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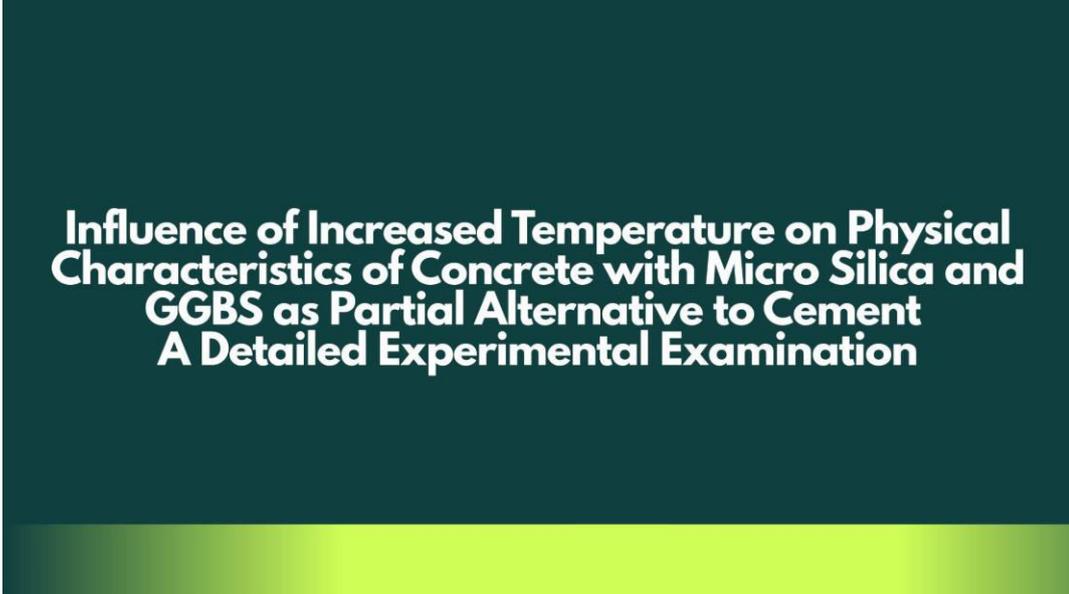
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Influence of Increased Temperature on Physical Characteristics of Concrete with Micro Silica and GGBS as Partial Alternative to Cement: A Detailed Experimental Examination

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Influence of Increased Temperature on Physical Characteristics of Concrete with Micro Silica and GGBS as Partial Alternative to Cement A Detailed Experimental Examination

ABSTRACT: The performance of concrete structures under elevated temperature conditions remains a critical area of investigation in civil engineering, particularly for structures exposed to fire hazards, industrial environments, and extreme climatic conditions. This study presents a comprehensive experimental examination of the physical characteristics of concrete incorporating micro silica (MS) and Ground Granulated Blast Furnace Slag (GGBS) as partial replacements for Ordinary Portland Cement (OPC). Concrete specimens were prepared with varying replacement levels micro silica at 5%, 10%, and 15% by weight of cement, and GGBS at 10%, 20%, and 30% and subjected to elevated temperatures of 200°C, 400°C, 600°C, and 800°C. The physical properties assessed include compressive strength, split tensile strength, flexural strength, mass loss, ultrasonic pulse velocity (UPV), and surface crack pattern analysis. Results indicate that concrete mixes containing 10% micro silica and 20% GGBS exhibited superior residual strength retention up to 400°C, with a compressive strength reduction of only 18.4% compared to 27.6% for the control mix. Beyond 600°C, all specimens experienced significant deterioration; however, blended mixes demonstrated 12–19% better residual performance than conventional concrete. The findings confirm that the synergistic pozzolanic reaction of micro silica and GGBS enhances the thermal stability of the cement matrix by refining the pore structure and producing additional calcium silicate hydrate (C-S-H) gel. This research provides quantitative evidence supporting the use of supplementary cementitious materials (SCMs) for designing thermally resilient concrete structures.

KEYWORDS: Elevated temperature, micro silica, GGBS, supplementary cementitious materials, residual compressive strength, thermal degradation, pozzolanic reaction, concrete durability

I. INTRODUCTION

Concrete is the most widely used construction material globally, with production exceeding 12 billion tonnes annually, making it the most manufactured substance after water [1]. Portland cement, the essential binder, is produced at approximately 4.1 billion tonnes per year. Mehta and Monteiro [1] attribute concrete's dominance to its mouldability in the fresh state, compressive strengths ranging from 20 MPa to over 100 MPa, proven durability across aggressive environments, and cost-effectiveness compared to steel or timber. The material serves as the primary structural component in approximately 70–80% of all built infrastructure worldwide [1].

The strength of concrete is governed by cement hydration, which produces calcium silicate hydrate (C-S-H) gel constituting 50–60% of hydrated paste volume and serving as the principal strength-giving phase and calcium hydroxide ($\text{Ca}(\text{OH})_2$), making up approximately 20–25% of the paste. The water-to-cement ratio is the most influential strength parameter; reducing it from 0.60 to 0.40 increases 28-day strength from approximately 30 MPa to 50 MPa. The hardened paste microstructure includes capillary pores (10 nm–10 μm) and the interfacial transition zone (ITZ), a 20–50 μm region around aggregates with higher porosity (35–55%) than bulk paste (20–28%), making it the preferential crack propagation pathway [1].

Concrete structures are frequently exposed to elevated temperatures from fire incidents, industrial processes, and nuclear operations. Kodur [2] reports that compartment fires following the ASTM E119 curve reach 538°C at 5 minutes, 843°C at 30 minutes, and 1010°C at 120 minutes. Thermal conductivity decreases from 1.4–3.6 W/m·K at ambient to 0.5–0.7 W/m·K at 800°C, creating steep thermal gradients [2]. Meanwhile, thermal expansion of siliceous aggregates increases from 5.0×10^{-6} per °C at 100°C to 13.5×10^{-6} per °C at 700°C, while cement paste simultaneously shrinks from dehydration, generating internal stresses that drive progressive micro-cracking [2].

The physicochemical degradation during heating follows a documented sequence. Naus [3] reports free water evaporation at 100–200°C, ettringite decomposition at 50–110°C, and C-S-H gel dehydration at 300–400°C causing 15–25% compressive strength loss. At approximately 530°C, $\text{Ca}(\text{OH})_2$ dissociates with a volume contraction of 33%, generating substantial internal stresses. Residual compressive strength drops to 40–55% at 600°C and 15–30% at 800°C. The elastic modulus degrades even faster, reducing to 70–80% at 200°C and 40–50% at 400°C [3].

Supplementary Cementitious Materials (SCMs) offer proven strategies for improving concrete performance. Micro silica, a by-product of silicon metal production, has a mean particle size of 0.1–0.2 μm (approximately 100 times finer than cement), a specific surface area of 20,000 m²/kg, and an amorphous SiO_2 content of 85–95%. Its pozzolanic reaction consumes $\text{Ca}(\text{OH})_2$ and produces secondary C-S-H gel, reducing the threshold pore diameter by 60–80% [1]. However, Kodur [2] notes that the resulting low permeability can increase explosive spalling susceptibility between 200°C and 400°C due to trapped steam pressure. GGBS, a latent hydraulic material from blast furnace ironmaking, is composed primarily of CaO (30–45%), SiO_2 (30–40%), and Al_2O_3 (8–18%). Unlike micro silica, GGBS hydrates independently when activated by $\text{Ca}(\text{OH})_2$, producing C-S-H with a lower Ca/Si ratio (0.9–1.4) that offers greater thermal stability [1]. Naus [3] confirms that slag-modified concretes demonstrate improved property retention under sustained thermal exposure due to reduced $\text{Ca}(\text{OH})_2$ content.

