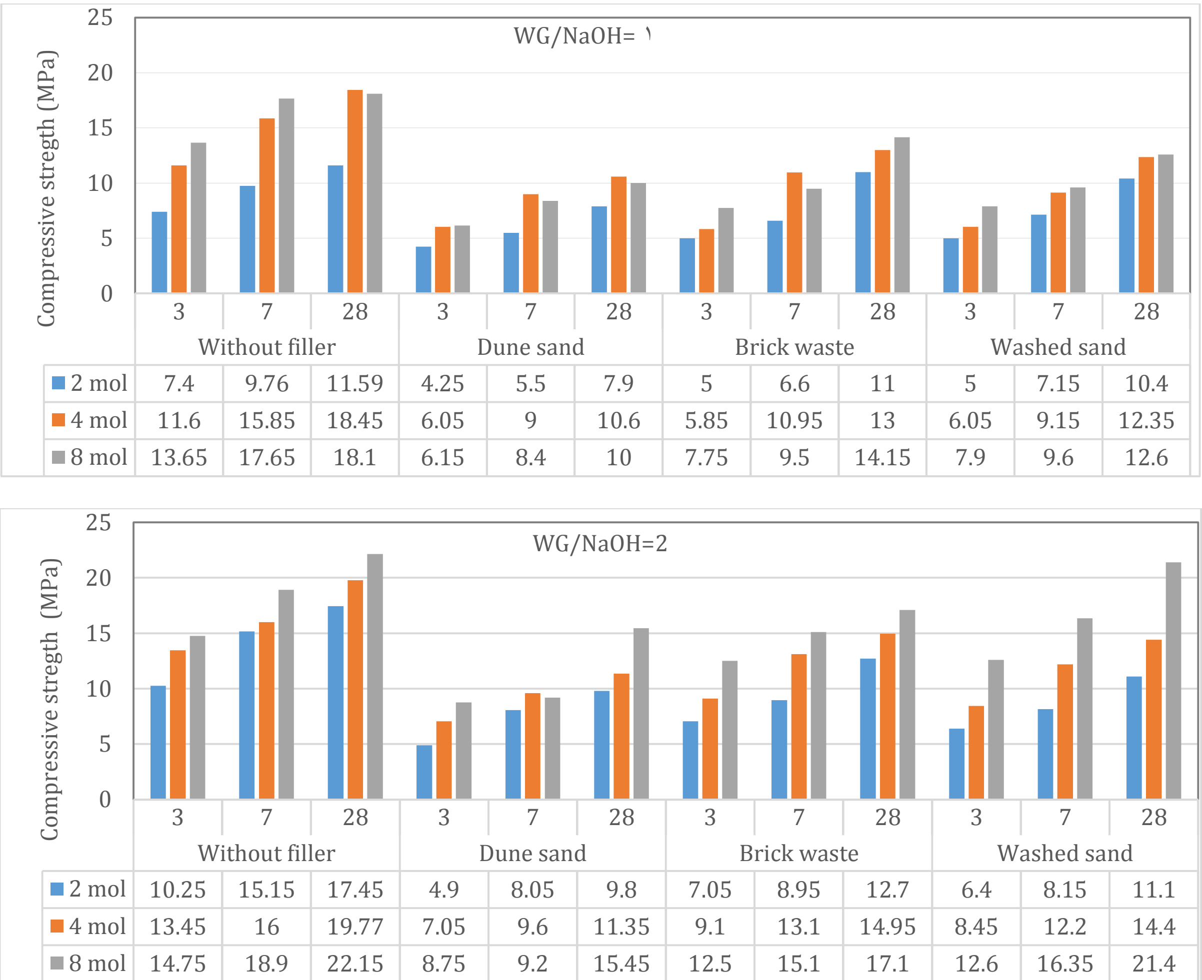
3.2. Compressive strength and water absorption of the cubic samples

The 3-, 7- and 28-day compressive strength of the geopolymer cubic samples (5×5×5cm), at two ratios of WG/NaOH=1 & 2, is presented in Fig. 5. In these graphs, the compressive strength of the samples made without the filler or with different fillers, including dune sand, brick waste and washed sand, have be compared. According to these graphs:

- The samples without filler had the highest compressive strength; by adding the filler, their compressive strength was decreased.
- In both groups, the compressive strength of the samples made using an alkaline solution containing 8 M of the sodium hydroxide solution at the age of 28 days was the highest of their kind. In contrast, samples made with 2 M of sodium hydroxide had the lowest compressive strength. Therefore, changes in the concentration of sodium hydroxide solution could affect the mechanical properties of the samples. In other words, by increasing the concentration of sodium hydroxide solution in the range of 2-8 molarity, the compressive strength could be elevated. This could attribute to the higher solubility of aluminasilicate compositions of the CBW powder with the increment of the alkaline solution concentration. This has also been reported by Boutterin and Davidovits (1988) and Reig, Tashima, Borrachero, Monzó, Cheeseman and Payá (2013), thus indicating that as the concentration

of sodium hydroxide solution is increased, the compressive strength is enhanced too. However, in other studies, with an excessive increase in the molarity of the NaOH solution (> 8 or 12 M), the compressive strength began to decrease. Higher molarities > 8M were not investigated in our study in terms of the negative effect of the higher concentrations of the alkaline solution and economy (due to high costs of preparing higher concentrations).

