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A study on alkali resistant glass fibre concrete and its exposure to elevated temperatures

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ABSTRACT

Purpose: Cement concrete is characterized as brittle in nature, the loading capacity of which is completely lost once failure is initiated. This characteristic, which limits the application of the material, can in one way be overcome by the addition of some small amount of short randomly distributed fibers (steel, glass, synthetic).

Design/methodology/approach: The present study deals with the inclusion of alkali resistant glass fibers in concrete by percentage weight of cement. The mechanical properties such as compressive strength and split tensile strength have been studied after exposing the concrete samples to elevated temperatures of up to 500°C. Water binder ratios of 0.4, 0.45, 0.5, 0.55 and 0.6 have been used to prepare design mix proportions of concrete to achieve a characteristic strength of 30 MPa. The depth of carbonation post elevated temperature exposure has been measured by subjecting the concrete samples to an accelerated carbonation (5%) condition in a controlled chamber.

Findings: Conclusions have been drawn in accordance to the effect of fiber replacement and temperature increment. The concrete mixes with fiber content of 1% by weight of cement had shown better strength in compression and tension compared to the other dosages and conventional concrete (without fiber). Microcracking due to internal stream pressure reduced the mechanical strengths of concrete at elevated temperatures. Also, from TGA it was observed that the amount of calcium carbonate in samples with fiber added, post carbonation was less than the mixes without fiber in it.

Research limitations/implications: The present study has been limited to alkali resistant glass fibers as the conventional glass fibers undergo corrosion due to hydration.

Practical implications: The glass fiber reinforced concrete can be used in the building renovation works, water and drainage works, b ridge and tunnel lining panels etc.

Originality/value: Based upon the available literature, very seldom the studies are addressing the behaviour of alkali resistant glass fiber concrete and its exposure to elevated temperatures.

Keywords: Alkali resistant glass fibres, Accelerated carbonation, Compressive strength, Thermogravimetric analysis, Scanning electron microscopy, Split tensile strength

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PROPERTIES

1. Introduction

Concrete is the most widely used construction material that has definite properties in compression, tension and flexure. If adequately designed and cast, concrete, in its service life, can have great resistance to weathering actions providing sufficient durability. Also, concrete being a brittle material, exhibits low tensile strength in comparison to its strength in compression. The hydration of cement leads to a reduction in volume of concrete after hardening due to the loss of water from surface of concrete accounting to its plastic shrinkage [1]. One of the ways of neutralizing these deficiencies, especially early age plastic shrinkage cracking, tensile strength and imparting toughness in concrete can be by providing fibrous reinforcement in concrete [2-6].

Amongst various fibers in existence, Steel fibers, glass fibers, carbon fibers and E-fibers are more prominently studied and used in accordance to their strength, durability and fiber content [7]. Addition of these fibers, though had no significant improvement in compressive strength and modulus of elasticity of concrete [8]; it increased the impact resistance and strain at peak stress by bonding with the cement matrix [9]. The high specific strength and stiffness of the fibers were instrumental in imparting some post cracking tensile strength in concrete [10-12].

Steel fibers, have been reported to have increased the tensile strength and fracture toughness of concrete [13-18]. But the shape of fiber, geometry, aspect ratio, volume fraction and deformity of the fiber greatly influence the mechanical properties. Hooked end steel fibers showed better bonding with cement matrix than the straight steel fibers [19]. Also, volume fraction and aspect ratio of the steel fibers have to be carefully chosen to avoid the reduction of workability in fresh concrete. Glass fibers on the other hand have been reported to have better Ultimate tensile strength and Young's modulus [20]. The combustion less manufacture and low production cost of glass fibers [21] had placed the glass fibers as a potential reinforcing medium in concrete. However, one of the major shortcoming of using this composite is the degradation of fiber due to formation of portlandite during hydration of cement [22-24]. The formation of portlandite ($Ca(OH)_2$) during hydration of cement makes the pore solution in concrete alkaline with a pH of 12.6 [25] which leads to deterioration of fibers by reducing its filament diameter [26]. The abundant hydroxyl ions present in pore solution of concrete break the Si-O-Si bond in fibers to form Si-OH causing disproportionate bonding and local concentration of stress at the surface of fibers [27]. Also, the hexagonal crystals from portlandite fills spaces between the fiber strands cementing them together to reduce the flexibility and strain capacity of the fibers leading to embrittlement [27-30]. One of the ways of protecting the fibers from alkaline attack is by using cement of low basicity [31-33]; by densifying the periphery between the cement matrix and fibers by using polymers to prevent lime diffusion [34] or by using supplementary cementitious materials [35].

Alkali resistant glass fibers had been developed by adding zirconium oxide to the fibers to impede the alkaline effect. In addition, the fibers improve the wear resistance of concrete along with the tensile strength hence transforming its properties from a brittle material to that with certain plastic properties [21].

The present study deals with the effects of alkali resistant glass fibers on concrete exposed to high temperatures. Concrete with strength designed for 30 MPa with water binder ratios 0.4, 0.45, 0.5, 0.55 and 0.6 had been used in the study. These specimens had been exposed to elevated temperatures of up to 500^0C for an hour after 28 days of water curing. The rate of heating was fixed to 20^0C/min. Alkali resistant glass fibers have been added to the concrete mixture by weight of cement. Design mix proportions of concrete with 0%, 0.5%, 1% and 1.5% fiber by weight of cement had been used in the present study. The restraint on dosage of glass fibers had been fixed on basis of trial and error method.

