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Durability and fire resistance performance of slag-based geopolymer composites

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The fresh and durability properties of alkali-activated mortar were investigated in this study. Ground granulated blast-furnace slag was used as a binder material. Both carbon fibres (CF) and polypropylene fibres (PP) were added at ratios of 0, 0.75, 1.00 and 1.25% by weight of the binder. Simultaneously, hybrid fibres were also used (CF 1.0% and PP 0.25%, CF 0.5% and PP 0.5%, and CF 0.25% and PP 1.0%). The fresh properties of the composite were investigated by performing a flow test. Durability properties such as fire resistance, water sorptivity, water absorption, density, porosity, efflorescence and sulfate attack were also investigated. According to the findings, increasing the fibre content reduces the flowability of the mixture. Simultaneously, the best fibre content studied was 1%, which significantly enhanced durability properties. Also, both fibres achieved excellent improvement. However, carbon fibre had more influence than polypropylene fibre on durability properties.

Keywords: absorption/efflorescence/fibre-reinforced geopolymer composite/fire resistance/sustainable development

Notation

A	area sample bottom surface
D	oven-dried weight of the specimen
Q	discharge of water through material by suction
S	submerged weight of the specimen
W	saturated weight of the specimen

1. Introduction

Concrete is the world's second most utilised material, behind water, and is at the top of applied construction materials. Geopolymer material is on its way to becoming a widely used building material. Geopolymer properties are still being studied by researchers. Portland cement is an unsustainable material due to significant air pollution concerns and cement exploitation. The main properties of geopolymer composites are fire resistance, low cost and environmental friendliness.

Geopolymers are novel construction materials that can be used instead of conventional Portland cement. Geopolymers are alkali-bound materials such as ceramics, mineral polymers, inorganic polymer glass and alkali-activated cement. Davidovits was the first to establish the term 'geopolymer' in 1978 (Davidovits and Davidovics, 1991). The binder materials of geopolymer concrete contain aluminosilicate compounds. Aluminosilicate compounds include fly ash, granulated blast-furnace slag and metakaolin. In comparison with Portland cement concrete, geopolymer products release less carbon dioxide (CO_2) (Messina *et al*., 2018). The utilisation of by-product waste such as fly ash as a raw material in geopolymer addresses the concerns about the environment (Messina *et al*., 2015).

The reaction of aluminosilicate materials with alkali activators produces geopolymers. The chemical composition of aluminosilicate compounds includes a high concentration of silica and alumina. They are also referred to as preparatory materials or predecessors. As binder materials, natural resources such as metakaolin and clay minerals (Mawlod, 2020) are utilised. Among industrial waste items utilised as binder-based materials include fly ash (Torralvo *et al*., 2018), ground granulated blast-furnace slag (GGBFS) (Gok and Sengul, 2021) and silica fume (Kejkar and Wanjari, 2021). Agricultural waste is often used as a geopolymer base material in various applications. The mechanism by which geopolymers gain strength and harden is not the same as that of conventional concrete. Geopolymers have a compressive strength of up to 100 MPa (Davidovits and Davidovics, 1991). Geopolymers have excellent resistance to fire, acid and alkali–silica reaction. They are also inorganic and non-toxic and dos not burn or pollute the environment. Moreover, geopolymers use fewer resources throughout the manufacturing process (Davidovits and Davidovics, 1991).

The fire resistance of geopolymer composites must be examined at the micro, meso and macro levels before they can be utilised as a fire-resistant material (Lahoti *et al*., 2018). Many researchers indicated that when exposed to high temperatures, geopolymer composites remained stable (Barbosa and MacKenzie, 2003).

The fire resistance of a fly-ash-based geopolymer paste was investigated. It was discovered that increasing the temperature from 100 to 1100°C progressively decreases the compressive strength (Jiang *et al*., 2020). Hassan *et al*. (2020) studied the strength loss of geopolymer concrete under both ambient and heat-cured conditions. The loss of strength of ambient-cured geopolymer concrete was lower (27%) than that of heat-cured geopolymer concrete, which was 50%.

The inclusion of fibres improves the fracture toughness of concrete by minimising microcrack propagation when the material is subjected to stress and regulating the volumetric change of the sample during shrinkage (Li and Maalej, 1996), particularly when

the material is subjected to high temperatures. The performance of geopolymers reinforced with different fibres such as carbon (He *et al*., 2010), glass (Puertas *et al*., 2006), polypropylene (Zhang *et al*., 2009), steel (Bernal *et al*., 2010), wollastonite (Silva and Thaumaturgo, 2003), poly(vinyl alcohol) (Zhang *et al*., 2006) and basalt (Li and Xu, 2009) fibres has been investigated.

Fibres reduce autogenous and drying shrinkage and enhance volumetric stability at room temperature. In general, adding fibres at an adequate ratio increases dimensional stability in terms of limiting thermal contraction and enables resisting temperatures of up to 1000°C, according to the findings (He *et al*., 2010). It is possible that this is due to a stronger connection between the fibre and the matrix interface. However, when subjected to temperatures over 1400°C, the fibres disintegrate, causing the mechanical qualities to degrade (Zhang *et al*., 2014). For fire-resistant applications, fibre-reinforced geopolymers were studied. Carbon fibre was shown to improve the performance of geopolymers at temperatures ranging from 200 to 500°C. At 700°C, carbon fibre had no obvious influence on compressive strength.

Furthermore, it was discovered that, among other fibres, polypropylene fibre was the most suitable for thermal insulation applications and lightweight materials. This phenomena may also be seen in geopolymers that can endure temperatures of up to 900°C (Aygörmez *et al*., 2020). Polypropylene fibre is inexpensive and extremely resistant to environmental abrasion (Bindiganavile *et al*., 2016).