- By raising the WG/NaOH ratio, the compressive strength of cubic geopolymer samples was also increased. By raising the WG/NaOH ratio from 1 to 2 for the samples made with 8M NaOH solution, the 7-day compressive strength was increased from 9.6 to 16.35; also, the 28-day compressive strength was raised from 12.6 to 21.4, which was approximately equal to a 70% growth in compressive strength. It means that an increment in the SiO_2/Na_2O ratio of the alkaline solution enhanced the mechanical strength.
- Among the filler-containing geopolymer samples, the maximum 28-day compressive strength (21.4 MPa) was gained for the washed sand filler, with 8 M sodium hydroxide and the ratio of WG/NaOH=2. This value was close to the 28-day compressive strength (22.15 MPa) of geopolymer samples made without any filler, 8 M sodium hydroxide, and a ratio of WG/NaOH:2. Therefore, economically, the sample made with the washed sand filler was preferred over samples without the filler.



	Without filler 3	Without filler 7	Without filler 28	Dune sand 3	Dune sand 7	Dune sand 28	Brick waste 3	Brick waste 7	Brick waste 28	Washed sand 3	Washed sand 7	Washed sand 28
2 mol	7.4	9.76	11.59	4.25	5.5	7.9	5	6.6	11	5	7.15	10.4
4 mol	11.6	15.85	18.45	6.05	9	10.6	5.85	10.95	13	6.05	9.15	12.35
8 mol	13.65	17.65	18.1	6.15	8.4	10	7.75	9.5	14.15	7.9	9.6	12.6

	Without filler 3	Without filler 7	Without filler 28	Dune sand 3	Dune sand 7	Dune sand 28	Brick waste 3	Brick waste 7	Brick waste 28	Washed sand 3	Washed sand 7	Washed sand 28
2 mol	10.25	15.15	17.45	4.9	8.05	9.8	7.05	8.95	12.7	6.4	8.15	11.1
4 mol	13.45	16	19.77	7.05	9.6	11.35	9.1	13.1	14.95	8.45	12.2	14.4
8 mol	14.75	18.9	22.15	8.75	9.2	15.45	12.5	15.1	17.1	12.6	16.35	21.4

Fig. 5. Compressive strength of 3-,7- and 28-day cubic geopolymer samples made without using a filler or with different fillers including dune sand, brick waste and washed sand

- The compressive strength of the samples with various percentages of washed sand filler (replacement with the CBW powder), 8M NaOH, and WG/NaOH=2 is depicted in Fig. 6. This type of mix design was applied to investigate the effect of adding different weight ratios of the filler to detect the optimal percentage to produce geopolymer samples with the optimal strength and cost. Due to the reduction of the CBW powder content in the samples, a decrease of compressive strength was observed. The compressive strength of cubic geopolymer samples made by using 30% by weight of washed sand was the highest, as compared to others. As the difference in the compressive strength of the samples with the 30% filler, as compared to the samples with 50%, was not significant, using 50% of washed sand as the filler in the production of bricks could be economically recommended. According to similar studies conducted by Allahverdi and Najafi Kani (2009) in this field, it was found that the compressive strength of geopolymer samples made from the clay brick waste powder was improved by increasing the concentration of sodium hydroxide solution.

