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EFFECTS OF POLYPROPYLENE FIBRES AND MICRO SILICA ON THE STRENGTH AND FIRE RESISTANCE OF M40 GRADE CONCRETE

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ABSTRACT

This study evaluates the effects of polypropylene (PP) fibers and micro silica additives on the mechanical and thermal performance of concrete. Four concrete mixes (M0 to M3) with varying additive proportions were tested for compressive strength, split tensile strength, impact resistance, heat penetration, and structural integrity after exposure to elevated temperatures (300°C and 800°C). Results show that micro silica significantly enhances compressive and tensile strength by improving bonding and matrix density, with Specimen M3 achieving the highest strength. Excessive PP fiber content in Specimen M2 reduced strength due to poor bonding and increased porosity. Impact resistance improved with a balanced combination of fibers and micro silica, while thermal exposure tests revealed Specimen M1 retained superior residual strength and structural integrity. Heat penetration was lowest in specimens with additives, indicating better thermal insulation. Moreover, specimens with additives resisted shattering upon impact, highlighting improved toughness. Overall, optimized use of PP fibers and micro silica improves concrete's strength, durability, and fire resistance, making it suitable for high-performance construction applications.

Keywords: polypropylene fiber, micro silica, compressive strength, thermal resistance, impact resistance.

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1. INTRODUCTION

Concrete, a fundamental construction material, is a composite consisting primarily of water, cement (binder), and aggregates, with optional inclusion of admixtures and reinforcing agents. Upon mixing, these components form a workable paste that can be molded into various shapes and, over time, hardens into a durable, stone-like mass (Neville & Brooks, 2010). Concrete's versatility, strength, and durability make it one of the most widely used construction materials globally. The binder component in concrete is typically Portland cement, which acts by setting and hardening through a hydration process. Ordinary Portland Cement (OPC), the most commonly used type, is produced by calcining a blend of limestone ($CaCO_3$) and argillaceous materials such as shale or clay at approximately 1450 °C. This high-temperature process yields a hard intermediate product called clinker, which is then ground with gypsum to produce cement (Taylor, 1997). While cement provides the essential binding action, its production is energy-intensive and contributes significantly to CO_2 emissions, prompting increased research into supplementary materials and efficient alternatives (Scrivener, John, & Gartner, 2018). Aggregates occupy roughly 70-80% of the concrete volume and play a crucial role in its structural performance and economy. They are broadly classified into fine aggregates (typically sand, passing through a 4.75 mm sieve) and coarse aggregates (generally gravel or crushed stone retained on a 4.75 mm sieve). Previously considered inert fillers, modern research acknowledges the chemical and physical interactions between aggregates and the cement matrix, particularly at the interfacial transition zone (Mehta & Monteiro, 2014). With escalating demand and environmental concerns surrounding river sand mining, manufactured sand (M-sand) has emerged as a sustainable alternative, offering consistent quality and availability (SCC & Khatib, 2017).

Admixtures, defined as materials other than water, aggregates, and cement added to the concrete mix either before or during mixing, are employed to modify fresh and hardened concrete properties. These include plasticizers, superplasticizers, retarders, accelerators, and bonding agents, each tailored to meet specific performance criteria under varying environmental and structural demands (ACI Committee 212, 2010). In the pursuit of more advanced materials, high-strength concrete (HSC) has gained prominence for its superior compressive strength, lower permeability, and enhanced durability compared to normal-strength concrete. HSC enables reduced member sizes and longer spans, thus optimizing design and cost efficiency (Neville, 2011). However, a critical limitation of HSC is its brittle nature and poor performance under high-temperature conditions such as fire exposure. This vulnerability can compromise the integrity of structural components during extreme events (Khoury, 2000).

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Table-1. Literature review on polypropylene fibers and silica-based additives in concrete.

