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Evaluation of Strength Properties of Fly ash and Metakaolin Based Composite Fiber (Glass and Polypropylene) Reinforced High-Performance Concrete

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***Abstract** - Pozzolanic materials Fly ash (FA) and Metakaolin (MK), 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 MK as replacement of cement partially. Glass fibers (GF) and Polypropylene fibers (PPF) are used as an addition to producing 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 MK were replaced in the range from 0% to 15% each, GF were added in volume percentages from 0% to 1%, and PPF was kept constant at 0.25%. The combined effect of FA and MK 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 MK-based CFRHPC were also derived from the experimental results of this investigation.*

Keywords: *Composite fibers, Glass fiber, High-Performance Concrete, Polypropylene fiber, Fly ash, Metakaolin, 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].

Alumino-silicate material which is present in thermally activated calcined kaolin clay, forms metakaolin [5]. MK is composed of highly reactive SiO_2 and Al_2O_3 in 50 to 55% and 40 to 45%. MK is a manufactured product, while other artificial or natural pozzolans like SF and fly ash are secondary products. Thus, MK can be manufactured with anticipated features. Concrete with 10% of MK has proved to have better compressive strength than the control mix of all ages[6]. Dr.H.Sudarsana Rao et al. [7] studied the deterioration and relative sulfate resistance of HPC in severe sulfate environments and suggested using Fly ash (FA), partially replacing natural pozzolana for enhanced performance. The widespread application of FA and MK in the construction industry results from extensive investigations on FA and MK use in concrete during the past two decades[8]–[13].

Investigation[14], 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[15]-[25] 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[26], 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 MK 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 MK-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. **Metakaolin** used was of pink color, having a specific gravity of 2.60 with a specific surface area of 12.7 m^2/g and had SiO_2 and Al_2O_3 at 52.4% and 43.18%, respectively. 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 MK 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 M indicates MK. The following number indicates the total percentage of cement replaced by FA and MK. Last alphabet indicates water binder ratios, i.e. A=0.275, B=0.300, C=0.325 and D=0.350. CPFM0A 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. For the CTFM10A mix, the cement of 719.15 kg/m^3 was used, and the quantity of FA and MK used was 39.95 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	MK	GF	PPF
			(%)				
CPFM0A	0.275	1.75	0.8	0	0	0	0
CPFM10A	0.275	1.75	0.8	5	5	0	0
CPFM20A	0.275	1.75	0.8	10	10	0	0
CPFM30A	0.275	1.75	0.8	15	15	0	0
CQFM0A	0.275	1.75	0.8	0	0	0.25	0.25
CQFM10A	0.275	1.75	0.8	5	5	0.25	0.25
CQFM20A	0.275	1.75	0.8	10	10	0.25	0.25
CQFM30A	0.275	1.75	0.8	15	15	0.25	0.25
CRFM0A	0.275	1.75	0.8	0	0	0.5	0.25
CRFM10A	0.275	1.75	0.8	5	5	0.5	0.25
CRFM20A	0.275	1.75	0.8	10	10	0.5	0.25
CRFM30A	0.275	1.75	0.8	15	15	0.5	0.25
CSFM0A	0.275	1.75	0.8	0	0	0.75	0.25
CSFM10A	0.275	1.75	0.8	5	5	0.75	0.25
CSFM20A	0.275	1.75	0.8	10	10	0.75	0.25
CSFM30A	0.275	1.75	0.8	15	15	0.75	0.25
CTFM0A	0.275	1.75	0.8	0	0	1	0.25
CTFM10A	0.275	1.75	0.8	5	5	1	0.25
CTFM20A	0.275	1.75	0.8	10	10	1	0.25
CTFM30A	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							
MK - Metakaolin							
GF - Glass fiber							
PPF - Polypropylene fiber							

B. Sample preparation, curing, and testing

Samples were prepared by mixing cement, fine aggregate, FA, and MK 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.

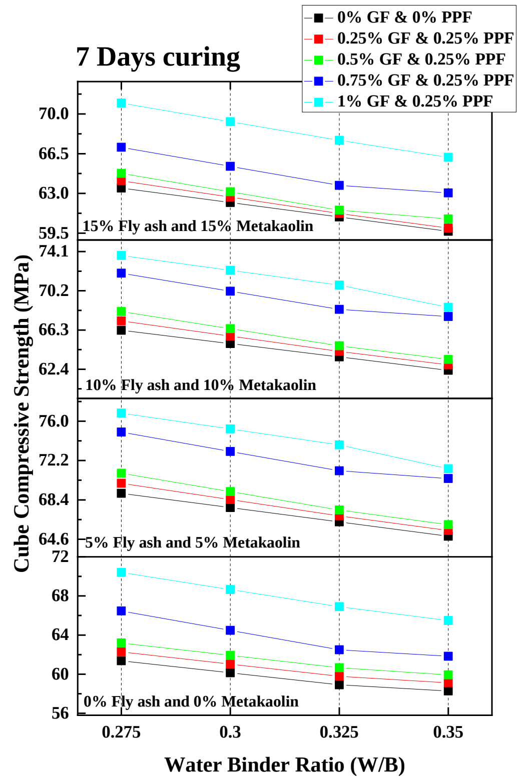

Fig 1. 7 days cube compressive strength versus water binder ratios for various volumes of composite fibers.

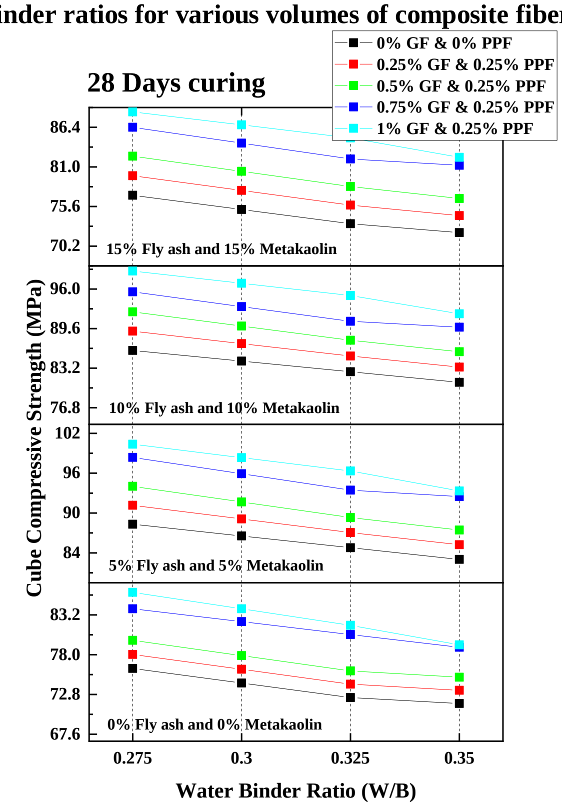

Fig 2. 28 days cube compressive strength versus water binder ratios for various volumes of composite fibers.

