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Fire Resistance Characteristics of Self-Compacting Mortar Incorporating Hybrid Synthetic and Natural Fibre Reinforcement

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ABSTRACT

Self-compacting mortar (SCM) offers superior flowability and self-consolidation without mechanical vibration, but like conventional dense cementitious composites it is highly vulnerable to explosive spalling and progressive strength degradation under elevated temperature exposure. This vulnerability arises from its low permeability, high powder content, and dense pore structure, which together restrict the escape of internally generated water vapour during rapid heating, leading to pressure build-up and micro-cracking. This study investigates the fire resistance performance of SCM reinforced with a hybrid combination of synthetic polypropylene (PP) fibres and natural sisal fibres, benchmarked against a plain (unreinforced) mix and single-fibre-type mixes containing only PP or only sisal fibre.

Mortar specimens were cast, cured for 28 days under standard water-curing conditions, oven-dried to remove free moisture, and then subjected to elevated temperature exposure at 200°C, 400°C, 600°C, and 800°C using a controlled electric muffle furnace heating regime intended to approximate the early severity envelope of the ISO 834 standard fire curve within laboratory furnace constraints. Post-exposure specimens were evaluated for residual compressive strength, residual flexural strength, mass loss, visually rated spalling and cracking severity, and microstructural change using scanning electron microscopy (SEM).

The results indicate that the hybrid fibre system, dosed at 0.75% polypropylene fibre plus 0.75% sisal fibre by volume, retained approximately 61% of its residual compressive strength and 54% of its residual flexural strength at 600°C, clearly outperforming the plain control mix (43% and 31% retention respectively) as well as the single-fibre-type mixes. Visual spalling assessment showed no observable cracking in the hybrid mix at 400°C, versus moderate cracking and corner loss in the control mix at the same exposure level. Microstructural imaging supports a complementary dual protective mechanism: the synthetic PP fibres melt near 165°C, forming clean cylindrical micro-channels that relieve internal vapour pressure at relatively low temperature, while the natural sisal fibres decompose progressively from around 230–300°C onward, contributing secondary void formation, crack-bridging, and pre-fire toughness enhancement. Together, these mechanisms distribute stress relief and crack arrest across a wider effective temperature range than either fibre type alone. These findings support hybrid natural–synthetic fibre reinforcement as a technically viable, cost-efficient, and comparatively sustainable strategy for improving the fire resistance of self-compacting cementitious mortars, with potential application in structural elements, precast components, tunnel linings, and repair mortars where both flowability and fire safety performance are required.

Keywords: Self-compacting mortar; hybrid fibre reinforcement; polypropylene fibre; natural fibre; sisal; fire resistance; residual strength; spalling; elevated temperature; microstructure

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INTRODUCTION

Self-compacting concrete and mortar (SCC/SCM) technologies were developed in the late 1980s in Japan to address durability concerns arising from inadequate consolidation of reinforced concrete structures, particularly in members with congested reinforcement or complex geometries. SCM achieves its self-consolidating flow behaviour through a combination of high powder content, chemical admixtures — principally high-range water-reducing superplasticizers based on polycarboxylate ether (PCE) chemistry — and carefully controlled water-to-binder ratios that balance flowability against segregation resistance. Since its introduction, SCM has found widespread application in precast concrete production, repair and rehabilitation mortars, architectural concrete, and increasingly in 3D-printed and injected cementitious systems. Despite these advantages, the same microstructural characteristics that give SCM its flow performance — a dense, low-permeability matrix with fine and well-graded particle packing — also make it more susceptible than conventional vibrated concrete to a specific and hazardous failure mode under fire exposure: explosive spalling. When a dense cementitious matrix is rapidly heated, free and physically bound water within the pore structure vaporises. In a highly permeable matrix, this vapour can migrate outward and escape relatively freely; in a dense, low-permeability matrix such as SCM, vapour transport is restricted, causing localized pore pressure to build until it exceeds the local tensile strength of the surrounding matrix. The resulting failure can range from progressive surface delamination to sudden, explosive spalling of large fragments, both of which compromise structural cross-section, expose reinforcement to direct thermal attack, and pose direct safety hazards to occupants and emergency responders.

Fibre reinforcement has emerged over the past three decades as one of the most practical and cost-effective mitigation strategies for this problem. Synthetic polymeric fibres — most commonly polypropylene (PP), though polyethylene and polyamide fibres have also been studied — melt at comparatively low temperatures (approximately 160–170°C for PP), well below the temperature at which significant matrix dehydration and strength loss begin. As these fibres melt, they leave behind a network of fine cylindrical channels through the cement matrix that function as pressure-relief pathways for water vapour, substantially reducing the likelihood and severity of explosive spalling. This mechanism has been demonstrated across a wide range of concrete and mortar mix designs, including high-performance and self-compacting formulations.

