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Durability and Fire-Resistive Analysis of GFRP Bars with Retardant Additives in RC Beam

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Abstract:

GFRP reinforcement offers excellent resistance to corrosion; however, its vulnerability to high temperatures reduces the flexural performance of GFRP-reinforced concrete beams under fire exposure. This study investigates the influence of the retardant additives chitin and metakaolin on the durability and fire resistance of GFRP-reinforced concrete beams. Experimental investigations were conducted on a total of eight beams divided into four mix categories. For each mix, two beams were cast: one was tested under normal conditions using a four-point loading arrangement, while the other was subjected to fire exposure for one hour and subsequently tested under the same loading configuration to evaluate its post-fire flexural performance. The durability characteristics were assessed through water absorption, acid resistance, and carbonation tests. Comparison of the test results indicated that the incorporation of chitin and metakaolin improved the performance of the beams after fire exposure. In contrast, the control specimen exhibited better behaviour under normal loading conditions. The findings suggest that the use of chitin and metakaolin is beneficial for enhancing the durability and fire resistance of GFRP-reinforced concrete structures.

Keywords — **GFRP Reinforcement, Chitin, Metakaolin, Flexural performance, Fire exposure, Durability.**

I. INTRODUCTION

Glass Fiber Reinforced Polymer (GFRP) bars are increasingly used in reinforced concrete structures as an alternative to conventional steel reinforcement because of their corrosion-resistant properties. However, exposure to elevated temperatures can adversely affect the performance of GFRP bars due to degradation of the polymer matrix. This degradation may reduce the stiffness and load-carrying capacity of GFRP-reinforced concrete members under fire conditions. Consequently, improving the fire resistance of such structural systems has become an important area of research.

To overcome this drawback, the use of fire-retardant additives in concrete has been explored. Chitin, a bio-based polysaccharide obtained from crustacean shells, is considered a sustainable additive that enhances fire resistance by forming a denser and more refined microstructure. Metakaolin, a highly reactive pozzolanic material produced from calcined kaolin clay, contributes to a denser concrete microstructure by reducing porosity and permeability, thereby improving both mechanical strength and durability. Its rich silica and alumina content also supports improved resistance to thermal degradation.

In this study, the durability and fire resistance of GFRP-reinforced concrete beams containing chitin and metakaolin are investigated. Durability characteristics were assessed through water absorption, acid resistance, and carbonation tests to evaluate resistance against moisture penetration, chemical attack, and carbonation effects. The flexural performance of beam specimens was evaluated under normal conditions and after fire exposure using four-point loading tests. The results were analyzed in terms of load-carrying capacity, deflection and durability performance. The findings of this study contribute to enhancing the durability and fire resistance of GFRP-reinforced concrete beams.

II. LITERATURE REVIEW

Flexural behaviour of GFRP reinforced concrete beams has been widely studied, with most investigations reporting satisfactory performance under normal conditions. However, serviceability limitations such as increased deflection and crack width have been consistently observed. It has also been reported that load-carrying capacity improves with higher reinforcement ratios [2].

The behaviour of concrete members under elevated temperatures has received significant attention. Fire exposure leads to deterioration and resulting in reductions in structural performance. When temperatures exceed approximately 200–300°C, mechanical degradation becomes more severe, leading to increased deformation and loss of residual strength. Improving fire resistance therefore remains an important research focus [8], [10].

Several studies have investigated the use of supplementary cementitious and bio-based additives to improve concrete performance under harsh conditions. Chitin-based materials have been reported to refine the microstructure, resulting in a denser matrix with improved mechanical response [11]. Similarly, metakaolin contributes to pore refinement and enhances resistance to high temperatures and improves durability [13], [14] . The present study focuses on evaluating the durability and fire resistance of GFRP-reinforced concrete beams incorporating chitin and metakaolin under fire exposure and flexural loading conditions

III. MATERIALS

The materials used in this experimental study were Ordinary Portland Cement (OPC 53 grade), fine aggregate (M sand), coarse aggregate, potable water, steel bars, Glass Fiber Reinforced Polymer (GFRP) bars, chitin, and metakaolin. GFRP bars were used as the primary reinforcement, while chitin and metakaolin were incorporated as retardant additives to enhance durability and fire resistance. The physical and mechanical properties of the materials were tested in accordance with relevant Indian Standard (IS) specifications.

A. Cement Tests

Physical properties of cement were tested as per IS 4031, including consistency, setting time, fineness, and specific gravity. The results are presented in Table 1.

