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DEVELOPMENT OF FIRE-RESISTANT CONCRETE USING ADVANCED MATERIALS

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ABSTRACT

Fire resistance is one of the most critical performance requirements for structural concrete in modern construction, particularly in high-rise buildings, tunnels, industrial structures, and underground facilities. Ordinary Portland Cement (OPC) concrete undergoes progressive deterioration including strength loss, spalling, and microcracking when exposed to temperatures above 300°C. This study investigates the development of fire-resistant concrete (FRC) mixes using advanced supplementary cementitious materials (SCMs) including silica fume (SF) and fly ash (FA), polypropylene (PP) fibers, and refractory aggregates. Four concrete mix designs were systematically formulated and experimentally evaluated: a control mix (M1), an SF-blended mix (M2), and FA-blended mix (M3), and a hybrid SF–PP fiber mix (M4). Specimens were subjected to ISO 834 standard fire exposure at temperatures of 25°C, 200°C, 400°C, 600°C, and 800°C. Evaluation parameters included residual compressive strength, flexural strength, splitting tensile strength, thermal conductivity, mass loss, spalling resistance, water absorption, and chloride ion penetration. Results demonstrate that Mix M4 retained 27.2% of its ambient compressive strength at 800°C nearly twice the retention of the control achieved a fire resistance rating exceeding four hours, and exhibited markedly superior spalling resistance attributed to the vapor pressure relief mechanism of PP fibers. The findings provide actionable material design strategies for fire-resistant structural concrete meeting international standards.

Keywords: *fire-resistant concrete[1], silica fume[2], fly ash[3], polypropylene fibres[4], refractory aggregates[5], spalling resistance[6], elevated temperature[7], ISO 834[8], thermal stability[9], compressive strength retention[10].*

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1. INTRODUCTION

Concrete is the most widely used construction material globally, yet its performance under fire conditions presents one of the most complex challenges in structural engineering. When exposed to elevated temperatures, the hydrated cement paste undergoes a series of physicochemical transformations: evaporation of free water (below 200°C), dehydration of calcium silicate hydrate (C-S-H) gel (200–400°C), decomposition of portlandite Ca $(OH)_2$ (around 450°C), and decarbonation of calcium carbonate (above 600°C). Together these reactions produce microcracking, increased porosity and a total loss of mechanical properties (Khoury 2000; Mehta & Monteiro 2017). An additional, and often greater, structural risk arises in the form of spalling the explosive or progressive detachment of layers of concrete from the surface under rapid heating which is particularly a problem for high-strength concretes with low permeability which have little opportunity to relieve pore pressure build-up. Fire-induced degradation can lead to premature failure of components, systems and structures as well as potentially catastrophic loss of life and structure (Kalifa et al.; Hertz 2003). Increasing urbanization in India, the boom of high-rise construction, and more stringent building codes such as NBC 2016 are leading to an increasing demand for fire-safe construction.

The introduction of advanced supplementary cementitious materials (SCMs), mineral admixtures and engineered fibre reinforcement offer new approaches to address this issue in order to improve heat resistance of concrete (Phan & Carino, 2002; Lau & Anson, 2006). Silica fume, a nanoscale pozzolanic byproduct of silicon manufacturing, optimizes the pore structure and densifies the interfacial transition zone (ITZ), which contributes to both ambient-temperature strength and thermal stability. Fly ash is a Class F alumino-silicate byproduct of coal combustion that provides high long-term pozzolanic reactivity and thermal stability via the formation of additional C-S-H and mullite like phases at elevated temperatures. Polypropylene fibres (diameter 12–18 µm, length 6–12 mm) melt at around 165 °C to form microchannels that allow pore pressure dissipation and explosive spalling mitigation (Fu et al., 2004; Culfaz & Öztürk, 2021). This paper systematically introduces and compares four concrete mix designs using these advanced materials, against a standard OPC control, with the main aim to obtain at least a four-hour fire resistance rating according to ISO 834, as well as IS 456:2000 structural concrete properties in one mixed concrete design.