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

Mix Designation	Cube Compressive strength		Cylindrical Compressive strength		Mix Designation	Cube Compressive strength		Cylindrical Compressive strength	
	MPa					MPa			
	7	28	7	28		7	28	7	28
	Days					Days			
CPFM0A	61.36	76.20	45.41	56.39	**CPFM0C**	58.91	72.40	43.59	53.58
CPFM10A	69.04	88.31	51.09	65.35	**CPFM10C**	66.27	84.78	49.04	62.74
CPFM20A	66.27	86.06	49.04	63.68	**CPFM20C**	63.62	82.61	47.08	61.13
CPFM30A	63.47	77.13	46.97	56.86	**CPFM30C**	60.93	73.25	45.09	54.21
CQFM0A	62.28	78.04	45.77	57.35	**CQFM0C**	59.78	74.14	43.94	54.49
CQFM10A	70.01	91.17	51.45	66.99	**CQFM10C**	66.85	87.05	49.26	63.97
CQFM20A	67.21	89.19	49.39	65.54	**CQFM20C**	64.18	85.16	47.37	62.58
CQFM30A	64.12	79.79	47.12	58.53	**CQFM30C**	61.23	75.79	45.45	55.70
CRFM0A	63.20	79.88	46.13	58.31	**CRFM0C**	60.66	75.89	44.28	55.40
CRFM10A	70.98	94.02	51.81	68.64	**CRFM10C**	67.43	89.32	49.56	65.21
CRFM20A	68.14	92.32	49.74	67.39	**CRFM20C**	64.73	87.70	47.72	64.02
CRFM30A	64.77	82.46	47.28	60.20	**CRFM30C**	61.53	78.34	45.69	57.19
CSFM0A	66.46	84.00	48.52	61.32	**CSFM0C**	62.49	80.63	45.62	58.86
CSFM10A	74.95	98.37	54.72	71.81	**CSFM10C**	71.21	93.45	51.98	68.22
CSFM20A	71.95	95.55	52.53	69.75	**CSFM20C**	68.36	90.78	49.90	66.27
CSFM30A	67.06	86.40	48.96	63.07	**CSFM30C**	63.71	82.08	46.51	59.92
CTFM0A	70.41	86.14	52.10	63.75	**CTFM0C**	66.90	81.84	49.50	60.56
CTFM10A	76.79	100.35	56.82	74.26	**CTFM10C**	73.72	96.34	54.55	71.29
CTFM20A	73.72	98.92	54.55	73.20	**CTFM20C**	70.77	94.96	52.37	70.27
CTFM30A	70.96	88.50	52.43	65.49	**CTFM30C**	67.67	84.96	50.08	62.87
CPFM0B	60.14	74.30	44.50	54.98	**CPFM0D**	58.28	71.63	43.13	53.00
CPFM10B	67.65	86.55	50.06	64.04	**CPFM10D**	64.89	83.01	48.02	61.43
CPFM20B	64.95	84.34	48.06	62.41	**CPFM20D**	62.30	80.89	46.10	59.86
CPFM30B	62.20	75.19	46.03	55.93	**CPFM30D**	59.66	72.03	44.15	53.90
CQFM0B	61.03	76.09	44.85	55.92	**CQFM0D**	59.11	73.34	43.38	53.90
CQFM10B	68.43	89.11	50.29	65.48	**CQFM10D**	65.45	85.23	48.22	62.63
CQFM20B	65.69	87.17	48.28	64.06	**CQFM20D**	62.83	83.37	46.28	61.27
CQFM30B	62.67	77.79	46.25	57.11	**CQFM30D**	59.95	74.36	44.53	54.94
CRFM0B	61.93	77.88	45.21	56.85	**CRFM0D**	59.93	75.06	43.59	54.79
CRFM10B	69.20	91.67	50.69	66.92	**CRFM10D**	66.01	87.44	48.65	63.83
CRFM20B	66.43	90.01	48.49	65.71	**CRFM20D**	63.37	85.86	46.68	62.68
CRFM30B	63.15	80.40	46.59	58.69	**CRFM30D**	60.75	76.69	44.75	55.98
CSFM0B	64.47	82.32	47.07	60.09	**CSFM0D**	61.83	78.96	45.14	57.64
CSFM10B	73.08	95.91	53.35	70.01	**CSFM10D**	70.46	92.47	51.43	67.50
CSFM20B	70.16	93.16	51.21	68.01	**CSFM20D**	67.64	89.82	49.38	65.57
CSFM30B	65.39	84.24	47.73	61.49	**CSFM30D**	63.04	81.21	46.02	59.29
CTFM0B	68.65	83.99	50.80	62.16	**CTFM0D**	65.48	79.29	48.45	58.67
CTFM10B	75.25	98.34	55.69	72.77	**CTFM10D**	71.41	93.33	52.84	69.06
CTFM20B	72.24	96.94	53.46	71.74	**CTFM20D**	68.55	92.00	50.73	68.08
CTFM30B	69.32	86.73	51.25	64.18	**CTFM30D**	66.18	82.30	49.20	60.90

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			
CPFM0A	3.86	5.29	5.93	8.13	**CPFM0C**	3.61	4.94	5.29	7.25
CPFM10A	4.26	5.83	6.45	8.84	**CPFM10C**	3.81	5.22	5.98	8.19
CPFM20A	4.03	5.52	6.15	8.42	**CPFM20C**	3.73	5.11	5.45	7.47
CPFM30A	3.89	5.33	6.07	8.31	**CPFM30C**	3.65	4.99	5.38	7.37
CQFM0A	3.97	5.52	5.95	8.27	**CQFM0C**	3.73	5.18	5.38	7.47
CQFM10A	4.49	6.24	6.72	9.33	**CQFM10C**	4.05	5.63	6.21	8.63
CQFM20A	4.22	5.86	6.28	8.72	**CQFM20C**	3.81	5.29	5.49	7.63
CQFM30A	4.00	5.56	6.11	8.48	**CQFM30C**	3.77	5.23	5.41	7.52
CRFM0A	4.10	5.77	6.19	8.72	**CRFM0C**	3.85	5.42	5.47	7.71
CRFM10A	4.59	6.47	7.29	10.27	**CRFM10C**	4.20	5.92	6.48	9.12
CRFM20A	4.28	6.03	6.50	9.15	**CRFM20C**	3.98	5.61	5.62	7.91
CRFM30A	4.13	5.81	6.30	8.87	**CRFM30C**	3.89	5.47	5.55	7.81
CSFM0A	4.14	5.91	6.24	8.84	**CSFM0C**	3.97	5.67	5.52	7.88
CSFM10A	4.70	6.71	7.57	10.81	**CSFM10C**	4.33	6.18	6.80	9.72
CSFM20A	4.47	6.38	6.59	9.27	**CSFM20C**	4.17	5.96	5.71	8.07
CSFM30A	4.17	5.96	6.34	8.96	**CSFM30C**	4.01	5.72	5.58	7.97
CTFM0A	4.26	6.09	6.29	8.98	**CTFM0C**	4.12	5.88	5.62	8.03
CTFM10A	4.91	7.02	7.78	11.12	**CTFM10C**	4.51	6.44	7.01	10.02
CTFM20A	4.64	6.63	6.78	9.69	**CTFM20C**	4.32	6.17	5.89	8.42
CTFM30A	4.30	6.14	6.40	9.14	**CTFM30C**	4.16	5.93	5.75	8.22
CPFM0B	3.78	5.18	5.68	7.78	**CPFM0D**	3.20	4.38	4.99	6.84
CPFM10B	4.07	5.57	6.22	8.52	**CPFM10D**	3.62	4.96	5.64	7.73
CPFM20B	3.91	5.36	5.83	7.98	**CPFM20D**	3.42	4.68	5.25	7.19
CPFM30B	3.82	5.22	5.77	7.89	**CPFM30D**	3.23	4.43	5.07	6.94
CQFM0B	3.88	5.39	5.73	7.96	**CQFM0D**	3.36	4.66	5.08	7.06
CQFM10B	4.26	5.92	6.44	8.94	**CQFM10D**	3.90	5.41	5.80	8.06
CQFM20B	4.11	5.71	5.88	8.16	**CQFM20D**	3.56	4.94	5.30	7.36
CQFM30B	3.91	5.43	5.80	8.06	**CQFM30D**	3.39	4.71	5.13	7.13
CRFM0B	4.00	5.64	5.81	8.18	**CRFM0D**	3.59	5.05	5.24	7.38
CRFM10B	4.37	6.15	6.71	9.45	**CRFM10D**	4.07	5.73	5.91	8.33
CRFM20B	4.22	5.95	5.97	8.41	**CRFM20D**	3.88	5.47	5.48	7.72
CRFM30B	4.07	5.68	5.96	8.31	**CRFM30D**	3.62	5.10	5.37	7.56
CSFM0B	4.08	5.83	5.86	8.24	**CSFM0D**	3.73	5.33	5.27	7.53
CSFM10B	4.52	6.46	7.04	10.06	**CSFM10D**	4.23	6.04	6.33	9.04
CSFM20B	4.39	6.27	6.06	8.66	**CSFM20D**	3.96	5.65	5.57	7.84
CSFM30B	4.11	5.87	6.00	8.45	**CSFM30D**	3.76	5.38	5.40	7.69
CTFM0B	4.16	5.94	5.96	8.52	**CTFM0D**	3.86	5.51	5.47	7.81
CTFM10B	4.72	6.74	7.17	10.24	**CTFM10D**	4.33	6.19	6.50	9.28
CTFM20B	4.54	6.49	6.24	8.91	**CTFM20D**	4.05	5.78	5.63	8.04
CTFM30B	4.21	5.98	6.09	8.64	**CTFM30D**	3.89	5.56	5.54	7.92