Table 1 Cement Properties

S. No.	Tests Performed	Results
1	Standard consistency	30 %
2	Initial setting time	50 mins
3	Final setting time	315 mins
4	Specific gravity	3.15
5	Fineness (<90 microns)	2.95

B. Fine Aggregate Tests

The physical properties of fine aggregate were tested as per IS 2386 (Part I and Part III), including fineness modulus, specific gravity, and water absorption. The results are presented in Table 2.

Table 2 Fine Aggregate Properties

S. No.	Tests Performed	Results
1	Fineness modulus	2.9
2	Specific gravity	2.7
3	Water absorption	1.1%

C. Coarse Aggregate Tests

The physical properties of coarse aggregate were tested as per IS 2386 (Part I and Part III), including specific gravity and water absorption. The results are presented in Table 3.

Table 3 Coarse Aggregate Properties

S. No.	Tests Performed	Results
1	Specific gravity	2.71
2	Water absorption	0.7%

D. Retardant Additives tests

The physical properties of the retardant additives, including specific gravity and fineness, were determined. The results are presented in Table 4.

Fig.1 Chitin

Fig.2 Metakaolin

Table 4 Retardant Additives Properties

S. No.	Properties	Results
1	Fineness (Chitin)	3%
2	Specific gravity (Metakaolin)	2.5
3	Fineness (Metakaolin)	2.5%

E. Mechanical Properties of GFRP Bars

The GFRP bars (12mm) were tested in UTM to determine tensile strength and modulus of elasticity. The results are presented in Table 5.

Table 5 Properties of GFRP Bars

S. No.	Mechanical Properties	Results
1	Tensile strength (MPa)	1018
2	Modulus of elasticity (MPa)	55000

IV. METHODOLOGY

F. Mix Design

The concrete mix design was carried out to achieve the required strength, workability, and durability for the experimental investigation. M25 grade concrete was designed in accordance with IS 10262:2019. The mix consisted of Ordinary Portland Cement (OPC 53 grade), fine aggregate, coarse aggregate, and water. A water–cement ratio of 0.48 was adopted for the mix design. The mix proportions obtained per cubic metre of concrete were 368.75 kg of cement, 706 kg of fine aggregate, and 1148 kg of coarse aggregate. The final mix ratio obtained was 1:1.91:3.12

G. Specimen preparation

The experimental study was conducted using M25 grade concrete with eight different mix compositions. These comprised a control mix, four mixes incorporating chitin at dosages of 0.5%, 1.0%, 1.5%, and 2.0% by weight of cement, and three mixes containing 5%, 10%, and 15% metakaolin as a cement replacement material. Compressive strength was determined using 72 concrete cubes measuring 150 mm × 150 mm × 150 mm. For each mix nine cubes were prepared, of these, three were tested at each curing age of 7, 14, and 28 days. The compressive strength results were used to identify the optimum mix and these were selected for durability evaluation through water absorption, acid resistance, and carbonation tests and further were used for casting beams of dimensions 150 mm x 200 mm x1000 mm.

V. RESULTS AND DISCUSSION

H. Slump Test

Workability of concrete was assessed using the slump cone test for eight different mixes. The slump values obtained for different concrete mixes are presented in Table 6

Table 6 Slump values

Mix	Slump Value mm
Control	100
Mix 1 (Chitin 0.5%)	97
Mix 2 (Chitin 1%)	95
Mix 3 (Chitin 1.5%)	93
Mix 4 (Chitin 2.0%)	90
Mix 5 (Metakaolin 5%)	95
Mix 6 (Metakaolin 10%)	90
Mix 7 (Metakaolin 15%)	80

The results indicate that workability decreases gradually with increasing chitin and metakaolin content.

Fig. 3 Slump test

I. *Compressive Strength Test*

The compressive strength of concrete was determined using cube specimens tested in a Compression Testing Machine (CTM). Three cube specimens from each mix were tested after 7, 14, and 28 days of curing. The compressive strength results for the different concrete mixes are summarized in Table 7

Table 7 Average Compressive Strength of Concrete Cube Specimens

Cube specimen	7 days (N/mm^2)	14 days (N/mm^2)	28 days (N/mm^2)
Control	21	25.2	31.1
Mix 1 (Chitin 0.5%)	22.3	25.7	32.4
Mix 2 (Chitin 1.0%)	21	24	30.9
Mix 3 (Chitin 1.5%)	20	22.9	28.9
Mix 4 (Chitin 2.0%)	19.2	22.3	27.8
Mix 5 (Metakaolin 5%)	22.4	25.7	31.9
Mix 6 (Metakaolin 10%)	21.2	24.6	30.5
Mix 7 (Metakaolin 15%)	20.7	23.9	29.5

The results indicate that the compressive strength increased with the incorporation of 0.5% chitin and 5% metakaolin compared to the control mix. Therefore, Mix 1(0.5% chitin) and Mix 5 (5% metakaolin) were selected as the optimum mixes.

