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Effect of Fly ash, Silica fume, Glass Fiber and Polypropylene Fiber on Strength Properties of Composite Fiber Reinforced High Performance Concrete

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Abstract - *Pozzolanic materials Fly ash (FA) and Silica fume (SF), finer than cement, are emerging in the production of concrete proven to individually enhance the concrete properties. This investigation utilizes the combined effect of FA and SF as replacement of cement partially. Glass fibers (GF) and Polypropylene fibers (PPF) are used as an addition to produce Composite-Fiber Reinforced High-Performance Concrete (CFRHPC), and it was proposed to investigate its mechanical properties. The water to binder ratios (W/B) of 0.275, 0.300, 0.325, and 0.350, with an aggregate to binder ratio (A/B) of 1.75, were adopted. FA and SF were replaced in the range from 0% to 15% each, GF were added in volume percentages from 0% to 1%, and PPF were kept constant at 0.25%. The combined effect of FA and SF at 5% each as replacement of cement and composite fiber dosage of GF=1% and PPF=0.25% for W/B of 0.275 was found to be an optimum combination to obtain maximum strength properties for CFRHPC. A relationship in the form of mathematical models between cube compressive strength with cylindrical compressive strength, split tensile strength, and flexural strength of FA and SF based CFRHPC was also derived from this investigation's experimental results.*

Keywords: *Composite fibers, Glass fiber, High-Performance Concrete, Polypropylene fiber, Fly ash, Silica fume, Mechanical properties.*

I. INTRODUCTION

Large quantities of concrete are being consumed due to urbanization and its demand globally, leading to the development of high-performance concrete (HPC), and its demand has increased due to its enhanced strength, which leads to leaner sections, reducing the weight of the structure. This will benefit consumers economically as HPC is used to construct skyscrapers, tunnels, bridges, foundations, etc., which are heavy structures[1]. Recent investigations have concluded that cement production using Portland cement leads to greenhouse gas emissions [2]. Global cement production in 2018 was estimated at approximately 3.99 bn tonnes[3]. To reduce cement consumption, CO_2 emissions, and energy consumption, researchers have proposed various cement replacements from other materials. Additionally, this replacement leads to the enhancement of the properties of concrete[4].

Researchers have reported that fly ash (FA), when used as a replacement of cement partially, will yield enhanced permeability and chemical resistance in concrete as FA combines with calcium hydroxide chemically to form additional products of cement [5]–[8]. K.Torii et al. reported a substantial reduction in permeability of chloride ions by the addition of SF in concrete, also causing a noteworthy increase in strength. This enhancement was due to micro-level changes in the transition zone and cement paste phase [9]. S. Barbhuiya et al. reported that the use of silica fume (SF) transformed concrete to resist water penetration and, in turn, enhancing chloride ion penetration resistance of concrete [10]. The widespread application of FA and SF in the construction industry is the result of extensive investigations on the use of FA and SF in concrete in the past twenty years [11]-[16]. Present authors also have investigated the effect of FA and SF based composite fiber-reinforced HPC on strength and durability properties and concluded the viability of using FA, SF, and Composite fibers in CFRHPC production for enhanced strength and durability properties [17]-[18]

Investigation[19], with intent to evaluate GF's effective utilization on concrete, concluded that compressive strength moderately increased for M20 grade concrete using GF with 0.33, 0.67, and 1.0 percentage compared with the control mix. Detailed studies[20]-[29] have proven that compression, bending, impact, tensile strength, and durability significantly improved with fibers' use, preferably glass fibers, which are lightweight, possess high tensile strength, and cost-effective. GF's inclusion has proved to be resistant to cracks due to shrinkage and achieved enhanced bending and tensile strengths. However, if fibers are used beyond 1%, there is a tendency to form lumps with workability problems. The hardened properties of HPC with the inclusion of PPF were investigated in the study [30], and results indicated that the strength of HPC reinforced with PPF revealed an increasing trend with the PPF volume.

HPC's strength properties using FA and SF as a cement replacement, with the addition of GF and PPF with superplasticizers, are yet to receive sufficient exploration from the research community as minimal studies are carried out to uphold their effectiveness in the context of strength behavior. Hence, there is a shortfall of research material available. Besides, Indian Standard Codes do not specify the tests to be executed for assessing the strength properties of HPC. This investigation presents the outcomes of experimental exploration performed to understand FA and SF-based composite fiber-reinforced HPC's strength behavior.

II. MATERIALS AND PROPERTIES

The **cement** used was OPC of grade 53, having a specific gravity of 3.10. **Fine aggregates** used were of specific gravity 2.67 collected from a locally available riverbed. **Coarse aggregates** used were of specific gravity 2.75, from a stone quarry available locally with 40% of 12.5 mm and 60% of 20 mm. **Fly ash** used was having a specific gravity of 2.18 with a specific surface area of 0.398 m^2/g and had SiO_2 and Al_2O_3 at 59.16% and 30.64%, respectively. The **silica fume** used was light to dark grey, having a specific gravity of 2.20 with a specific surface area of 22.2 m^2/g, and had SiO_2 as a significant ingredient at 91.36%. A CemFil AntiCrack HD **Glass fiber** with 14 μm diameter and 12 mm length was used during concrete production. These fibers are water dispersible, allowing complete GF dispersion into individual filaments upon mixing in an aqueous environment. **Polypropylene fibers** used were engineered microfibers with a unique triangular cross-section of length 12mm and 38-μm diameter. Potable fresh **water** without organic and acid ingredients was used for concrete mixing. A chloride-free **Superplasticizer** (SP) of Fosroc make with a specific gravity of 1.18 was used.

III. EXPERIMENTAL PROCEDURE

A. Mix proportions

To study the behavior of CFRHPC, 19 mixes along with one HPC mix without any mineral admixtures and composite fibers were prepared for each water binder ratio. The CFRHPC mixes were designed with W/B of 0.275, 0.300, 0.325, and 0.350 with a constant A/B of 1.75. FA and SF of 5%, 10% and 15% each were adapted as cement replacement with addition of 0%, 0.25%, 0.5%, 0.75% and 1% GF content along with constant PPF of 0.25% of concrete volume. SP was used at 0.8% by the weight of the binder. These relative proportions were obtained by the absolute volume method. Recently manufactured single batch OPC of 53 grade has been used. The first letter in the mix designation indicates composite matrix containing GF and PPF, second letter indicates percentage of GF and PPF used, i.e. P=0%GF & 0%PPF, Q=0.25%GF & 0.25%PPF, R=0.5%GF & 0.25%PPF, S=0.75%GF & 0.25%PPF and T=1%GF & 0.25%PPF. F indicates FA, and S indicates SF. The following number indicates the total percentage of cement replaced by FA and SF. Last alphabet indicates water binder ratios, i.e. A=0.275, B=0.300, C=0.325 and D=0.350. CPFS0A indicates a plain high-performance concrete mix without any cement replacement by mineral admixtures and without the addition of any fibers for W/B of 0.275 with the cement of 805.43 kg/m^3. CTFS10A mix indicates a composite fiber-reinforced high-performance concrete mix with combined 10% cement replacement by mineral admixtures fly ash and silica fume and with the addition of 1% glass fiber and 0.25% polypropylene fiber for W/B of 0.275 with the cement of 717.15kg/m^3 and the quantity of fly ash and silica fume was 39.84 kg/m^3 each. The proportion of ingredients used for W/B of 0.275 are tabulated in Table 1. Similar patterns of ingredients were used for W/B of 0.300, 0.325, and 0.350.

Table 1: Nomenclature of mix with W/B of 0.275.

Mix Designation	W/B	A/B	SP	FA	SF	GF	PPF
			(%)				
CPFS0A	0.275	1.75	0.8	0	0	0	0
CPFS10A	0.275	1.75	0.8	5	5	0	0
CPFS20A	0.275	1.75	0.8	10	10	0	0
CPFS30A	0.275	1.75	0.8	15	15	0	0
CQFS0A	0.275	1.75	0.8	0	0	0.25	0.25
CQFS10A	0.275	1.75	0.8	5	5	0.25	0.25
CQFS20A	0.275	1.75	0.8	10	10	0.25	0.25
CQFS30A	0.275	1.75	0.8	15	15	0.25	0.25
CRFS0A	0.275	1.75	0.8	0	0	0.5	0.25
CRFS10A	0.275	1.75	0.8	5	5	0.5	0.25
CRFS20A	0.275	1.75	0.8	10	10	0.5	0.25
CRFS30A	0.275	1.75	0.8	15	15	0.5	0.25
CSFS0A	0.275	1.75	0.8	0	0	0.75	0.25
CSFS10A	0.275	1.75	0.8	5	5	0.75	0.25
CSFS20A	0.275	1.75	0.8	10	10	0.75	0.25
CSFS30A	0.275	1.75	0.8	15	15	0.75	0.25
CTFS0A	0.275	1.75	0.8	0	0	1	0.25
CTFS10A	0.275	1.75	0.8	5	5	1	0.25
CTFS20A	0.275	1.75	0.8	10	10	1	0.25
CTFS30A	0.275	1.75	0.8	15	15	1	0.25
W/B - Water to Binder ratio							
A/B - Aggregate to Binder ratio							
SP - Superplasticizer							
FA – Fly ash							
SF – Silica fume							
GF - Glass fiber							
PPF - Polypropylene fiber							

B. Sample preparation, curing, and testing

Samples were prepared by mixing cement, fine aggregate, FA, and SF thoroughly by manual means first to achieve a uniform mix, and then composite fibers were added to the mixture, followed by coarse aggregates and water mixed with a superplasticizer.

80 mixes were prepared with 6 specimens each of cubes and beams with 12 specimens of cylinders for each mix. Cube specimens of 150mm, cylindrical specimens of 150mm diameter and 300mm height, and prismatic specimens of 100 x 100 x 500mm were cast.

As initial curing, a wet cloth was used for covering the exposed portion of specimens before demoulding. After the concrete was set, specimens were demoulded and were cured in a transparent water tank at 27° ± 2°C until the testing age.