Author(s) and Year	Objective	Findings
Sadrmomtazi *et al.* (2014)	Investigated mechanical properties of concrete with polypropylene fibers and silica fume.	Combined use improved both compressive and tensile strengths significantly.
Fallah & Nematzadeh (2016)	To investigate the effects of different amounts of polypropylene (PP) and macro-polymeric (MP) fibers on the mechanical properties and durability of high-strength concrete containing silica fume and nano-silica.	Nano-silica and silica fume improved concrete mechanical properties and durability. Macro-polymeric fibers improved mechanical properties. High volume fractions of polypropylene fibers had negative effects.
Piroti *et al*. (2019)	To experimentally assess the effect of polypropylene fibers on the improvement of nano-silica concrete behavior, considering the water-cement ratio.	Significant improvement in mechanical properties (compressive, abrasion, tensile, flexural strength) and permeability. Tensile strength, flexural strength, and abrasion resistance increased by up to 22%, 40%, and 27%, respectively.
Elkatatny *et al*. (2020)	To evaluate the effect of adding polypropylene fiber (PPF) to Saudi Class G cement under HPHT conditions on cement quality.	PPF significantly decreased thickening time (e.g., 0.75% BWOC reduced by 75%), improved tensile (18% with 0.75% PPF) and compressive (17.8% with 0.5% PPF) strength, and decreased porosity and permeability by filling pores.
Hassan *et al.* (2023)	To experimentally study the properties of ultra-high-strength geopolymer concrete with polypropylene fibers and nano-silica.	Optimal 2% PPF and 10% NS significantly improved compressive, splitting tensile, flexural, and bond strength; enhanced drying shrinkage, fracture, and elevated temperature resistance.

To address this challenge, fiber-reinforced concrete (FRC) has been introduced, incorporating short, randomly distributed fibers into the matrix. Polypropylene fibers, in particular, are recognized for their ability to enhance spalling resistance under fire by melting and creating microchannels for vapor escape, thereby reducing internal pressure (Kodur & Phan, 2007). Additionally, microsilica (silica fume), a by-product of silicon and ferrosilicon alloy production, has been shown to improve the density and bond strength of the concrete matrix. Combined, these materials can significantly improve fire resistance and post-fire mechanical performance (Behnood & Ghandehari, 2009).

A notable study found that concrete specimens incorporating 0 to 3 kg/m^3 polypropylene fibers and 0 to 10% microsilica (by weight of cement) exhibited higher residual compressive strength after exposure to temperatures of 100°C and 600°C for up to 8 hours compared to control specimens. These findings highlight the synergistic effect of fiber and pozzolanic additions in enhancing fire resistance (Behnood & Ghandehari, 2009). Table-1 summarizes key studies from 2014 to 2023 on the effects of polypropylene fibers (PPF) and silica-based additives (silica fume [SF] and nano-silica [NS]) on concrete properties, including compressive strength, tensile strength, and fire resistance.

The primary objectives of this research are to evaluate the mechanical and fire-resistant performance of M40 grade concrete modified with composite additives. Specifically, the study aims to assess the compressive and split tensile strengths of concrete incorporating an 8% composite addition made up of varying proportions of micro silica and polypropylene fibers in 50-50%, 75-25%, and 25-75% combinations. Furthermore, the research investigates the fire resistance of these concrete mixes by subjecting them to elevated temperatures, analyzing the residual mechanical performance after thermal exposure.

2. EXPERIMENTATION

2.1 Materials

This study investigates the effects of incorporating polypropylene fibres and micro silica powder into M40 grade concrete to enhance its strength and fire resistance characteristics.

2.1.1 Polypropylene fibre

Polypropylene is a thermoplastic polymer widely used in various industries due to its durability and

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chemical resistance. In this study, fibrillated polypropylene fibres with a length of 12 mm and diameter of 34 microns were used, having a low density of 0.9 kg/m³. These fibres are non-hydrophilic, chemically inert, and exhibit resistance to alkalis, chlorides, and heat transfer. When added to concrete, polypropylene fibres reduce the formation of microcracks during curing, thereby enhancing the structural integrity and durability of the concrete. They are particularly beneficial in applications subjected to cyclic or fatigue loading, such as pavements, bridge decks, offshore structures, and machine foundations. However, fibre addition slightly reduces workability. The optimum dosage for improved fire resistance was found to be 0.45 kg/m³, significantly reducing strength loss at high temperatures (e.g., 600°C for 6 hours).

