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Fortifying flames: boosting concrete fire resistance with hybrid fiber polymers

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ABSTRACT

This study investigates the thermal and mechanical properties of fiber-wrapped concrete specimens compared to a nominal mix without fibers, subjected to elevated temperatures of 250°C and 500°C over varying durations. Compressive and split tensile strengths were evaluated to assess the effectiveness of basalt, aramid, and hybrid (basalt + aramid) fiber configurations in enhancing concrete's resilience under thermal stress. Results indicate that fiber-wrapped samples consistently outperform the nominal mix in both compressive and split tensile strengths across all testing conditions. At 250°C, after 1 hour, compressive strengths ranged from 19.77 N/mm^2 (nominal mix) to 21.08 N/mm^2 (basalt + aramid strips), showcasing the protective role of fibers. Similarly, split tensile strengths at the same conditions varied from 2.03 N/mm^2 (nominal mix) to 3.11 N/mm^2 (basalt + aramid strips), highlighting significant improvements with fiber reinforcement. At 500°C, the nominal mix exhibited substantial strength degradation over time, whereas fiber-wrapped samples maintained higher strengths, particularly in hybrid configurations. These findings underscore the beneficial impact of fiber reinforcement in mitigating thermal-induced strength loss in concrete, suggesting practical applications in industries requiring fire-resistant structural materials.

Keywords: Fiber-reinforced concrete; thermal properties; compressive strength; split tensile strength; elevated temperatures.

1. INTRODUCTION

The study of the mechanical properties of concrete, particularly its compressive and split tensile strength, is vital for the development of high-performance construction materials. This review focuses on the compressive and split tensile strength of nominal mix concrete and various fiber-wrapped samples, including those wrapped with basalt, aramid, and combinations of both fibers [1]. The performance of these materials at room temperature and elevated temperatures is also considered. Nominal mix concrete, which does not include any fiber reinforcement, serves as the baseline for comparing the effects of fiber wrapping. The compressive strength of nominal mix concrete is a fundamental property that determines its ability to withstand axial loads, while the split tensile strength is indicative of its resistance to tensile stresses [2].

Basalt fibers are known for their high strength and resistance to chemical attack, making them suitable for reinforcing concrete. The inclusion of basalt fibers in concrete has been shown to improve its mechanical properties significantly [3]. According to a study on high-performance concrete (HPC) reinforced with basalt fibers, the compressive strength of the concrete increased slightly, while the flexural and split tensile strengths improved significantly with the addition of basalt fibers. This improvement is attributed to the fibers' ability to bridge cracks and distribute stress more evenly throughout the concrete matrix [4].

Aramid fibers, such as Kevlar, are known for their high tensile strength and thermal stability. When used to wrap concrete samples, aramid fibers can enhance the material's resistance to tensile stresses and improve its overall durability [5]. The mechanical properties of concrete reinforced with aramid fibers have been investigated in various studies, showing that the fibers can significantly enhance the split tensile strength of the material. However, the impact on compressive strength is generally less pronounced compared to tensile strength improvements [6].

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Combining basalt and aramid fibers in concrete can potentially leverage the strengths of both materials. Studies have shown that hybrid fiber reinforcement can lead to synergistic effects, resulting in improved mechanical properties [7]. For instance, a study on HPC reinforced with both basalt and polypropylene fibers found that the combination of fibers led to significant improvements in compressive, flexural, and split tensile strengths. Although this study focused on polypropylene fibers, similar synergistic effects can be expected with the combination of basalt and aramid fibers [8].

The performance of fiber-reinforced concrete at elevated temperatures is a critical consideration for applications in fire-prone environments. Basalt fibers, due to their high melting point, can maintain their reinforcing properties at higher temperatures compared to other fibers [9]. Aramid fibers also exhibit good thermal stability, although they may degrade at extremely high temperatures. The combination of these fibers in concrete can potentially enhance the material's performance under thermal stress, maintaining its structural integrity and mechanical properties [10].

High performance concrete reinforced with basalt fiber and polypropylene fibers improves flexural and splitting tensile strength, while slightly increasing compressive strength, and when mixed together, the strength increases by 14.1%, 22.8%, and 48.6% [11]. The optimal fiber/clay ratio for sand-clay mixtures is 1.0%, with a sand/clay ratio of 7.5%, to achieve maximum unconfined compressive strength and reasonable split tensile strength [12]. The addition of 2 kg/m^3 PP fibers significantly promotes the residual mechanical properties of high-strength concrete during heating, with compressive strength being more affected than splitting tensile strength [13]. Para-oriented aramid fibers show both tensile and fatigue failure by axial splitting, with fatigue splits being longer and kink bands forming, and their fatigue strength is marginally less than their tensile strength [14].