After the curing period for the specified testing age (7 and 28 days), samples were removed from the water and dried under the shade before testing. Cube compression, cylindrical compression, and split tensile tests were done on the digital compression testing machine of 3000 kN capacity, with the least count of 1 kN. Loads on the cube and cylinder (placed horizontally for split tensile strength and vertical for cylindrical compressive strength) were applied at a constant rate until the specimens' failure. A flexural testing machine was supported at the bottom with two steel rollers of 38 mm diameter, and these rollers were mounted at a distance of 400mm from center to center of specimens. The load was applied through two 38mm diameter steel rollers from the top at the third point from the center to the center of the supporting span. The load was evenly divided among these rollers. Each strength result was the average of the specimens tested at the same time for the same mix.

IV. RESULTS AND DISCUSSION

Mechanical properties obtained for CFRHPC mixes are tabularized in Tables 2 and 3.

A. Cube compressive strength

a) Effects of water binder ratios on cube compressive strength of CFRHPC: To understand the development of strength for each mix, cube compressive strengths for both ages of testing were plotted against the water binder ratios for different volumes of composite fibers in Figs. 1 and 2, respectively. Values presented in Table 2 represent the 7 days and 28 days cube compressive strength results. Fig.1 shows that 7 days cube compressive strength of CFRHPC reduced with an escalation in water binder ratio, with all other mixes presenting the same trend.

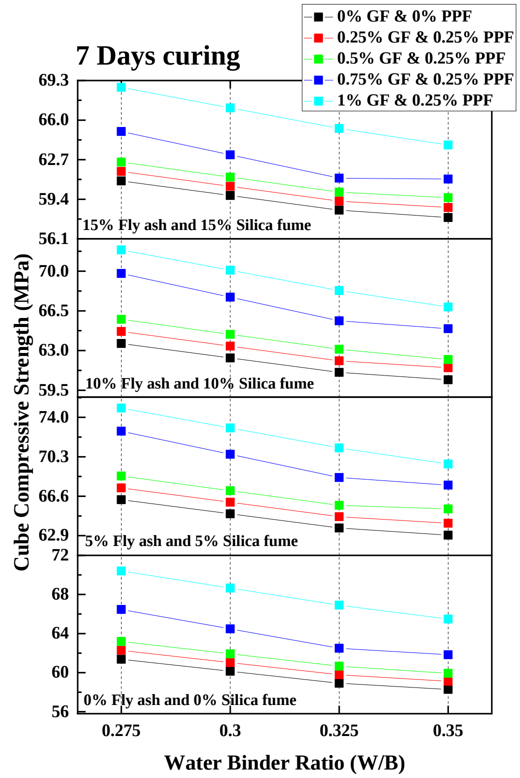

Fig 1. 7 days cube compressive strength versus water binder ratios for various volumes of composite fibers.

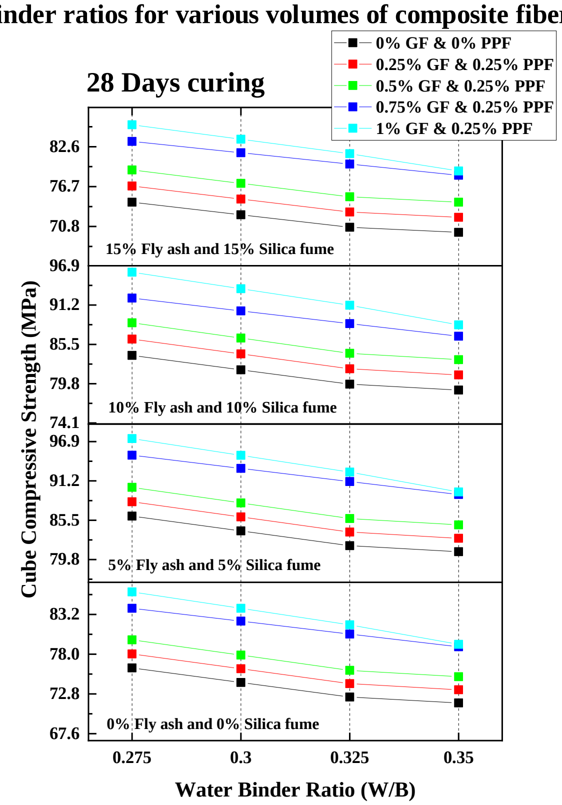

Fig 2. 28 days cube compressive strength versus water binder ratios for various volumes of composite fibers.

Table 2. Cube and Cylindrical compressive strengths of CFRHPC mixes.

Mix Designation	Cube Compressive strength (MPa) 7 Days	Cube Compressive strength (MPa) 28 Days	Cylindrical Compressive strength (MPa) 7 Days	Cylindrical Compressive strength (MPa) 28 Days	Mix Designation	Cube Compressive strength (MPa) 7 Days	Cube Compressive strength (MPa) 28 Days	Cylindrical Compressive strength (MPa) 7 Days	Cylindrical Compressive strength (MPa) 28 Days
CPFS0A	61.36	76.20	45.41	56.39	**CPFS0C**	58.91	72.40	43.59	53.58
CPFS10A	66.27	86.10	49.04	63.72	**CPFS10C**	63.62	81.81	47.08	60.54
CPFS20A	63.62	83.91	47.08	62.09	**CPFS20C**	61.08	79.72	45.20	58.99
CPFS30A	60.93	74.39	45.09	55.05	**CPFS30C**	58.49	70.69	43.28	52.31
CQFS0A	62.28	78.04	45.77	57.35	**CQFS0C**	59.78	74.14	43.94	54.49
CQFS10A	67.38	88.18	49.52	64.80	**CQFS10C**	64.68	83.78	47.54	61.57
CQFS20A	64.69	86.27	47.54	63.39	**CQFS20C**	62.10	81.96	45.64	60.23
CQFS30A	61.71	76.78	45.36	56.42	**CQFS30C**	59.24	72.95	43.54	53.60
CRFS0A	63.20	79.88	46.13	58.31	**CRFS0C**	60.66	75.89	44.28	55.40
CRFS10A	68.49	90.26	50.00	65.89	**CRFS10C**	65.74	85.75	47.99	62.60
CRFS20A	65.75	88.63	48.00	64.70	**CRFS20C**	63.11	84.19	46.07	61.46
CRFS30A	62.50	79.16	45.62	57.79	**CRFS30C**	59.99	75.21	43.79	54.90
CSFS0A	66.46	84.00	48.52	61.32	**CSFS0C**	62.49	80.63	45.62	58.86
CSFS10A	72.70	94.93	53.07	69.30	**CSFS10C**	68.36	91.11	49.90	66.51
CSFS20A	69.80	92.21	50.95	67.31	**CSFS20C**	65.62	88.51	47.90	64.61
CSFS30A	65.05	83.37	47.49	60.86	**CSFS30C**	61.16	80.02	44.65	58.42
CTFS0A	70.41	86.14	52.10	63.75	**CTFS0C**	66.90	81.84	49.50	60.56
CTFS10A	74.87	97.34	55.40	72.03	**CTFS10C**	71.14	92.48	52.64	68.44
CTFS20A	71.87	95.95	53.19	71.01	**CTFS20C**	68.29	91.17	50.53	67.46
CTFS30A	68.73	85.84	50.86	63.52	**CTFS30C**	65.30	81.56	48.33	60.35
CPFS0B	60.14	74.30	44.50	54.98	**CPFS0D**	58.28	71.63	43.13	53.00
CPFS10B	64.95	83.96	48.06	62.13	**CPFS10D**	62.95	80.94	46.58	59.89
CPFS20B	62.35	81.81	46.14	60.54	**CPFS20D**	60.43	78.87	44.72	58.36
CPFS30B	59.71	72.54	44.19	53.68	**CPFS30D**	57.87	69.93	42.82	51.75
CQFS0B	61.03	76.09	44.85	55.92	**CQFS0D**	59.11	73.34	43.38	53.90
CQFS10B	66.03	85.98	48.53	63.19	**CQFS10D**	64.07	82.88	47.03	60.91
CQFS20B	63.39	84.11	46.59	61.81	**CQFS20D**	61.49	81.08	45.20	59.58
CQFS30B	60.48	74.86	44.45	55.01	**CQFS30D**	58.71	72.16	43.14	53.03
CRFS0B	61.93	77.88	45.21	56.85	**CRFS0D**	59.93	75.06	43.59	54.79
CRFS10B	67.12	88.01	49.00	64.25	**CRFS10D**	65.41	84.82	47.51	61.92
CRFS20B	64.43	86.41	47.04	63.08	**CRFS20D**	62.21	83.28	45.66	60.80
CRFS30B	61.24	77.18	44.71	56.34	**CRFS30D**	59.53	74.39	43.45	54.30
CSFS0B	64.47	82.32	47.07	60.09	**CSFS0D**	61.83	78.96	45.14	57.64
CSFS10B	70.53	93.02	51.49	67.90	**CSFS10D**	67.64	89.23	49.38	65.14
CSFS20B	67.71	90.36	49.43	65.96	**CSFS20D**	64.93	86.68	47.40	63.27
CSFS30B	63.11	81.70	46.07	59.64	**CSFS30D**	61.08	78.37	44.18	57.21
CTFS0B	68.65	83.99	50.80	62.16	**CTFS0D**	65.48	79.29	48.45	58.67
CTFS10B	73.00	94.91	54.02	70.24	**CTFS10D**	69.63	89.59	51.52	66.30
CTFS20B	70.08	93.56	51.86	69.23	**CTFS20D**	66.84	88.32	49.46	65.35
CTFS30B	67.02	83.70	49.59	61.94	**CTFS30D**	63.92	79.01	47.30	58.47

Table 3. Split tensile and flexural strengths of CFRHPC mixes.

