Advances in Materials Research, *Vol. 14, No. 1 (2025) 31-42*
https://doi.org/10.12989/amr.2025.14.1.031

Compressive strength of geopolymer brick samples based on sand-washing waste with different particle sizes

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(*Received April 12, 2023, Revised October 6, 2024, Accepted November 28, 2024*)

Abstract. The objective of this study is to minimize the negative impact on the environment and maximize the use of natural resources by exploring the feasibility of manufacturing geopolymeric bricks from industrial waste in a sustainable and cost-effective manner. This study utilized waste from sand washing as a source of alkaline activators and aluminosilicate for the manufacturing of geopolymer bricks. Through the creation of various combinations with varying proportions of raw materials, the impact of these variables on the durability and mechanical characteristics of the bricks that are created has been assessed. Additionally, studies on the composition and structure of geopolymer bricks have been conducted using microscopic analyses such as EDAX, SEM, and FESEM. The findings demonstrate that waste sand can be used to create geopolymeric bricks with an appropriate water absorption rate (8% on average) and compressive strength (24 MPa). In addition, the hardening process and microscopic characteristics of geopolymeric bricks indicated their very low porosity. In conclusion, the compressive strength of geopolymer brick samples based on sand-washing waste with different particles sizes are increased when it was using pozzolanic sources containing aluminosilicate and alkaline activators.

Keywords: aluminosilicate; compressive strength; geopolymer brick; sand washing waste powder; sieve effect; water absorption

1. Introduction

As a new type of green material, the geopolymer has good engineering technical properties

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http://www.techno-press.org/?journal=amr&subpage=5 ISSN: 2234-0912 (Print), 2234-179X (Online)