2. Test materials and methodologies

2.1. Test materials

Cement

The Ordinary Portland cement of 53 grade has been chosen for the present study. The chemical composition and the physical properties of the cement used in the study are tabulated in Tables 1 and 2, respectively. The cement used has been tested for various properties as per IS: 4031 [36] and found to be conforming to specifications of IS: 12269-1987 [37]. The normal consistency of cement was 33% and the initial setting time was measured to be 45 min.

Table 1.
Chemical composition of cement

Chemical composition						
SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	LOI
21.5	4.5	4	62	2.5	2.5	3

Table 2.
Physical properties of cement

Physical properties		
Density, g/cm^3	Specific gravity	Fineness, m^2/kg
3.09	3.17	310

Aggregates

Crushed basalt and sand were used as coarse and fine aggregates, respectively. The specific gravity of the aggregates was measured in accordance to IS 2386 Part III [38]. The range of particle size and specific gravity of the aggregates has been tabulated in Table 3 along with impact and abrasion values of coarse aggregates.

Glass fiber

Alkali resistant glass fiber has been used in the present study. Fibers of length 12 mm and filament diameter of 12-15 µm with a tensile strength of 1700 MPa had been taken up for the study as shown in Figure 1. The zirconia content in the fiber was 19%.

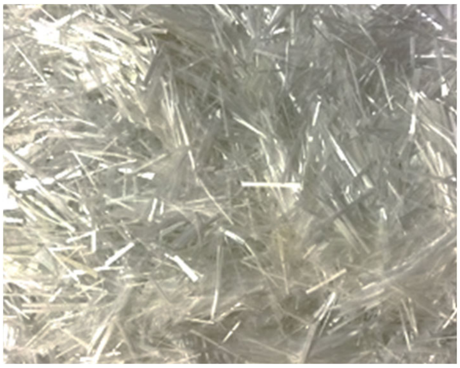

Fig. 1. Alkali resistant glass fiber

Design mix proportions of concrete

The water-binder ratio, proportions of cement, aggregates and water, percentage addition of glass fibers by weight of cement have been varied to obtain various concrete mixes with different proportions. The water binder ratio chosen for the study have been confirmed in accordance to IS 10262 (2009) [39]. The mixes were designed for medium workability and strength of 30-35 MPa. For each of the mixes, glass fiber has been added by 0%, 0.5%, 1% and 1.5% by the weight of cement. The design mix proportions used in the present study are tabulated in Table 4.

2.2. Test specimen and methodology

Mechanical strength

Concrete cubes of 15x15x15 cm and cylinders of 15 cm diameter and 30 cm height were cast to test the strength of concrete in compression and direct tension. These specimens after 28 days of water curing were dried and placed in a furnace and exposed to temperature of 100°C, 200°C, 300°C, 400°C and 500°C for an hour (Fig. 2). They were then cooled down to room temperature and tested for their strength in compression and tension. The compressive strength is measured by placing the cubes in the machine in such a way that the load is applied to opposite sides of the cubes. It is calculated by dividing the maximum load applied to the specimen during the test by cross sectional area. To measure the split tensile strength of the concrete, the cylinders were placed in the centering jig with packing strip and loading pieces carefully positioning along the top and bottom of the plane of loading of the specimen. The jig is then be placed in the machine so that the specimen is located centrally.

Table 3.
Physical properties of aggregates

Aggregate	Physical property			
	Size range, mm	Specific gravity	Impact value, %	Abrasion value, %
Fine aggregate	0.075-4.75	2.60	-	-
Coarse aggregate	10.5-20	2.72	20	25

Table 4.
Concrete design mix proportions

Mix	Water cement ratio	Cement	Water	Fine Aggregate	Coarse Aggregate	Slump, mm
C40	0.40	450	197	581	1235	100
C45	0.45	438	197	600	1218	95
C50	0.50	394	197	631	1225	83
C55	0.55	358	197	661	1227	75
C60	0.60	328	197	689	1225	60

Fig. 2. Furnace used in the study

Depth of carbonation

Carbonation is the gradual ingress of gaseous carbon dioxide into pore solution of concrete to precipitate carbonate ions. These ions react with calcium ions in concrete to form calcium carbonate. The formation of calcite lowers the pH of pore solution of concrete obliterating the passive oxide film that restricts the steel reinforcement in concrete from bring corroded [40]. The natural process of carbonation takes decades to initiate as the carbon dioxide concentration in atmosphere is around 0.035-0.04% and concrete is not very porous. To accelerate the process, concrete cubes of 15x15x15 cm, post elevated temperature exposure for an hour were kept in an accelerated carbonation chamber with carbon dioxide concentration of 5% by volume and a relative humidity of 65-70%, for a month. They were then removed, split and sprayed with phenolphthalein indicator to measure the carbonation depth. The colourless region after being sprayed by the indicator represents the carbonated zone. Figure 3 shows the concrete cube after being sprayed by the phenolphthalein indicator and the measurement of carbonation depth by the average of values measured in all four directions.