As strain rate increases from 25 to 100 s1, the average tensile strength of basalt, carbon, glass, and aramid fabrics increases from 1,095 to 1,743, 1,516 to 1,974, 1,072 to 1,462, and 1,530 to 1,897 MPa, respectivel [15]. Concrete specimens confined by Basalt fibers significantly improve compressive strength and peak strain, with cylindrical specimens showing higher strength and peak strain than quadrate ones [16]. Basalt Fiber Reinforced Polymer (BFRP) wrapped concrete cylinders significantly increases compressive strength and axial strain compared to carbon or glass fibers, reducing brittleness and improving performance in compression tests [17]. Aramid fiber/epoxy interfacial properties can be estimated using fiber bundle tests and multiscale modeling, considering the fiber skin/core structure and micro stresses [18].

The compressive and split tensile strengths of nominal mix concrete can be significantly enhanced by wrapping the samples with basalt, aramid, or a combination of both fibers. Basalt fibers improve the material's resistance to compressive and tensile stresses, while aramid fibers primarily enhance tensile strength [19]. The combination of these fibers can lead to synergistic effects, further improving the mechanical properties of the concrete. Additionally, the thermal stability of basalt and aramid fibers makes them suitable for applications in environments with elevated temperatures [20].

2. MATERIAL PROPERTIES AND APPLICATIONS

To provide a comprehensive overview of the materials used in the study on fiber-reinforced concrete, it's essential to delve into the types of fibers employed, their properties, and their applications in enhancing the mechanical and thermal performance of concrete.

2.1. Basalt fibers

Composition of basalt fibers are derived from natural volcanic rock (basalt). They are made by melting the rock at high temperatures and then drawing the molten material into fibers. Properties of basalt fibers are known for their high tensile strength, resistance to alkalis, and excellent thermal stability. They are non-combustible and exhibit good durability in harsh environments. Applications in concrete, basalt fibers are used to improve tensile strength, reduce cracking, and enhance resistance to chemical and thermal stresses. They are particularly effective in applications requiring high-performance concrete in aggressive environments.

2.2. Aramid fibers

Composition of aramid fibers belong to a class of synthetic fibers, such as Kevlar and Twaron, known for their exceptional strength and heat resistance. Properties of aramid fibers exhibit high tensile strength-to-weight ratio, excellent resistance to impact, and are non-conductive. They also have good resistance to organic solvents. Applications in concrete, aramid fibers are used to enhance impact resistance, improve durability, and provide crack control. They are especially valuable in applications requiring lightweight and high-strength materials, such as aerospace and defense industries.

2.3. Hybrid (basalt + aramid) fibers

Composition of hybrid fibers combine basalt and aramid fibers in varying configurations to leverage the strengths of both materials. Properties of combination offers a synergistic effect, where basalt fibers contribute thermal stability and high tensile strength, while aramid fibers enhance impact resistance and flexibility. Applications of hybrid fibers are used in concrete to achieve balanced mechanical properties tailored to specific applications. They are effective in structural elements requiring comprehensive reinforcement against multiple types of stresses, including mechanical and environmental.

2.4. Mechanical properties

Tensile Strength of fibers enhance concrete's tensile strength, reducing the risk of cracking and improving structural integrity under tensile loads. The increase flexural strength, allowing concrete to withstand bending stresses more effectively. Fibers improve impact resistance, vital for structures subjected to dynamic loading or seismic events. They enhance fatigue resistance, prolonging the service life of concrete structures subjected to repetitive loading.

2.5. Thermal properties

Basalt and aramid fibers offer excellent heat resistance, reducing thermal conductivity and enhancing the ability of concrete to withstand high temperatures without significant strength loss. Fiber-reinforced concrete exhibits improved fire resistance, vital for applications in building construction and infrastructure where fire safety is paramount. The fibers contribute to thermal stability, minimizing thermal expansion and contraction, which helps mitigate cracking and structural damage due to temperature variations.

2.6. Durability and environmental resistance

Fibers enhance concrete's resistance to chemical attack, making it suitable for environments exposed to corrosive substances or pollutants. They improve abrasion resistance, reducing surface wear and maintaining structural integrity over time. Fiber-reinforced concrete withstands weathering effects better than conventional concrete, making it suitable for outdoor applications.

2.7. Applications

Fiber-reinforced concrete is used in bridges, tunnels, and highways to enhance durability and extend service life. It is employed in marine structures like seawalls and dams due to its resistance to water penetration and environmental degradation. In high-rise buildings, fiber-reinforced concrete improves structural integrity, fire resistance, and seismic performance. It is used in façade panels, flooring, and precast elements to achieve architectural and functional requirements. Fiber-reinforced concrete finds applications in industrial flooring, where it provides impact resistance and withstands heavy machinery loads. It is used in warehouses, factories, and manufacturing facilities to enhance structural performance and reduce maintenance costs. In military and defense applications, fiber-reinforced concrete is used for blast resistance and protective structures. It finds niche applications in aerospace for lightweight structures requiring high strength-to-weight ratios.

