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Original Research Article

# Low carbon building: Experimental insight on the use of fly ash and glass fibre for making geopolymer concrete

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ABSTRACT

Due to the environmental impacts resulting from the production of Ordinary Portland cement (OPC), the drive to develop alternative binders that can totally replace OPC is gaining huge consideration in the construction field. In the current study, attempt was made to determine the strength characteristics of glass fibre-reinforced fly ash based geopolymer concrete. Sodium hydroxide (NaOH) and sodium silicate ($Na_2SiO_3$) were used as alkaline solutions (for activation of geopolymer reaction) at 12, 16, 20 M. Glass fibres were added to the geopolymer concrete in varying proportions of 0.1–0.5% (in steps of 0.1%) by weight of concrete. A constant weight ratio of alkaline solution to fly ash content of 0.43 was adopted for all mixes. British standard concrete test specimens were cast for measuring compressive strength, split-tensile strength, and flexural strength. Concrete specimens were cured by heating in oven at 90 °C for 24 h and natural environment, respectively. From the results, thermally cured concrete samples had better mechanical properties than the ambient (natural) cured samples. Thermally cured concrete specimen, containing 0.3% glass fibre and 16 M NaoH, achieved a maximum compressive strength of 24.8 MPa after 28 d, while naturally cured samples achieved a strength of 22.2 MPa. There was substantial increase in tensile strength of geopolymer concrete due to the addition of glass fibres. Split tensile strength increased by 5–10% in glass fibre-reinforced geopolymer concrete, containing 0.1–0.5% glass fibre and 16 M NaoH when compared to the unreinforced geopolymer concrete (1.15 MPa).


## 1. Introduction

The environmental impacts emanating from the production of Ordinary Portland cement (OPC) are not friendly to the biodiversity. For production of one ton of OPC, about one ton of $CO_2$ is released into the atmosphere [1,2]. Annually, an approximate 1600 Mt of greenhouse gases ($CO_2$, $CH_4$, and $N_2O$) are emitted by cement industries worldwide [2–4], and this significantly affects global warming. However, a sustainable alternative to OPC has been found in geopolymer based materials, which have minimal or no impact on the ecosystem. The production of geopolymers entails activating a pozzolanic material such as, fly ash [5], steel slag [6], ceramic [7], wood ash [8], and many more, that are highly rich in silica ($SiO_2$) and alumina ($Al_2O_3$) (through a process of polymerization), using an alkaline solution [9–11]. Of many discovered pozzolanic materials, fly ash, ground granulated blast furnace slag, and rice husk ash are commonly used for making geopolymers, because they contain significant amount of $SiO_2$ and $Al_2O_3$.

The use of geopolymers as binders in concrete is gaining attention in the construction field due to their environmental benefits, and also improvement of concrete strength. In addition, geopolymer concrete exhibits similar strength properties as the conventional OPC concrete [12–15], which makes it a suitable material for civil engineering applications.

Furthermore, a major advancement in the construction industries over the years includes the incorporation of fibres as replacement for conventional steel reinforcement. Because of the increasing cost of steel reinforcement, fibres from artificial or natural origin are considered for concrete reinforcement. Fibres are

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**Table 1**
Oxide composition of the fly ash used.

| Oxides | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | CaO | MgO | $Na_2O$ | $K_2O$ | $P_2O_5$ | $TiO_2$ | LOI |
|---|---|---|---|---|---|---|---|---|---|---|
| Fly ash (wt%) | 50.0 | 28.25 | 13.5 | 1.79 | 0.89 | 0.32 | 0.46 | 0.98 | 1.54 | 0.64 |

**Table 2**
Properties of glass fibre used.

| Aspect ratio | Density (kg $m^{-3}$) | Specific gravity | Failure strain (%) | Elastic modulus (MPa) | Tensile strength (MPa) |
|---|---|---|---|---|---|
| 600 | 2540 | 2.4 | 3.0 | 82,000 | 2500 |

able to control the propagation of shrinkage cracks in fresh concrete and also improve post-crack strength of concrete [16]. The commonly used materials for fibres are steel, glass, and polypropylene. But the current study is focused on using glass fibre and fly ash for the production of geopolymer concrete. Studies have shown that fibre reduces the workability of concrete but improves its density, compressive and flexural strengths [17,18]. However, there is a need to investigate further the significance of glass fibres when they are included in geopolymer concrete.