Polypropylene fibre was investigated to decrease concrete spalling after an explosion. Two key reasons contributing to concrete spalling are increased pore pressure and the creation of thermal stress (Khaliq and Kodur, 2018). Polypropylene fibres were shown to reduce spalling induced by pore pressure. Furthermore, polypropylene fibres have minimal influence on thermal stress. This might be due to a flaw in the usage of polypropylene fibre in avoiding concrete explosions.

Because of their limited porosity, slag-based geopolymer composites can withstand the corrosive effects of chlorides and sulfates (Puertas *et al*., 2002). They also have high compressive strength and low hydration heat (Bilim and Atiş, 2012; Rashad, 2013; Rodríguez *et al*., 2008). However, they have a significant rate of drying shrinkage (Krizan and Zivanovic, 2002; Melo *et al*., 2008; Palacios and Puertas, 2007). The addition of short fibres to brittle materials such as concrete can decrease shrinkage and increase tensile strength (Aly *et al*., 2008; Borja Varona *et al*., 2015). The impact resistance of slag-based geopolymer concrete was considerably improved by replacing aggregate with crump rubber (Aly *et al*., 2019; Niş *et al*., 2022).

Alves *et al*. (2021) investigated the bond performance of slag-based geopolymers with carbon and glass fibres. It was concluded that carbon fibre with a 20 mm embedded length showed significant bond performance.

Türkmen *et al*. (2016) studied the fire resistance performance of slag-based geopolymer concrete. It was concluded that slag-based geopolymer concrete showed better performance compared with conventional concrete. Aljanabi *et al*. (2022) and Kadhim *et al*. (2022) investigated the residual strength of lightweight aggregate fibre-reinforced geopolymer composites. It was stated that the strength of a geopolymer composite subjected to 250°C was improved due to further geopolymerisation. Gülşan *et al*. (2019) and Niş *et al*. (2021) studied the fresh properties of fly ash/slag-based geopolymer containing steel fibre. It was explained that steel fibre had a negative impact on the flowability of the fresh mixes.

According to researchers, the chemical reaction between aluminosilicate materials and alkali solutions is an endothermic reaction. Utilising fly ash as a base material, which requires heat for curing, limits the application of geopolymers (Noushini *et al*., 2016). Noushini *et al*. (2016) revealed that 18 h and 75°C were the optimum curing time and temperature. Researchers are trying to produce ambient-cured geopolymer composites to overcome this limitation. According to studies, hydration and geopolymerisation in materials such as slag generate calcium silicate hydrate and sodium aluminosilicate hydrate gels, which may achieve high compressive strength and sulfate attack resistance (Bernal *et al*., 2012; van Deventer *et al*., 2015; Winnefeld *et al*., 2015; Yang *et al*., 2012). Researchers indicated that increasing the slag content improves compressive strength, decreases flowability and accelerates the setting time (El-Hassan and Ismail, 2018). Geopolymer mixtures with a high slag content are more suitable for ambient curing and on-site application.

There have been fewer research studies that have focused substantially on the durability characteristics of ambient-cured fibre-reinforced slag-based geopolymer mortar. As a result, the purpose of this study is to investigate the influence of carbon fibre, polypropylene fibre and hybrid fibres on the fresh and durability characteristics of geopolymer mortar. The fibre-reinforced slag-based geopolymer composite can be proposed for the production of tunnel lining segments, as these items are more vulnerable to fire risk and weather action, such as those durability properties that were studied in this experimental work.

2. Experimental programme

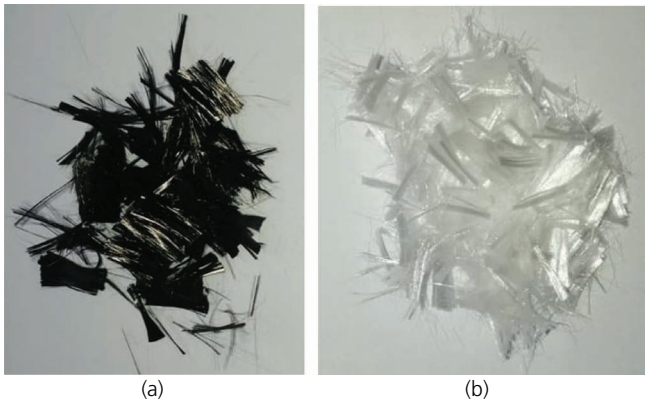
2.1 Materials

Geopolymer composite samples were prepared using GGBFS as the base material, which was obtained from the company Don Construction Products (DPC) in Erbil, Iraq. The chemical composition of the slag is shown in Table 1. The geopolymer was reinforced using carbon and polypropylene fibres from the company Sika in Erbil, Iraq, as shown in Figure 1. The properties of the fibres are presented in Table 2. Sodium hydroxide (NaOH) in flake form with a purity of 99% was used to produce a solution with a concentration of 12 M. The used alkali activator was a mixture of sodium silicate (Na_2SiO_3) with sodium hydroxide solution with a ratio of sodium silicate/sodium hydroxide = 2.5 (Kwek *et al*., 2021). Both activators were provided by DCP. High naphthalene content

Table 1. Chemical composition of GGBFS

Oxide/ property	Silicon dioxide (SiO_2): %	Aluminium oxide (Al_2O_3): %	Calcium oxide (CaO): %	Iron (III) oxide (Fe_2O_3): %	Magnesium oxide (MgO): %	Sulfur trioxide (SO_3): %	Sodium oxide (Na_2O): %	Potassium oxide (K_2O): %	SG	BF: m^2/kg
Value	28.17	8.572	47.75	0.414	3.805	1.452	0.021	0.295	0.76	419

SG, specific gravity; BF, specific surface area according to Blaine



(a) (b)

Figure 1. (a) Carbon fibre; (b) polypropylene fibre

superplasticiser admixture SP1 to gain a workable mixture and a shrinkage reducer admixture SP2 were utilised to minimise the drying shrinkage from a local Sika supplier under the brand name Sikament-1 N Plus. Locally available fine aggregate that conforms to ASTM C 33 (ASTM, 2007) was used.