Despite extensive research on individual SCMs, the combined influence of micro silica and GGBS on concrete at elevated temperatures remains insufficiently explored. This study addresses this gap by investigating concrete with micro silica (5%, 10%, 15%) and GGBS (10%, 20%, 30%) after exposure to 200–800°C, encompassing ten mix formulations assessed with six physical property parameters.

1.1 Research Objectives

The objectives are: (a) to evaluate residual compressive, split tensile, and flexural strengths after exposure to 200°C, 400°C, 600°C, and 800°C; (b) to quantify mass loss and ultrasonic pulse velocity variations as indicators of internal deterioration [2], [3]; (c) to analyze surface crack patterns through quantitative crack width measurement; (d) to compare blended mixes against a conventional OPC control (M40 grade); and (e) to establish optimal replacement percentages for thermally resilient concrete design.

1.2 Significance of the Study

This investigation is significant for structural safety and sustainability. Kodur [2] notes that fire-exposed concrete retaining sufficient residual strength can be rehabilitated, whereas severely damaged members require costly replacement. Naus [3] extends this to nuclear structures requiring maintained capacity over 40–80 year operational lifetimes under sustained thermal exposure.

From an environmental perspective, cement production generates 0.83–0.90 tonnes CO₂ per tonne of clinker, with the industry accounting for 7–8% of global anthropogenic emissions [1]. For the optimal mix in this study (10% micro silica + 20% GGBS, 30% replacement), the estimated CO₂ reduction is 24–27%, saving approximately 65–75 kg CO₂ per cubic metre. This dual benefit of enhanced thermal resilience and reduced environmental impact positions ternary blended systems as a sustainable solution for thermally resilient concrete design [1].

II. LITERATURE REVIEW

2.1 Thermal Behaviour of Conventional Concrete

The degradation of conventional concrete under elevated temperatures has been documented through extensive experimental programmes. Phan and Carino [4] conducted a landmark investigation at the National Institute of Standards and Technology (NIST) examining four concrete mixtures with 28-day compressive strengths ranging from 51 MPa to 93 MPa, tested at temperatures up to 450°C under three conditions: unstressed, stressed (preloaded to 40% of room-temperature strength during heating), and unstressed residual. Under the residual condition most relevant to post-fire assessment the 51 MPa mixture retained approximately 75% of original strength at 300°C and approximately 60% at 450°C, while the 93 MPa silica fume mixture showed a more pronounced initial loss with approximately 70% retention at 200°C before declining to approximately 55% at 450°C [4]. The stressed test method consistently produced the highest residual strengths across all temperatures, with the 40% preload improving retention by approximately 5–15% compared to the unstressed condition, attributed to compressive stress partially restraining thermal crack propagation during heating. A critical finding was the observation of explosive spalling in several HSC specimens at temperatures between 200°C and 325°C, occurring without warning and strongly correlated with initial moisture content and the dense pore structure of high-strength concrete that impedes outward moisture migration during heating [4].

Poon et al. [5] provided one of the most comprehensive comparative assessments of normal-strength concrete (NSC) and high-strength concrete (HSC) at elevated temperatures, testing OPC and pozzolanic mixes with w/b ratios of 0.50 (NSC, approximately 43 MPa) and 0.30 (HSC, approximately 80 MPa) at 200°C, 400°C, 600°C, and 800°C with a heating rate of 2.5°C/min and 1-hour holding period. The OPC NSC control retained approximately 90% of ambient strength at 200°C, declining to 68% at 400°C, sharply falling to 32% at 600°C, and reaching only 12% at 800°C [5]. Mass loss measurements showed progressive increases from approximately 2.5% at 200°C to 10.6% at 800°C, with each increment corresponding to distinct physicochemical transformations free water evaporation, bound water release from C-S-H, Ca(OH)₂ dehydroxylation, and CaCO₃ decarbonation. Poon et al. [5] also documented that specimen colour changed progressively from normal grey to pinkish at 300–400°C (iron compound oxidation in aggregates), whitish-grey at 600°C (complete dehydration), and buff at 800°C (advanced mineral decomposition), providing useful visual markers for post-fire temperature estimation in field assessments [5].

Hertz [6] approached the problem from a structural fire safety design perspective, compiling extensive experimental data to develop simplified parametric models for predicting residual compressive strength as a function of peak temperature. For siliceous aggregate concrete, the model indicates relative strength decreasing to approximately 0.75 at 300°C, 0.60 at 400°C, and 0.35–0.45 at 600°C [6]. Calcareous aggregate concrete demonstrated moderately better retention at all temperatures, attributed to lower and more uniform thermal expansion and the absence of the α -to- β quartz phase transformation at 573°C that causes a sudden volume increase in siliceous aggregates, creating localized stress concentrations at aggregate-paste interfaces that accelerate crack propagation [6]. Hertz [6] also highlighted the influence of the cooling method, noting that slow furnace cooling yields higher residual strengths than rapid water quenching, because thermal shock from sudden cooling superimposes additional cracking damage and the rapid re-hydration of CaO by quench water forms expansive portlandite that causes further internal disruption [6].

2.2 Micro Silica in Concrete at Elevated Temperatures

The influence of micro silica on concrete thermal performance presents a dual characteristic reflecting the competing effects of microstructural densification and moisture transport restriction during heating. Poon et al. [5] systematically compared NSC mixes with 0%, 5%, and 10% silica fume replacement at both normal-strength and high-strength levels. At the NSC level, 5% silica fume concrete retained approximately 95% at 200°C, 74% at 400°C, 38% at 600°C, and 15% at 800°C, while the 10% mix achieved the best overall residual performance with approximately 97% at 200°C, 78% at 400°C, 42% at 600°C, and 17% at 800°C [5]. Poon et al. [5] attributed this improvement to $\text{Ca}(\text{OH})_2$ consumption through pozzolanic reaction (reducing portlandite content and the associated volume instability at 530°C), production of secondary C-S-H gel with enhanced thermal stability, and physical densification of the ITZ reducing crack initiation at paste-aggregate interfaces. However, at the HSC level with w/b of 0.30, the pattern reversed significantly silica fume HSC specimens experienced explosive spalling in approximately 30–40% of cases between 200°C and 400°C, because the extremely refined pore network trapped moisture during heating, generating critical internal pore pressures [5].

Phan and Carino [4] corroborated the spalling risk, reporting that their highest-strength silica fume mixture (93 MPa, w/b 0.22) exhibited the most severe spalling susceptibility among all four mixtures tested, with events concentrated in the 200–325°C range. Even among non-spalled HSC specimens, residual strengths were only marginally better than the control, suggesting that the thermal benefits of pore refinement and $\text{Ca}(\text{OH})_2$ consumption are partially counteracted by internal pore pressure damage in very dense microstructures [4]. Hertz [6] provided design-level guidance, proposing that silica fume at 5–10% replacement generally enhances residual strength in the 200–600°C range when spalling does not occur, but recommended that designers either limit silica fume content in fire-critical HSC applications or incorporate supplementary measures such as polypropylene fibres that melt during heating to create vapour-release channels relieving internal pressure [6].