(Marandi *et al*. 2023, Yao *et al*. 2021, Hang *et al*. 2019). Construction and demolition waste is a global concern and should be managed throughout the construction cycle (Esa *et al*. 2017, Mymrin *et al*. 2020, Abbas Kazmi 2020). The high durability against acid, fire, and various environmental conditions, high mechanical strength; low thermal exchange and low shrinkage are among the advantages of geopolymer materials (Duxson *et al*. 2007, Davidovits 1991). Sand washing waste is a waste by-product that is annually produced from the manufacturing process of crushed aggregates (Park *et al*. 2016). The waste of sand washing factories (Sand washing waste) is released as waste into the environment in the process of producing sand materials, and due to its fineness, it is easily moved by the wind and causes many environmental hazards. In research, the use of 10-30% by weight of sand washing waste in the production of alkaline activated samples based on fly ash and slag has been investigated (Choi *et al*. 2010). Also, in another research, the use of this material as a supplementary cementitious material has been investigated (Restrepo-Baena *et al*. 2020, Ghiasi *et al*. 2023). In another research, the prediction of upgraded properties of the concrete with the washed sand waste has been evaluated (Patil *et al*. 2022). This waste was used as adsorbents for heavy metals and as a partial replacement for silica powder in extruded cement panels and making artificial aggregates (Song *et al*. 2014, Chin *et al*. 2000, Chang. *et al*. 2010). Also, it was used as filler to produce controlled low-strength materials and lightweight foamed concrete (Horiguchi *et al*. 2011, Kim *et al*. 2006). It was used for the stabilization of clayey soil with lime (Roohbakhshan and Kalantari 2016). This type of waste can often be used as a filler in the production of cement mortars and epoxy resins (Rajeshwar *et al*. 2020, Yemam *et al*. 2017, Lakhiar *et al*. 2022). With the enlargement of fly ash particle size, the unconfined compressive strength of fly ash foamed geopolymer samples decreases first and then increases, and the porosity and the quantity of middle and large macro-pores increase first and then decrease. Besides, 0.125~0.25 mm is the turning point for both of them. Bulk density, post-immersion absorption, and volume to permeable pore space ratio increased when fly ash with a smaller mean particle size distribution was used. Compressive strength was increased by using a finer particle size distribution. Particle size distribution has a potential effect on the durability of geopolymer concrete because it affects the permeable voids and immersion ratio (Xiong *et al*. 2019, Assi *et al*. 2018). The effect of fly ash particle size is more pronounced at the low temperature of reaction whereas, at the higher temperature, the negligible difference is observed in peak amplitude and required time to reach. The finer sizes are prone to dissolute into alkali solution and therefore, subsequent precipitation and further reaction rate improve (Nath and Kumar 2019, Ghiasi and Moradi 2018, Ghiasi and Mozafari 2018). For the fly ash based geopolymer samples, the compressive strengths of geopolymer formed by 45-lm (325 mesh) particle size had greater compressive strength in comparison with the coarser one. Apparent porosity was found to decrease with increasing fineness and addition of sodium silicate. Grinding decreased the mean particle size of raw fly ash by more than 50% and homogenized the particle size distribution. There was an increase in the specific surface area of the fly ashes with grinding, which contributed to their reactiveness. Consequently, specific compressive strength doubled for all geopolymer wood composites made from ground ash (Grinded fly ash) (Sharma *et al*. 2019, Asante *et al*. 2021). There is an increase in compressive strength with an increase in fineness (percentage of fine particle content) of the fly ash, irrespective of the activator type. This may be due to the increase in the specific surface area of the fly ash particles. A larger surface area means a large fraction of the molecules on the surface, making them easier to participate in the geopolymerization reaction with the binders. So, there will be a greater dissolution of fly ash particles in the activator solution leading to better chemical interactions between fly ash particles and activator solution leading to the formation of geopolymer composition (Kumar and Kumar 2011, Villaquirán-Caicedo *et al*. 2015, Turner and Collins 2013). Reactive ultra-fine fly ash has better reactivity than fly ash (Chen *et al*. 2021). The results indicate that the setting time of paste decreases with an increase in fly-ash fineness. The flow, strength, and drying-shrinkage characteristics of mortars were improved using fine fly ash (Chindaprasirt *et al*. 2011). For the coal gangue based geopolymer, the optimum particle size is 200 mesh (Li *et al*. 2021). For the volcanic ash based geopolymer, the resulting compressive strength is linearly affected by the average particle size distribution (Alanqari *et al*. 2022). The results showed that the dissolution efficiency of Al3+ and Si4+ decreased with an increase in the mean particle size, and the setting time and fluidity of the red-mud-based geopolymer increased with finer mean particle size, the compressive strength decreased first and then increased with the increment of red mud particle fractions, and the particles finer than 39 μm has the highest compressive strength of 7-day and 28-day (Zhang *et al*. 2020, 2021). The granularity of blast furnace slag powders made a great impact on the compressive strength of geopolymer. It was obvious that the optimum blast furnace slag granularity to prepare geopolymer was 0·053–0·075 m (Huang *et al*. 2015).

A significant environmental and financial concern is the production of waste from sand washing in the mining and building sectors. In addition to causing land occupancy, burying these wastes in the wild can pollute the ecosystem. However, there is a growing need for high-performing, eco-friendly building materials.

The feasibility of employing these wastes in the manufacturing of geopolymer bricks has been studied in this research with the objective of lowering the volume of sand washing waste and generating value-added construction materials. The superior mechanical and durability qualities of geopolymer bricks have drawn the attention of researchers as an ecologically benign substitute for conventional bricks.

2. Materials and equipment

The aluminosilicate material used to make the geopolymer brick samples in this research is the waste powder of the sand washing plant obtained from Zawaraq area of Bonab city. The sand particles left on the No 8 sieve (2.36-4.75 mm) were used as filler. The oxide compounds in the sand washing waste powder are based on the results of XRF analysis according to Table 1. To prepare the alkaline activator solution, sodium hydroxide (Chlor Pars company profit 99%) and the characteristics of industrial glass water according to Table 2 with a Ratio: of 2/4 were used. Municipal drinking water was used to make a sodium hydroxide alkaline solution. The tools and equipment used in this research include an oven, a pan mixer, a 5 x 20 x 10 cm rectangular wooden mold, a vibrator, and a mortar breaker.