Mix Designation	Split tensile strength		Flexural strength		Mix Designation	Split tensile strength		Flexural strength	
	MPa					MPa			
	7	28	7	28		7	28	7	28
	Days					Days			
CPFS0A	3.86	5.29	5.93	8.13	**CPFS0C**	3.61	4.94	5.29	7.25
CPFS10A	4.09	5.68	6.20	8.62	**CPFS10C**	3.75	5.04	5.88	7.90
CPFS20A	3.89	5.38	5.99	8.21	**CPFS20C**	3.65	4.98	5.33	7.31
CPFS30A	3.74	5.14	5.82	8.02	**CPFS30C**	3.41	4.69	5.03	6.93
CQFS0A	3.97	5.52	5.95	8.27	**CQFS0C**	3.73	5.18	5.38	7.47
CQFS10A	4.32	6.04	6.47	9.02	**CQFS10C**	3.92	5.42	6.01	8.31
CQFS20A	4.06	5.67	6.04	8.43	**CQFS20C**	3.77	5.22	5.44	7.53
CQFS30A	3.85	5.35	5.88	8.16	**CQFS30C**	3.52	4.87	5.06	7.00
CRFS0A	4.10	5.77	6.19	8.72	**CRFS0C**	3.85	5.42	5.47	7.71
CRFS10A	4.43	6.21	7.04	9.86	**CRFS10C**	4.10	5.68	6.31	8.76
CRFS20A	4.13	5.92	6.27	8.98	**CRFS20C**	3.88	5.46	5.51	7.77
CRFS30A	3.98	5.58	6.08	8.52	**CRFS30C**	3.73	5.17	5.32	7.39
CSFS0A	4.14	5.91	6.24	8.84	**CSFS0C**	3.97	5.67	5.52	7.88
CSFS10A	4.56	6.48	7.34	10.43	**CSFS10C**	4.15	6.03	6.53	9.48
CSFS20A	4.33	6.16	6.32	9.12	**CSFS20C**	4.01	5.71	5.56	7.94
CSFS30A	4.05	5.75	6.12	8.65	**CSFS30C**	3.80	5.34	5.36	7.44
CTFS0A	4.26	6.09	6.29	8.98	**CTFS0C**	4.12	5.88	5.62	8.03
CTFS10A	4.79	6.81	7.59	10.79	**CTFS10C**	4.35	6.18	6.77	9.62
CTFS20A	4.52	6.43	6.61	9.40	**CTFS20C**	4.17	5.92	5.66	8.09
CTFS30A	4.16	5.96	6.20	8.87	**CTFS30C**	4.01	5.69	5.55	7.89
CPFS0B	3.78	5.18	5.68	7.78	**CPFS0D**	3.20	4.38	4.99	6.84
CPFS10B	3.90	5.40	5.97	8.27	**CPFS10D**	3.51	4.84	5.47	7.54
CPFS20B	3.87	5.28	5.76	7.86	**CPFS20D**	3.31	4.56	5.09	7.01
CPFS30B	3.57	4.91	5.39	7.42	**CPFS30D**	3.12	4.28	4.90	6.71
CQFS0B	3.88	5.39	5.73	7.96	**CQFS0D**	3.36	4.66	5.08	7.06
CQFS10B	4.11	5.71	6.21	8.63	**CQFS10D**	3.81	5.26	5.68	7.84
CQFS20B	3.97	5.51	5.81	8.04	**CQFS20D**	3.48	4.80	5.19	7.16
CQFS30B	3.76	5.21	5.58	7.73	**CQFS30D**	3.26	4.48	4.94	6.79
CRFS0B	4.00	5.64	5.81	8.18	**CRFS0D**	3.59	5.05	5.24	7.38
CRFS10B	4.23	5.90	6.51	9.07	**CRFS10D**	4.03	5.56	5.86	8.08
CRFS20B	4.10	5.71	5.89	8.26	**CRFS20D**	3.68	5.31	5.34	7.49
CRFS30B	3.91	5.45	5.72	7.98	**CRFS30D**	3.46	4.82	5.13	7.15
CSFS0B	4.08	5.83	5.86	8.24	**CSFS0D**	3.73	5.33	5.27	7.53
CSFS10B	4.36	6.27	6.80	9.76	**CSFS10D**	4.06	5.83	6.07	8.72
CSFS20B	4.24	6.08	5.94	8.40	**CSFS20D**	3.88	5.45	5.38	7.70
CSFS30B	3.98	5.57	5.76	8.01	**CSFS30D**	3.57	5.09	5.17	7.27
CTFS0B	4.16	5.94	5.96	8.52	**CTFS0D**	3.86	5.51	5.47	7.81
CTFS10B	4.58	6.50	6.95	9.88	**CTFS10D**	4.22	5.94	6.33	8.91
CTFS20B	4.41	6.26	6.04	8.60	**CTFS20D**	3.94	5.58	5.57	7.98
CTFS30B	4.07	5.81	5.89	8.39	**CTFS30D**	3.76	5.34	5.36	7.60

Fig.2 shows that 28 days cube compressive strength of CFRHPC reduced with an escalation in water binder ratio, and all other mixes followed the same trend. Maximum 28 days cube compressive strength was obtained for a mix with a 0.275 water binder ratio and valid for all other mixes with different percentages of cement replacements and composite fibers. The maximum cube compressive strength obtained at 28 days was 97.34 MPa for CTFS10A. Further, for the same mix, when the water binder ratio was increased to 0.3, its cube compressive strength was reduced by 2.5% with respect to the CTFS10A mix, and it was further reduced to 4.99% and 7.96% for W/B ratios of 0.325 and 0.35, with respect to CTFS10A mix.

b) Effects of cement replacement by fly ash and silica fume on cube compressive strength of CFRHPC: To understand the development of strength due to cement replacement by FA and SF for each mix, cube compressive strengths for both ages of testing for all W/B are plotted against the percentages of FA and SF for different volumes of composite fibers in Figs. 3 and 4, respectively.

28 days cube compressive strength versus percentages of FA and SF are plotted in Fig.4. It shows that the 28 days cube compressive strength was enhanced with cement replacement by combined FA and SF. The addition of FA and SF enhances the load-carrying capacity of the mix. At 10% replacement of cement by combined FA and SF, maximum cube compressive strength was obtained for all composite fibers' volumes. Further increase in FA and SF decreased the value of cube compressive strength. The maximum 28 days cube compressive strength percentage increase for CFRHPC was 27.75% by CTFS10A mix over the CPFS0A mix. Hence, the highest cube compressive strengths for all ages were produced by adding 5% FA and 5% SF.

7 days cube compressive strength versus percentages of FA and SF are plotted in Fig.3, which showed a similar trend. Gain in strength until 10% replacement was due to packing of fine FA and SF particles in the interfacial transition zone (micro filler effect) and pozzolanic reactions by the fine mineral admixtures FA and SF. At dosages of more than 10%, cube compressive strength was reduced because the mixture did not have enough $Ca(OH)_2$ for pozzolanic reaction, while FA and SF worked only as fillers.

c) Effects of volumes of composite fibers on cube compressive strength of CFRHPC: To understand the impact of composite fibers on the development of strength for each mix, cube compressive strengths for both ages of testing for various W/B are plotted in Figs.5 and 6 against the volume percentages of composite fibers for various percentages of FA and SF.

Fig.5 indicates that 7 days cube compressive strength of CFRHPC mixes enhanced with addition in percentage volumes of composite fibers.

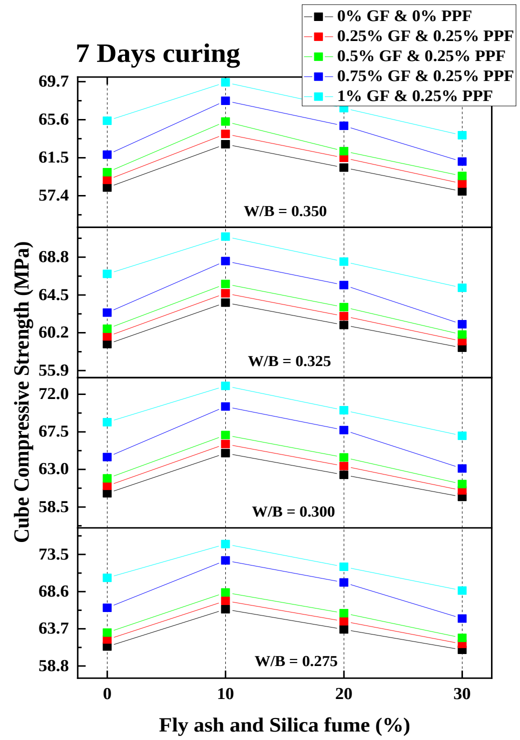

Fig 3. 7 days cube compressive strength versus percentages of FA and SF for various composite fibers' volumes.

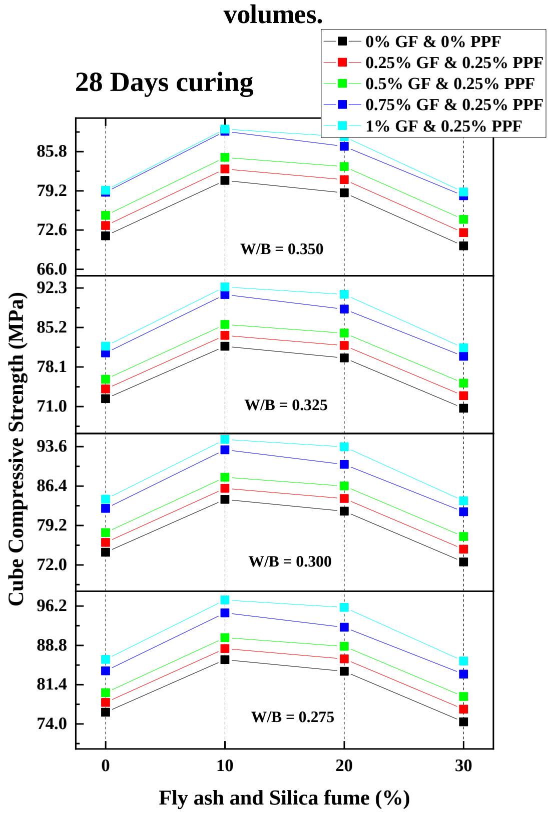

Fig 4. 28 days cube compressive strength versus percentages of FA and SF for various composite fibers' volumes.

