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Effect of Hybrid Fibers on Water absorption and Mechanical Strengths of Geopolymer Concrete based on Blast Furnace Slag

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ABSTRACT

In recent years, geopolymers, as a new class of green cement binders, have gained significant attention as an environmental-friendly alternative to Ordinary Portland Cement (OPC) which can potentially reduce negative environmental impacts of OPC. Fiber Reinforced Geopolymer Concrete (FRGPC) is known as a new type of concrete with enhanced ductility characteristics over conventional concrete. In this experimental study, hybrid fibers of 12mm modified polypropylene and 55mm polyolefin were used to manufacture FRGPC specimens based on Granulated Ground Blast Furnace Slag (GGBFS). In this regard, FRGPC and non-fiber specimens were produced. The specimens were subjected to compressive, indirect tensile and 3-point flexural tests, as well as water absorption capacity and specific density studies. The obtained results showed that using hybrid fibers decreased the specific density and water absorption, a slight increase in compressive strength and a significant improvement in tensile and flexural strengths of FRGPC specimens compared to non-fiber specimens.

Keyword: Fiber Reinforced Geopolymer Concrete, Hybrid Fibers, Compressive Strength, Tensile Strength, Flexural Strength

1. INTRODUCTION

Ordinary Portland Cement (OPC) as the main constituent of conventional concrete is the most widely used cementitious material in the construction industry [1-4]. Portland cement production has major environmental disadvantages, including high energy consumption, natural resources exhaustion and carbon dioxide (CO2) emissions [1,5]. Production of 1 ton of OPC releases approximately 1 ton of CO2 into the environment [6-8] and consumes 1.5 tons of raw materials [9]. On the other hand, pollution and global warming phenomenon have become a major concern in developed countries [2]. Global warming is caused by the emission of greenhouse gases and among the greenhouse gases, CO2 plays a major role in global warming with a 60% share [10]. The production process of OPC is accounted for 7 to 10% of global CO2 emissions [11]. Our country (Iran), as the fifth largest producer of OPC worldwide, is also exposed to these environmental problems. In recent years, geopolymers have been introduced as a new cementitious material and green alternative to OPC. Geopolymers were first developed by Davidovits, as a new family of binders of inorganic origin. Usage of geopolymer cements can reduce carbon dioxide emissions by 44-64% compared to Portland cement [12]. It also improves waste management which has a positive impact on the environment [13]. Regarding civil engineering applications, Geopolymer Concrete (GPC) has showed enhanced physical and mechanical properties over conventional concrete, e.g. higher mechanical strength [14-16], enhanced durability [17], higher resistance to elevated temperatures and fire [18-20], lower permeability, improved resistance to solvents and acids [21,22] and lower creep effects [23,24]. Geopolymers are inorganic alumino-silicate materials produced from raw materials, rich in silica (SiO_2) and alumina (Al_2O_3), in combination with an alkaline activator solution [25,26]. The geopolymerization process involves a substantially fast chemical reaction under alkaline condition on Si-Al minerals, that results in a three-dimensional polymeric chain and ring structure consisting of Si-O-Al bonds [27-29]. Davidovits utilized the name "Poly(sialate)" to indicate the chemical composition of geopolymers, in which "Poly" represented the polymeric nature, and "sialate" was an abbreviation for the silicon-oxo-aluminate chain. He has also distinguished 3 types of monomers that form the basis of the geopolymer structure:the Poly(sialate) type (PS), the Poly(sialate-siloxo) type (PSS) and the Poly(sialate-disiloxo) type (PSDS) [31,32]. The alkaline activator solution is one of the two main constituents of geopolymers, playing a significant role in the formation of Al and Si crystals, and is normally chosen based on Na and K (solvent alkali metals) solutions. The most convenient alkali solution used in geopolymerization is a compound solution of NaOH or KOH and Na_2SiO_3 or K_2SiO_3 [32]. The aluminosilicate source, also known by other names such as raw material, geopolymerization source and source material, plays the most important role in geopolymer cements, as the supplier of Si and Al. The raw material, depending on required characteristics, cost and availability, can be of natural origin (e.g. zeolite), synthetic (e.g. metakaolin) or waste materials (e.g. fly ash or Granulated Ground Blast Furnace Slag (GGBFS)).As aforementioned, concrete, and especially GPC, has many advantages but the disadvantages of concrete also have