

Behaviour of Carbon and Basalt Fibres Reinforced Fly Ash Geopolymer at Elevated Temperatures

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Abstract: This paper presents the behaviour of potassium activators synthesized fly ash geopolymer containing carbon and basalt fibre at ambient and elevated temperature. Six series of fly ash based geopolymer were cast where carbon and basalt fibre were added as 0.5, 1 and 1.5% by weight of fly ash. One extra control series without any fibre was also cast. Each series of samples were tested at ambient temperature and also heated at 200, 400, 600 and 800 °C and thus a total of 35 series of samples were tested in this study. The result shows that the geopolymer containing 1 wt% basalt and 1 wt% carbon fibre exhibited better compressive strength, lower volumetric shrinkage and mass loss than other fibre contents. Among two fibres composites, the carbon fibre geopolymer exhibited better performance than its basalt fibre counterpart regardless of temperature. The microstructure of carbon fibre reinforced geopolymer composite is more compact containing fewer pores/voids than its basalt based counterpart at elevated temperatures. The results also support the fact that carbon fibre is better than basalt fibre at elevated temperature and showed better bonding with geopolymer at elevated temperature.

Keywords: fly ash, basalt fibre, carbon fibre, potassium hydroxide, potassium silicate, geopolymer.

1. Introduction

Geopolymer is an environmentally friendly inorganic—amorphous binder which exhibit ceramic like property in fire or at elevated temperatures. At ambient temperature geopolymers are amorphous and transform to crystalline above 500 °C (Zoulgami et al. 2002). Extensive researches have been conducted to study various mechanical and durability properties of geopolymer (Davidovits 1991; Duxson et al. 2007; Rangan 2008; Duan et al. 2016). Significant efforts have also been made by many researchers to study the effect of elevated temperatures on mechanical properties of geopolymer. However, most of the studies were on different geopolymers which consisted of various types of source materials and alkali activators, e.g., fly ash activated by sodium based alkali activators, fly ash activated by combined sodium and potassium based activators, combined fly ash and slag activated by sodium based activator, metakaolin activated by combined sodium and potassium based activators, etc. (Bakharev 2006; Kong et al. 2007; Kong and Sanjayan 2008, 2010; Guerrieri and Sanjayan 2010; Rickard et al. 2012; Abdulkareem et al. 2014; Ranjbar et al. 2014; Shaikh and Vimonsatit 2015).

Fillers and aggregates can be added to geopolymers to reduce the thermal expansion/shrinkage of the composite

and extend the usable temperature range. Various additives are used in geopolymer matrix to improve its fire resistance e.g., α -quartz and granite aggregates (van Riessen 2007; Kamseu et al. 2010), α -alumina particles (Bell et al. 2005; Lin et al. 2009), wollastonite (Silva et al. 1999), etc. Various organic and inorganic fibres are also added to reinforce geopolymers to improve its fire resistance. Masi et al. (2015) reported a study where poly vinyl alcohol (PVA) and basalt short fibres are added to fly ash based geopolymer activated by sodium hydroxide and sodium aluminate solutions. Results show better mechanical properties of basalt fibre reinforced geopolymer at elevated temperatures than its PVA fibre reinforced counterpart. In another study the effect of elevated temperatures on fibre-matrix interaction of continuous basalt fibre reinforced dehydroxylated halloysite geopolymer is evaluated (Welter et al. 2015). Zhang et al. (2014) reported effects of various short carbon fibre contents on the compressive and bending strength of metakaolin-fly ash geopolymers at evaluated temperatures. Results show that 2% carbon fibre reinforced geopolymer containing 50% fly ash and 50% metakaolin exhibited excellent behaviour at 500 °C. In a comprehensive review of properties of basalt fibre composites in Fiore et al. (2015) it is shown that basalt fibre can be a sustainable alternative to steel and other fibres due to their environmental friendliness and suitability with various matrix. Although both basalt and carbon fibres show excellent thermal stability at elevated temperatures and class F fly ash is commonly used as source material for geopolymer not enough research studied the behaviour of carbon and basalt fibre reinforced fly ash based geopolymer at elevated temperatures. In a recent study the authors

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(Hosan et al. 2016) show better fire resistance of class F fly ash geopolymer synthesized by potassium based alkali activators than that of sodium based activators. In this paper the above potassium hydroxide and potassium silicate synthesized class F fly ash geopolymer is reinforced with various wt % of carbon and basalt fibres to study their compressive and physical behaviour as well as the microstructures of the geopolymer composites at various elevated temperatures of 200, 400, 600 and 800 °C.

2. Methodology

The class F fly ash geopolymer is synthesized using potassium silicate and potassium hydroxide and the resulting matrix is reinforced with different wt% of basalt and carbon fibres at 0.5, 1 and 1.5%. Potassium silicate to potassium hydroxide ratios of 3 was selected in this study as this ratio was found as the optimum content for fire resistant based on authors previous research (Hosan et al. 2016). Control geopolymer paste synthesized by sodium and potassium based activators without any fibers was also cast as control. A constant activator/fly ash ratio of 0.35 was considered in all the series in both parts. For each series fibre reinforced geopolymers, six 50 mm cube specimens were casted and heated at 200, 400, 600 and 800 °C temperatures.

3. Materials, Mixing and Methods

Class F fly ash supplied by Gladstone power station of Queensland, Australia was used as source material to prepare the geopolymer pastes. Table 1 shows the chemical compositions of the fly ash. The activators were potassium hydroxide (KOH) and potassium silicate (K₂SiO₃) solutions. KOH solution was prepared with a concentration of 8.0 M using KOH flakes of 90% purity supplied by Perth Scientific, Australia and tap water. The K₂SiO₃ (KASIL 2236 Grade) solution was supplied by PQ Australia with a specific gravity of 1.32 and a modulus ratio (Ms) of 2.23 (where Ms = SiO₂/K₂O, K₂O = 11.2%, SiO₂ = 24.8% and water = 64%). KOH and K₂SiO₃ solutions were mixed together with K₂SiO₃/KOH mass ratio of 3 to prepare the K-based activators. The chopped basalt fibres were 13 µm in diameter and 12.7 mm in length while the chopped carbon fibres were 11 µm in diameter and 6 mm in length. The basalt fibres were manufactured in Russia while the carbon fibres were manufactured in Japan.

All the samples were prepared in a Hobart mixer. The ingredients were mixed for about 4 min. The fresh geopolymer pastes were cast into standard 50 mm plastic

cube moulds and compacted using a vibrating table. The specimens were subjected to heat curing. In this regard, all moulds were sealed to minimize moisture loss and placed in an oven at 70 °C for 24 h. At the end of heat curing period, the specimens were removed from the oven and kept undisturbed until being cool and then removed from the moulds and left in the laboratory at ambient temperature until the day of testing. Compressive strength of all specimens was measured according to AS 1012.9 (2014) using a loading rate of 0.33 MPa/s. For each mix, at least three specimens were tested in order to check the variability of performance under compression. The volumetric shrinkage of pastes was determined by measuring the length of three sides of the cubes before and after heating at respective elevated temperatures. The difference in volume changes indicates the volumetric shrinkage and six specimens were used to measure the volumetric shrinkage for each series. Similar method was also used to determine the mass loss of geopolymer pastes after exposed to respective elevated temperatures.