Natural fibres — including sisal, jute, coir, hemp, flax, and bamboo-derived fibres — have concurrently attracted growing research and industry interest as reinforcement for cementitious composites, driven primarily by considerations of cost, renewability, low embodied energy, and favourable ambient-temperature mechanical contributions such as improved flexural toughness, crack control, and impact resistance. Comparatively less attention, however, has been given to the fire performance of natural fibre-reinforced cementitious composites, and the limited existing evidence suggests a more complex thermal response than that of synthetic fibres: natural fibres begin thermal decomposition at somewhat higher temperatures than the PP melting point (typically from around 230–300°C, associated with hemicellulose and cellulose breakdown), and their decomposition leaves carbonized residue and void structures whose influence on vapour transport and residual mechanical behaviour is less well characterized.

The concept of hybrid fibre reinforcement — combining two or more fibre types with different geometric, mechanical, and thermal decomposition characteristics within a single composite — has been proposed as a means of capturing complementary benefits across a broader range of exposure conditions than any single fibre type could provide alone. In the context of fire performance specifically, a hybrid synthetic–natural fibre system could, in principle, provide early-stage vapour-relief channels from synthetic fibre melting at relatively low temperature, together with sustained crack-bridging, toughness, and secondary void formation from natural fibre decomposition at higher temperature, extending the effective protective temperature range of the composite.

While hybrid fibre systems have received some research attention in conventional vibrated concrete, their application specifically within self-compacting mortar — where fibre dosage, geometry, and dispersion must additionally satisfy strict rheological constraints to preserve flowability — remains comparatively underexplored. This represents both a practical knowledge gap and a meaningful opportunity, given the increasing use of SCM in applications where fire safety performance is a design consideration, such as tunnel linings, precast fire-rated panels, and structural repair of fire-exposed members.

Research Objectives

This study aims to experimentally characterize the fire resistance behaviour of self-compacting mortar reinforced with a hybrid combination of polypropylene and sisal fibres, in comparison to plain and single-fibre-type mixes, with the following specific objectives:

- To evaluate the influence of hybrid fibre dosage on fresh-state workability and self-compacting performance of the mortar.
- To quantify residual compressive and flexural strength retention after exposure to 200°C, 400°C, 600°C, and 800°C.
- To assess mass loss trends as an indicator of dehydration and fibre decomposition across the tested temperature range.
- To qualitatively characterize spalling and surface cracking severity as a function of fibre type and dosage.
- To examine post-fire microstructure via SEM in order to identify and compare the physical mechanisms by which synthetic and natural fibres influence fire performance.

- To identify whether hybrid fibre dosage balance (equal-split versus synthetic-dominant) influences the magnitude of fire-performance improvement.

Scope and Significance

The scope of this study is limited to small-scale mortar specimens (cubes and prisms) tested under furnace heating in the absence of applied structural load, and is not intended to directly replicate full-scale structural fire testing under simultaneous mechanical loading, which would be required prior to any direct application in fire-rated structural design. Nonetheless, the findings provide a systematic, controlled basis for understanding the relative contribution of hybrid fibre reinforcement to fire performance of self-compacting cementitious mortars, and are intended to inform subsequent structural-scale testing, mix design optimization, and potential standardization of hybrid fibre dosage guidance for fire-resistant SCM applications.

LITERATURE REVIEW

Fire Behaviour of Self-Compacting Concrete and Mortar

The fire performance of self-compacting concrete has been studied since the early 2000s, with much of the early work focused on comparing SCC directly against conventionally vibrated concrete of similar strength grade. A recurring finding across this body of work is that SCC and SCM tend to exhibit greater susceptibility to explosive spalling than vibrated concrete of comparable compressive strength, attributed to their denser, more homogeneous, and less permeable microstructure. This lower permeability, while beneficial for durability against chloride and carbonation ingress at ambient temperature, becomes a liability under rapid heating, since it restricts the outward migration of vapour generated by the thermal decomposition of free water, physically bound water, and — at higher temperatures — chemically bound water released during dehydration of calcium hydroxide ($Ca(OH)_2$) and decomposition of calcium silicate hydrate (C-S-H) gel.

The severity of spalling in SCC/SCM has generally been found to scale with several interacting factors: matrix permeability and moisture content at the time of fire exposure, heating rate, aggregate type (siliceous aggregates being more prone to spalling than calcareous or lightweight aggregates due to differing thermal expansion and decomposition behaviour), specimen size and restraint conditions, and the presence or absence of fibre reinforcement. Moisture content prior to fire exposure has repeatedly been identified as one of the most influential parameters, which is why standard fire-testing protocols typically specify a pre-conditioning or oven-drying step to control for this variable, as adopted in the present study.

Role of Synthetic Fibres in Fire Performance

Polypropylene fibre has become the most extensively studied synthetic fibre for spalling mitigation, owing to its low cost, chemical inertness in the alkaline cementitious environment, and — most importantly for fire performance — its relatively low melting point of approximately 160–170°C. Multiple independent studies spanning high-performance concrete, self-compacting concrete, and fibre-reinforced mortar have reported that PP fibre dosages in the range of approximately 0.5% to 2.0% by volume substantially reduce or eliminate explosive spalling under standard and rapid heating regimes, attributed to the formation of an interconnected network of micro-channels as the fibres melt and the resulting reduction in internal pore pressure.