Table 1 Oxide compounds present in sand washing waste powder, based on XRF analysis results

SiO_2	Al_2O_3	CaO	Fe_2O_3	MgO	Na_2O	K_2O	TiO_2	P_2O_5	SO_3
58.84	16.89	10.88	4.72	3.38	2.36	1.85	0.72	0.25	0.11

Table 2 Characteristics of the glass water used

Ratio	Na_2O %	SiO_2 %
2.4	13-13.89	31.2-33.33

Fig. 1 Samples of geopolymer brick made based on sand washing waste powder with sand filler

3. Methods

To create samples of geopolymer bricks, sodium hydroxide solutions of 4, 8, and 12 M were utilized. The mass ratio of glass water to sodium hydroxides 1 and 2 was selected to prepare the alkaline activating solution. For example, the name of the G-F 12-2 geopolymeric mortar sample indicates the use of 12 M sodium hydroxide solution and the mass ratio of glass water to sodium hydroxide solution of 2. The sand washing waste powder passed from the No 50 sieve (particle size < 300 μm) and sieve No100 (particle size < 150 μm) was selected as aluminosilicate base solid material, and the sand filler left on sieve No 8 was selected as filler. Then the powder of sand washing waste and sand filler was poured into a plastic container, and an alkaline activator was slowly added to it and mixed. Then the mentioned materials were poured into a pan mixer, and after 5 minutes of complete mixing, the materials were poured into 5x20x10 cm wooden molds and vibrated on a vibrating machine. An image of the geopolymer brick samples made according to Fig. 1 is given.

The samples (3 samples from each test design) and the mold were cured for three days in an oven with a certain temperature (100 degrees Celsius) and a compressive strength of 7 and 28 days after leaving the oven and cooling down by a jack-mortar machine. Measured and the average compressive strength of three samples was calculated. Water absorption of each mixing plan with different molarity was also done at the age of 7 and 28 days. The test schedule and mixing plan of geopolymer brick samples are according to Table 3. Several clay brick samples were also purchased from the market and subjected to pressure and water absorption tests as control samples (with the plan of mixing clay, silica sand, and water and baking in a furnace at a temperature of 1000 degrees Celsius).

In this study, a comprehensive experimental design was taken into consideration in order to examine the impact of various parameters on the compressive strength of geopolymeric bricks generated from waste from sand washing. The concentration of sodium hydroxide solution, the water glass to sodium hydroxide ratio, and the size of the aluminosilicate raw material’s particles were among the variables examined in this study. Different geopolymer brick samples were made, and their compressive strength was tested at different ages by varying the amounts of each of these components. As a consequence, the impact of every parameter and the ways in which these elements

Table 3 Testing schedule and mixing plan of geopolymer brick samples

Number	Sample name	Ratio of activator to pozzolan	Mass of consumables (grams)				Number of samples
			Sand washing waste powder	Sand filler	Sodium hydroxide solution	Glass water	
1	G-F 4-1	0.45	950	950	213/75	213/75	4×3
2	G-F 4-2	0.45	950	950	142/5	285	4×3
3	G-F 8-1	0.45	950	950	213/75	213/75	4×3
4	G-F 8-2	0.45	950	950	142/5	285	4×3
5	G-F 12-1	0.45	950	950	213/75	213/75	4×3
6	G-F 12-2	0.45	950	950	142/5	285	4×3

