Jordan Journal of Civil Engineering, Volume **17**, No. **2**, **2023**
DOI: https://doi.org/10.14525/JJCE.v17i2.06

Mechanical and Durability Performances of Alkali-resistant Glass Fiber-reinforced Concrete

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ABSTRACT

Concrete, being the most widely used construction material in the world, lacks strength in direct tension and flexure. Attempts to reinforce concrete in tension include the use of steel rebars to strengthen the tensile side of concrete as well as the use of discrete fibers as a reinforcing medium. The study conducted in this manuscript details the effects of including alkali-resistant glass fibers in concrete. Mechanical strength, such as strength in compression and flexure, chord modulus of elasticity and bond pull-out strength, have been measured along with porosity and resistance to accelerated carbonation. Five different water to binder ratios in a range of 0.4 to 0.6 had been used to prepare the design mix proportions. The optimum fiber dosage was found to be 1.5% by weight of cement used. The same had been adopted in the design mix proportions. The average increase in compressive strength and flexural strength was 13% and 28%, respectively. Alkali-resistant glass fiber concrete showed less resistance to carbonation when compared to control mix. Results indicate that glass fibers play a predominant role in providing flexural strength to concrete. The pull-out strength of fiber was added to extra post-cracking flexural strength. The inclusion of alkali-resistant glass fibers imparted a maximum addition of 44% increase in the flexural strength compared to control concrete. The inclusion of alkali-resistant glass fibers in concrete paves the way for a leaner mix and eradicates the possibility of congestion of steel reinforcement for certain structures.

KEYWORDS: Alkali-resistant glass fibers, Accelerated carbonation, Bond strength, Compressive strength, Flexural strength.

INTRODUCTION

Concrete, being an excellent construction material, is very strong in compression and is equally weak in tension. Various studies in the past have been carried out to counter this predicament of the world's second most widely used material (Kizilkanat et al., 2015; Pakravan & Ozbakkaloglu, 2019). One of the efficient ways of countering these deficiencies, apart from using steel reinforcement, is to incorporate discrete discontinuous fibers into concrete. Inelastic deformation of concrete due to the formation and propagation of micro-cracks can also be addressed to a certain extent by the random dispersion of fibers into concrete, as the presence of fibers resists the opening of cracks (Betterman et al., 1995; Skourup & Erdogmus, 2009). Studies on fiber reinforcement in concrete concluded that the inclusion of fibers in concrete not only counters the weak tensile strength of concrete, but also provides fracture toughness, fatigue resistance, abrasion resistance and impact strength and improves post-cracking ductility of concrete (Balaguru & Najm, 2004; Banthia & Soleimani, 2005; Ghugal & Deshmukh, 2006; Yoo et al., 2015). Though the cost of the fibers used may pose an economic hindrance, the benefits by inculcating fibers in concrete for special structures outweigh the cost increase (Brandt, 2008). The fibers have been reported to have enhanced the mechanical properties of concrete, thereby replacing the traditional steel reinforcements for shear and tensile strength (Krassowska et al., 2019).

Received on 27/8/2022.
Accepted for Publication on 12/12/2022.

The behaviour of fiber-reinforced concrete (FRC) is subjected to various factors, such as modulus of elasticity, aspect ratio of fiber and matrix mix ingredients (Ghugal & Deshmukh, 2006). In the concrete mix, some fibers exhibit a better thermal behaviour compared to the resin and as a result prove to be effective in supporting force in longitudinal axis. But, the downside of the composite undergoes a slight reduction in tensile force transfer from fibers to resin (Xu & Shi, 2009).

Various fibers that are commercially available in the market are: glass, steel, carbon, natural and synthetic fibers (Al-Taan et al., 2020; Kavya et al., 2022; Koohestani et al., 2019; Sadrmomtazi et al., 2018; Wu et al., 2019). Steel fibers have been used to evaluate the performance of fine reclaimed asphalt pavement when they have been used as in-pavement materials in concrete (Paluri et al., 2020; Paluri et al., 2021). Hybrid fibers, such as a combination of more than one type of fiber, have proven to improve the pre-peak and post-peak behaviour in concrete (Koniki et al., 2021; Prathipati & Rao, 2021). When polypropylene fibers and glass fibers have been used with optimal water to cement ratio, the water-absorption capacity of the concrete mixes remained stable (Yuan & Jia, 2021). Glass fibers proved to be lightweight and economical and exhibited a high tensile strength of around 3400 MPa (Cao et al., 2019). Though speculated that the strength and toughness of a composite increased with the quantity of fiber at higher dosages, the concrete lost its workability due to bundling of fibers, thereby leading to a reduction in strength and toughness (ACI Committee 544, 2009). A blend of short and long fibers when they are properly graded at a particular volume fraction has been reported to have improved the overall strength and resistance to deformation of the composite and its strain hardening and softening capacity (Kasagani & Rao, 2018; Kasagani et al., 2021). The short fibers though delay the initiation of cracks and exhibit an isotropic behaviour (Alberti et al., 2016). Fibers help in improving cement's tensile strength, whereas cement mortar helps in avoiding buckling of glass fibers. These fibers help in transferring loads at internal micro-cracks. The fibers reduce the workability of concrete by entangling around aggregate particles and hence the mix has less chance of segregation resulting in improvement of concrete properties (Mirza & Soroushian, 2002). The strength of glass fiber-reinforced concrete specimens in tension was found to be 9-13% of its compressive strength (Kene et al., 2012). Recycled glass fibers too have been reported to have enhanced the split tensile strength of a mortar mix drastically (97.6%) when used in appropriate dosages (Małek et al., 2021).