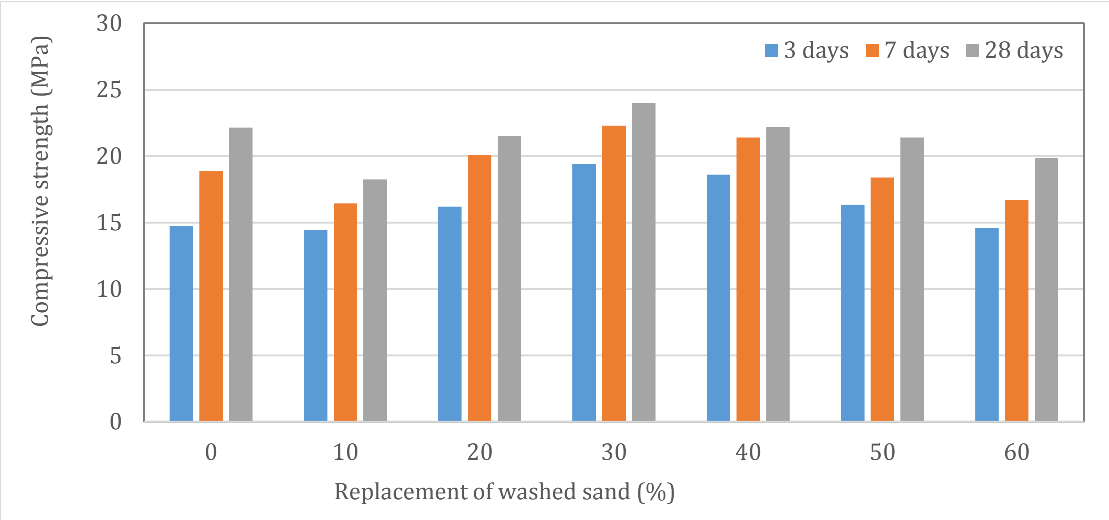


Fig. 6. Compressive strength of cubic geopolymer samples made with different percentages of washed-sand

The results of water absorption for cubic (5×5×5cm) geopolymer samples are illustrated in Fig. 7. According to this graph:

- The water absorption of all samples made with a mass ratio of WG/NaOH:2 was less than that of the samples made with a mass ratio of WG/NaOH:1. Among the samples made with different concentrations of sodium hydroxide solution, those developed with the 8 M concentration had the least water absorption.
- The samples without filler demonstrated the highest, while those made with the washed sand filler showed the lowest water absorption. Thus, increasing the concentration of sodium hydroxide or the WG/NaOH ratio and adding the filler could play a significant role in reducing water absorption. Two types of geopolymer samples, including the samples made without filler or those with CBW grains as the filler, had higher water absorption. By comparing these samples with other samples (made with dune sand and washed sand as the filler), it could be concluded that the water absorption of the samples made with these substances was relatively high because of the higher water absorption property of CBW grains and CBW powder as the raw materials. Consequently, when other fillers (except CBW grains) were incorporated at 50% in the samples, because their water absorption was less than that of the CBW materials, the water absorption of geopolymer samples incorporating them (dune sand and washed sand) was reduced as well. In addition to the mentioned cases, some studies were also conducted to investigate the water absorption of geopolymer samples made from clay brick waste powder; according to their results, water absorption was decreased by replacing slag with the clay brick powder in geopolymer samples (Zawrah, Gado, Feltin, Ducourtieux and Devoille, 2016). Also, in ceramic-based geopolymeric samples, With the increment of the clay brick powder, water absorption was decreased (Khater, El Nagar and Ezzat, 2016).
- Geopolymer samples achieved most of their strength at an early age, so there was little difference between the 7 and 28-day strength.

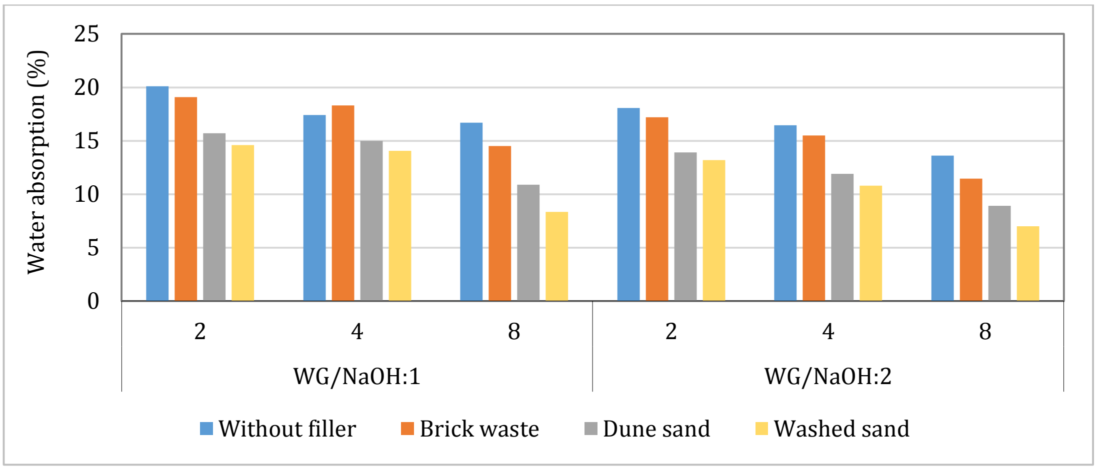
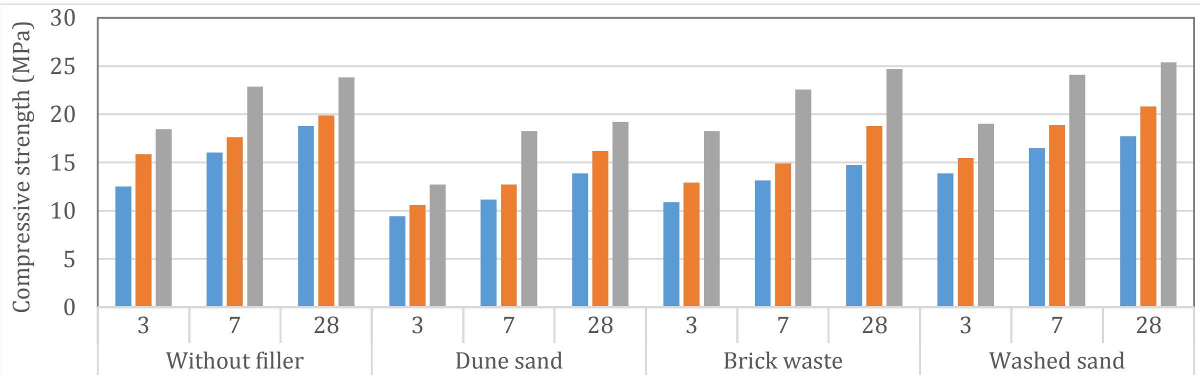