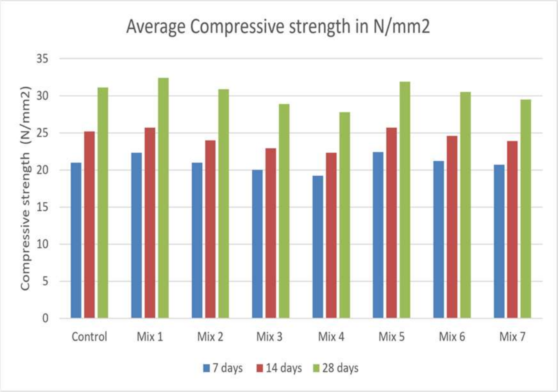


Fig. 4 Compressive Strength Variation

Figure 4 shows the variation in compressive strength of different concrete mixes at 7, 14, and 28 days

Fig. 5 Compressive Strength test

J. *Durability Tests*

1. *Water Absorption Test*

The water absorption test was conducted on the control mix, optimum chitin mix, and optimum metakaolin mix to assess the porosity and durability of hardened concrete. Concrete cube specimens were cured in water for 28 days. After curing, the specimens were removed from the water, surface-dried, and their dry weight (W_1) was recorded. The specimens were then immersed in water for 24 hours, after which their wet weight (W_2) was measured. The water absorption percentage was calculated using the difference between the dry and wet weights of the specimens.

$$\text{Water absorption (\%)} = \frac{w2-w1}{w1} \text{ x } 100$$

The water absorption values obtained are summarized in Table 8

Table 8 Water absorption test

Cube specimen	Dry weight W1 in g	Wet weight W2 in g	Water absorption %
Control	8540	8967	5
Chitin optimum mix	8544	8885	4
Metakaolin optimum mix	8582	8968	4.5

The results indicate that the optimum chitin and metakaolin mixes exhibited lower water absorption, reduced permeability, and enhanced resistance to moisture penetration compared to the control mix

2. *Acid Resistance Test*

The acid resistance test was conducted on the control mix, optimum chitin mix, and optimum metakaolin mix to evaluate durability against chemical attack. Concrete cube specimens were water-cured for 28 days and weighed to determine the initial weight (W_1). The specimens were then immersed in a 5% sulfuric acid (H_2SO_4) solution for 28 days. After immersion, the cubes were washed, surface-dried, and weighed to obtain the final weight (W_2). The percentage weight loss was calculated using the difference between the initial and final weights of the specimens.

$$\text{Weight loss } \% = \frac{w1-w2}{w1} \text{ x } 100$$

The results of the acid resistance test are summarized in Table 9.

Table 9 Acid Resistance test

Cube specimen	Initial weight w1 in g	Final weight W2 in g	Weight loss %
Control	8558	7744	9.5
Chitin optimum mix	8567	7898	7.8
Metakaolin optimum mix	8605	7916	8

The results indicate that the optimum chitin and metakaolin mixes exhibited lower weight loss than the control mix, demonstrating enhanced resistance to acid attack.

Fig. 6 Acid Resistance test

3. *Carbonation Test*

The carbonation test was conducted on the control mix, optimum chitin mix, and optimum metakaolin mix to evaluate the resistance of concrete to carbon dioxide penetration. After completing 28 days of water curing, the cube specimens were allowed to dry under ambient conditions and exposed to the atmosphere for an additional 14 days to allow carbonation. After exposure period, each specimen was split into two halves and sprayed with a phenolphthalein indicator solution. The non-carbonated concrete developed a pink colour, whereas the carbonated region remained colourless. The carbonation depth was then determined by measuring the distance from the exposed surface to the carbonated zone. The measured carbonation depths are presented in Table 10.

Table 10 Carbonation test

Cube specimen	Carbonation depth (mm)
Control	6
Chitin optimum mix	4
Metakaolin optimum mix	3

The results indicate that the optimum chitin and metakaolin mixes exhibited lower carbonation depth than the control mix, demonstrating enhanced resistance to carbonation and improved durability.

Fig. 7 Carbonation test

K. Testing of Beams

A total of eight GFRP-reinforced concrete beams of size 150 × 200 × 1000 mm were cast and cured in water for 28 days. The beams were divided into four mix types, and for each mix, two beams were cast, including a control mix without additives, a chitin-incorporated mix, a metakaolin-incorporated mix, and a mix containing both chitin and metakaolin. One beam from each mix was tested for flexural performance under normal conditions by a four-point loading test, while the other beam was subjected to fire exposure for one hour, followed by four-point loading test to evaluate the performance of GFRP-reinforced concrete beams under normal and fire-exposed conditions, with and without retardant additives.