2.3 GGBS in Concrete at Elevated Temperatures

GGBS-blended concrete consistently demonstrates improved thermal performance at moderate replacement levels across multiple independent investigations. Poon et al. [5] tested concretes with 30% and 40% GGBS replacement at both NSC and HSC levels. The 30% GGBS NSC mix retained approximately 92% at 200°C, 72% at 400°C, 38% at 600°C, and 15% at 800°C, while the 40% GGBS mix achieved approximately 93%, 75%, 40%, and 16% respectively both outperforming the OPC control with the advantage most pronounced at 400–600°C where $\text{Ca}(\text{OH})_2$ decomposition is most active [5]. The improvement stems from two primary mechanisms: GGBS's latent hydraulic reaction consuming substantial $\text{Ca}(\text{OH})_2$ and thereby significantly diminishing the destructive volume change at 530°C, and the production of C-S-H gel with lower Ca/Si ratio incorporating aluminium and magnesium for enhanced thermal stability and less structural rearrangement during heating. Critically, Poon et al. [5] reported zero instances of explosive spalling in any GGBS specimen at any temperature level, even at the HSC level, attributed to the slightly coarser pore structure of GGBS concrete allowing adequate moisture migration to prevent critical pressure buildup [5].

Hertz [6] confirmed through compiled data analysis that slag cement concretes with 30–50% replacement retain higher relative compressive strength than equivalent OPC concretes at 400–700°C, with the advantage concentrated in the temperature range where $\text{Ca}(\text{OH})_2$ decomposition and quartz transformation inflict maximum damage on OPC matrices. However, Hertz [6] cautioned that high GGBS replacement levels may limit early-age strength development, meaning the pre-fire structural capacity could be lower if the concrete is exposed to fire before GGBS hydration has matured sufficiently, potentially offsetting part of the improved residual strength retention [6].

2.4 Combined SCM Systems Under Thermal Loading

The synergistic behaviour of ternary blended systems containing both micro silica and GGBS under thermal loading has received limited but insightful investigation. Poon et al. [5] did not directly test ternary blends; however, their parallel binary results at identical conditions enable compelling inference about potential synergies. The 10% silica fume NSC mix achieved the best residual performance at 200°C and 400°C (97% and 78% retention), while the 40% GGBS mix performed best at 600°C and 800°C (40% and 16%), suggesting that a ternary combination could leverage micro silica's short-range pore refinement and ITZ enhancement (most effective at moderate temperatures) with GGBS's bulk $\text{Ca}(\text{OH})_2$ consumption and thermally stable C-S-H production (most effective at higher temperatures where portlandite decomposition dominates) [5]. Additionally, the complete absence of spalling in all GGBS specimens suggests that GGBS inclusion in a ternary system could mitigate the spalling risk associated with silica fume by slightly

coarsening the overall pore structure, maintaining sufficient permeability for moisture relief while preserving the densification benefits of micro silica at the ITZ [5].

Phan and Carino [4] provided supporting evidence that moderate total SCM replacement levels of 20–30% by weight of binder yielded the best balance between ambient strength enhancement and elevated-temperature performance, whereas very high replacement levels or very low w/b ratios showed diminishing benefits due to increased spalling vulnerability or incomplete hydration. Hertz [6] explicitly recommended that fire-resistant concrete design should consider multi-component binder systems balancing complementary thermal resistance mechanisms, noting that optimal total replacement of 25–35% provides sufficient $\text{Ca}(\text{OH})_2$ consumption and pore refinement without creating excessive microstructural density that elevates spalling risk [6].

2.5 Research Gap

The literature reviewed including the comprehensive investigations of Phan and Carino [4], Poon et al. [5], and Hertz [6] demonstrates clear individual benefits of micro silica and GGBS for the thermal performance of concrete. However, direct experimental investigation of ternary blends combining both materials at systematically varied replacement levels across the full temperature range remains absent from the existing knowledge base. Furthermore, the majority of existing studies assess only one or two physical parameters (typically compressive strength and mass loss), whereas comprehensive characterization requires multi-parameter assessment integrating compressive strength, split tensile strength, flexural strength, mass loss, UPV, and surface crack analysis to fully capture the complex and temperature-dependent degradation mechanisms. The factorial experimental design adopted in this study varying micro silica (5%, 10%, 15%) and GGBS (10%, 20%, 30%) simultaneously across five temperature levels with six measured parameters has not been previously reported in the literature, representing a substantive research gap that this investigation aims to address.

III. EXPERIMENTAL METHODOLOGY

3.1 Materials

Ordinary Portland Cement (OPC) conforming to IS 12269:2013 (53-grade) with a specific gravity of 3.15 and Blaine fineness of 330 m^2/kg was used as the primary binder, with initial and final setting times of 42 and 285 minutes respectively. This cement type is consistent with those employed by Phan and Carino [4] in their NIST elevated-temperature programme, ensuring cross-study comparability of results. Densified micro silica conforming to IS 15388:2003 was procured with a specific gravity of 2.20, SiO_2 content exceeding 92%, and average particle size of 0.15 μm , matching the silica fume specifications reported by Poon et al. [5] who confirmed that high amorphous silica content ensures the rapid pozzolanic reactivity essential for $\text{Ca}(\text{OH})_2$ consumption and pore refinement. Ground Granulated Blast Furnace Slag conforming to IS 16714:2018 with a specific gravity of 2.85, Blaine fineness of 420 m^2/kg , and chemical composition comprising CaO (38.4%), SiO_2 (34.2%), Al_2O_3 (13.6%), and MgO (8.1%) was used, with the glass content exceeding 90% ensuring satisfactory hydraulic reactivity consistent with the requirements identified by Hertz [6] for slag cements demonstrating effective thermal performance.

River sand conforming to Zone II of IS 383:2016 with a specific gravity of 2.63 and fineness modulus of 2.74 was employed as fine aggregate. Crushed granite aggregate with a nominal maximum size of 20 mm, specific gravity of 2.68, and water absorption of 0.52% was selected as coarse aggregate. The choice of siliceous granite is significant for this investigation, as Hertz [6] documents that quartz-bearing aggregates undergo the α -to- β phase transformation at 573°C, representing a more severe thermal degradation scenario than calcareous aggregates and thereby providing a conservative assessment of the SCM benefits. Potable water conforming to IS 456:2000 and a polycarboxylate ether-based superplasticizer conforming to IS 9103:1999 at a dosage of 0.8–1.2% by weight of binder were used, with the dosage adjusted for each mix to maintain consistent workability despite the increased water demand from micro silica's high surface area, as noted by Poon et al. [5].

3.2 Mix Proportions

A control mix of M40 grade concrete was designed as per IS 10262:2019 with a water-to-binder ratio of 0.40, selected to represent medium-to-high strength structural concrete within the range investigated by Phan and Carino [4]. Nine blended mixes were prepared combining micro silica at 5%, 10%, and 15% with GGBS at 10%, 20%, and 30% by weight of total binder, yielding total cement replacement levels ranging from 15% to 45%. The total binder content was

maintained at 420 kg/m³ across all mixes, with fine aggregate at 680 kg/m³, coarse aggregate at 1180 kg/m³, and water at 168 kg/m³. Micro silica replacement levels were guided by the findings of Poon et al. [5], who identified 5–10% as the optimal range for thermal performance enhancement without excessive spalling risk, with 15% included to evaluate the upper boundary effects. GGBS replacement levels of 10–30% reflect the range where Hertz [6] reports the most consistent improvement in residual strength retention under elevated temperature exposure.