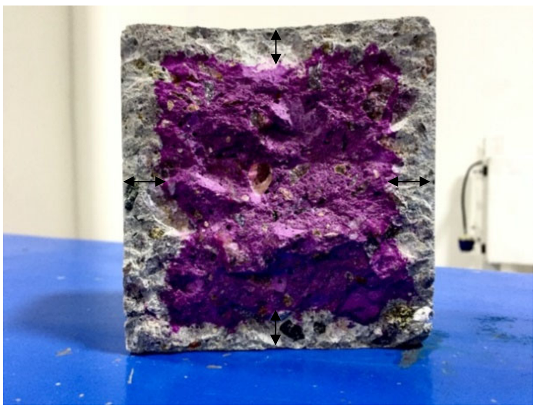

Fig. 3 Depth of carbonation measurement

2.3. Microstructural analysis

Scanning Electron Microscopy

The micro structure of glass fibers prior and post hydration of cement have been studied by the microscopic imagery of the hydrated products. These images had been identified using Back scattered images of the FE-SEM. Concrete samples from the specimens were scrapped out after temperature exposure were stored in acetone for 7 days to arrest further hydration of cement.

Thermogravimetric analysis

The concrete specimens after quenching in acetone were subjected to thermogravimetric analysis where the specimens were heated till 900°C at 20°C/min and the weight loss in the specimen in accordance to the temperature and time are measured. The drop in specimen weight at 120°C, 420°C, 480°C and 750°C signifies dehydration of pore water, calcium silicates hydrates, dihydroxylation of portlandite and calcination of calcite, respectively [41]. The peaks from DTG curve can give a rough estimate of portlandite and calcite in samples with and without fibers.

3. Results and discussion

3.1. Mechanical strength

The compressive and split tensile strengths of concrete mixes reduced with an increase in the water binder ratio as expected. Figures 4a-d and Figures 5a-d represents a plot of compressive strength and split tensile strength with respect to increase in temperature, respectively. But with the rise in temperature, the strengths reduced significantly. This might be accounted by the reduction of pore water due to dehydration and microcracking due to formation of internal stream pressure at elevated temperatures. Also, at temperatures closer to 400-450°C, the loss of interlayer water, which is present in the microscopic pores of the concrete, changes the sizes of the crystalline structure, without breaking it down. Due to dehydroxylation of the portlandite that is responsible for the strength in hardened concrete, upon exposure to higher temperatures, the compressive strength and split tensile strength of concrete reduced significantly.

The reduction in strength can also be due to the internally restrained thermal shrinkage after the samples are cured post exposure to elevated temperatures. For the increase in the percentage of fiber dosage in concrete, the compressive and split tensile strengths increased to its maximum at 1% fiber addition and then decreased with any further addition of fiber to concrete.