Fig. 8 Reinforcement detailing of beam

Fig.9 GFRP Reinforcement

Fig.10 Casting of GFRP reinforced beam

Fig.11 Curing of beams

Fig.12 GFRP reinforced beams

1. *Flexural performance under Four-Point Loading*

The flexural performance of the GFRP-reinforced concrete beams was investigated under a four-point loading arrangement using a leaf spring testing machine with a loading capacity of 200 kN. The load corresponding to the first crack, the ultimate load carrying capacity , and the maximum deflection were recorded for each beam. The experimental results obtained under normal conditions are presented in Table 11

Table 11 Flexural performance of beams under normal conditions

Beam Specimen	Load at First crack(kN)	Ultimate load at failure(kN)	Deflection (mm)
Control	38.64	68.32	3.1
Chitin incorporated mix (0.5%)	33.75	66.16	3.8
Metakaolin incorporated mix (5%)	27.92	63.84	4.1
Combined mix (0.5% chitin + 5% metakaolin)	32.68	66.8	3.6

Among the beams, the control beam recorded the highest ultimate load of 68.32 kN, with a first-crack load of 38.64 kN and a corresponding deflection of 3.1 mm. The beam incorporating 0.5% chitin achieved an ultimate load of 66.16 kN, while the beams containing 5% metakaolin and the combined mix (0.5% chitin + 5% metakaolin) reached 63.84 kN and 66.80 kN, respectively. Their corresponding first-crack loads were 33.75 kN, 27.92 kN, and 32.68 kN, with deflections of 3.8 mm, 4.1 mm, and 3.6 mm. The additives incorporated beams showed a slight reduction in performance compared to the control beam under normal conditions the comparative load deflection behaviour of the beams are summarized in Table 12

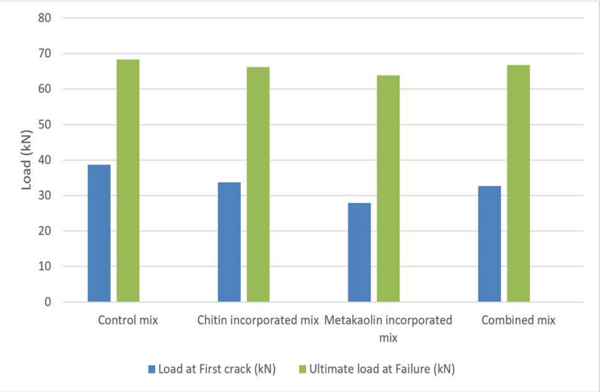


Fig.13 Flexural performance of beams (Load at First crack & Ultimate load at failure)

Figure 13 shows the flexural performance of the beams under normal conditions.

Table 12 Load-Deflection Behaviour of Beams

Load (kN)	Deflection (mm)			
	Control	Chitin incorporated mix	Metakaolin incorporated mix	Combined mix
10	0.2	0.3	0.5	0.3
20	0.7	0.9	1.1	0.8
30	1.2	1.3	1.7	1.2
40	1.7	1.9	2.4	1.8
50	2.2	2.5	3.0	2.4
60	2.7	3.1	3.7	3.0
70	-	-	-	-

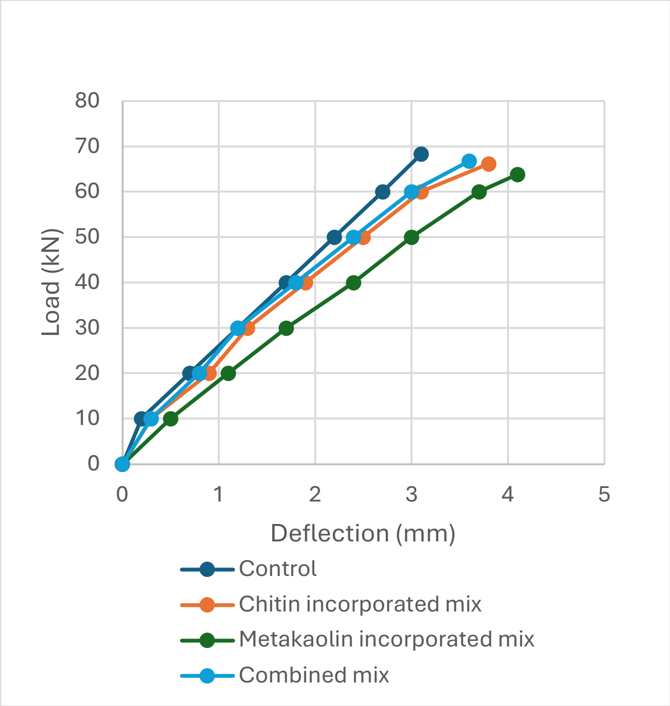


Fig. 14 Load-Deflection Behaviour of beams under normal conditions

Figure 14 shows the load–deflection behaviour of the beams.

