

Chloride Penetration Resistance and Behaviour Under Acid Attack of Metakaolin and Silica Fume Based Composite Fiber (Glass and Polypropylene) Reinforced High Performance Concrete

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Abstract - This investigation evaluates the effect of cement being partially replaced by combined metakaolin and silica fume with glass fibers and polypropylene fibers as an addition to producing high-performance concrete with composite fiber for resistance to hydrochloric acid, magnesium sulfate, sulphuric acid, and chloride penetration for 30, 60 and 90 days. The water to binder ratios (W/B) of 0.275, 0.300, 0.325, and 0.350 and an aggregate to binder ratio (A/B) of 1.75 were adopted. Metakaolin and silica fume were replaced in the range from 0% to 15% each, glass fibers were added in volume percentages from 0% to 1%, and polypropylene fibers were kept constant at 0.25%. The combined effect of metakaolin and silica fume at 5% each as replacement of cement and the addition of composite fiber dosage of glass fiber=1% and polypropylene fibers =0.25% for W/B of 0.275 was found to be the optimum combination to obtain maximum acid attack and Chloride Penetration resistance.

Keywords: Composite fibers, Metakaolin, Silica fume, Rapid chloride permeability, Acid attack, Durability.

I. INTRODUCTION

Concrete is being used extensively all over the world due to its adaptable strength and durability. Durable concrete structures need to be produced as these structures are subjected to severe environments but are anticipated to last with hardly any maintenance for longer periods. Chloride ingress is the major issue for reinforced concrete bridges, which leads to corrosion of steel-reinforced, resulting in deterioration of strength and the need for premature repair or demolition of the structure. To overcome this issue, a relatively impenetrable concrete needs to be produced, which stops chlorides from reaching the reinforced steel. To produce such impenetrable concrete, the penetration ability of chloride ions must then be identified in view of design and quality. The penetration process of chloride ions into the concrete is very slow, which cannot be determined in a

constrained period. Thus, a method of testing that fastens the process of assessing chloride penetration in a reasonable time is needed. In this viewpoint, ASTM standardized the Rapid Chloride Permeability Test (RCPT) over 16 years ago, which is being used for assessing the quality of concrete [1]. Sulfates are also the most detrimental aggressive chemicals found in seawaters, effluents of industries, and even in groundwater as hydrated cement paste reacts with harmful calcium, sodium, magnesium, and ammonium sulfates leading to cracking and swelling, which leads to spalling with ultimately loss of concrete strength [2]. Glass fibers (GF) and Polypropylene fibers (PPF) are among the most multipurpose engineering materials acknowledged today all over the world, which are manufactured from raw materials, which are accessible in almost infinite supply. These fibers inherit properties such as hardness, transparency, chemical attack resistance, stability, and inertness, which provide strength, flexibility, and stiffness to concrete structures. [3]-[5] When both fibers are used in HPC, Composite Fibre Reinforced High-Performance Concrete (CFRHPC) is developed.

The supplementary cementing material being used recently to produce high-performance concrete (HPC) is High reactivity Metakaolin (HRM). HRM is produced by driving off the water inside of the kaolin by treating kaolin clay of high purity by controlled thermal activation so that its structure collapses, which results in amorphous aluminosilicate i.e. Metakaolin (MK) [6]. Researchers have reported that MK when used as a replacement of cement partially, will yield enhanced permeability and chemical resistance in concrete as MK combines with calcium hydroxide chemically to form additional products of cement [7]-[10]. K.Torii et al. reported that there was a strong reduction in permeability of chloride ion 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[11]. S.



Barbhuiya et al. reported that the use of SF transformed concrete to resist water penetration and, in turn, enhancing chloride ion penetration resistance of concrete [12]. The widespread application of MK and SF in the construction industry is the result of extensive investigations on the use of MK and SF in concrete in the past twenty years[13]-[18]. Present authors also have investigated the effect of MK and SF-based composite fiber-reinforced HPC on strength properties and concluded the viability of using MK, SF, and Composite fibers in CFRHPC production for enhanced strength properties [19]. Shannag and Shaia [20] studied the deterioration and the relative sulphate resistance of HPC in severe sulphate environments and suggested the use of silica fume (SF) by partially replacing natural pozzolana for enhanced performance. National standards of various countries are established, that determine only the degree of attack based on the concentration of hostile substances [21]–[27].

The chemical resistance of HPC produced using SF and MK as a cement replacement, with the addition of GF and PPF with superplasticizers are issues that are yet to receive sufficient exploration from the research community as very limited studies are carried out to uphold their effectiveness in the context of durability. Hence, there is a shortfall of research material available. Besides, Indian Standard Codes do not specify the tests to be executed for assessing the durability of HPC. This Investigation presents the outcomes of experimental exploration performed to understand the behavior of MK and SF-based composite fiber-reinforced HPC under acid and chloride attack.

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, which were from a stone quarry available locally with 40% of 12.5 mm and 60% of 20 mm size. **Metakaolin** used was of pink colour having a specific gravity of 2.60 with a specific surface area of 12.7 m²/g and had SiO₂ and Al₂O₃ at 52.4% and 43.18% 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 m²/g and had SiO₂ as a major 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, which allows full dispersion of GF 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** free from organic and acid substances was used for concrete mixing. A chloride-free **Superplasticizer (SP)** of Fosroc make with a specific gravity of 1.18 was used. The acids used in the investigation were **Hydrochloric acid (HCl)**,

Magnesium sulfate (MgSO₄), and **Sulfuric acid (H₂SO₄)** in the form of 5% concentration solutions.

III. EXPERIMENTAL PROCEDURE

A. Mix proportions

To study the behaviour of CFRHPC, 19 mixes along with one HPC mix without any mineral admixtures and composite fibers were prepared for each water binder ratio.

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

Mix Designation	W/B	A/B	SP	MK	SF	GF	PPF
			(%)				
CPMS0A	0.275	1.75	0.8	0	0	0	0
CPMS10A	0.275	1.75	0.8	5	5	0	0
CPMS20A	0.275	1.75	0.8	10	10	0	0
CPMS30A	0.275	1.75	0.8	15	15	0	0
CQMS0A	0.275	1.75	0.8	0	0	0.25	0.25
CQMS10A	0.275	1.75	0.8	5	5	0.25	0.25
CQMS20A	0.275	1.75	0.8	10	10	0.25	0.25
CQMS30A	0.275	1.75	0.8	15	15	0.25	0.25
CRMS0A	0.275	1.75	0.8	0	0	0.5	0.25
CRMS10A	0.275	1.75	0.8	5	5	0.5	0.25
CRMS20A	0.275	1.75	0.8	10	10	0.5	0.25
CRMS30A	0.275	1.75	0.8	15	15	0.5	0.25
CSMS0A	0.275	1.75	0.8	0	0	0.75	0.25
CSMS10A	0.275	1.75	0.8	5	5	0.75	0.25
CSMS20A	0.275	1.75	0.8	10	10	0.75	0.25
CSMS30A	0.275	1.75	0.8	15	15	0.75	0.25
CTMS0A	0.275	1.75	0.8	0	0	1	0.25
CTMS10A	0.275	1.75	0.8	5	5	1	0.25
CTMS20A	0.275	1.75	0.8	10	10	1	0.25
CTMS30A	0.275	1.75	0.8	15	15	1	0.25
W/B - Water Binder ratio							
A/B - Aggregate Binder ratio							
SP - Superplasticizer							
MK - Metakaolin							
SF - Silica fume							
GF - Glass fiber							
PPF - Polypropylene fiber							

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. MK 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 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. M indicates MK, and S indicates SF. The following number indicates the total percentage of cement replaced by MK and SF. Last alphabet indicates water binder ratios, i.e. A=0.275, B=0.300, C=0.325 and D=0.350. CPMS0A 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/m³. For the CTMS10A mix, the cement of 719.27 kg/m³ was used, and the quantity of MK and SF used was 39.96 kg/m³ 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.

B. Sample preparation, curing, and testing

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

a) Acid attack: 80 mixes were prepared, and for each mix, 30 cubes, specimens of 100mm were cast for each water binder ratio.

As initial curing, a wet cloth was used for covering the exposed portion of all 30 specimens before demoulding. After the concrete was set, specimens were demoulded, and out of 30 cube specimens cast for each mix, 3 cubes were cured in a clear water tank at 27° ± 2°C until 28 days testing age. And out of the remaining 27 cubes, 9 cubes each were immersed in 5% concentration solutions of HCl, MgSO₄, and H₂SO₄. Out of 9 cubes immersed in acids, 3 cubes each were immersed for 30, 60, and 90 days.

After the curing period for the specified testing age, all 30 samples were removed out of the water and acids and were dried under the shade. Among these mentioned 28 days, compressive strength was tested for 3 water cured cubes on the 3000 kN digital compression testing machine by applying a constant rate of loading up to the failure of the specimens. And out of the remaining 27 acids immersed cubes, 3 cubes each was tested at 30, 60, and 90 days for residual compressive strength for each type of acid immersion.

b) Chloride penetration resistance: 80 mixes were prepared with 9 specimens for each mix. Cylindrical specimens of 100mm diameter and 50mm height were cast. All the specimens were tested at ages 30, 60, and 90 days.

After the curing period for the specified testing age, samples were removed out of the water, were dried under the shade, and were then vacuum-saturated as per ASTM C1202. 50mm thick specimen was placed between two acrylic cells

as shown in Fig 1. 3.0 % NaCl solution was filled inside the Cell in contact with the surface of the specimen, which was exposed while preparing and was connected to the negative terminal of the power supply.