This measurement was performed with a PoreMaster series—Quantachrome instruments, with a pressure ranged between 0.0083 and 207 MPa, and the pore diameter and intrusion mercury volume were recorded at each pressure point. Small broken pieces of approximately 10 mm in sides are collected from the crushed geopolymer cubes containing 1 wt% carbon and basalt fibres at ambient, 400 and 800 °C temperatures. The pressures were converted to equivalent pore diameter using the Washburn equation (Washburn 1921), as expressed in Eq. (1):

$$d = \frac{-4\gamma \cos \theta}{P} \quad (1)$$

where d is the pore diameter (µm), γ is the surface tension (mN/m), θ is the contact angle between mercury and the pore wall (°), and P is the net pressure across the mercury meniscus at the time of the cumulative intrusion measurement (MPa).

4. Elevated Temperature Exposure

A locally manufactured kiln was used to heat the geopolymer specimens, where the specimens were heated at 200, 400, 600 and 800 °C. The specimens were positioned inside the kiln where two thermocouples touched the specimens, and two more thermocouples were also inserted inside the kiln to monitor the kiln air temperature. The thermocouples were connected to the data logger and were

Table 1 Chemical composition of fly ash (mass%).

| Compounds | SiO ₂ | Al ₂ O ₃ | Fe ₂ O ₃ | CaO | Na ₂ O | K ₂ O | TiO ₂ | MgO | P ₂ O ₅ | SO ₃ | TiO ₂ | MnO | LOI |
|-----------|------------------|--------------------------------|--------------------------------|-----|-------------------|------------------|------------------|------|-------------------------------|-----------------|------------------|------|------|
| Fly ash | 51.11 | 25.56 | 12.48 | 4.3 | 0.77 | 0.7 | 1.57 | 1.45 | 0.885 | 0.24 | 1.32 | 0.15 | 0.57 |

used to monitor the temperature on the mortar surface and the kiln air as shown in Fig. 1. A heating rate of 5 °C per minute was selected, which is very close to the RILEM recommended heating rate (RILEM TC 129-MHT 1995). During heating process, the temperatures of four thermocouples were monitored. Once the specimen's surface reached the target temperature, the temperature inside the kiln was held for 1 h. The rate of temperature increase in the kiln and in the specimen is shown in Fig. 2. As can be seen in the figure, there is a significant lag between the surface temperature of cubes and air temperature inside the kiln, particularly for the 200 and 400 °C temperature profiles. This is due to the heat capacity of the specimens and the rate at which they are able to absorb heat. However, the difference in temperature between the kiln and the cubes at 600 and 800 °C is less. Even though the difference in temperature between the kiln and the cubes existed, the target test temperatures in all cubes were maintained for 1 h, which can be seen in the thermocouples readings in Fig. 2.

5. Results and Discussion

5.1 Physical Behaviour

Figures 3 and 4 show the effect of various wt% of basalt and carbon fibres on the volume stability and mass loss of fly ash geopolymer at various elevated temperatures up to 800 °C. It can be seen in Figs. 3 and 4 that the geopolymer containing carbon fibres performed better in terms of measured volumetric shrinkage and mass loss at all elevated temperatures than those containing basalt fibres. Among three different contents of fibres, 1 wt% of both carbon and basalt fibres is found to be the optimum fibre content in terms of lowest mass loss and volumetric shrinkage at all elevated temperatures. After exposure to 200 °C, no significant change in volumetric shrinkage of geopolymer is



Fig. 1 Locally manufactured kiln to heat the geopolymer composite specimens at various elevated temperatures.

observed in the case of both fibres. However, the addition of 1 wt% carbon fibre significantly reduced the volumetric shrinkage of geopolymer by 79 and 19% at 400 and 600 °C, respectively, while in the case of basalt fibre this reduction was only 15 and 5%, respectively. After exposure to 800 °C, both fibres at 1 wt% exhibited same reduction of volumetric shrinkage of geopolymer. Similar behaviour in terms of reduction of mass loss of geopolymer at various elevated temperatures due to addition of 1 wt% of carbon and basalt fibres can also be seen in Fig. 4.

Figure 5 shows the cracking behaviour of the samples with 1 wt% of both fibres content after heated at elevated temperatures (200, 400, 600, 800 °C) and pure geopolymer samples. It can be seen from the figure that the samples containing 1 wt% carbon fibre exhibits negligible cracking up to 600 °C compared to its pure geopolymer and basalt fibre counterpart. At 800 °C some micro cracks are formed in carbon fibre composite, however, the cracking is significantly less than pure geopolymer and slightly less intensive than that in basalt fibre composite at same temperatures. In general, the less cracking observed in carbon fibre composite at elevated temperatures than its counterpart basalt fibre geopolymer composite and pure geopolymer can be explained by the reduced volumetric shrinkage and mass loss observed in the former than the latter described before. The added reinforcing fibres aided in reducing the severity of the dehydration cracking by bridging the cracks as they developed. High temperature treatment data shows that the 1 wt% carbon and basalt fibre reinforced geopolymer actually dehydrated slower than the pure geopolymer and there was less water loss at all temperatures, reaching about 91 wt% of residual mass at 800 °C, compared with about 90 wt% for pure geopolymer. This slightly higher mass loss in geopolymer composites containing 1 wt% carbon and basalt fibre than the pure geopolymer paste can be attributed to the additional pathways for water to escape that were created by the fibre matrix interface. These pathways could help to gently dehydrate the geopolymer matrix during curing, reducing pressure gradients through the thickness of the specimen and avoiding cracking of the composite (Ribero and Kriven 2016).