Despite the benefits of glass fibers in concrete, the long-term durability of concrete suffered due to the formation of calcium hydroxide crystals during hydration of cement (Gilbert, 2004; Litherland et al., 1981). The formation of portlandite ($Ca(OH)_2$) is responsible for alkalinity of pore solution in concrete. The pH of concrete due to presence of portlandite is 12.6 and this leads to the reduction in filament diameter of fiber (Charles, 1958), finally deteriorating it. The Si-O-Si bond in the fibers is majorly affected by the abundance of hydroxyl ions in concrete pore solution, resulting in the formation of Si-OH bonds, which further leads to development of stress concentration at fiber edges (Hayashi et al., 1985). Calcium hydroxide hexagonal crystals occupy the space between the fiber strands and lead to embrittlement due to reduction in the strain capacity of fibers. This phenomenon also leads to reduction in the flexibility of the composite (Cohen & Sidney, 1975; Majumdar, 1980). Using low-basicity cement, supplementary cementitious materials or densifying the boundary between the matrix and fiber may theoretically protect the fibers from the portlandite attack (Oh & Kim, 2011; Péra & Ambroise, 2004; Scheffler et al., 2009).

If the surface of the fibers is coated with zirconia (15% or more by weight), the resistance to alkali attack on the fibers can be improved (Gao et al., 2003). This leads to alkali-resistant glass fibers which came into prominence and are now widely used in construction. These fibers have been reported to have increased the split tensile strength and wear resistance of the composite (Domagała et al., 2019; Sivakumar & Santhanam, 2007; Zhu et al., 2019).

Furthermore, to counter the corrosion issues of the steel reinforcement in coastal regions due to chloride attack and aggressive environmental exposures by alkalinity reduction in concrete, researchers have started using fiber-reinforced polymer (FRP) rebars (Baena et al., 2009; Gu et al., 2016; Jiang et al., 2018; Li et al., 2017). FRP rebars made of glass, carbon, basalt and aramid are under use due to their superior durability resistance in aggressive environments (High et al., 2015; Tighiouart et al., 1998). In the production of the FRP rebars, epoxies and resins are usually used to hold together the strands and bundles of fibers by a process called pultrusion (Dong et al., 2016). The factors that influence the bond behaviour of the FRP rebars in concrete are diameter of the rebar, material of the rebar, embedded length of the rebar and strength of adjoining concrete (Baena et al., 2009; Danying & Brahim, 2001; Dong et al., 2016; Gu et al., 2016; High et al., 2015; Jiang et al., 2018; Li et al., 2017; Mazaheripour et al., 2013; Mazaheripour et al., 2013; Tighiouart et al., 1998). Though the use of FRP rebars in concrete yielded less bond strength when compared to conventional steel rebars, the slip of FRP rebars has been reported to have been more than that of steel rebars (Bank et al., 1998; Tighiouart et al., 1998).

The present article attempts to study the influence of alkali-resistant glass fibers in concrete with water to binder ratios from 0.40 to 0.60. The optimum dosage of fibers was fixed by trial-and-error method. Hardened concrete properties, such as the strength in compression and flexure and the modulus of elasticity have been studied along with depth of carbonation and porosity for durability. The bond strength of glass fiber-reinforced polymer (GFRP) rebars in conventional concrete and glass fiber-reinforced concrete has also been studied.

MATERIALS

Materials Used

The cementitious material used in the present study was ordinary Portland cement of grade OPC 53. The specific gravity, density, fineness, water demand, initial and final setting times of the cement used are presented in Table 1. The chemical composition and the clinker composition of cement is tabulated in Table 2.

Table 1. Physical properties of cement

S. No.	Physical property	Value
1	Specific gravity	3.12
2	Density (g/cm^3)	3.09
3	Fineness (m^2/kg)	310
4	Water demand (%)	33
5	Initial setting time (min)	48

Table 2. Chemical composition and clinker composition of cement (%)

Material	Chemical composition							Clinker composition			
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	LOI	C_3S	C_2S	C_3A	C_4AF
OPC	21.5	4.5	4	62	2.4	2.6	3.1	51.67	18.36	11.30	10.65

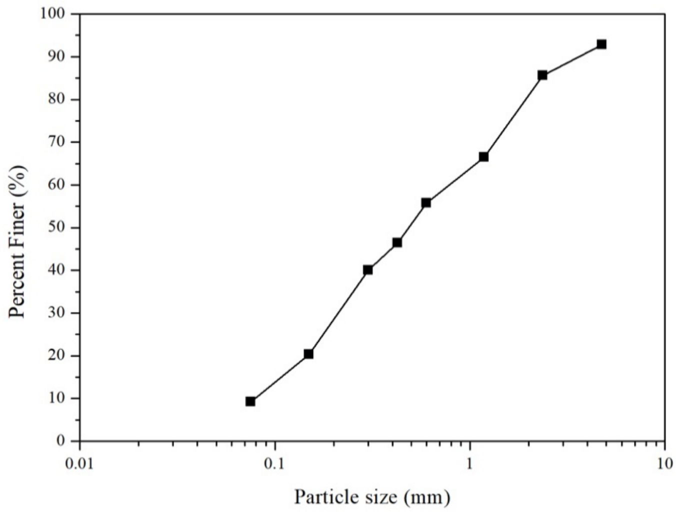

Figure (1): Particle-size distribution curve of fine aggregate

The specific gravity of crushed basalt and sand used as coarse and fine aggregates, respectively, was measured in accordance to IS 2386 Part III (1963) and the values have been found to be 2.72 and 2.60, respectively. The range of particle size of coarse aggregates was 10.5-20mm and the same for fine aggregates was found to be 0.075-4.75mm. The particle-size distribution of the fine aggregates is represented in Figure 1.