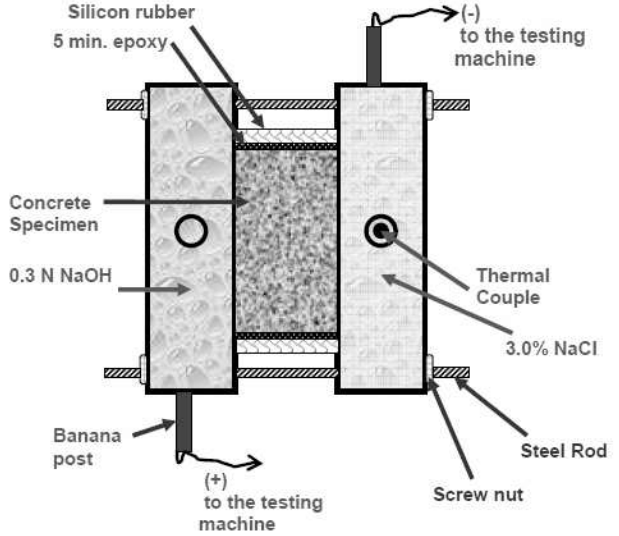


Fig 1. RCPT test setup.

0.3 N NaOH solution was filled in the other side of the cell and was connected to the positive terminal of the power supply. The cells were connected to a 60V power source, and the current was recorded at an interval of 30 minutes for 6 hours[28]. The total charge passed was measured using Eq 1, which is the electrical conductance of the concrete during the period of the test.

$$Q = 900 (I_0 + 2I_{30} + 2I_{60} + \dots + 2I_{300} + 2I_{330} + I_{360}) \quad (1)$$

where:

Q = charge passed (coulombs),

I₀ = current (amperes) immediately after the voltage is applied, and

I_t = current (amperes) at t min after the voltage is applied.

Each result was the average of the specimens tested at the same time for the same mix. Table 2 was used to evaluate the test results as per ASTM standards.

Table 2: Chloride ion penetrability based on charge passed (ASTM-C1202)

Charge Passed (coulombs)	Chloride Ion Penetrability
>4,000	High
2,000–4,000	Moderate
1,000–2,000	Low
100–1,000	Very Low
<100	Negligible

IV. RESULTS AND DISCUSSION

RCPT values obtained for CFRHPC mixes are presented in Table 3, and Residual compressive strengths of various metakaolin and silica fume-based CFRHPC are presented in Tables 4, 5, and 6.

Table 3: RCPT results of CFRHPC mixes

Mix Designation	Charge Passed			Mix Designation	Charge Passed		
	Coulombs				Coulombs		
	30	60	90		30	60	90
	Days				Days		
CPMS0A	1590	1331	1198	CPMS0C	1661	1392	1253
CPMS10A	906	868	781	CPMS10C	1018	916	824
CPMS20A	785	741	667	CPMS20C	876	761	683
CPMS30A	712	645	578	CPMS30C	740	674	605
CQMS0A	1450	1213	1093	CQMS0C	1505	1261	1134
CQMS10A	770	737	664	CQMS10C	861	776	699
CQMS20A	697	661	596	CQMS20C	766	673	604
CQMS30A	649	596	536	CQMS30C	659	616	554
CRMS0A	1295	1084	976	CRMS0C	1343	1125	1013
CRMS10A	675	647	582	CRMS10C	755	680	612
CRMS20A	622	589	530	CRMS20C	681	596	535
CRMS30A	583	531	477	CRMS30C	579	547	493
CSMS0A	1156	967	871	CSMS0C	1197	1003	903
CSMS10A	606	579	522	CSMS10C	676	610	548
CSMS20A	558	526	474	CSMS20C	607	531	475
CSMS30A	522	472	425	CSMS30C	508	486	437
CTMS0A	1081	905	814	CTMS0C	1119	937	844
CTMS10A	571	547	492	CTMS10C	638	575	517
CTMS20A	526	497	447	CTMS20C	572	499	447
CTMS30A	491	445	399	CTMS30C	474	456	410
CPMS0B	1626	1361	1225	CPMS0D	1825	1542	1388
CPMS10B	962	892	802	CPMS10D	1121	1022	920
CPMS20B	830	751	674	CPMS20D	977	835	751
CPMS30B	727	660	592	CPMS30D	807	718	644
CQMS0B	1478	1237	1113	CQMS0D	1631	1376	1238
CQMS10B	816	757	682	CQMS10D	945	862	777
CQMS20B	731	668	600	CQMS20D	846	726	654
CQMS30B	655	607	546	CQMS30D	707	641	576
CRMS0B	1319	1104	994	CRMS0D	1453	1226	1103
CRMS10B	715	664	597	CRMS10D	828	756	680
CRMS20B	651	594	533	CRMS20D	752	640	575
CRMS30B	582	541	487	CRMS30D	616	561	504
CSMS0B	1177	985	886	CSMS0D	1293	1091	982
CSMS10B	641	595	536	CSMS10D	741	676	609
CSMS20B	582	530	476	CSMS20D	670	565	508
CSMS30B	516	481	434	CSMS30D	537	490	441
CTMS0B	1100	921	829	CTMS0D	1208	1018	916
CTMS10B	605	561	505	CTMS10D	698	638	575
CTMS20B	549	499	448	CTMS20D	630	530	477
CTMS30B	484	452	407	CTMS30D	498	457	411

A. Effects of cement replacement by metakaolin and silica fume on chloride penetration resistance and residual compressive strength of CFRHPC

a) **Chloride penetration resistance:** To understand the chloride penetration resistance for each mix, chloride penetrability for all ages of testing for W/B of 0.275 is plotted against the percentages of MK and SF for different

volumes of composite fibers in Figs. 2, 3, and 4, respectively. Values presented in Table 3 represent the RCPT results for 30, 60, and 90 days.

It can be observed that the replacement of cement with metakaolin and silica fume dosages decreased the chloride ion penetration and was true for all other mixes with varying mineral admixtures. Chloride penetrability of plain mix CPMS0A showed that the RCPT value of 1590 C and falls under the category of low penetrability as per ASTM C1202. Further, with increasing the combined dosages of metakaolin and silica fume from 0% to 10%, the RCPT value decreased by an average of 58.29% of all mixes concerning mix CPMS0A. On further increasing the combined dosage to 20%, RCPT value decreased by average 62.62% and by 66.20% average on further increasing combined admixture dosages to 30% compared to the CPMS0A mix. It can be observed from Figs 2, 3, and 4 that on the addition of combined mineral admixtures, all the mixes were falling under a very low penetrability category as per ASTM C1202. The maximum chloride resistance was obtained for mix CTMS30A with a combined 30% mineral admixture dosage with a chloride resistance increase of 69.09% compared to plain CPMS0A mix, but the mixes with combined 10% cement replacement with metakaolin and silica fume are treated as optimum dosage as there was a considerable amount of increase in chloride resistance when cement was replaced by combined 10% admixtures compared to 20% and 30% cement replacement. This behavior was observed since both metakaolin and silica fume enhance the distribution of pore size and pore shape of concrete.

b) **Acid attack:** The deterioration in compressive strength after 30, 60, and 90 days of acid immersion for W/B of 0.275 with varying percentages of MK and SF are presented in Figs. 5, 6, and 7, respectively.

It can be witnessed from these figures that the depreciation of compressive strength decreased with cement being replaced by combined MK and SF percentages from 0 to 10. The addition of MK and SF enhanced the load-carrying capacity of the mix as both MK and SF improved the pore size distribution as well as the pore shape of concrete. Further increase in the percentage of mineral admixtures, i.e., 20 and 30, decreased the residual compressive strength but not less than the plain CPMS0A mix and was true for all mixes of CFRHPC designed in this analysis. Maximum residual compressive strength was obtained for 10% cement replacement for all ages of

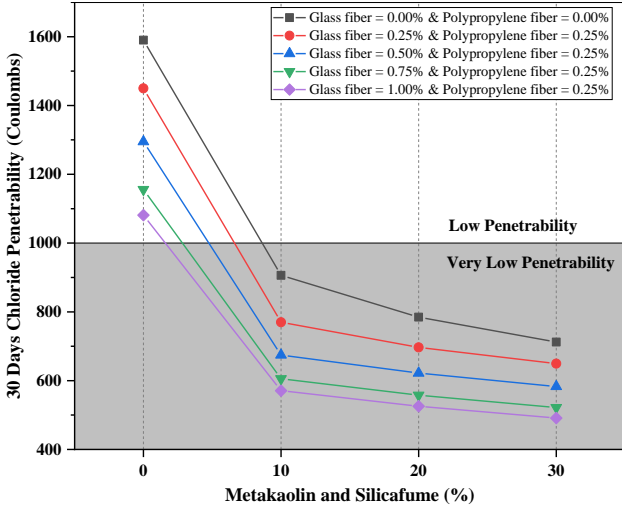


Fig 2. 30 days chloride penetrability versus percentages of MK and SF for various volumes of composite fibers.