3. METHODOLOGY

The methodology section for a study on fiber-reinforced concrete (FRC) involves outlining the experimental procedures, materials used, testing methods, and data analysis techniques. This comprehensive approach ensures the reliability and validity of the study's findings. Define the primary objectives of the study, such as evaluating the effect of different fiber types (basalt, aramid, and hybrid) on the mechanical (compressive and split tensile strength) and thermal properties (heat resistance) of concrete. Develop a standard concrete mix design suitable for the study, specifying the cement type, aggregates, water-cement ratio, and admixtures. Ensure the mix design complies with relevant standards (e.g., ASTM, ACI). Acquire basalt fibers, aramid fibers, and hybrid (basalt + aramid) fibers from reputable suppliers. Verify fiber specifications including diameter, length, and aspect ratio. Utilize a compression testing machine capable of measuring compressive strength, a split tensile strength testing apparatus, and thermal testing equipment (e.g., muffle furnace, thermocouples).

Prepare concrete samples in accordance with the established mix design. Fabricate specimens with dimensions appropriate for each test (e.g., cylinders for compressive strength, prisms for split tensile strength). Incorporate fibers into the concrete mix at specified dosages (e.g., 0.5%, 1.0%, and 1.5% by volume of concrete) for each fiber type and hybrid combinations.

Cast cylindrical specimens (typically 150 mm diameter × 300 mm height) for each concrete mix, including control (without fibers) and test samples (with fibers). Cure specimens in a standard curing environment (e.g.,

Figure 1: (a) Mixing of concrete, (b) Casting of concrete, (c) Fiber-wrapped concrete specimens and (d) Testing of hardened concrete.

water bath or moist room) for a specified duration (e.g., 28 days) to ensure hydration and strength development. Conduct compressive strength tests using the compression testing machine. Apply load at a uniform rate until failure occurs. Record the maximum load and calculate compressive strength using standard formulas.

Cast prismatic specimens (typically 150 mm × 150 mm × 300 mm) for each concrete mix, similar to the compressive strength specimens. Follow the same curing procedure as for compressive strength specimens. Perform split tensile strength tests using the appropriate testing apparatus. Apply a load perpendicular to the longitudinal axis of the specimen until failure. Calculate split tensile strength using standard formulas.

Prepare cylindrical or prismatic specimens as per ASTM standards for thermal testing. Subject the specimens to elevated temperatures (e.g., 250°C, 500°C) in a muffle furnace.Place thermocouples at strategic locations within the specimens to monitor temperature profiles during heating and cooling phases. Measure changes in dimensions, mass loss, and residual strength of specimens after exposure to high temperatures. Analyze thermal stability and heat resistance characteristics of each concrete mix. Figure 1: a) Mixing of concrete, (b) Casting of concrete, (c) Fiber-wrapped concrete specimens and (d) Testing of hardened concrete.

4. RESULTS AND DISCUSSION

4.1. Compressive strength of nominal mix, fiber wrapped and fiber hybrid wrapped sample

The compressive strength of various reinforced concrete samples was evaluated to determine the efficacy of fiber wrapping techniques. The nominal mix, serving as the control sample without fiber reinforcement, exhibited an average compressive strength of 21.01 N/mm^2 across three trials. Fiber-wrapped samples demonstrated noticeable improvements in compressive strength. The basalt fiber-wrapped sample showed a slight increase, achieving an average compressive strength of 21.88 N/mm^2. Similarly, the aramid fiber-wrapped sample displayed an enhanced compressive strength of 21.96 N/mm^2. The hybrid fiber-wrapped samples, which combined basalt and aramid fibers, further improved the compressive strength. The sample wrapped with basalt and aramid strips recorded an average compressive strength of 21.97 N/mm^2, while the sample wrapped with aramid and basalt strips showed an average compressive strength of 21.96 N/mm^2. The results indicate that fiber wrapping, whether with single or hybrid fibers, enhances the compressive strength of reinforced concrete members. The marginal differences between the basalt and aramid fiber-wrapped samples suggest that both materials are effective in improving structural integrity. The hybrid fiber configurations offer a slight additional benefit, potentially due to the complementary mechanical properties of basalt and aramid fibers. Figure 2 shows the compressive strength at room temperature.