Fig.15 Test setup of control beam

Fig.16 Test setup of beam with retardant additives (Chitin)

Fig.17 Test setup of beam with retardant additives (Metakaolin)

Fig.18 Test setup of beam with retardant additives (Combined Chitin & Metakaolin)

2. ***Fire Exposure Test***

Four GFRP reinforced concrete beams were subjected to fire exposure using a gas stove setup at a temperature range of 400 °C for a duration of one hour. After heating, the beams were allowed to cool naturally at room temperature for 24 hours. The beams were then tested under four-point loading to evaluate their post-fire performance in terms of residual load-carrying capacity and deflection behaviour. The results obtained from the four-point loading test conducted after fire exposure, including load at first crack, ultimate load at failure, and corresponding deflection, are summarized in Table 13.

Fig.19 Fire exposure test on GFRP Reinforced Beams

Fig.20 Temperature measurement using infrared thermometer

Table 13 Flexural performance of beams after fire exposure

Beam Specimen	Load at First crack(kN)	Ultimate load at failure(kN)	Deflection (mm)
Control	26.31	58.95	5.1
Chitin incorporated mix (0.5%)	28.22	62.86	4.8
Metakaolin Incorporated mix (5%)	29.36	62.48	4.3
Combined mix (0.5% chitin + 5% metakaolin)	27.12	61.65	4.5

The results indicate that the control beam exhibited the lowest residual load-carrying capacity after fire exposure (58.95 kN), with a first-crack load of 26.31 kN and a deflection of 5.1 mm. The chitin-incorporated, metakaolin-incorporated, and combined (chitin + metakaolin) beams showed improved residual load-carrying capacity, with ultimate loads of 62.86 kN, 62.48 kN, and 61.65 kN, respectively, along with corresponding first-crack loads of 28.22 kN, 29.36 kN, and 27.12 kN. A reduction in deflection was also observed for these beams (4.8 mm, 4.3 mm, and 4.5 mm, respectively) compared to the control beam. These findings demonstrate that the incorporation of retardant additives enhanced the fire resistance of the beams, resulting in improved post-fire structural performance**.** The comparative load–deflection behaviour of the beams subjected to fire are summarized in Table 14.

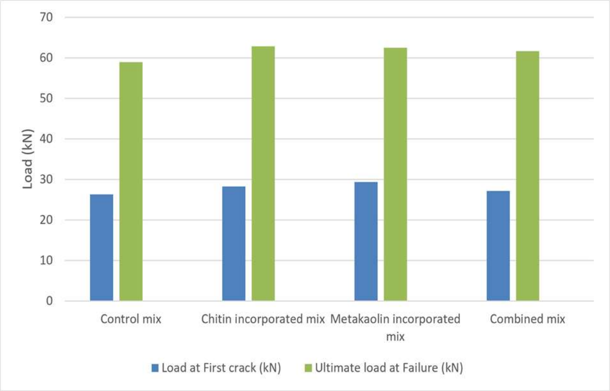


Fig.21 Post-fire Flexural performance of beams (Load at First crack & Ultimate load at failure)

Figure 21 shows the post-fire flexural performance of the beams

Table 14 Load-Deflection Behaviour of Beams subjected to fire

Load (kN)	Deflection (mm)			
	Control	Chitin incorporated mix	Metakaolin incorporated mix	Combined mix
10	0.8	0.6	0.6	0.7
20	1.6	1.3	1.1	0.8
30	2.3	2.1	1.9	1.2
40	3.2	2.8	2.4	1.8
50	4.2	3.5	3.2	2.4
60	-	4.3	3.9	4.2
70	-	-	-	-