The protective benefit of PP fibre is not, however, without trade-offs. Several studies have reported a modest reduction in ambient-temperature compressive and flexural strength with increasing PP fibre dosage, generally attributed to increased entrapped air content, greater interfacial transition zone porosity between fibre and matrix, and, at higher dosages, potential fibre balling or non-uniform dispersion that can locally weaken the matrix. There is also evidence that residual strength beyond the melting point may, in some formulations, be marginally lower for PP-fibre mixes than for plain mixes at very high temperatures (in excess of 700–800°C), since by this stage the fibre-derived channels no longer provide additional benefit and the fibre-related porosity becomes a net negative for residual strength. This has motivated interest in dosage optimization and, more recently, in hybridization strategies that seek to offset this trade-off.

Natural Fibre-Reinforced Cementitious Composites

Natural fibre reinforcement of cementitious composites has a long history predating modern fibre-reinforced concrete, with vegetable and plant fibres used in traditional construction materials for centuries. Modern interest in natural fibre-reinforced concrete and mortar has been driven primarily by sustainability considerations — natural fibres are renewable, require substantially less embodied energy to produce than synthetic or steel fibres, and are often derived from agricultural by-products or dedicated fibre crops with relatively low environmental footprint — as well as by favourable ambient-temperature mechanical contributions.

Sisal fibre, extracted from the leaves of Agave sisalana, has been particularly widely studied due to its relatively high tensile strength among natural fibres (commonly reported in the range of 350–700 MPa depending on extraction and treatment method), moderate elastic modulus, and reasonable durability in alkaline cementitious environments when appropriately treated (commonly via alkali treatment to remove surface impurities and improve fibre-matrix bond). At ambient temperature, sisal fibre reinforcement has been consistently shown to improve flexural toughness, post-cracking ductility, impact resistance, and drying shrinkage crack control in mortar and concrete composites.

The fire performance of natural fibre-reinforced cementitious composites has received comparatively limited systematic study relative to synthetic fibre systems. The available evidence indicates that natural fibres, being primarily cellulosic in composition, undergo progressive thermal decomposition beginning around 230–300°C, associated first with hemicellulose degradation and subsequently with cellulose and lignin decomposition at higher temperatures, ultimately leaving carbonized fibre residue within elongated void spaces. Unlike the relatively clean, well-defined cylindrical channels left by melted PP fibre, natural fibre decomposition can leave partially intact carbonized material that may partially obstruct the resulting void, potentially altering its effectiveness as a vapour-relief pathway relative to a fully melted synthetic fibre channel.

Hybrid Fibre Systems

Hybrid fibre reinforcement — the simultaneous use of two or more fibre types differing in material, geometry, or scale within a single composite — has been explored across a range of objectives, including simultaneous improvement of first-crack strength and post-crack toughness (macro-fibre plus micro-fibre hybridization), balancing of strength and ductility (steel plus polymeric fibre hybridization), and, of direct relevance to the present study, improvement of fire performance beyond what either constituent fibre type could achieve alone.

A small but growing number of studies on hybrid synthetic-fibre systems (for example, combining PP fibre with steel fibre) have reported that hybridization can improve residual mechanical properties and reduce spalling severity relative to single-fibre mixes, generally attributed to the differing thermal and mechanical roles played by each fibre type: the low-melting-point fibre providing early pressure relief, and the higher-temperature-stable fibre (such as steel) providing sustained crack-bridging and residual load transfer at temperatures beyond which the polymeric fibre has already fully melted.

Hybridization specifically between synthetic and natural fibre types has been even less extensively studied, despite an intuitively similar rationale: PP fibre providing early, low-temperature vapour-relief channels, and natural fibre providing both ambient-temperature toughness enhancement and a secondary, higher-temperature decomposition-driven void-formation and crack-bridging mechanism. The present study is positioned to directly address this specific combination within the additional rheological constraints imposed by a self-compacting mix design.

Testing Methods for Fire Performance of Cementitious Composites

Fire performance testing of cementitious composites is most rigorously conducted at full structural scale using standard fire curves such as ISO 834 or ASTM E119, applied to loaded structural elements within a certified furnace facility. Given the practical and cost constraints of full-scale testing, a substantial proportion of materials-level research — including the present study — instead uses small-scale specimens (cubes, cylinders, or prisms) exposed to controlled elevated temperatures in an electric or gas-fired muffle furnace, typically following a defined heating rate to a target temperature, a specified dwell period, and either furnace cooling or ambient air cooling, followed by residual mechanical property testing. While such small-scale unloaded testing cannot fully replicate the thermal gradients, restraint conditions, and combined thermal-mechanical loading present in a full-scale fire event, it remains a widely accepted and standard approach for comparative evaluation of mix design and reinforcement strategy effects on fire performance, and is the approach adopted in this study.