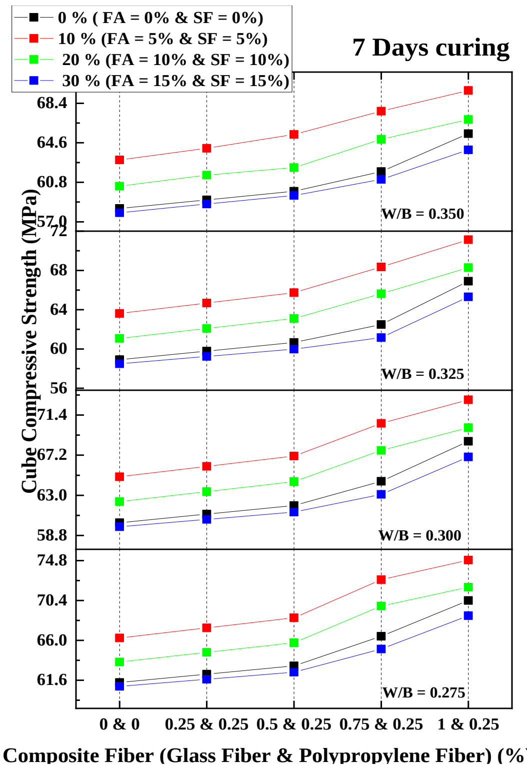

Fig 5. 7 days cube compressive strength versus volume percentages of composite fibers for various FA and SF percentages.

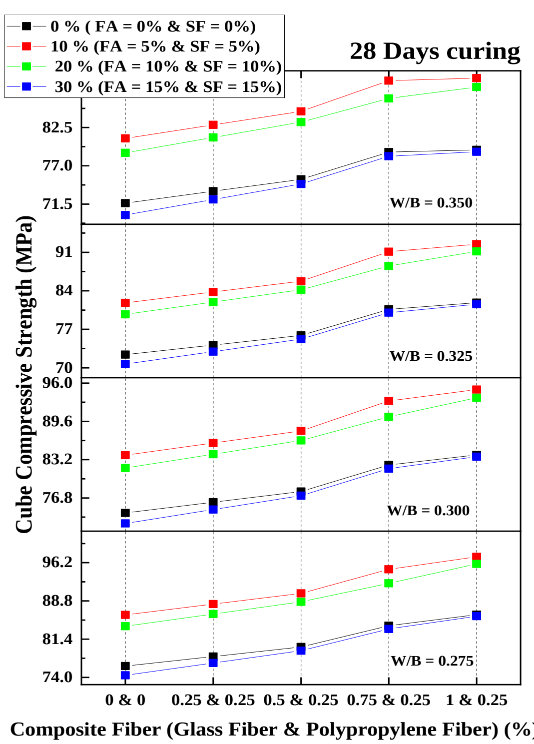

Fig 6. 28 days cube compressive strength versus volume percentages of composite fibers for various FA and SF percentages.

Fig.6 shows that 28 days cube compressive strength was enhanced with the addition of composite fibers, i.e., 0, 0.25, 0.5, 0.75, and 1% GF and constant PPF of 0.25%. The addition of composite fibers enhances the cube compressive strength of the mix. It is evident from the plot that maximum compressive strength was obtained for 1% GF and 0.25% PPF for different percentages of FA and SF. 28 days cube compressive strength of CQFS10A, CRFS10A, CSFS10A, and CTFS10A mixes was increased by 15.73%, 18.46%, 24.58%, and 27.75% respectively with respect to CPFS0A mix. This behavior is obtained as these fibers can work as reinforcement at both micro and macro levels. The micro-cracks development are arrested by these fibers at the micro-level. The number of fibers available in the matrix plays a significant role in controlling the development of microcracks. These fibers prevent crack openings from further widening and increase the capacity of energy absorption at macro levels. Thus, with more fibers in the matrix, higher will be the chances of preventing micro and macro cracks leading to higher strength concrete.

Adding composite fibers to regular concrete increases only ductility. In this study addition of composite fibers and mineral admixtures have been added, which substantially improved the strength over plain concrete due to the strain hardening type of response of CFRHPC.

The highest cube compressive strengths achieved at 7 and 28 days were 74.87 MPa and 97.34 MPa for the CTFS10A mix.

B. Cylindrical compressive strength

a) Effects of water binder ratios on cylindrical compressive strength of CFRHPC: Values presented in Table 2 represent the 7 days and 28 days cylindrical compressive strength results. Cylindrical compressive strengths for both ages of testing are plotted against the water binder ratios for different volumes of composite fibers in Figs. 7 and 8, respectively.

Fig.7 shows that 7 days cylindrical compressive strength of CFRHPC reduced with an escalation in water binder ratio and all other mixes follow the same trend. Fig.8 shows that 28 days cylindrical compressive strength of CFRHPC reduced with an escalation in water binder ratio and all other mixes follow the same trend. Maximum 28 days cylindrical compressive strength was obtained for a mix with a 0.275 water binder ratio and was valid for all other mixes with different percentages of cement replacements and the addition of composite fibers. The maximum cylindrical compressive strength obtained at 28 days was 72.03 MPa for CTFS10A. Further, for the same mix on increasing water binder ratio to 0.3, its cylindrical compressive strength reduced by 2.49% for the CTFS10A mix, and it further reduced to 4.98% and 7.96% for W/B ratios of 0.325 and 0.35 respectively with respect to CTFS10A mix.

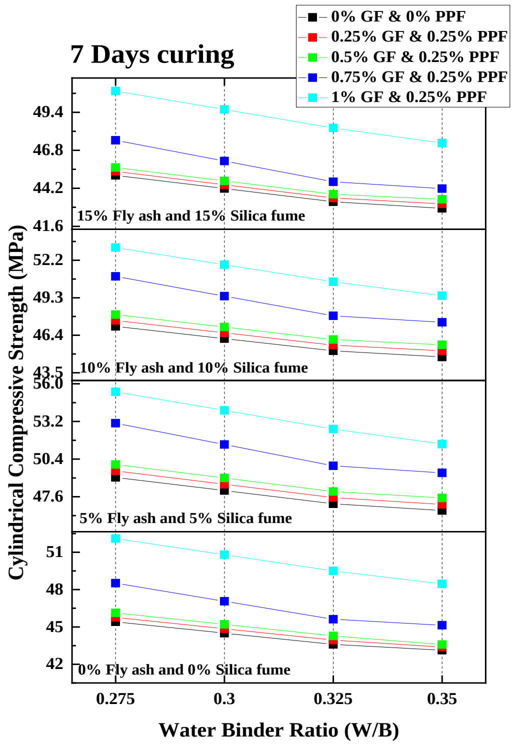

Fig 7. 7 days cylindrical compressive strength versus water binder ratios for various volumes of composite fibers.

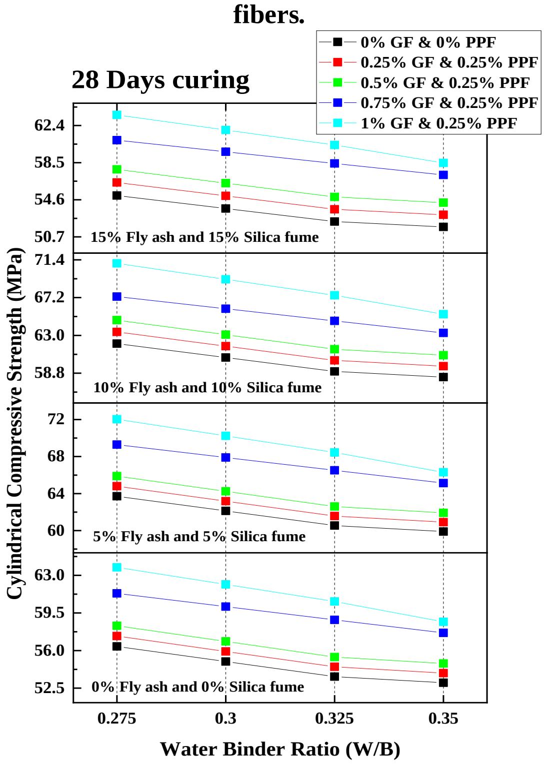

Fig 8. 28 days cylindrical compressive strength versus water binder ratios for various volumes of composite fibers.

b) Effects of cement replacement by fly ash and silica fume on cylindrical compressive strength of CFRHPC: To assess the effect of admixtures on strength for each mix, cylindrical compressive strengths for both ages of testing for all W/B are plotted against the percentages of FA and SF for different volumes of composite fibers in Figs. 9 and 10, respectively.

28 days cylindrical compressive strength versus percentages of FA and SF are plotted in Fig.10. It shows that the 28 days cylindrical compressive strength was enhanced with cement replacement by combined FA and SF. The addition of FA and SF boosts the load-carrying ability of the mix. At 10% replacement of cement by combined FA and SF, maximum cylindrical compressive strength was obtained for all composite fibers' volumes. Further increase in FA and SF decreases the value of cylindrical compressive strength. The maximum 28 days cylindrical compressive strength percentage increase for CFRHPC was 27.75% by CTFS10A mix over the CPFS0A mix. 7 days cylindrical compressive strength versus percentages of FA and SF are plotted in Fig.9, which showed a similar trend. Hence, the highest cylindrical compressive strengths for all ages were produced by adding 5% FA and 5% SF. Gain in strength until 10% replacement was due to packing of fine FA and SF particles in the interfacial transition zone (micro filler effect) and pozzolanic reactions by the fine mineral admixtures FA and SF. At dosages of more than 10%, cylindrical compressive strength was reduced since the mixture did not have enough $Ca(OH)_2$ for a pozzolanic reaction, while FA and SF worked only as fillers.

c) Effects of composite fiber on cylindrical compressive strength of CFRHPC: To understand the development of strength due to composite fibers, cylindrical compressive strengths for both ages of testing for various W/B are plotted in Figs.11 and 12 against the volume percentages of composite fibers for various percentages of FA and SF.