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 100.35 MPa for CTFM10A. Further, for the same mix, when the water binder ratio was increased to 0.3, its cube compressive strength was reduced by 2% for the CTFM10A mix, and it was further reduced to 4% and 7% for W/B ratios of 0.325 and 0.35, respectively for CTFM10A mix.

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

28 days cube compressive strength versus percentages of FA and MK are plotted in Fig.4. It shows that the 28 days cube compressive strength was enhanced with cement replacement by combined FA and MK. The addition of FA and MK enhances the load-carrying capacity of the mix. At 10% replacement of cement by combined FA and MK, maximum cube compressive strength was obtained for all composite fibers' volumes. Further increase in FA and MK decreased the value of cube compressive strength. The maximum 28 days cube compressive strength percentage increase for CFRHPC was 24.06% by CTFM10A mix over the CPFM0A mix. Hence, the highest cube compressive strengths for all ages were produced by adding 5% FA and 5% MK.

7 days cube compressive strength versus percentages of FA and MK are plotted in Fig.3, which showed a similar trend. Gain in strength until 10% replacement was due to the packing of fine FA and MK particles in the interfacial transition zone (micro filler effect) and pozzolanic reactions by the fine mineral admixtures FA and MK. 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 MK 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 MK.

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

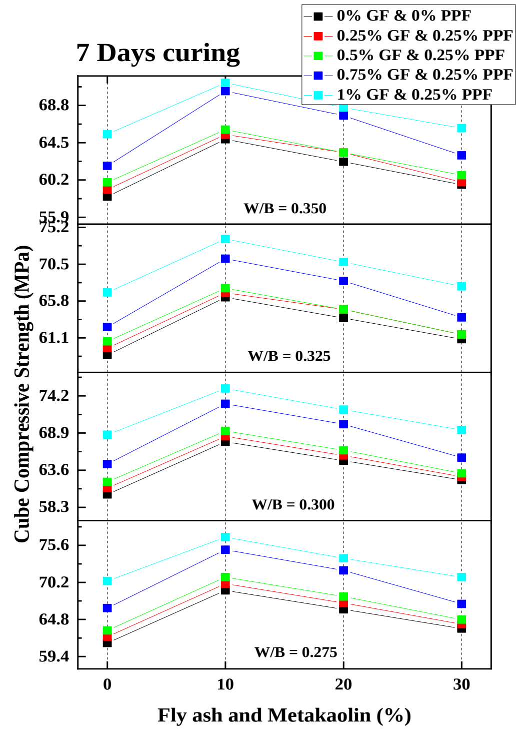

Fig 3. 7 days cube compressive strength versus percentages of FA and MK for various composite fibers' volumes.

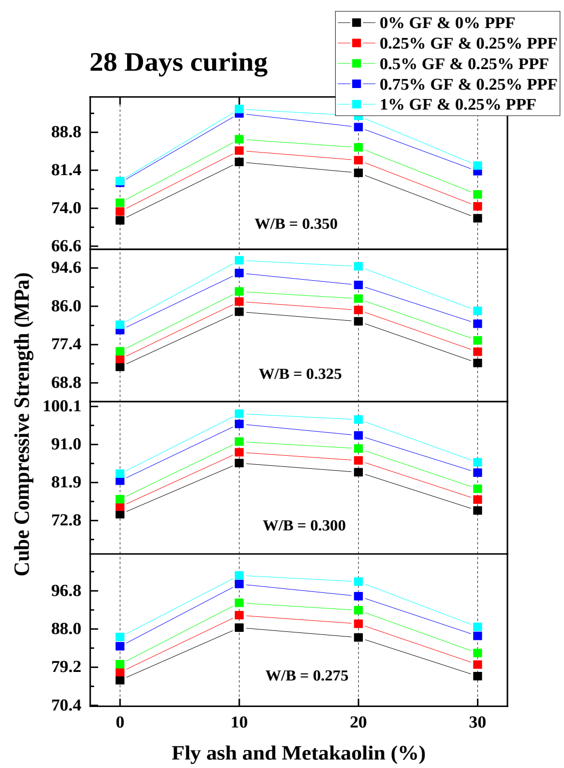

Fig 4. 28 days cube compressive strength versus percentages of FA and MK for various composite fibers' volumes.

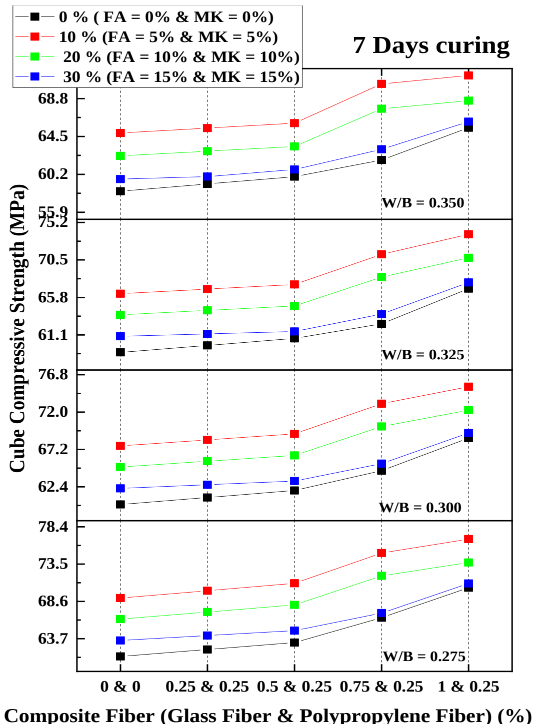

Fig 5. 7 days cube compressive strength versus volume percentages of composite fibers for various FA and MK percentages.