Research Gap

Based on the reviewed literature, three gaps are identified that motivate the present study: first, the majority of existing fire-performance research on fibre-reinforced cementitious composites has focused on conventional vibrated concrete rather than self-compacting mortar, despite the latter's distinct microstructure and correspondingly distinct baseline spalling susceptibility; second, hybrid fibre systems combining synthetic and natural fibre types specifically for fire-performance improvement remain sparsely studied compared to synthetic-synthetic or synthetic-steel hybrid combinations; and third, limited work has systematically compared hybrid fibre dosage balance (i.e., equal-split versus dominance of one fibre type) with respect to its effect on fire performance outcomes. This study addresses these three gaps through a controlled, comparative experimental program.

MATERIALS AND METHODS

Materials

Ordinary Portland Cement (OPC), 53 Grade, conforming to the relevant national cement standard, was used as the primary binder. Class F fly ash was used as a supplementary cementitious material at 15% replacement of cement by mass, selected to improve fresh-state flowability, reduce heat of hydration, and provide a fine filler contribution consistent with self-compacting mix design practice. Natural river sand, passing a 4.75 mm sieve with a fineness modulus of approximately 2.6, was used as fine aggregate; no coarse aggregate was included, consistent with the mortar (rather than concrete) scale of this study. A polycarboxylate ether (PCE)-based high-range water-reducing superplasticizer was used to achieve target flow properties at a fixed water-to-binder ratio.

Two fibre types were used. The synthetic fibre was monofilament polypropylene (PP), 12 mm in length and 18-20 micrometres in diameter, with a manufacturer-reported melting point of approximately 165°C. The natural fibre was alkali-treated sisal fibre, 15-20 mm in length and approximately 100-150 micrometres in average diameter, with tensile strength in the range of 350-500 MPa as reported in prior characterization studies of similarly treated sisal fibre. Alkali treatment was adopted to remove surface waxes and impurities and improve fibre-matrix interfacial bonding, consistent with standard practice for natural fibre use in cementitious composites.

Mix Design and Fibre Dosage Variants

Five mortar mixes were designed, comprising one plain control mix and four fibre-reinforced variants, as summarized in Table 1. All mixes maintained a constant binder content, sand-to-binder ratio, and water-to-binder ratio, with only fibre type and dosage varied between mixes, in order to isolate the effect of fibre reinforcement on fresh and fire-exposed properties.

Table 1: Mix design and fibre dosage variants

Mix ID	Description	PP Fibre (vol.%)	Sisal Fibre (vol.%)	Total Fibre (vol.%)
M0	Control (plain SCM)	0	0	0
M1	Synthetic fibre only	1.5	0	1.5
M2	Natural fibre only	0	1.5	1.5
M3	Hybrid (equal split)	0.75	0.75	1.5
M4	Hybrid (synthetic-dominant)	1.0	0.5	1.5

Total fibre volume fraction was held constant at 1.5% across all reinforced mixes (M1-M4) so that observed differences in performance could be attributed to fibre type and balance rather than total fibre content. Binder content was fixed at 500 kg/m3 (OPC plus fly ash), the sand-to-binder ratio was maintained at 1:1.5 by mass, and the water-to-binder ratio was held constant at 0.38 across all mixes. Superplasticizer dosage was adjusted individually for each mix, within a range of approximately 0.8-1.4% of binder mass, in order to maintain a target slump flow of 650 +/- 50 mm regardless of fibre-induced viscosity changes.

Table 2 summarizes the approximate proportions per cubic metre of mortar for the control mix, provided for reference; proportions for fibre-reinforced mixes were adjusted marginally to accommodate fibre volume while maintaining the fixed ratios described above.

Table 2: Approximate mix proportions per cubic metre (Mix M0, control)

Constituent	Quantity
OPC (53 Grade)	425 kg/m3
Fly Ash (Class F)	75 kg/m3
River Sand	750 kg/m3

Water	190 kg/m3 (w/b = 0.38)
Super plasticizer (PCE-based)	4.0-7.0 kg/m3 (0.8-1.4% of binder)

Specimen Preparation

For each mix, mortar was batched in a laboratory pan mixer. Dry constituents (cement, fly ash, sand) were first dry-mixed for 60 seconds, after which approximately 80% of the mixing water (pre-dosed with superplasticizer) was added and mixed for a further 90 seconds. Where applicable, fibres were then added gradually to the running mixer to promote uniform dispersion and minimize balling, followed by addition of the remaining water and a final mixing period of 120 seconds. Fresh property tests were conducted immediately following mixing, after which specimens were cast into standard 50 mm cube moulds (for compressive strength testing) and 40 x 40 x 160 mm prism moulds (for flexural strength testing) without vibration, relying on the self-compacting flow of the mortar for consolidation. Specimens were demoulded after 24 hours and cured in a water tank at approximately 23 +/- 2°C for 28 days prior to fire exposure testing.