2.2 Mixing, casting and curing

Sodium hydroxide flakes were melted in tap water and combined at a ratio of 2.5 with sodium silicate (Kwek *et al*., 2021) to prepare the alkali solution. Slag and fibres were combined 1:1 with sand under dry conditions. The alkali solution was mixed with the dry materials. The mixture was poured into moulds in two layers and manually compacted. Compressive strength and durability tests were conducted using cubic moulds with dimensions of 50 × 50 × 50 mm. The samples were put in a plastic bag to avoid drying shrinkage. Then, the samples were cured at room temperature for 28 days before being examined; the examination results are shown in Table 3. Some of the samples were cured in a magnesium sulfate solution with a concentration of 5% for 6 months.

2.3 Testing procedure

2.3.1 Flow table test

The flow table test is one of the methods for determining the workability and fluidity of a mixture. This test fulfils the requirements of BS 1881-105:1984 (BSI, 1984). Two equal layers of the mixture are placed within a cone. A wooden rod is used to tamp each layer ten times. The top of the mould is levelled after filling, and the cone is then raised vertically. After raising and lowering the table 15 times, the two diameters are measured. The fluidity is determined by taking the average of the two diameters. The apparatus used for conducting the test is shown in Figure 2.

2.3.2 Fire resistance

After 28 days of curing, samples with dimensions of 50 × 50 × 50 mm were tested. Three specimens for each combination were exposed to

Table 2. Physical and mechanical properties of carbon and polypropylene fibres

Type of fibre	Length: mm	Diameter: μ	Density: g/cm^3	Melting point: °C	Tensile strength: MPa	Modulus of elasticity: MPa
Carbon	20	8	1.82	180	4000	240 000
Polypropylene	12	32	0.91	160	30	7100

Table 3. Mix proportions of mixes

Mix	Code	Slag: g	Sand: g	CF: g	PP: g	Solution/binder	Alkaline solution: g	SP1: g	SP2: g
M0	F0	4750	4750	0	0	0.40	1900	285	95
M1	CF0.75	4750	4750	36	0	0.40	1900	285	95
M2	CF1.0	4275	4750	48	0	0.40	1900	285	95
M3	CF1.25	3800	4750	60	0	0.40	1900	285	95
M4	PP0.75	4750	4750	0	36	0.40	1900	285	95
M5	PP1.0	4275	4750	0	48	0.40	1900	285	95
M6	PP1.25	3800	4750	0	60	0.40	1900	285	95
M7	CF1.0PP0.25	4750	4750	48	12	0.40	1900	285	95
M8	CF0.5PP0.5	4275	4750	24	24	0.40	1900	285	95
M9	CF0.25PP1.0	3800	4750	12	48	0.40	1900	285	95

CF, carbon fibre; PP, polypropylene fibre

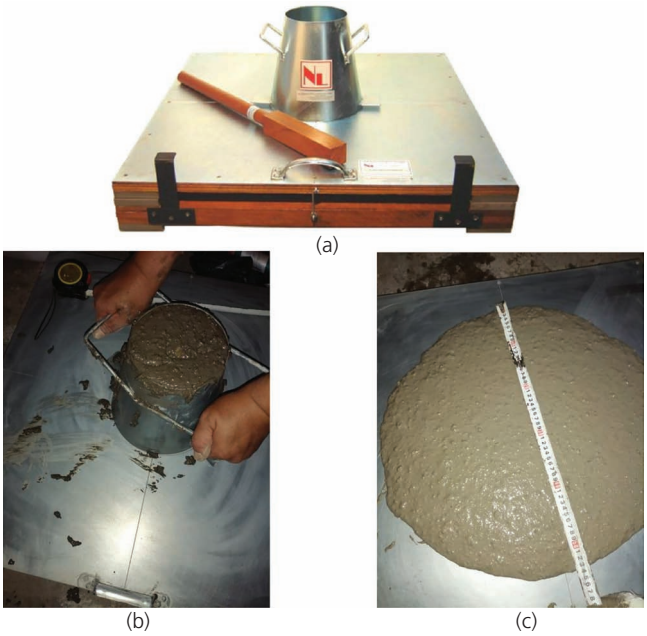


Figure 2. Cone and table used to conduct flow table test and evaluate the flowability of the mixture: (a) flow table devices; (b) compacted fresh geopolymer mortar inside the cone; (c) flowed geopolymer mortar

temperatures of 750 and 1000°C for 2 h, as shown in Figure 3. The samples were allowed to cool to room temperature. The apparent density was recorded, as well as the residual compressive strength.

Figure 3. Furnace with 1200°C temperature

2.3.3 Water sorptivity

Water sorptivity is the ability of a material to absorb water by suction. It is one of the properties related to the durability of the material and is measured by evaluating the entrance of water through the material. The water sorptivity of alkali-activated mortar was tested according to the ASTM C 1585 standard (ASTM, 2011). Three 50 × 50 × 50 mm specimens from each mix were utilised to determine the water sorptivity of the alkali-activated specimens. In an oven, the specimens for each mix were dried to a constant mass at 105°C. After drying, the specimens were removed and cooled to room temperature before being covered with silicone sealant to prevent water from entering from the sides, as shown in Figure 4. They were then maintained in water at a depth of no more than 4 mm above the bottom of the sample. The wetted height of the specimen was calculated by dividing the increase in the mass of the specimen weighed at different time intervals by the bottom surface area of the specimen and the density of water. These numbers were plotted against the square root of time, and the sorptivity index of the mortar was computed using the slope of the best-fit line.