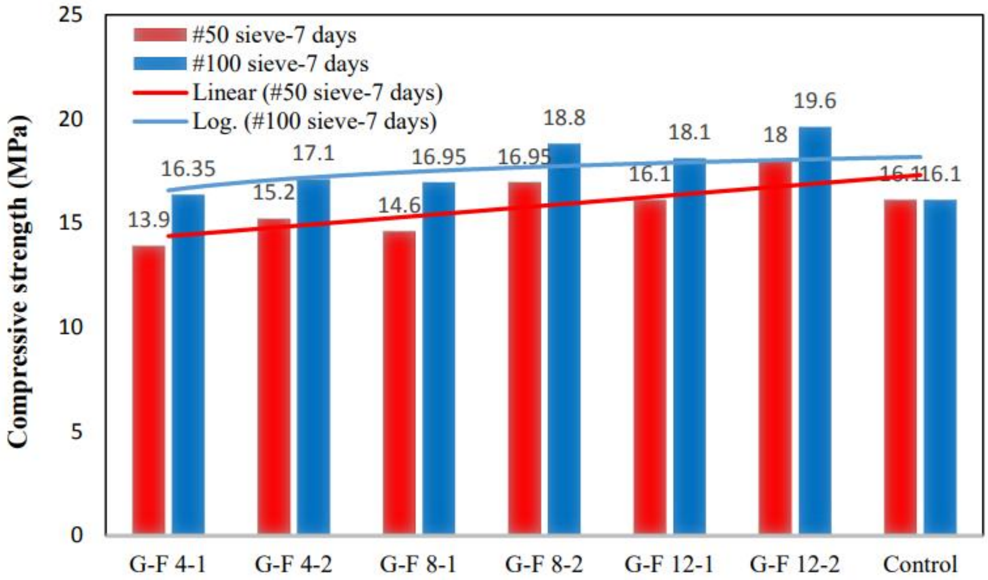

Fig. 2 7-day average compressive strength of geopolymer brick samples

interact with one another on compressive strength were examined, and the outcomes were visually shown in figures. The development of novel uses for this kind of building material as well as the improvement of the production process for geopolymer bricks with the highest compressive strength were made possible by the research's findings.

4. Compressive strength results

The specific weight of ordinary pressure brick is 1700 kg/m3, the weight of one brick is about 1800 gr, and the number of bricks per ton is about 500-550. The geopolymer brick based on sand washing waste introduced in this study also has similar weight characteristics.

The average compressive strength of 7 and 28 days of geopolymer brick samples is presented according to the graphs in Figs. 2 and 3, respectively, for the bricks made from sand-washing waste