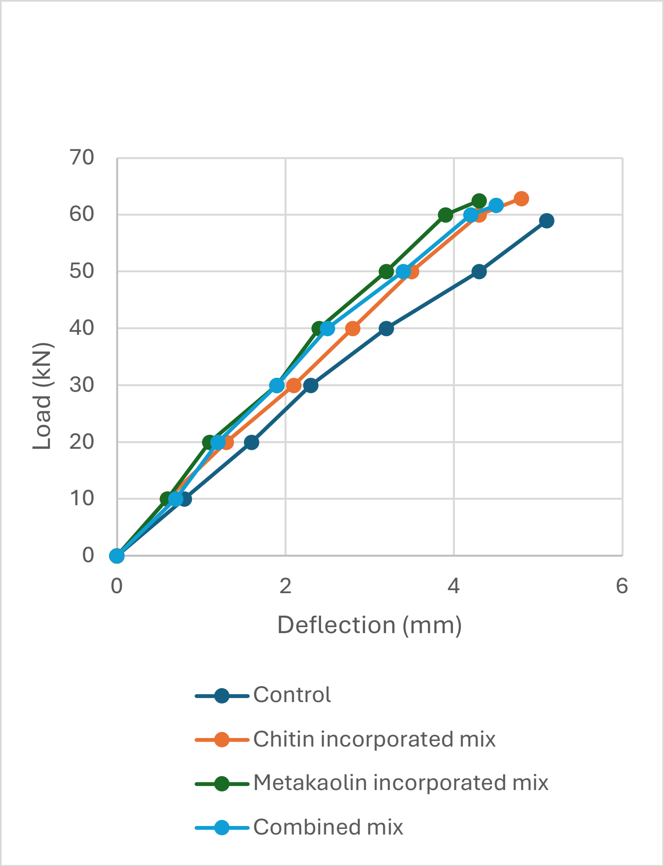


Fig. 22 Load-Deflection Behaviour of beams subjected to fire

Figure 22 shows the load–deflection behaviour of the beams subjected to fire.

Fig.23 Test setup of control beam subjected to fire

Fig.24 Test setup of beam with retardant additives (Chitin) subjected to fire

Fig.25 Test setup of beam with retardant additives (Metakaolin) subjected to fire

Fig.26 Test setup of beam with retardant additives (Combined Chitin & Metakaolin) subjected to fire

Fig.27 Failure crack pattern of control beam

Fig.28 Failure crack pattern of beam with retardant additives (Chitin)

Fig.29 Failure crack pattern of beam with retardant additives (Metakaolin)

Fig.30 Failure crack pattern of beam with retardant additives (Combined Chitin & Metakaolin)

Fig.31 Failure crack pattern of control beam subjected to fire

Fig.32 Failure crack pattern of beam with retardant additives (Chitin) subjected to fire

Fig.33 Failure crack pattern of beam with retardant additives (Metakaolin) subjected to fire

Fig.34 Failure crack pattern of beam with retardant additives (Combined Chitin & Metakaolin) subjected to fire

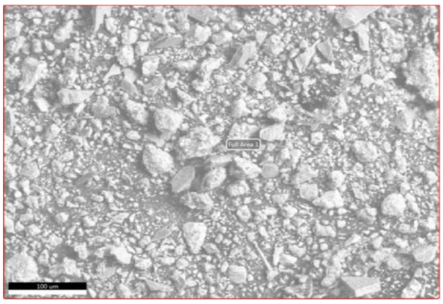
All the tested GFRP reinforced concrete beams showed flexural mode of failure under four-point loading. Failure was governed by bending stresses, with only flexural cracks observed, and no diagonal or inclined cracks observed, indicating no shear failure. Initial cracks appeared in the tension zone at the bottom fibre of the beam within the constant moment region. As the load increased, these cracks propagated vertically towards the compression zone and gradually widened.

L. Scanning Electron Microscope Analysis

SEM–EDX analysis was carried out to investigate the microstructure, hydration products, and elemental composition of the control, chitin-incorporated, and metakaolin-incorporated concrete specimens.

1. *SEM-EDX analysis of control concrete*

The SEM–EDX analysis of the control concrete specimen is presented in Figure 36. The EDX spectrum indicates oxygen (46.7 wt.%), calcium (19.9 wt.%), and silicon (9.2 wt.%) as the major elemental constituents. The relatively high oxygen content together with calcium reflects the presence of hydration products within the cement matrix. The coexistence of calcium and silicon confirms the formation of calcium silicate hydrate (C–S–H) gel, the primary binding phase responsible for strength development in concrete. The results indicate the development of a well-hydrated cementitious matrix in the control specimen