to be considered. Low tensile strength and consequent low ductility and high brittleness, is of the major disadvantages of concrete. Introduction of fibers in the concrete mix is a solution developed in the past decades to overcome this issue. Usage of fibers to enhance brittle composites dates back to 3500 years ago when straw-reinforced sun-dried bricks were used to build the 57-meter-high hill of Aqar Quf near Baghdad [33]. Horse tail hair is also used to reinforce mortar and plaster [34]. Application of different types and geometries of fibers in concrete, "Fiber Reinforced Concrete (FRC)", has shown to effectively control crack propagation and improve physical and mechanical properties of the concrete composite, e.g. tensile strength [35]. Nowadays, fibers are widely used to improve a variety of properties such as: compressive, flexural and tensile strengths, resistance to impact and extreme temperatures, etc. in different types of concrete. These fibers range from metallic to polymeric fibers but research on concrete reinforced with polymer-based fiber types, due to their economic benefit over steel fibers, is high on the agenda. Polyolefin is a relatively new type of polymer-based fiber. These fibers are used to make elasto-plastic concrete which has shown to increase flexural toughness, fatigue strength and impact resistance and reduce crack propagation in concrete composites [36]. On the other hand, in recent years, application of 2-part and multipart hybrid fibers to enhance various properties of the concrete composite has gained significant interest. Fiber Reinforced Geopolymer Concrete (FRGPC) is a new type of concrete with higher ductility than convenient concrete [37] andhas been the subject of many recent studies to investigate its potential pros and cons.Gao et al [38] conducted research on GPC reinforced with 6 and 12mm long steel fibers and showed that the shorter fiber is more effective in controlling micro cracks, while the longer fiber provides ductility at extensive cracking scenarios. Furthermore, a hybrid fiber configuration showed to yield optimal crack-control features and prevents cracking in both macro and micro phases. Asrani et al [39] investigated slag-based FRGPC using Polypropylene or PP (13 mm long), glass (15 mm long) and 3D-steel (60 mm long) fibers of 0.3, 0.3 and 1.6 % volume content, respectively, and as single and hybrid fiber GPC configurations. The results showed that incorporating only PP fiber results in a significant increase (about 108%) of flexural strength over plain GPC. Hybridization showed to further improve strength characteristics, e.g. a hybrid PP and steel FRGPC composite displayed 30 and 200 % growth in compressive and flexural strength over plain GPC, respectively. Alberti et al [40] studied the properties of Polyolefin fiber-reinforced concrete enhanced with steel fibers in low ratios and concluded that the use of polyolefin fibers improves mechanical strength and provides considerable ductility and flexural toughness. Han et al [41] investigated the effect of Polyolefin fibers on the specifications of concrete containing silica fume. The results showed that using these fibers resulted in a 13% increase in flexural strength as well as a 70% decrease in crack propagation. Additionally, the specimens containing Polyolefin fibers exhibited 2 times higher impact resistance than those containing steel fibers and 14 times more than the control (no fiber) specimens. Deng et al [42] also studied the effect of macro-Polyolefin fibers on the concrete properties. The researchers observed the positive effects of Polyolefin fibers in preventing crack propagation by increasing the fiber content. Celik et al [36] studied the effect of different fiber types for FRGPC, on its resistance to elevated temperatures. Polyolefin, Basalt, Modified Polyamide and PVA fibers and incorporated as non-hybrid composites were considered. The results showed that the use of Polyolefin fibers at the optimum percentage (i.e. 1.2%) increased compressive strength by 4.7% and flexural strength by 25% compared to the control (non-fiber) specimen. In this experimental study, new types of hybrid polymer fibers, including: long twist Polyolefin fibers and short modified Polypropylene fibers, was used to manufacture FRGPC composites. After conducting initial tests to achieve the final mix design of the GGBFS-based geopolymer concrete, the effect of hybrid Polyolefin fibers on water absorption capacity, specific density and compressive, tensile and flexural strengths of FRGPC, were studied. In this regard, FRGPC and non-fiber specimens were produced. Thereafter, the specimens were subjected to the compressive, indirect tensile and 3-point flexural strength tests as well as water absorption capacity and specific density investigations. Finally, the obtained experimental results were collected, analyzed and reported.