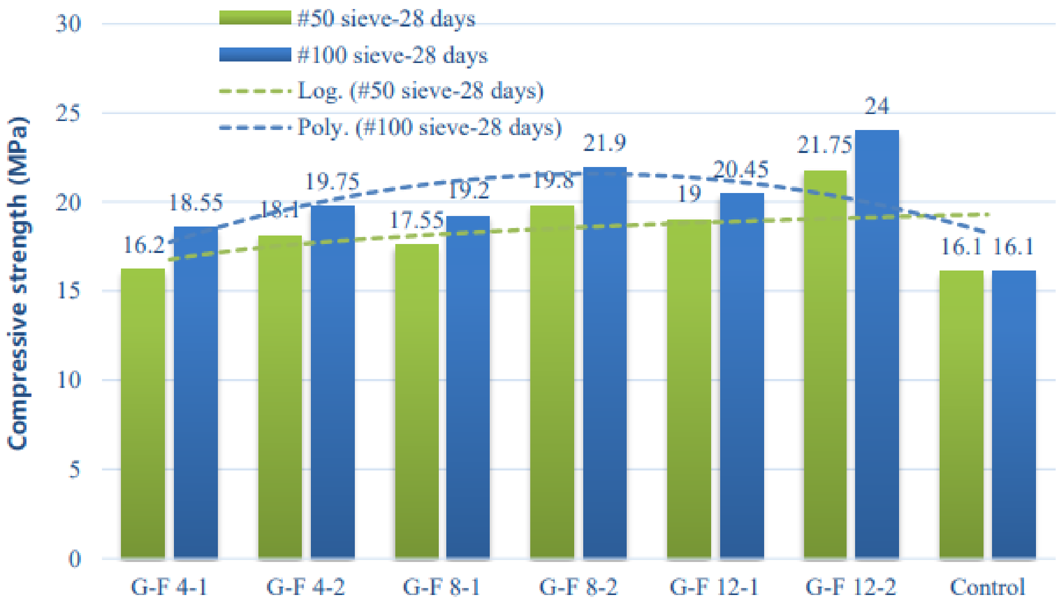

Fig. 3 28-day average compressive strength of geopolymer brick samples

powder passing through the No 50 and No 100 sieves. It can be seen that the 7-day compressive strength of all samples cured in the oven was more than 13 MPa. It is noteworthy that this high resistance is achieved at an early age. Also, for the use of finer particles (particle size < 150 µm), the highest resistance is in the concentration of sodium hydroxide solution of 12 M; the mass ratio of glass water to sodium hydroxide solution is 2 (21.75 MPa). The lowest resistance is also in the concentration of sodium hydroxide solution of 4 M and the mass ratio of glass water to the sodium hydroxide solution 1 (13.9 MPa). For the case of using a sieve score of 100, the highest resistance is at the concentration of sodium hydroxide solution of 12 M. The mass ratio of glass water to the sodium hydroxide solution is 2 (24 MPa). The lowest resistance is also at the concentration of sodium hydroxide solution was 4 M, and the mass ratio of glass water to sodium hydroxide solution was 1 (16.35 MPa). (Although, in this case, the pressure resistance of 8 M concentration is not significantly different from 4 M).

To better compare the effect of sieve size, the compressive strength of all samples at the age of 7 and 28 days are shown in Figs. 2 and 3, respectively. In the case of using sand-washing waste passing through a No100 sieve (particle size < 300 µm), the compressive strength of bricks is generally higher than in the case of using sand-washing waste powder passing through a No 50 sieve (particle size < 300 µm). This difference is 7.6 to 17.6 percent. It seems that the reason for this is the finer grains of sand washing waste powder and their higher specific surface area, which improves geopolymerization reactions.

Figs. 2 and 3 illustrate the small variation in compressive strength (average increase of about 15%) between the 7 and 28-day samples, which can be attributed to early oven curing. This had accelerated the geopolymer samples' setting time; the primary strength of these samples was attained after three days of oven curing. Furthermore, when the amount of aluminosilicate sources is increased, the adhesive particles' specific surface area increases, which enhances their reactivity