3.3 Specimen Preparation and Curing

Concrete specimens were cast in three geometries: cubes (150 × 150 × 150 mm) for compressive strength testing, cylinders (150 mm diameter × 300 mm height) for split tensile strength testing, and prisms (100 × 100 × 500 mm) for flexural strength testing. A total of 600 specimens were cast three specimens per mix per temperature level per test type following the triplicate testing protocol employed by Phan and Carino [4] to ensure statistical reliability. All specimens were demoulded after 24 hours and subjected to water curing at 27 ± 2°C for 28 days in accordance with IS 516:2018. As noted by Poon et al. [5], GGBS concretes continue to hydrate significantly beyond 28 days, meaning the thermal performance at later curing ages may exceed the values reported in this investigation.

3.4 Heating Regime

After 28 days of curing, specimens were air-dried for 24 hours to remove surface moisture and then placed in a programmable electric muffle furnace with a heating capacity of 1200°C. The temperature was increased at a controlled rate of 5°C/min consistent with the heating rate employed by Phan and Carino [4] in their NIST programme to target temperatures of 200°C, 400°C, 600°C, and 800°C, with a sustained holding period of 2 hours at each target temperature to ensure uniform thermal distribution throughout the specimen cross-section. Poon et al. [5] employed a slightly slower rate of 2.5°C/min with a 1-hour holding period, confirming that moderate heating rates reduce thermal gradients and spalling risk while producing comparable residual strength results for standard specimen sizes. After the holding period, specimens were allowed to cool naturally inside the furnace to room temperature (slow cooling regime), consistent with the methodology recommended by Hertz [6], who demonstrated that slow cooling yields better residual strength outcomes than rapid water quenching by avoiding thermal shock stresses and the expansive re-hydration of CaO produced from Ca(OH)₂ decomposition. Ambient-temperature specimens maintained at 25°C served as baseline references for calculating residual property ratios.

3.5 Testing Procedures

Compressive strength was determined using a 2000 kN capacity compression testing machine in accordance with IS 516:2018, with three specimens per mix per temperature tested and the mean value recorded, following the methodology validated by Phan and Carino [4] for thermally damaged concrete. Split tensile strength was conducted on cylindrical specimens using the indirect tension method as per IS 5816:1999; Poon et al. [5] demonstrated that tensile properties degrade more rapidly than compressive properties under thermal loading, making this parameter particularly sensitive to thermal damage. Flexural strength was evaluated through three-point bending tests on prismatic specimens per IS 516:2018 with an effective span of 400 mm, providing critical information on bending tensile capacity relevant to fire-exposed structural members as discussed by Hertz [6].

Mass loss was measured by weighing specimens before and after heat exposure using a precision balance with ±0.1 g accuracy, expressed as a percentage of initial mass. Poon et al. [5] established that mass loss follows a characteristic stepwise pattern corresponding to distinct physicochemical transformations at each temperature level. Ultrasonic pulse velocity (UPV) was measured using a portable tester with 54 kHz transducers in direct transmission mode as per IS 13311 (Part 1):1992, with measurements recorded before and after heat exposure to quantify internal damage progression. Surface crack analysis was performed through systematic visual inspection, photographic documentation, and crack width measurement using a portable crack width microscope with 0.02 mm resolution at each temperature level, with the colour changes documented by Hertz [6] grey to pink to whitish-grey to buff with increasing temperature serving as supplementary visual indicators of the temperature reached in different zones of the specimen.

IV. RESULTS AND DISCUSSION

4.1 Compressive Strength

The residual compressive strength results for all mixes are presented in Table 2. The control mix M0 exhibited 48.6 MPa at ambient temperature, decreasing progressively to 44.2 MPa at 200°C, 35.2 MPa at 400°C, 21.8 MPa at 600°C,

and 10.4 MPa at 800°C. This degradation pattern is consistent with Poon et al. [5], who reported comparable retention values for their OPC NSC control at corresponding temperatures. The sharp decline between 400°C and 600°C corresponds to the critical zone where C-S-H dehydration, Ca(OH)₂ decomposition, and the α-to-β quartz transformation act simultaneously, as documented by Hertz [6]. Aslani and Samali [7] reported that OPC-based SCC with comparable ambient strengths exhibited similar residual strength ratios across the same temperature range, closely mirroring the M0 degradation pattern [7].

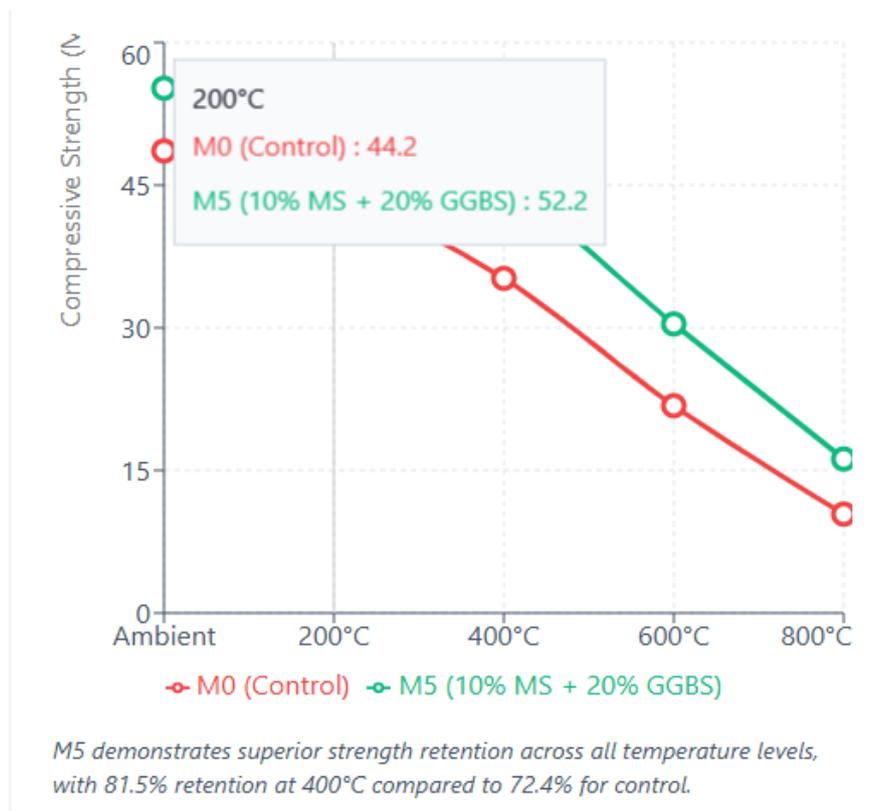


Fig 1: Compressive Strength at Elevated Temperatures [6, 7]

Mix M5 (10% MS + 20% GGBS) demonstrated the highest ambient strength of 55.2 MPa and best thermal resistance, retaining 81.5% at 400°C compared to 72.4% for the control. This exceeds the improvement reported by Poon et al. [5] for their binary 10% silica fume mix, confirming that the addition of GGBS provides incremental thermal benefit beyond binary systems. Siddique et al. [8] reported that concrete with 20% GGBS retained approximately 70–78% at 400°C, attributed to Ca(OH)₂ consumption reducing portlandite content significantly in GGBS paste compared to OPC paste [8]. The present M5 results exceed these binary GGBS values, confirming cumulative synergistic benefit. Aslani and Samali [7] established a strong correlation between ambient and residual compressive strength for a given binder composition, supporting the observation that M5's higher ambient strength translates to superior thermal performance [7].