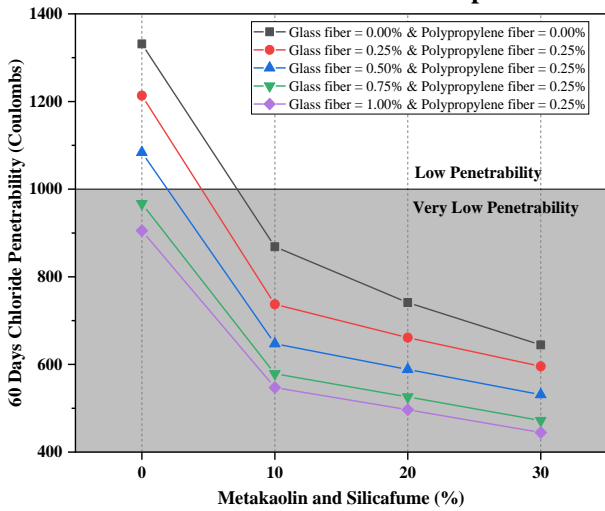


Fig 3. 60 days chloride penetrability versus percentages of MK and SF for various volumes of composite fibers.

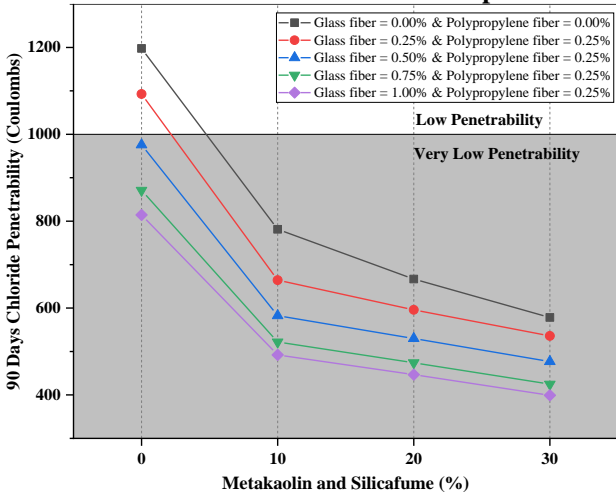


Fig 4. 90 days chloride penetrability versus percentages of MK and SF for various volumes of composite fibers.

Curing and type of acid immersions. From these figures, it was also evident that as the age of acid immersion was increased, residual compressive strength decreased and was true for all CFRHPC mixes. The maximum residual compressive strengths obtained for the CTMS10A mix were 97.57 MPa, 93.89 MPa, and 88.77 MPa for 30, 60, and 90 days HCl immersion. Similarly, 96.44 MPa, 92.61 MPa, and 88.30 MPa for 30, 60, and 90 days $MgSO_4$ immersion and 94.25 MPa, 89.90 MPa, and 84.84 MPa for 30, 60, and 90 days H_2SO_4 immersion. Compressive strength of CFRHPC mix CTMS10A attacked by HCl reduced by 5.6%, 9.16%, and 14.12% for 30, 60, and 90 days compared to the same water cured mix at 28 days. Similarly, $MgSO_4$ reduced compressive strength by 6.7%, 10.4%, and 14.58%, and H_2SO_4 by 7.10%, 11.07%, and 16.39% for 30, 60, and 90 days compared to the same water cured mix at 28 days. Residual compressive strength decreased with the age of acid immersion, with a maximum depreciation in compressive strength witnessed at 90 days of all three acid curings due to an increase in the formation of ettringites with the age of acid immersion.

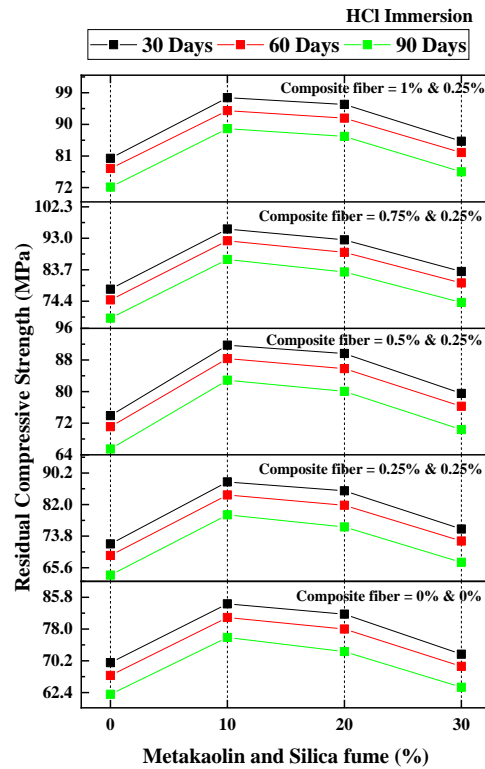


Fig 5. Residual compressive strength versus percentages of MK and SF for various CFRHPC mixes immersed in HCl.

Table 4: Water cured compressive strength at 28 days, and HCl immersed residual compressive strength results.

Mix Designation	Compressive strength	Residual Compressive Strength			Mix Designation	Compressive strength	Residual Compressive Strength		
	MPa	MPa				MPa	MPa		
	28	30	60	90		28	30	60	90
	Days					Days			
CPMS0A	76.2	69.74	66.59	61.98	CPMS0C	72.4	66.03	62.95	58.17
CPMS10A	90.52	84.17	80.82	75.92	CPMS10C	87.75	81.4	78.06	72.9
CPMS20A	88.21	81.65	78	72.46	CPMS20C	85.51	78.96	75.32	69.52
CPMS30A	78.21	71.81	68.83	63.69	CPMS30C	75.81	69.43	66.45	61.09
CQMS0A	78.04	71.76	68.78	63.66	CQMS0C	74.14	67.92	65.04	59.91
CQMS10A	94.15	87.88	84.5	79.33	CQMS10C	90.32	84.09	80.78	75.53
CQMS20A	92.11	85.57	81.82	76.18	CQMS20C	88.36	81.86	78.19	72.48
CQMS30A	81.99	75.64	72.53	67	CQMS30C	78.64	72.33	69.29	63.74
CRMS0A	79.88	73.9	71.09	65.45	CRMS0C	75.89	69.92	67.25	61.76
CRMS10A	97.79	91.73	88.34	82.88	CRMS10C	92.9	86.9	83.64	78.3
CRMS20A	96.01	89.63	85.79	80.05	CRMS20C	91.21	84.89	81.19	75.59
CRMS30A	85.76	79.51	76.28	70.36	CRMS30C	81.47	75.27	72.18	66.43
CSMS0A	84	77.98	74.8	69.41	CSMS0C	80.63	74.47	71.38	66.19
CSMS10A	101.81	95.75	92.25	86.74	CSMS10C	95.79	89.75	86.39	81.15
CSMS20A	98.9	92.54	88.84	83.04	CSMS20C	93.04	86.72	83.17	77.66
CSMS30A	89.42	83.18	79.8	74.04	CSMS30C	84.13	77.92	74.68	69.21
CTMS0A	86.14	80.34	77.44	72.15	CTMS0C	81.84	76.11	73.08	67.96
CTMS10A	103.36	97.57	93.89	88.77	CTMS10C	100.19	94.39	90.51	85.43
CTMS20A	101.89	95.67	91.77	86.59	CTMS20C	98.76	92.53	88.42	83.26
CTMS30A	91.15	85.19	81.96	76.47	CTMS30C	88.36	82.37	78.95	73.52
CPMS0B	74.3	67.88	64.76	60.07	CPMS0D	71.63	65.1	61.96	57.13
CPMS10B	89.13	82.78	79.43	74.4	CPMS10D	85.09	78.76	75.42	70.28
CPMS20B	86.86	80.31	76.66	70.99	CPMS20D	82.92	76.39	72.75	67
CPMS30B	77.01	70.62	67.64	62.38	CPMS30D	73.52	67.14	64.17	58.86
CQMS0B	76.09	69.84	66.91	61.78	CQMS0D	73.34	66.97	64.04	58.85
CQMS10B	92.24	85.98	82.64	77.42	CQMS10D	87.58	81.35	78.05	72.82
CQMS20B	90.23	83.71	80	74.32	CQMS20D	85.67	79.19	75.52	69.85
CQMS30B	80.31	73.98	70.91	65.36	CQMS30D	76.25	69.95	66.92	61.41
CRMS0B	77.88	71.9	69.17	63.6	CRMS0D	75.06	68.95	66.23	60.67
CRMS10B	95.34	89.31	85.99	80.59	CRMS10D	90.07	84.07	80.82	75.49
CRMS20B	93.61	87.26	83.49	77.81	CRMS20D	88.43	82.11	78.42	72.84
CRMS30B	83.62	77.39	74.23	68.39	CRMS30D	78.99	72.79	69.7	64.01
CSMS0B	82.32	76.22	73.09	67.8	CSMS0D	78.96	72.71	69.6	64.4
CSMS10B	98.8	92.74	89.31	83.94	CSMS10D	94.83	88.66	85.23	79.89
CSMS20B	95.97	89.62	86	80.35	CSMS20D	92.11	85.65	82.03	76.43
CSMS30B	86.77	80.54	77.23	71.62	CSMS30D	83.29	76.93	73.63	68.09
CTMS0B	83.99	78.22	75.26	70.05	CTMS0D	79.29	73.53	70.51	65.41
CTMS10B	101.78	95.98	92.2	87.09	CTMS10D	97.06	91.25	87.39	82.31
CTMS20B	100.33	94.1	90.09	84.92	CTMS20D	95.68	89.44	85.35	80.18
CTMS30B	89.75	83.78	80.45	74.99	CTMS30D	85.59	79.59	76.18	70.79

Table 5: Water cured compressive strength at 28 days, and MgSO₄ immersed residual compressive strength results.