Fig. 7. Water absorption of 28-day cubic geopolymer samples (in the samples made with the filler, 50% filler replacement with the CBW powder was used).

3.3. Compressive strength and water absorption of brick-shaped geopolymer samples

According to Fig. 8, the results related to the compressive strength of geopolymer brick-shape samples (20×10×5 cm) were similar to those of geopolymer cubic samples; by increasing the concentration of sodium hydroxide solution, the compressive strength was raised. Clay brick specifications, according to the 5th National Building Regulations in Iran, are presented in Table 4. The 28-day average compressive strength of brick-shaped geopolymer samples was 19.2-25.4 MPa; so they could replace different types of clay brick (except for engineering brick grade 1). Moreover, the 28-day compressive strength of brick-shaped geopolymer samples (19.2-25.4 MPa) was within the allowable range for several classes of bricks, according to ASTM 62 . The compressive strength could be promoted by increasing the curing temperature or time; however, this is another research study that is under investigation in a separate research project.

The results of the water absorption test on brick-shape geopolymer samples, as presented in Fig. 9, are similar to those obtained for cubic samples. In these bricks, the water absorption of all samples made with a mass ratio of WG/NaOH:2 was lesser than that of the samples made with a mass ratio of WG/NaOH:1. Among the samples constructed with various concentrations of NaOH, those made with an 8 M concentration of sodium hydroxide showed lower water absorption, as compared to 2 M and 4 M concentrations. Furthermore, the samples made without the filler had the highest water absorption, whereas those made with washed sand filler displayed the lowest one. Water absorption of the bricks with washed sand filler and dune sand was almost the same. According to Table 4, if we consider water absorption as another criterion for the quality of facade and built-in bricks, most of the brick-shape geopolymer samples with water absorption of 8-18% could be qualified; so, only bricks made with the 8 M washed sand filler (7.1% water absorption) might not be approved.



	Without filler 3	Without filler 7	Without filler 28	Dune sand 3	Dune sand 7	Dune sand 28	Brick waste 3	Brick waste 7	Brick waste 28	Washed sand 3	Washed sand 7	Washed sand 28
2	12.53	16.02	18.8	9.42	11.15	13.87	10.9	13.15	14.75	13.87	16.48	17.74
4	15.88	17.62	19.87	10.6	12.72	16.21	12.92	14.89	18.77	15.48	18.89	20.81
8	18.45	22.87	23.83	12.72	18.25	19.22	18.25	22.56	24.7	19.01	24.1	25.38