5.2 Compressive Strength

The effects of various wt% of carbon and basalt fibres on the compressive strength of fly ash geopolymer at ambient and various elevated temperatures are shown in Fig. 6a, b. The increase in compressive strength of geopolymer matrix due to addition of carbon and basalt fibres at different contents is also shown in Fig. 7a, b. It can be seen that the ambient compressive strength of geopolymer is increased due to addition of both fibres at all three fibre contents except 0.5 wt% of basalt fibre which showed about 7% reduction in ambient temperature compressive strength. The carbon fibre at all three fibre contents showed higher improvement in compressive strength of geopolymer than those of basalt fibre contents at all elevated temperatures. This can be attributed to the formation of excessive voids due to non-uniform dispersion of long basalt fibre than

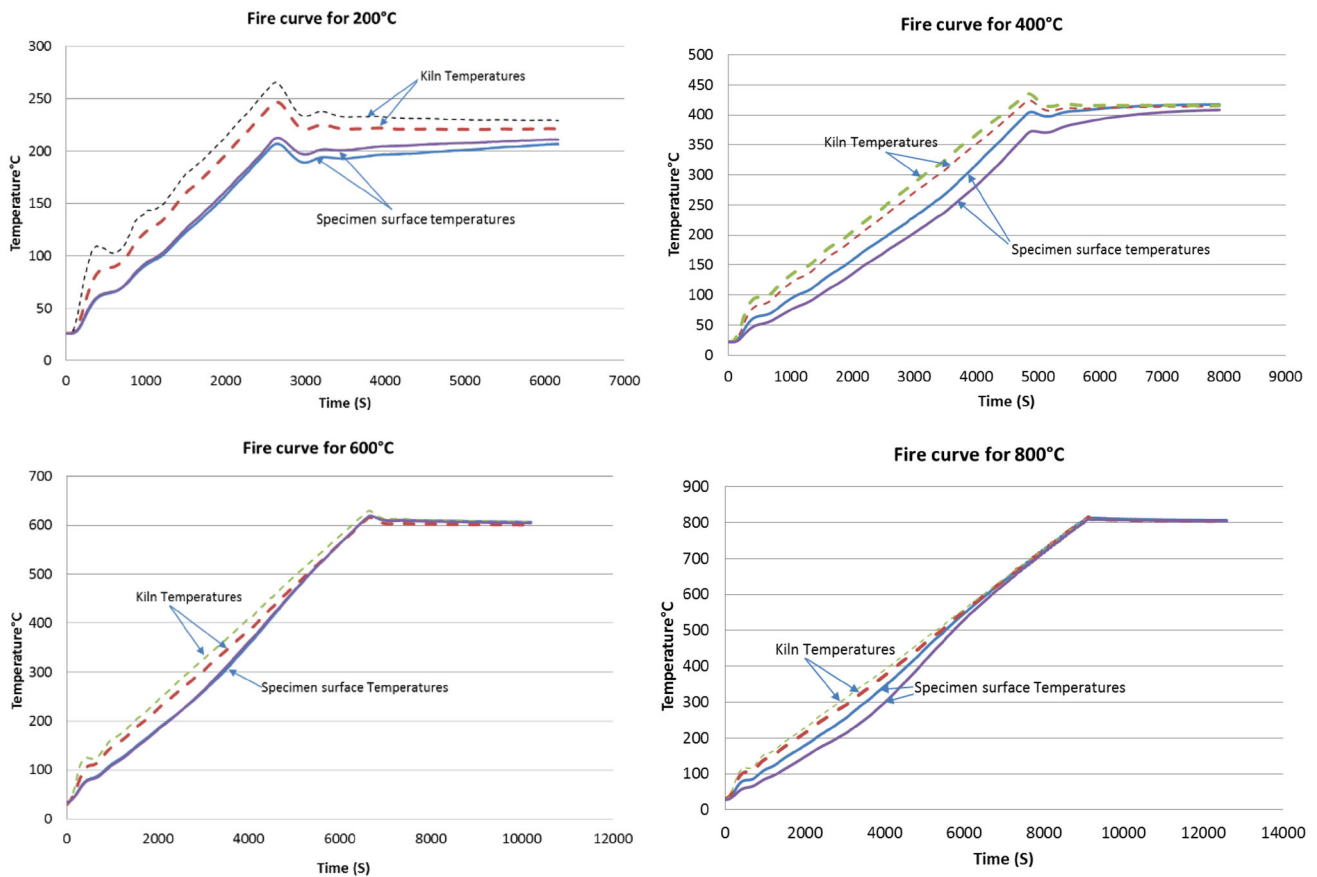
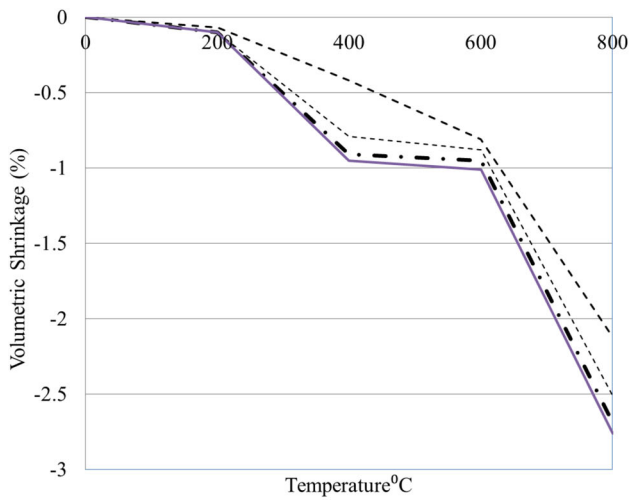


Fig. 2 Fire curves for different elevated temperatures in the kiln during heating.

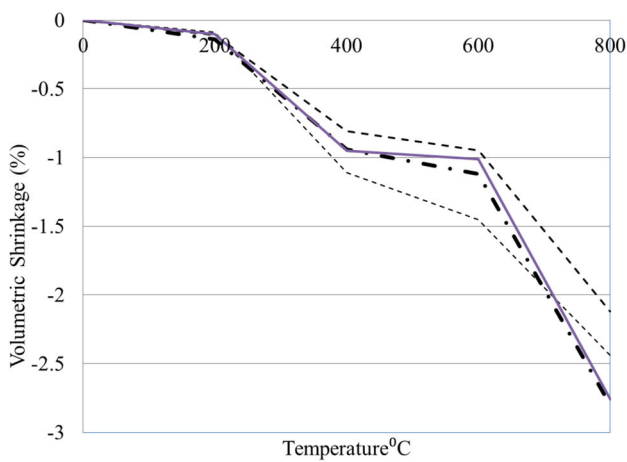
carbon fibres and higher number of cracks in basalt fibre geopolymer composite than its carbon fibre counterpart at elevated temperatures especially at 600 and 800 °C. Generally long fibres have tendency to form more fibre clumps than shot fibres in cementitious composites during mixing as extra length of the fibres hampers their uniform dispersion. This adversely affects the workability, forms additional voids and affect the strength properties of fibre composites as have been reported in many studies (Ali et al. 1975; Santos et al. 2017). There is also established correlation between reduction in compressive strength and presence of higher air voids in cementitious composites (Lian et al. 2011; Chen et al. 2013). Therefore, the lower ambient temperature compressive strength of basalt fibre geopolymer composite than carbon fibre geopolymer composite indicate higher amount of pores/voids in the former than the latter and upon heating at various elevated temperatures the moisture evaporated from these pores easily and increased the porosity. After exposure to various elevated temperatures, it can be seen that the compressive strength of 1 wt% carbon fibre reinforced geopolymer improved significantly by about 35, 27, 16 and 12% at 200, 400, 600 and 800 °C respectively compared to control geopolymer. On the other hand in the case of 1 wt% basalt fibre geopolymer composite, these improvements are 28, 7, 1 and 3% respectively. The other fibre contents at both fibres composites showed lesser improvement in compressive strength of geopolymer than 1 wt%. It can be seen that the compressive strength of 1 wt% carbon fibre geopolymer at elevated temperatures of

200, 400, 600 and 800 °C is about 5, 18, 15 and 10% respectively higher than its basalt fibre geopolymer counterpart at the corresponding elevated temperatures, however, it is also interesting to see that the compressive strength gain with increase in elevated temperatures is comparable in both fibre reinforced geopolymer composites. Hence, based on compressive strength, volumetric shrinkage and mass loss measurements, the 1 wt% can be considered as optimum fibre content of both carbon and basalt fibres for fire resistance of fly ash geopolymer.

