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Mini-Review on Structural Performance of Fiber Reinforced Geopolymer Concrete

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ABSTRACT

Development of alternate eco-friendly and sustainable construction solutions for meeting rising infrastructural demands have become an attractive area of research. The purpose of this study is to demonstrate and review past research works based on fiber reinforced geopolymer concrete (FRGC). Geopolymers are highly promising low-carbon, cement-less composite materials possessing enhanced mechanical and serviceability criteria in comparison to OPC based construction materials. These inorganic composites are made up of industrial wastes with higher alumina and silica content as base material using 'alkali activating solution' as binder agent, but are quasi-brittle in nature hence, their ductility can be improved by proper reinforcing materials preferably "fibers". This study discusses and suggests that FRGC exhibits good thermal stability, light weight and lesser shrinkage property by understanding of previous works. Thus, rapid innovation of fiber reinforced geopolymers is highly anticipated in the near future. This paper also reviews development of FRGC and its properties; fresh and hardened. The recent developments regarding serviceability (Deflection, Crack width Control and thermal stability) are highlighted based on past literatures. The outcomes of this review paper will serve to provide a technical background of FRGC for researchers for conducting future experimental works.

Keywords: Fiber; fiber-reinforced geopolymer; geopolymer concrete; Mechanical property; Thermo-mechanical property; serviceability; durability

1. INTRODUCTION

The source materials used for production of geopolymers are generally aluminosilicates in nature. Three-dimensional tetrahedral chain-polymerisation of aluminosilicate materials when reacted with a mixture of hydroxides and silicates of sodium or potassium results in formation of inorganic polymers known as geopolymers. This new class of sustainable materials have all the preferable mechanical properties like normal cement paste such as compressive strength, toughness, thermal resistance, low permeability, volume stability and exhibits good durable properties like sulphate resistance and resistance to acid attacks. However, geopolymers lack inherited tensile strength, flexural strength and develops higher early age shrinkage. Another major positive attribute of geopolymer is that they require almost no mixing water to form paste and after 24 hours, it can be easily be de-moulded and cured at ambient temperature [1-3] unlike use of elevated temperatures; as reported in previous literatures [4,5]. Industrial waste materials such as fly ash (FA), ground granulated blast furnace slag (GGBFS), silica fume or natural sources like metakaolin clay, volcanic ash, red mud are used as source materials along with an alkaline solution. As the source materials contains low amount of calcium in comparison to OPC, carbon emissions are greatly reduced. Hence, geopolymers can be very a promising alternative for total replacement of OPC as a binder for concrete production.

As discussed earlier that geopolymers fail suddenly due to its brittle property, therefore more emphasis is required to be given upon increasing its tensile strength. Fiber reinforced structures show better tensile properties and post peak characteristics than conventional bar reinforcing method because smaller strands of the fibers when mixed well homogeneously, trigger maximum volume in smaller parts to arrest tensile and shrinkage cracks. In the modern OPC based fiber reinforced concrete, well bonding between fiber and cement has been observed [6]. Both fibers and cement possess equal thermal coefficient of expansion and an irregular boundary structure hence sudden debonding failure does not occur because of thermal load. This same criterion of fiber reinforcement is needed to be maintained in geopolymer concrete because of the remarkable benefits of fiber addition on the overall properties of concrete. Debonding, pulling out and sliding of fibers are the basic mechanisms which reduces the gap between micro level and macro level cracking of the base matrix which in returns increases the energy demand for crack to propagate further [6]. Therefore, the choice of base material and the type of fiber used for production of geopolymers significantly affects the overall properties of geopolymer composites.

There are three basic serviceability criteria that needed to be checked for structural safety of constructed members viz. Deflection, Crack width, and newly implemented Thermal load resistivity. Deflection criteria is almost related to mechanical properties of individual materials i.e. fibers and matrix. In some studies, it is found that geopolymer performs in a better way to counterpart deflection with increased loading with use of fibers. The stress-strain behaviour of geopolymer based structural member has shown better energy absorption trend because fibers leads to work mechanically in the micro level [7]. FRGC has shown better crack width resistance property when optimum fiber content (especially short fibers) are being used explicitly. Short fibers occupy maximum numbers per volume of specimens and are able to trigger crack width propagation effectively [8].Structural members when subjected to thermal loading generally fails due to multidirectional shrinkage of the material causing loss of strength. In FRGC it is observed that shrinkage of fibers are limited to one direction only up to specific higher value of temperature loading which indicates relatively lesser loss of strength due to fiber shrinkage and sustainability to thermal loading [9].

With ongoing researches which only solve a specific criterion about application of FRGC, there are very few sources available which provides a collective information on conventional use of fiber reinforced geopolymer concrete in modern construction era. Therefore, this paper aims to serve as a handy model for the reader giving an overall basic idea about structural application of geopolymer concrete keeping view of all the necessary ideas like type of fibers, variation in mechanical properties of FRGC specimens with fiber type and proportions and also variation in behaviour of the structural members according to fiber type and fiber proportion in serviceability condition.