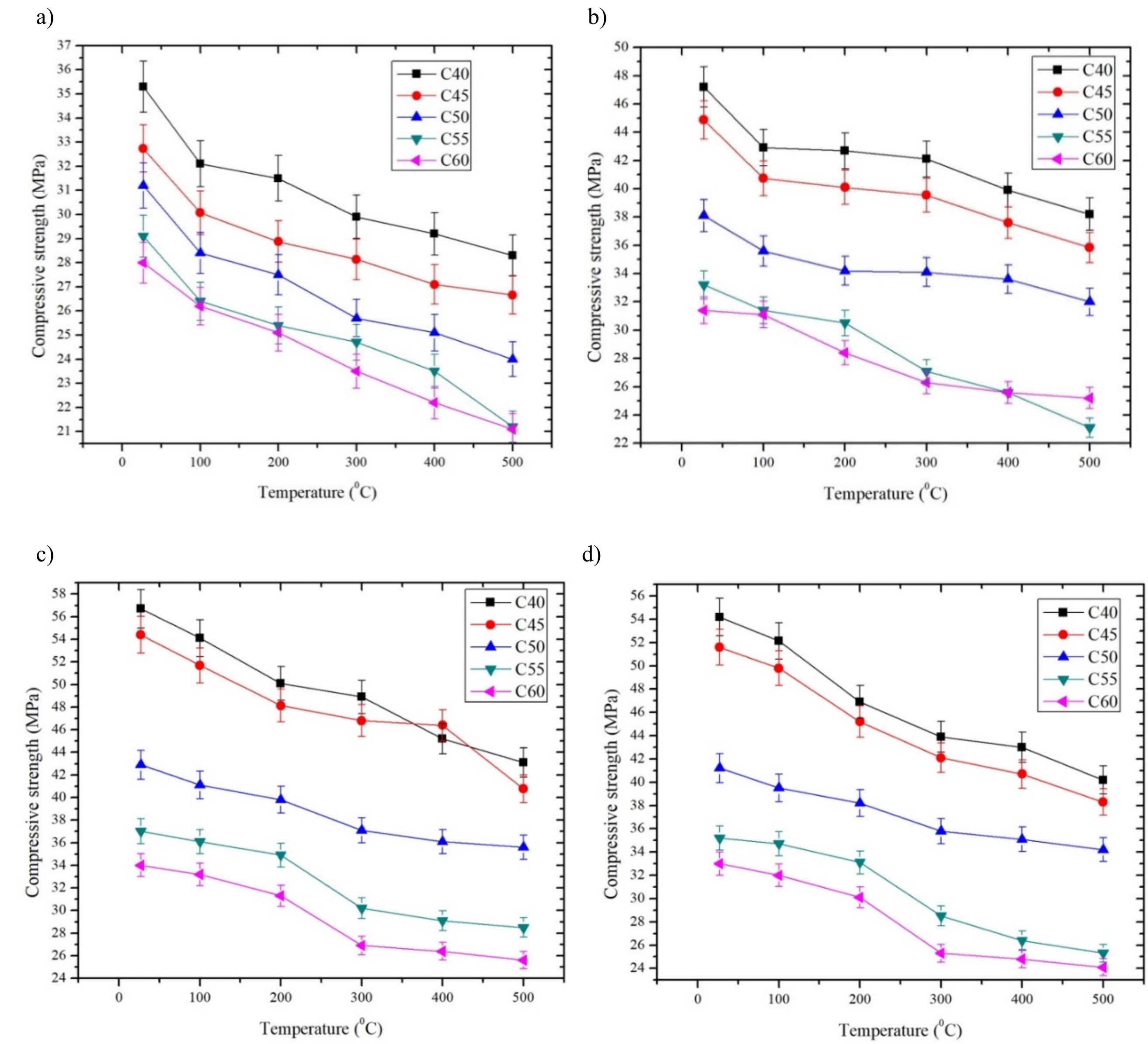

Fig. 4. Compressive strength of: a) OPC concrete vs temperature, b) GFRC concrete (0.5%) vs temperature, c) GFRC concrete (1.0%) vs temperature, d) GFRC concrete (1.5%) vs temperature

3.2. Depth of carbonation

Figures 6a-d represent the plot of carbonation depth in accordance to rise in temperature. The concrete mixes with glass fibers added to the cement showed better resistance to carbonation than the mixes with no fiber in it.

The carbonation of the portlandite is more rapid than the carbonation of calcium silicate hydrates. But the portlandite formed during hydration is most likely filled in spaces between fibers leading to notching by calcium hydroxide crystals [42-44]. Hence the carbonation front is more dependent on the decalsification of the calcium silicate hydrates. The mixes with higher water binder ratios had higher depth of carbonation due to relatively more porosity of the hardened concrete.

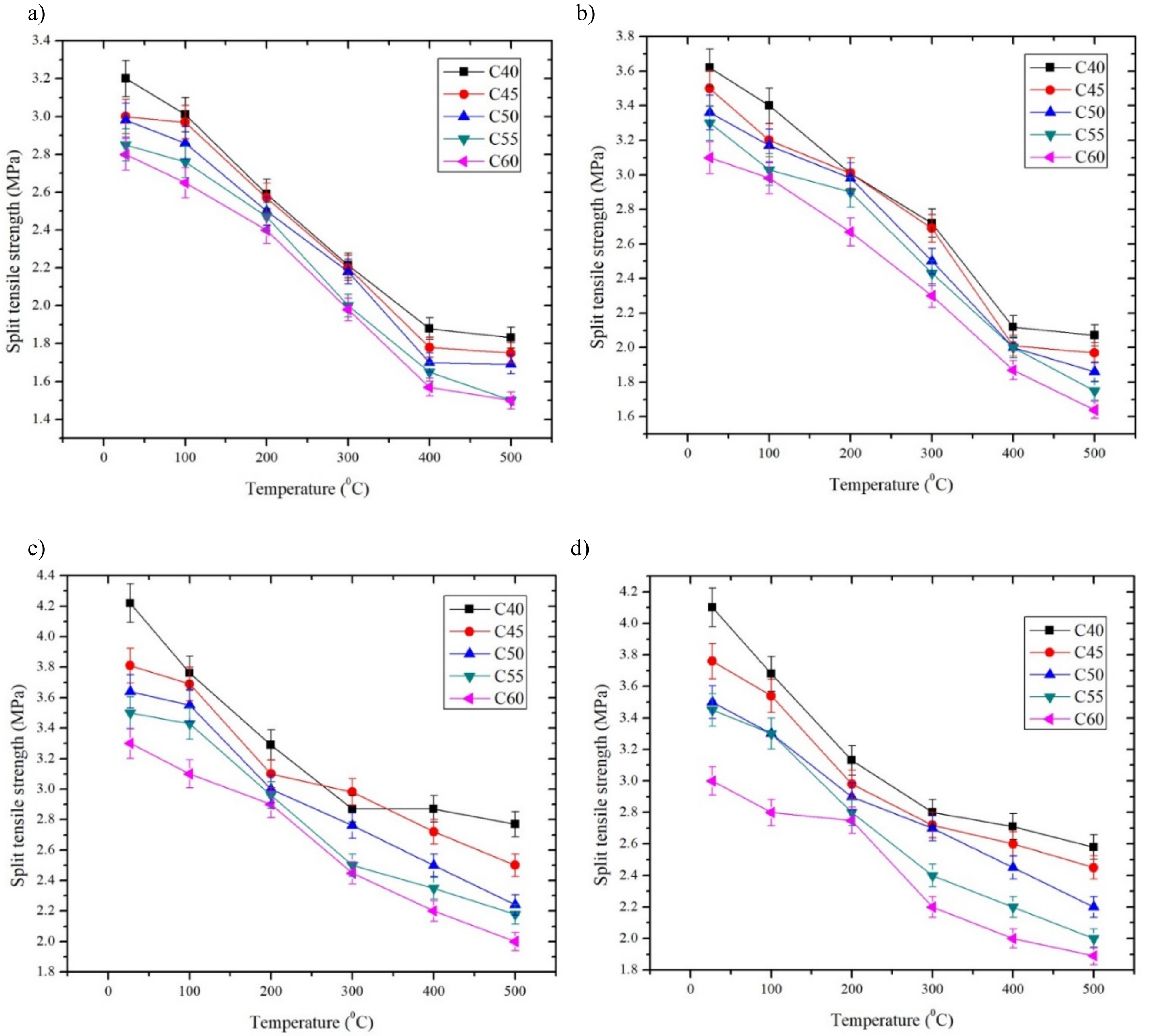

Fig. 5. Split tensile strength of: a) OPC concrete vs temperature, b) GFRC concrete (0.5%) vs temperature, c) GFRC concrete (1.0%) vs temperature, d) GFRC concrete (1.5%) vs temperature