On the other hand, one of the factors that influences the strength development in fly ash based geopolymer concrete is the curing medium. A few experimental reports indicate that heat curing is the most suitable for fly ash based geopolymer concrete [12,19], because heating helps to speed up the geopolymer reaction. Moreover, adequate heating provides escape routes for trapped moisture in geopolymer concrete [12], which in turns reduces permeability of the concrete. However, heat curing may not be adequate when geopolymer concrete is to be used for *in situ* construction.

Therefore, the current study attempts to contribute to the previous reports in the field of geopolymers by examining the strength properties of glass fibre-reinforced fly ash based geopolymer concrete, which is cured by heating, and natural exposure conditions.

## 2. Materials and methods

The fly ash used in this study was a low-calcium (ASTM class F) of approximate particle size of 16 μm and specific surface of 420 $m^2$ $kg^{-1}$. It was sourced from Mettur thermal power station. The environmental consideration on the use of fly ash can be a major concern during its reuse; however, when fly ash is to be used in concrete, its effect on the environment can be monitored through a process known as beneficiation, which entails the reduction of the amount of heavy metals content in fly ash. Low-calcium fly ash was preferable due to its slow setting time compared to the class C fly ash (having high calcium). Rapid setting on the other hand was reported [12,20] as not suitable for geopolymer concrete, because it affects the strength development. The chemical composition of the fly ash is presented in Table 1. The amount of carbon present in the fly ash is very low, based on the obtained low Loss on Ignition (LOI) value. The molar Si-to-Al ratio of the fly ash was about 2.

River sand (finer than 425 μm BS sieve) having specific gravity of 2.65, water absorption of 6.5% and fineness modulus of 2.36 was used as fine aggregate. Granite of nominal sizes of 10 mm, having specific gravity of 2.66, aggregate crushing value of 26.13%, aggregate impact value of 13.99%, and water absorption of 2.5% was used as coarse aggregate. The granite and the river sand were obtained from a quarry near Tamil Nadu, India.

The fly ash was activated using an alkaline solution which comprised of NaOH and $Na_2SiO_3$, followed the procedure by Torres-Carrasco and Puertas [21]. Thus, alkaline solutions of 12, 16 and 20 M were prepared and utilized for fly ash activation.

The glass fibres (GF) used is of E category, which are mostly characterized by their high strength, and high resistance to temperature and corrosion [22]. The properties of the glass fibre are shown in Table 2. The glass fibre was added in varying proportions of 0.1–0.5% (in steps of 0.1%) by weight of concrete. Glass fibre was added to the mixture after the chemicals were mixed with the aggregate. Some of the materials used are presented in Fig. 1. The weight ratio of alkaline liquid to fly ash was fixed as 0.43. The sodium hydroxide solution was prepared 1 d before use, so as to control temperature rise caused by its dissolution in water. Thereafter, sodium silicate ($Na_2SiO_3$) solution and the sodium hydroxide (NaOH) were mixed to form the alkaline liquid. This study adopted the mixing procedure reported by Zhao and Sanjayan [23]. The mix proportion includes: 0% GF, 0.1% GF, 0.2% GF, 0.3% GF, 0.4% GF, and 0.5% GF, and the materials proportions were: river sand (570 kg $m^{-3}$), granite (680 kg $m^{-3}$), fly ash (350 kg $m^{-3}$), NaoH (75.3 kg $m^{-3}$), $Na_2SiO_3$ (75.3 kg $m^{-3}$), and additional mixing water (60.6 kg $m^{-3}$). Only glass fibre content was varied as a percentage of the weight of concrete.

The workability of the fresh concrete mix was determined by slump and compaction factor tests, following BS EN 12350