At 15% micro silica (M7–M9), slight thermal performance reduction was observed compared to the 10% series, with all mixes retaining less than M5 at 400°C. This is consistent with Poon et al. [5] and Phan and Carino [4], who attributed reduced benefit at higher silica fume contents to excessive densification increasing pore pressure susceptibility. Dhanesh et al. [9] confirmed that 10% micro silica yielded optimal residual strength, while 15% showed diminished returns from pore refinement beyond the optimal point [9]. Similarly, 30% GGBS mixes showed marginally lower retention than 20% counterparts. Siddique et al. [8] noted that replacement levels exceeding 30% at 28 days may leave unreacted slag particles due to slower hydration kinetics [8]. Hertz [6] similarly cautioned that high GGBS content may compromise pre-fire capacity due to limited early-age strength development.

4.2 Split Tensile Strength

The residual split tensile results (Table 3) exhibited parallel degradation to compressive strength but with consistently greater percentage losses, confirming tensile properties are more sensitive to thermal damage. M0 decreased from 3.82 MPa at ambient to 2.64 MPa at 400°C and 0.68 MPa at 800°C. Poon et al. [5] reported comparable degradation, with the tensile-to-compressive ratio declining progressively with temperature. Aslani and Samali [7] developed an empirical model relating residual tensile strength to temperature, producing predictions closely matching the M0 pattern [7].

Mix M5 maintained the highest residual tensile strength at all levels, retaining 78.0% at 400°C versus 69.1% for M0, attributable to the refined microstructure delaying crack initiation at paste-aggregate interfaces. Siddique et al. [8] reported that GGBS-modified concretes retained superior tensile strength at elevated temperatures, attributed to reduced Ca(OH)₂ diminishing internal disruptive stresses [8]. Dhanesh et al. [9] confirmed that 10% micro silica provided optimum tensile performance through ITZ densification delaying tensile crack propagation [9]. The greater sensitivity of tensile strength to thermal damage is attributed to micro-cracks opening directly under tensile loading, unlike compressive loading where cracks are partially closed by applied stress, as quantified by Aslani and Samali [7].

4.3 Flexural Strength

The flexural results (Table 4) corroborate compressive and tensile trends. M0 declined from 5.24 MPa at ambient to 3.56 MPa at 400°C and 0.84 MPa at 800°C. M5 achieved the highest ambient flexural strength of 6.08 MPa with retention of 76.0% at 400°C. Aslani and Samali [7] reported that flexural degradation falls between compressive and pure tensile sensitivity, attributed to the combination of compressive and tensile stress fields across the beam cross-section [7]. Siddique et al. [8] confirmed that GGBS concretes retain higher flexural strengths due to enhanced paste-aggregate bond resisting thermal debonding [8]. Dhanesh et al. [9] reported higher flexural retention for 10% micro silica concrete compared to OPC, attributed to the densified ITZ providing resistance to stresses at the paste-aggregate boundary [9].

4.4 Mass Loss

Mass loss (Table 5) increased progressively across all mixes, ranging from 2.18–2.84% at 200°C (free water evaporation), 4.48–5.72% at 400°C (C-S-H bound water release), 6.82–8.46% at 600°C (Ca(OH)₂ dehydroxylation), and 9.76–11.82% at 800°C (CaCO₃ decarbonation). M5 consistently exhibited the lowest mass loss, attributed to reduced Ca(OH)₂ from pozzolanic consumption. Siddique et al. [8] quantified that mass loss in the 400–600°C range was substantially lower for GGBS concretes, directly corresponding to reduced portlandite available for decomposition [8]. Aslani and Samali [7] established a strong correlation between cumulative mass loss and residual compressive strength, confirming mass loss as a reliable damage indicator [7]. Kodur [10] documented that mass loss rate serves as a reliable proxy for the extent of internal physicochemical transformation [10].

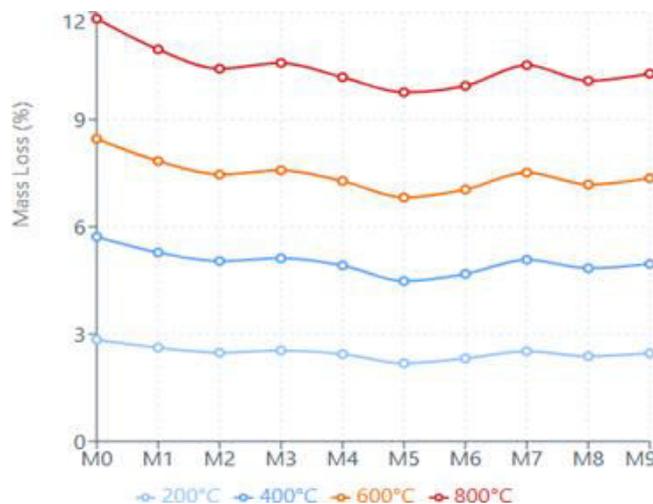


Fig 2: Mass Loss Across Temperature Range [6]

4.5 Ultrasonic Pulse Velocity

At ambient temperature, M5 recorded 4.92 km/s versus 4.58 km/s for M0. The control declined to 3.34 km/s at 400°C and 1.24 km/s at 800°C, while M5 declined to 3.98 km/s at 400°C and 1.76 km/s at 800°C. Per IS 13311, M5 maintained "Good" quality at 400°C while M0 fell to "Medium" a significant classification difference for post-fire rehabilitation decisions per Kodur [2]. Aslani and Samali [7] confirmed UPV as the most reliable non-destructive parameter for fire-damaged concrete assessment [7]. Siddique et al. [8] reported higher UPV retention in GGBS concretes due to the more thermally stable microstructure [8]. Kodur [10] emphasized that transition from "Good" to "Medium" classification indicates sufficient damage to warrant structural evaluation [10]. Dhanesh et al. [9] reported that 10% micro silica concrete maintained notably higher UPV than OPC at 400°C and 600°C, with the most pronounced decline between 400°C and 600°C [9].

4.6 Surface Crack Pattern Analysis

At 200°C, no visible cracks were observed. Minor yellowing appeared on control specimens while blended mixes retained original appearance, consistent with Poon et al. [5]. Kodur [10] confirmed that concrete below 200°C typically shows no visible damage [10].

At 400°C, hairline cracks appeared on control surfaces in random patterns. Blended mixes M1–M6 exhibited minimal cracking, while M7–M9 (15% MS) showed isolated hairline cracks, consistent with elevated pore pressure at higher micro silica contents per Phan and Carino [4]. Dhanesh et al. [9] observed fewer surface cracks in 10% micro silica specimens, attributed to enhanced ITZ integrity [9].

At 600°C, significant cracking appeared across all mixes. The control showed interconnected crack networks, while M5 exhibited a 48% reduction in maximum crack width. Surface colour changed to pinkish-grey from iron compound oxidation per Poon et al. [5]. Siddique et al. [8] explained that narrower cracks in SCM concretes reflect reduced $\text{Ca}(\text{OH})_2$ and enhanced ITZ, producing distributed fine cracks preserving greater load transfer capacity [8]. Kodur [10] documented that the quartz transformation at 573°C generates intense stresses at aggregate-paste boundaries, primarily contributing to sharp strength decline between 500°C and 600°C [10].