3.3. Scanning Electron Microscopy

The microstructural observations made through SEM are displayed in Figures 7 and 8. Figure 7 is a microstructural image of an alkali resistant glass fiber strand before mixing it into concrete. Figure 8 is a post cement hydration fiber strand plucked from hardened concrete. Calcium hydroxide is formed in between the fiber space and on it. The undulations on the surface of the fiber are due to high pH of the matrix.

3.4. Thermogravimetric analysis

Hardened concrete specimen after exposure to elevated temperature and cooled down and subjected to thermo-gravimetric analysis. Samples from mixes with water binder

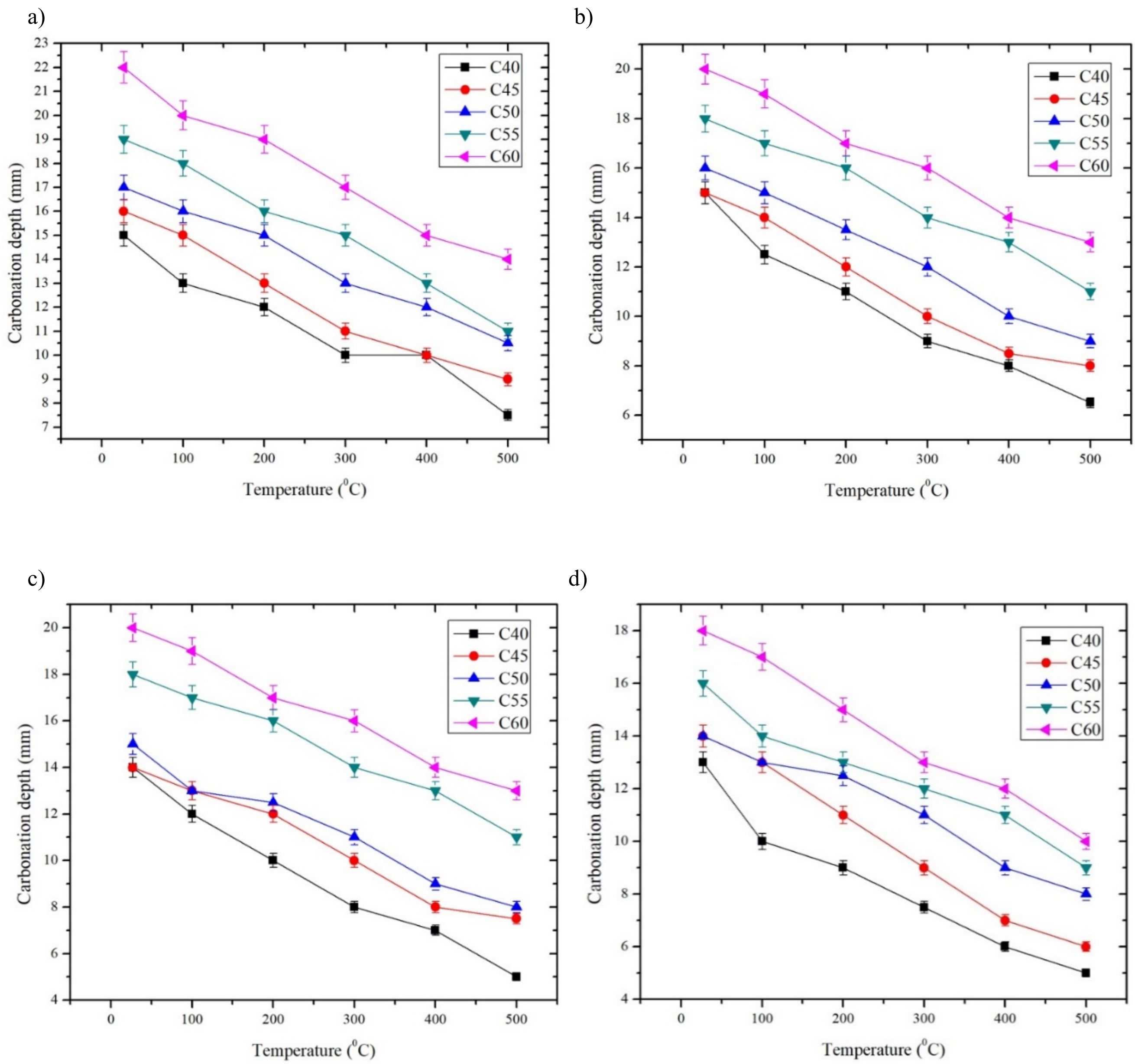

Fig. 6. Carbonation depth of: a) OPC concrete vs temperature, b) GFRC concrete (0.5%) vs temperature, c) GFRC concrete (1.0%) vs temperature, d) GFRC concrete (1.5%) vs temperature

ratio of 0.4, 0.5 and 0.6 with (1.5%) and without fiber were taken and their DTG (Derivative thermogravimetric) plots were studied to identify the peaks corresponding to dehydroxylation of portlandite and calcination of calcium carbonates. Figure 9 shows the DTG plots of mixes used in the study. The peaks at 700°C-800°C correspond to the calcination of calcium carbonates. From the fig., it is clear that the mixes with fiber added to concrete had less calcium carbonates compared to the mixes without fibers. Also, the amount of calcium carbonates is more for the mixes with higher water binder ratios due to more availability of hydroxyl ions.