Fig.11 indicates that 7 days cylindrical compressive strength of CFRHPC mixes enhanced with addition in percentage volumes of composite fibers. Fig.12 shows that 28 days cylindrical compressive strength was enhanced with the addition of composite fibers, i.e., 0, 0.25, 0.5, 0.75, and 1% GF and constant PPF of 0.25%. The addition of composite fibers enhanced the cylindrical compressive strength of the mix. The maximum cylindrical compressive strength was attained for 1% GF and 0.25% PPF for different percentages of FA and SF. 28 days cylindrical compressive strength of CQFS10A, CRFS10A, CSFS10A, and CTFS10A mixes increased by 14.93%, 16.86%, 22.89%, and 27.75% respectively with respect to CPFS0A plain mix. This behavior was observed as the matrix's energy absorption capacity was increased by fibers that regulate cracks.

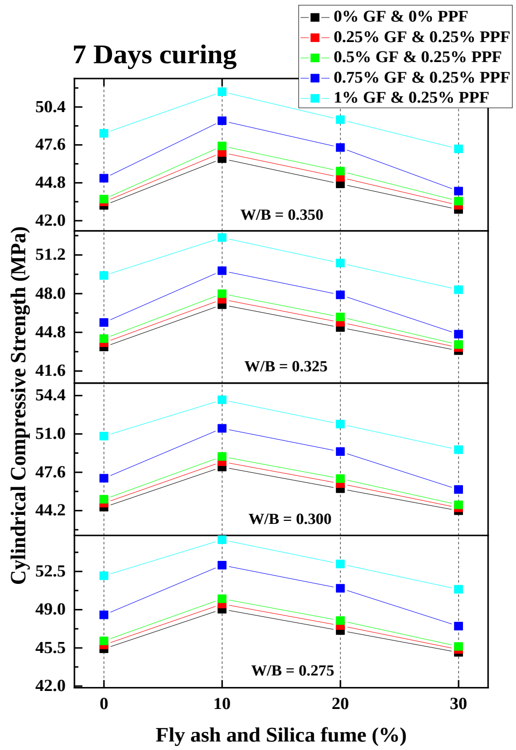

Fig 9. 7 days cylindrical compressive strength versus percentages of FA and SF for various composite fibers' volumes.

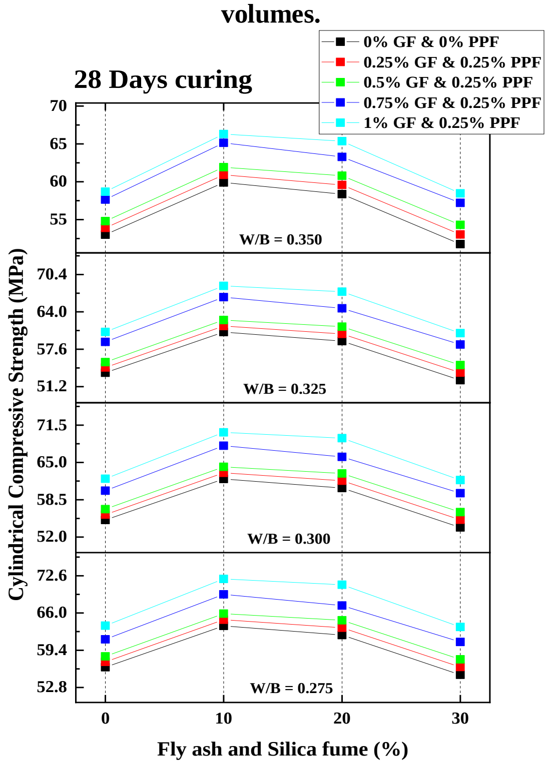

Fig 10. 28 days cylindrical compressive strength versus percentages of FA and SF for various composite fibers' volumes.

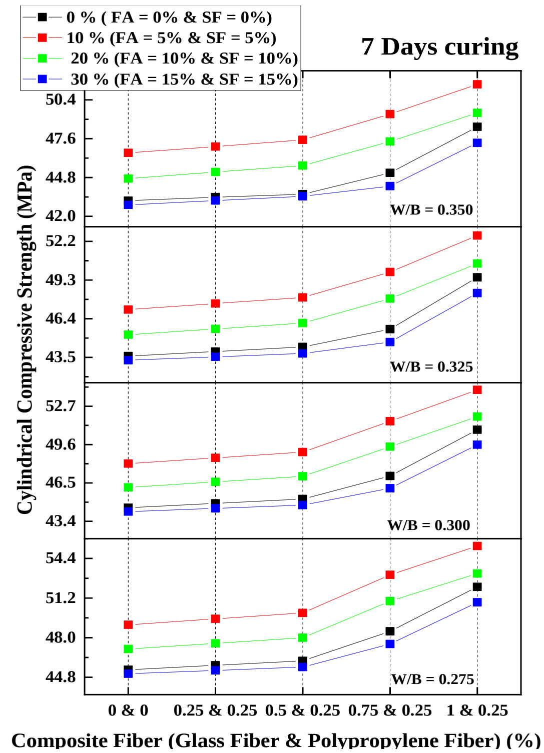

Fig 11. 7 days cylindrical compressive strength versus volume percentages of composite fibers for various FA and SF percentages.

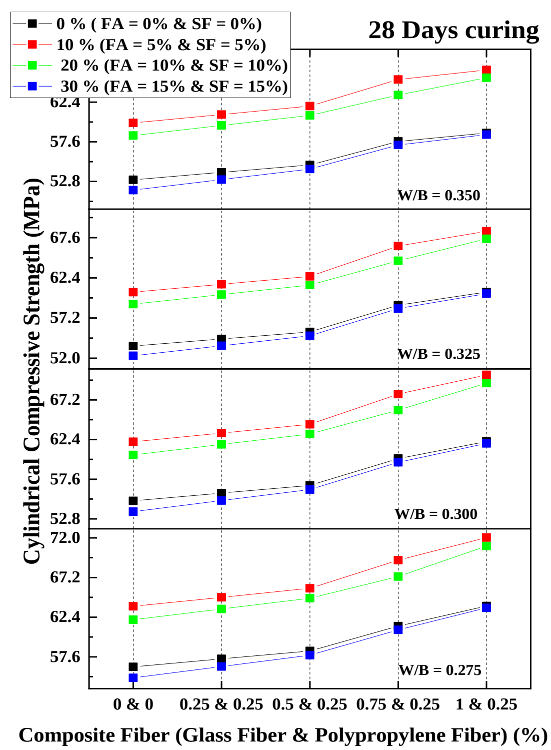

Fig 12. 28 days cylindrical compressive strength versus volume percentages of composite fibers for various FA and SF percentages.

Hence, the addition of composite fibers also contributes to the cylindrical compressive strength of the mix.

Adding composite fibers to regular concrete increases only ductility. In this study addition of composite fibers and mineral admixtures have been added, which substantially improved the strength over plain concrete due to the strain hardening type of response of CFRHPC.

The highest cylindrical compressive strengths achieved at 7 and 28 days were 55.40 MPa and 72.03 MPa for the CTFS10A mix.

C. Split tensile strength

a) Effects of water binder ratios on split tensile strength of CFRHPC: To understand the effect of water binder ratio on the development of strength for each mix, split tensile strengths for both ages of testing are plotted against the water binder ratios for different volumes of composite fibers in Figs. 13 and 14 respectively.

Values presented in Table 3 represent the 7 days and 28 days split tensile strength results. Fig.13 shows that 7 days split tensile strength of CFRHPC decreased with an increase in water binder ratio, and all other mixes follow the same trend.

Fig.14 shows that 28 days split tensile strength of CFRHPC also reduced with an escalation in water binder ratio and all other mixes followed the same trend. Maximum 28 days split tensile strength was obtained for a mix with a 0.275 water binder ratio and was valid for all other mixes with different percentages of cement replacements and the addition of composite fibers. The maximum split tensile strength obtained at 28 days was 6.81 MPa for CTFS10A. Further, for the same mix, when the water binder ratio was increased to 0.3, its split tensile strength was reduced by 4.55% for the CTFS10A mix, and it further reduced to 9.25% and 12.78% for W/B ratios of 0.325 and 0.35 respectively, with respect to CTFS10A mix.

b) Effects of cement replacement by fly ash and silica fume on split tensile strength of CFRHPC: To assess the development of strength for each mix due to mineral admixtures, split tensile strengths for both ages of testing for all W/B are plotted against the percentages of FA and SF for different volumes of composite fibers in Figs. 15 and 16, respectively.

28 days split tensile strength versus percentages of FA and SF are plotted in Fig.16. It shows that the 28 days split tensile strength was enhanced with cement replacement by combined FA and SF. The addition of FA and SF boosts the load-carrying ability of the mix. 7 days of split tensile strength versus percentages of FA and SF are plotted in Fig.15, which showed a similar trend.

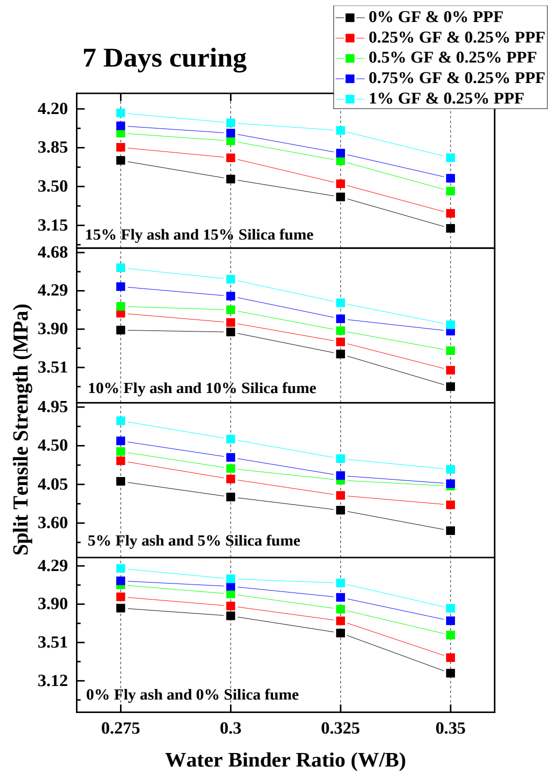

Fig 13. 7 days split tensile strength versus water binder ratios for various volumes of composite fibers.