It can be seen in both cases the 1.5% shows very similar volumetric shrinkage to the pure geopolymer. Whereas the other contents shows slight deviation at 400 and 600 °C, however they show slightly lower volumetric shrinkage at 800 °C. If we compare these phenomenon with measured residual compressive strength in Fig. 6 we can also see that in carbon fibre geopolymer the 0.5 and 1.0% show slightly higher compressive strength at all temperatures. And in the case of basalt fibre geopolymer it was 1.0%. It seems to the authors that at lower fibre content e.g., at 0.5 and 1.0% both fibres might have dispersed more uniformly in the geopolymer than at higher fibre content. These well dispersed fibres at lower fibre content might have bridged the micro cracks more effectively which prevented the further propagation and/or formation of cracks, as a result higher residual compressive strength and lower volumetric shrinkage in geopolymer containing those lower fibre contents are observed.



--- Carbon 0.5% --- Carbon 1% - · Carbon 1.5% — Control
(a)

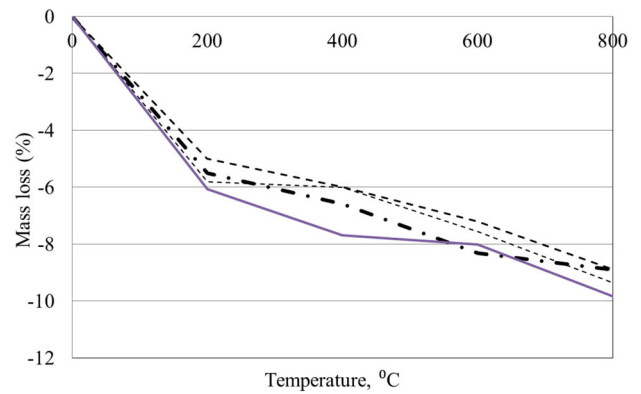


--- Basalt 0.5% --- Basalt 1% - · Basalt 1.5% — Control
(b)

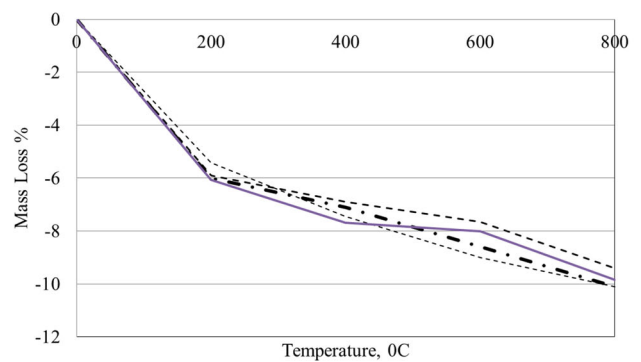
Fig. 3 Volumetric shrinkage of carbon and basalt fibre reinforced fly ash geopolymer composites at various elevated temperatures. **a** Carbon fibre reinforced fly ash geopolymer composite and **b** Basalt fibre reinforced fly ash geopolymer composite.

5.3 Porosity and Microstructure of Geopolymer with Fibre

Mercury intrusion porosimetry (MIP) analysis is widely used to evaluate total porosity and size distributions of pores in cement, polymer and geopolymer matrix. The MIP results of the geopolymer samples containing 1 wt% of carbon and basalt fibres after exposure to 400 and 800 °C temperatures and at ambient temperature are shown in Figs. 8 and 9. It shows the relationship between cumulative pore volume and pore diameter in the range of 0.01–100 micron. Zhang and Islam (2012) classified the pores from 10 to 0.05 micron as large capillary pores, from 0.05 to 0.01 micron as medium capillary pores and < 0.01 micron as gel pores. From Fig. 8 it can be seen that the pore size distributions of both carbon and basalt fibre reinforced geopolymer at ambient temperature have the same general shape as those exposed to 400



--- Carbon 0.5% --- Carbon 1% - · Carbon 1.5% — Control
(a)



--- Basalt 0.5% --- Basalt 1% - · Basalt 1.5% — Control
(b)

Fig. 4 Mass loss of carbon and basalt fibre reinforced fly ash geopolymer composites at various elevated temperatures. **a** Carbon fibre reinforced fly ash geopolymer composite and **b** Basalt fibre reinforced fly ash geopolymer composite.

and 800 °C temperatures. The calculated cumulative pore volume of carbon and basalt fibre geopolymer at ambient temperature is 0.28 and 0.2 cm³/g, respectively. However, the basalt fibre reinforced geopolymer is found more porous than the corresponding carbon fibre geopolymer at both 400 and 800 °C temperatures with higher pore volume of large diameter pores. For example, the cumulative pore volumes of basalt fibre geopolymer at 400 and 800 °C are 0.27 and 0.19 cm³/g compared to 0.17 cm³/g in carbon fibre geopolymer at both temperatures. In particular the total cumulative pore volume of both medium and large capillary pores of basalt fibre geopolymer increased significantly after exposure to elevated temperatures (Fig. 8b), which can explain the lower compressive strength observed in this composite at elevated temperatures than that of carbon fibre composite. Figure 9b also supports this observation where the maximum concentration of pores of basalt fibre composites are shifted towards medium to large capillary pores after exposure to elevated temperatures. No significant increase pore volume of pore size above 1 µm can be seen in the case of carbon fibre geopolymer composites nor any shift in the maximum concentration of pores after exposures to