2.3.4 Water absorption

Water absorption refers to the capacity of a material to absorb and retain water under specified conditions. A water absorption test may be used to assess the durability of materials. In this investigation, three specimens of each mix were dried to a constant mass in an oven at 105°C for 24 h. Following that, the specimens were allowed to cool to room temperature. The specimens were submerged in water for 24 h to determine their saturated mass. Water absorption is defined as the percentage increase in mass to dry mass.

$$\text{WA}(\%) = \frac{W - D}{D} \times 100 \quad (1)$$

where WA is the amount of water absorbed and D and W are the oven-dried weight and saturated weight of the specimen, respectively.

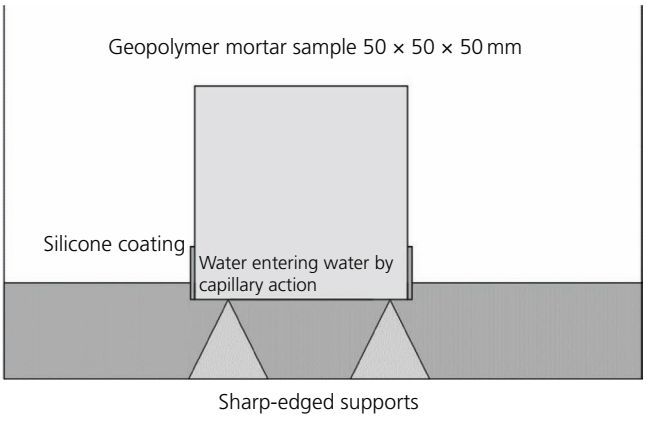


Figure 4. Sorptivity test for geopolymer mortar

2.3.5 Density

The density of a material indicates the presence of pores inside it. To determine the density, the following actions were performed: The samples were dried by placing them in an oven at 105–115°C for 24 h. The samples were allowed to cool for 30 min at room temperature. The weight of the samples was recorded and taken into account (D). The samples were then submerged in water at a temperature of 20 ± 2°C for 24 h. After 3 min, the specimens were removed from the water and cleaned with a moist towel. Following that, the samples were weighed again and the weight was recorded as W. The weight of the empty basket in water was determined using a balance and an appropriate device for suspending the sample container in water. The sample was placed in a basket, and the weight of the fully saturated samples was determined using a balance and appropriate apparatus for suspending the sample container in water. The weight of saturated samples (S) was then calculated by subtracting the weight of the empty basket from the weight of the basket containing the sample:

$$2.\quad \text{density} = D/(W - S)$$

where W refers to the saturated surface dry weight, D refers to the oven-dried weight and S refers to the submerged weight.

2.3.6 Porosity

Porosity is substantially affected by the microstructural characteristics of particles with silica and calcium content in the binder material. As porosity rises, permeability also increases. A durable material should have low water absorption and permeability. The porosity test, in general, reveals the accessible voids and the volume percentage of the structure. Greater compressive strength is obtained from specimens with lower porosity (Thokchom *et al*., 2009).

$$3.\quad \text{porosity} = (W - D)/(W - S) \times 100\,\%$$

where W indicates the saturated surface dry weight, D indicates the oven-dried weight and S indicates the submerged weight.

2.3.7 Efflorescence

In accordance with the Iraqi standard IQS 24-1988 (IQS, 1988), one of the six faces of the sample was placed vertically in a tray dish containing 25 mm of water at room temperature (20–30°C) for 7 days until the entire water was absorbed or evaporated. The dish was refilled with water to a depth of 25 mm, and the sample was allowed to absorb the water. The sample was then dried for 3 days at room temperature in the same dish. The efflorescence rate was then computed using the following equation:

$$\text{efflorescence rate}\ (\%) = \text{white deposited area/total surface area} \times 100 \qquad 4.$$

2.3.8 Sulfate attack

The cubic samples were submerged in magnesium sulfate solution with a concentration of 5%. After 6 months, a compressive strength test was conducted, and then the results were compared with those of the corresponding ambient-cured samples. Changes in the mass of the samples were also recorded. The surface of the samples was considered in terms of the appearance of any indication of sulfate attack.

3. Results and discussion

3.1 Flow table test

Figure 5 shows how the flowability of mortar varies with fibre type and content of the mixtures. Increasing the fibre content (carbon and polypropylene fibres) reduces the flowability of the mortar. Increasing the carbon fibre content to 0.75, 1.00 and 1.25% reduces the flowability of the fresh mixture by 43, 47 and 55%, respectively. Increasing the polypropylene fibre content to 0.75, 1.00 and 1.25% reduces the flowability of the mixture by 42, 43 and 45%, respectively. This is the result of the network space produced by randomly dispersed fibres (Zhao *et al*., 2009). Fibres improve resistance to flowability (Ranjbar *et al*., 2016; Zhang *et al*., 2009). Carbon fibre exhibited more flow resistance than polypropylene fibre due to its longer length, larger surface area and greater watertightness.

3.2 Fire resistance

Figure 6 shows the compressive strength of fibre-reinforced geopolymer mortar before and after being exposed to two high temperatures. The figure clearly shows that when the geopolymer composite was exposed to high temperatures, it considerably diminished the compressive strength. The geopolymer mortar lost 55–90 and 30–80% of strength at temperatures of 750 and 1000°C, respectively, when compared with the ambient-cured samples. The strength losses of the carbon fibre and polypropylene fibre-reinforced geopolymer mortar were 50–65 and 60–80%, respectively.