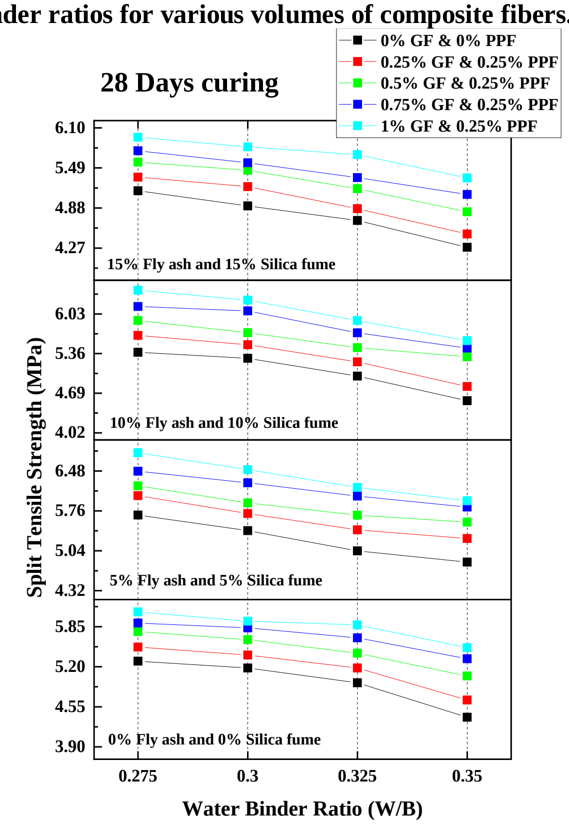

Fig 14. 28 days split tensile strength versus water binder ratios for various volumes of composite fibers.

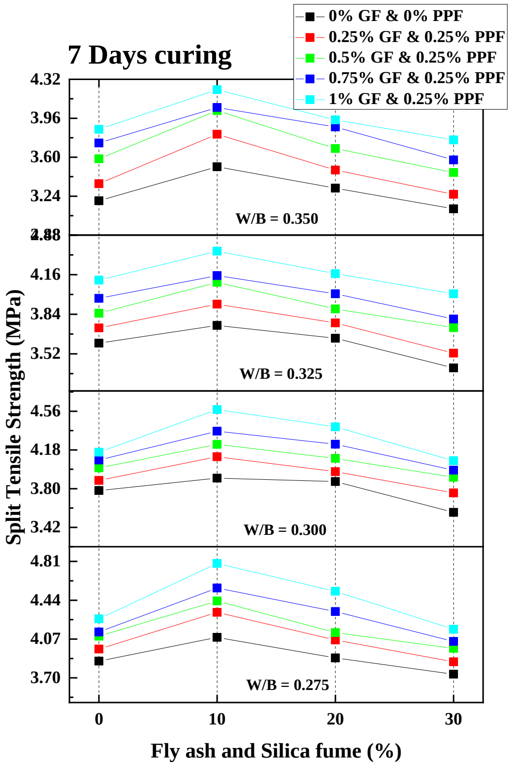

Fig 15. 7 days split tensile strength versus percentages of FA and SF for various composite fibers' volumes.

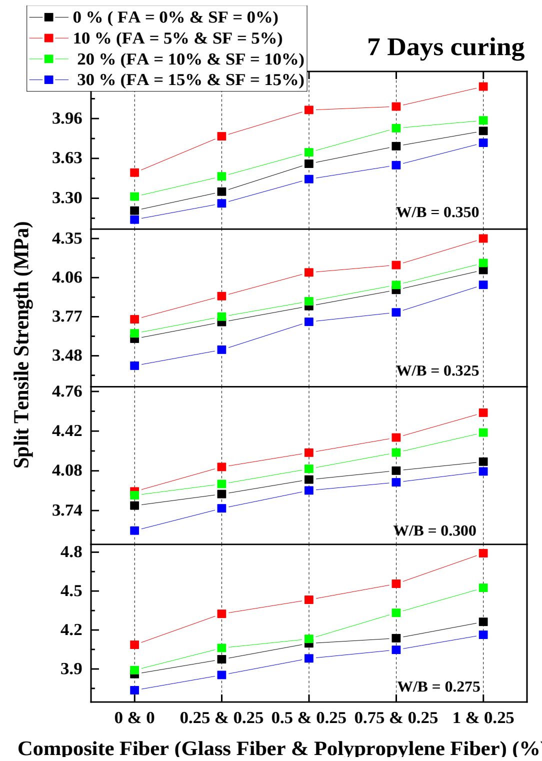

Fig 17. 7 days split tensile strength versus volume percentages of composite fibers for various FA and SF percentages.

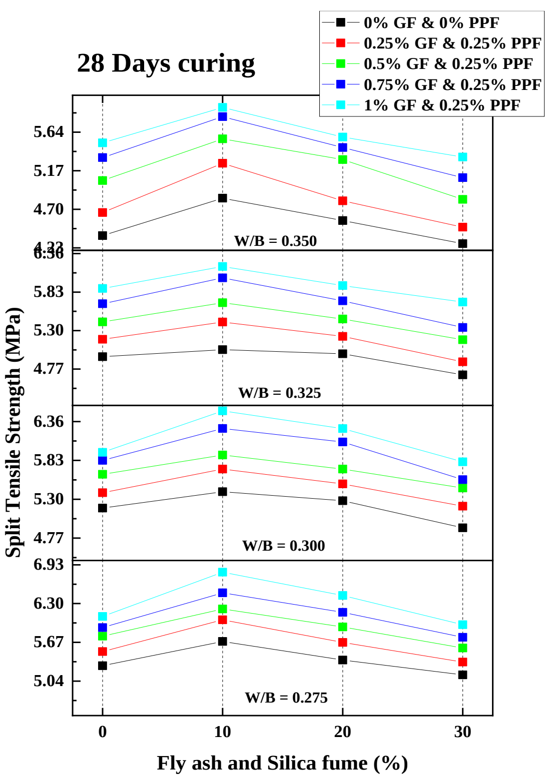

Fig 16. 28 days split tensile strength versus percentages of FA and SF for various volumes of composite fibers.

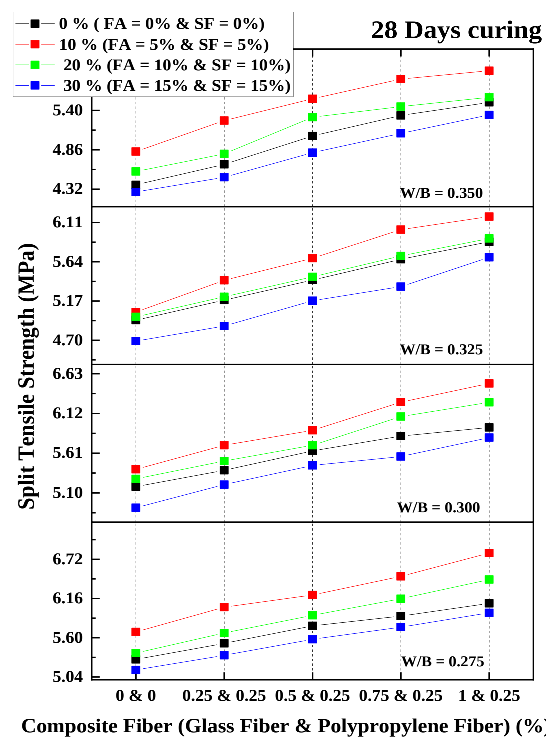

Fig 18. 28 days split tensile strength versus volume percentages of composite fibers for various FA and SF percentages.

At 10% replacement of cement by combined FA and SF, maximum split tensile strength was obtained for all volumes of composite fibers as combined pozzolanic activity, and the addition of FA and SF enhanced micro filler effects. Further increase in FA and SF decreases the value of split tensile strength due to lack of $Ca(OH)_2$ for the pozzolanic reaction. The maximum 28 days split strength percentage increase for CFRHPC was 28.72% for the CTFS10A mix over the CPFS0A mix. Hence, the highest split tensile strengths for all ages were produced by adding 5% FA and 5% SF.

c) Effects of composite fiber on split tensile strength of CFRHPC: To understand the development of split tensile strength for each mix, split tensile strengths for both ages of testing for all W/B are plotted in Figs.17 and 18 against the volume percentages of composite fibers for various percentages of FA and SF.

Fig.17 indicates that 7 days split tensile strength of CFRHPC mixes enhanced with addition in percentage volumes of composite fibers. Fig.18 shows that 28 days split tensile strength was enhanced with the addition of composite fibers, i.e., 0, 0.25, 0.5, 0.75, and 1% GF and constant PPF of 0.25%. These results justify that the reinforcing of composite fibers contributes to the split tensile strength for the CFRHPC. It can be further observed that maximum split tensile strength was obtained for 1% GF and 0.25% PPF for different FA and SF percentages. Split tensile strength of CQFS10A, CRFS10A, CSFS10A, and CTFS10A mixes were increased by 14.10%, 17.41%, 22.40%, and 28.72%, respectively, with respect to the CPFS0A mix for 28 days. It can be confidently concluded that higher volumes of fibers in the medium delay forming the foremost major crack as bonding is formed between matrix and fibers, which stabilizes the micro-cracks forming at the micro-level. This action increases the matrix's tensile strength, proving that fiber inclusion in CFRHPC mixes is more productive in improving tensile strength than compressive strength. The highest split tensile strengths achieved at 7 and 28 days were 4.79 MPa and 6.81 MPa, respectively, for the CTFS10A mix.

D. Flexural strength

a) Effects of water binder ratios on flexural strength of CFRHPC: Values presented in Table 3 represent the 7 days and 28 days flexural strength results. For both ages of testing, flexural strengths are plotted against the water binder ratios for different volumes of composite fibers in Figs. 19 and 20 respectively.