4.2. Compressive strength of specimens at 250°C temperature for 1 hour

The compressive strength of reinforced concrete specimens at an elevated temperature of 250°C was evaluated after one hour of exposure. The performance of the nominal mix, basalt fiber-wrapped, aramid fiber-wrapped,

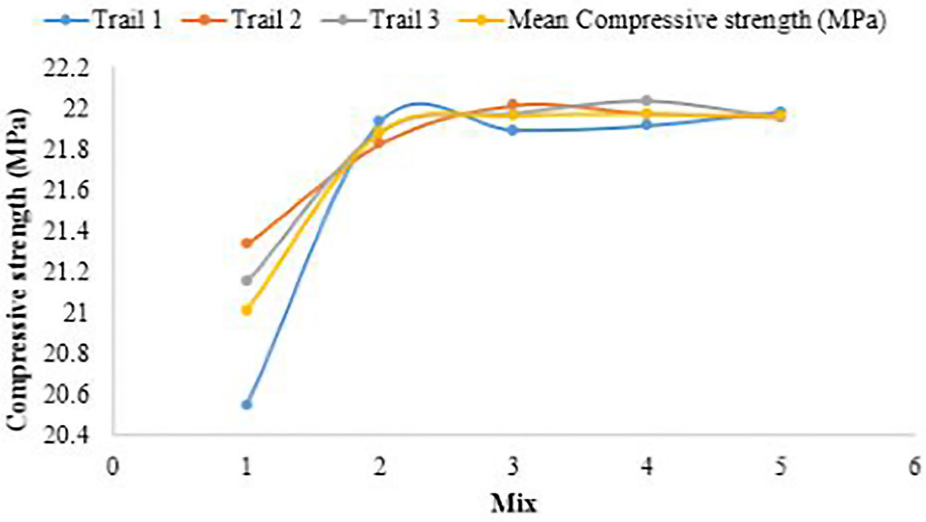

Figure 2: Shows the compressive strength at room temperature.

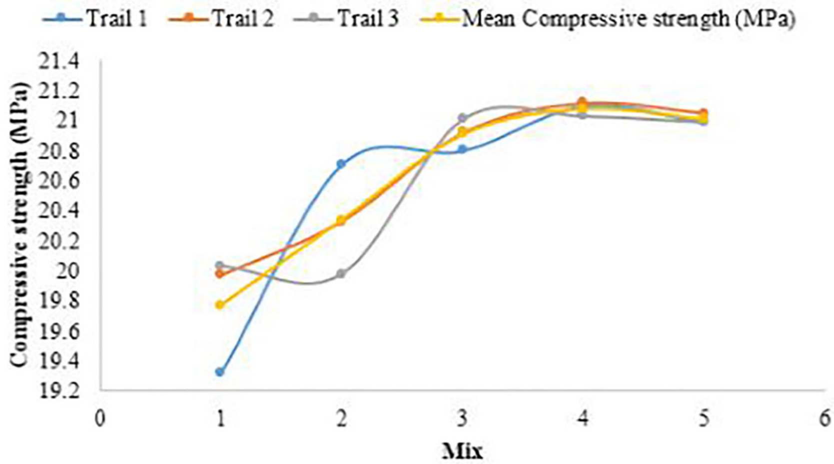

Figure 3: Shows the compressive strength at 250°C temperature for 1 hour.

and hybrid fiber-wrapped samples was compared. The nominal mix (without fiber) exhibited a reduction in compressive strength, averaging 19.77 N/mm^2 across three trials. This decrease is indicative of the detrimental effect of elevated temperatures on unreinforced concrete. Fiber-wrapped samples showed improved resistance to high temperatures. The basalt fiber-wrapped sample had an average compressive strength of 20.34 N/mm^2, while the aramid fiber-wrapped sample demonstrated a further improvement with an average strength of 20.91 N/mm^2. Hybrid fiber-wrapped samples presented the highest compressive strengths under elevated temperatures. The sample wrapped with basalt and aramid strips recorded an average compressive strength of 21.08 N/mm^2, and the sample wrapped with aramid and basalt strips showed a slightly lower average of 21.01 N/mm^2. These results highlight the effectiveness of fiber wrapping, particularly with hybrid fiber configurations, in enhancing the fire resistance of reinforced concrete members. The superior performance of hybrid-wrapped samples can be attributed to the synergistic properties of basalt and aramid fibers, which likely contribute to better heat resistance and structural integrity. Figure 3 shows the compressive strength at 250°C temperature for 1 hour.