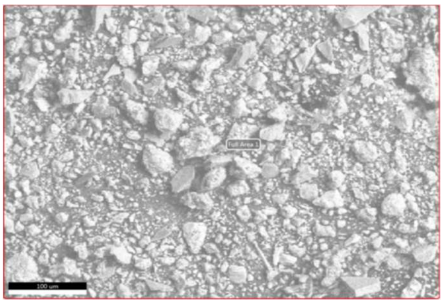
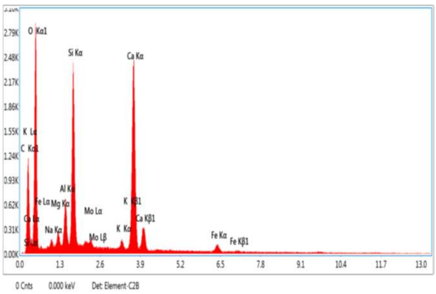


Fig.35 SEM Microstructure of Control concrete



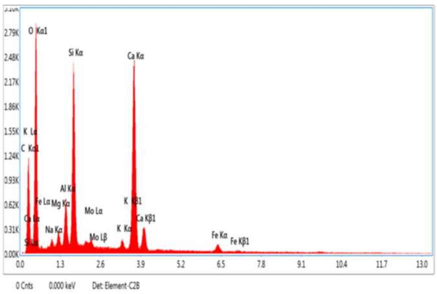


Fig 36 SEM–EDX Analysis Showing Elemental Composition of Control concrete

2. *SEM-EDX analysis of chitin incorporated concrete*

The SEM–EDX analysis of the chitin-incorporated concrete specimen is presented in Figure 38. The EDX spectrum indicates oxygen (48.2 wt.%), calcium (27.5 wt.%), and silicon (11.5 wt.%) as the major elemental constituents. Compared with the control specimen, higher calcium and silicon contents indicate increased formation of hydration products and calcium silicate hydrate (C–S–H) gel, resulting in improved matrix development and confirming a denser and more hydrated microstructure in the chitin-incorporated concrete specimen.

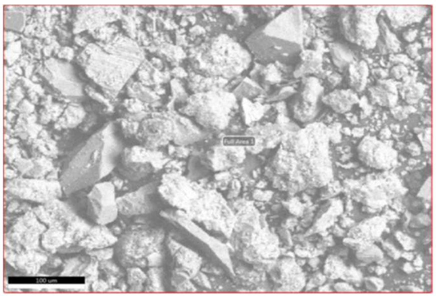


Fig.37 SEM Microstructure of Chitin incorporated concrete

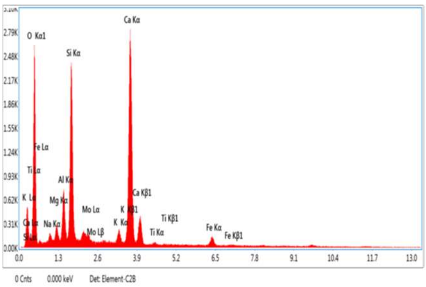


Fig 38 SEM–EDX Analysis Showing Elemental Composition of Chitin incorporated concrete

3. *SEM-EDX analysis of metakaolin incorporated concrete*

The SEM–EDX analysis of the metakaolin-incorporated concrete specimen is presented in Figure 40. The EDX spectrum indicates oxygen (46.6 wt.%), calcium (21.9 wt.%), and silicon (9.3 wt.%) as the major elemental constituents. Compared with the control specimen, the higher calcium and silicon contents indicate increased formation of hydration products and calcium silicate hydrate (C–S–H) gel. The pozzolanic activity of metakaolin, where reactive silica and alumina react with calcium hydroxide released during cement hydration, contributes to additional C–S–H gel formation, resulting in improved matrix development and confirming a more hydrated and refined cementitious matrix.

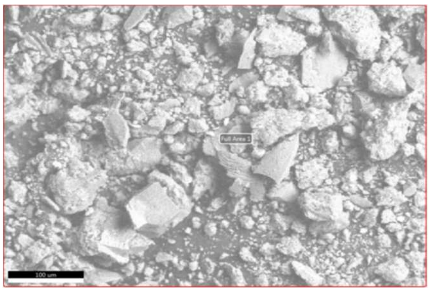


Fig.39 SEM Microstructure of Metakaolin incorporated concrete

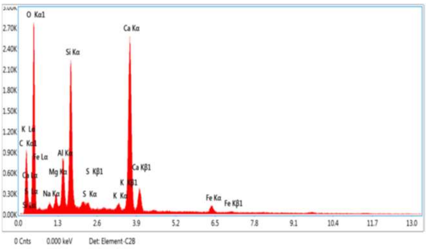


Fig 40 SEM–EDX Analysis Showing Elemental Composition of Metakaolin incorporated concrete