Alkali-resistant glass fibers with 12mm length and 12-15 μm filament diameter, as shown in Figure 2, have been used in the present study. The tensile strength of the fiber was 1.7 GPa and the zirconia content in the fibers was 19%, as shown in Table 3. Also, two types of rebars have been used in the present study; steel and GFRP rebars. Steel rebars of tensile strength of 500 MPa were used for pull-out strength test as a reference. The results are compared to those of FRP rebars (1100MPa tensile strength) in terms of pull-out strength with and without glass fibers in concrete. The rebars have not been surface-treated and have been used as procured from the local market. Diameter of both the rebars has been maintained at 12mm. Figure 2 also shows the GFRP rebars used in the study.

Table 3. Physical characteristics of alkali-resistant glass fibers

	Density (g/cm^3)	Tensile strength (GPa)	Elongation (%)
Alkali-resistant glass fiber	0.3	1.7	4.4

Figure (2): Alkali-resistant glass fiber & FRP rebar

The design mix proportions of the concrete mixes used in the present study are tabulated in Table 4. The variation in water to binder ratios in accordance with slump and the amount of cementitious material used in the study are designed with respect to IS 10262 (2009). The design mix proportions have been calculated to cater to ‘severe’ environmental exposure conditions to achieve a stipulated minimum strength of 25MPa in the most economic manner. A standard deviation of 5 has been adopted in the design process. The concrete and its ingredients have been quantified as per weigh batching with respect to their specific gravities and the mix is designed to attain a slump of 75-100mm. 60% of the coarse aggregates were of 20mm size and 40% of them were of 10mm size. This proportion was achieved by trial-and-error method. Fiber contents of 0.5%, 1%, 1.5% and 2% by cement weight have been used for trial mixes and compared to ordinary Portland cement concrete mix. The compressive strength of concrete mix with fiber as 1.5% by weight of cement has shown highest strength after 28 days of curing. The values of compressive strength for trial mixes 0.5%, 1.0%, 1.5% and 2.0% dosages of fibers by weight of cement were 20.9MPa, 22MPa, 24.1MPa and 23.4MPa, respectively. The value of compressive strength for the control mix (without fiber) was found to be 23.25MPa. Hence, the trial mix with fiber dosage of 1.5% has been observed to be optimum. Also, to maintain sufficient workability, a water-reducing super-plasticizer of sulphonated naphthalene formaldehyde was used in the study. The percentage of super-plasticizer varied with water to binder ratio, where the mixes with water to binder ratios of 0.4, 0.45, 0.5 and 0.55 had a super-plasticizer of 2%, 1.5%, 1% and 0.5%, respectively, by weight of cement added to the mix. The mix design with water to binder ratio of 0.60 was cast without any super-plasticizer, as the value of slump was more than 50mm.

METHODOLOGY

The concrete specimens casted in accordance with the design mix proportions mentioned in Table 4 are tested for their strength in compression and flexure and durability. Apart from tests on strength in compression and flexure, modulus of elasticity test had also been performed to evaluate the mechanical strength of concrete. Porosity, water absorption and depth of carbonation tests had been performed to evaluate the durability.

Table 4. Concrete design mix proportions and fresh concrete workability

Design mix proportions (kg/m^3)						Slump (mm)
Mix name	Water to cement ratio	Cement	Water	Fine aggregate	Coarse aggregate	
MO40	0.40	450	197	581	1235	100
MO45	0.45	438	197	600	1218	95
MO50	0.50	394	197	631	1225	83
MO55	0.55	358	197	661	1227	75
MO60	0.60	328	197	689	1225	60

Compressive strength is the maximum axial compressive stress that a solid material can resist without fracture. It is that property of concrete which is responsible for the strength of the structure. The concrete specimen was put in a compression testing machine and the load was applied at a constant rate of approximately 140 kg/cm^2 /min. Load at which the specimen broke was noted in kN and converted into Newtons and then divided by the area of cross-section of the cylinder to obtain strength in compression.

Similarly, flexural strength of concrete samples has been measured by concrete prisms of dimensions 10x10x50cm. The load (180kg/min) was applied as a point load, where the points are spaced 13.3cm apart on the surface of the prism. The highest load sustained by the specimen is noted and converted into modulus of rupture to calculate the flexural strength. The compressive strength and flexural strength of concrete were measured in accordance with IS 516-1959.

Modulus of elasticity is the rate of change of unit stress with respect to unit strain under uniaxial loading. Chord modulus of elasticity was measured using a strain gauge and compression testing machine on cylinders of 30cm height and 15cm diameter. Coordinates on the plot of stress-strain curve of the samples at a strain of 50micron/m and a stress of 40% failure stress are noted to measure the chord modulus of elasticity as per ASTM C469-02 (2002).

Pull-out strength: Bond strength of concrete is the strength required to pull the reinforcing bar out of the concrete. The strength of concrete's pull-out resistance depends on various factors, such as water to binder ratio, type of rebar, diameter of the rebar and embedded length. The pull-out resistance of concrete with the rebar is essential in obtaining the development length in reinforced structures constructed with that particular rebar. The bond strength of the conventional concrete and GFRC mix has been calculated in accordance with IS 2770 (2007). Concrete cubes of 100mm ×100mm× 100mm and rebar (steel and GFRP) of 12mm diameter have been used in the study, where only a half of the concrete has rebar embedded in it from above. The total length of the rebar was 400mm and the setup is shown in Figure 3. The cubes have been cured for 28 days and then tested for maximum pull-out load.

The mixes used in the study were also used to measure the durability of concrete in terms of its water absorption and porosity as a volume of permeable voids. The specimens after curing were kept in an oven for 24 hrs at a temperature of 110°C and were then immersed in water for 48 hrs. After immersion, the specimens were surface-dried and subjected to rigorous boiling for 5 hrs and then weighed after 14 hrs in accordance with ASTM C 642- 06. After this, the specimen's apparent weight of each specimen in water was recorded.