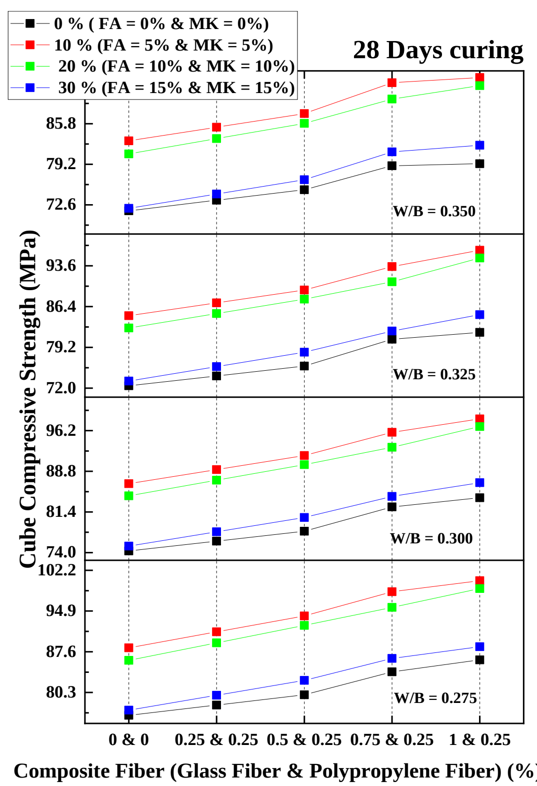

Fig 6. 28 days cube compressive strength versus volume percentages of composite fibers for various FA and MK percentages.

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 MK. 28 days cube compressive strength of CQFM10A, CRFM10A, CSFM10A, and CTFM10A mixes was increased by 16.41%, 18.95%, 22.53%, and 24.06% respectively for CPFM0A mix. This behavior is obtained as these fibers can work as reinforcement at both micro and macro levels. The micro-cracks development is 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 76.79 MPa and 100.35 MPa for the CTFM10A 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 of 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 74.26 MPa for CTFM10A. Further, for the same mix on increasing water binder ratio to 0.3, its cylindrical compressive strength reduced by 2.01% for the CTFM10A mix, and it further reduced to 4.07% and 6.99% for W/B ratios of 0.325 and 0.35 respectively for CTFM10A mix.

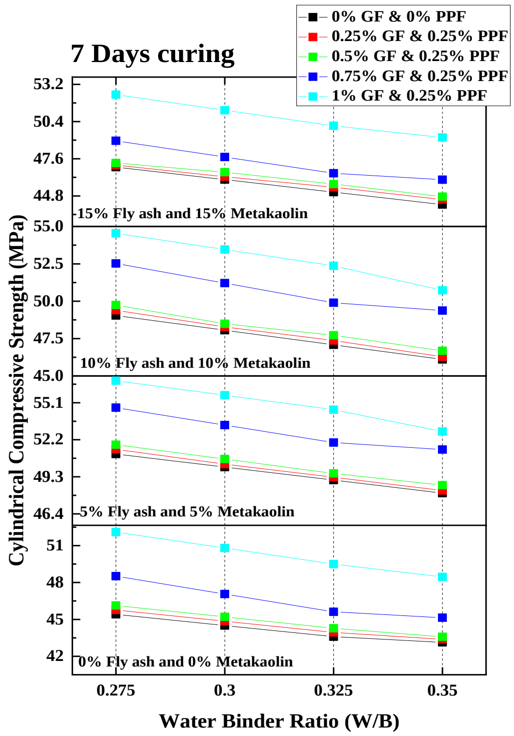

Fig 7. 7 days cylindrical compressive strength versus water binder ratios for various volumes of composite fibers.

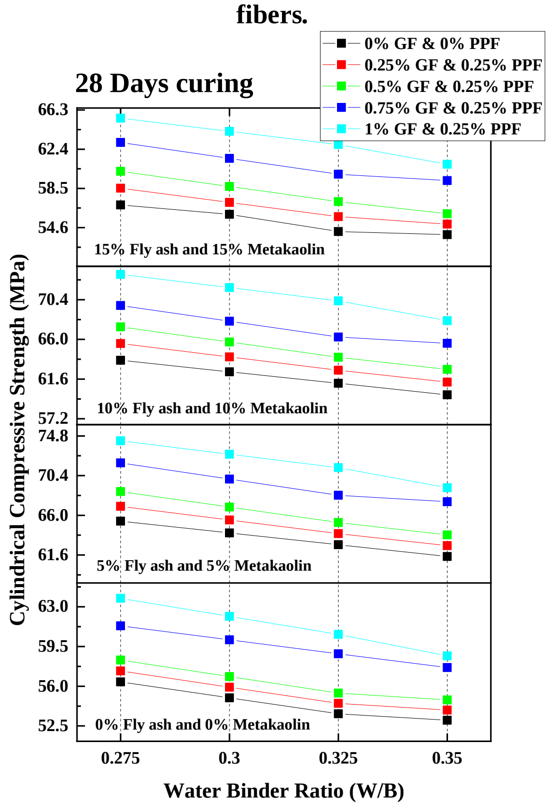

Fig 8. 28 days cylindrical compressive strength versus water binder ratios for various volumes of composite fibers.

b) Effects of cement replacement by fly ash and metakaolin 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 MK for different volumes of composite fibers in Figs. 9 and 10, respectively.

28 days cylindrical compressive strength versus percentages of FA and MK are plotted in Fig.10. It shows that the 28 days cylindrical compressive strength was enhanced with cement replacement by combined FA and MK. The addition of FA and MK boosts the load-carrying ability of the mix. At 10% replacement of cement by combined FA and MK, maximum cylindrical compressive strength was obtained for all composite fibers' volumes. Further increase in FA and MK decreases the value of cylindrical compressive strength. The maximum 28 days cylindrical compressive strength percentage increase for CFRHPC was 24.06% by CTFM10A mix over the CPFM0A mix. 7 days cylindrical compressive strength versus percentages of FA and MK 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% MK. Gain in strength until 10% replacement was due to the packing of fine FA and MK particles in the interfacial transition zone (micro filler effect) and pozzolanic reactions by the fine mineral admixtures FA and MK. 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 MK 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 MK.

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 MK. 28 days cylindrical compressive strength of CQFM10A, CRFM10A, CSFM10A, and CTFM10A mixes increased by 15.83%, 17.84%, 21.47%, and 24.06% respectively for CPFM0A plain mix. This behavior was observed as the capacity of the matrix's energy absorption was increased by fibers that regulate cracks.

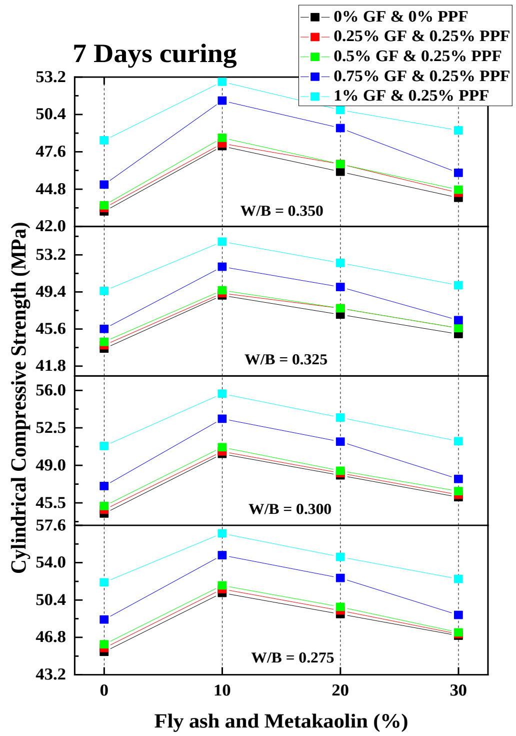

Fig 9. 7 days cylindrical compressive strength versus percentages of FA and MK for various composite fibers' volumes.