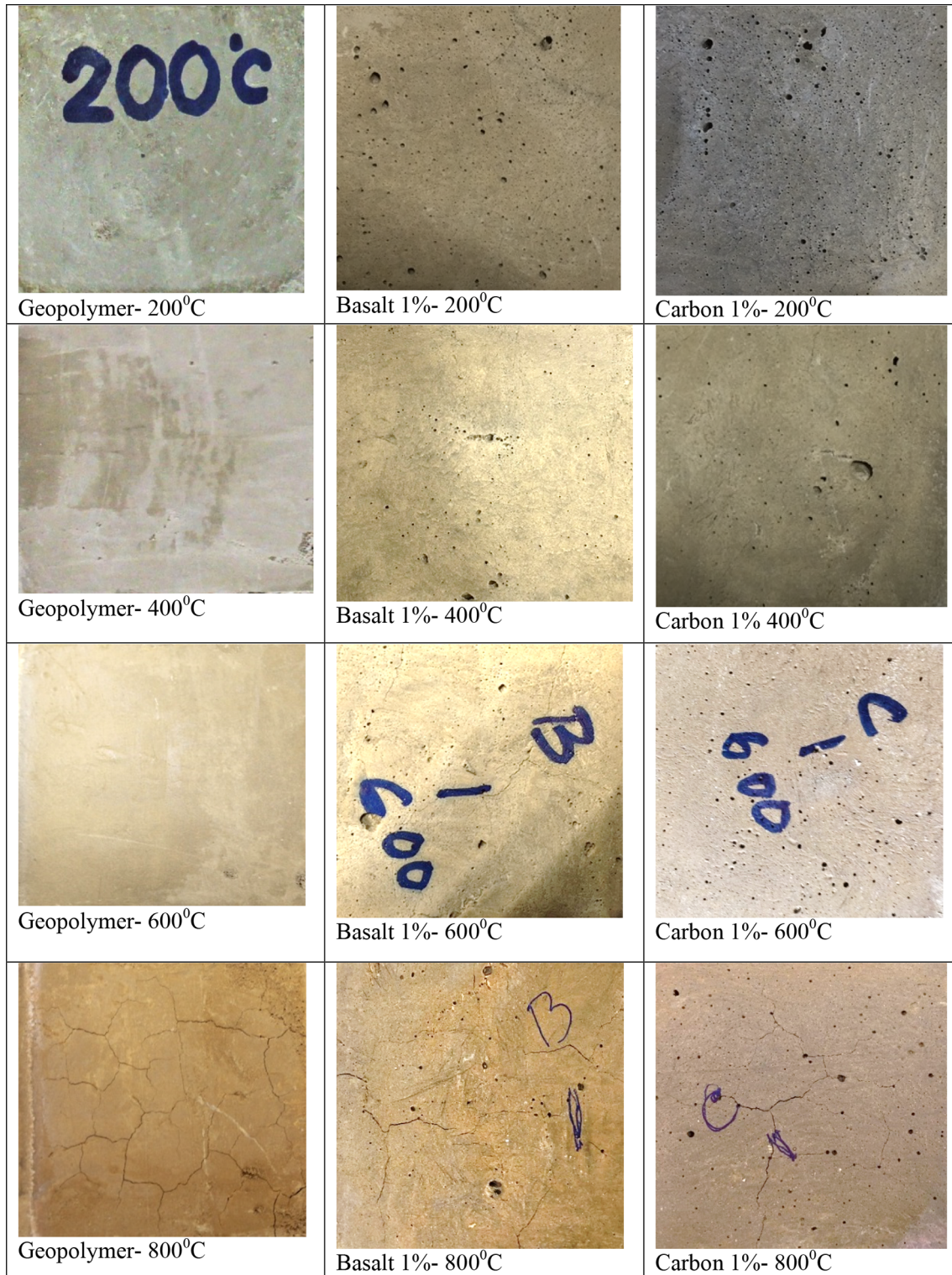
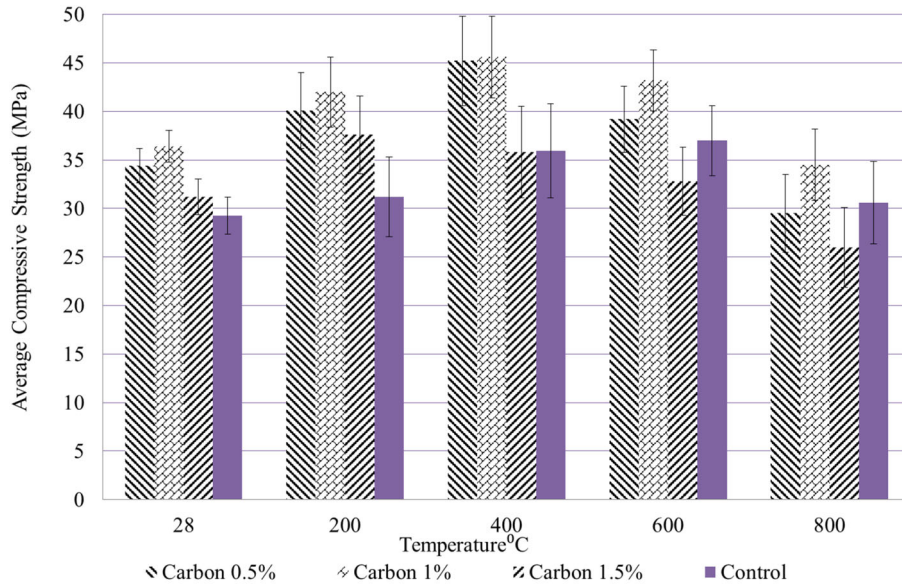


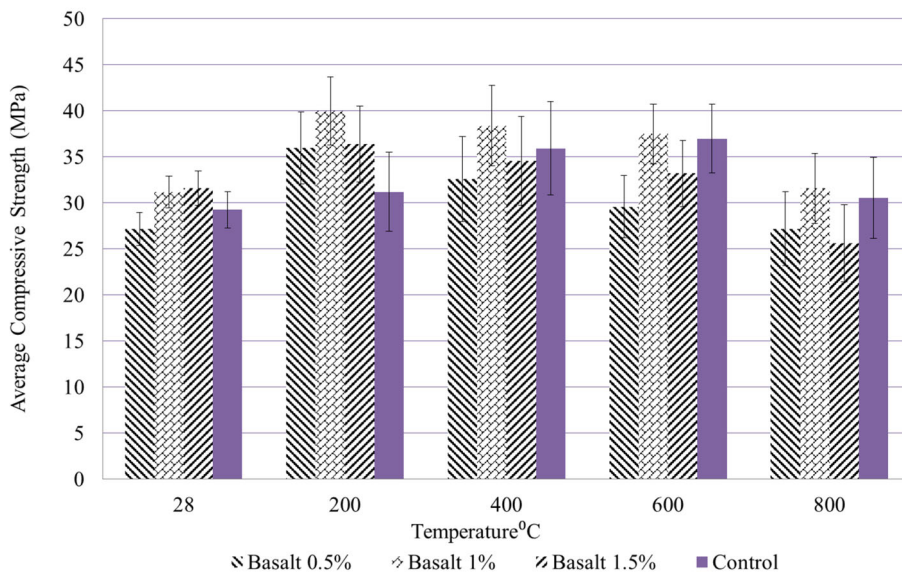
Fig. 5 Cracking behaviour of pure geopolymer and geopolymer composite containing 1 wt% of carbon and basalt fibres at various elevated temperatures.

400 and 800 °C temperatures. This might explain the better results observed in carbon fibre geopolymer than its basalt fibre counterpart. As reported higher amount of voids are entrapped in fibre composites containing long fibre than that of short fibre due to restrain provided by the extra length of long fibres than short fibres. As a result fibres are clamped inside the composite during mixing and hence increase the pores/voids in the composites (Ali et al. 1975; Santos et al.