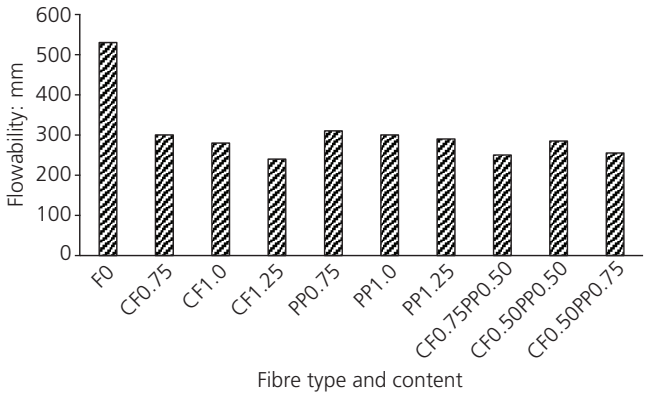


Figure 5. Influence of type and fibre content on alkali-activated mortar flowability

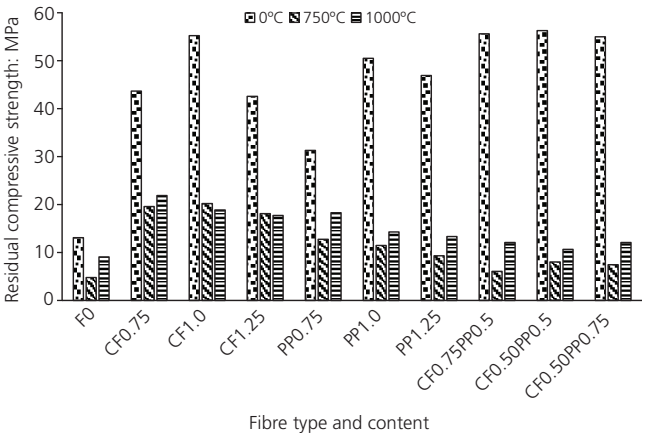


Figure 6. Effect of type and fibre content on the fire resistance of geopolymer composites

Partially melted fibres at high temperatures lead to minimising internal thermal stress. Increasing the carbon and polypropylene fibre content to 0.75, 1.00 or 1.25% increases the residual strength of the mixture slightly. Increasing the melted fibre content means increasing the pore content, as melted fibres lead to a loss in compressive strength. Polypropylene fibres are known to melt at roughly 165°C (Sayyad and Patankar, 2013). At ambient curing, it appears that the bond performance and bridging fracture mechanism produced by fibres are most effective at mild and low temperatures, as shown in Figures 7(c) and 7(d). However, at high temperatures, such processes appear to be offset as shown in Figures 7(a) and 7(b), perhaps by the previously noted non-uniform thermal deformation in the matrix and melting of the polypropylene fibre (Bindiganavile *et al*., 2016).

3.3 Water sorptivity

Figure 8 presents the effect of fibre type and content on water sorptivity test findings. It was noted that increasing the fibre content decreases water sorptivity. Increasing the fibre level from 0 to 0.75–1.00% reduces the water sorptivity of the mixture significantly. Following that, a further increase in fibre content of 1.25% resulted in an increase in water sorptivity. This might be because the extra fibres were not equally distributed in the matrix, resulting in an uneven structure (Behfarnia and Rostami, 2017). According to the findings, the optimal fibre incorporation ratio was 1%.

3.4 Water absorption

The results of the water absorption test are presented in Figure 9. It is self-evident that increasing the fibre content reduces water absorption to some extent. Increasing the fibre level from 0 to 0.75–1.00% reduced the water absorption of the mixture considerably. Following that, every increment in fibre content of 1.25% produced an increase in water absorption. This might be owing to the limiting shrinkage and microfractures of the fibres. Polypropylene fibre is more effective than carbon fibre at reducing water absorption. The random dispersion of fibres recovers microfractures and prevents new ones from growing in the geopolymer matrix. This process causes the density of the geopolymeric matrix structure to increase, resulting in a reduction in water absorption capacity (Zhang *et al*., 2009). Excessive fibres will not be uniformly distributed in the matrix, resulting in an uneven structure. Furthermore, when the fibre is added, holes and cavities occur, increasing the water absorption of the mixture. Besides, the creation of extremely small holes at the concrete–fibre interface during mixing might be another cause of the increased permeability of the mixture (Behfarnia and Rostami, 2017). From the data, the appropriate incorporation of fibres was 1%.

3.5 Porosity

The porosity findings for the fibre-reinforced slag-based geopolymer mortar are shown in Figure 10. The results show that increasing the fibre content decreased porosity. Increasing the fibre content from 0 to 0.75–1.00% decreased the porosity of the samples. Following that, a further increase in fibre content of 1.25% resulted in an increase in porosity. This might be owing to the limited amount of material being properly mixed and compacted manually. The fibres prevent the opening of a shrinkage crack due to increasing porosity (Behfarnia and Rostami, 2017). The excessive fibres will not be equally distributed in the matrix, resulting in an irregular structure. According to the findings, the optimal fibre incorporation rate was 1%.