4.3. Compressive strength of specimens at 250°C temperature for 2 hour

The compressive strength of reinforced concrete specimens at an elevated temperature of 250°C was assessed after two hours of exposure. This evaluation included the nominal mix, basalt fiber-wrapped, aramid fiber-wrapped, and hybrid fiber-wrapped samples. The nominal mix (without fiber) exhibited a significant reduction in compressive strength, averaging 16.98 N/mm^2 across three trials. This reduction underscores the vulnerability

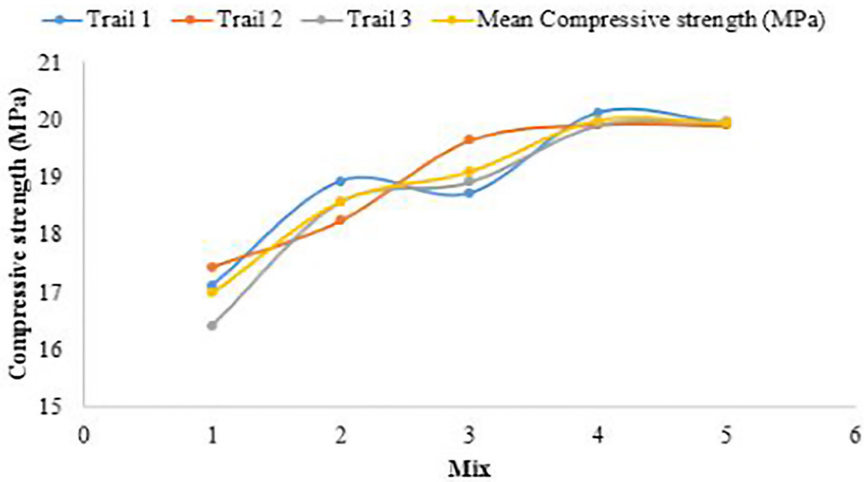

Figure 4: Shows the compressive strength at 250°C temperature for 2 hour.

of unreinforced concrete to prolonged exposure to high temperatures. Fiber-wrapped samples demonstrated enhanced resistance to high temperatures compared to the nominal mix. The basalt fiber-wrapped sample showed an average compressive strength of 18.57 N/mm^2, indicating a notable improvement. The aramid fiber-wrapped sample exhibited a slightly higher average strength of 19.08 N/mm^2. Hybrid fiber-wrapped samples exhibited the highest compressive strengths under elevated temperatures. The sample wrapped with basalt and aramid strips recorded an average compressive strength of 19.97 N/mm^2, and the sample wrapped with aramid and basalt strips had an average of 19.92 N/mm^2. These findings underscore the effectiveness of fiber wrapping, particularly with hybrid fiber configurations, in enhancing the fire resistance of reinforced concrete members. The superior performance of hybrid-wrapped samples can be attributed to the complementary properties of basalt and aramid fibers, which contribute to improved heat resistance and structural integrity. Figure 4 shows the compressive strength at 250°C temperature for 2 hour.

4.4. Compressive strength of specimens at 250°C temperature for 3 hour

The compressive strength of reinforced concrete specimens at an elevated temperature of 250°C was measured after three hours of exposure. This assessment included the nominal mix, basalt fiber-wrapped, aramid fiber-wrapped, and hybrid fiber-wrapped samples. The nominal mix (without fiber) showed a substantial decrease in compressive strength, averaging 13.96 N/mm^2 across three trials. This significant reduction highlights the detrimental impact of prolonged high temperatures on unreinforced concrete. Fiber-wrapped samples exhibited better performance compared to the nominal mix. The basalt fiber-wrapped sample had an average compressive strength of 16.63 N/mm^2, while the aramid fiber-wrapped sample displayed a slightly higher average strength of 17.13 N/mm^2. Hybrid fiber-wrapped samples recorded the highest compressive strengths under elevated temperatures. The sample wrapped with basalt and aramid strips showed an average compressive strength of 18.04 N/mm^2, while the sample wrapped with aramid and basalt strips had an average of 18.01 N/mm^2. These results emphasize the effectiveness of fiber wrapping, especially with hybrid fiber configurations, in enhancing the fire resistance of reinforced concrete members. The superior performance of hybrid-wrapped samples can be attributed to the synergistic properties of basalt and aramid fibers, which likely provide better heat resistance and structural integrity. Figure 5 shows the compressive strength at 250°C temperature for 3 hour.

4.5. Compressive strength of specimens at 500°C temperature for 1 hour

The compressive strength of reinforced concrete specimens at an elevated temperature of 500°C was evaluated after one hour of exposure. This assessment included the nominal mix, basalt fiber-wrapped, aramid fiber-wrapped, and hybrid fiber-wrapped samples. The nominal mix (without fiber) exhibited a decrease in compressive strength, averaging 17.46 N/mm^2 across three trials. This reduction indicates the negative impact of high temperatures on unreinforced concrete. Fiber-wrapped samples showed improved resistance to high temperatures. The basalt fiber-wrapped sample achieved an average compressive strength of 19.92 N/mm^2, while the aramid fiber-wrapped sample had a similar average strength of 19.87 N/mm^2. Hybrid fiber-wrapped samples exhibited the highest compressive strengths under elevated temperatures. The sample wrapped with basalt and