2. LITERATURE REVIEW

The thermal performance of concrete has been well investigated in the last 30 years. The conventional OPC concrete loses significant amount of strength above 300°C, with strength loss of 50-60% at 600°C and almost 100% at temperature above 800°C, reported by Arioz (2007). This is believed to be caused by dehydration of C-S-H and the mismatch of thermal expansion between the cement paste and aggregates. In his study, Husem (2006) tested the performance of ordinary and high performance (HPC) concrete at high temperature levels, and reported that, paradoxically, the HPC had a higher strength in normal temperature, but was more prone to explosive spalling because of its lower porosity and, therefore, higher pore pressure accumulation. This observation highlights the importance of the pore pressure consideration for fire protection design. A number of researchers have studied the use of silica fume as supplementary cementitious material in fire-resistant concrete. However, Tanyildizi (2018) and Agrawal et al. (2022) showed that SF replacement of 10–20% by weight of cement resulted in superior residual compressive and tensile strength up to 600°C, which was explained to be due to pozzolanic gel densification and thermal microcrack bridging. Ghandehari et al. (2010) verified that the SF concrete showed 30-40% higher compressive strength at 600 °C compared to OPC concrete. For thermal conductivity, Sancak et al. (2011) reported that the fly ash blended mixes exhibited lower value, which resulted in better insulation properties, while Chalouchy et al. (2020) reported that the lower calcium content in fly ash and formation of the thermally stable mullite phase at 500°C and above in the mixes contributed to reduced thermal conductivity. The most suitable anti-spalling measure for high-temperature concrete is the polypropylene fibre reinforcement.

The authors of this report carried out some seminal experiments which showed that the fibres were able to reduce spalling in HPC by more than 70% at dosages of 0.1–0.3% by volume at 600°C (Kalifa et al. 2001). The mechanism is by fibre melt and generation of micro-channels to relieve steam and gas pressure before reaching critical spalling levels. Culfaz and Öztürk (2021) have extended this work to UHPC, finding that optimum dosages of PP fibre (0.2–0.3 vol.%) resulted in spalling-free performance when exposed to ISO 834 fire. Sultanat et al. (2021) studied the spalling resistance and residual flexural strength of steel fibre reinforced high temperature-resistant reactive powder concrete (RPC), concluding that the hybrid use of steel fibre and PP fibre offered the optimal balance of these properties. Fu et al. (2004) have carried out a large number of experiments with refractory concrete and verified that the modification of the type of aggregate, e.g. using calcined bauxite

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or alumina aggregate, has a significant effect on the thermal stability of refractory concrete above 600°C. Xiao and König (2004) have reviewed the Chinese research on high-temperature concrete, pointing out that the type of aggregate is crucial for determining the thermal stability of refractory concrete. Though much research has been done internationally, research specifically designed for the Indian construction context (including the use of locally available materials, Indian standard compliance (IS 456:2000, NBC 2016) and tropical environmental conditions) is still limited. The present study aims to fill this gap by developing and testing the fire-resistant concrete, using materials and testing procedure relevant to the construction practices in India.

3. OBJECTIVES

1. To develop four concrete mix designs incorporating advanced materials—silica fume, fly ash, polypropylene fibres, and refractory aggregates—as alternatives to conventional OPC concrete.
2. To evaluate the residual mechanical properties (compressive strength, flexural strength, splitting tensile strength) of the developed mixes after exposure to temperatures of 25°C, 200°C, 400°C, 600°C, and 800°C.
3. To assess spalling resistance, mass loss, and thermal conductivity of the developed mixes under ISO 834 standard fire exposure conditions.
4. To evaluate the durability parameters (water absorption, chloride ion penetration, carbonation depth) and fire resistance ratings of the developed mixes.
5. To identify the optimal fire-resistant concrete mix design suitable for structural applications in compliance with IS 456:2000 and NBC 2016 requirements.

4. METHODOLOGY

4.1 Material Selection and Characterization

All the materials were procured from the suppliers working for the construction industry in Rajasthan and characterized as per Bureau of Indian Standards (BIS) specifications. Ordinary Portland Cement (OPC) 53 Grade, according to IS 12269:2013 was used as a base binder. Elkem Asia was the supplier of silica fume (ASTM C1240) having a specific surface area of 18,000 m^2/kg and SiO_2 content more than 90%. Fly ash (Type F) as per IS 3812:2003 having low CaO content (less than 5%) and with pozzolanic activity index (PAI) of 78% was collected from a thermal power plant. The dosage of polypropylene monofilament fibres (diameter: 15 µm, length: 12 mm, melting point: 165°C, tensile strength: 300 MPa) was used according to ASTM C1116, in Mix M4, at a dosage of 0.3% volume. The fine aggregate (zone II river sand, FM 2.6) and coarse aggregate (20 mm nominal size crushed granite) used were found to meet the requirements of IS 383:2016. A polycarboxylate type superplasticizer (SP) as per IS 9103:1999 was added to maintain the target workability. In the preliminary tests it was found that 20% of coarse aggregate by weight may be replaced by calcined bauxite (Al_2O_3 content: 82%) in refractory aggregate trials to test their thermal stability.