Fig.19 shows that 7 days flexural strength of CFRHPC reduced with an escalation in water binder ratio, and all other mixes follow the same trend.

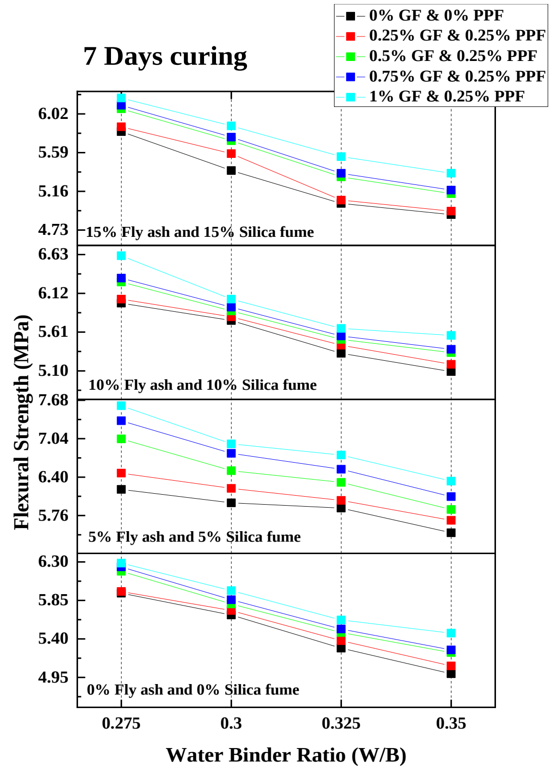

Fig 19. 7 days split tensile strength versus water binder ratios for various volumes of composite fibers.

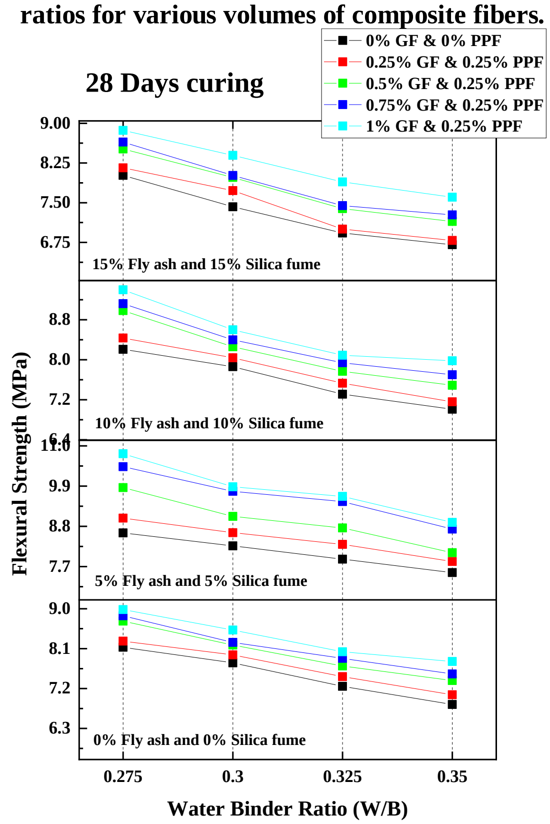

Fig 20. 28 days split tensile strength versus water binder ratios for various volumes of composite fibers.

Fig.20 shows that 28 days flexural strength of CFRHPC also reduced with an escalation in water binder ratio, and all other mixes follow the same trend. Maximum 28 days flexural strength was obtained for a mix with a 0.275 water binder ratio and was valid for all other mixes with different percentages of cement replacements and the addition of composite fibers. The maximum flexural strength obtained at 28 days was 10.79 MPa for the CTFS10A mix. Further, for the same mix, when the water binder ratio was increased to 0.3, its compressive strength was reduced by 8.43% for the CTFS10A mix, and it was further reduced to 10.84% and 17.42% for W/B ratios of 0.325 and 0.35, respectively with respect to CTFS10A mix.

b) Effects of cement replacement by fly ash and silica fume on flexural strength of CFRHPC: Flexural strengths for both ages of testing are plotted versus the percentages of FA and SF for all W/B with different volumes of composite fibers in Figs. 21 and 22, respectively.

Values presented in Table 2 represent the 7 days and 28 days flexural strength results. 28 days flexural strength versus percentages of FA and SF are plotted in Fig.22. It shows that the flexural strength at 28 days was also enhanced with cement replacement by combined FA and SF. The combined effect of FA and SF boosts the load-carrying ability of the mix. FA and SF obtain maximum flexural strength at 10% replacement of cement for all composite fibers' volumes. Fig.21 shows that 7 days flexural strength of CFRHPC mixes also showed a similar trend.

Further increase in FA and SF decreases the value of flexural strength as these mineral admixtures acted only as fillers rather than contributing to pozzolanic reaction due to lack of calcium hydroxide. The maximum 28 days flexural strength percentage increase for CFRHPC was 32.67% by CTFS10A mix over the CPFS0A mix. Hence, the highest flexural strengths for all ages were produced by adding 5% FA and 5% SF.

c) Effects of composite fiber on flexural strength of CFRHPC: To understand the effects of volumes of composite fibers on flexural strength for each mix, the 7 days and 28 days flexural strengths for all W/B are plotted in figs.23 and 24 against the volume percentages of composite fibers for various percentages of FA and SF.

Fig.23 indicates that 7 days flexural strengths of the CFRHPC mix were enhanced with the addition of percentage volumes of composite fibers. Fig.24 shows that 28 days of flexural strength was also enhanced with the addition of composite fibers, i.e., 0, 0.25, 0.5, 0.75, and 1% GF and constant PPF of 0.25%. The adding of composite fibers enhanced the flexural strength of the CFRHPC. Maximum flexural strength was obtained for 1% GF and 0.25% PPF for different percentages of FA and SF. 28 days flexural strength of CQFS10A, CRFS10A, CSFS10A, and CTFS10A mixes

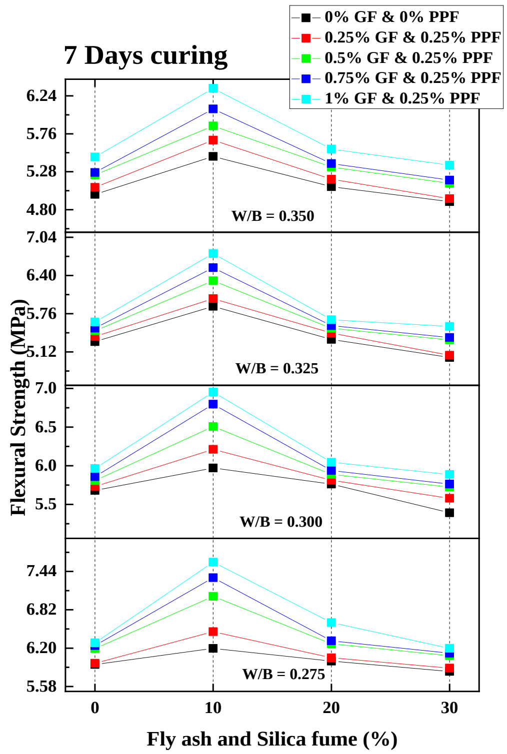

Fig 21. 7 days flexural strength versus percentages of FA and SF for various composite fibers volumes.

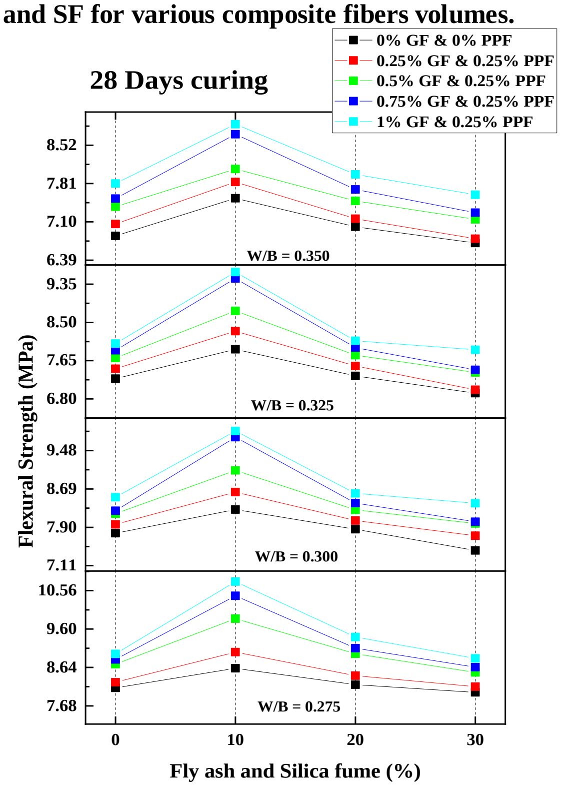

Fig 22. 28 days flexural strength versus percentages of FA and SF for various composite fibers' volumes.

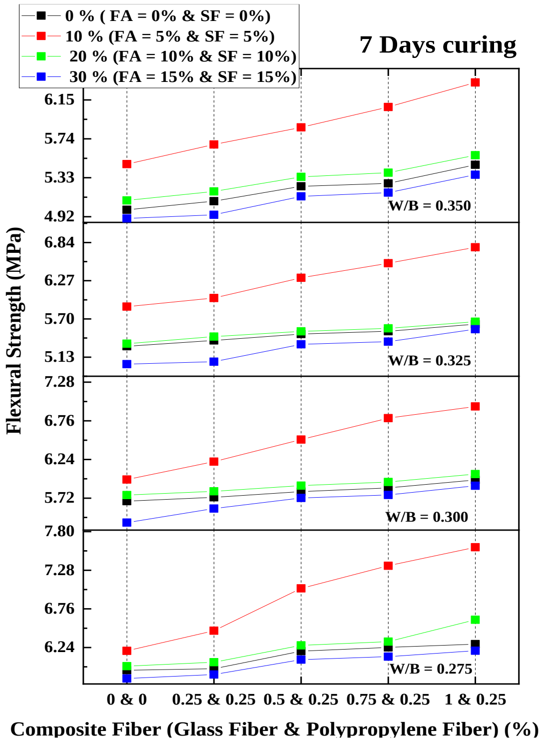

Fig 23. 7 days flexural strength versus volume percentages of composite fibers for various FA and SF percentages.