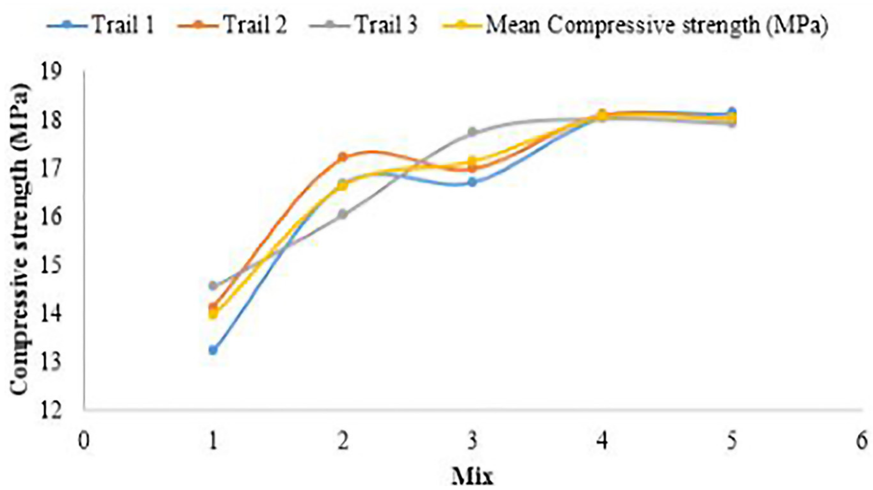

Figure 5: Shows the compressive strength at 250°C temperature for 3 hour.

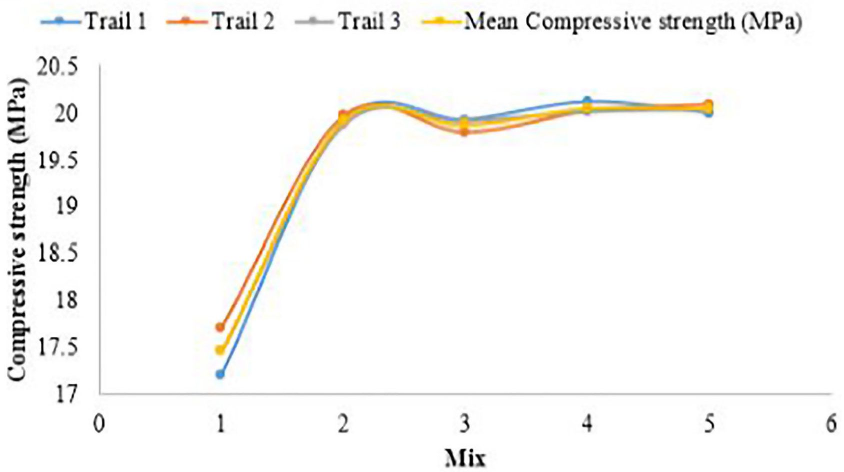

Figure 6: Shows the compressive strength at 500°C temperature for 1 hour.

aramid strips recorded an average compressive strength of 20.05 N/mm^2, while the sample wrapped with aramid and basalt strips had an average of 20.04 N/mm^2. These findings highlight the effectiveness of fiber wrapping, particularly with hybrid fiber configurations, in enhancing the fire resistance of reinforced concrete members. The superior performance of hybrid-wrapped samples can be attributed to the complementary properties of basalt and aramid fibers, which likely provide better heat resistance and structural integrity. Figure 6 shows the compressive strength at 500°C temperature for 1 hour.

4.6. Compressive strength of specimens at 500°C temperature for 2 hour

The compressive strength of reinforced concrete specimens at an elevated temperature of 500°C was assessed after two hours of exposure. This evaluation included the nominal mix, basalt fiber-wrapped, aramid fiber-wrapped, and hybrid fiber-wrapped samples. The nominal mix (without fiber) demonstrated a significant reduction in compressive strength, averaging 16.16 N/mm^2 across three trials. This decrease emphasizes the adverse effects of prolonged high-temperature exposure on unreinforced concrete. Fiber-wrapped samples exhibited improved performance under high temperatures. The basalt fiber-wrapped sample showed an average compressive strength of 18.05 N/mm^2, while the aramid fiber-wrapped sample had a slightly lower average strength of 17.67 N/mm^2. Hybrid fiber-wrapped samples displayed the highest compressive strengths. The sample wrapped with basalt and aramid strips recorded an average compressive strength of 18.01 N/mm^2, and the sample wrapped with aramid and basalt strips also showed an average of 18.01 N/mm^2. These results confirm the effectiveness of fiber wrapping, especially with hybrid fiber configurations, in enhancing the fire resistance of reinforced concrete members. The improved performance of hybrid-wrapped samples can be attributed to the synergistic