Fig. 8. Compressive strength of geopolymer bricks with WG/NaOH=2

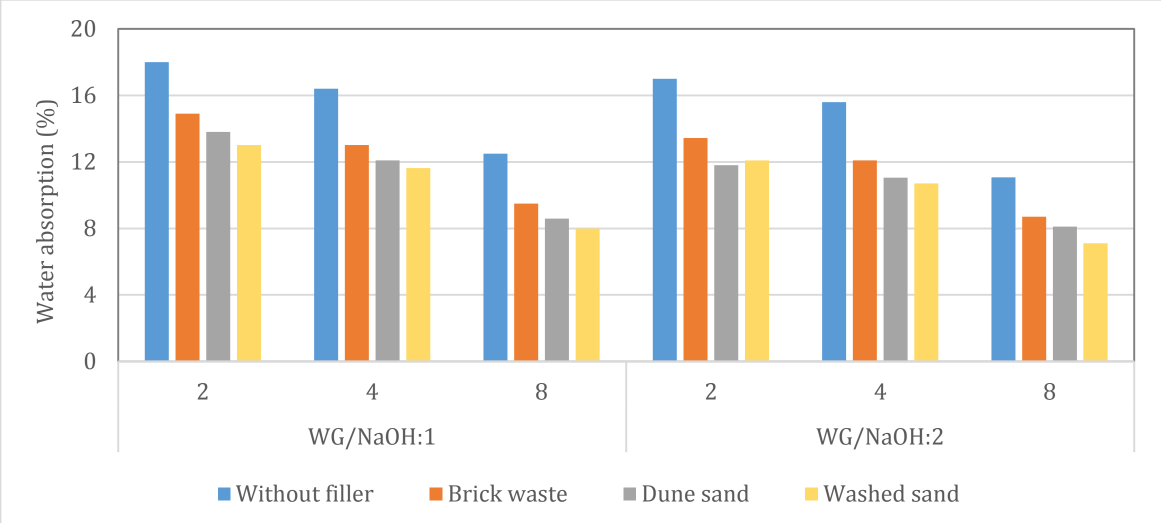


Fig. 9. The 28-day water absorption of brick-shaped geopolymer samples

Table 4. Clay brick specifications, according to the 5th National Building Regulations in Iran

Type of brick	Minimum compressive strength (MPa)		Maximum water absorption* (%)	
	Individual Brick	Average of Bricks	Individual Brick	Average of Bricks
Engineering brick (Grad1)	30	35	15	12
Engineering brick (Grad2)	20	25		
Facade brick (Grad1)	11	14	20	18
Facade brick (Grad2)	9	12		
Built-in brick (load-bearing)	6	8	-	-
Built-in brick (non-load bearing)	3	4	-	-

**Water absorption should not be less than 8%.*

3.4. FESEM Analysis

The SEM images of CBW powder-based geopolymer samples, including samples without filler (A), with the CBW filler (B), with the dune sand filler (C), and with washed sand filler (D), are presented in Fig. 10. A concentration of 8M sodium hydroxide and a ratio of WG/NaOH=2 were adopted to make these samples. For the geopolymer sample without filler, the high compressive strength was related to the lower voids (Fig. 10-A). Among the geopolymer samples made with various fillers, the samples containing washed sand (Fig. 10-D) had lower voids and micro-cracks when compared to the others (Fig. 10-B and Fig. 10-C); therefore, they had a higher compressive strength. The selected washed sand was procured from a sand-crushing plant in which high-quality sand and gravel grains were produced to make concrete. This high quality of the sieved washed sand used as the filler (2.36-4.75 mm in diameter) in the geopolymer sample promoted its compressive strength.

SEM images of the sample containing the dune sand at different magnifications are represented in Fig. 11. Because of the dissolution of CBW powder particles (diameter < 600 μm) as an alumina-silicate source with alkaline solutions, they were converted to a geopolymeric binder and were not visible in the images. Nevertheless, dune sand grains (300 μm in diameter) were calcareous and not dissolved in the alkaline solution; therefore, they were visible in the images.

3.5. EDAX and XRD examinations

The XRD examination of the CBW powder (top) and the CBW-based geopolymer sample (made with 2, 4 and 8M NaOH solution and WG/NaOH=2) is displayed in Fig. 12. As mentioned, the peaks of the CBW powder consisted of augite, quartz and dolomite. The patterns of XRD graphs were changed and a new material was created after geo-polymerization.

The EDAX examination of the CBW powder (top) and CBW-based geopolymer sample (made with 8M NaOH solution and WG/NaOH=2) is depicted in Fig. 13. For the geopolymer sample, the height of the peaks related to Si and Na for the geopolymer sample was increased, as compared to the CBW powder. Since, several days before FESEM-EDAX examination, the geopolymer sample was immersed in water (to eliminate the possible residual non-reacted NaOH and water glass raw materials in the produced matrix), the increased Si and Na were due to the produced geopolymer composition.

3.5. Economic consideration

According to the study conducted in this field by Thaarrini and Dhivya (2016), it was found that the cost of producing OPC mortar was higher than that of producing geopolymer mortar, which varied from 1.7 to 11 percent. For geopolymeric materials (such as mortars and brick), the costs of production include collecting construction derbies, grinding, sieving, separating the powder and aggregates of bricks, providing the sodium hydroxide and water glass to organize the alkaline solutions, mixing the prepared materials in mixers, casting and curing in industrial ovens, ensuring labor resources, shipping, and considering other miscellaneous costs.