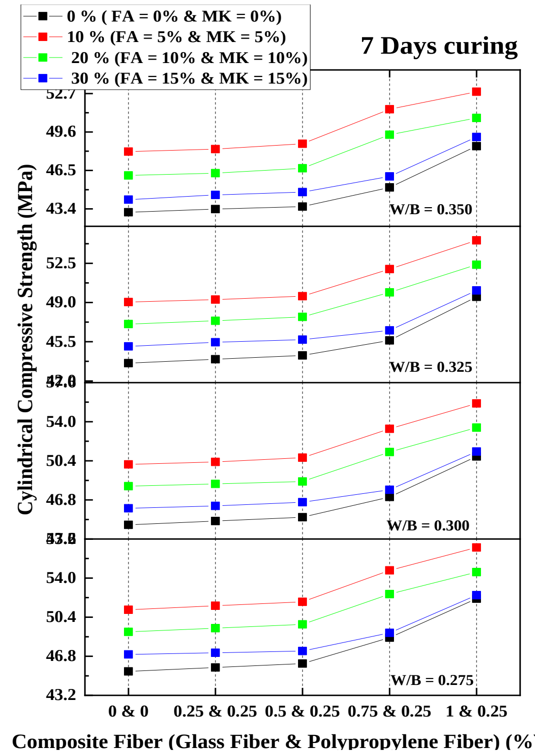

Fig 11. 7 days cylindrical compressive strength versus volume percentages of composite fibers for various FA and MK percentages.

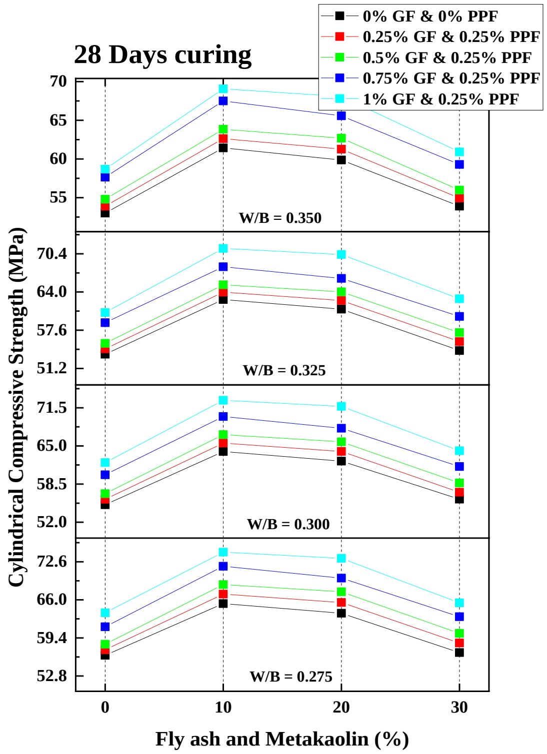

Fig 10. 28 days cylindrical compressive strength versus percentages of FA and MK for various composite fibers' volumes.

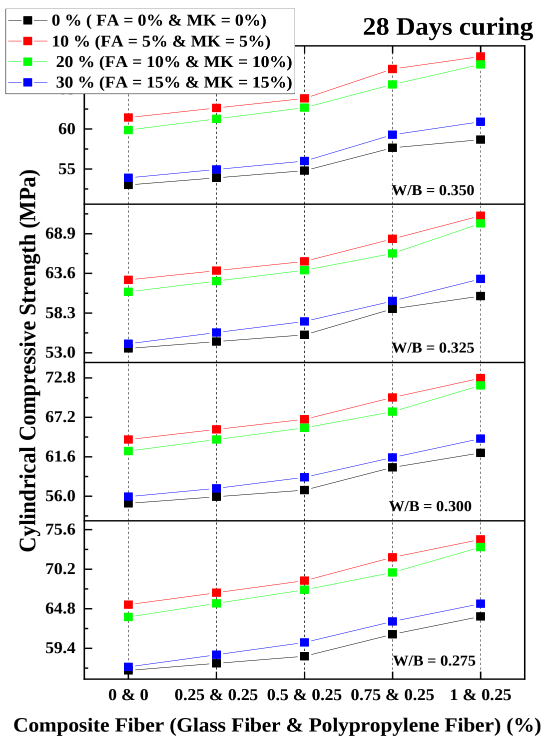

Fig 12. 28 days cylindrical compressive strength versus volume percentages of composite fibers for various FA and MK percentages.

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 56.82 MPa and 74.26 MPa for the CTFM10A 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 7.02 MPa for CTFM10A. Further, for the same mix, when the water binder ratio was increased to 0.3, its split tensile strength was reduced by 3.99% for the CTFM10A mix, and it further reduced to 8.26% and 11.82% for W/B ratios of 0.325 and 0.35 respectively for CTFM10A mix.

b) Effects of cement replacement by fly ash and metakaolin 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 MK for different volumes of composite fibers in Figs. 15 and 16, respectively.

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

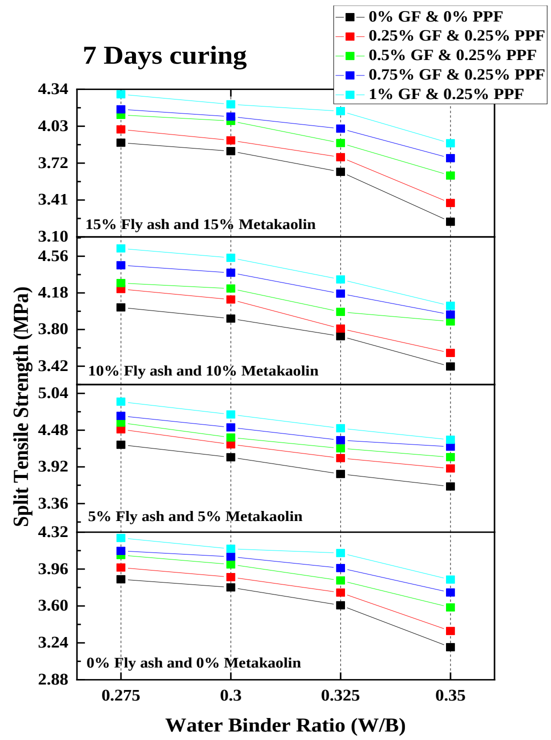

Fig 13. 7 days split tensile strength versus water binder ratios for various volumes of composite fibers.