Mix Designation	Compressive strength	Residual Compressive Strength			Mix Designation	Compressive strength	Residual Compressive Strength		
	MPa	MPa				MPa	MPa		
	28	30	60	90		28	30	60	90
	Days					Days			
CPMS0A	76.2	69.56	66.35	61.09	CPMS0C	72.4	65.9	62.76	57.38
CPMS10A	90.52	83.73	80.23	74.89	CPMS10C	87.75	80.97	77.47	71.86
CPMS20A	88.21	80.85	77.03	71.37	CPMS20C	85.51	78.18	74.36	68.43
CPMS30A	78.21	71.63	68.52	62.91	CPMS30C	75.81	69.24	66.13	60.3
CQMS0A	78.04	71.28	67.99	63.16	CQMS0C	74.14	67.5	64.31	59.46
CQMS10A	94.15	87.28	83.74	78.41	CQMS10C	90.32	83.5	80.04	74.62
CQMS20A	92.11	84.71	80.78	75.35	CQMS20C	88.36	81.03	77.18	71.66
CQMS30A	81.99	75.13	71.88	66.57	CQMS30C	78.64	71.83	68.65	63.29
CRMS0A	79.88	73.39	70.22	65.36	CRMS0C	75.89	69.4	66.38	61.67
CRMS10A	97.79	90.96	87.4	82.1	CRMS10C	92.9	86.15	82.73	77.53
CRMS20A	96.01	88.71	84.68	79.52	CRMS20C	91.21	84	80.13	75.06
CRMS30A	85.76	78.96	75.32	70.31	CRMS30C	81.47	74.72	71.22	66.36
CSMS0A	84	77.52	74.01	69.11	CSMS0C	80.63	73.99	70.57	65.9
CSMS10A	101.81	94.79	91.18	86.08	CSMS10C	95.79	88.84	85.38	80.52
CSMS20A	98.9	91.57	87.76	82.82	CSMS20C	93.04	85.8	82.14	77.45
CSMS30A	89.42	82.69	78.96	73.68	CSMS30C	84.13	77.42	73.84	68.89
CTMS0A	86.14	79.94	76.71	71.5	CTMS0C	81.84	75.71	72.33	67.3
CTMS10A	103.36	96.44	92.61	88.3	CTMS10C	100.19	93.28	89.25	84.94
CTMS20A	101.89	94.65	90.6	86.44	CTMS20C	98.76	91.53	87.26	83.15
CTMS30A	91.15	84.77	81.17	75.67	CTMS30C	88.36	81.94	78.12	72.76
CPMS0B	74.3	67.73	64.55	59.23	CPMS0D	71.63	65.01	61.81	56.37
CPMS10B	89.13	82.35	78.85	73.37	CPMS10D	85.09	78.33	74.84	69.26
CPMS20B	86.86	79.51	75.69	69.89	CPMS20D	82.92	75.61	71.81	65.92
CPMS30B	77.01	70.44	67.32	61.6	CPMS30D	73.52	66.96	63.85	58.08
CQMS0B	76.09	69.39	66.14	61.3	CQMS0D	73.34	66.58	63.33	58.42
CQMS10B	92.24	85.39	81.89	76.51	CQMS10D	87.58	80.78	77.32	71.92
CQMS20B	90.23	82.87	78.98	73.5	CQMS20D	85.67	78.37	74.53	69.03
CQMS30B	80.31	73.48	70.26	64.93	CQMS30D	76.25	69.46	66.28	60.96
CRMS0B	77.88	71.39	68.29	63.51	CRMS0D	75.06	68.41	65.33	60.59
CRMS10B	95.34	88.55	85.06	79.81	CRMS10D	90.07	83.34	79.92	74.73
CRMS20B	93.61	86.36	82.4	77.29	CRMS20D	88.43	81.24	77.37	72.31
CRMS30B	83.62	76.83	73.27	68.33	CRMS30D	78.99	72.23	68.74	63.92
CSMS0B	82.32	75.75	72.29	67.5	CSMS0D	78.96	72.22	68.77	64.11
CSMS10B	98.8	91.81	88.27	83.29	CSMS10D	94.83	87.75	84.22	79.25
CSMS20B	95.97	88.68	84.94	80.13	CSMS20D	92.11	84.73	81	76.2
CSMS30B	86.77	80.05	76.39	71.28	CSMS30D	83.29	76.42	72.77	67.78
CTMS0B	83.99	77.82	74.52	69.39	CTMS0D	79.29	73.11	69.75	64.75
CTMS10B	101.78	94.86	90.93	86.62	CTMS10D	97.06	90.17	86.16	81.82
CTMS20B	100.33	93.09	88.92	84.79	CTMS20D	95.68	88.46	84.21	80.08
CTMS30B	89.75	83.35	79.64	74.21	CTMS30D	85.59	79.15	75.35	70.07

Table 6: Water cured compressive strength at 28 days and H₂SO₄ immersed residual compressive strength results.

Mix Designation	Compressive strength	Residual Compressive Strength				Mix Designation	Compressive strength	Residual Compressive Strength			
	MPa	MPa					MPa	MPa			
	28	30	60	90	28		30	60	90		
	Days				Days						
CPMS0A	76.2	69.11	65.59	59.37	CPMS0C	72.4	65.41	61.96	55.61		
CPMS10A	90.52	82.92	79.17	71.89	CPMS10C	87.75	80.17	76.42	68.91		
CPMS20A	88.21	80.45	76.36	69.25	CPMS20C	85.51	77.77	73.68	66.32		
CPMS30A	78.21	71.17	67.83	60.99	CPMS30C	75.81	68.78	65.45	58.4		
CQMS0A	78.04	71.19	67.84	61.63	CQMS0C	74.14	67.35	64.11	57.92		
CQMS10A	94.15	86.55	82.75	75.65	CQMS10C	90.32	82.79	79.07	71.93		
CQMS20A	92.11	84.3	80.09	73.29	CQMS20C	88.36	80.62	76.48	69.64		
CQMS30A	81.99	75.04	71.55	64.86	CQMS30C	78.64	71.73	68.31	61.61		
CRMS0A	79.88	73.1	69.73	64.03	CRMS0C	75.89	69.18	65.95	60.36		
CRMS10A	97.79	90.32	86.49	79.58	CRMS10C	92.9	85.53	81.85	75.11		
CRMS20A	96.01	88.3	83.96	77.53	CRMS20C	91.21	83.59	79.42	73.14		
CRMS30A	85.76	78.65	75.26	68.82	CRMS30C	81.47	74.44	71.2	64.92		
CSMS0A	84	76.81	73.56	68.3	CSMS0C	80.63	73.38	70.2	65.08		
CSMS10A	101.81	94.25	90.38	83.83	CSMS10C	95.79	88.31	84.6	78.37		
CSMS20A	98.9	91.16	87.07	80.94	CSMS20C	93.04	85.39	81.46	75.64		
CSMS30A	89.42	81.94	78.46	72.82	CSMS30C	84.13	76.74	73.41	68.04		
CTMS0A	86.14	78.81	75.6	71.43	CTMS0C	81.84	74.67	71.33	67.17		
CTMS10A	103.36	96.02	91.92	86.42	CTMS10C	100.19	92.86	88.54	83.08		
CTMS20A	101.89	94.25	89.9	84.84	CTMS20C	98.76	91.12	86.54	81.52		
CTMS30A	91.15	83.58	80.22	75.58	CTMS30C	88.36	80.8	77.24	72.61		
CPMS0B	74.3	67.26	63.77	57.48	CPMS0D	71.63	64.46	60.94	54.54		
CPMS10B	89.13	81.54	77.79	70.4	CPMS10D	85.09	77.54	73.8	66.37		
CPMS20B	86.86	79.11	75.02	67.78	CPMS20D	82.92	75.2	71.13	63.84		
CPMS30B	77.01	69.97	66.64	59.69	CPMS30D	73.52	66.5	63.17	56.2		
CQMS0B	76.09	69.27	65.97	59.77	CQMS0D	73.34	66.38	63.08	56.82		
CQMS10B	92.24	84.67	80.91	73.78	CQMS10D	87.58	80.07	76.36	69.27		
CQMS20B	90.23	82.46	78.28	71.46	CQMS20D	85.67	77.95	73.83	67.04		
CQMS30B	80.31	73.38	69.93	63.23	CQMS30D	76.25	69.34	65.93	59.3		
CRMS0B	77.88	71.13	67.83	62.19	CRMS0D	75.06	68.23	64.94	59.23		
CRMS10B	95.34	87.92	84.16	77.34	CRMS10D	90.07	82.72	79.04	72.34		
CRMS20B	93.61	85.94	81.69	75.33	CRMS20D	88.43	80.83	76.66	70.41		
CRMS30B	83.62	76.54	73.23	66.86	CRMS30D	78.99	71.98	68.64	62.49		
CSMS0B	82.32	75.09	71.88	66.69	CSMS0D	78.96	71.66	68.45	63.26		
CSMS10B	98.8	91.27	87.48	81.1	CSMS10D	94.83	87.21	83.42	77.1		
CSMS20B	95.97	88.27	84.26	78.28	CSMS20D	92.11	84.31	80.31	74.38		
CSMS30B	86.77	79.34	75.93	70.42	CSMS30D	83.29	75.76	72.36	66.89		
CTMS0B	83.99	76.74	73.46	69.29	CTMS0D	79.29	72.13	68.81	64.56		
CTMS10B	101.78	94.44	90.23	84.74	CTMS10D	97.06	89.75	85.45	79.98		
CTMS20B	100.33	92.68	88.21	83.17	CTMS20D	95.68	88.05	83.49	78.45		
CTMS30B	89.75	82.19	78.72	74.09	CTMS30D	85.59	78.06	74.52	69.87		