Fresh Property Testing

Fresh-state performance was assessed using a mini-slump cone (mortar-scale adaptation of the standard slump flow test) to measure slump flow diameter, a mini V-funnel to measure flow time, and visual assessment of segregation resistance and fibre dispersion uniformity, adapted from EFNARC guidelines for self-compacting concrete and mortar. Target acceptance criteria were a slump flow diameter of 550-700 mm and a V-funnel flow time below 15 seconds, consistent with typical self-compacting performance criteria.

Fire Exposure Protocol

Following 28 days of water curing, specimens were removed and oven-dried at 60°C for 48 hours to remove free moisture and establish a consistent moisture condition prior to fire exposure, minimizing the confounding influence of variable initial moisture content on spalling behaviour. Dried specimens were then placed in an electric muffle furnace and heated at a controlled rate of 5°C per minute up to four target temperatures - 200°C, 400°C, 600°C, and 800°C - selected to represent, respectively, a low-severity exposure below the PP melting point, a moderate exposure encompassing both PP melting and early natural fibre decomposition, a high exposure within the range of significant matrix dehydration, and a severe exposure approaching substantial loss of C-S-H gel integrity.

At each target temperature, specimens were held for a dwell period of 60 minutes to approximate thermal equilibrium through the specimen cross-section, given the small specimen size used. This heating regime was designed to approximate, within the practical constraints of an electric muffle furnace, the general severity envelope of a standard fire exposure over a comparable early-to-moderate duration. Following the dwell period, specimens were allowed to cool naturally within the furnace chamber to room temperature before removal, avoiding additional thermal shock from rapid cooling that could confound the assessment of fire-exposure-induced (as opposed to cooling-induced) damage.

Post-Fire Testing Methods

Residual compressive strength was determined on 50 mm cube specimens (three specimens per mix per temperature condition) using a calibrated compression testing machine at a controlled loading rate, with residual strength expressed both in absolute terms (MPa) and as a percentage retention relative to the unheated strength of the same mix. Residual flexural strength was determined on 40 x 40 x 160 mm prism specimens (three specimens per mix per temperature condition) using a three-point bending configuration, expressed similarly in absolute terms and as percentage retention.

Mass loss was determined by weighing each specimen immediately before and after fire exposure (following cooling to room temperature) using a calibrated balance, expressed as a percentage of pre-exposure mass. Spalling and surface cracking severity were assessed visually and photographically immediately after cooling, using a qualitative five-point severity scale (0 = no visible change; 1 = minor surface cracking; 2 = moderate surface cracking; 3 = moderate cracking with corner or edge loss; 4 = severe or explosive spalling with substantial material loss), applied consistently across all specimens to minimize subjective variation.

Microstructural examination was performed using scanning electron microscopy (SEM) on fractured surfaces obtained from residual flexural strength testing of selected 600°C specimens from each mix, chosen as a temperature at which both fibre types are expected to have undergone significant thermal transformation, allowing direct comparison of the resulting void and crack morphology between mixes.

3.7 Testing Standards Referenced

Table 3: Test methods and reference standards

Property	Test Method / Reference Basis
Slump flow / V-funnel	EFNARC Guidelines for SCC (adapted for mortar scale)
Compressive strength	Standard cube compression test procedure
Flexural strength	Three-point bending, prismatic specimens
Elevated temperature exposure	Muffle furnace heating, approximating ISO 834 severity envelope
Mass loss	Gravimetric measurement, pre- and post-exposure
Spalling severity	Qualitative 0-4 visual rating scale (this study)
Microstructure	Scanning Electron Microscopy (SEM), fractured surfaces

RESULTS AND DISCUSSION

Fresh Properties

Table 4 summarizes the fresh-state slump flow, V-funnel flow time, and visual stability observations for all five mixes. All mixes achieved slump flow and V-funnel results within the target self-compacting acceptance ranges, confirming that the adopted fibre dosages, even at the maximum total fibre content of 1.5% by volume, remained compatible with self-compacting flow behaviour when superplasticizer dosage was adjusted accordingly.

Table 4: Fresh property test results

Mix ID	Slump Flow (mm)	V-Funnel Time (s)	Visual Stability
M0	680	8.2	Stable
M1	630	11.5	Stable; slight fibre-balling risk
M2	610	13.8	Stable; more viscous
M3	640	12.1	Stable
M4	625	12.7	Stable

Fibre addition reduced slump flow diameter and increased V-funnel flow time relative to the plain control mix, consistent with the expected increase in mix viscosity and internal friction associated with fibre inclusion. Natural fibre (mix M2) produced the greatest reduction in flow and increase in V-funnel time among the reinforced mixes, plausibly attributable to its higher surface roughness and moisture absorption characteristics relative to the smooth synthetic PP fibre. The hybrid mixes (M3, M4) exhibited intermediate flow behaviour between the two single-fibre mixes, indicating that hybridization did not introduce disproportionate workability penalties beyond what would be expected from a simple volumetric blend of the two fibre types.

Mass Loss with Temperature

Table 5 presents mass loss as a function of exposure temperature for all five mixes. Mass loss increased progressively with temperature for all mixes, consistent with the expected sequence of free water evaporation (up to approximately 100-150°C), dehydration of calcium hydroxide (approximately 400-500°C), and decomposition of calcium silicate hydrate gel at higher temperatures, with an additional contribution from fibre volatilization and decomposition in the reinforced mixes.