2.1.2 Micro silica powder

Micro silica, also known as silica fume, is an amorphous, ultrafine form of silicon dioxide collected as a by-product of silicon or ferrosilicon alloy production. The material used in this study had a fineness of 3% retained on the 45-micron sieve. With an average particle size of 0.15 µm and a specific gravity between 2.2 and 2.3, micro silica enhances concrete properties through its high pozzolanic activity. It fills the micro voids between cement particles, reducing permeability, improving aggregate bonding, and increasing durability and strength. Micro silica also contributes to improved pumpability, reduced bleeding, low heat of hydration, and a superior surface finish.



Figure-1. Sample of polypropylene fibre and micro silica powder.

2.2 Concrete Mix Design and Casting

The mix design for M40 grade concrete was carried out by IS 10262:2009 and IS 456:2000 (Bureau of Indian Standards, 2009, 2010), targeting a characteristic compressive strength of 40 MPa and a mean strength of 48.25 MPa. A water-cement ratio of 0.40 was adopted, and based on a water content of 180 kg/m³, the required cement content was calculated as 450 kg/m³. Volume batching was done using the specific gravities of cement (3.15), fine aggregate (2.6), and coarse aggregate (2.6), leading to a finalized mix ratio of 1:1.386:2.411 (Cement: Fine Aggregate: Coarse Aggregate). The concrete mix was modified by partially replacing cement with micro silica and polypropylene (PP) fibres to evaluate the improvement in mechanical properties and fire resistance. Three mixes were prepared with a total of 8% replacement by weight of cement using micro silica and PP fibre in different proportions: 50-50% (M1), 25-75% (M2), and 75-25% (M3). The control mix without any replacement was designated as M0. For all mixes, the water-binder ratio was kept constant at 0.42, and the total binder content was fixed at 400 kg/m³. The fine and coarse aggregates were kept the same across all mixes at 554.4 kg/m³ and 964.4 kg/m³, respectively. The mixed ingredients were thoroughly blended in a concrete mixer for 10-15 minutes to ensure uniform distribution of fibres and silica particles. Concrete was then cast into different moulds shown in Figure-2, including 16 cubes of size 150×150×150 mm (average weight 8.8 kg), 8 cylinders of 150×300 mm (average weight 13.8 kg), and 8 mini cubes of 30×30×30 mm (average weight 740 g). Each mould was filled in layers and compacted by 25 strokes per layer using a tamping rod, as per IS 516:1959 guidelines. After 24 hours of casting, specimens were demoulded and cured in water for 7 days before testing.

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Table-2. Mix proportion for M40 grade concrete (kg/m³).

	Cement (kg/m³)	Micro Silica (kg/m³)	PP Fibre (kg/m³)	Fine Aggregate (kg/m³)	Coarse Aggregate (kg/m³)	Water (kg/m³)	w/b Ratio
M0	400	0	0	554.4	964.4	180	0.42
M1	368	16	16	554.4	964.4	180	0.42
M2	368	8	24	554.4	964.4	180	0.42
M3	368	24	8	554.4	964.4	180	0.42



Figure-2. Specimens of cast cylinder, large cube, and small cube.

2.3 Testing Procedures and Evaluation Methods

The testing of specimens was carried out to evaluate the mechanical and fire-resisting properties of M40 grade concrete reinforced with polypropylene fibres and micro silica in various mix proportions (50:50%, 75:25%, and 25:75%). Compressive strength was assessed using 150 mm cube specimens tested in a digital Compression Testing Machine (CTM) after 7 days of curing, following IS 516:1959. The maximum load at failure was recorded, and strength was calculated by dividing the load by the cross-sectional area. Splitting tensile strength was determined using cylindrical specimens (150 mm diameter × 300 mm height) placed horizontally in the CTM with plywood strips for uniform load distribution. Load was applied along the diameter until failure, and tensile strength was computed using the standard formula. Impact resistance was evaluated on 30 mm cube specimens using a Charpy Impact Testing Machine, and the energy absorbed during fracture was used to calculate impact strength. For fire resistance evaluation, 150 mm cube specimens were exposed to elevated temperatures of 300°C in an oven and 800°C in a crucible furnace for 8 hours. Heat penetration tests involved exposing one face of 150 mm cubes to a 1300°C flame while monitoring the temperature rise on the opposite face using heat sensors. Additionally, a drop test was performed by dropping the heated specimens from a height of 3 meters to assess structural integrity and brittleness. Figure-3 showing the testing setup for various tests is included to illustrate the procedure.