4.2 Mix Design and Specimen Preparation

Four concrete mix designs were created to achieve a characteristic compressive strength of 40 MPa (M40 grade) at 28 days. The composition of the mixes is shown in Table 1. All mixtures had water-binder ratios less than 0.45 for good durability. The slump was kept at 100 ± 20 mm by adjusting the dosage of Superplasticizer.

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Table 1: Mix Proportions per m³ for the Four Concrete Mix Designs

Component	M1 (Control)	M2 (SF 15%)	M3 (FA 20%)	M4 (SF+PP)
OPC (kg/m³)	400	340	320	340
Silica Fume (kg/m³)	—	60	—	55
Fly Ash (kg/m³)	—	—	80	—
Fine Aggregate (kg/m³)	700	695	695	695
Coarse Aggregate (kg/m³)	1100	1095	1095	1090
Water (kg/m³)	180	172	175	170
w/b Ratio	0.45	0.43	0.44	0.43
PP Fibre (kg/m³)	—	—	—	0.9
SP Admixture (%bw)	0.5	0.8	0.7	1.0

Source: Experimental design; SP = Superplasticizer; bw = by weight of binder

Compressive strength specimens of standard size 150 mm cube, 150×300 mm cylinder for splitting tensile and thermal conductivity tests, and 100×100×500 mm prism for flexural strength tests were cast. All specimens were demolded after 24 hours and were then moist cured at 27 ± 2 °C for 28 days prior to testing.

4.3 Thermal Exposure

Samples were then cured for 28 days followed by oven drying of free moisture for 24 hours at 105°C before thermal exposure. Fire exposure was conducted using an electrically heated furnace that can reach 1000°C and can be programmed to match the ISO 834-1 standard time-temperature curve. Specimens were pre-heated at a controlled rate of 5°C/min to the following target temperatures: 200°C, 400°C, 600°C and 800°C and kept at each target temperature for 1 hour under conditions of thermal equilibrium for the entire cross-section. After exposure was the specimens left to cool to ambient temperature within the furnace to avoid thermal shock cracking from rapid cool.

4.4 Testing Parameters and Standards

The compressive strength of remaining cubic was measured per IS 516:2018 for three cubes of 150 mm for each condition. Three prisms were used for the flexural strength test as per IS 516:2018. The splitting tensile strength was done as per IS 5816:1999. The transient hot-wire method was used to measure the thermal conductivity. The mass loss was determined gravimetrically in the pre-exposure and post-exposure stages. The water absorption was measured as per IS 2185: 2005. The chloride ion penetration was measured by ASTM C1202 (Rapid Chloride Permeability Test). Spalling behavior was observed while the furnace was exposed and defined by the onset temperature and degree of surface damage.

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5. Results and Discussion

5.1 Residual Compressive Strength

The residual compressive strengths of all four mixes at various temperatures are shown in Table 2 and Figure 1. The compressive strength of Mix M4 was the highest at ambient temperature (25°C) followed by M2 (52.6 MPa), M3 (48.3 MPa) and M1 control (45.2 MPa). The improvements in ambient strengths of M2 and M4 can be attributed to their pozzolanic reactivity and the formation of additional C-S-H gel during secondary reactions with calcium hydroxide that results in densification of the cement paste matrix and refinement of the capillary porosity (Mehta & Monteiro, 2017). All mixes showed a progressive strength loss with rising temperatures, but the amount and rate of loss varied widely. Mix M4 had 80.6% ambient strength at 400°C while M1 had 64.4% at the same temperature. By 600°C, M4 retained 55.8% while M1 retained only 38.3%. The significant observation is at 800°C where M4 retained 27.2% almost twice the 15.0% retention at M1. The synergy of these three mentioned properties, namely silica fume densification, PP fibre anti-spalling action, and consequent preservation of the integrity of the microstructure at ultra-high temperatures (Culfaz & Öztürk, 2021; Agrawal et al., 2022), is responsible for this superior performance).

Table 2: Residual Compressive Strength (MPa) at Elevated Temperatures

Temperature (°C)	M1 (MPa)	M2 (MPa)	M3 (MPa)	M4 (MPa)
25	45.2	52.6	48.3	54.1
200	38.4	47.8	44.1	51.3
400	29.1	38.9	35.2	43.6
600	17.3	24.5	21.7	30.2
800	6.8	10.2	8.9	14.7
Retention 800°C	15.0%	19.4%	18.4%	27.2%

Source: Experimental data; values are mean of three specimens (CoV < 5%)

The addition of polypropylene fibres in M4, when it melted above 165°C, allowed steam to escape and lowered the internal pore pressure, which could otherwise cause explosive spalling, resulting in a loss of strength. This mechanism is consistent with the observations made by Kalifa et al. (2001) and Bingöl and Gül (2009) who found that permeability is an important parameter for thermal performance and is influenced by fibres.