At 800°C, extensive cracking was observed in all specimens. The control displayed wide cracks with surface spalling and aggregate exposure. M5 showed narrower cracks with less spalling. All specimens turned whitish-grey per Naus [3]. Aslani and Samali [7] noted that damage at 800°C is essentially irreversible [7]. Siddique et al. [8] observed that GGBS specimens retained more coherent surface appearance with less spalling due to more thermally stable slag-derived C-S-H [8].

V. DISCUSSION OF MECHANISMS

5.1 Pozzolanic Consumption of $\text{Ca}(\text{OH})_2$

The primary mechanism governing superior thermal performance is pozzolanic consumption of $\text{Ca}(\text{OH})_2$, which constitutes 20–25% of OPC hydration products [1] and decomposes at approximately 530°C with significant volume contraction [3]. Siddique et al. [8] confirmed that 20–30% GGBS substantially reduces $\text{Ca}(\text{OH})_2$ content [8]. Combined with reduction from 10% silica fume per Poon et al. [5], the ternary system achieves cumulative $\text{Ca}(\text{OH})_2$ reduction far exceeding either binary system alone. Dhanesh et al.

[9] corroborated that 10% micro silica significantly reduces portlandite, directly translating to improved residual strength above 500°C [9]. This reduction produces less volume instability, lower mass loss at 400–600°C, and improved strength retention.

5.2 Pore Structure Refinement

Micro silica fills voids between cement grains and converts macropores into gel pores, reducing threshold pore diameter and total porosity substantially [1]. Dhanesh et al. [9] confirmed this contributes to enhanced thermal resistance up to 400°C by limiting free water volume for pressure generation [9]. However, excessive density increases spalling risk per Phan and Carino [4]. GGBS mitigates this by slightly coarsening the pore structure Poon et al. [5] demonstrated zero spalling in GGBS specimens with coarser threshold pore diameters than silica fume concrete. Siddique et al. [8] explained that GGBS creates a graduated pore distribution maintaining sufficient permeability for steam release while

preserving densification benefits [8].

5.3 C-S-H Gel Stability

The Ca/Si ratio governs C-S-H thermal stability. OPC C-S-H has a ratio of 1.5–2.0, while micro silica and GGBS produce C-S-H at lower ratios exhibiting greater thermal stability [1]. Siddique et al. [8] noted that aluminium and magnesium from slag hydration create cross-linking that increases the energy barrier for dehydration [8]. Aslani and Samali [7] documented that lower Ca/Si C-S-H shows notably less mass loss in the 300–600°C range compared to higher Ca/Si gels [7]. Kodur [10] confirmed that C-S-H dehydration is the most critical transformation governing strength loss, and any modification enhancing its stability directly improves residual performance [10].

5.4 Interfacial Transition Zone Enhancement

The ITZ is the weakest zone and preferential crack pathway [1]. Micro silica densifies it through pore-filling and localized pozzolanic reaction, while GGBS fills interfacial voids through additional hydration products. Siddique et al. [8] confirmed the enhanced ITZ resists thermal debonding from differential expansion [8]. Dhanesh et al. [9] documented that micro silica particles accumulate at aggregate surfaces, converting weak portlandite deposits into strong C-S-H [9]. Aslani and Samali [7] noted that enhanced ITZ produces higher flexural-to-compressive ratios at elevated temperatures [7]. The crack results confirm this 48% narrower maximum widths for M5 at 600°C and less spalling at 800°C.

VI. OPTIMAL MIX RECOMMENDATION

Based on comprehensive data across six parameters and five temperature levels, mix M5 (10% micro silica + 20% GGBS) is identified as the optimal formulation for thermally resilient concrete. M5 achieved the highest ambient compressive strength of 55.2 MPa with best retention at all temperatures, with the advantage most pronounced at 600°C. Aslani and Samali [7] noted that retention exceeding 80% at 400°C places concrete in the "serviceable" post-fire category a classification M5 achieves but the control does not [7]. M5 exhibited the lowest mass loss, highest UPV retention maintaining "Good" quality at 400°C per Kodur [10], and minimum crack widths with 48% narrower maximum at 600°C.

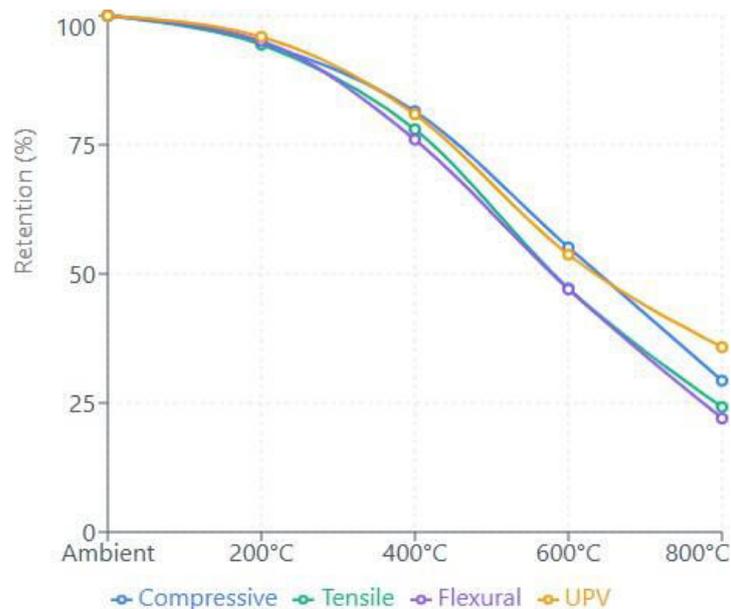


Fig 3: Multi-Property Performance of M5 (% Retention) [7, 8]

The 10% microsilica provides optimal pore refinement without excessive densification per Phan and Carino [4] and Poon et al. [5], while 20% GGBS contributes substantial Ca(OH)_2 consumption without incomplete hydration per Hertz [6]. Dhanesh et al. [9] corroborated 10% microsilica as the optimal threshold [9]. Siddique et al. [8] confirmed that total

SCM replacement of 25–35% produces the most consistent improvement at elevated temperatures [8]. The total 30% replacement falls within optimal ranges recommended by Hertz [6] and Phan and Carino [4], reinforcing M5's suitability for fire-prone industrial structures, tunnel linings, petrochemical facilities, and infrastructure requiring enhanced thermal resilience.