Figure (3): Casting of specimen for bond strength

The carbonation resistance of the samples with alkali-resistant glass fibers is measured using phenolphthalein indicator. Because the natural process of carbonation is a slow process, an accelerating carbonation chamber had been used in the present study. The carbon-dioxide concentration in the accelerating carbonation chamber was maintained at 3% and the relative humidity was 65-70%. The hardened concrete samples had been kept in the carbonation chamber for a duration of 3 months. Once removed from the carbonation chamber, the specimens were split and sprayed by a phenolphthalein indicator. The colourless region after being sprayed by the indicator represents the carbonated zone.

Micro-structural Analysis

Thermogravimetric analysis was performed to identify the carbonates and hydroxides in the concrete samples. The specimens after acetone quenching were subjected to temperatures up to 900^0C at 20^0C/min. The loss in weight in accordance with temperature change is noted. The drop in weight at a particular temperature range signifies the presence of certain hydration products of cement. The test specimens extracted from the concrete samples post hydration were quenched in acetone for 7 days to arrest hydration and then packed airtight. The specimens extracted for FTIR and scanning electron microscopy (SEM) were also packed similarly.

Fourier transform infrared spectroscopy (FTIR) was performed using FTIR-Alpha 1, Brand Bruker, Vertex Series on the specimens extracted from mixes MO40, MO50 and MO60 with and without fiber addition. The test results were used to identify the structural evolution of amorphous alumino-silicates exhibiting high heterogeneity and to identify specific molecular components and structures.

RESULTS AND DISCUSSION

Mechanical Strength

Figure 4 depicts the trends of compression, flexure and bond strength along with modulus of elasticity with respect to different water to cement ratios after 28 days of water curing under standard room temperature conditions. With increase in water-cement ratio, a significant decrease in compressive strength and flexural strength was observed. Fiber-reinforced concrete mix with water to binder ratio of 0.45 showed 13% increase in compressive strength when compared to the mix without fiber in it. An overall average increase of 8% in compressive strength was observed in all mixes with fiber embedded in them. Similar observations have been made by Chandramouli et al. (2010) who observed a 20% increase in compressive strength by inclusion of fibers in concrete. For flexural strength, fiber-reinforced concrete mix with water to binder ratio of 0.50 showed 44% increase in strength when compared to the mix without fiber in it. An overall average increase of 28% in flexural strength was observed in all mixes with fiber embedded in them.

Pull-out behaviour and strength of the alkali-resistant glass fiber strand may be the reasons for a significant rise in mechanical strength. The increase is also due to high dispersion of the fibers, which is in line with observations made by Wang et al. (2021). The resistance offered by the glass fibers required a certain amount of pull-out force to break the bond between fiber and the interfacial transition zone, leading to an overall increase in flexural strength. After sufficient flexure was generated in the specimen, the bond between fiber and the matrix broke giving rise to crack. Usually, this crack is initiated at the weakest location. As the crack develops into a major crack, the pull-out resistance of the fiber from the concrete matrix becomes crucial in the overall flexural strength (Kasagani & Rao, 2016).