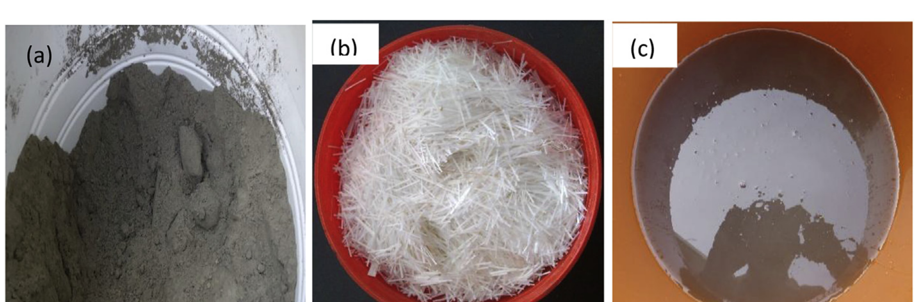


**Fig. 1.** Some of the materials used (a) class F Fly ash, (b) glass fibres, (c) alkaline solution.

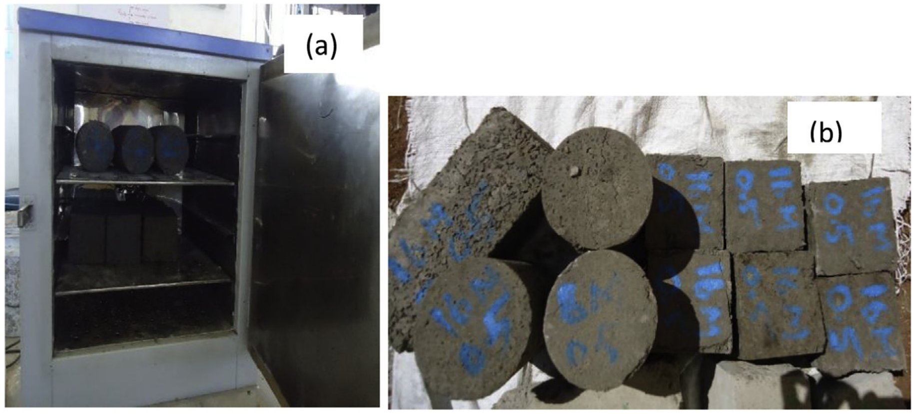


**Fig. 2.** Curing of concrete samples (a) heat curing (b) natural curing.

procedure [24]. The slump and compacting factor values obtained for the mixes were in ranges of 100–130 and 0.8–1, respectively. Concrete cubes of 150 mm dimension were cast for compressive strength test in accordance with BS EN 12390-6 [25], concrete cylinders of 100 mm diameter and 200 mm height were cast for split-tensile test in accordance with BS EN 12390-6 [26], and prisms of 100 × 100 × 500 mm dimension were cast for flexural strength test, following BS EN 12390-5 [27] procedure.

Natural curing was carried out by keeping the concrete samples at normal conditions after demoulding, at a temperature of