3.6 Density

The density of the fibre-reinforced slag-based geopolymer mortar is shown in Figure 11. The results show that when the fibre content increased, density increased considerably. Increasing the fibre content from 0 to 0.75–1.0% increased the density of the samples. Following that, a further increase in fibre content of 1.25% resulted in a reduction in density. The random dispersion of fibres stitches microcracks and prevents new ones from opening in the geopolymer matrix. This process causes the density of the geopolymeric matrix structure to increase (Zhang *et al*., 2009). Excessive fibres will not be uniformly distributed in the mixture, resulting in an uneven structure. According to the findings, the optimal fibre incorporation ratio was 1%.

3.7 Efflorescence

Figure 12 shows the efflorescence rate. It is obvious that increasing the fibre content minimises efflorescence. Increasing the fibre content from 0 to 0.75–1.00% reduced the efflorescence rate of the samples substantially. Following that, every incremental increase in fibre content of 1.25% increased the efflorescence rate of the mortar. Excessive fibres will not be uniformly distributed in the matrix, resulting in an uneven structure (Behfarnia and Rostami, 2017). According to the findings, the optimal fibre incorporation ratio was 1%.

3.8 Sulfate attack

3.8.1 Visual appearance

Figure 13 shows the appearance of the samples cured in magnesium sulfate solution with a concentration of 5% after 6

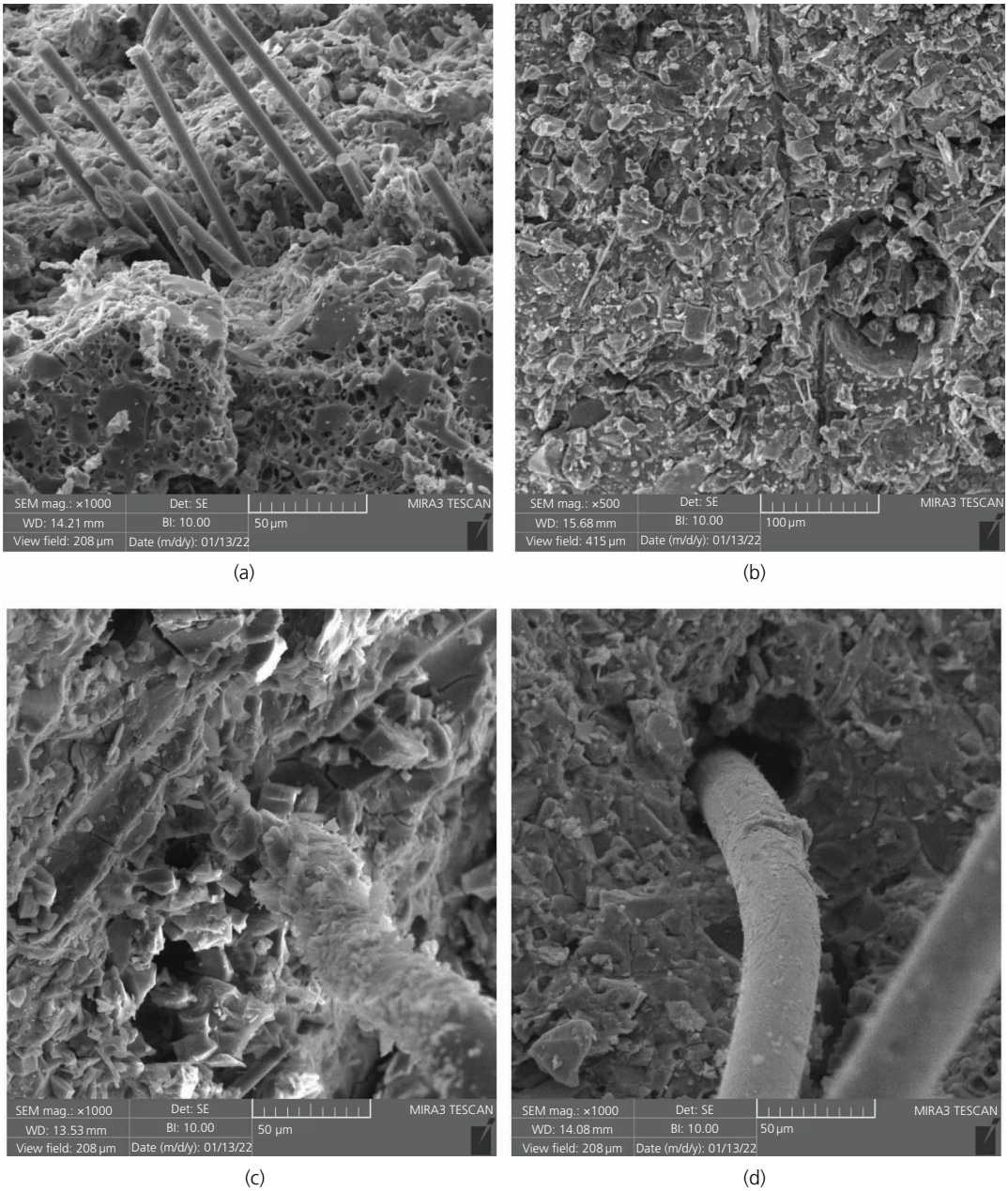


Figure 7. Carbon-fibre-reinforced geopolymer mortar: samples was exposed to (a) 750 and (b) 1000°C; (c, d) control samples

months. No indications of occurring chemical reactions were observed on the surface, such as white deposits, gypsum or ettringite formation, as what occurs in ordinary Portland cement concrete. Furthermore, no cracks or spalling were observed. The findings of Bakharev (2005) also support this study.

3.8.2 Mass change

A change in mass occurred after the samples had been submerged in magnesium sulfate solution with a concentration of 5% after 6 months as shown in Figure 14. It is obvious that fibre-reinforced magnesium sulfate-cured samples lost 0–1.56% of mass, while the plain geopolymer sample lost approximately 1.64% when cured in the same magnesium sulfate solution. The cured specimens in magnesium sulfate suffered mass loss due to dissolution of the geopolymer gel, which led to the production of a porous mass and structural damage. This result was also achieved by other authors (Guo *et al*., 2020).