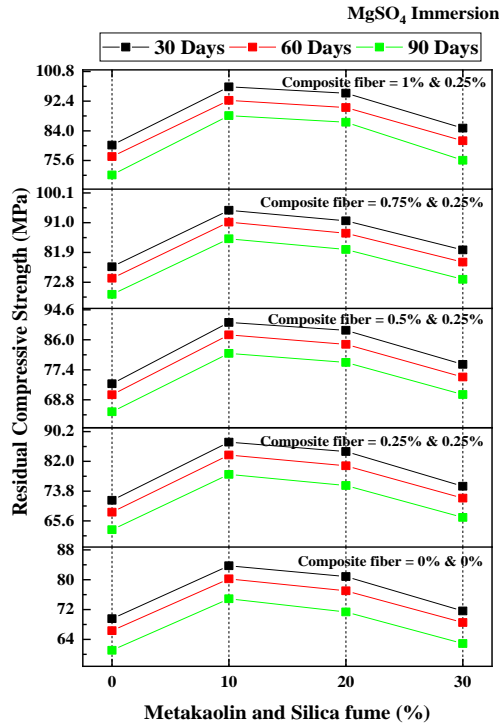


Fig 6. Residual compressive strength versus percentages of MK and SF for various CFRHPC mixes immersed in $MgSO_4$.

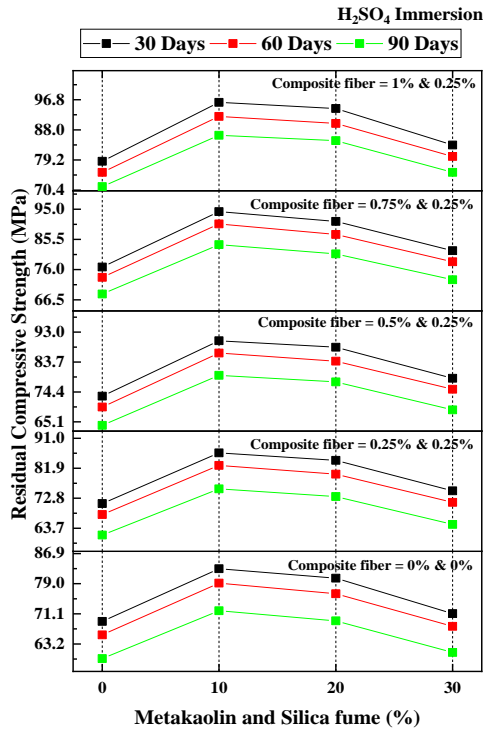


Fig 7. Residual compressive strength versus percentages of MK and SF for various CFRHPC mixes immersed in H_2SO_4 .

B. Effects of volumes of composite fibers on chloride penetration resistance and residual compressive strength of CFRHPC

a) **Chloride penetration resistance:** To show the chloride resistance of each mix, the Chloride penetrability at the ages of 30, 60, and 90 days for W/B of 0.275 are plotted against the percentages of composite fibers for different percentages of MK and SF in Figs. 8, 9, and 10, respectively.

It can be observed from the figures that with an increase in the composite fiber volume, the chloride ion permeability decreased. This was true for all the types of CFRHPC mixes tried in this study. When a dosage of 0.25% GF and PPF each were added, there was an average increase in chloride resistance by 10.66% for mixes with the same composite fiber dosages when compared to mixes without composite fibers. Similarly, when the dosage was off 0.5% GF and 0.25% PPF, 0.75% GF and 0.25% PPF, 1% GF, and 0.25% PPF, the average increase in chloride resistance was found to be 20.61%, 29.04%, and 33.25% respectively when compared to mixes without composite fibers.

The maximum chloride resistance was offered by mix with 1% GF and 0.25% PPF and was in the very low penetrability range compared to plain mix CPMS0A that was in low penetrability range as per ASTM C1202. Chloride ion permeability of mixes prepared without composite fibers was considerably higher than those prepared with composite fibers, as these fibers were effective in arresting both macro and micro level cracks. The development of microcracks was stopped by fibers at a micro level. The number of fibers played a major role in controlling the growth of microcracking. At the macro level, crack openings were controlled by fibers and thus increasing the energy absorption capacity of the composite.

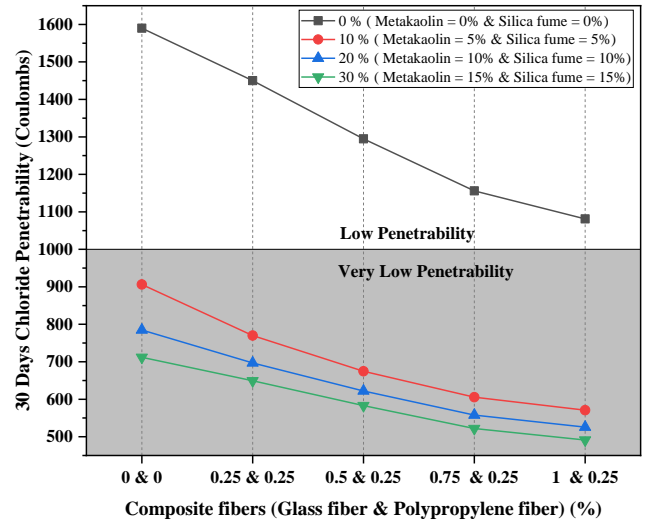


Fig 2. Variation of 30 days chloride penetrability with percentages of composite fibers for different percentages of MK and SF.

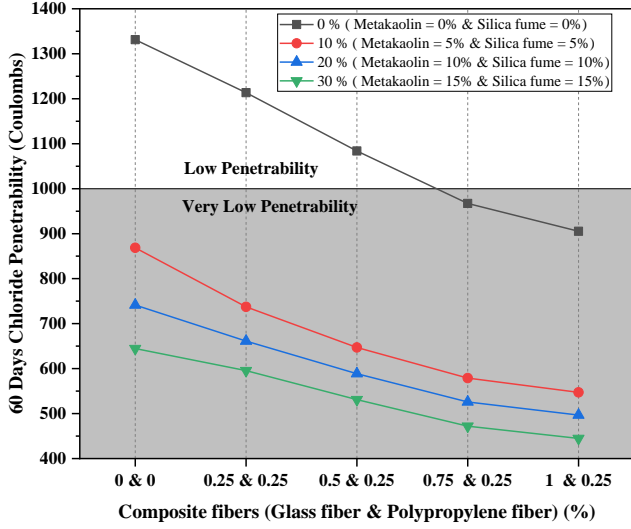


Fig 3. Variation of 60 days chloride penetrability with percentages of composite fibers for different percentages of MK and SF.

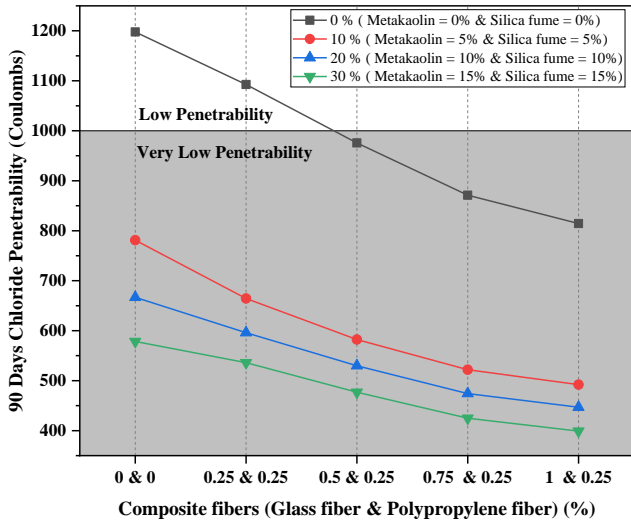


Fig 4. Variation of 90 days chloride penetrability with percentages of composite fibers for different percentages of MK and SF.

b) Acid attack: The deterioration in compressive strength after acid immersions for W/B of 0.275 with varying percentages of composite fibers are presented in Figs. 11, 12, and 13 respectively. It can be perceived that with an escalation in the composite fiber volume the residual compressive strength increased. This trend was true for all the types of CFRHPC mixes tried in this study. For every increase in 0.25% GF and constant PPF of 0.25% dosages, there was an average increase in residual compressive strength by 4.23%, 8.24%, 12.28% and 14.82% for mixes with the same composite fiber dosages when compared to mixes without composite fibers for HCl cured mixes. Similarly, the residual compressive strength increased by 4.18%, 8.26%, 12.32%, and 14.81% for MgSO₄ cured mixes and by 4.54%, 8.7%, 12.84%, and 15.37% for H₂SO₄ cured

mixes. The residual compressive strength of mixes prepared without composite fibers were considerably lesser than those

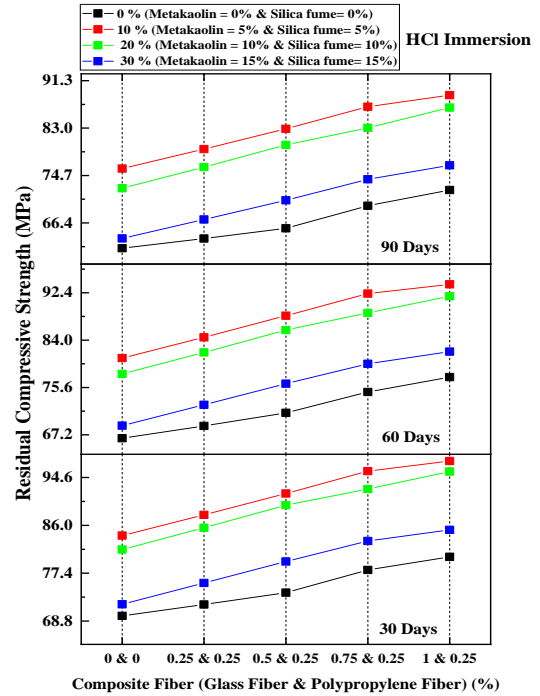


Fig 5. Residual compressive strength versus percentages of composite fibers for various CFRHPC mixes immersed in HCl.