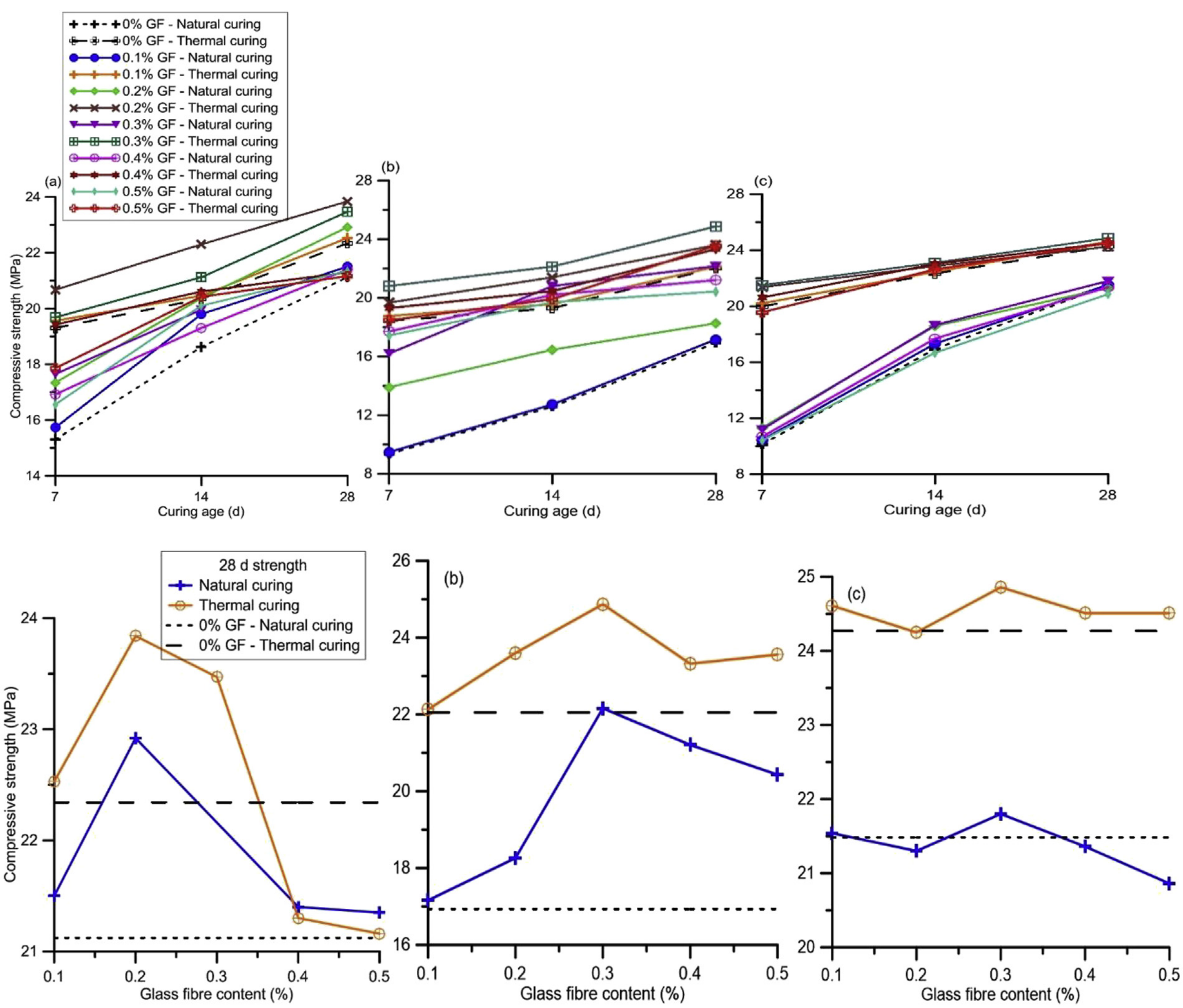


**Fig. 3.** Compressive strength development with curing age and glass fibre (a) 12 M (b) 16 M (c) 20 M.

27 ± 2 °C. This curing approach was performed in order to assess the suitability of the glass fibre-reinforced geopolymer concrete for *in situ* construction. For thermal curing, temperature was maintained at 100 °C for 24 h in an oven. Fig. 2 shows the curing procedures adopted. After 1 d thermal curing, concrete samples were kept at normal room temperature.

Lastly, scanning electron microscope (SEM) was used to analyse selected geopolymer samples, in an attempt to understand some intrinsic internal structure of the samples, which can influence their strength performances.

## 3. Results and discussion

### 3.1. Compressive strength

The compressive strength results of concrete specimens which were activated using 12, 16 and 20 M alkaline solution are presented in Fig. 3. The strength of the geopolymer concrete increased with increasing curing age under the two curing conditions. A similar attribute is reported with conventional OPC concrete [28]. As can be seen in Fig. 3a–c, thermal curing aids early strength gain through maturity in the samples than curing them in the natural environment. The rapid strength gained under thermal curing at 100 °C, is attributable to absorption of excess moisture from the concrete during steady heating. Singh et al. [12] made a similar observation on steel fibre reinforced geopolymer concrete. Further, a report by Awoyera [29] has revealed that subjecting concrete to a temperature below 100 °C can significantly influence its strength properties without causing any severe damage to the concrete structure. Fig. 3 also demonstrates the effect of glass fibre content on the compressive strength development in the samples. For the samples containing 12 M NaOH (Fig. 3a), addition of 0.2% of glass fibre (GF) produced the highest compressive strength, thus yielding 23.8 and 22.9 MPa strengths under both thermal and natural curing conditions respectively.

Also, for the geopolymers activated using 16 M alkaline solution (Fig. 3b), the compressive strength of the concrete increased with increasing curing age under the two curing conditions. Maximum compressive strength achieved by thermally cured and naturally cured concrete samples at 28 d were 24.8 and 22.2 MPa, respectively. Geopolymer concrete with 16 M alkaline solutions has better compressive strength than the concrete with 12 M solutions. However, a 0.3% of glass fibre addition (Fig. 3b) produced the maximum compressive strengths for both natural and thermal curing.

There is similarity between the 16 and 20 M activated geopolymers, in that addition of 0.3% of glass fibre produced the maximum compressive strengths for both natural and thermal curing. For the samples containing 20 M NaOH, Fig. 3c shows the compressive strength development with curing age, and with fibre additions. The maximum compressive strength achieved by thermally cured and naturally cured concrete samples at 28 d were 24.7 and 21.8 MPa, respectively. In a similar investigation on steel fibre reinforced geopolymers, Reed et al. [15] and Vijai et al. [30] found that oven dried geopolymers developed higher compressive strength than ambient cured samples. However, in this study, it can be seen that only a slight variation in strength exists between thermal curing and natural method, as such, it shows the viability of using geopolymer of this composition as *in situ* construction concrete. The compressive strength development with different alkaline solutions is presented in Fig. 4. The geopolymer concrete with 20 M alkaline solutions had better compressive strength than the concrete with 12 and 16 M solutions. This result suggests that, when molarity of the alkaline solution is increased to 20 M, there is upsurge in the geopolymerisation reaction [31], which could have aided the increase in strength.