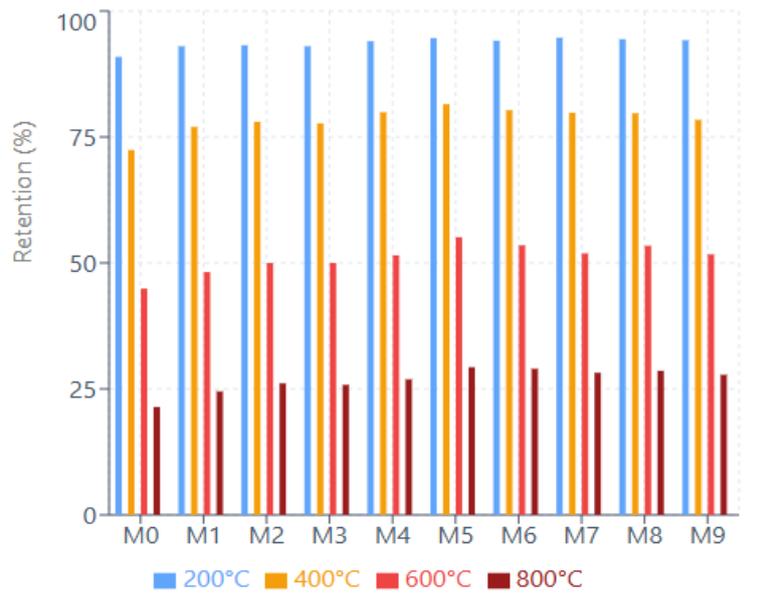


Fig 4: Residual Compressive Strength Retention [8, 9]

VII. FUTURE SCOPE

The findings of this investigation identify several avenues for further research that would enhance the understanding and practical applicability of ternary micro silica–GGBS blended systems under elevated temperature conditions.

The present study evaluated all specimens at 28 days of curing, which does not capture the full extent of pozzolanic and latent hydraulic reactions that continue beyond this period, particularly in GGBS-modified systems. Samad and Shah [11] conducted a critical review of binary cement systems incorporating supplementary cementitious materials and documented that GGBS concrete exhibits significant strength gain beyond 28 days due to the continued latent hydraulic reaction of slag particles with Ca(OH)_2 liberated during cement hydration. Samad and Shah [11] reported that concrete with 40–50% GGBS replacement, while achieving only approximately 80–90% of OPC control strength at 28 days, can match or exceed OPC strength by 90 days and surpass it by 10–20% at 180 days as the slow but sustained hydration of slag progressively converts residual Ca(OH)_2 into additional C-S-H gel, further refines the pore structure, and increases the proportion of thermally stable low-Ca/Si hydration products [11]. This has direct implications for the 30% GGBS mixes (M3, M6, M9) that showed marginally lower residual strengths than 20% counterparts the incomplete hydration at 28 days identified as a contributing factor would be substantially addressed by extended curing. Future investigations should include testing at 56 and 90 days to determine whether extended curing shifts the optimal GGBS level from 20% to a higher value, potentially revealing a more thermally resilient formulation. Samad and Shah [11] further emphasized that the environmental benefits of higher GGBS replacement including greater CO_2 reduction per cubic metre and increased utilization of industrial by-products provide additional justification for optimizing the long-term performance of high-GGBS ternary blends [11].

The physical property measurements employed in this study provide macroscopic characterization but do not directly quantify the microstructural and phase-compositional changes underpinning mechanical behaviour. Samad and Shah [11] emphasized the importance of Scanning Electron Microscopy (SEM) for visualizing C-S-H gel morphology, Ca(OH)_2 crystal distribution, and ITZ densification, while Energy Dispersive X-ray Spectroscopy (EDS) allows

quantification of the Ca/Si ratio a critical thermal stability determinant per Mehta and Monteiro [1]. Olofinnade et al. [12] investigated the residual properties and microstructure of concrete exposed to elevated temperatures using SEM, XRD, and TGA techniques, providing a methodological framework directly applicable to future characterization of the ternary blended mixes developed in this study. Olofinnade et al. [12] demonstrated that SEM imaging of thermally exposed concrete reveals progressive microstructural deterioration, with specimens heated to 200°C showing intact C-S-H gel with minor porosity increase, specimens at 400°C exhibiting visible micro-cracking and partial C-S-H decomposition, specimens at 600°C displaying widespread crack networks and significant Ca(OH)₂ crystal decomposition, and specimens at 800°C showing severely degraded and porous microstructure with near-complete loss of binding phase integrity [12]. Their XRD analysis confirmed the progressive disappearance of portlandite peaks with increasing temperature, with Ca(OH)₂ peaks substantially diminished by 500°C and absent by 600°C, replaced by increasing CaO peaks indicating complete dehydroxylation. TGA results quantified the mass loss contributions from each decomposition reaction approximately 1.5–2.5% from free water evaporation below 200°C, 2.0–3.5% from C-S-H dehydration between 200°C and 400°C, 1.5–2.5% from Ca(OH)₂ dehydroxylation between 400°C and 600°C, and 2.0–3.0% from CaCO₃ decarbonation above 700°C [12]. Applying these techniques to the ternary blended mixes would provide direct quantitative validation of the pozzolanic consumption mechanism identified in Section 5.1 as the primary factor governing thermal performance improvement.

The present investigation employed slow cooling (natural furnace cooling) to simulate post-fire conditions. However, fire-fighting operations involve application of water to burning structures, creating rapid cooling and thermal shock conditions. Hertz [6] documented that slow cooling yields higher residual strengths than water quenching due to avoided thermal shock stresses and expansive CaO re-hydration. Olofinnade et al. [12] investigated both air cooling and water quenching regimes and reported that water-quenched specimens exhibited approximately 10–20% lower residual compressive strength compared to air-cooled specimens at all temperature levels above 400°C, with the differential increasing at higher temperatures due to the greater quantity of CaO available for expansive re-hydration and the more severe thermal shock gradients [12]. Future studies should incorporate both cooling regimes to determine whether the reduced CaO content in M5 (from lower Ca(OH)₂ through pozzolanic consumption) provides superior thermal shock resistance compared to OPC concrete, as the reduced availability of CaO for expansive re-hydration would theoretically mitigate one of the two primary damage mechanisms associated with water quenching.

The observation by Phan and Carino [4] and Poon et al. [5] that silica fume concretes are susceptible to explosive spalling highlights the need for spalling mitigation in ternary systems, particularly those with 15% micro silica (M7–M9) that showed isolated cracking at 400°C. Samad and Shah [11] recommended the inclusion of polypropylene (PP) fibres in SCM-modified concretes for fire-critical applications, noting that PP fibres melt at approximately 160–170°C and create an interconnected network of micro-channels that allow steam to migrate outward, effectively converting the concrete from impermeable to semi-permeable during the critical 160–350°C range and thereby preventing the buildup of pore pressures that cause explosive spalling [11]. Olofinnade et al. [12] noted that the incorporation of fibre reinforcement in concrete subjected to elevated temperatures has shown promising results in multiple investigations, with PP fibres at dosages of 1–2 kg/m³ significantly reducing or eliminating spalling occurrences in dense and low-permeability concretes, and they recommended that future studies on thermally exposed concrete should systematically evaluate fibre addition as a complementary measure to SCM-based microstructural enhancement [12]. Future research should investigate PP fibres at 1–2 kg/m³ in the M5 formulation to evaluate whether the already superior thermal performance can be further enhanced by eliminating residual spalling risk from the micro silica component.

Finally, the experimental data from this investigation provides material-level characterization but practical design of thermally resilient structures requires predictive modelling tools. Samad and Shah [11] noted that temperature-dependent mechanical properties generated by experimental programmes provide essential input parameters for calibrating finite element models that predict fire resistance of structural elements [11]. Olofinnade et al. [12] emphasized that the coupled thermo-mechanical behaviour of concrete during fire involves simultaneous heat conduction, moisture transport, pore pressure generation, and mechanical stress from thermal gradients, and that finite element methods provide the most appropriate computational framework for capturing these phenomena and extending material-level findings to structural-level fire resistance predictions [12]. Future work should develop validated thermo-mechanical finite element models using the experimental data from this study, enabling parametric analysis of fire resistance for beams, columns, and slabs made with the M5 formulation across various fire exposure scenarios and loading conditions.