2. MATERIALS AND METHODS

2.1. MATERIALS

The X-Ray Fluorescence (XRF) chemical analysis of the GGBFS used in this study is given in Table 1. NaOH with 98% purity and liquid Na2SiO3 with SiO2/Na2O molar ratio of 2, were used to prepare the alkaline activator solution. Table 2 represents the chemical analysis of the Na2SiO3, NaOH, and KOH substances.

Table 1: XRF chemical analysis of GGBFS

Chemical substance	SiO2	Al2O3	CaO	Fe2O3	Na2O	K2O	MgO	MnO	SO3	Cl	LOI
Weight %	34.4	11.2	37.2	0.6	0.62	0.68	9.8	1.58	1.2	0.02	0.5

Table 2: Chemical analysis of NaOH and Na2SiO3 solutions

NaOH			Na2SiO3		
Chemical substance	Result	Unit	Chemical substance	Result	Unit
NaOH	98	%	SiO2	30	%
Na2CO3	1	%	Na2O	14.5	%
NaCl	200	ppm	Water	55.5	%
Fe	6	ppm			
SiO2	15.7	ppm			
Appearance	White flake		Appearance	Clear liquid	

The aggregates were obtained from quarries around Tehran. Aggregates with granular sizes of 7-10 mm was used as coarse aggregate (sand), and < 4 mm sized aggregates were used as fine aggregate. Fine and coarse aggregates were sieved according to ASTM C33 [43]. The fineness modulus (using ASTM C136 [44]) and sand equivalent (using ASTM D2419 [45]) values of the fine aggregates were measured equal to 3.01 and 73, respectively. To reduce water content and improve workability of concrete, polycarboxylate-based Super Plasticizer (SP) was incorporated. The fibers used in this study was obtained from Nanonakh Sirjan Company. The main properties of the fibers are presented in Table 3 and Figure 1 displays the fibers used in this study.

Figure 1: Image of fibers used in this study

Table 3: Properties of fibers

Properties	Hybrid fibers
Length (mm)	12,55
Density (gr/cm3)	0.91-0.95
Tensile strength (MPa)	350-750
Module of elasticity (GPa)	4.5
Water absorbency	No
Alkaline and acid resistant	Excellent
Melting point (°C)	165

2.2. EXPERIMENTAL PROGRAM

In this part, 5 mix designs were defined, as illustrated in Table 4. To optimize the fiber volume content, different values of fiber volume content were added to the GPC specimens: 0.15%, 0.2% and 0.25%. Initially, the alkaline activator solution, constituting of NaOH (14M), Na2SiO3, SP and the extra water (according to each mix design) are combined and allowed to cool for 24 hrs. In the mixing process, the aggregates, GGBFS and fibers were first dry mixed in the mixer for 3 minutes. Next, the alkaline activator solution was added and the concrete was mixed for a further 2 minutes. Subsequently, compressive (100x100x100 mm cubes), tensile (200x100 mm cylinders) and flexural (100x100x500 mm beams) specimens were molded and vibrated for 10 seconds on a vibrating table. The specimens were cured in the oven (90 ˚C) for 24hrs. After the curing process, the specimens were allowed to rest at laboratory ambient temperature. The specimens were subjected to the 7- and 28-day compressive, tensile (Brazilian) and 3-point flexural strength tests, as well as water absorption capacity and specific density tests.

Table 4: Fiber Reinforced GPC mix designs

Mix ID	GGBFS (Kg/m3)	NaOH (Kg/m3)	Na2SiO3 (Kg/m3)	Coarse aggregates (Kg/m3)	Fine aggregates (Kg/m3)	SP (Kg/m3)	Extra water (Kg/m3)	Fiber content (%)
Control	400	80	120	840	840	8	10	0
F-0.15	400	80	120	840	840	8	10	0.15
F-0.2	400	80	120	840	840	8	10	0.2
F-0.25	400	80	120	840	840	8	10	0.25

The various tests were conducted according to standard testing procedures: compressive strength test according to the BS1881: Part116 [46], indirect tensile strength test according to ASTM C496 [47], 3-point flexural strength test according to ASTM C293 [48] and ASTM C1018 [49], water absorption capacity and specific density tests according to ASTM C642 [50].