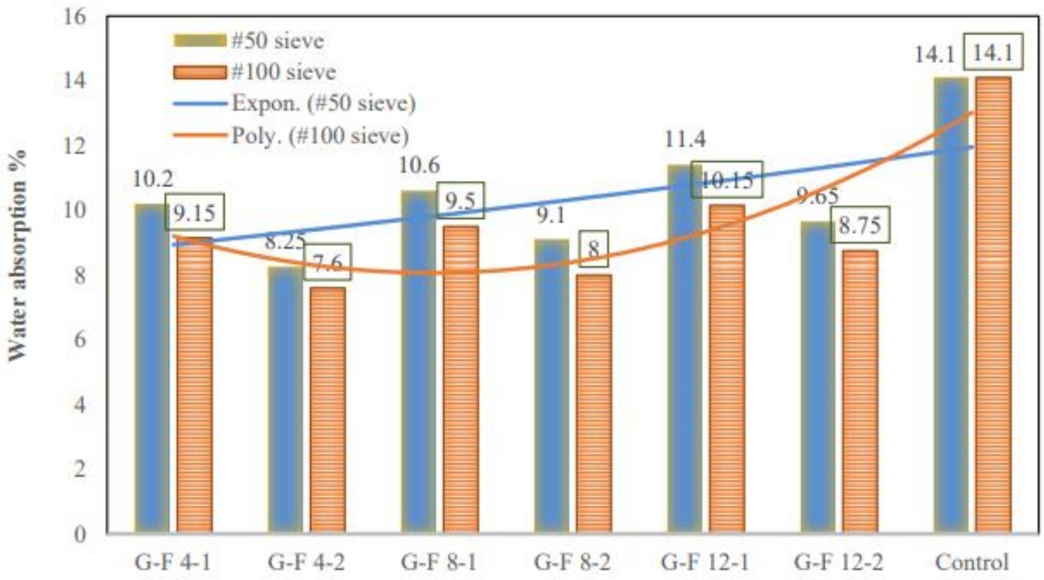

Fig. 4 The average percentage of water absorption of geopolymer brick samples

Table 4 General comparison between geopolymer and control samples

Variable parameter	Geopolymer brick	Control sample	Outcome
Compressive strength (MPa)	24	16.1	50% increase in geopolymer
Water absorption (wt.%)	8	14.1	38% reduction in geopolymer

with the alkaline solution, facilitates the easy formation of the geopolymer matrix, and increases compressive strength. As previously indicated, the compressive strength of the geopolymer samples increased practically linearly with increasing concentrations of glass water and sodium hydroxide solution. Thus, in 28-day samples produced with sieve #100, increasing the concentration of sodium hydroxide solution from 4 to 12 moles and the ratio of water glass to sodium hydroxide from 1 to 2 resulted in increases of around 11% and 30%, respectively.

5. Results of water absorption percentage

The average percentage of water absorption of geopolymer brick samples is presented according to the diagram in Fig. 4 for bricks made from sand-washing waste powder passing through the No 50 and No100 sieves. It can be seen that the percentage of water absorption of all the samples passing through sieve No 50 cured in the oven was less than 11.5%, and the samples passing through sieve No100 cured in the oven were less than 10.2%. The percentage of water absorption has also increased by increasing the concentration of sodium hydroxide solution and the mass ratio of glass water to sodium hydroxide solution. The highest percentage of water absorption of geopolymer brick samples is related to a 12 M sodium hydroxide solution with a mass ratio of glass water to sodium hydroxide equal to 1. The lowest percentage of water absorption is related to the samples made using