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Figure-3. Concrete specimens undergoing various tests.

4. RESULTS AND DISCUSSIONS

4.1 Compressive Strength and Split Tensile Strength Analysis

As illustrated in Figure-4 (a), Specimen M3 exhibited the highest compressive strength, reaching a value of 31.53 MPa. This superior performance is attributed to the presence of a significant amount of micro silica within its composition. Micro silica is known to enhance the bonding characteristics of materials, contributing to a denser and stronger matrix, thereby increasing resistance to compressive stress.

Conversely, Specimen M2 demonstrated the lowest compressive strength at 14.32 MPa. This significantly reduced strength is hypothesized to be a direct consequence of the large quantity of polypropylene fiber incorporated into its design. While fibers can sometimes improve tensile properties, an excessive amount can hinder the proper bonding of other constituent materials, leading to a weaker overall structure under compression and thus a lower stress capacity. This observation highlights the importance of optimizing additive quantities to avoid compromising material integrity. Specimen M1 showed a higher compressive strength (30.16 MPa) compared to Specimen M0 (27.53 MPa). The text indicates that Specimen M0 had no additives, suggesting that the additives present in Specimen M1 contributed to its enhanced strength. This supports the notion that carefully selected additives can positively influence the compressive properties of the material, allowing it to withstand greater compressive stress. The increase in strength from Specimen M0 to Specimen M1 underscores the potential benefits of material modification.

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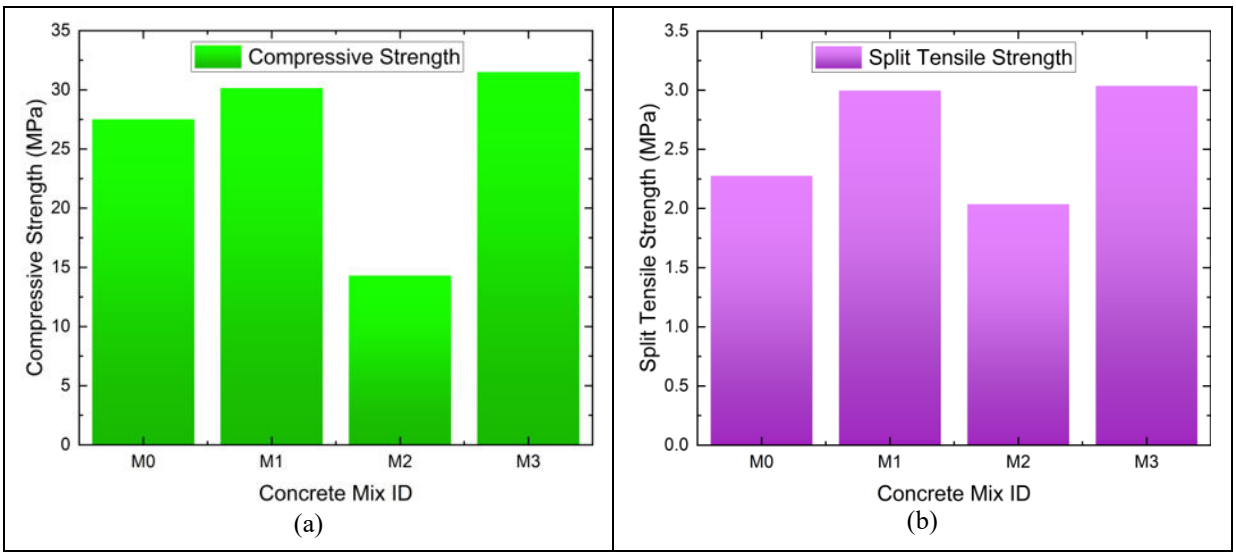


Figure-4 (a), (b). Compressive strength and split strength analysis of concrete specimens.