3. RESULTS AND DISCUSSION

3.1.WATER ABSORPTION AND SPECIFIC DENSITY

Figures 2 and 3 display the specific density and water absorption capacity of the FRGPC and unreinforced GPC specimens, respectively.

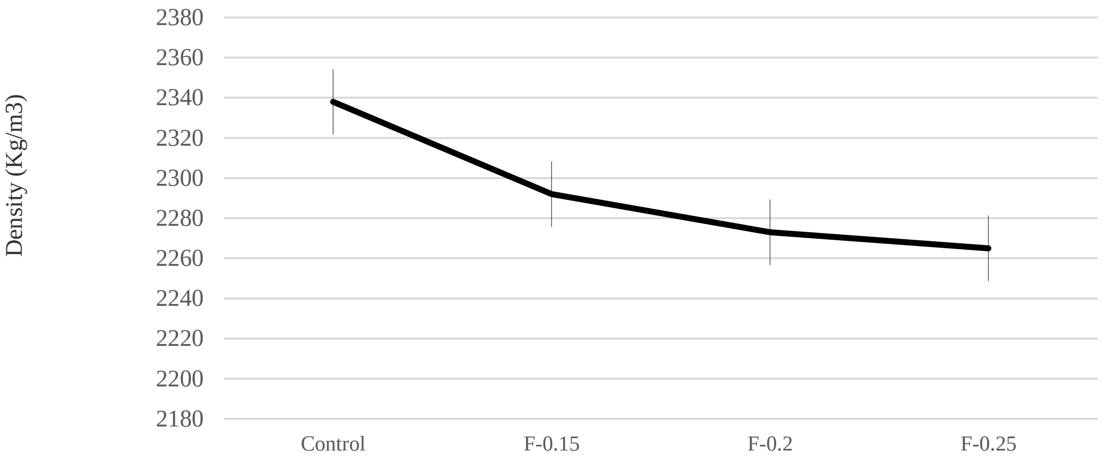

Figure 2: Specific density of the FRGPC and control specimens

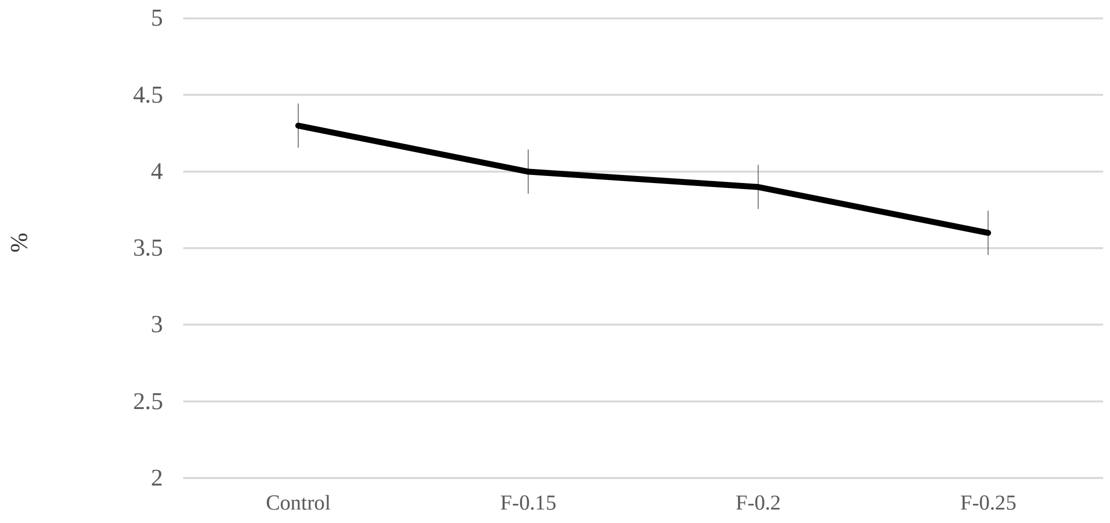

Figure 3: Water absorption of the FRGPC and control specimens

The specific density of the control specimen (unreinforced GPC) is calculated equal to 2338 kg/m^3. Usage of fibers in the GPC shows to reduce specific density with fiber volume content. Also, increasing the fiber content resulted in a further reduction in the specific density of the specimens, so that in the FRGPC containing 0.25% fibers, almost 3% of the specific density was reduced. This can be explained to the lower specific density of the fibers compared to the GPC matrix. The specific density of the fibers used is in the range of 0.91-0.95 gr/cm^3 (equivalent to 910-950 kg/m^3), thus reducing the specific density of the FRGPC specimens compared to the control specimen. The water absorption capacity of the control specimen is around 4.3%. Water absorption capacity of the FRGPC composites reduces with fiber content. The random dispersion of the micro and macro size fibers allow them to stitch micro cracks and prevent development of new ones in the geopolymer matrix. This mechanism results in the higher density of the geopolymeric matrix structure and consequent reduction in water absorption capacity [51].

3.2. COMPRESSIVE STRENGTH

The 7- and 28-day compressive strengths of the FRGPC composites are illustrated in Figure 4. The 7 and 28-day compressive strengths of the control specimen was 95.5 and 101 MPa, respectively. In the hybrid FRGPC composites, 0.15, 0.2 and 0.25% fiber content resulted in approximately 2.2, 6 and 3.4% improvement in compressive strengths compared to the control specimen, respectively. This issue may be due to the reinforcement of the concrete matrix by hybrid fibers and the improvement of the Interfacial Transition Zone (ITZ). The ITZ, is the boundary area between the cement paste and the surface of aggregates, fibers or rebar which plays an important role in permeability, durability and strength of concrete. The microstructures of the ITZ and the cement paste are different and compared to the cement paste, the ITZ microstructure has more porosity and micro cracks. The thickness of the ITZ depends on parameters such as fiber type, cement type, pozzolan type, etc. [52]. Using nanomaterials and fibers can strengthen the ITZ and improve the mechanical properties of concrete. But on the other hand, with increasing fiber content from 0.2 to 0.25%, the compressive strength decreased slightly. All fibers used were of polymeric materials, which due to high flexibility, can result in fiber balling in the concrete mix at high fiber contents. This phenomenon leads to perforations in the mortar matrix and subsequent internal flaws in interfacial transition zones and thus reduction in GPC compressive strength [53]. From the results obtained, in general, the fiber used had no significant influence on compressive strength of the GPC specimens.