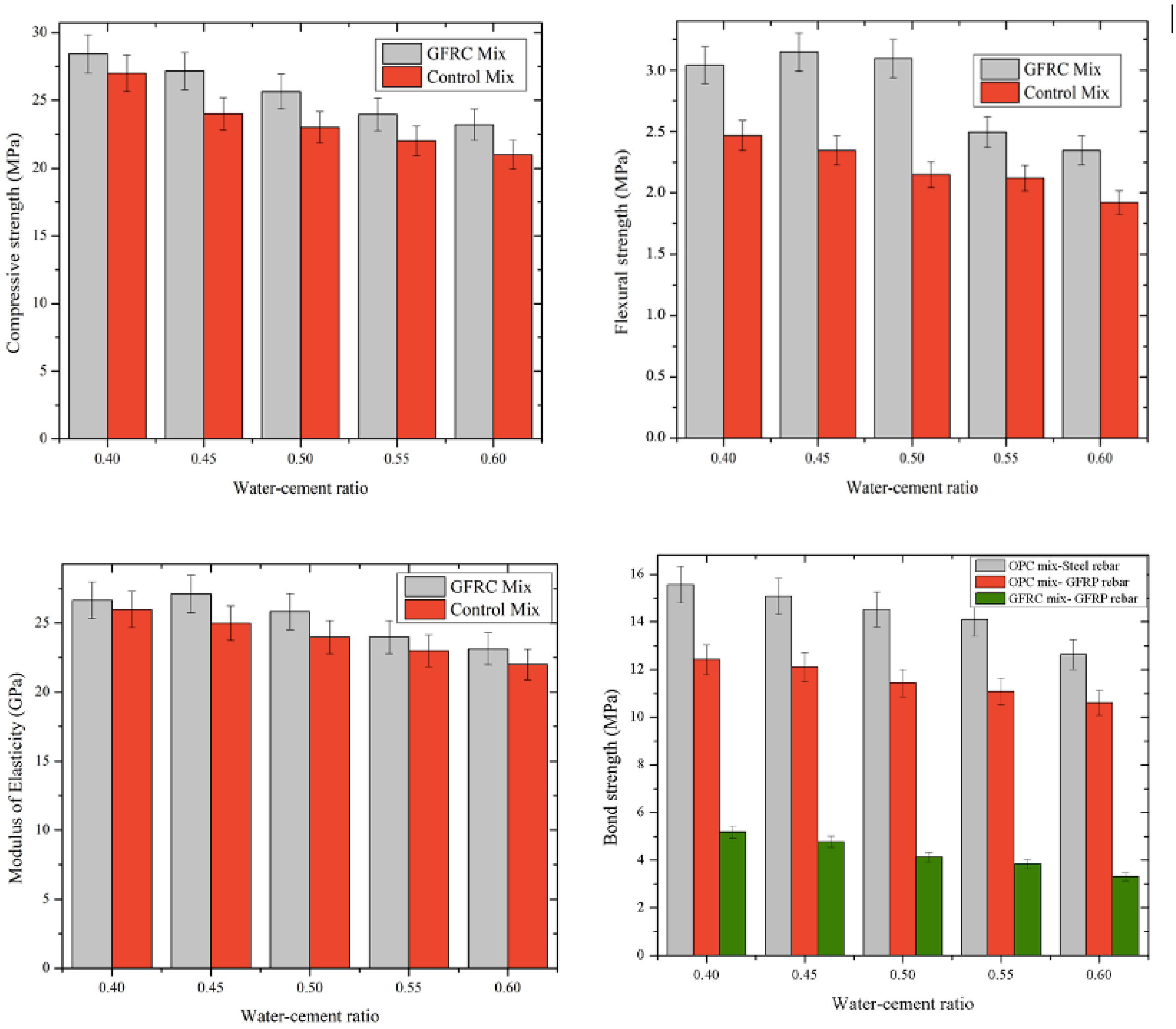

Figure (4): Mechanical strength of GFRC mix and control mix

Modulus of elasticity (MOE) is the rate of change of unit stress with respect to unit strain under uniaxial loading within the proportional (or elastic) limits of the material. In this experiment, it was measured using a strain gauge and a compression testing machine on a cylinder (15×30 cm). From Figure 4, it is observed that the specimen with a W/C ratio of 0.45 exhibits the highest modulus of elasticity with a value of 2800 MPa against the specimen exhibiting 2500 MPa with the same water ratio having ordinary Portland cement. The concrete specimen with a W/C ratio of 0.60 exhibited the least value of modulus of elasticity amongst all the mixes. Fibers work in the redistribution of the stress in concrete and bridge micro-cracks improving the modulus of elasticity (Abaeian et al., 2018; Atewi et al., 2019).

Bond strengths of the specimens used in the study along with their pull-out loads are tabulated in Table 5. As per the terminologies adopted in the table, the notation OPC-S-40-1 stands for Sample 1 of OPC mix and steel rebars with a water to binder ratio of 0.4. Similarly, the notation OPC-F-40-2 stands for Sample 2 of OPC mix and GFRP rebars with a water to binder ratio of 0.40.

It has been observed that the value of bond strength decreased with the increase in water to binder ratio. Moreover, the bond strength of GFRC mix – GFRP rebars was found less than that of OPC mix - GFRP rebars. The average decrease in bond strength was found to be 55%. The decrease in strength was maximum for mix proportion of water to binder ratio 0.55. Both these mixes had bond strength less than that of OPC mix - steel rebars. Figure 4 shows the trend in the bond strength of the FRP rebars in comparison to steel rebars.

Common failure modes observed in the bond strength test are failure due to pull-out of rebars, failure due to concrete cracking and failure due to yielding or rupture of rebars (Michaud & Fam, 2021; Zheng et al., 2021). In the present study, all the samples have been observed to have failed in pull-out of rebars.

The results obtained from the experiments as tabulated in Table 5 have been furthermore validated using the mathematical equation which is currently recommended in the ACI 440.1R-15 for predicting the bond strength of FRP rebars. The expression used to validate the results is given in Equation 1. Table 6 gives the comparison of predicted values with experimental values.

$$\frac{u}{0.083\sqrt{f_c'}} = 4.0 + 3.0\frac{C}{d_b} + 100\frac{d_b}{l_e} \quad (1)$$

where u is the average bond stress on the FRP rebars;
f_c' is the compressive strength of concrete;
d_b is the diameter of the rebars;
l_e is the embedded length of the rebars;
C is the lesser of the cover to the center of the bar or one-half of the center-on-center spacing of the bars being developed.

Table 5. Pull-out load and bond strength

S. No.	Specimen	Pull-out load (kN)	Bond strength (τ) (MPa)	Average bond strength (τ) (MPa)
1	OPC-S-40-1	31.5	16.7	15.57
2	OPC-S-40-2	30.0	15.9	
3	OPC-S-40-3	26.6	14.1	
4	OPC-S-45-1	31.1	16.5	15.07
5	OPC-S-45-2	24.9	13.2	
6	OPC-S-45-3	29.2	15.5	
7	OPC-S-50-1	28.5	15.1	14.53
8	OPC-S-50-2	27.9	14.8	
9	OPC-S-50-3	25.8	13.7	
10	OPC-S-55-1	26.8	14.2	14.10
11	OPC-S-55-2	26.2	13.9	
12	OPC-S-55-3	26.8	14.2	
13	OPC-S-60-1	24.5	13	12.63
14	OPC-S-60-2	23.6	12.5	
15	OPC-S-60-3	23.4	12.4	
16	OPC-F-40-1	22.6	12	12.43
17	OPC-F-40-2	19.2	10.2	
18	OPC-F-40-3	28.5	15.1	
19	OPC-F-45-1	20.0	10.6	12.10
20	OPC-F-45-2	23.7	12.6	
21	OPC-F-45-3	24.7	13.1	
22	OPC-F-50-1	20.7	11	11.43
23	OPC-F-50-2	23.6	12.5	
24	OPC-F-50-3	20.4	10.8	
25	OPC-F-55-1	20.2	10.7	11.09
26	OPC-F-55-2	21.2	11.2	
27	OPC-F-55-3	21.3	11.3	
28	OPC-F-60-1	19.7	10.5	10.61
29	OPC-F-60-2	20.4	10.8	