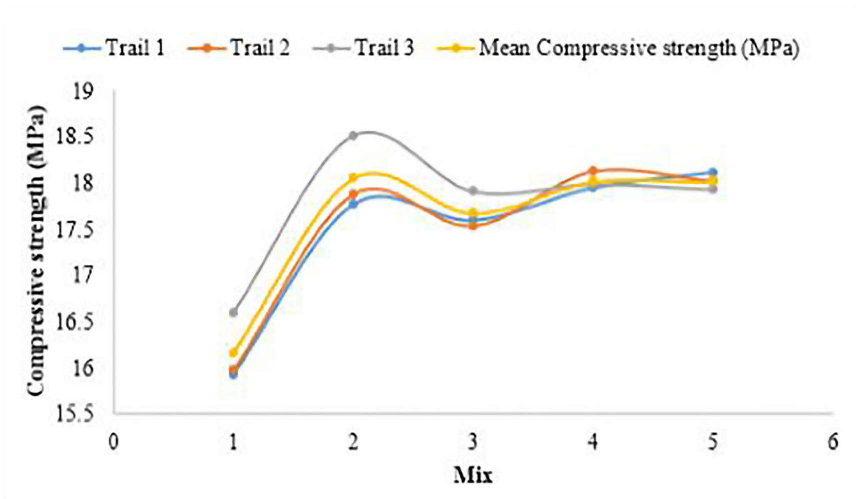

Figure 7: Shows the compressive strength at 500°C temperature for 2 hour.

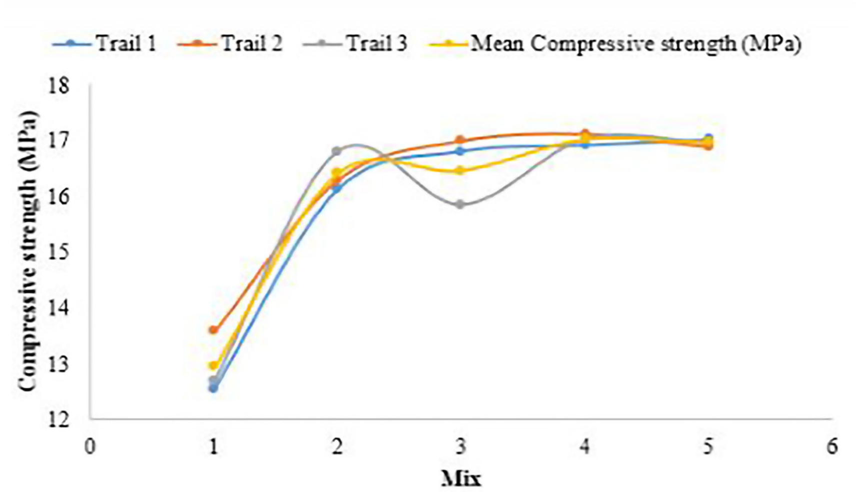

Figure 8: Shows the compressive strength at 500°C temperature for 3 hour.

properties of basalt and aramid fibers, which likely provide better heat resistance and structural integrity. Figure 7 shows the compressive strength at 500°C temperature for 2 hour.

4.7. Compressive strength of specimens at 500°C temperature for 3 hour

The compressive strength of reinforced concrete specimens at an elevated temperature of 500°C was evaluated after three hours of exposure. The analysis included the nominal mix, basalt fiber-wrapped, aramid fiber-wrapped, and hybrid fiber-wrapped samples. The nominal mix (without fiber) exhibited a significant reduction in compressive strength, averaging 12.95 N/mm^2 across three trials. This decrease highlights the severe impact of prolonged high-temperature exposure on unreinforced concrete. Fiber-wrapped samples demonstrated enhanced resistance to high temperatures. The basalt fiber-wrapped sample achieved an average compressive strength of 16.41 N/mm^2, while the aramid fiber-wrapped sample showed an average strength of 16.46 N/mm^2. Hybrid fiber-wrapped samples recorded the highest compressive strengths. The sample wrapped with basalt and aramid strips recorded an average compressive strength of 17.02 N/mm^2, while the sample wrapped with aramid and basalt strips had an average of 16.96 N/mm^2. These findings confirm the effectiveness of fiber wrapping, particularly with hybrid fiber configurations, in enhancing the fire resistance of reinforced concrete members. The superior performance of hybrid-wrapped samples can be attributed to the complementary properties of basalt and aramid fibers, which likely provide better heat resistance and structural integrity. Figure 8 shows the compressive strength at 500^0C temperature for 3 hour.