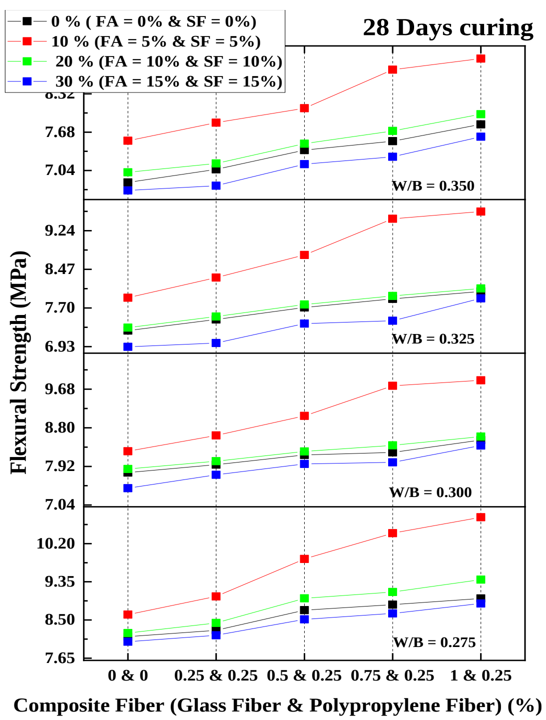

Fig 24. 28 days flexural strength versus volume percentages of composite fibers for various FA and SF percentages.

increased by 11%, 21.27%, 28.31%, and 32.67%, respectively, with respect to CPFS0A mix. Hence, the addition of composite fibers also contributes to the flexural strength of the mix due to the presence of these uniformly dispersed composite fibers, which acts as crack arresters to enhance the properties of concrete as bonding is formed between matrix and fibers, which in turn stabilizes the micro-cracks forming at the micro-level.

The highest flexural strengths achieved at 7 and 28 days were 7.59 MPa and 10.79 MPa for the CTFS10A mix.

E. Inter-Relationships between various properties of fly ash and silica fume based CFRHPC

There is an absence of efficient research to propose an inter-relationship between Cube compressive strength with cylindrical compressive strength, split tensile strength, and flexural strength for FA and SF based CFRHPC. From the experimental investigation results on various FA and SF-based CFRHPC mixes, inter-relationships between the different properties such as cube compressive strength, cylindrical compressive strength, split tensile strength, and flexural strength were derived. The inter-relationships will be valuable to estimate the cylindrical compressive strength, tensile strength, and flexural strength of any FA and SF based CFRHPC mixes from its cube compressive strength.

a) Relationship between cube compressive strength and cylindrical compressive strength: The relationship between the cube compressive strength and cylindrical compressive strength of FA and SF based CFRHPC mixes are presented in Fig 25.

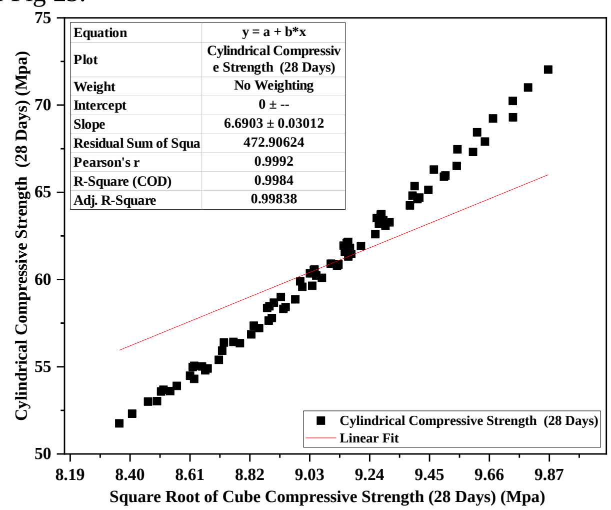

Fig 25. The square root of 28 days cubes compressive strength versus 28 days cylindrical compressive strength of FA and SF based CFRHPC.

Using the square root function, a basic regression model has been established based on the CFRHPC behavior in the present investigation to forecast the cylindrical compressive strength of FA and SF based CFRHPC mixes and shown below.

$$f_{ccs} = 6.690\sqrt{f_{ck}}$$

Where f_{ccs} is the Cylindrical compressive strength and f_{ck} is the Cube compressive strength in MPa. This relation can be used for predicting the cylindrical compressive strength of FA and SF based CFRHPC mixes.

b) Relationship between cube compressive strength and split tensile strength: The relationship between the cube compressive strength and split tensile strength of FA and SF based CFRHPC mixes is presented in Figure 26.

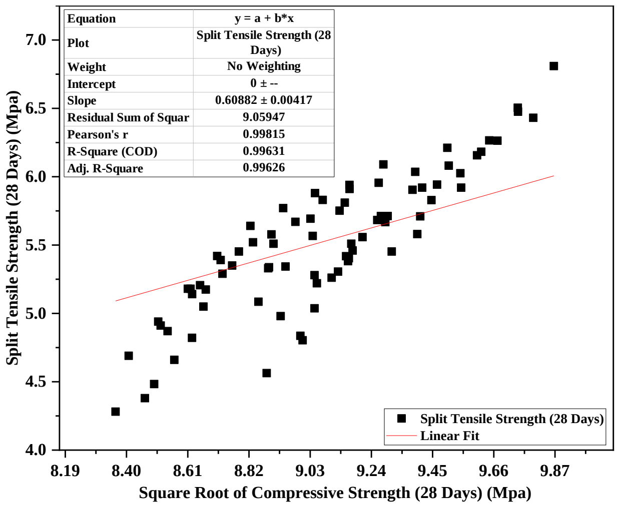

Fig 26. The square root of 28 days cube compressive strength versus 28 days split tensile strength of FA and SF based CFRHPC.

Using the square root function, a basic regression model has been established based on the CFRHPC behavior in the present investigation for forecasting the split tensile strength of FA and SF based CFRHPC mixes and is shown below.

$$f_{sts} = 0.608\sqrt{f_{ck}}$$

Where f_{sts} is the Split tensile strength and f_{ck} is the Cube compressive strength in MPa. This relation can be used for predicting the split tensile strength of FA and SF based CFRHPC mixes.

c) Relationship between cube compressive strength and flexural strength: The relationship between the cube compressive and flexural strengths of FA and SF based CFRHPC mixes is presented in Fig 27 from the present experimental study results.

The following relationship between cube compressive strength and flexural strength of CFRHPC is developed from the linear regression presented in the figure.

$$f_{fs} = 0.901\sqrt{f_{ck}}$$

Where f_{fs} is the Flexural strength and f_{ck} is the Cube compressive strength in MPa.

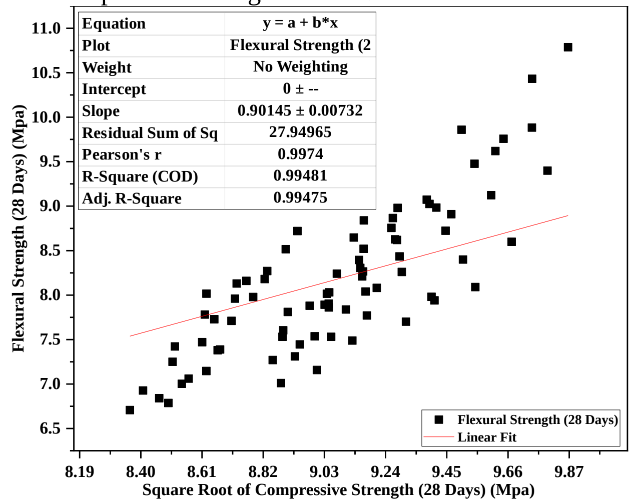

Fig 27. The square root of 28 days cubes compressive strength versus 28 days flexural strength of FA and SF based CFRHPC.

V. CONCLUSIONS

In this experimental work, the performance of CFRHPC produced with FA, SF, GF, and PPF was investigated. The following conclusions are drawn after the analysis of the results

- It can be concluded that the compressive, tensile, and flexural strengths of CFRHPC reduced with an escalation in water binder ratio, and all other mixes followed the same trend. For both ages of curing, maximum strengths were obtained for a mix with a 0.275 water binder ratio and valid for all other mixes with different percentages of cement replacements and composite fibers.

- It is evident from the analysis of experimental results that for all the ages of concrete testing done, the mechanical properties of CFRHPC mix increases with a rise in the percentage of FA and SF up to 10% replacement level and further, strength decreases with an increase in cement replacement beyond 10% level. Thus, CFRHPC mixes with a 10% mineral admixture replacement level produced maximum values of mechanical properties and is valid for both ages of testing done.

- For both testing ages of concrete done, composite fibers' addition enhanced the strength properties of CFRHPC mixes. The maximum values of strength properties were obtained for CFRHPC mixes with 1% GF and 0.25% PPF and valid for both ages of testing.

- It can be concluded that the split tensile strength and flexural strength of high-performance concrete reinforced with GF and PPF were enhanced with the composite fibers' inclusion. However, composite fibers' effect on the cube compressive strength and cylindrical compressive strength was minimal.

- The regression equations developed to indicate a good correlation. These relationships can be effectively used for predicting the cylindrical compressive strength, split tensile strength flexural strength of FA and SF based CFRHPC mixes.

- Hence, it can be concluded that the combined effect of FA and SF at 5% each as replacement of cement and the addition of composite fiber dosage of GF=1% and PPF=0.25% for W/B of 0.275 was found to be the optimum combination to obtain maximum mechanical properties for CFRHPC.

The conclusions above demonstrate the viability of using FA and SF and composite fibers (GF and PFF) in CFRHPC production, minimizing enormous cement production and safeguards the environment from pollution.

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