The remainder of the paper is organized as follows: Section 2 of this paper describes about type of fibers used as reinforcement and further subdivided into parts according to fibers providing better serviceability conditions (Section 2.1), workability (Section 2.2), compressive strength (Section 2.3), split tensile and flexural strength (Section 2.4), and durability (Section 2.5). Finally, section 3 concludes this research article with further research recommendations.

2. FIBER REINFORCED GEOPOLYMER COMPOSITES

For preparation of geopolymers, there is an extensive range of types of fibers but certain types containing material like steel, carbon and glass provide the best results in terms of strength and other mechanical properties. Fibers can be categorized into metallic and non-metallic. Steel is an example of metallic fiber and carbon, glass fiber etc. are the types of non-metallic fibers. Furthermore, type of fibers can be natural and synthetic according to their source of extraction. Jute, cotton fibers, coconut etc. are some of the examples of natural fibers while polypropylene (PP) is an example of synthetic fiber [24]. Choice of fiber is the most important parameter in achieving the desired properties of geopolymer composites. Some sort of fibers provides superior energy absorption and flexural strength while some fibers provide better ductility and good resistance to thermal load and chemical hazards. Hence selection of fiber material and considering its geometrical property play a major role when implementing it for preparation of geopolymer composites for a desired application. Modern fibers are obtainable in various forms such as nano particles, threads, filaments, whiskers etc. It is necessary that fibers should own property for providing suitable interfacial bonding to enhance stress transmission and optimum aspect ratio is also a primary requirement for strength development of composites. Some of the properties of fiber reinforced geopolymer composites (esp. concrete) have been discussed in the sections below.

2.1 Serviceability (Deflection, Crack width Control and thermal stability)

Vaidya and Allouche [7] experimented on geopolymer reinforced with electrically conductive carbon fibers. The carbon fiber reinforced geopolymer (CFRGC) specimens were loaded physically and electrical conductivity test was done at the same time along with observation of stress-strain state of same. Results from three-point bending tests on beam specimens shows that electrical resistance reduced with increase in bending stresses, which may be achieved by reduction of conduction length due to physical shortening of the beam compression surface and micro-structural change within geopolymer matrix. Axially loaded cylindrical CFRGC specimens resulted in fluctuating electrical resistance which was due to densification of the matrix and development of crack inside the specimen. Electrical resistance of CFRGC members can provide necessary information upon serviceability criteria (i.e., vertical deflection of flexural members) as well as permanent damage (e.g. on-set of cracks, fractures). Ohno et. al. [8] used randomly oriented short PVA fibers to develop strain hardening ductile FRGC. Cube compression test and dog-bone tensile testing resulted in 4% increase in overall ductility and further improved performance observed after temperature curing. From digital correlation technique, crack width was observed having a lesser maximum average value of 117 micro-m and 45micro-m respectively even at 4.5% higher stain level [8]. Tie-song et al. [9] studied the thermo-mechanical effect on short carbon fiber reinforced geopolymer composites which were tested subjected to temperature up to 1200°C. From room temperature to 1000°C, shrinkage in shorter fiber direction of fiber orientation were observed however after 1000°C shrinkage in both the direction was noted due to densification and crystallisation of the materials. At the temperature range of 600−800°C, flexural strength and fracture work of the composites got reduced due to the loss of the hydration water of geopolymer matrix. At Lucite phase, because of addition of α-Al_2O_3 particles into the composites, the onset crystalline temperature of the matrix increases and the volume change of the composites reduce resulting in improved mechanical property to a certain extent of thermal load. Thermal stability is achieved by curbing up the fiber pulling criteria due to addition of α-Al_2O_3[9].

2.2 Workability

Faris et al. [10] investigated workability properties of fresh geopolymer concrete involving different percentage of steel wool fibers (0 %, 1%, 3% and 5%) and they reported that workability decreased with addition of steel wool fibers in comparison to the mixes without fibers. However, in another study [11], it was reported that the fresh FRGC mix with crimped end steel fibers (1% of concrete by volume.) exhibited good workability with a slump of 140 mm without showing any signs of fast setting. Nematollahi et al. [12] observed that addition of glass fibers into the geopolymer matrix decreased the workability though all the measured slumps value were more than 150 mm. The mix was stiff and cohesive when compared to conventional cement-based concrete. Higher volumetric replacement of glass fibers in the geopolymer concrete mix lowered the slump values significantly.

2.3 Compressive strength

Majidi et al. [13] established that addition of steel fibers to the geopolymer system along with GGBFS and Silica Fume (SF) had a significant impact on compressive strength development of geopolymer specimens. At higher content of GGBFS, improvement in compressive strength of Steel fiber reinforced geopolymer concrete (SFRGC) was observed in comparison to the mixes without steel fibers. In a study by Shaikh et al. [14] studied the effects of elevated temperatures on the mechanical properties of SFRGC with two types of alkaline activators; sodium (Na) and potassium (K) and the results were analysed and compared with steel reinforced OPC concrete (SFRC). It was reported in the study that incorporation of steel fibers increased the compressive strength appreciably both in case of SFRGC and SFRC. However, SFRGC exhibited higher compressive strength at elevated temperature curing conditions when compared with SFRC [14]. Similarly, Alomayri et al. [15] demonstrated the use of cotton fiber (0-1.0% by wt.) for preparation of geopolymer composites and examined their effects on mechanical properties. The compressive strength of the geopolymer paste with cotton fibers reached up to 46 MPa after addition of 0.5% of cotton fibers (by wt.). But reduction in compressive strength was noted when cotton fibers were added beyond 0.5% by wt. The reason is attributed to free water consumption of cotton fibers making the bonds weaker [15]. Li et al. [16] also observed similar trends in the results of compressive strength development of hemp fiber reinforced concrete.