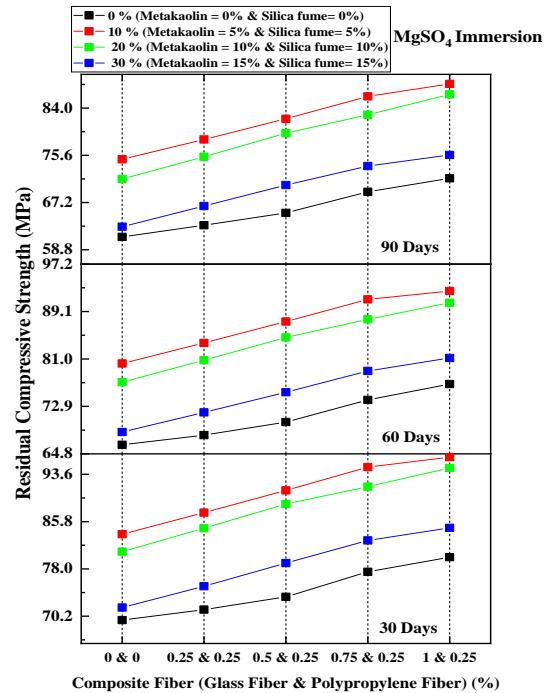


Fig 6. Residual compressive strength versus percentages of composite fibers for various CFRHPC mixes immersed in MgSO₄.

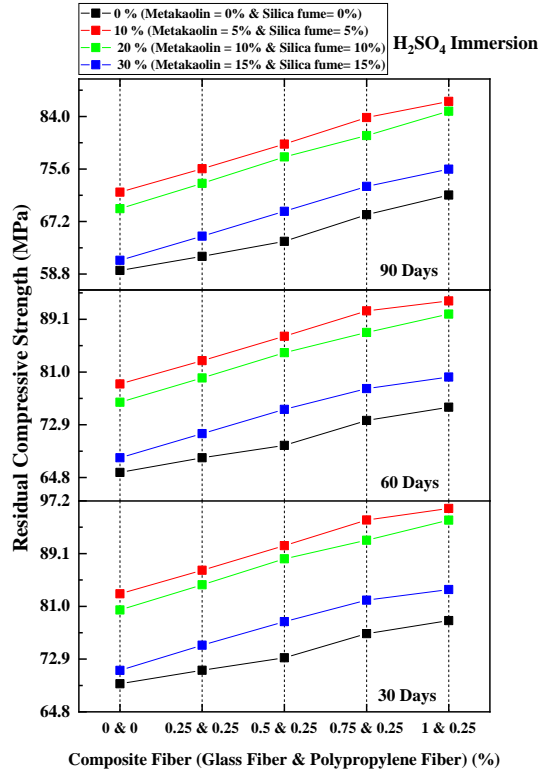


Fig 7. Residual compressive strength versus percentages of composite fibers for various CFRHPC mixes immersed in H₂SO₄.

Prepared with composite fibers, as these fibers were effective in arresting both macro and micro level cracks. The development of microcracks was stopped by fibers at a micro level. The number of fibers played a major role in controlling the growth of microcracking. At the macro level, crack openings were controlled by fibers and thus increasing the energy absorption capacity of the composite.

C. Effects of water binder ratios on chloride penetration resistance and residual compressive strength of CFRHPC

a) Chloride penetration resistance: To understand the chloride penetration resistance for each mix, chloride penetrability for all ages of testing is plotted against the water binder ratios for different volumes of composite fibers in Figs. 14, 15, and 16, respectively, which show that 30, 60, and 90 days chloride penetration resistance of CFRHPC mixes decreased with an increase in water binder ratio, and all other mixes followed the same trend. Maximum chloride penetration resistance was obtained for a mix with a 0.275 water binder ratio and was true for all other mixes with different percentages of cement replacements and the addition of composite fibers. The optimum chloride penetration resistance obtained at 30, 60, and 90 days were 571 C, 547 C, and 492 C, respectively for the CTMS10A mix.

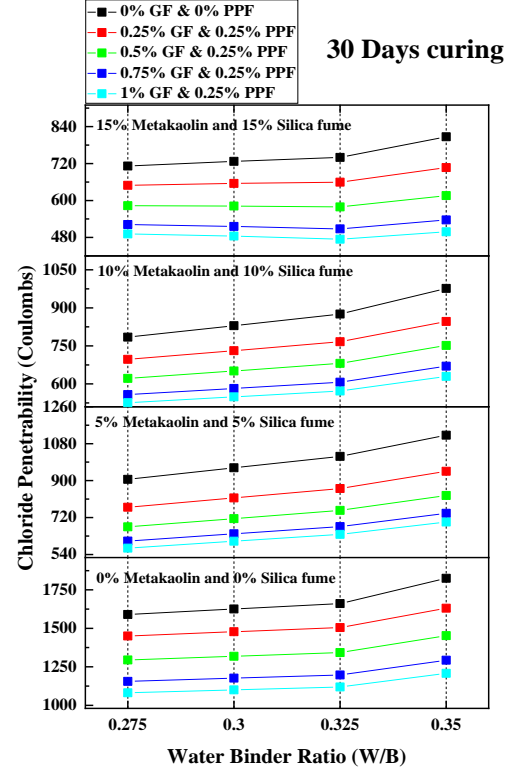


Fig 14. 30 days chloride penetrability versus water binder ratios for various volumes of composite fibers.

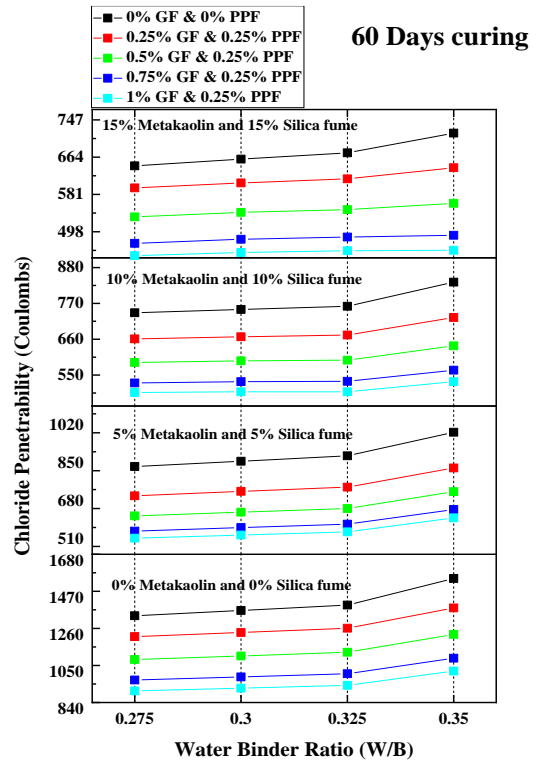


Fig 15. 60 days chloride penetrability versus water binder ratios for various volumes of composite fibers.

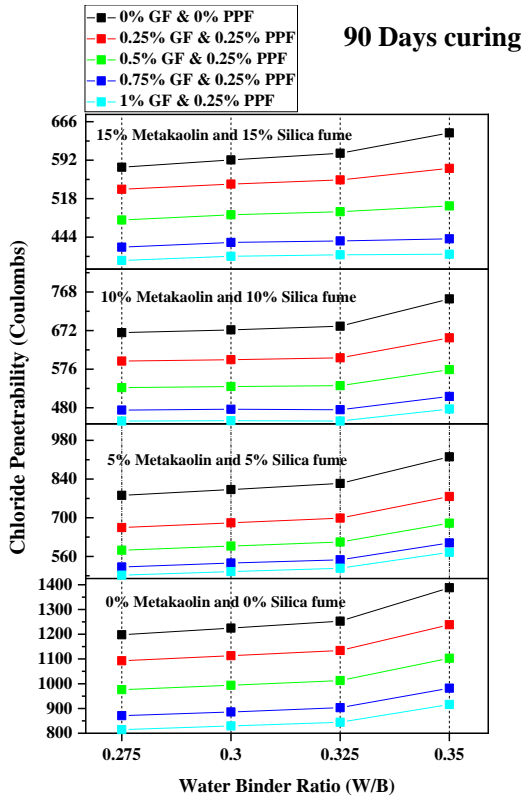


Fig 16. 90 days chloride penetrability versus water binder ratios for various volumes of composite fibers.