### 3.2. Split-tensile strength

Fig. 5 show the split-tensile strength for 12, 16 and 20 M geopolymers. As seen in the compressive strength results, the split-tensile strength also increased with the curing age. For 12 M activated geopolymers (Fig. 5a), maximum tensile strength achieved by thermally cured and naturally cured concrete samples at

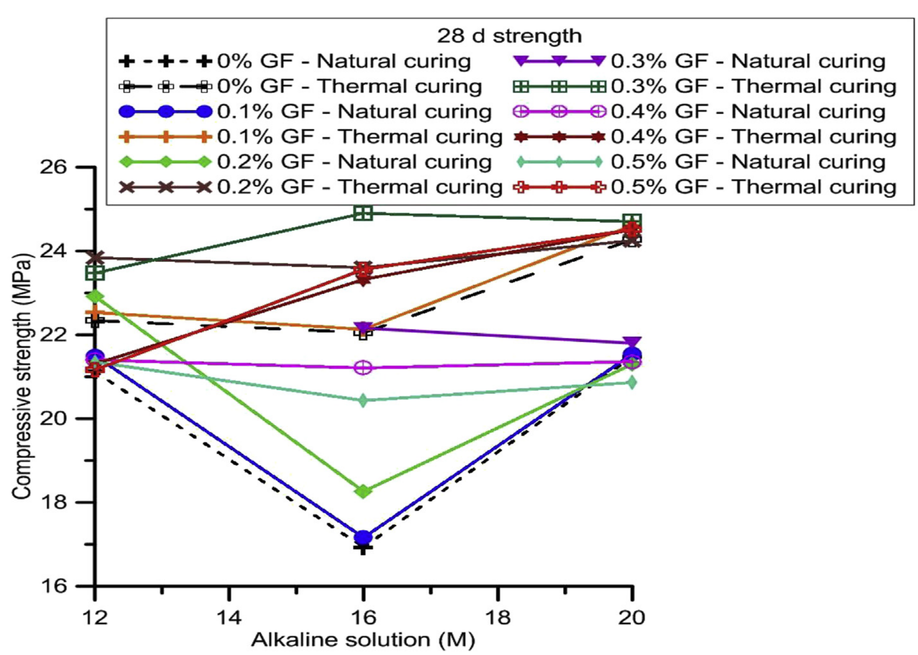


**Fig. 4.** Effect of alkaline solution on compressive strength of specimens.

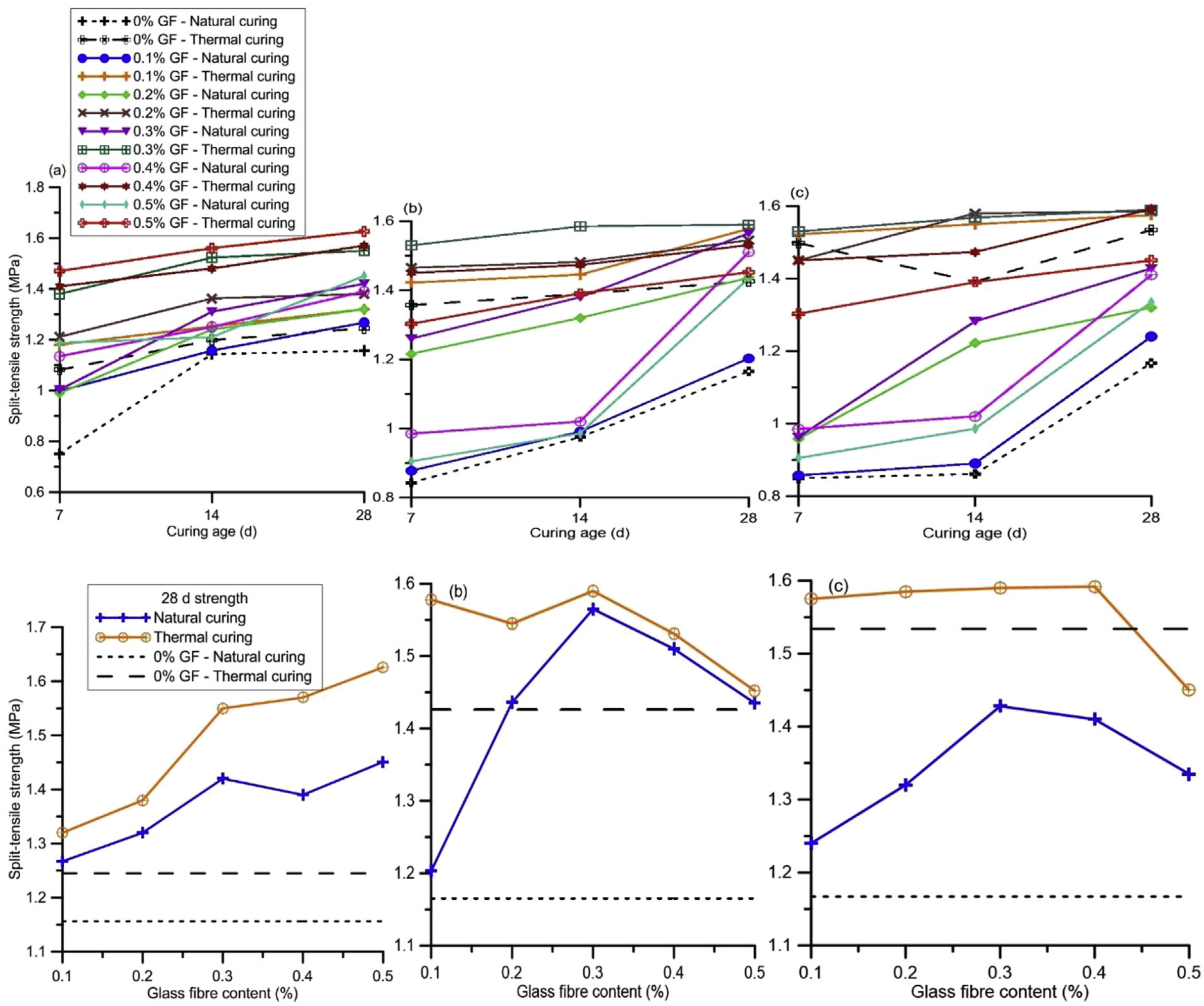


**Fig. 5.** Split-tensile strength development with curing age and glass fibre (a) 12 M (b) 16 M (c) 20 M.

28 d were 1.63 and 1.45 MPa at 0.5% of glass fibre. In contrast, for 16 M activated geopolymers (Fig. 5b), 0.3% of glass fibre addition produced maximum tensile strength of 1.59 and 1.56 MPa at 28 d, under thermal and natural curing respectively. Further, for 20 M activated geopolymers, addition of 0.4% of glass fibre yielded maximum tensile strength of 1.58 and 1.41 MPa at 28 d for thermally cured and naturally cured concrete samples, respectively. Thus, the presence of higher fibre content in 12 M geopolymers enhanced its tensile strength than the 16 and 20 M activated geopolymers. It can be insinuated that the increased fibre content was able to hold firmly a weak geopolymer concrete matrix resulting in the increased tensile strengths obtained in samples 12 and 16 M geopolymers than 20 M. The tensile strength development with alkaline solution molarity is summarized in Fig. 6. From the result, it was seen that, 12 M alkaline solution (with increased fibre content) yielded the highest split-tensile strength.

### 3.3. *Flexural strength*

Fig. 7 shows the flexural strength development with glass fibre addition for three different strengths of NaOH activated geopolymers. The flexural strengths of the geopolymers increased with increasing fibre content up to 0.3% (Fig. 7a and b), and 0.4% (Fig. 7c) for 12, 16 and 20 M activated geopolymers, respectively. The presence of the glass fibre was significant, as it enhanced the flexural strengths of the reinforced specimens than strengths obtained from unreinforced geopolymers. Again, thermally cured specimens produced slightly higher flexural strengths than natural cured specimens. The effect of alkaline solution molarity on the flexural strengths of the geopolymers is presented in Fig. 8. The 16 M solution activated geopolymers have the highest flexural strength, which was obtained at 0.3% fibre addition. The increase in strength can be as a result of the presence of reactive amorphous phase in the geopolymerisation reaction [32].

### 3.4. *Microstructural analysis*

Based on the strength results obtained, sample containing 0.3% GF, having higher strength value than the other samples, and 0% GF (control sample), were selected for the microstructural analysis. The SEM images of the samples are shown in Fig. 9. As can be seen, the control sample contains disjointed crystals with some internal pores. The pores are most likely present due to a slow hydration rate of the matrix. However, in the samples containing 0.3% glass