2.4 Split tensile and flexural strength

Patil et al. [17] examined the effect of using Polypropylene Fibre on mechanical properties of geopolymer concrete. Alkaline solution-to-binder ratio was kept at 0.5.

Polypropylene fiber of two different lengths (12 mm and 20 mm) were incorporated in the volume of the concrete. The results revealed that inclusion of PFRGC led to increase in split tensile strength and other mechanical properties in comparison to OPC based concrete and the mixes without fibers. Ganesan et al. [18] explored the engineering properties of SFRGC. The grade of geopolymer concrete was considered to be M40. It was reported that addition of 1% of steel fibers by volume led to significant improvement in the split tensile strength of specimens (61.63%) in comparison to 0.25 % volumetric steel fiber replacement. Vijai et al. [19] studied the effects of inclusion of glass fibers in the properties of Fly ash-OPC based geopolymer concrete. Glass fibers were added to the geopolymer mix in the range of 0.01%, 0.02% and 0.03% by volume of total concrete. The results showed that with addition of 0.03% of glass fibers increased the split tensile strength by 1% where the split tensile strength reduced for other two inclusions (0.01% and 0.02%).

Behforouz et al. [20] demonstrated the influence of polypropylene (PP) fiber on the mechanical properties of geopolymer concrete containing metakaolin and recycled coarse aggregates. A remarkable increment in flexural strength development was observed by the inclusion of 1% of PP fiber content. Zhou et al. [21] explored the effect of size and content of cotton stalk fibers (CSF) on the mechanical properties of bio-geopolymer composite. Untreated CSF in the geopolymer matrix slightly increased the flexural strength. However, CSF treated with alkaline solution exhibited maximum increment of 11.5% in case of flexural strength development. Natali et. al. [22] investigated different variety of composite fiber reinforcement materials eligible to be incorporated on sustainable geopolymer base matrix. The type of fibers selected had better adhesion properties which helped in effective bridging in-between fiber and matrix and was able to control micro-crack propagation along the matrix. Comparing to glass fiber, polymer fibers were proved to provide better overall behavior. Experimental results obtained by providing 1% (by weight) of reinforcing fibers showed an increment in flexural strength ranging from 30% to 70% when compared to unreinforced GPC specimen [22].

2.5 Durability

Ganesan et al. [23] conducted durability studies on plain and fiber reinforced geopolymer concrete and also presented the comparison with OPC based concrete. The results established that geopolymer specimens showed better durability properties with respect to conventional concrete. It was observed that fiber reinforced geopolymer specimens suffered negligible weight loss when subjected to sulphate attack and 2.2% when subjected to acid environment (3% of sulphuric acid) [23]. However, Rapid chloride penetrability test (RCPT) revealed that addition of fibers have no undesirable effect on chloride resistance of both geopolymer and OPC based concrete which is also confirmed by [24]. In a study, Behfarnia1 et al. [25] investigated the consequence of adding PP fiber to produce alkali activated concrete with slag based on its mechanical and durability properties. The results indicated that addition of PP fibers (0.24% by volume) decreased the chloride resistance of the specimens. Another study conducted by Funke et al. [26], established the durability characteristics of fiber reinforced alkali activated binder (FRAAB) based on alkali resistance (1 mol/L NaOH). Akali-resistant (AR-glass), basalt, E-glass, and carbon fibers were incorporated at 0.5% by volume as the reinforcement of the alkali activated binder matrix and the specimens were cured at ambient conditions.

The results of the investigation showed that AR-glass and carbon fibers exhibited highest durability characteristics under alkaline environment in comparison to E-glass and basalt fibers. The weight loss was significant in case of E-glass and basalt fibers reinforced alkali activated binder matrix under alkaline attack.

3. CONCLUSION

This research study highlights the recent developments in the production of FRGC. Currently, there has been an increasing interest for wider implementation of geopolymer concrete to reduce OPC usage and carbon footprints. As discussed in the paper, to overcome the brittle behaviour of geopolymers, incorporation of different types of fibers in the geopolymer matrix have proved to be very useful in achieving desired mechanical and durability properties. Although geopolymer has been introduced a few years back but presently, it still lags in the application part especially in the area of flexural and tensile strength criteria. Hence further rigorous research studies and data on the effect of various fibers upon structural, mechanical and thermal criteria of geopolymer based concrete must be conducted for its widespread applications. The information in this paper will certainly contribute to the present understanding of FRGC and encourage its further developments for a greener future.

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CONFLICT OF INTERESTS

The authors would like to confirm that there is no conflict of interests associated with this publication and there is no financial fund for this work that can affect the research outcomes.

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