30	OPC-F-60-3	19.9	10.6	
31	GFRC-F-40-1	9.0	4.8	5.17
32	GFRC-F-40-2	9.8	5.2	
33	GFRC-F-40-3	10.4	5.5	
34	GFRC-F-45-1	7.9	4.2	4.77
35	GFRC-F-45-2	9.8	5.2	
36	GFRC-F-45-3	9.2	4.9	
37	GFRC-F-50-1	7.7	4.1	4.13
38	GFRC-F-50-2	7.2	3.8	
39	GFRC-F-50-3	8.5	4.5	
40	GFRC-F-55-1	6.0	3.2	3.83
41	GFRC-F-55-2	8.3	4.4	
42	GFRC-F-55-3	7.3	3.9	
43	GFRC-F-60-1	5.5	2.9	3.30
44	GFRC-F-60-2	6.0	3.2	
45	GFRC-F-60-3	7.2	3.8	

Table 6. Comparison of bond strengths from experimental and predicted values

S. No.	Specimen	Average bond strength	Predicted bond strength
1	OPC-F-40	12.43	12.61
2	OPC-F-45	12.1	11.89
3	OPC-F-50	11.43	11.64
4	OPC-F-55	11.09	11.39
5	OPC-F-60	10.61	11.13
6	GFRC-F-40	5.17	12.94
7	GFRC-F-45	4.77	12.65
8	GFRC-F-50	4.13	12.30
9	GFRC-F-55	3.83	11.88
10	GFRC-F-60	3.3	11.69

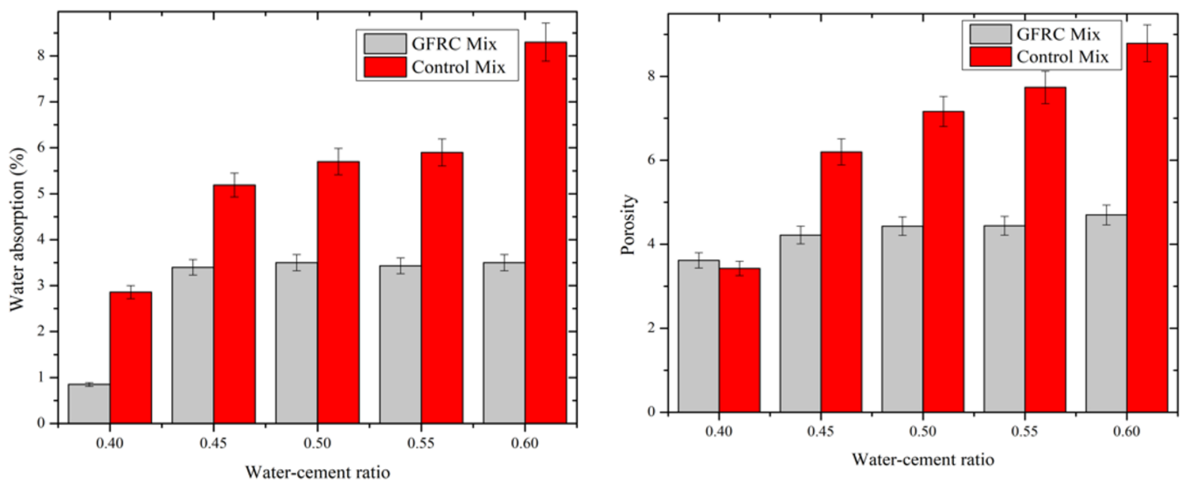

Figure (5): Water absorption and porosity of GFRC mix and control mix

The values from Table 6 clearly state that the design standard or recommendation for prediction of bond strength is adequate for FRP rebars embedded in OPC concrete with an average error of 2.52%, but is inadequate for GFRC concrete embedded with FRP rebars. For the GFRC concrete mixes, the values of bond strength obtained from experimental results are far less in magnitude when compared to the predicted values. Despite the higher compressive strength of GFRC mix in comparison to the OPC mix, the non-homogeneity of the mix and more slip provided lesser bond strength in GFRC concrete with FRP rebars.

Durability

The test results pertaining to water absorption and porosity in terms of volume of permeable voids are shown in Figure 5. From both the graphs shown in Figure 5, an increasing trend in the values has been observed as the water to cement ratio rose. On the other hand, with inclusion of glass fiber in concrete, the water-absorption capacity and volume of permeable voids decreased. This could be explained due to the ability of glass fiber-reinforced concrete to control the restrained shrinkage cracking and to reduce the crack width. The percentage of decrease was witnessed highest in the specimen with a water to cement ratio of 0.60. In this specimen, 8.3% of water was absorbed against 3.5% in the specimen embedded with GFRC. Correspondingly, in the volume of permeable voids experiment, the specimen with water to cement ratio of 0.60 exhibited 8.7%, whereas the specimen with GFRC showed 4.7%. The reduction of percentage water absorption and volume of permeable voids is only applicable for specimens with water to cement ratios up to 0.40 and 0.45. For mixes with W/C ratios greater than 0.45, no significant increase was observed and hence it can be neglected.

Mixing up carbon di-oxide with calcium hydroxide present in concrete to form calcium carbonate is termed as carbonation. In the presence of moisture in the environment, CO_2 changes into dilute carbonic acid, which further increases the corrosion effect in the reinforcement by reducing the alkalinity of concrete. Carbonation depth is assessed by spraying the phenolphthalein indicator in the broken part of concrete after exposure to accelerated carbon dioxide concentrations for 3 months. The solution upon being sprayed changes its colour to pink on coming in contact with alkaline concrete with pH values exceeding 9.0. From Figure 6, it was found that the depth of carbonation was directly proportional to the W/C ratio. It showed a maximum depth of 13mm with the specimen having a W/C ratio of 0.60 with glass fiber in it. Its counterpart with ordinary Portland cement having the same W/C ratio exhibited a depth of 10mm.