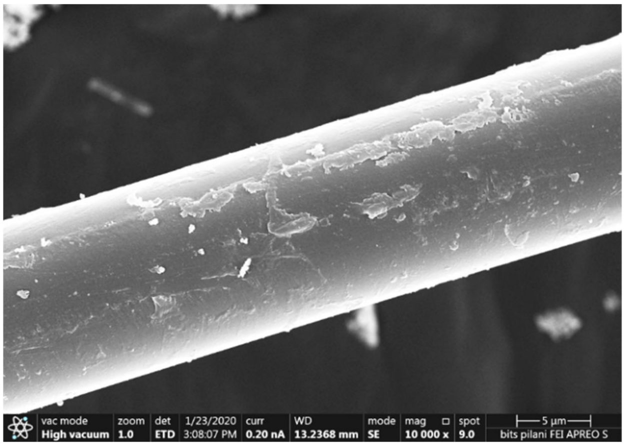

Fig. 7. Microstructural (SEM) image of an alkali resistant glass fiber strand prior to hydration

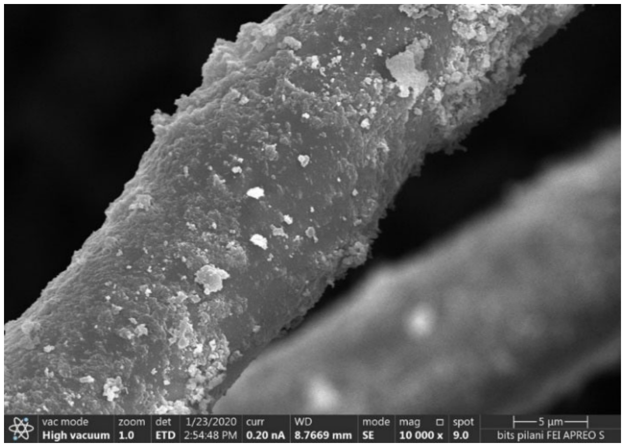

Fig. 8. Microstructural (SEM) image of an alkali resistant glass fiber strand post hydration

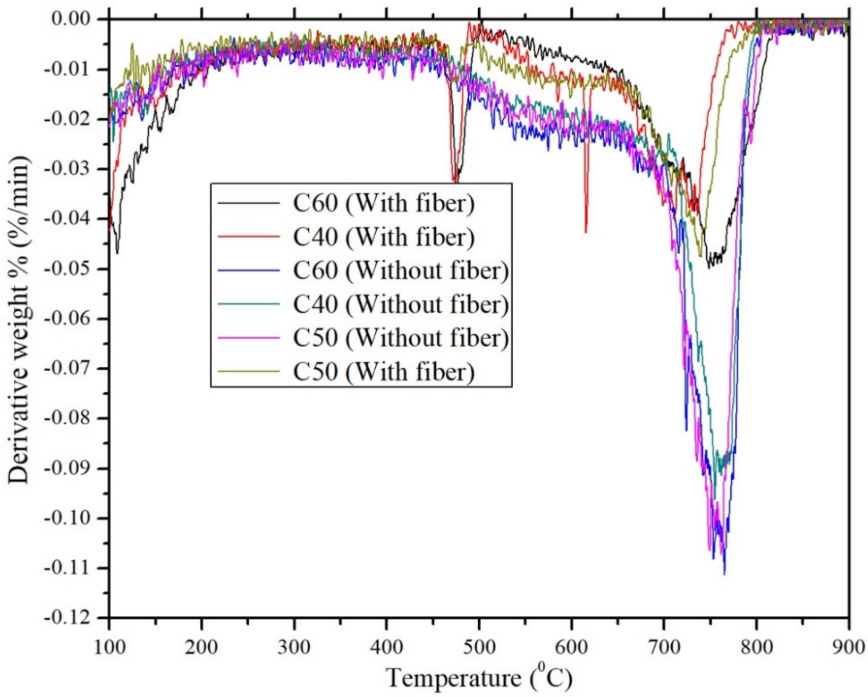

Fig. 9. DTG curves of samples from concrete mixes with and without fibers

4. Conclusions

Within the scope of the present study, following conclusions have been drawn:

i. The hardened concrete samples with fiber added to cement showed better mechanical strength in compression and tension.
ii. The tensile strength seems to have improved significantly and the increase is highest for a fiber dosage of 1.0%.
iii. With the rise in temperature, the strengths reduced significantly due to the reduction of pore water due to dehydration and microcracking due to formation of internal stream pressure at elevated temperatures.

iv. The concrete mixes with glass fibers added to the cement showed better resistance to carbonation than the mixes with no fiber in them.
v. After hydration, the spaces between fibers are mostly filled with portlandite crystals. This would have deteriorated the normal glass fiber.
vi. The mixes with fiber added to concrete had less calcium carbonates compared to the mixes without fibers as observed from DTG curve. Also, the amount of calcium carbonates is more for the mixes with higher water binder ratios due to more availability of hydroxyl ions.