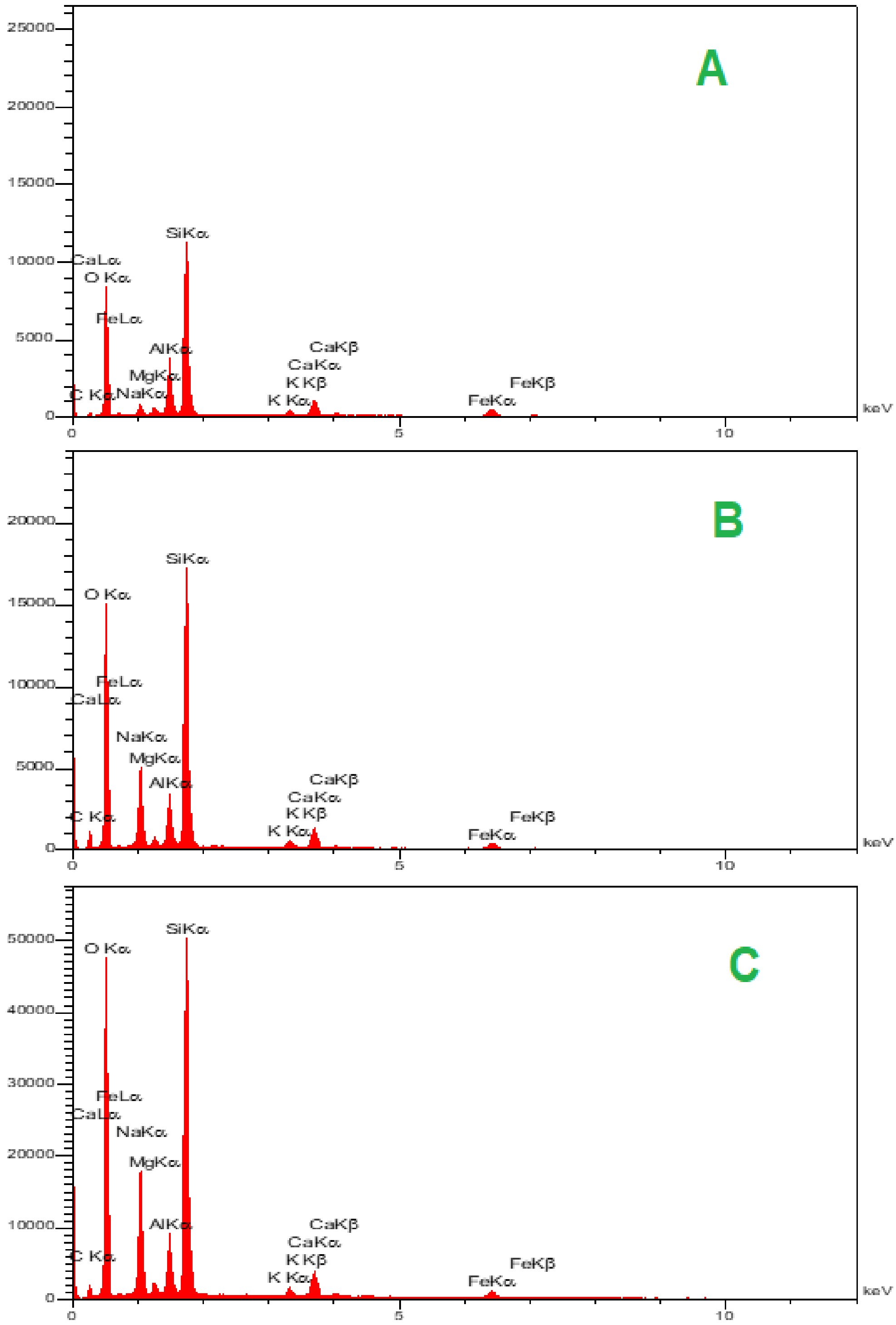

Fig. 5 EDAX analysis of sand washing waste residue sample (A) and geopolymer samples based on sand washing waste G-F 8-2 (B) and G-F 12-2 (C)