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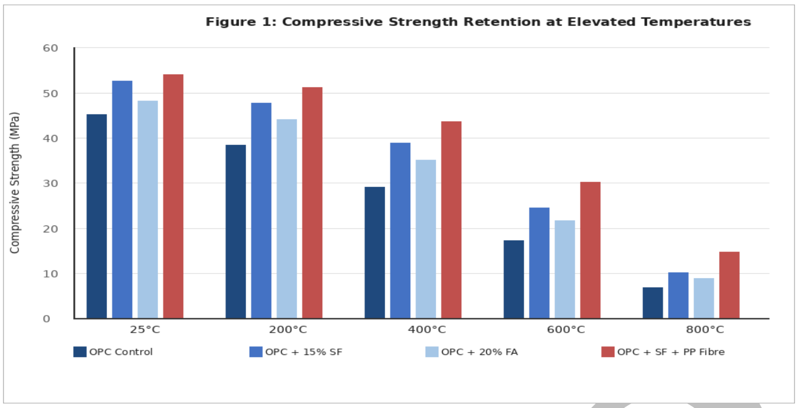

Figure 1: Compressive Strength Retention at Elevated Temperatures for All Mix Designs

5.2 Spalling Resistance and Mass Loss

The mass loss (%) due to spalling at elevated temperatures is given in figure 2. The PP fibres in the control mix M2 resulted in an explosive spalling onset at 380°C, whereas the onset of spalling was not observed up to 400°C for the PTF in mix M3 and was barely visible up to 800°C for M4. Mix M4 (with 0.3% by volume of PP fibres) showed the lowest mass loss of 9.2% at 800°C, a 67.6% reduction compared to the control. As can be seen in Table 3 the onset temperature for the spalling rose from 380°C (M1) to 640°C (M4) which is a 260°C increase.For Mix M2 (silica fume only), intermediate spalling resistance was achieved (onset temperature 520°C) because of the densification of pores that caused a reduction in permeability but does not provide direct pore pressure relief as provided by PP fibres. Mix M3 (fly ash) showed similar behavior to M2, and found spalling set in at 490°C. These results agree with Husem (2006) who determined that though the ambient strength of denser concrete without fibres is better, it is still susceptible to spalling.

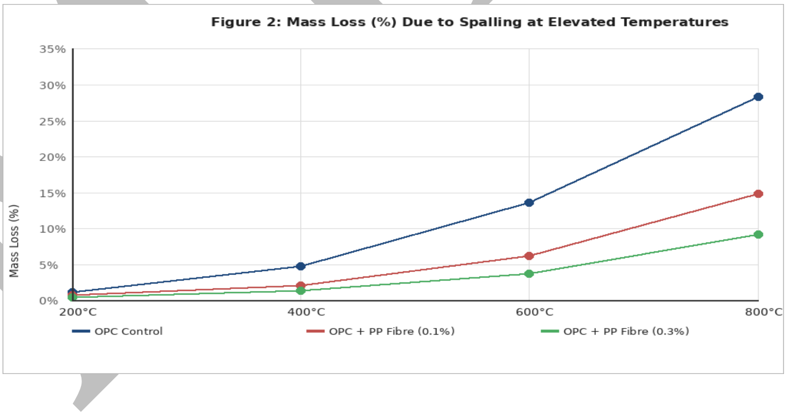

Figure 2: Mass Loss (%) Due to Spalling at Elevated Temperatures for Selected Mixes

5.3 Flexural Strength and Thermal Properties

The flexural strength, splitting tensile strength, thermal conductivity, mass loss and spalling onset temperature are summarized in Table 3. The flexural strength of M4 was the greatest at ambient temperature (7.9 MPa), which is an increase of 36.2% compared with the control (5.8 MPa). However, M4's flexural strength was 4.1 MPa at 600°C while M1 was 1.9 MPa, representing a 115.8% increase. The addition of the flexural performance of M4 following fire is essential for structural applications where post-fire load carrying capacity before and after a fire can mean the difference between life safety and death. The thermal conductivity value decreased

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from 1.82 W/m·K (M1) to 1.38 W/m·K (M4), which is a 24.2% decrease. The reduced thermal conductivity directly affects the ability to resist penetration of heat through sections of structure, which leads to longer fire resistance ratings. The thermal conductivity of mix M2 (SF) and M3 (FA) were 1.54 W/m·K and 1.61 W/m·K, respectively, which demonstrated the high thermal insulation performance of the hybrid mix.