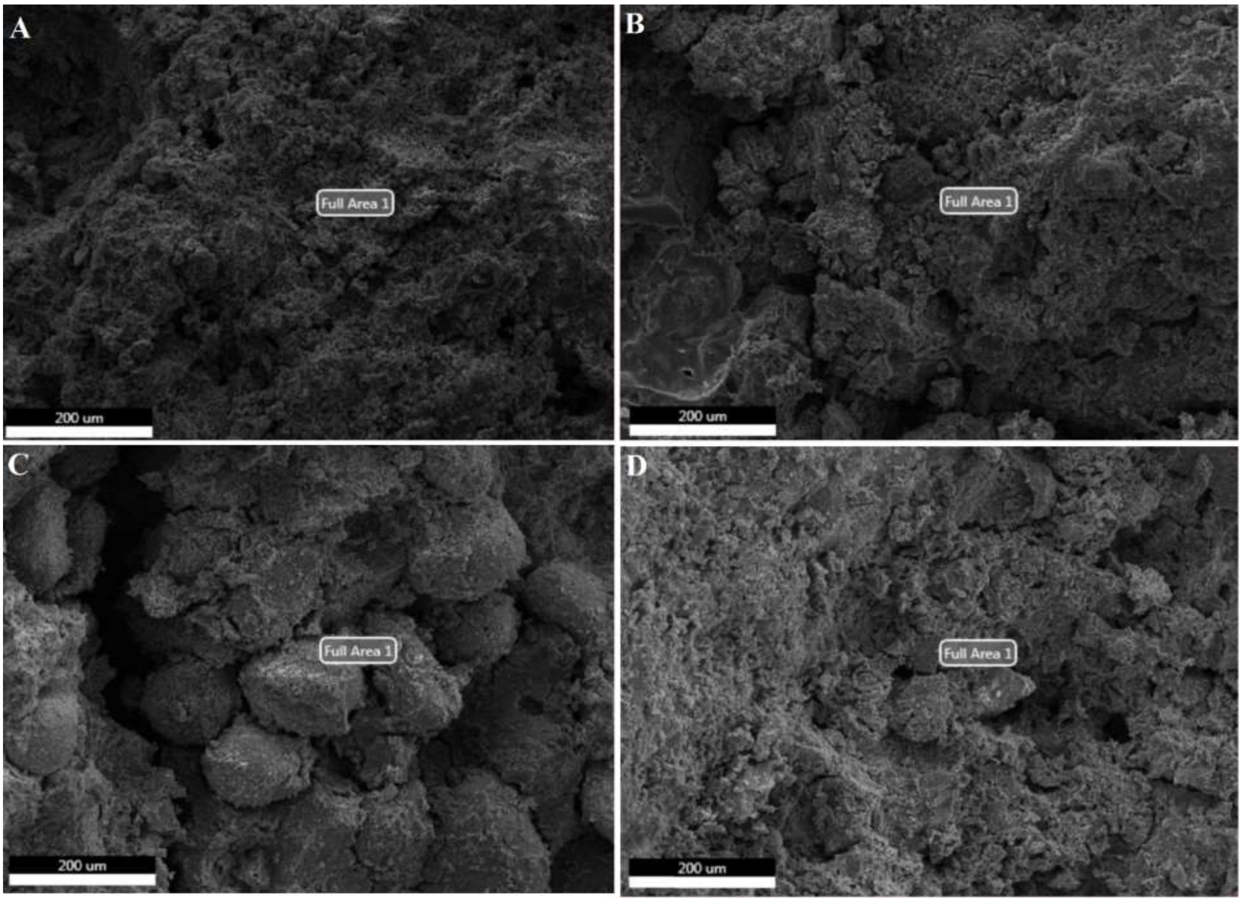


Fig. 10. SEM images of CBW powder-based geopolymer samples without filler (A), with CBW fillers (B), the dune sand filler (C), and the washed sand filler (D)