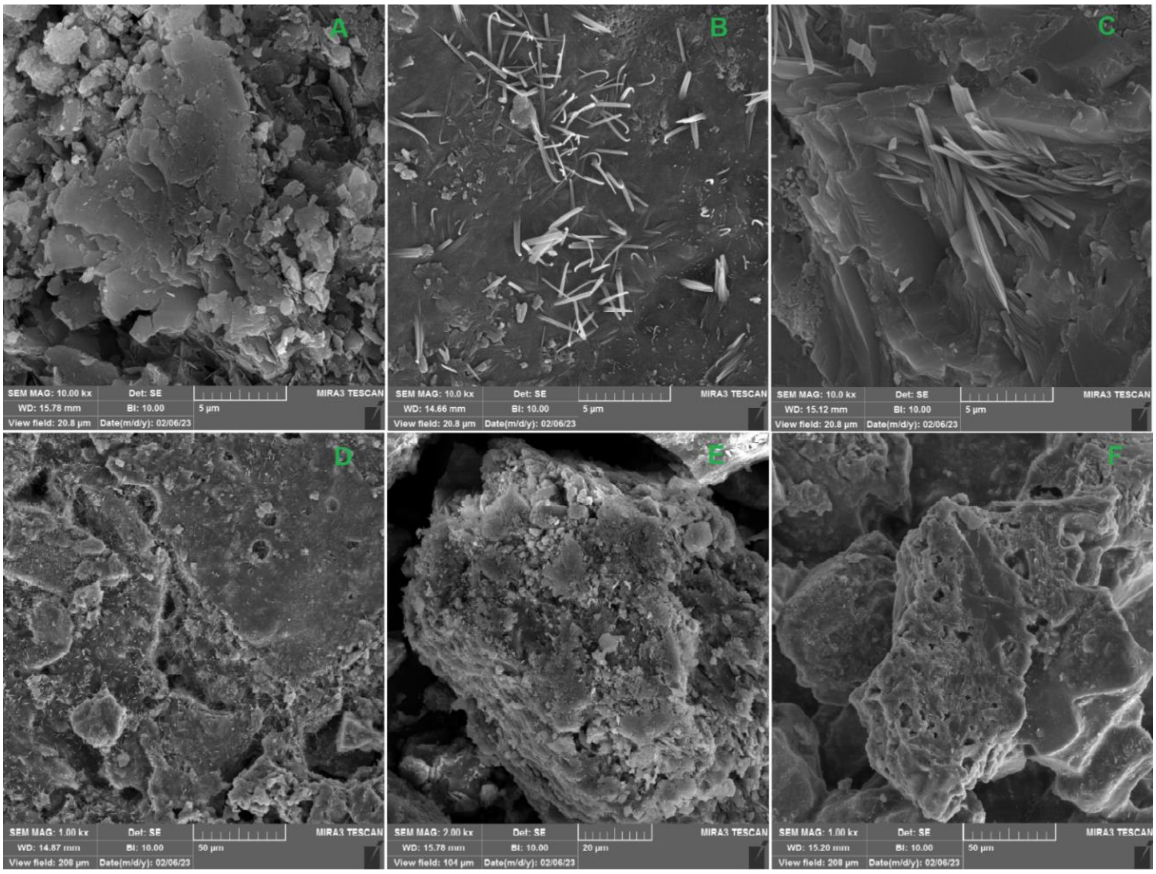

Fig. 6 SEM examination based on sand washing waste powder and geopolymeric samples

4 M sodium hydroxide solution with a mass ratio of glass water to sodium Hydroxide equal to 2. Generally, the percentage of water absorption of geopolymeric bricks introduced here is 33 to 85.5% less than the control clay bricks. At the same time, it provides the minimum percentage of water absorption necessary for adhesion to the mortar.

Fig. 4 illustrates how water absorption increases linearly with sodium hydroxide concentration. However, when the ratio of water glass to sodium hydroxide is increased from 1 to 2, water absorption slightly decreases. The average water absorption of geopolymer samples is 38% lower than that of the control sample. In Table 4, a general comparison has been made between geopolymer samples and control samples.

6. FESEM, EDX analysis

EDX analysis of the powder sample of sand washing waste (A) and geopolymer samples based on sand washing waste G-F 8-2 (B) and G-F 12-2 (C) according to Fig. 5. But in geopolymeric samples, Na element was detected with a higher percentage. The weight percentage of sodium in sample G-F 8-2 and sample G-F 12-2 was reported as 13.21% and 15.51%, respectively.

SEM examination of sand washing waste powder (A, D), geopolymer sample G-F 8-2 (B, E), geopolymer sample G-F 12-2 (C, F) according to Fig. 6 with 10000 and 1000 magnification. FESEM examination of geopolymer samples (B, E) and (C, F) shows that the structure of geopolymer samples has completely changed compared to the powder materials of sand washing waste (A, D). Also, to increase the molarity of sodium hydroxide C to F, the porosity of geopolymer samples decreased. As a result of the use of added materials, new bonds have been formed, which has increased the strength and resistance of the raw material, which is shown in the sections of Fig. 6.

7. Conclusions

The present work represents a simple, innovative, environmentally friendly approach to geopolymer bricks production using recyclable sand-washing waste as a pozzolanic material. Mixing the alkaline activator solution with waste powder and sand filler, the cured brick at relatively low temperature showed high compressive strength within a very short time.

Comparison of the above with the traditional clay bricks gives a compressive strength to be within a comparable range (18.55-24 MPa), while water absorption has been considerably lower (about 8 wt.%). The above holds good for load-bearing or structural purposes. The results show that sand-washing waste can be a rewarding source for construction and help the building industry make developments toward attaining sustainability coupled with resource efficiency.

Acknowledgments

The research described in this paper was financially supported by Malayer University.

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