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References

[1] F. Aslani, R. Gedeon, Experimental investigation into the properties of self-compacting rubberised concrete incorporating polypropylene and steel fibers, Structural Concrete 20/1 (2019) 267-281. DOI: https://doi.org/10.1002/suco.201800182
[2] Y.M. Ghugal, S.B. Deshmukh, Performance of alkali-resistant glass fiber reinforced concrete, Journal of Reinforced Plastics and Composites 25/6 (2006) 617-630. DOI: https://doi.org/10.1177%2F0731684405058273
[3] A. Ateş, Mechanical properties of sandy soils reinforced with cement and randomly distributed glass fibers (GRC), Composites Part B: Engineering 96 (2016) 295-304. DOI: https://doi.org/10.1016/j.compositesb.2016.04.049
[4] N. Banthia, S.M. Soleimani, Flexural response of hybrid fiber-reinforced cementitious composites, ACI Materials Journal 102/6 (2005) 382-389.
[5] F. Bayramov, C. Taşdemir, M.A. Taşdemir, Optimisation of steel fibre reinforced concretes by means of statistical response surface method, Cement and Concrete Composites 26/6 (2004) 665-675. DOI: https://doi.org/10.1016/S0958-9465(03)00161-6
[6] P. Balaguru, H. Najm, High-performance fiber-reinforced concrete mixture proportions with high fiber volume fractions, Materials Journal 101/4 (2004) 281-286.
[7] K. Ramesh, D. Rama Seshu, M. Prabhakar, Constitutive behaviour of confined fibre reinforced concrete under axial compression, Cement and Concrete Composites 25/3 (2003) 343-350. DOI: https://doi.org/10.1016/S0958-9465(02)00051-3
[8] S.P. Shah, J.I. Daniel, S.H. Ahmad, M. Arockiasamy, P. Balaguru, C.G. Ball, H.P. Ball et al, Measurement of properties of fiber reinforced concrete, Materials Journal 85/6 (1988) 583-593.
[9] Y. Choi, R.L. Yuan, Experimental relationship between splitting tensile strength and compressive strength of GFRC and PFRC, Cement and Concrete Research 35/8 (2005) 1587-1591. DOI: https://doi.org/10.1016/j.cemconres.2004.09.010
[10] C. Signorini, A. Sola, B. Malchiodi, A. Nobili, A. Gatto, Failure mechanism of silica coated polypropylene fibres for Fibre Reinforced Concrete (FRC), Construction and Building Materials 236 (2020) 117549. DOI: https://doi.org/10.1016/j.conbuildmat.2019.117549
[11] R.N. Swamy, Fibre-Reinforced Concrete: Mechanics, Properties, and Applications, 1974.
[12] D.J. Hananth, Fiber cements and fiber concretes, John Wiley and Sons Ltd. 1998, 81-98.
[13] P. Ramadoss, K. Nagamani, Investigations on the tensile strength of high-performance fiber reinforced concrete using statistical methods. Computers and Concrete 3/6 (2006) 389-400. DOI: http://dx.doi.org/10.12989/cac.2006.3.6.389
[14] J. Thomas, A. Ramaswamy, Mechanical properties of steel fiber-reinforced concrete, Journal of Materials in Civil Engineering 19/5 (2007) 385-392. DOI: https://doi.org/10.1061/(ASCE)0899-1561(2007)19:5(385)
[15] F. Köksal, F. Altun, İ. Yiğit, Y. Şahin, Combined effect of silica fume and steel fiber on the mechanical properties of high strength concretes, Construction and Building Materials 22/8 (2008) 1874-1880. DOI: https://doi.org/10.1016/j.conbuildmat.2007.04.017
[16] H.B. Dhonde, Y.L. Mo, T.T.C. Hsu, J. Vogel, Fresh and hardened properties of self-consolidating fiber-reinforced concrete, Materials Journal 104/5 (2007) 491-500.
[17] M. Sahmaran, I.O. Yaman, Hybrid fiber reinforced self-compacting concrete with a high-volume coarse fly ash, Construction and Building Materials 21/1 (2007) 150-156. DOI: https://doi.org/10.1016/j.conbuildmat.2005.06.032
[18] Y. Mohammadi, S.P. Singh, S.K. Kaushik, Properties of steel fibrous concrete containing mixed fibres in fresh and hardened state, Construction and