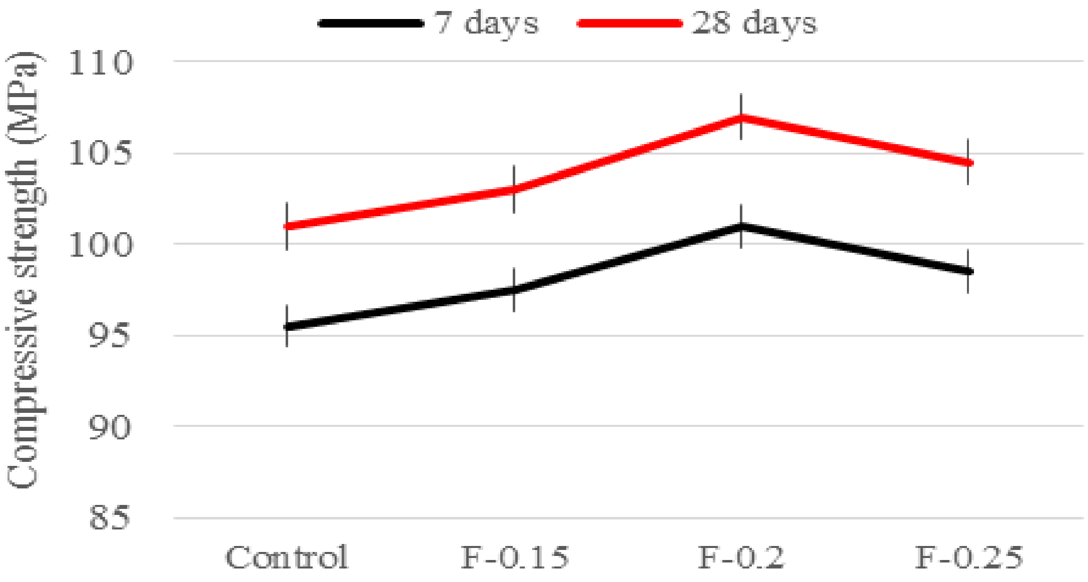

Figure 4: Compressive strength of the FRGPC and control specimens

3.3. TENSILE AND FLEXURAL STRENGTHS

The 7- and 28-day tensile strengths of the FRGPC and control specimens are represented in Figures 5. The lowest 7- and 28- day tensile strength were measured in the control specimen (3.72 and 4.4 MPa, respectively), and the 0.2% hybrid FRGPC specimen (F-0.2) showed the highest 7- and 28-day tensile strengths (4.61 and 5.45 MPa, respectively) among all FRGPC specimens. In the hybrid FRGPC composites, 0.15, 0.2 and 0.25% fiber content results in approximately 12, 24 and 22% improvement in tensile strengths compared to the control specimen, respectively. The obtained results indicated that using hybrid fibers improved tensile strength values compared to the control specimen and optimal results are achieved at 0.2% fiber content. Further increase in fiber content from 0.2 to 0.25% caused a slight decrease in tensile strength compared to the optimum value (0.2%).