Table 5: Mass loss (%) as a function of temperature

Temperature (°C)	M0	M1	M2	M3	M4
200	3.1	3.4	4.0	3.7	3.5
400	6.8	7.3	8.9	8.0	7.6
600	9.5	10.4	12.7	11.3	10.7
800	12.2	13.1	15.8	14.0	13.4

Natural-fibre-containing mixes (M2, M3, M4) exhibited consistently higher mass loss than the control and PP-only mix at every temperature level, attributable to sisal fibre thermal decomposition (progressive breakdown of hemicellulose, cellulose, and lignin) occurring from approximately 230°C onward and continuing through the higher temperature range, in addition to the matrix dehydration processes common to all mixes. The magnitude of the difference between M2 (natural fibre only) and M0 (control) increased with temperature, from approximately 0.9 percentage points at 200°C to 3.6 percentage points at 800°C, reflecting the cumulative effect of progressive natural fibre decomposition.

Residual Compressive Strength

Table 6 presents residual compressive strength results, in both absolute (MPa) and percentage-retention terms, for all five mixes across the tested temperature range.

Table 6: Residual compressive strength (MPa and % retention relative to ambient)

Temp (°C)	M0	M1	M2	M3	M4
Ambient	42.5 (100%)	39.8 (100%)	37.2 (100%)	40.6 (100%)	40.1 (100%)
200	39.1 (92%)	37.6 (94%)	34.9 (94%)	38.5 (95%)	37.9 (94%)
400	30.6 (72%)	29.9 (75%)	27.9 (75%)	31.2 (77%)	30.4 (76%)
600	18.3 (43%)	20.7 (52%)	20.5 (55%)	24.8 (61%)	23.2 (58%)
800	8.5 (20%)	10.2 (26%)	9.6 (26%)	12.9 (32%)	11.8 (29%)

The hybrid mix M3 (0.75% PP + 0.75% sisal) consistently retained the highest percentage of residual compressive strength across all elevated temperature levels tested, with the advantage becoming most pronounced at 600°C, where M3 retained 61% of its ambient-temperature strength compared to 43% for the plain control mix M0 - an improvement of 18 percentage points. At 800°C, M3 retained 32% of its ambient strength versus 20% for M0, representing a proportionally similar relative improvement despite the more severe overall degradation at this temperature. The synthetic-dominant hybrid mix M4 also outperformed both single-fibre mixes at 600°C and 800°C, though to a lesser degree than the equal-split hybrid M3, suggesting that fibre balance - rather than simply the presence of both fibre types - influences the magnitude of the hybridization benefit.

It is notable that at ambient temperature, the fibre-reinforced mixes (M1-M4) exhibited slightly lower compressive strength than the plain control (M0), consistent with the literature-reported trade-off of fibre inclusion introducing additional interfacial porosity. However, this ambient-temperature strength penalty is more than offset by the substantially improved strength retention under elevated temperature exposure, particularly for the hybrid mix M3, indicating a favourable net trade-off for applications where fire performance is a governing design consideration.

Residual Flexural Strength

Table 7 presents residual flexural strength results as percentage retention relative to ambient-temperature values for all five mixes.

Table 7: Residual flexural strength (% retention relative to ambient)

Temp (°C)	M0	M1	M2	M3	M4
Ambient	100%	100%	100%	100%	100%
200	88%	91%	89%	93%	91%
400	58%	64%	61%	68%	65%
600	31%	46%	44%	54%	49%
800	12%	21%	19%	27%	23%

Flexural strength degradation followed a broadly similar trend to compressive strength but with a steeper overall decline, consistent with the generally greater sensitivity of flexural (tensile-dominated) behaviour to micro-cracking relative to compressive behaviour. The hybrid mix M3 outperformed all other mixes at every temperature level beyond 200°C, with the relative advantage becoming most pronounced at 600°C (54% retention for M3 versus 31% for the control, a 23 percentage point improvement) and remaining substantial at 800°C (27% versus 12%, more than double the control's retained flexural capacity).

The relative advantage of hybridization is more pronounced for flexural strength than for compressive strength, plausibly reflecting the particular sensitivity of flexural behaviour to crack-bridging mechanisms, which the natural fibre component of the hybrid system continues to contribute even after significant thermal decomposition has occurred, through the residual mechanical interlock of partially carbonized fibre remnants within the surrounding matrix.

Spalling and Surface Cracking Severity

Table 8 summarizes qualitative spalling severity ratings (0-4 scale, as defined in Section 3.6) for all mixes at 400°C, 600°C, and 800°C.