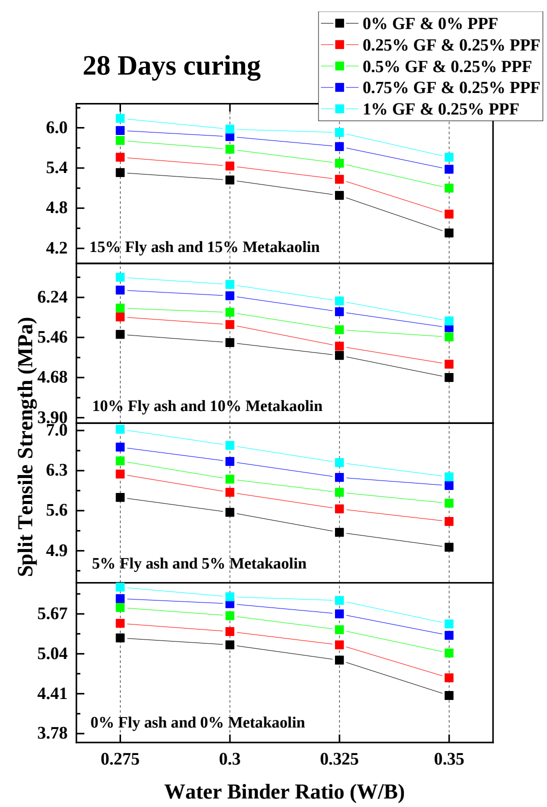

Fig 14. 28 days split tensile strength versus water binder ratios for various volumes of composite fibers.

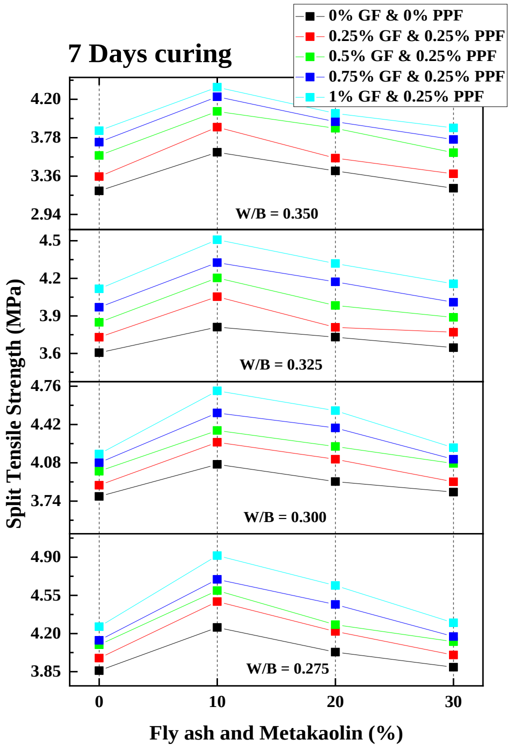

Fig 15. 7 days split tensile strength versus percentages of FA and MK for various composite fibers' volumes.

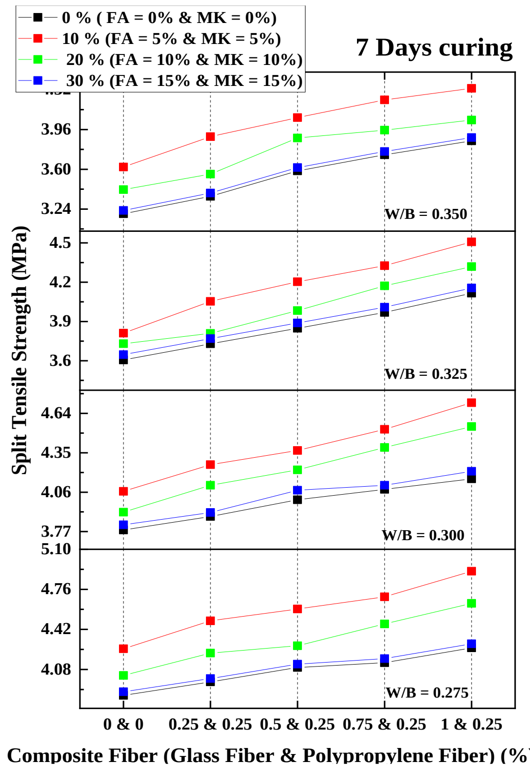

Fig 17. 7 days split tensile strength versus volume percentages of composite fibers for various FA and MK percentages.

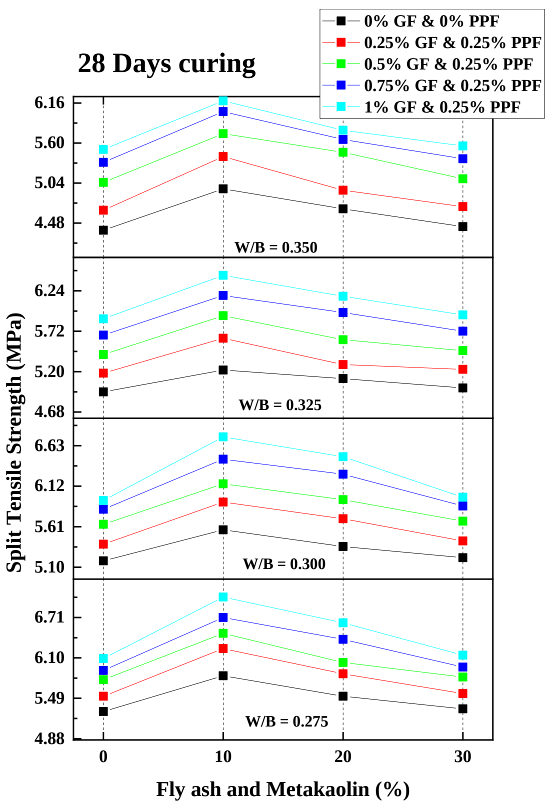

Fig 16. 28 days split tensile strength versus percentages of FA and MK for various volumes of composite fibers.

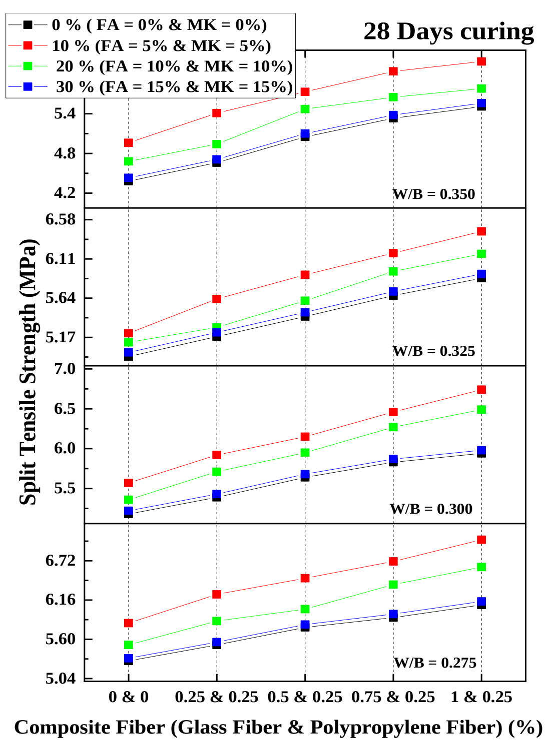

Fig 18. 28 days split tensile strength versus volume percentages of composite fibers for various FA and MK percentages.

At 10% replacement of cement by combined FA and MK, maximum split tensile strength was obtained for all volumes of composite fibers as combined pozzolanic activity, and the addition of FA and MK enhanced micro filler effects. Further increase in FA and MK 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 24.60% for the CTFM10A mix over the CPFM0A mix. Hence, the highest split tensile strengths for all ages were produced by adding 5% FA and 5% MK.

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 MK.

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 MK percentages. Split tensile strength of CQFM10A, CRFM10A, CSFM10A, and CTFM10A mixes were increased by 15.22%, 18.24%, 21.16%, and 24.64%, respectively, for the CPFM0A 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 4.91 MPa and 7.02 MPa, respectively, for the CTFM10A 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.