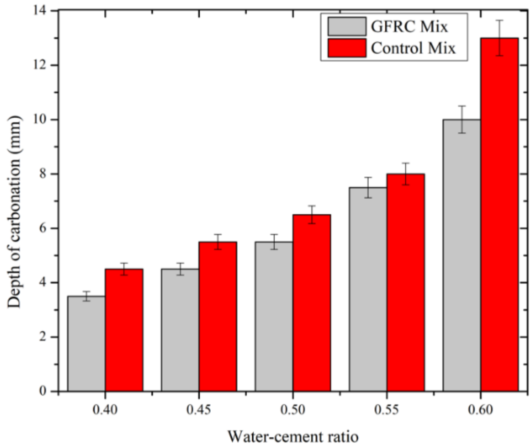

Figure (6): Carbonation depth of GFRC mix and control mix

Microstructural Analysis

The results of thermogravimetric analysis for the concrete mixes with water to binder ratios of 0.4, 0.5 and 0.6 (with and without fiber) are shown in Figure 7. The plot indicates the TGA (thermogravimetric analysis) curve and DTG (derivative thermogravimetry) curve on the left and right axis, respectively. The plots have been studied for the peaks corresponding to dehydroxylation of portlandite and calcination of calcium carbonates. The calcination of carbonates is identified from the peaks ranging between temperatures of 700°C-800°C. From the plot, the peaks of concrete mixes without glass fibers are steeper than those of the mixes with fiber in them, indicating the presence of carbonates. Also, from the peaks, concrete mixes with higher water to binder ratios had more carbonates due to better availability of hydroxyl ions.

The results of Fourier transform infrared spectroscopy (FTIR) are shown in Figure 8. The transmission peak at 973 cm^{-1} corresponds to Si-O of C-S-H bond during hydration of cement. The peaks at 2904 cm^{-1} correspond to stretching and bending modes of the C-H group. The bands at 1122 are due to ν1 and ν2 vibrations of sulphate ions associated with gypsum. The peaks at 2375cm^{-1} and 1452 cm^{-1} correspond to stretching of $CaCO_3$.

The SEM micrographs of fiber used in the present study and fiber-embedded concrete are shown in Figure 9, depicting the structure of alkali-resistant glass fiber before being used in the concrete and post hydration after being used in the concrete. Figure 10 shows the SEM image of interparticle interaction between fiber and the concrete matrix.