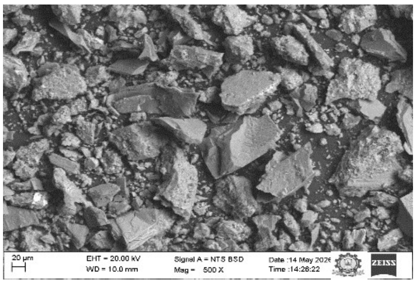


Fig.41 SEM Microstructure of Control concrete subjected to fire

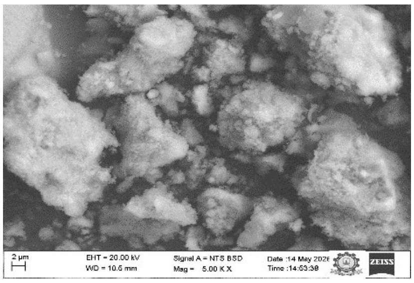


Fig.42 SEM Microstructure of Chitin incorporated concrete subjected to fire

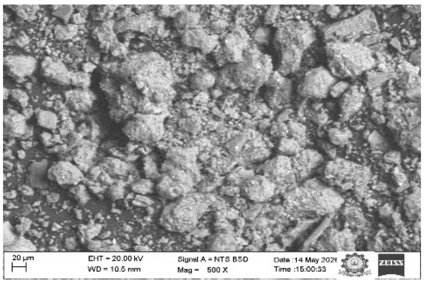


Fig.43 SEM Microstructure of Metakaolin incorporated concrete subjected to fire

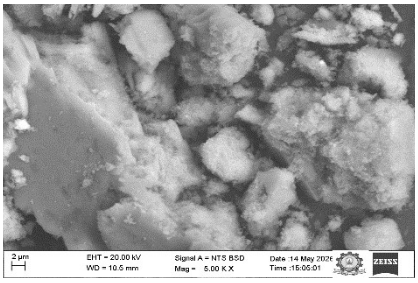


Fig.44 SEM Microstructure of combined Chitin &Metakaolin incorporated concrete subjected to fire

VI. CONCLUSION

The experimental investigation on the durability and fire resistive analysis of GFRP bars with retardant additives in RC beams was conducted to evaluate the influence of the additives on the workability and compressive strength of concrete, durability performance, flexural behaviour under four-point loading, and post-fire performance of GFRP-reinforced beams.

The workability of concrete decreased gradually with increasing content of chitin and metakaolin.

The compressive strength results indicate that 0.5% chitin-incorporated and 5% metakaolin-incorporated mixes achieved higher strength and were identified as the optimum mixes for casting GFRP-reinforced beams and conducting durability tests.

The durability tests conducted on concrete specimens, including water absorption, acid resistance, and carbonation, indicate that the incorporation of chitin and metakaolin in concrete enhances resistance to moisture ingress, chemical attack, and carbonation, resulting in improved performance compared to the control specimens.

The four-point loading test on GFRP-reinforced beams indicate that, under normal conditions, the control beam exhibited the highest ultimate load-carrying capacity of 68.32 kN, compared to the chitin-incorporated (66.16 kN), metakaolin-incorporated (63.84 kN), and combined (chitin+metakaolin) (66.80 kN) beams. However, the additive-incorporated beams also exhibited satisfactory flexural performance, with only a slight reduction in ultimate load-carrying capacity compared to the control beam.

The beams subjected to fire exposure and tested under four-point loading demonstrated lower flexural performance compared to the beams tested under normal conditions. The post-fire performance of the GFRP-reinforced beams indicates that the control beam showed a significant reduction in residual load-carrying capacity to 58.95 kN, along with higher deflection and multiple cracks. The chitin-incorporated (62.86 kN), metakaolin-incorporated (62.48 kN), and combined (chitin +

metakaolin) (61.65 kN) beams exhibited enhanced post-fire performance compared to the control beam

The SEM–EDX analysis of the control, chitin-incorporated, and metakaolin-incorporated concrete specimens confirmed the formation of a well-hydrated cementitious matrix, with oxygen, calcium, and silicon as the major elemental constituents. Compared to the control specimen, the chitin- and metakaolin-incorporated specimens exhibited higher calcium and silicon contents, indicating increased formation of hydration products and calcium silicate hydrate (C–S–H) gel. These microstructural observations indicate a denser, more refined, and improved cementitious matrix in the additive-incorporated concrete specimens.

Overall, the investigation indicates that GFRP-reinforced concrete beams exhibit reduced performance when subjected to fire exposure with a consequent reduction in flexural performance, whereas the incorporation of chitin and metakaolin as retardant additives significantly improves fire resistance and enhances post-fire flexural performance. The combined experimental and SEM–EDX results confirm that these retardant additives contribute to improved durability and fire resistance of GFRP-reinforced concrete structures.

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