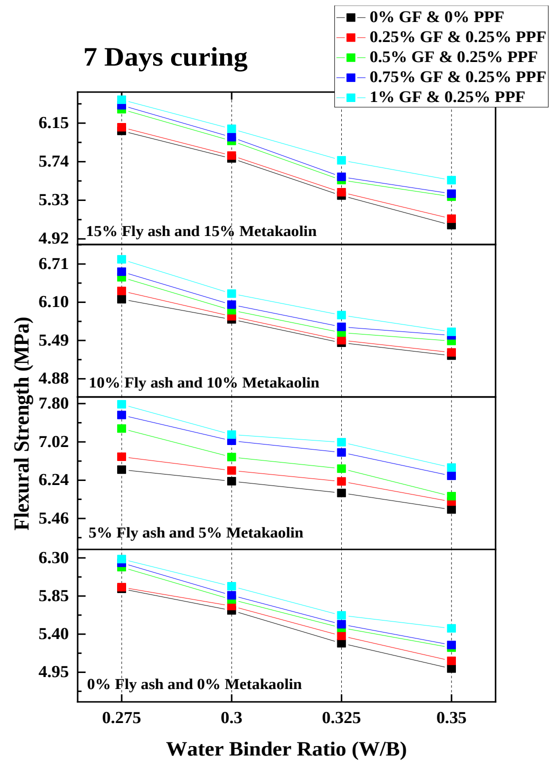

Fig 19. 7 days split tensile strength versus water binder ratios for various volumes of composite fibers.

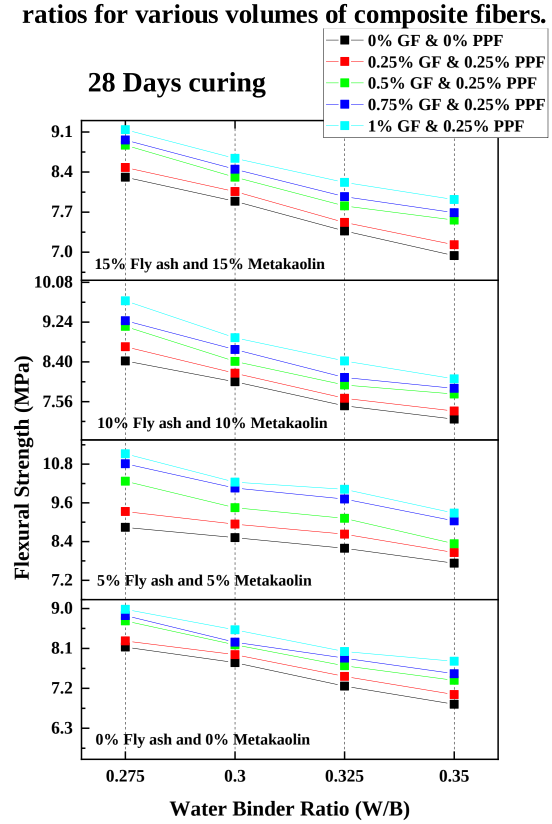

Fig 20. 28 days split tensile strength versus water binder ratios for various volumes of composite fibers.

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 11.12 MPa for the CTFM10A mix. Further, for the same mix, when the water binder ratio was increased to 0.3, its compressive strength was reduced by 7.91% for the CTFM10A mix, and it was further reduced to 9.89% and 16.55% for W/B ratios of 0.325 and 0.35, respectively for CTFM10A mix.

b) Effects of cement replacement by fly ash and metakaolin on flexural strength of CFRHPC: Flexural strengths for both ages of testing are plotted versus the percentages of FA and MK 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 MK are plotted in Fig.22. It shows that the flexural strength at 28 days was also enhanced with cement replacement by combined FA and MK. The combined effect of FA and MK boosts the load-carrying ability of the mix. FA and MK 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 MK 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 26.89% by CTFM10A mix over the CPFM0A mix. Hence, the highest flexural strengths for all ages were produced by adding 5% FA and 5% MK.

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 MK.

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 MK. 28 days flexural strength of CQFM10A, CRFM10A, CSFM10A, and CTFM10A mixes

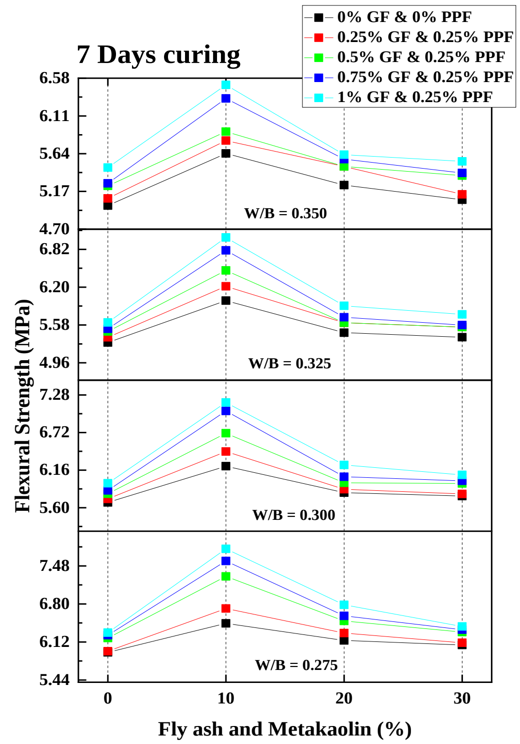

Fig 21. 7 days flexural strength versus percentages of FA and MK for various composite fibers volumes.

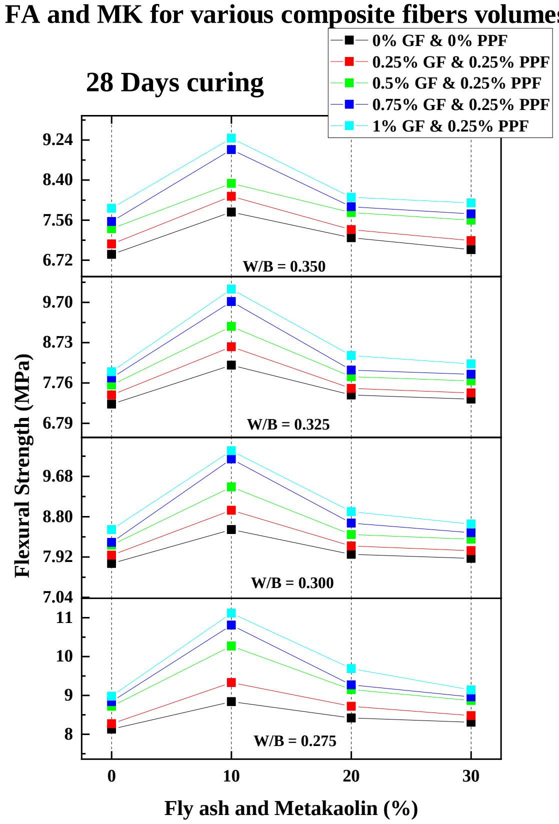

Fig 22. 28 days flexural strength versus percentages of FA and MK for various composite fibers' volumes.