Building Materials 22/5 (2008) 956-965. DOI: https://doi.org/10.1016/j.conbuildmat.2006.12.004
[19] N. Banthia, A study of some factors affecting the fiber-matrix bond in steel fiber reinforced concrete, Canadian Journal of Civil Engineering 17/4 (1990) 610-620. DOI: https://doi.org/10.1139/l90-069
[20] C. Zanotti, N. Banthia, G. Plizzari, A study of some factors affecting bond in cementitious fiber reinforced repairs, Cement and Concrete Research 63 (2014) 117-126. DOI: https://doi.org/10.1016/j.cemconres.2014.05.008
[21] Q. Xiaochun, L. Xiaoming, C. Xiaopei, The applicability of alkaline-resistant glass fiber in cement mortar of road pavement: corrosion mechanism and performance analysis, International Journal of Pavement Research and Technology 10/6 (2017) 536-544. DOI: https://doi.org/10.1016/j.ijprt.2017.06.003
[22] G.T. Gilbert, GFRC–30 Years of High Fiber Cement Composite Applications Worldwide, Special Publication 224 (2004) 1-20.
[23] A. Bentur, S. Mindess, Fibre reinforced cementitious composites, CRC Press, 2006.
[24] K.L. Litherland, D.R. Oakley, B.A. Proctor, The use of accelerated ageing procedures to predict the long term strength of GRC composites, Cement and Concrete Research 11/3 (1981) 455-466. DOI: https://doi.org/10.1016/0008-8846(81)90117-4
[25] F. Deschner, F. Winnefeld, B. Lothenbach, S. Seufert, P. Schwesig, S. Dittrich, F. Goetz-Neunhoeffer, J. Neubauer, Hydration of Portland cement with high replacement by siliceous fly ash, Cement and Concrete Research 42/10 (2012) 1389-1400. DOI: https://doi.org/10.1016/j.cemconres.2012.06.009
[26] R.J. Charles, Static fatigue of glass. II, Journal of Applied Physics 29/11 (1958) 1554. DOI: https://doi.org/10.1063/1.1722992
[27] M. Hayashi, S. Sato, H. Fujii, Some ways to improve durability of GFRC, Proceedings of the Symposium on Durability of Glass-fibre Reinforced Concrete, vol. 270, Prestressed Concrete Institute, Chicago, 1985.
[28] A.J. Majumdar, Some aspects of glass fibre reinforced cement research, in: Advances in Cement-Matrix Composites, Materials Research Society Boston, 1980, 37-60.
[29] M.S. Stucke, A.J. Majumdar, Microstructure of glass fibre-reinforced cement composites, Journal of Materials Science 11/6 (1976) 1019-1030. DOI: https://doi.org/10.1007/BF00553110
[30] E.B. Cohen, S. Diamond, Validity of flexural strength reduction as an indication of alkali attack on glass in fibre reinforced cement composites, Proceedings of the Fibre Reinforced Cement and Concrete, RILEM Symposium, 1975, 315-325.
[31] P. Purnell, N.R. Short, C.L. Page, A.J. Majumdar, Microstructural observations in new matrix glass fibre reinforced cement, Cement and Concrete Research 30/11 (2000) 1747-1753. DOI: https://doi.org/10.1016/S0008-8846(00)00407-5
[32] J. Péra, J. Ambroise, New applications of calcium sulfoaluminate cement. Cement and Concrete Research 34/4 (2004) 671-676. DOI: https://doi.org/10.1016/j.cemconres.2003.10.019
[33] H. Cuypers, J. Wastiels, P. Van Itterbeeck, E. De Bolster, J. Orlowsky, M. Raupach, Durability of glass fibre reinforced composites experimental methods and results, Composites Part A: Applied Science and Manufacturing 37/2 (2006) 207-215. DOI: https://doi.org/10.1016/j.compositesa.2005.03.027
[34] C. Scheffler, S.L. Gao, R. Plonka, E. Mäder, S. Hempel, M. Butler, V. Mechtcherine, Interphase modification of alkali-resistant glass fibres and carbon fibres for textile reinforced concrete II: Water adsorption and composite interphases, Composites Science and Technology 69/7-8 (2009) 905-912. DOI: https://doi.org/10.1016/j.compscitech.2008.12.020
[35] H.S. Oh, D.Y. Moon, S.D. Kim, An investigation on durability of mixture of alkali-resistant glass and epoxy for civil engineering application, Procedia Engineering 14 (2011) 2223-2229. DOI: https://doi.org/10.1016/j.proeng.2011.07.280
[36] IS: 4031. Methods of physical tests for hydraulic cement, Indian Standard, New Delhi, 1988.
[37] IS: 12269. Specifications for 53 grade ordinary Portland cement, 1987.
[38] IS: 2386. Methods of test for aggregates for concrete–Part 3: Specific gravity, density, voids, absorption and bulking, 1963.
[39] IS: 10262. Recommended Guidelines for Concrete Mix Design, 2009.
[40] S. Hussain, D. Bhunia, S.B. Singh, M. Aggrawal, Mechanical strength and durability of mineral admixture concrete subjected to accelerated carbonation, Journal of Structural Integrity and Maintenance 3/1 (2018) 44-51. DOI: https://doi.org/10.1080/24705314.2018.1426170

[41] C.-F. Chang, J.-W. Chen, The experimental investigation of concrete carbonation depth, Cement and Concrete Research 36/9 (2006) 1760-1767. DOI: https://doi.org/10.1016/j.cemconres.2004.07.025

[42] G.W. Groves, A. Brough, I.G. Richardson, C.M. Dobson, Progressive changes in the structure of hardened C3S cement pastes due to carbonation, Journal of the American Ceramic Society 74/11 (1991) 2891-2896. DOI: https://doi.org/10.1111/j.1151-2916.1991.tb06859.x

[43] A.M. Dunster, An investigation of the carbonation of cement paste using trimethylsilylation, Advances in Cement Research 2/7 (1989) 99-106. DOI: https://doi.org/10.1680/adcr.1989.2.7.99

[44] B. Bary, C. Mügler, Simplified modelling and numerical simulations of concrete carbonation in unsaturated conditions, Revue Européenne de Génie Civil 10/9 (2006) 1049-1072. DOI: https://doi.org/10.1080/17747120.2006.9692905