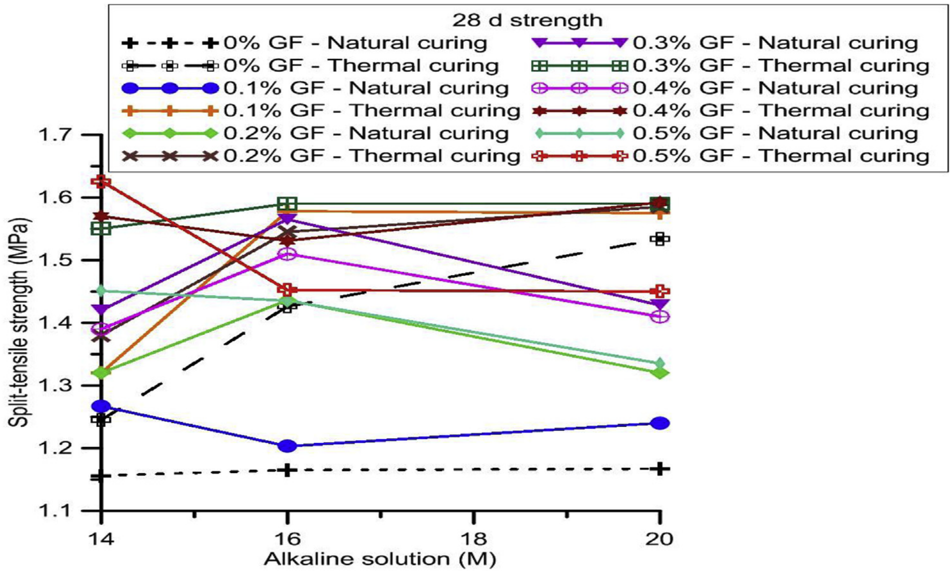


**Fig. 6.** Effect of alkaline solution on split-tensile strength of specimens.

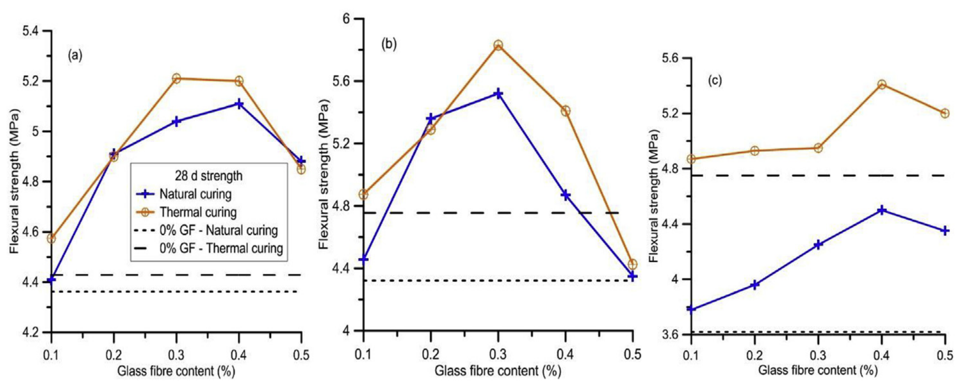


**Fig. 7.** Effect of glass fibre (GF) content on flexural strength of (a) 12 M, (b) 16 M, and (c) 20 M activated geopolymers.