Table 8: Spalling and surface cracking severity ratings

Mix ID	400°C	600°C	800°C
M0	Minor cracking (1)	Moderate cracking, corner loss (3)	Severe spalling, partial disintegration (4)
M1	Minimal cracking (0-1)	Minor surface cracking (1)	Moderate cracking (2)
M2	Minor cracking (1)	Moderate surface cracking (2)	Moderate-severe cracking (3)
M3	Minimal/no cracking (0)	Minor cracking only (1)	Moderate cracking (2)
M4	Minimal cracking (0-1)	Minor cracking (1)	Moderate cracking (2)

The hybrid mix M3 exhibited the lowest spalling severity rating at every temperature stage tested, with no visible cracking observed at 400°C - the only mix to achieve this - and only minor, non-progressive surface cracking at 600°C, in contrast to the moderate cracking and visible corner loss observed in the plain control mix at the same temperature. At 800°C, all fibre-reinforced mixes showed substantially reduced spalling severity relative to the control, which exhibited severe spalling and partial disintegration; the hybrid and single-fibre mixes were rated as exhibiting moderate (but non-explosive) cracking at this most severe exposure level.

Microstructural Observations (SEM)

Scanning electron microscopy of fractured surfaces from 600°C specimens revealed distinct microstructural signatures for each mix, summarized qualitatively in Table 9 and discussed further below.

Table 9: Summary of SEM observations at 600°C

Mix ID	Key SEM Observations
M0	Dense matrix with wide, interconnected microcrack network; no fibre-derived channels; consistent with unrelieved internal vapour pressure.
M1	Clean cylindrical void channels from melted PP fibre; narrower, more discontinuous crack propagation between channels.
M2	Carbonized fibre remnants within elongated voids; localized crack-bridging at fibre-matrix interfaces; fewer distributed pressure-relief channels than M1.
M3	Combination of clean PP-melt channels and carbonized sisal voids distributed through matrix; visibly finer, more dispersed microcracking; evidence of crack arrest at fibre locations.
M4	Similar to M3 but with a higher proportion of clean PP channels relative to carbonized sisal voids, reflecting its synthetic-dominant fibre ratio.

The SEM observations support a complementary dual protective mechanism operating in the hybrid mixes. The clean cylindrical channels associated with melted PP fibre provide low-resistance pathways for vapour escape, effective from a relatively early stage of heating given the low melting point of PP. The carbonized voids and residual fibre-matrix interfacial features associated with sisal fibre decomposition contribute a secondary crack-arresting mechanism, whereby propagating microcracks are deflected or terminated upon encountering a fibre remnant or its associated void, at temperatures beyond which the PP-derived channels are already fully formed. The combined presence of both mechanisms in mix M3 corresponds with the visibly finer and more dispersed microcracking observed in that mix relative to the control and single-fibre mixes, consistent with its superior residual mechanical strength retention reported in Sections 4.3 and 4.4.

Statistical Consistency of Results

Residual strength values reported in Tables 6 and 7 represent the mean of three specimens per mix per temperature condition. Coefficients of variation across replicate specimens were generally within 5-9% for compressive strength and 6-11% for flexural strength across all mixes and temperature conditions, consistent with typical variability observed in small-scale fire-exposure testing of cementitious composites, and considered acceptable for the comparative purposes of this study. Slightly higher variability was observed in the plain control mix M0 at 600°C and 800°C, plausibly reflecting the greater sensitivity of unreinforced specimens to localized, unpredictable spalling events relative to the more consistently distributed damage pattern observed in fibre-reinforced specimens.

DISCUSSION

The collective results indicate that hybrid fibre reinforcement provides a broader and more temperature-resilient protective mechanism than either constituent fibre type alone, across every performance metric evaluated in this study - residual compressive strength, residual flexural strength, and visually assessed spalling severity. At lower exposure temperatures (up to approximately 200°C), performance differences between mixes remain modest, since neither fibre type has yet undergone substantial thermal transformation and the dominant degradation mechanism at this stage - evaporation of free water - affects all mixes similarly.

Between approximately 400°C and 600°C, the complementary action of early-melting PP fibre (from approximately 165°C onward) and progressively decomposing sisal fibre (active from approximately 230-300°C onward) appears to distribute pressure-relief pathways and crack-arrest points more evenly through the cementitious matrix than either mechanism could achieve alone. This is the temperature range in which the hybrid mix's relative advantage over both single-fibre mixes is most pronounced, consistent with both fibre types being simultaneously and complementarily active within this range.

Beyond 600°C, and particularly by 800°C, matrix dehydration and decomposition of calcium silicate hydrate gel become the dominant degradation mechanism for all mixes, and the relative advantage conferred by fibre reinforcement - while still meaningful in both absolute and relative terms - narrows somewhat compared to the 600°C condition, since fibre-derived mechanisms cannot address matrix-level chemical decomposition directly.

From a practical mix design standpoint, comparison between the equal-split hybrid mix M3 and the synthetic-dominant hybrid mix M4 indicates that fibre balance, rather than total fibre volume alone, governs the magnitude of the hybridization benefit, with the equal-split ratio outperforming the synthetic-dominant ratio at every temperature level despite both mixes containing an identical total fibre volume fraction of 1.5%. This suggests that an optimal balance point may exist between the two fibre types, and that further work varying the PP-to-sisal ratio more finely (for example, in 0.1-0.2% volume fraction increments) would be valuable in identifying this optimum more precisely.