Further, for the same mix when the water binder ratio was increased to 0.3, its 30 days chloride penetration resistance reduced by 5.95% with respect to the CTMS10A mix, and it further reduced to 11.73% and 22.24% for W/B ratios of 0.325 and 0.35 respectively with respect to CTMS10A mix. Similarly, 60 days chloride penetration resistance was reduced by 2.56%, 5.12%, and 16.63%, and 90 days chloride resistance was reduced by 2.64%, 5.08%, and 16.87% respectively with reference to chloride resistance of respective 0.275 water binder ratio. This behaviour was witnessed, as there was not enough water for complete hydration leading to early strength gain, and was true for all other mixes with different percentages of cement replacements and addition of composite fibers.

b) Acid attack: Values presented in Tables 4, 5, and 6 represent the 30, 60, and 90 days residual compressive strength results immersed in HCl, MgSO₄, and H₂SO₄, respectively. It is evident that 30, 60, and 90 days residual compressive strength of mixes tried decreased when water binder ratio was increased, and all other mixes followed the same trend. Maximum residual compressive strength was obtained for a mix with a 0.275 water binder ratio and was true for all other mixes with different percentages of cement replacements and the addition of composite fibers. The maximum compressive strength retained after 30, 60, and 90 days for HCl immersion were 97.57 MPa, 93.89 MPa, and

88.77 MPa, respectively for the CTMS10A mix. Further, for the same mix when the water binder ratio was increased to 0.3, its 30 days residual compressive strength was reduced by 1.63% with respect to the CTMS10A mix, and it was further reduced to 3.27% and 6.48% for W/B ratios of 0.325 and 0.35 respectively with respect to CTMS10A mix. Similarly, 60 days residual compressive strength was reduced by 1.8%, 3.6%, and 6.92%, and 90 days residual compressive strength was reduced by 1.89%, 3.77%, and 7.28% respectively with reference to the residual compressive strength of the respective 0.275 water binder ratio.

Similar behaviour was witnessed for mixes immersed in MgSO₄ and H₂SO₄, wherein deterioration of compressive strength increased with increasing water binder ratios. The maximum residual strength was obtained in mixes with 0.275 water to binder ratio, as less water was available for hydration in the concrete leading to early strength gain.

D. Effects of type of acid on residual compressive strength of CFRHPC

CFRHPC mixes were subjected to 5 percent concentrated solutions of HCl, MgSO₄, and H₂SO₄. The effect of these acids on the deterioration of compressive strength in different CFRHPC mixes with W/B of 0.275 is presented in Figs. 17, 18, 19, and 20 respectively.

It is evident from the figures that the maximum depreciation of compressive strength was reported for cubes with H₂SO₄ acid immersion than that of HCl and MgSO₄.

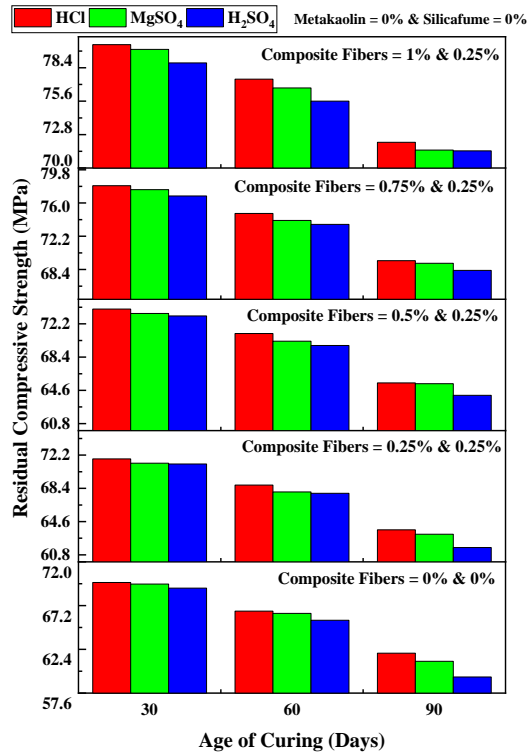


Fig 8. Residual compressive strength versus days of acid curing for various CFRHPC mixes with 0% mineral admixtures (0% MK and 0% SF).

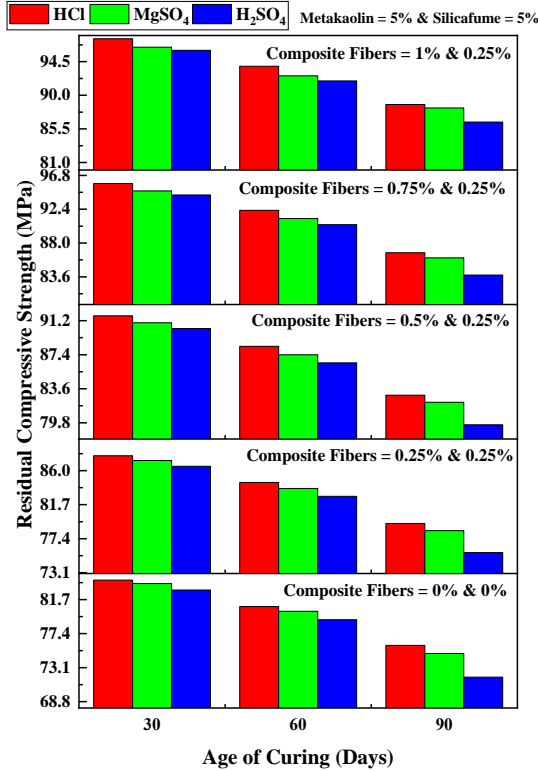


Fig 9. Residual compressive strength versus days of acid curing for various CFRHPC mixes with 10% mineral admixtures (5% MK and 5% SF).

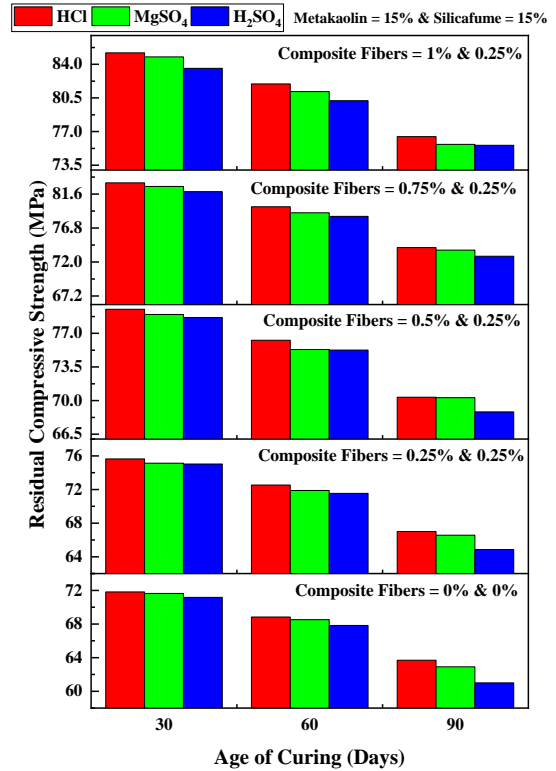


Fig 20. Residual compressive strength versus days of acid curing for various CFRHPC mixes with 30% mineral admixtures (15% MK and 15% SF).

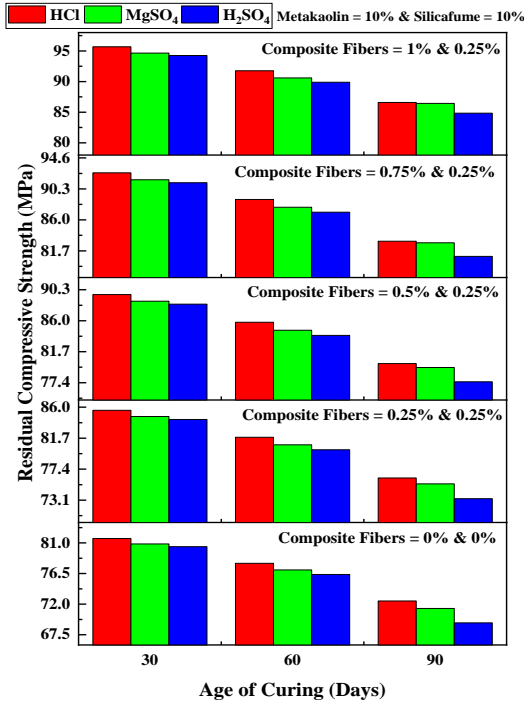


Fig 10. Residual compressive strength versus days of acid curing for various CFRHPC mixes with 20% mineral admixtures (10% MK and 10% SF).

The same trend was followed by all the three dosages of mineral admixtures tried in the present investigation. Out of the three acids HCl, MgSO₄, and H₂SO₄, the HCl acid immersion reported the least loss of compressive strength for all mineral admixtures replacement levels of cement and the addition of composite fibers. For the CTMS10A mix, the deteriorated compressive strength after 30 days of HCl immersion was 97.57 MPa, and it was reduced to 96.44 MPa and 96.02 MPa for MgSO₄ and H₂SO₄ with a reduction of 1.16% and 1.59% in comparison with 30 days HCl cured CTMS10A mix. Similarly, there was a reduction of 1.36% and 2.10% and 0.53% and 2.65% for 60 and 90 days residual compressive strengths, respectively indicating the severity of H₂SO₄ as it led to the formation of CaSO₄ which reacted with C3A, resulting in the formation of expansive ettringite which leads to deterioration of concrete's compressive strength. Similar trends were observed for other mixes as well. It can be concluded that the attack of H₂SO₄ was major on CFRHPC, and that of HCl was the least out of three acids tried in this study.