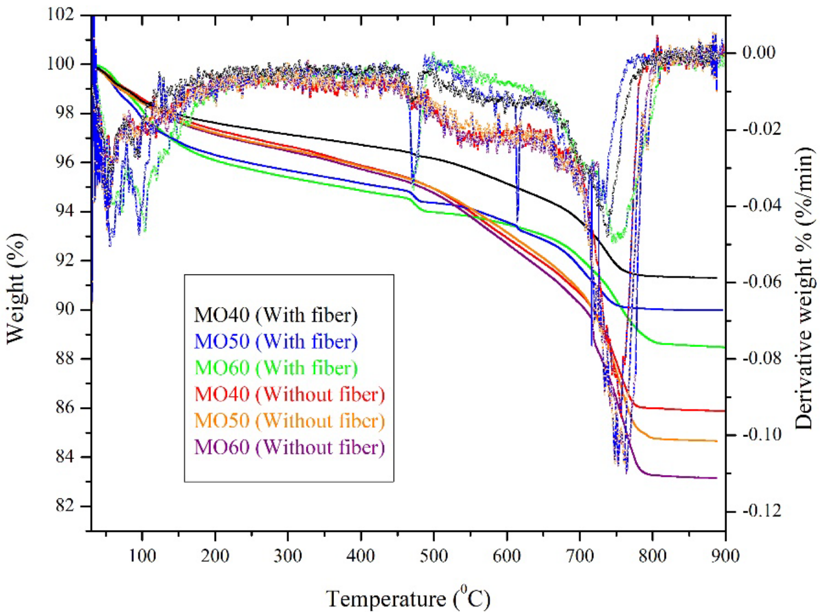

Figure (7): TGA/DTG plot of GFRC mix and control mix

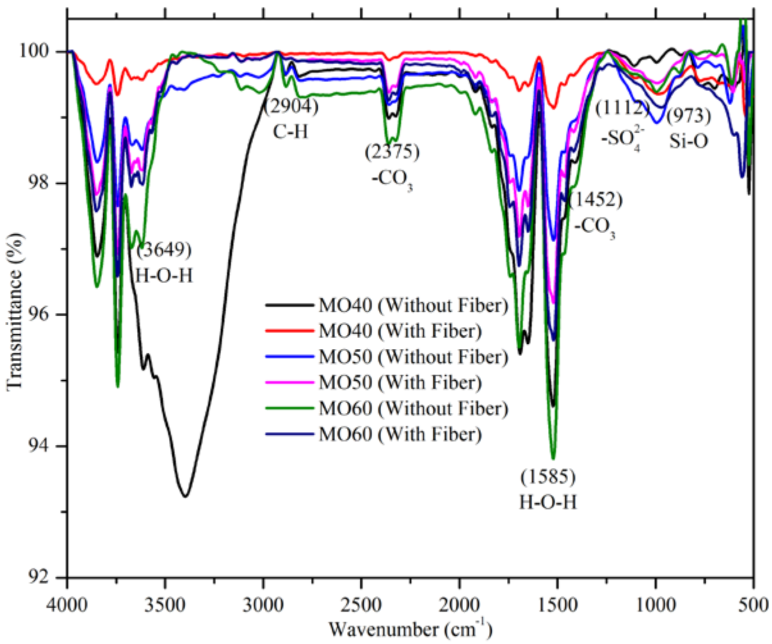

Figure (8): FTIR spectra of GFRC mix and control mix

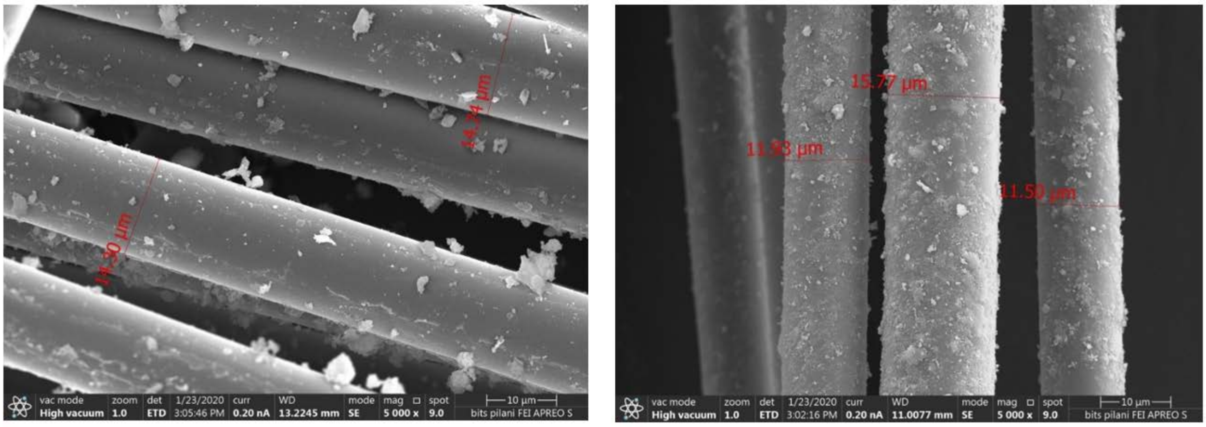

Figure (9): SEM micrograph of alkali-resistant glass fiber pre and post hydration in concrete

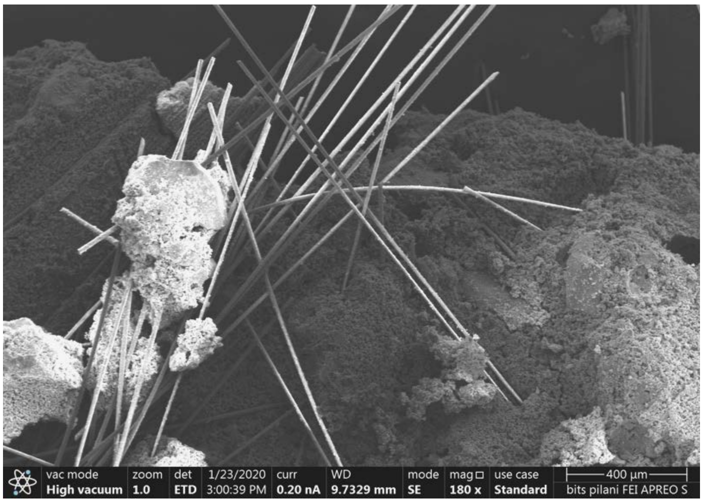

Figure (10): Interparticle interaction of fiber and matrix

CONCLUSIONS

The study on possible application of alkali-resistant glass fibers in concrete is presented. The development of such fibrous concrete is essential for refractory structures and structures that are exposed to the impact of fatigue. From the experimental investigations conducted in the present study, the following conclusions have been drawn:

- Alkali-resistant glass fiber-reinforced concrete mixes showed an average of 8% increase in compressive strength compared to control mixes. Fiber-reinforced concrete mix with a water to binder ratio of 0.45 displayed the highest increase in compressive strength of about 13%.
- For flexural strength, fiber-reinforced concrete mix with a water to binder ratio of 0.50 showed 44% increase in strength when compared to the mix without fiber in it. An overall average increase of 28% in flexural strength was obsreved in all mixes with fiber embedded in them.
- Alkali-resistant glass fiber-reinforced concrete mix MO45 exhibited the highest modulus of elasticity with a value of 2800 MPa against the specimen exhibiting 2500 MPa with the same water ratio having ordinary Portland cement.
- The formulae mentioned in ACI440.1R-15 are inadequate in predicting the bond strength of FRP rebars in glass fiber-reinforced concrete. The values obtained in the experiments are far less in magnitude compared to the predicted values due to slip in the rebars and fiber matrix.
- With the inclusion of alkali-esistant glass fiber in concrete, the water-absorption capacity and volume

of permeable voids decreased due to the ability of glass fiber-reinforced concrete to control the restrained shrinkage cracking and to reduce the crack width. The percentage of decrease was witnessed highest in mix MO60. In this specimen, 8.3% of water was absorbed against 3.5% in the specimen embedded with GFRC. Correspondingly, in the volume of permeable voids experiment, the specimen with a water to cement ratio of 0.60 exhibitted 8.7%, whereas the specimen with GFRC showed 4.7%.

- Alkali-resistant glass fiber-reinforced concrete mix MO60 showed a maximum carbonation depth of 13mm. Its counterpart with ordinary Portland cement having the same W/C ratio exhibited a depth of 10mm. The other mixes did not exhibit any significant differences.

Acknowledgements

The research work presented in this article has been carried out in the Civil Engineering Department, Manipal University Jaipur. Any opinions, findings and recommendations expressed in this article are those of the authors and do not necessarily reflect the views of the organization.

List of Abbreviations

DTG: Derivative Thermogravimetry
FRC: Fiber-reinforced concrete
FRP: Fiber-reinforced polymer
FTIR: Fourier transform infrared spectroscopy
GFRP: Glass fiber-reinforced polymer
MOE: Modulus of elasticity
OPC: Ordinary Portland cement
TGA: Thermogravimetric analysis.

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