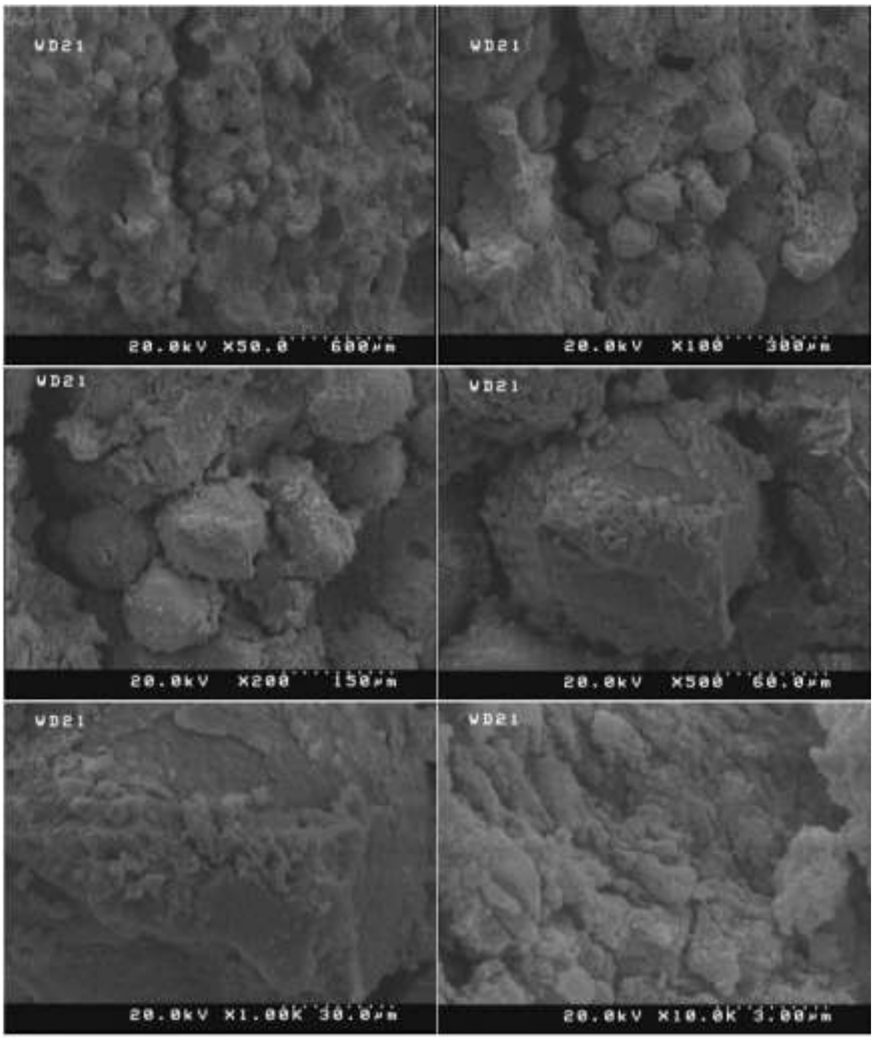


Fig. 11. SEM images of the sample containing dune sand at different magnifications

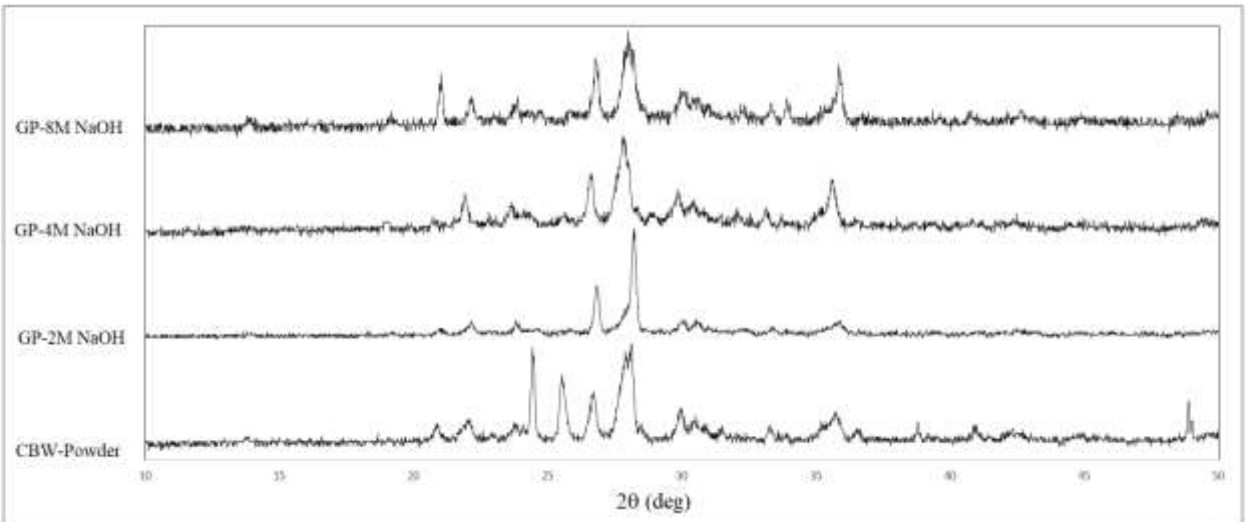


Fig. 12. XRD examination of the CBW powder and CBW-based geopolymer sample (made with 2, 4 and 8M NaOH solution, and WG/NaOH=2)