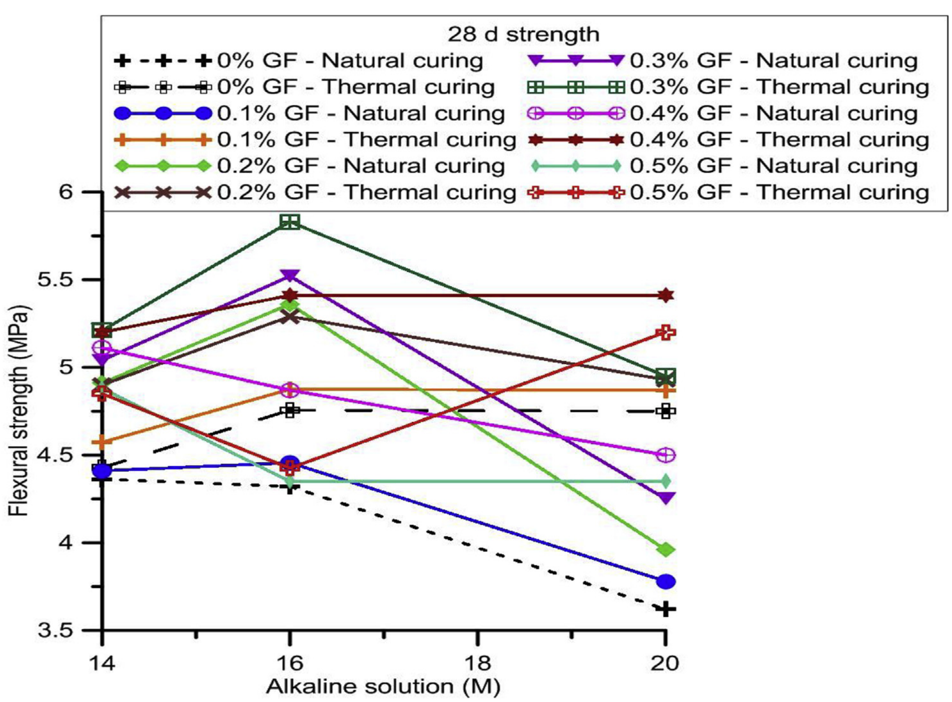


**Fig. 8.** Effect of alkaline solution on flexural strength of specimens.

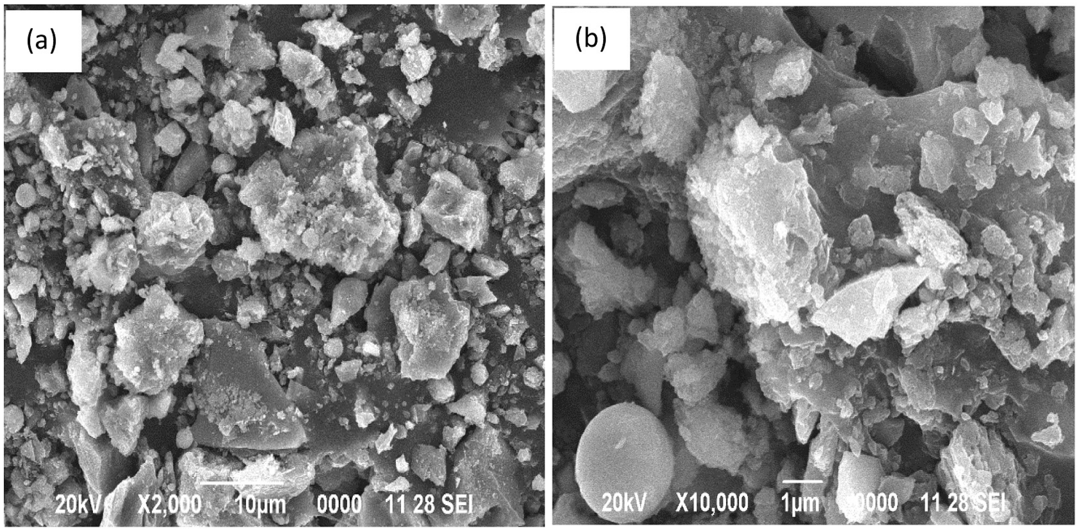


**Fig. 9.** SEM images of geopolymer concrete containing (a) 0% GF (b) 0.3% GF.

fibre, large well jointed crystals can be seen due to adequate hydration [33] and more importantly pozzolanic reaction resulting from the glass fibre fragments.

## 4. Conclusions

This study has determined the strength characteristics of glass fibre reinforced flash based geopolymer concrete, the following conclusions are drawn:

1. For most of the specimens, there was no significant increase in the compressive strength of thermally cured geopolymer concrete with the curing age. Thermally cured concrete specimens achieved more than 60% of its total compressive strength within the early age (7 d).
2. The geopolymer concrete specimens which were cured in the natural conditions, developed compressive strength with increasing curing age. The compressive strength result of specimens cured in natural specimens depends largely on the average temperature and intensity of light the specimen received during the first week after casting. When the average room temperature was high, there was appreciable increase in the compressive strength.
3. Thermally-cured geopolymer concrete achieved higher compressive strength when compared to the naturally cured concrete specimens. Thermally cured concrete specimen containing 0.3% glass fibre and 16 M NaOH achieved a maximum compressive strength of 24.8 MPa after 28 d, while naturally cured samples achieved a strength of 22.2 MPa.
4. Molarity of the alkaline solution also had significant effects in the mechanical properties of the concrete specimens. Concrete specimens with 16 M alkaline solutions achieved maximum compressive, flexural and tensile strength when compared to the concrete with the 12 and 20 M alkaline solutions. So, 20 M alkaline solution is not preferred for geopolymer concrete.
5. Fibre addition in geopolymer concrete resulted in variations in the mechanical properties of concrete. Addition of 0.3% of glass fibre gained maximum results in most concrete specimens. Further addition of glass fibre reduced the strength of concrete. Adding 0.3% of fibre increased the compressive strength of fly ash-based geopolymer concrete by 16%, when compared to the conventional geopolymer concrete.

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