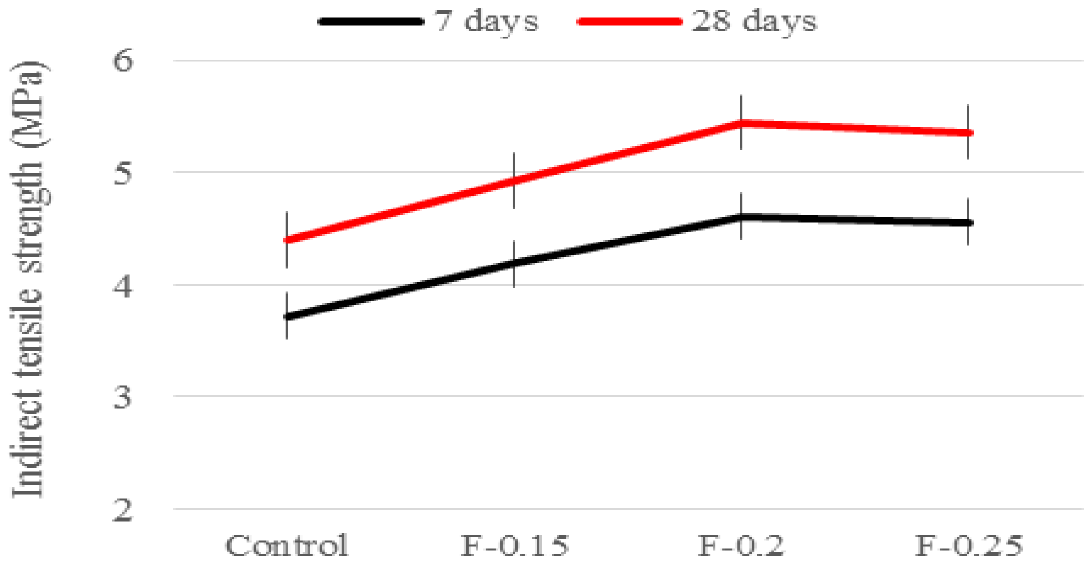

Figure 5: Tensile strength of the FRGPC and control specimens

The 7- and 28-day flexural strengths of the FRGPC and control specimens are illustrated in Figure 6. The 7- and 28-day flexural strengths of the control specimen were 5.82 and 7.11 MPa, respectively. Using 0.15, 0.2 and 0.25% (by volume) of hybrid fibers in GPC mixture, yield to approximately 56, 33 and 51% increase in flexural strengths compared to the control specimen, respectively. The optimal hybrid fiber content for maximum flexural strength improvement was 0.15%. However, the flexural strength decreases from 0.15 to 0.2% fiber content, and increases from 0.2 to 0.25%. The advantageous effect of fibers on the tensile strength of GPC composites leads to enhanced ductility characteristics over plain (no fiber) GPC. The polymeric fibers improve the geopolymeric matrix of the composites in terms of formation and/or redistribution of cracks [54]. The basic geopolymer structure includes the formed amorphous geopolymeric gel, residual unreacted raw material particles and varied pores [54-56]. Fibers can offer a bridging effect over the pores or cracks by embedding its two thrums in the cementitious matrix, resulting in increased toughness and strength of the geopolymeric matrix [54]. As a result, higher tensile and flexural strengths were observed in FRGPC specimens than non-fiber ones. On the other hand, fibers used in this study were hybridized using short and long lengths. Hybridization of fibers in terms of size and type results in the synergistic effect of fibers. The positive synergetic effects of hybridization stems from the different mechanisms of short and long fibers in the GPC matrix. Shorter fibers are more effective against smaller minor cracks, while longer fibers are mainly activated at higher loading scenarios to prevent formation and opening of major cracks. Therefore, the simultaneous usage of different fiber geometries develops positive features in the GPC composite for different levels of exerted loads [38,57].