2017). The moisture entrapped in these additional pores/voids in these porous fibre composites are evaporates easily when exposed to elevated temperatures and increase the overall porosity of the composites. And this has been observed in the case of basalt fibre geopolymer composite and the carbon fibre composite due to longer length of basalt fibre than the carbon fibre.



(a)



(b)

Fig. 6 Compressive strength of pure geopolymer and carbon and basalt fibre reinforced geopolymer at ambient and at various elevated temperatures. **a** Carbon fibre geopolymer composites and **b** Basalt fibre geopolymer composites.

The change in microstructure of geopolymer composites after exposure to elevated temperature is also studied using scanning electron microscope (SEM) and the SEM images are shown in Fig. 10. By comparing the surfaces of both carbon and basalt fibres in geopolymer after exposure to 400 and 800 °C temperatures with those at ambient condition, it can be seen no significant damage and change in diameter of both fibres at elevated temperatures, hence, indicating high temperature resistance characteristics of these two fibres. By comparing microstructures of both composites, the carbon fibre geopolymer composite exhibited more compact microstructures even after exposure to elevated temperatures than its counterpart basalt fibre composite, which is consistent with the observed higher compressive strength, lower

volumetric shrinkage and mass loss of the former than the latter as discussed earlier.

It can be seen in the experiment that the measured compressive strength of basalt fibre composite at ambient temperature is lower than its carbon fibre counterpart. There is also established correlation between reduction in compressive strength and presence of higher air voids in cementitious composites (Lian et al. 2011; Santos et al. 2017). Therefore, the lower ambient temperature compressive strength of basalt fibre geopolymer composite than carbon fibre geopolymer composite indicate higher amount of pores/voids in the former than the latter and upon heating at various elevated temperatures the moisture evaporated from these pores increased the porosity. This has also been observed in the MIP and SEM tests. It is also found that the

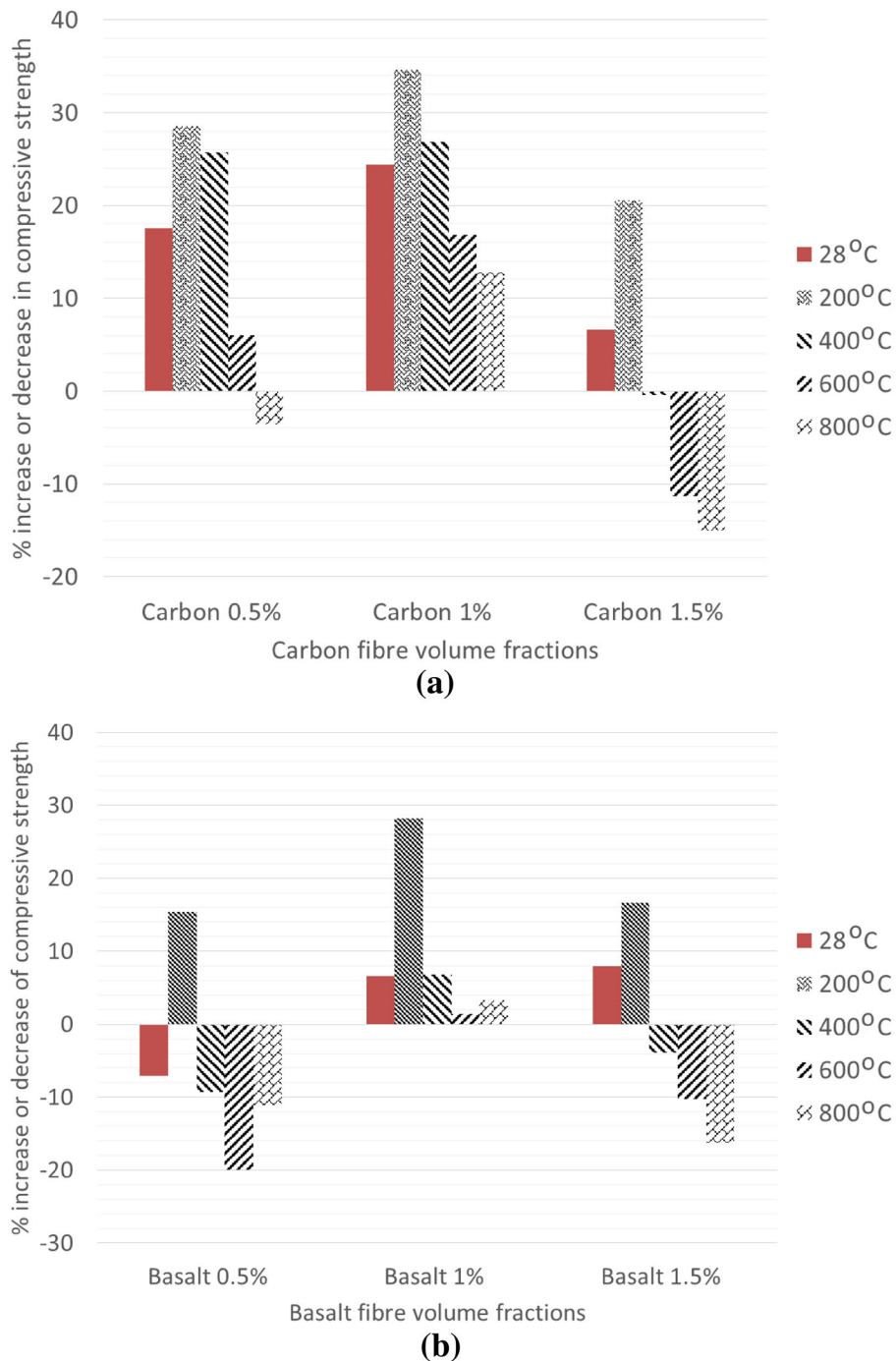


Fig. 7 Percent increase and decrease in compressive strength of geopolymer matrix due to addition of **a** Carbon fibre reinforced geopolymer composite and **b** basalt fibre reinforced geopolymer composite.

fibre content of 1 wt% in both basalt and carbon geopolymer composites exhibited higher ambient as well as elevated temperatures compressive strengths, lower mass loss and lower volumetric shrinkage than other fibre contents e.g., 0.5 and 1.5% in this study. Based on above discussion it is clear that the likelihood of higher pores/voids in geopolymer composites containing 1.5 wt% carbon and basalt fibres is higher than that containing 1 wt% of carbon and basalt fibres, which caused lower compressive strength at ambient as well as at elevated temperatures. Similar results are also observed in the case of mass loss. However, the composites containing 1.5 wt% carbon and basalt fibres shrinks slightly

more than other fibre contents which is not clear and deserve more research in future.