The split tensile strength of the specimens, depicted in Figure-4 (b), clearly demonstrates the significant impact of incorporated additives. Specimen M3, containing micro silica powder, achieved the maximum tensile strength of approximately 3.40 MPa, underscoring micro silica's role in improving bonding and material integrity. In sharp contrast, Specimen M2, with a high concentration of polypropylene (PP) fiber, registered the minimum tensile strength of about 2.04 MPa, indicating that excessive fiber content can impair tensile strength development. A notable improvement in tensile performance was also observed in Specimen M1 (approximately 3.00 MPa) over Specimen M0 (approximately 2.28 MPa), suggesting that specific additives in M1 positively contributed to its tensile resistance. These findings collectively reinforce that additives are crucial determinants of the material's tensile stress capacity; specifically, micro silica proved effective, while an overabundance of polypropylene fiber proved detrimental.

4.2 Impact Resistance Analysis

The impact test results presented in Figure-5 show notable differences in the impact resistance of the concrete specimens. Specimen M2 recorded the highest impact resistance (146 kN), which is attributed to the combined effect of micro silica and polypropylene (PP) fibres in balanced proportions. This combination likely improved the matrix density and crack-bridging ability, allowing the specimen to absorb more impact energy before failure. Specimen M0, which contained no additives, exhibited the lowest resistance (98 kN), indicating a brittle failure pattern typical of plain concrete. The absence of fibres or pozzolanic materials resulted in reduced energy absorption capacity under dynamic loading.

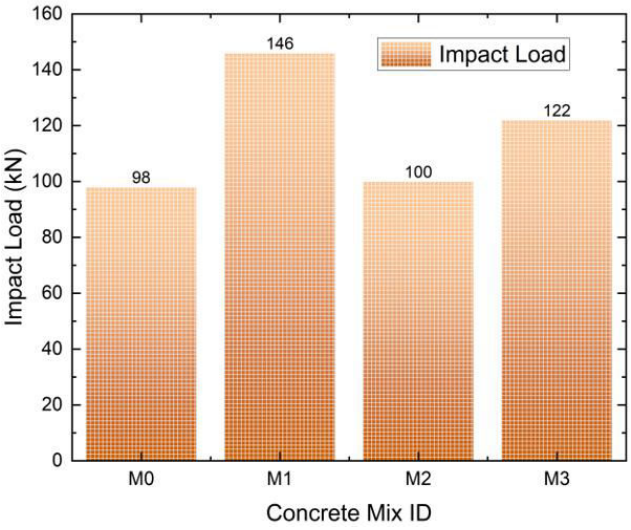


Figure-5. Impact load on various concrete specimens.

Specimen M3, with both additives but in different proportions, showed good impact resistance (122 kN), though slightly lower than M2. This suggests that the presence of additives enhances impact strength, but the effectiveness depends on the mix proportion and distribution. Specimen M1, despite containing PP fibres, showed a relatively low impact value (100 kN). This could be due to the high fibre content affecting workability and internal bonding, leading to weak zones and reduced toughness. These results confirm that optimum proportions of micro silica and fibres significantly improve the impact resistance of concrete, while excessive fibre content or the absence of additives can adversely affect performance.

4.3 Exposure to Heat: Compressive Strength and Structural Integrity

The compressive strength of concrete specimens after exposure to elevated temperatures is presented in

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Figure-6. At 300°C, all specimens retained a significant portion of their original strength. Specimen M1 exhibited the highest strength (29.83 MPa), indicating enhanced thermal resistance due to the presence of both polypropylene (PP) fibers and micro silica. Specimen M3, which also included both additives but in a different proportion, showed a slightly lower value (25.09 MPa), suggesting a less optimal mix. At 800°C, all specimens experienced a marked reduction in strength, consistent with thermal degradation effects such as microcracking, dehydration, and loss of bond integrity. However, M1 still retained the highest residual strength (17.78 MPa), confirming its superior thermal performance. In contrast, M2, with a higher fiber content and possibly poor dispersion, showed the lowest strength at both temperatures (4.93 MPa at 300°C and 2.22 MPa at 800°C). This can be attributed to the combustion of excess PP fiber, leading to increased porosity and reduced matrix cohesion.