3.8.3 Compressive strength change

The variation in compressive strength occurred after the samples had been submerged in magnesium sulfate solution with a concentration of 5% for about 6 months, as shown in Figure 15. The fibre-reinforced magnesium sulfate-cured samples lost

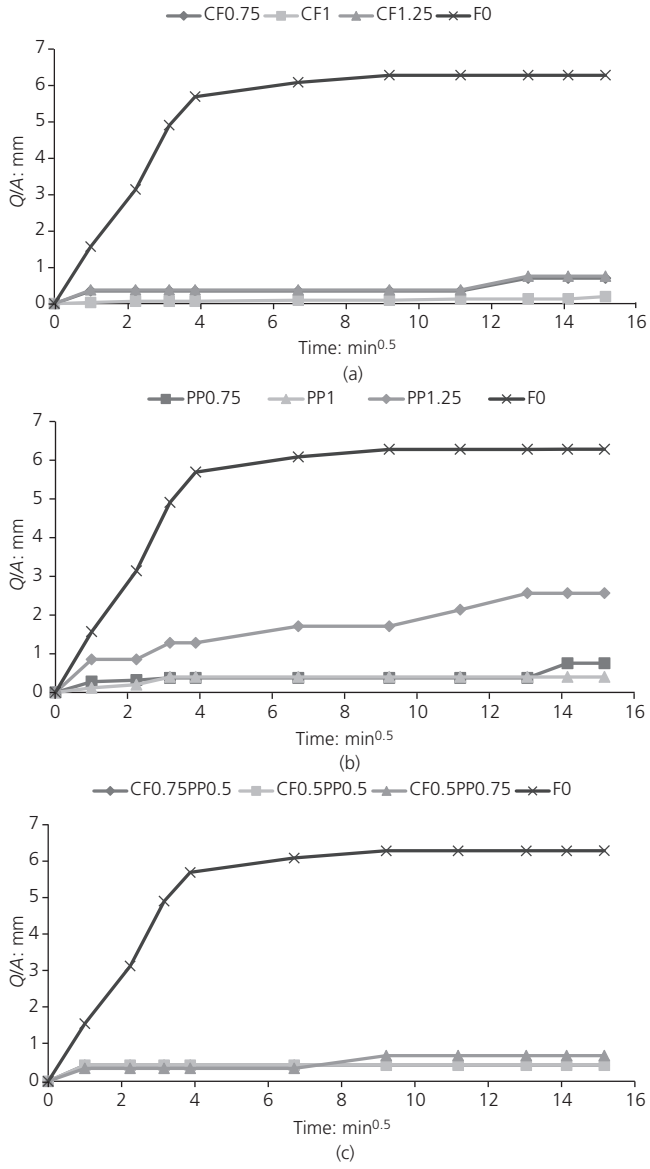


Figure 8. Effect of type and fibre content on the water sorptivity of geopolymer composites: (a) carbon fibre; (b) polypropylene fibre; (c) hybrid fibre

13–18% of strength, while the plain geopolymer sample lost approximately 1.64% when cured in the same magnesium sulfate solution. The cured specimens in magnesium sulfate suffered mass loss due to dissolution of the geopolymer gel, which led to the production of a porous mass and structural damage. This result was also achieved by other authors (Guo *et al*., 2020).

4. Conclusion

In the current research, the fresh and durability properties of the slag-based alkali-activated mortar, including both carbon and polypropylene fibres, were studied. The following conclusions can be drawn according to the outcomes studied herein.

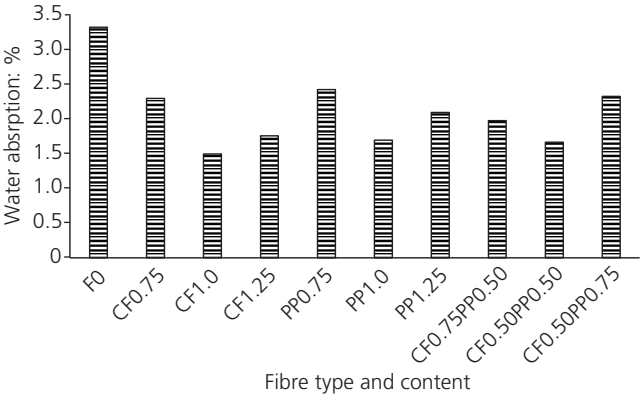


Figure 9. Effect of type and fibre content on the water absorption of geopolymer composites

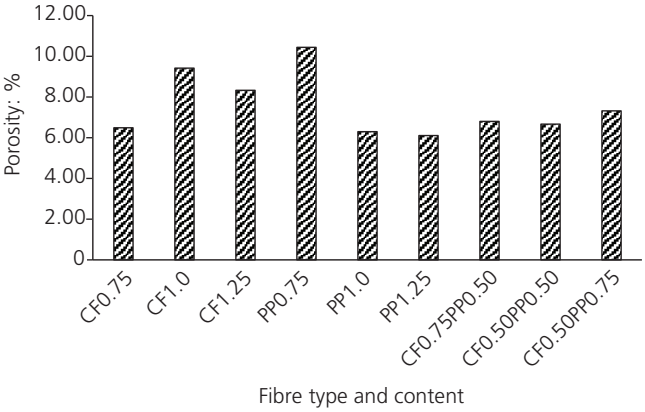


Figure 10. Effect of type and fibre content on the porosity of geopolymer composites