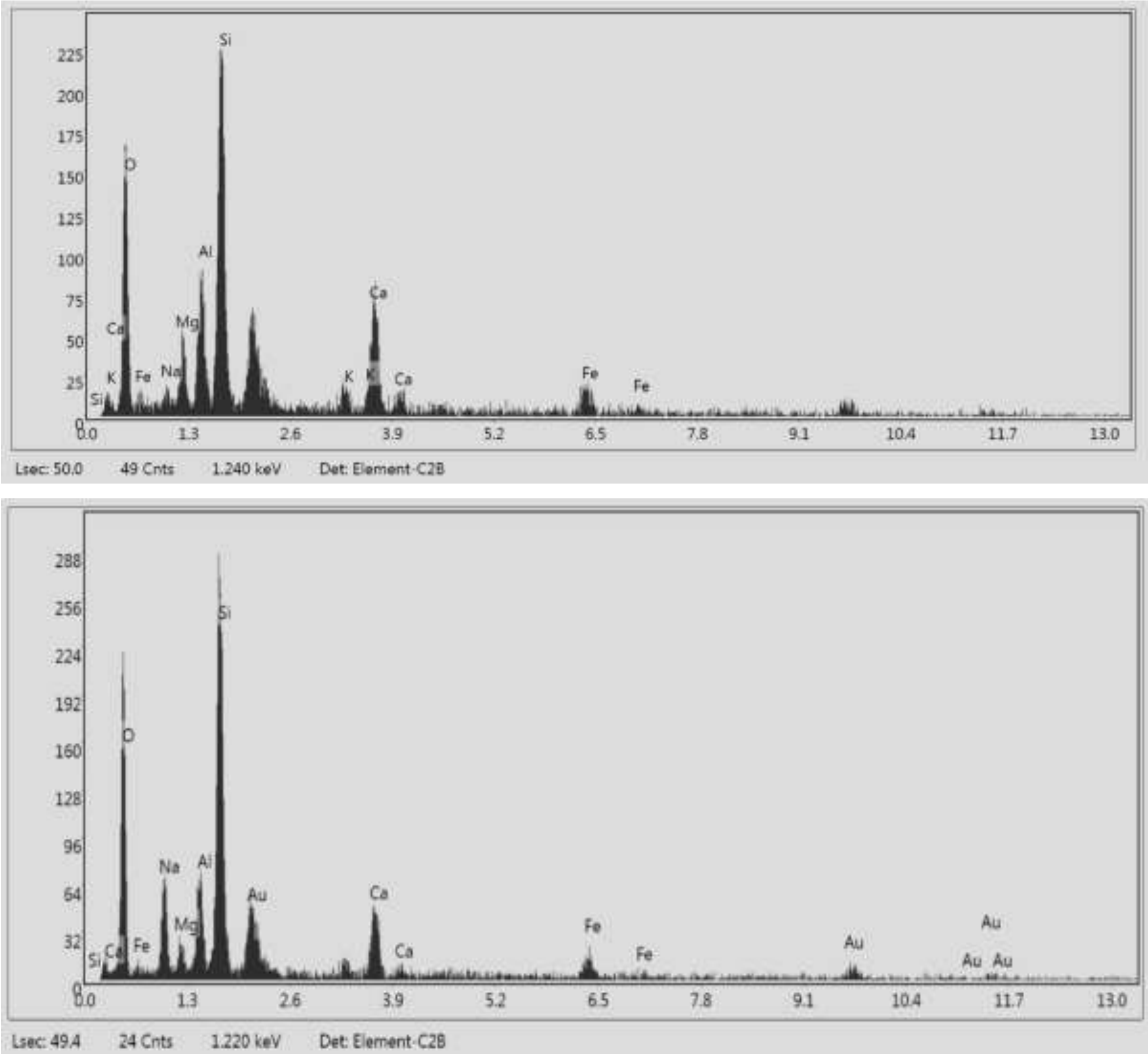


Fig. 13. EDAX examination of the CBW powder (top) and CBW-based geopolymer sample (made with 8M NaOH solution and WG/NaOH=2)

4. Conclusion

To mitigate the environmental impacts of clay brick manufacturing and its produced waste (CBW) after the demolition of old buildings, the production of new brick materials with eco-friendly technology, namely, geo-polymerization, is recommended. To reduce the cost of CBW-powder-based geo-polymeric bricks, materials such as dune sand, washed sand and CBW grains could be incorporated. The sustainable manufacturing of geopolymer bricks from CBW and inexpensive filler materials can be a step toward alleviating the environmental impact of construction and demolition waste. The important results of this study are as follows:

- The compressive strength test results of most samples (according to the regulations related to clay brick) were in the standard range. By further studies, such as changing the curing temperature, time or other effective factors, optimal values could be achieved for making CBW-based geopolymer bricks with the desired quality and price.
- The water absorption test results of some samples (according to the regulations related to clay brick) were in the standard range.
- Among the geopolymer bricks made with the filler, bricks constructed with washed sand filler had the highest compressive strength and the lowest water absorption percentage. A decrement of the production cost is a major advantage of using fillers in the matrix of geo-polymeric materials.
- Geopolymer samples constructed with an alkaline solution at a mass ratio of WS/NaOH=2 had higher compressive strength.
- Geopolymer samples attained most of their strength at an early age, so there was little difference between the 7- and 28-day strength.
- The increase in the concentration of the sodium hydroxide solution, the water glass-to-sodium hydroxide ratio, and addition of the filler played

significant roles in water absorption.

- The chemical properties of CBW change, depending on several parameters, including the raw materials, kiln type, building types and the years following building construction. Future studies should demonstrate the differences in the chemical properties of CBW materials prepared from various demolished buildings with different construction ages; they should also examine their effects on mechanical properties and durability of the produced geopolymer bricks.

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