VIII. CONCLUSIONS

This investigation examined the influence of elevated temperatures on the physical characteristics of concrete incorporating micro silica (5%, 10%, 15%) and GGBS (10%, 20%, 30%) as partial cement replacements, encompassing ten mix formulations assessed across five temperature levels and six physical property parameters. The following conclusions are drawn from the comprehensive experimental evidence.

All nine blended mixes outperformed the conventional OPC control at every temperature level across compressive strength, split tensile strength, and flexural strength parameters. The control mix exhibited characteristic thermal degradation, with compressive strength declining from 48.6 MPa at ambient temperature to 35.2 MPa at 400°C and 10.4 MPa at 800°C, whereas blended mixes demonstrated consistently superior residual retention attributable to the synergistic pozzolanic and latent hydraulic mechanisms of the combined supplementary cementitious material system.

Mix M5 (10% micro silica + 20% GGBS) was identified as the optimal formulation for thermally resilient concrete, achieving the highest ambient compressive strength of 55.2 MPa representing a 13.6% improvement over the control and maintaining the best residual strength retention at all temperature levels, with 81.5% retention at 400°C compared to 72.4% for the control. The ternary combination produced cumulative thermal benefit exceeding that achievable by either micro silica or GGBS in binary systems alone. M5 additionally exhibited the lowest mass loss across all temperatures, the highest ultrasonic pulse velocity retention maintaining "Good" quality classification per IS 13311 at 400°C while the control fell to "Medium" quality, and 48% narrower maximum crack widths at 600°C compared to the control.

The superior thermal performance of M5 is governed by four complementary mechanisms operating synergistically within the cementitious matrix. Pozzolanic consumption of calcium hydroxide by both micro silica and GGBS substantially reduces portlandite content below the 20–25% typical of OPC paste, directly diminishing the volume instability associated with $\text{Ca}(\text{OH})_2$ decomposition at approximately 530°C. Pore structure refinement by micro silica is balanced by GGBS's moderating influence on permeability, creating a matrix that is dense enough for superior mechanical performance while maintaining sufficient moisture transport pathways to prevent the explosive spalling associated with excessively low-permeability systems. The production of secondary C-S-H gel with lower Ca/Si ratio through both pozzolanic and latent hydraulic reactions creates a binding phase with enhanced thermal stability that undergoes less structural rearrangement during heating. The densification of the interfacial transition zone through micro silica's pore-filling action combined with GGBS's additional hydration products strengthens the paste-aggregate bond, resisting the thermal debonding stresses generated by differential expansion between expanding aggregates and shrinking paste.

Micro silica replacement beyond 10% showed diminished thermal benefits, with the 15% series retaining less strength than corresponding 10% mixes at all temperatures, attributed to excessive microstructural density elevating pore pressure susceptibility during heating. GGBS replacement beyond 20% similarly showed reduced performance at 28 days of curing, attributed to incomplete hydration of the higher slag fraction, though extended curing periods would be expected to improve these mixes through continued latent hydraulic reaction. The temperature range of 400–600°C was confirmed as the most critical zone for structural degradation across all mixes, corresponding to the simultaneous occurrence of C-S-H dehydration, $\text{Ca}(\text{OH})_2$ dehydroxylation, and the α -to- β quartz transformation in siliceous aggregates. However, blended mixes delayed the onset and reduced the severity of degradation within this critical interval, with M5 retaining 55.1% of ambient compressive strength at 600°C compared to 44.9% for the control.

The 30% total cement replacement in M5 simultaneously reduces CO_2 emissions by approximately 24–27% compared to equivalent OPC concrete, demonstrating that enhanced thermal resilience and environmental sustainability are achievable concurrently rather than at the expense of one another. The UPV quality classification system and progressive colour change observations provide practical field-applicable indicators for post-fire structural assessment of SCM-modified concrete, enabling informed rehabilitation-versus-demolition decisions.

In summary, the ternary blended formulation of 10% micro silica and 20% GGBS (M5) delivers superior performance across all six assessed physical parameters at all elevated temperature levels compared to conventional OPC concrete. The 30% total replacement level effectively balances the complementary thermal resistance mechanisms of micro silica

and GGBS without the drawbacks of excessive densification or incomplete hydration, and falls within the optimal replacement range of 25–35% identified in the broader literature for fire-resistant concrete design. These findings support the specification of M5 as a technically sound, economically viable, and environmentally responsible formulation for designing thermally resilient concrete structures in fire-prone industrial zones, petrochemical facilities, tunnel linings, nuclear containment structures, and other critical infrastructure where elevated temperature exposure constitutes a primary design consideration.

REFERENCES

- [1] P. Kumar Mehtaa & et al, “Concrete-Microstructure-Properties-and-Materials,” Available : https://worksaccounts.com/wp-content/uploads/2020/08/Concrete-Microstructure-Properties-and-Material_s.pdf
- [2] Venkatesh R. Kodur, “Properties of Concrete at Elevated Temperature,” March 2014, Available: https://www.researchgate.net/publication/275473728_Properties_of_Concrete_at_Elevated_Temperatures
- [3] D. J. Naus, “The Effect of Elevated Temperature on Concrete Materials and Structures: A Literature Review,” 2005, Available: <https://info.ornl.gov/sites/publications/files/Pub1043.pdf>
- [4] Long T. Phan, et al, “Effects of Test Conditions and Mixture Proportions on Behavior of High-Strength Concrete Exposed to High Temperatures,” Available: https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=860335
- [5] Chi-Sun Poon, et al, “Comparison of the strength and durability performance of normal- and high-strength pozzolanic concretes at elevated temperatures,” Available : <https://www.sciencedirect.com/science/article/abs/pii/S0008884601005804>
- [6] Kristian Hertz, “Concrete strength for fire safety design,” 2005, Available : https://www.researchgate.net/publication/250072674_Concrete_strength_for_fire_safety_design
- [7] Amjad Alhamad, et al, “Performance of Different Concrete Types Exposed to Elevated Temperatures: A Review,” Available : <https://www.mdpi.com/1996-1944/15/14/5032>
- [8] Di Qin, et al, “A comprehensive review on fire damage assessment of reinforced concrete structures,” 2022, Available: <https://www.sciencedirect.com/science/article/pii/S2214509521003582>
- [9] Arimanwa, et al, “Effect of Elevated Temperature on Compressive Strength of Fly Ash Blended Cement Concrete,” 2021, Available: <https://www.ijerd.com/paper/vol17-issue10/B17100814.pdf>
- [10] Venkatesh Kodur, “Properties of Concrete at Elevated Temperatures,” 2014, Available: <https://onlinelibrary.wiley.com/doi/10.1155/2014/468510>
- [11] S. Samad, et al, “Role of binary cement including Supplementary Cementitious Material (SCM), in production of environmentally sustainable concrete: A critical review,” 2017, Available: <https://www.sciencedirect.com/science/article/pii/S2212609017300225>
- [12] Jean Calvin Bidoung, et al, “Experimental and Numerical Study of Mechanical Behaviour of Fired Clay Bricks after Exposure to High Temperatures,” 2023, Available: <https://www.scirp.org/journal/paperinformation?paperid=127557>



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