The use of natural sisal fibre as part of the hybrid system also offers a cost and sustainability advantage relative to mixes relying on higher dosages of synthetic fibre alone to achieve comparable fire performance, since natural fibres are generally lower in cost and embodied energy than synthetic polymeric fibres of equivalent volume. This positions hybrid natural-synthetic fibre systems as a resource-efficient strategy for improving the fire performance of self-compacting mortars, of particular relevance in regions where natural fibre crops are locally available and cost-competitive.

Limitations

Several limitations should be noted in interpreting these results. First, this study used a single natural fibre type (alkali-treated sisal) and a single synthetic fibre type (PP); the generalizability of the hybridization benefit to other natural fibre types (jute, coir, hemp, flax) or synthetic fibre types remains to be confirmed. Second, fire exposure testing was conducted on small, unloaded specimens under furnace heating rather than full-scale structural elements under standard fire curve exposure with simultaneous mechanical loading; the latter would be required prior to direct application of these findings in fire-rated structural design. Third, the heating regime adopted, while designed to approximate the general severity envelope of a standard fire curve within furnace constraints, does not fully replicate the rapid early-stage heating rate of ISO 834 or ASTM E119 curves. Fourth, only one hybrid dosage ratio beyond the equal split and synthetic-dominant variants was evaluated; a finer-resolution dosage sweep would better identify the optimal hybrid ratio. Finally, potential effects of natural fibre alkali treatment method, ageing, and prior moisture/weathering exposure on fire performance were not evaluated and merit dedicated future study.

CONCLUSION

This study evaluated the fire resistance performance of self-compacting mortar reinforced with a hybrid combination of polypropylene and sisal fibres, in comparison to a plain control mix and single-fibre-type mixes, across an elevated temperature range of 200-800°C. The principal findings and their implications are summarized as follows:

- Hybrid fibre reinforcement at an equal-split dosage (0.75% PP + 0.75% sisal by volume) achieved the highest residual compressive strength retention among all tested mixes at every elevated temperature level, most notably 61% retention at 600°C compared to 43% for the plain control mix.
- The same hybrid mix achieved the highest residual flexural strength retention, with 54% retention at 600°C compared to 31% for the control - a proportionally larger relative improvement than observed for compressive strength, consistent with the particular sensitivity of flexural behaviour to fibre-derived crack-bridging mechanisms.
- Visually assessed spalling and surface cracking severity was substantially reduced in the hybrid mix relative to the control at every temperature level, with no visible cracking observed at 400°C and only minor cracking at 600°C, versus moderate cracking and corner loss in the control mix.
- Scanning electron microscopy supports a complementary dual protective mechanism: early formation of clean pressure-relief channels from PP fibre melting (from approximately 165°C), combined with crack-bridging and secondary void formation from progressive sisal fibre decomposition (from approximately 230-300°C onward), together providing protection across a broader effective temperature range than either fibre type alone.
- Fresh-state workability remained within acceptable self-compacting performance ranges for all tested fibre dosages, indicating that hybrid fibre incorporation at the levels studied is practically feasible without compromising the self-compacting characteristics of the mortar.
- Comparison between equal-split and synthetic-dominant hybrid dosage ratios indicates that fibre balance, rather than total fibre volume alone, influences the magnitude of fire-performance improvement, with the equal-split ratio outperforming the synthetic-dominant ratio at every temperature level tested despite identical total fibre content.

Taken together, these findings support hybrid synthetic-natural fibre reinforcement as a technically viable and comparatively cost-efficient strategy for improving the fire resistance of self-compacting cementitious mortars, with potential relevance to structural elements, precast components, tunnel linings, and fire-exposed repair applications where both flowability during placement and fire safety performance in service are design considerations.

Recommendations for Future Work

- Extend testing to full-scale structural elements under standard fire curve exposure (ISO 834 / ASTM E119) with simultaneous mechanical loading, to validate small-scale findings under realistic structural fire conditions.

- Conduct a finer-resolution sweep of hybrid fibre dosage ratios to more precisely identify the optimal PP-to-natural-fibre balance for fire performance.
- Evaluate alternative natural fibre types (jute, coir, hemp, flax, bamboo-derived fibres) and treatment methods within the same hybrid framework to assess generalizability of the observed benefits.
- Investigate the durability of hybrid-fibre self-compacting mortar under combined environmental ageing (moisture, alkaline exposure, freeze-thaw) and subsequent fire exposure, to assess whether pre-fire degradation of natural fibre affects its fire-performance contribution.
- Explore the influence of specimen size and heating rate on hybrid fibre performance, given that small-scale unloaded specimens may not fully capture the thermal gradient and restraint effects present in larger structural members.
- Develop and validate a simplified analytical or numerical model of coupled heat and mass transfer in hybrid-fibre SCM, informed by the experimental pore-pressure-relief and crack-bridging mechanisms identified in this study, to support predictive fire design.

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