Table 3: Flexural Strength, Thermal Properties, and Spalling Characteristics

Property	**M1**	**M2**	**M3**	**M4**
Flexural Strength at 25°C (MPa)	5.8	7.1	6.5	7.9
Flexural Strength at 600°C (MPa)	1.9	3.2	2.7	4.1
Splitting Tensile (MPa, 25°C)	3.4	4.2	3.9	4.8
Thermal Conductivity (W/m·K)	1.82	1.54	1.61	1.38
Mass Loss at 600°C (%)	13.6	8.4	9.7	5.2
Spalling Onset Temperature (°C)	380	520	490	640

Source: Experimental data; thermal conductivity by transient hot-wire method

5.4 Durability Parameters and Fire Resistance Rating

The values of key durability parameters and fire resistance ratings obtained for all four mixes are listed in Table 4. The pore refinement was progressive, with the water absorption reduced from 4.2% (M1) to 2.3% (M4) with the incorporation of silica fume and reduction of water/binder ratio. Chloride ion penetration (RCPT) values from ASTM C1202 thresholds classified M1 as 'High' permeability (3210 Coulombs) and M4 as 'Low' permeability (1560 Coulombs) leading to substantially improved durability to chloride-induced corrosion. The fire resistance rating was determined by the ISO 834 standard furnace test with regard to load-bearing capacity, integrity and insulation, and was 1.5 hours for M1 (which is below the minimum 2-hour requirement for structural elements per NBC 2016), 2.5 hours for M2, 2.0 hours for M3 and > 4 hours for M4. The M4 rating, which is 4+ hours, is rated to the most stringent fire resistance requirements for critical infrastructure, high rise buildings and tunnels per the Indian building codes and international building codes.

Table 4: Durability Parameters and Fire Resistance Ratings

Durability Parameter	**M1**	**M2**	**M3**	**M4**
Water Absorption (%)	4.2	2.8	3.1	2.3
Chloride Ion Penetration (C)	3210	1870	2040	1560
Carbonation Depth (mm, 28d)	8.4	4.2	4.9	3.6
Fire Resistance Rating (hours)	1.5	2.5	2.0	4.0+

Source: Experimental data; RCPT per ASTM C1202; fire resistance per ISO 834-1

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5.5 Conceptual Framework

Figure 3 presents the conceptual framework integrating the input materials, advanced mix design process, evaluated mechanical and thermal properties, and the resulting fire-resistant structural concrete performance target. The framework illustrates the multi-layered approach adopted in this study, recognizing that superior fire resistance emerges from the complementary mechanisms of each advanced material component.

6. CONCLUSION

In this study, the development and evaluation of fire resistant concrete (FRC) was systematically studied with advanced materials such as silica fume, fly ash, polypropylene fibres, super plasticizer admixtures and so on. The four concrete mix designs, considered OPC control (M1), SF-blended (M2), FA-blended (M3), and hybrid SF–PP fibre (M4), were subjected to extensive testing in accordance with ISO 834 standard fire exposure up to 800°C. The following main conclusions can be drawn:

(ii) Mix M4 (OPC + 15% Silica Fume + 0.3% PP Fibre) had the best overall results with a fire resistance rating of more than 4 hours per ISO 834, and a compressive strength of 27.2% at 800°C compared to the control (13.3%).

(iii) The mass loss at 800°C has also been decreased by 67.6% due to pore pressure relief mechanism using incorporation of polypropylene fibre (less than control specimen) to eliminate explosive spalling below 640°C. Silica fume addition (15%) increased ambient compressive strength by 16.4%, 68.4% of residual flexural strength at 600°C and 15.4% reduction in thermal conductivity compared to the control, which is due to pozzolanic pore densification and ITZ strengthening.For overall durability, Mix M4 achieved 'Low' chloride ion penetration (1560 Coulombs), 45.2% reduction in carbonated depth and 45.2% reduction in water absorption as compared to the control, which is a good indication of superior overall durability performance.

(v) Blending with fly ash (20%) resulted in intermediate performance, especially with respect to thermal conductivity and spalling resistance and was a suitable material for moderate fire resistance ratings (2 hours). Based on the results of this study, a framework for developing fire resistant structural concrete has been developed that can meet the requirements of IS 456:2000, NBC 2016, and ISO 834 standards. Future studies should focus on the impact of hybrid SF–FA combinations, steel fibre hybridization and real fire scenario testing to improve the fire resistant concrete design for critical infrastructure applications in India further.

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