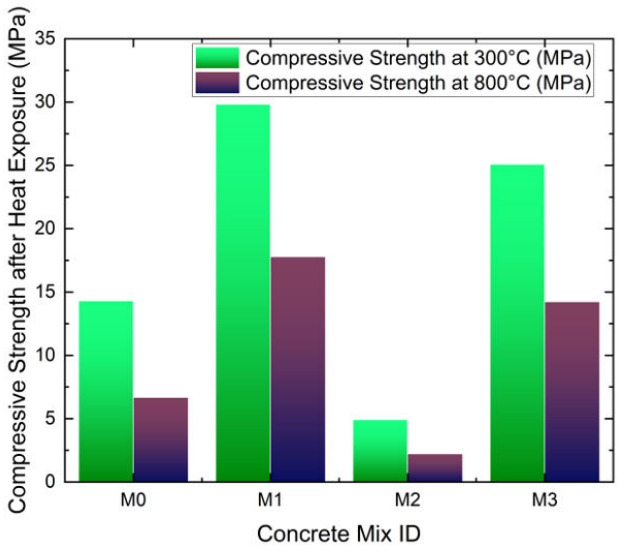


Figure-6. Compressive strength of concrete specimens at elevated temperatures.

In terms of structural integrity, visual and tactile evaluations after exposure to 800°C revealed that specimen M1 maintained high integrity, showing minimal cracking and good shape retention. M3 exhibited moderate integrity with surface cracking. M0 (control mix) and M2 showed poor integrity, with visible spalling and significant deterioration. The absence of additives in M0 and the excessive fiber burnout in M2 compromised their structural performance at high temperatures. These results demonstrate that a balanced incorporation of micro silica and a moderate dosage of PP fiber can significantly enhance the fire resistance and residual strength of concrete, making M1 the most effective mix in terms of both mechanical performance and structural stability after thermal exposure.

4.4 Thermal and Shattering Resistance of Concrete Specimens

In the heat penetration test, an external heat source was applied to one surface of the specimen, and the temperature transmitted through to the opposite surface was measured.



Figure-7. Heat penetration test.



Figure-8. M0 Concrete specimen after shattering test.

Specimen M1 exhibited the lowest heat penetration (16°C), indicating excellent thermal resistance due to the combined effect of polypropylene (PP) fiber and micro silica, which reduce porosity and thermal conductivity. Specimen M3 also showed good resistance (18.3°C), while Specimen M2 allowed more heat penetration (22°C), likely due to excessive fiber content causing internal voids. Specimen M0, with no additives, showed the highest heat penetration (23.6°C), confirming its poor insulation properties.

In the fall-from-height (shattering) test, the specimens were dropped from a fixed height to assess their resistance to cracking and fragmentation. Specimen M0 shattered completely upon impact, demonstrating its brittle nature in the absence of additives. Conversely, Specimens M1, M2, and M3 resisted shattering. The PP fibers improved toughness by bridging microcracks, while micro

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silica enhanced matrix bonding and compactness, preventing disintegration under sudden impact. These results collectively confirm that the addition of PP fiber and micro silica significantly enhances both the thermal resistance and mechanical integrity of concrete, making it more suitable for applications involving elevated temperatures and dynamic loading conditions.

Table-3. Heat penetration and shattering resistance of concrete specimens.

Concrete Mix ID	Heat Penetration Test (˚C)	Fall from Height (Shattering Resistance Test)
M0	23.6	YES
M1	16	NO
M2	22	NO
M3	18.3	NO

5. CONCLUSIONS

The major conclusions drawn from this experimental study are as follows:

- Specimen M1 (with optimized PP fiber and micro silica) showed the best overall performance in strength, thermal resistance, and structural integrity.
- Highest compressive (31.53 MPa) and split tensile strength (3.40 MPa) were achieved by M1 due to improved matrix bonding and densification.
- M2 had the highest impact resistance (146 kN), but excess fiber content reduced its compressive and tensile strength.
- M0 (control mix with no additives) consistently showed the poorest performance in all tests, including complete shattering on impact.
- After exposure to 800°C, M1 retained the highest residual strength (17.78 MPa) and showed minimal damage.
- Heat penetration was lowest in M1 (16°C), confirming its superior insulation properties.
- Only M0 shattered in the drop test; all other specimens resisted fragmentation due to fiber and silica reinforcement.

A balanced mix of polypropylene fiber and micro silica significantly improves strength, fire resistance, and durability, making it ideal for structural and fire-exposed applications. Future research can focus on studying the use of admixtures and superplasticizers to improve the uniform distribution of fibers within the concrete matrix without adversely affecting its properties.

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