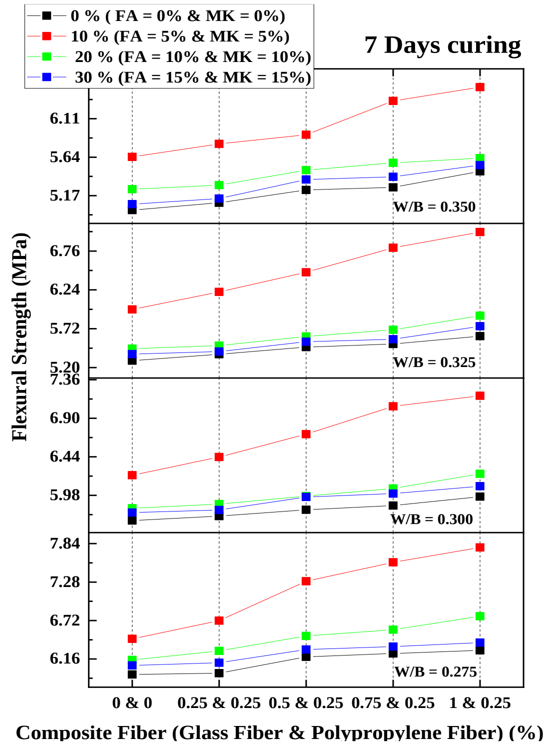

Fig 23. 7 days flexural strength versus volume percentages of composite fibers for various FA and MK percentages.

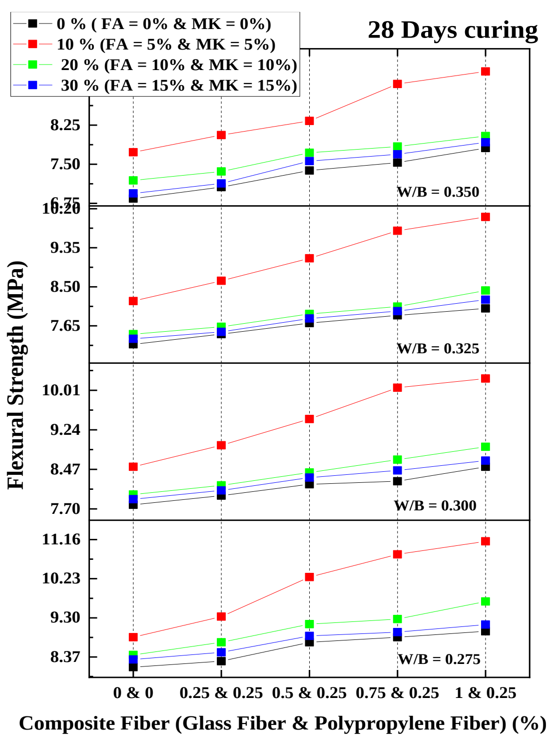

Fig 24. 28 days flexural strength versus volume percentages of composite fibers for various FA and MK percentages.

increased by 12.86%, 20.84%, 24.79%, and 26.89%, respectively, for CPFM0A 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 7.78 MPa and 11.12 MPa for the CTFM10A mix.

E. Inter-Relationships between various properties of fly ash and metakaolin 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 MK-based CFRHPC. From the experimental investigation results on various FA and MK-based CFRHPC mixes, inter-relationships between the different properties such as cube compressive strength, cylindrical compressive strength, split tensile strength, and flexural strength was derived. The inter-relationships will be valuable to estimate the cylindrical compressive strength, tensile strength, and flexural strength of any FA and MK-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 MK-based CFRHPC mixes is presented in Fig 25.

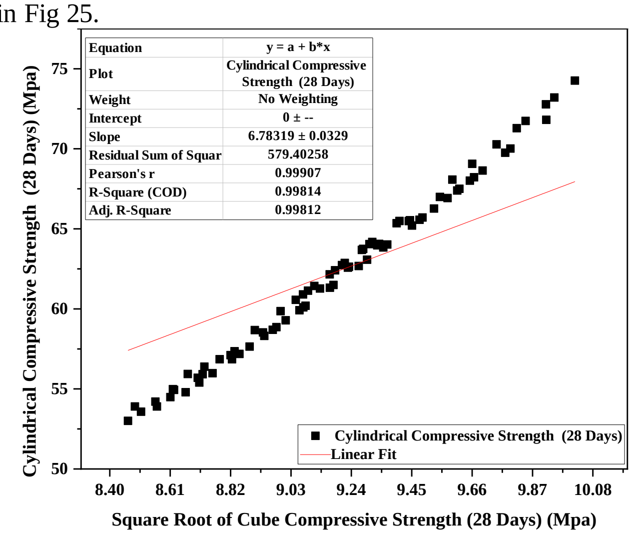

Fig 25. The square root of 28 days cubes compressive strength versus 28 days cylindrical compressive strength of FA and MK based CFRHPC.

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 MK-based CFRHPC mixes, and shown below.

$$f_{ccs} = 6.783\sqrt{f_{ck}}$$

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 MK-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 MK-based CFRHPC mixes is presented in Figure 26.

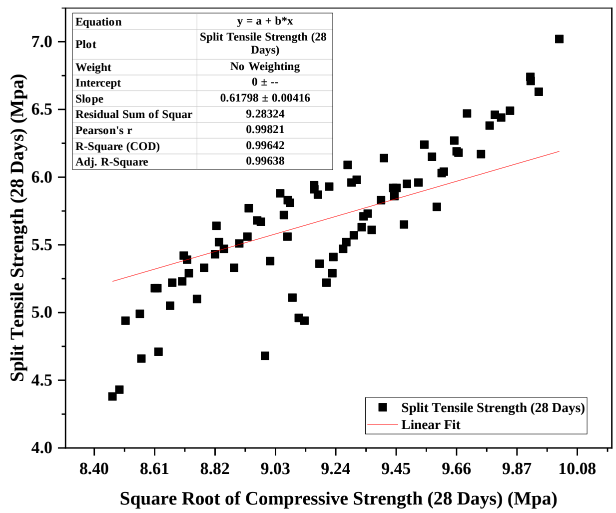

Fig 26. The square root of 28 days cube compressive strength versus 28 days split tensile strength of FA and MK based CFRHPC.

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 MK-based CFRHPC mixes and is shown below.

$$f_{sts} = 0.617\sqrt{f_{ck}}$$

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 MK-based CFRHPC mixes.

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

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

$$f_{fs} = 0.913\sqrt{f_{ck}}$$

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

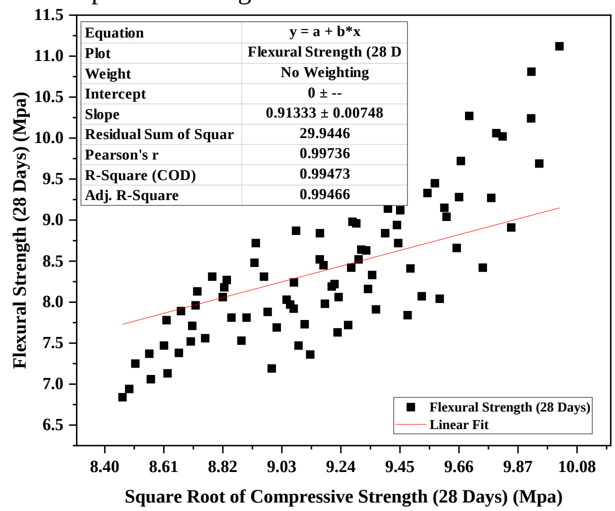

Fig 27. The square root of 28 days cubes compressive strength versus 28 days flexural strength of FA and MK based CFRHPC.

V. CONCLUSIONS

In this experimental work, the performance of CFRHPC produced with FM, MK, 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 MK 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, the flexural strength of FA, and MK-based CFRHPC mixes.

- Hence, it can be concluded that the combined effect of FA and MK 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 MK and composite fibers (GF and PFF) in CFRHPC production, minimizing enormous cement production and safeguards the environment from pollution.

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