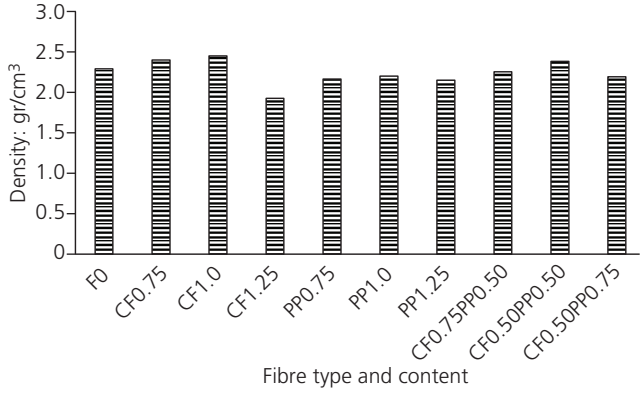


Figure 11. Effect of type and fibre content on the density of geopolymer composites

- Fibres produce a space network that decreases flowability. Increasing the carbon fibre content to 0.75, 1.00 and 1.25%

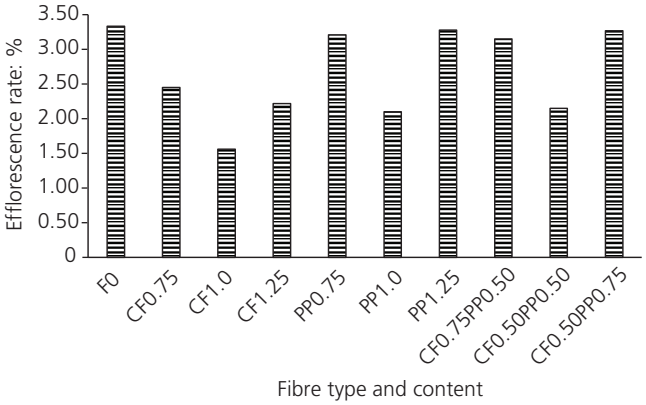


Figure 12. Effect of type and fibre content on the efflorescence of geopolymer composites

Figure 13. Visual appearance of the magnesium sulfate-cured geopolymer composite samples

reduces the flowability of the mixture by 43, 47 and 55%, respectively. Increasing the polypropylene fibre content to 0.75, 1.00 and 1.25% reduces the flowability of the mixture by 42, 43 and 45%, respectively.

- Partially melted fibres at high temperatures lead to minimising internal thermal stress. Increasing the carbon fibre content to 0.75, 1.00 or 1.25% increases the residual strength of the mixture slightly. The residual strength of the mixture increases when the polypropylene content is increased to 0.75, 1.00 and 1.25%. The residual strength of carbon fibre-reinforced mortar was greater than that of polypropylene fibre-reinforced mortar.

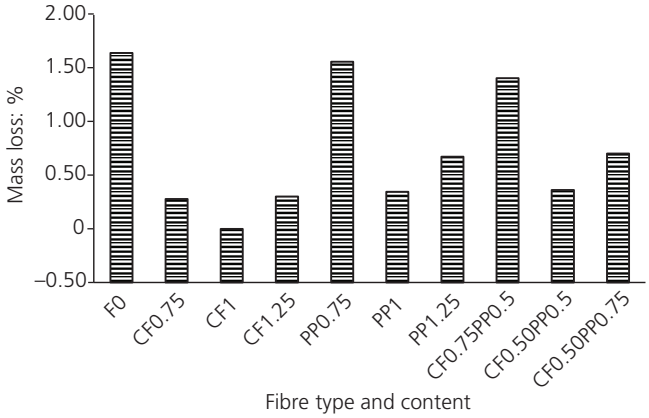


Figure 14. Mass loss percentage of samples cured in magnesium sulfate

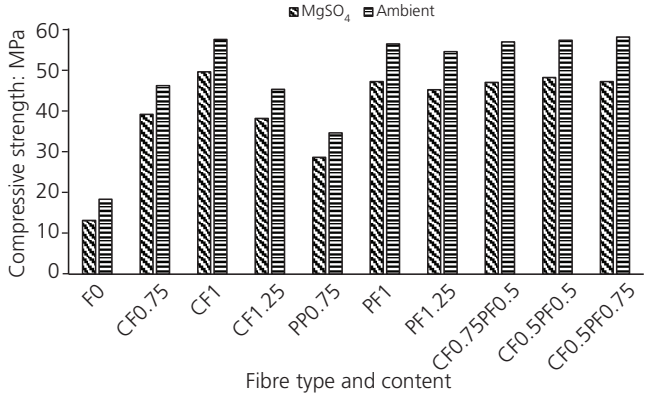


Figure 15. Compressive strength loss percentage of samples cured in magnesium sulfate

- Increasing the fibre content to 0.75 and 1.0% slightly reduces the water sorptivity, absorption and porosity of the mixture. At the same time, it increases the density. Following that, a further increase in fibre content to 1.25% induces an increase in water sorptivity, absorption and porosity and adversely decreases the density.
- Putting the samples in a plastic bag to avoid drying shrinkage and minimise interconnected voids leads to the least amount of efflorescence. Increasing the fibre content from 0 to 0.75–1.00% slightly decreases the efflorescence rate of the samples. After that, a further increase in fibre content to 1.25% causes an increase in the efflorescence rate of the mortar.
- Comparably, the geopolymer composite has good resistance to sulfate attack. There was no indication of sulfate attack on the sample surfaces such as white deposit, cracks or spalling. The samples lose nearly 1.5% of mass as a result of slightly fewer gel decomposition. The fibre-reinforced geopolymer composites lost around 13–18% of the compressive strength, while the plain geopolymer mortar lost around 28%.

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