6. Conclusions

Based on limited studies on physical, mechanical and microstructural characteristics of carbon and basalt fibre reinforced geopolymer composites at various elevated temperatures exposure the following conclusions can be drawn:

1. Geopolymer containing 1 wt% basalt and 1 wt% carbon fibre exhibited better compressive strength, lower

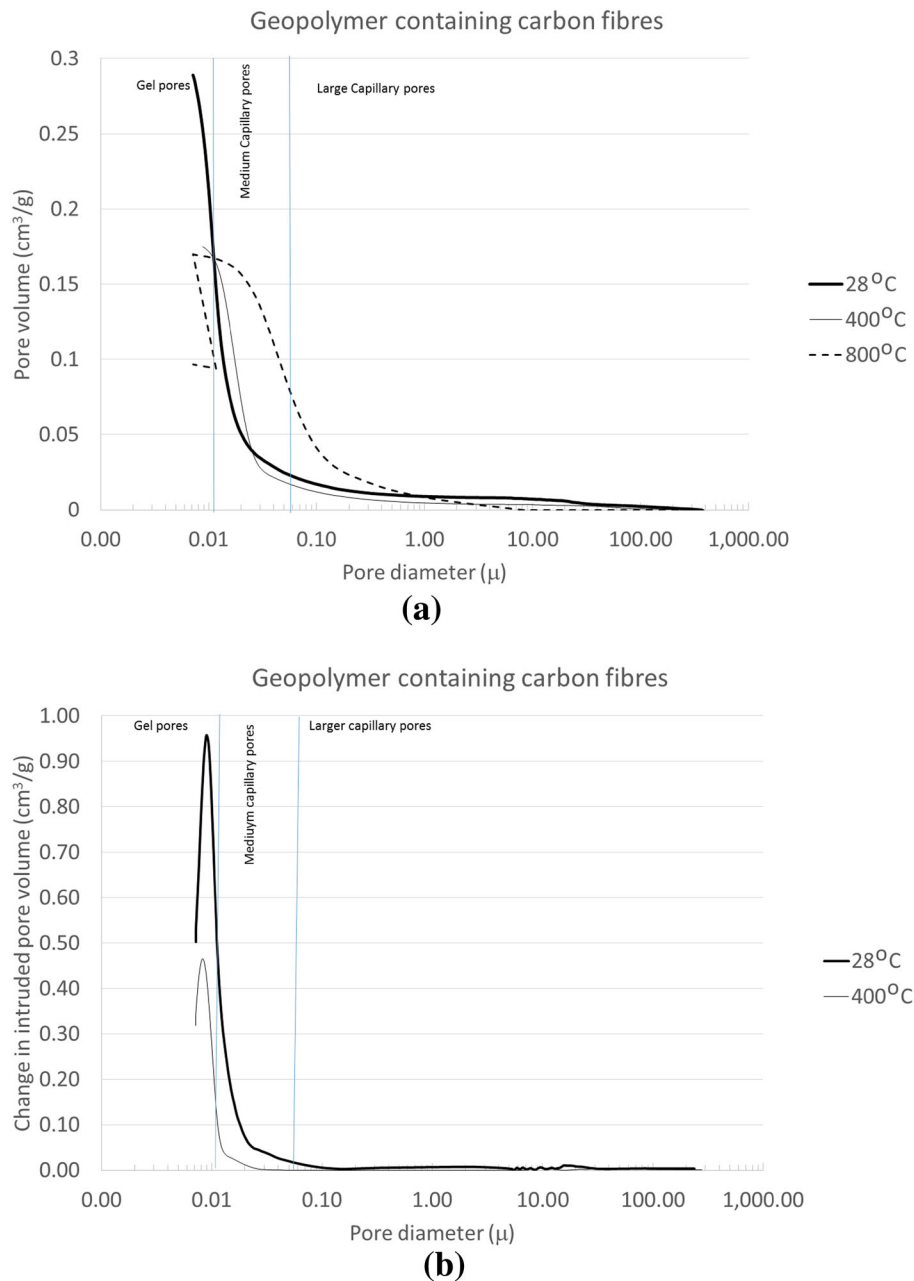


Fig. 8 Cumulative pore volume of 1 wt% carbon and basalt fibre reinforced geopolymer at ambient and at various elevated temperatures. **a** Carbon fibre reinforced geopolymer composite and **b** Basalt fibre reinforced geopolymer composite.

volumetric shrinkage and mass loss than other fibre contents at all elevated temperatures. Among two fibres composites, the carbon fibre geopolymer exhibited better performance than its basalt fibre counterpart at all elevated temperatures and ambient temperature. 1 wt% of carbon and basalt fibres are the optimum fibre content in fly ash geopolymer at elevated temperatures. 1 wt% carbon fibre reinforced geopolymer exhibited negligible cracking than its basalt fibre counterpart and pure geopolymer up to 600 °C. At 800 °C the cracking in 1 wt% carbon fibre reinforced geopolymer is less than its basalt fibre counterpart and pure geopolymer.

2. The microstructure of carbon fibre reinforced geopolymer composite is also better in terms of lower pores/

voids and more compact microstructure than its basalt based counterpart at elevated temperatures. Pore volume of larger diameter pores is increased at elevated temperatures in basalt fibre geopolymer than that of carbon fibre geopolymer. The maximum concentration of pores of basalt fibre composites are shifted towards medium to large capillary pores after exposure to elevated temperatures.

3. No significant damage and change in diameter of both fibres at elevated temperatures are observed in SEM analysis. The results also support the fact that carbon fibre is better than basalt fibre at elevated temperature and showed better bonding with geopolymer at elevated temperature, which is indicated by more compact microstructure of carbon fibre geopolymer.