E. Effects of age of curing on chloride penetration resistance of CFRHPC

To show the chloride resistance of each mix, the Chloride penetrability at the ages of 30, 60, and 90 days for W/B of 0.275 are plotted against the percentages of composite fibers for different percentages of MK and SF in Figs. 20, 21, 22, and 23, respectively.

From Figs, it can be observed that chloride penetration resistance of CFRHPC mixes increased with the age of curing and was true for all mixes. If mixes with 0% mineral admixtures are considered, it shows that at the 30 days age of curing, all those mixes were at a low penetrability range as per ASTM C1202. However, as the age of curing was increased, it can be seen that majority of those mixes move to a very low penetrability range at the end of 90 days age of curing.

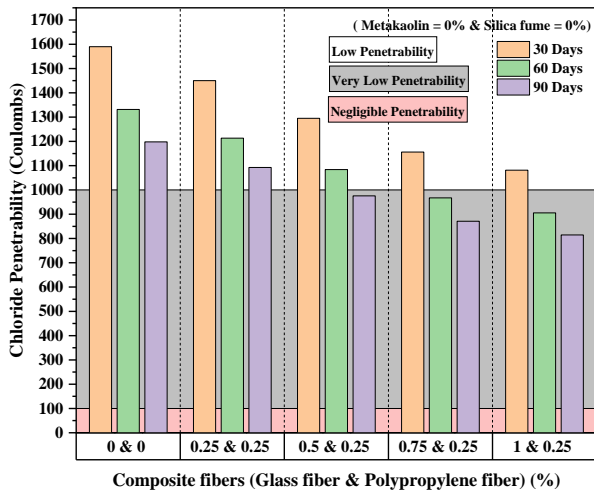


Fig 20. Variation of Chloride penetrability with percentages of composite fibers for 30, 60, and 90 Days (for 0% admixtures)

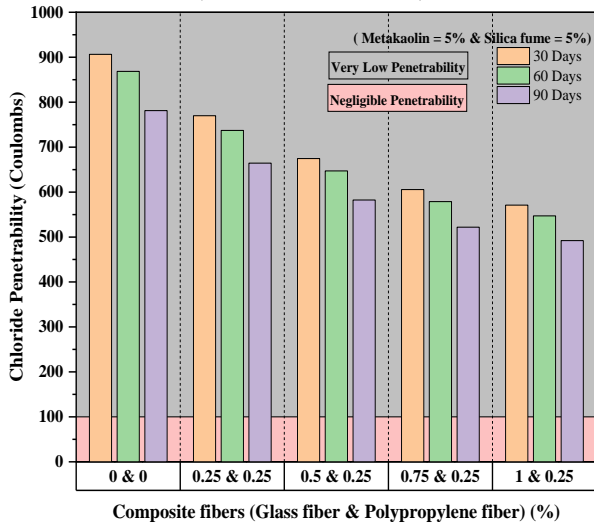


Fig 21. Variation of Chloride penetrability with percentages of composite fibers for 30, 60, and 90 Days (for 10% admixtures)

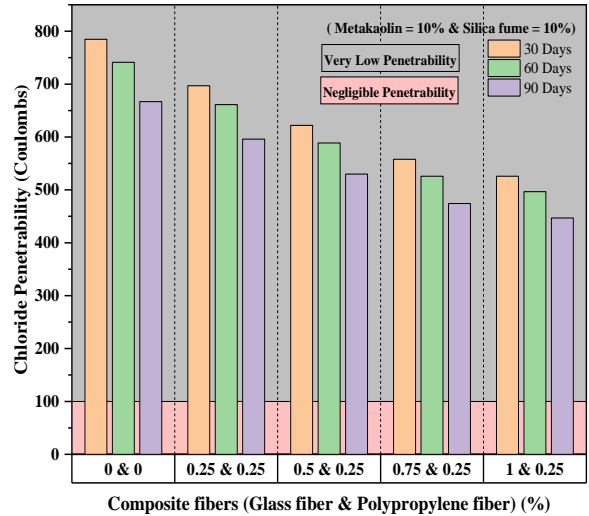


Fig 22. Variation of Chloride penetrability with percentages of composite fibers for 30, 60, and 90 Days (for 20% admixtures)

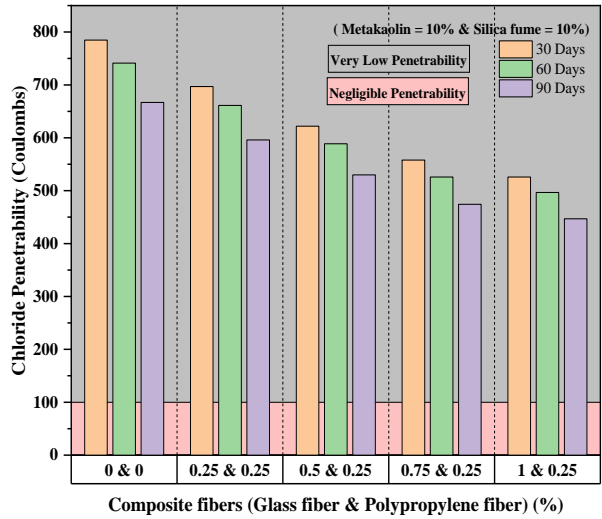


Fig 23. Variation of Chloride penetrability with percentages of composite fibers for 30, 60, and 90 Days (for 30% admixtures)

The average increase in chloride resistance for all mixes from 30 days to 60 days was 8.78% and a further 10% from 60 days to 90 days. The maximum increase in chloride resistance observed was 1191 C after 90 days of curing for the CTMS30A mix in comparison to the plain CPMS0A mix. The least chloride penetrability obtained was 399 C at 90 days of curing and falls in the very low penetrability category as per ASTM C1202. Thus, as concrete gets older, the better will be the quantity of hydration that will occur, resulting in a highly developed pore structure, which is the obvious behavior of concrete with slower reacting supplementary cementing materials, which require a longer time to hydrate.

V. CONCLUSIONS

In this experimental work, the chloride penetration resistance and acid attack resistance of CFRHPC produced with MK, SF, GF, and PPF were investigated. The following conclusions are drawn after the investigation of the results

A. Chloride penetration resistance:

- Chloride penetration resistance of CFRHPC mixes decreased with an increase in water binder ratio. Maximum chloride penetration resistance was obtained for a mix with a water binder ratio of 0.275.
- An increase in the replacement level of cement with metakaolin and silica fume dosages decreased the chloride ion penetration. The chloride penetration decreased rapidly up to 10% replacement level of mineral admixture dosage, and beyond 10%, the decrease in chloride penetration is marginal.
- The chloride ion permeability of CFRHPC mixes decreases with an increase in fiber content. The addition of fibers in the ranges 0-1% decreased the chloride ion permeability well below 1000 coulombs which are classified as very low permeability as per ASTM-C 1202 and can be safely adopted. The maximum chloride resistance was offered by a mix with 1% GF and 0.25% PPF and was in the very low penetrability range.
- Chloride penetration resistance of CFRHPC mixes increases with the age of curing and is true for all mixes. Thus, as concrete gets older, the better will be the quantity of hydration that will occur, resulting in a highly developed pore structure.
- The charge transfer in RCPT was as low as 399 Coulombs for CFRHPC, and this shows the structure with dense microstructure and less interconnected pores.
- Thus, it can be concluded that the combined effect of MK 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 for Chloride Penetration Resistance for CFRHPC.

B. Acid attack:

- The loss in compressive strength of CFRHPC mixes increased along with increased water to binder ratio. Maximum residual compressive strength was obtained for a mix with a 0.275 water binder ratio and is true for all other mixes with different percentages of cement replacements, the addition of composite fibers, and the type of acid immersed.
- MK and SF-based CFRHPC mix counterattacked the acid attack effectively in comparison to plain CPMS0A/B/C/D mixes at all ages of HCl, MgSO₄, and H₂SO₄ exposure.
- It was perceived that the deterioration in compressive

strengths of all CFRHPC mixes is substantially lower than that of plain CPMS0A/B/C/D mix at all ages of HCl, MgSO₄, and H₂SO₄ exposures.

- The degradation of compressive strength in CFRHPC mixes due to acid attack was least at 10% (5%MK+5%SF) combined cement replacement. Hence, 10% replacement, i.e., 5% each of MK and SF, is considered as optimum dosage.
- The degradation of compressive strength in CTMS10A mix is 16.80% for MK and SF-based CFRHPC mixes after 90 days of dipping in H₂SO₄ acid, while a loss of 22.09% was reported in similar exposure for plain CPMS0A mix. This proves the superiority of MK and SF-based CFRHPC in fighting acid attacks.
- The loss in compressive strength of CFRHPC increased with an increase in the duration of acid curing. Maximum degradation of compressive strength has been witnessed at 90 days of acid immersion. The behavior of all acids tried in the present analysis followed the same trend.
- Degradation of compressive strength decreases with the addition of composite fibers. The minimum degradation in compressive strength was obtained for mixes with 1% GF and 0.25% PPF dosage and is applicable for all mixes tried in this analysis.
- The maximum harm to compressive strength happened in the circumstance of H₂SO₄ acid curing in comparison to HCl and MgSO₄ acids. Out of the three acids, the least degradation of compressive strength was documented for HCl acid immersion.
- Thus, it can be concluded that the combined effect of MK 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 acid attack resistance for CFRHPC.

The conclusions above demonstrate the viability of using MK an SF and composite fibers (GF and PPF) in CFRHPC production, which minimizes enormous cement production and safeguards the environment from pollution and concrete from environmental pollution throughout its service life.

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