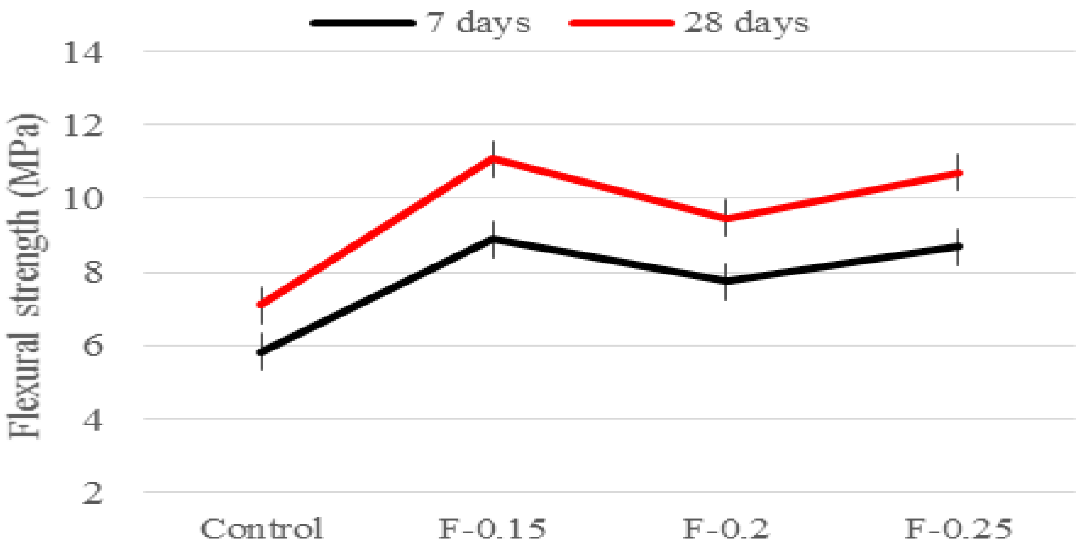

Figure 6: Flexural strength of the FRGPC and control specimens

4. CONCLUSIONS

In this paper, the mechanical and physical properties of GGBFS-based GPC reinforced with hybrid fibers of different volume content (0.15, 0.2 and 0.25%) is investigated. The main results drawn from this study, with regard to its limitations, can be summarized as below:

1- Presence of fibers cause reduction of specific density and water absorption of GPC composites, due to micro-structure enhancement and increased density of the matrix. These effects displayed a direct relation with fiber content and independent of fiber type.

2- Hybrid fibers improve the compressive strength of GPC due to the reinforcement of the concrete matrix and the improvement of the Interfacial Transition Zone (ITZ). The increase in compressive strength due to the relatively low modulus and strength of the fibers (compared to steel fibers) was not significant; the hybrid fibers used at optimum content (0.2) increased compressive strength by 6% compared to the non-fiber GPC specimens.

3- Due to the crack-bridging mechanism of the fibers, the fiber reinforced GPC composites displayed significant improvement in tensile and flexural strength over unreinforced GPC. Using hybrid fibers at optimum content (0.2% for tensile strength and 0.15% for bending strength), resulted in 24% and 56% increase in tensile and flexural strengths of the GPC specimens compared to non-fiber ones, respectively.

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AUTHORS CONTRIBUTION
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CONFLICT OF INTEREST
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