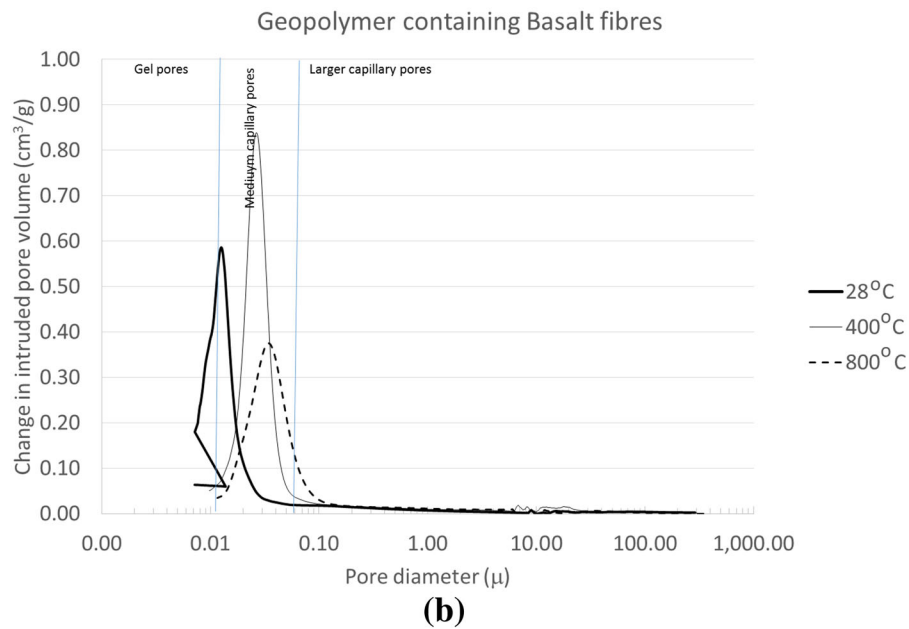
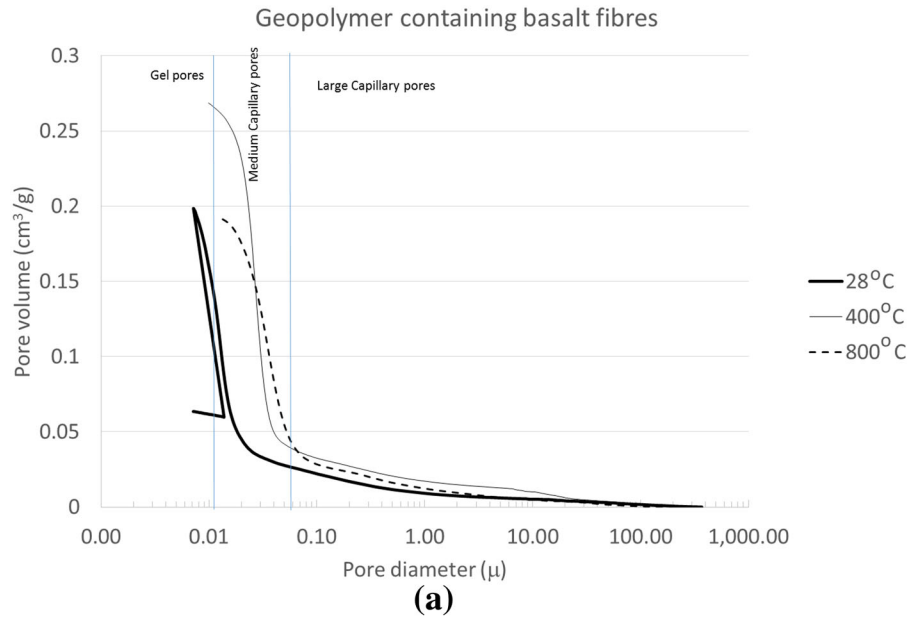


Fig. 9 Pore volume distribution of 1 wt% carbon and basalt fibre reinforced geopolymer at ambient and at various elevated temperatures. **a** Carbon fibre reinforced geopolymer composite and **b** Basalt fibre reinforced geopolymer composite.

4. The higher compressive strength and lower mass loss and volumetric shrinkage of carbon fibre reinforced fly ash geopolymer at various elevated temperatures up to 800 °C indicate its superior role as filler in geopolymer at fire than that of basalt fibre.

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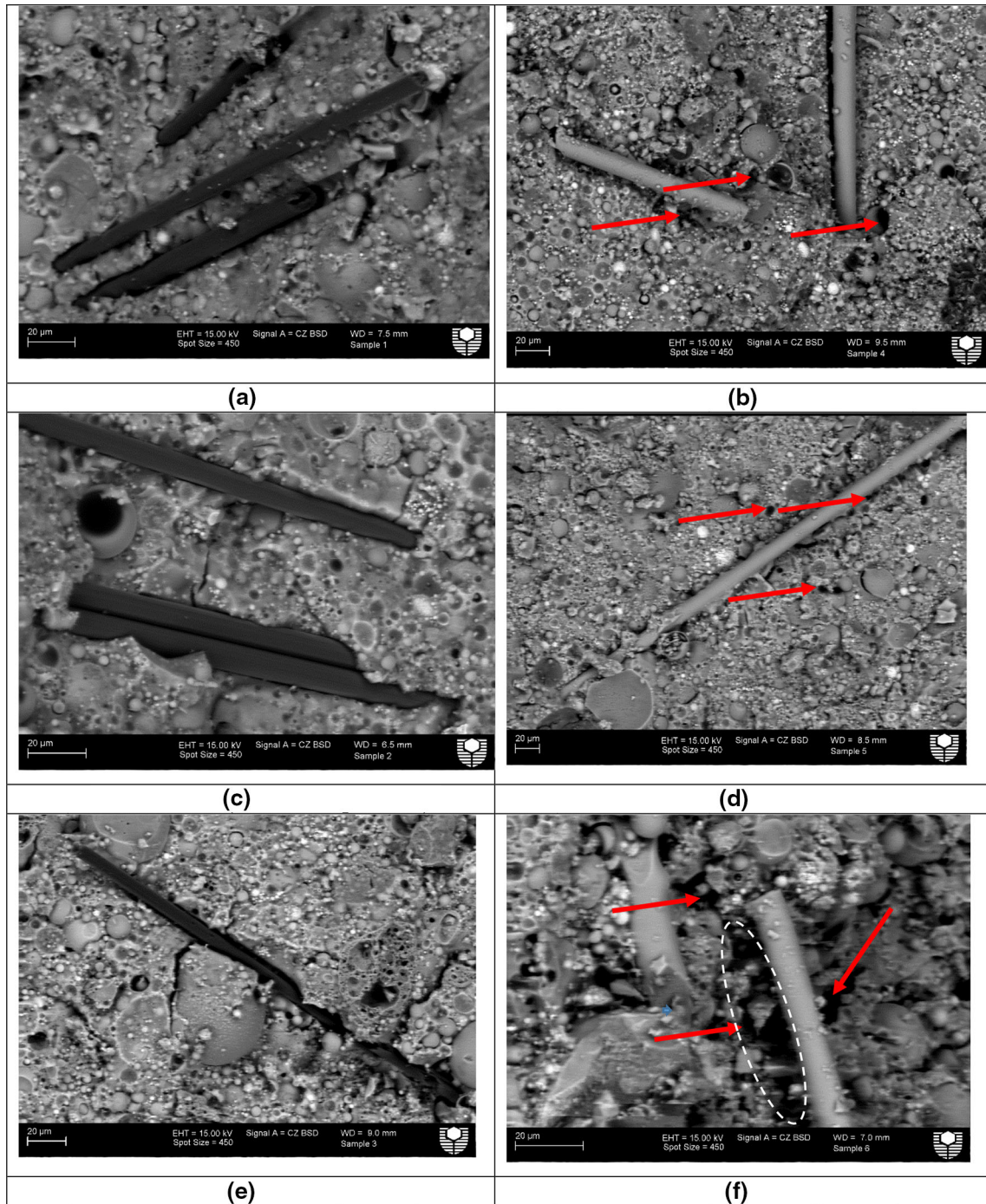


Fig. 10 SEM images of fly ash based geopolymer with carbon and basalt fibre at different elevated temperatures. **a** Carbon fiber (ambient temperature), **b** Basalt fiber (ambient temperature), **c** Carbon fiber (400 °C temperature), **d** Basalt fiber (400 °C temperature), **e** Carbon fiber (800 °C temperature), and **f** Basalt fiber (800 C temperature) [arrows in **b**, **d** and **f** indicate the voids/pores in basalt fibre composite].

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