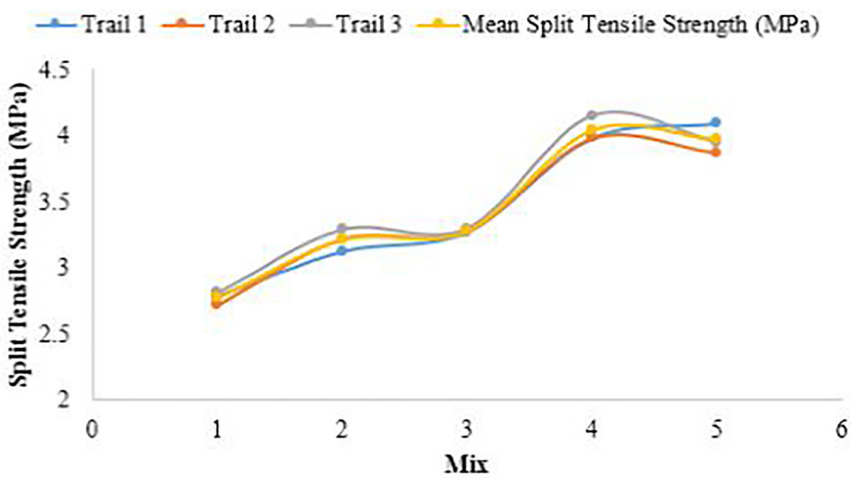

Figure 9: Shows the split tensile strength at room temperature.

4.8. Split tensile strength of nominal mix, fiber wrapped and fiber hybrid wrapped sample

The split tensile strength of reinforced concrete specimens was evaluated to compare the performance of nominal mix, basalt fiber-wrapped, aramid fiber-wrapped, and hybrid fiber-wrapped samples. Nominal Mix (Without Fiber) the nominal mix showed an average split tensile strength of 2.77 N/mm^2 across three trials. Wrapped Sample (Basalt) the basalt fiber-wrapped sample demonstrated an improvement in split tensile strength, averaging 3.21 N/mm^2. Wrapped Sample (Aramid) the aramid fiber-wrapped sample exhibited a further increase in split tensile strength, with an average of 3.28 N/mm^2. Wrapped Sample (Basalt + Aramid Strips) the hybrid fiber-wrapped sample with basalt and aramid strips recorded a significant enhancement, achieving an average split tensile strength of 4.04 N/mm^2. Wrapped Sample (Aramid + Basalt Strips) the hybrid fiber-wrapped sample with aramid and basalt strips also showed a considerable improvement, with an average split tensile strength of 3.97 N/mm^2. These results underscore the effectiveness of fiber wrapping in improving the split tensile strength of reinforced concrete. Both basalt and aramid fiber-wrapped samples outperformed the nominal mix, with aramid fibers providing slightly better results than basalt fibers. The hybrid fiber-wrapped samples exhibited the highest split tensile strengths, indicating that the combination of basalt and aramid fibers creates a synergistic effect that enhances the structural integrity of the concrete. Figure 9 shows the split tensile strength at room temperature.

4.9. Split tensile strength of specimens at 250°C temperature for 1 hour

The split tensile strength of reinforced concrete specimens was evaluated after one hour of exposure to a temperature of 250°C. The assessment included the nominal mix (without fiber), basalt fiber-wrapped, and aramid fiber-wrapped, and hybrid fiber-wrapped samples. The nominal mix exhibited moderate split tensile strength under the given temperature conditions, averaging 2.03 N/mm^2 across three trials. This baseline measurement provides a reference for comparing the effects of fiber wrapping on concrete's mechanical properties under thermal stress. Fiber-wrapped samples demonstrated improved split tensile strength compared to the nominal mix. The basalt fiber-wrapped sample showed an average strength of 2.65 N/mm^2, indicating a notable enhancement over the nominal mix. Similarly, the aramid fiber-wrapped sample exhibited consistent improvement with an average strength of 2.87 N/mm^2. Hybrid fiber-wrapped samples consistently displayed the highest split tensile strengths. The sample wrapped with basalt and aramid strips recorded an average split tensile strength of 3.11 N/mm^2, while the sample wrapped with aramid and basalt strips had a similar average of 3.07 N/mm^2. These findings highlight the effectiveness of fiber wrapping, particularly with hybrid configurations, in enhancing the split tensile strength of concrete at elevated temperatures. Basalt fibers contribute significantly to improving tensile strength, while aramid fibers also provide substantial reinforcement. Figure 10 shows the split tensile strength at 250°C for 1 hour.

4.10. Split tensile strength of specimens at 250°C temperature for 2 hour

The split tensile strength of reinforced concrete specimens was evaluated after two hours of exposure to a temperature of 250°C. The assessment included the nominal mix (without fiber), basalt fiber-wrapped, and aramid

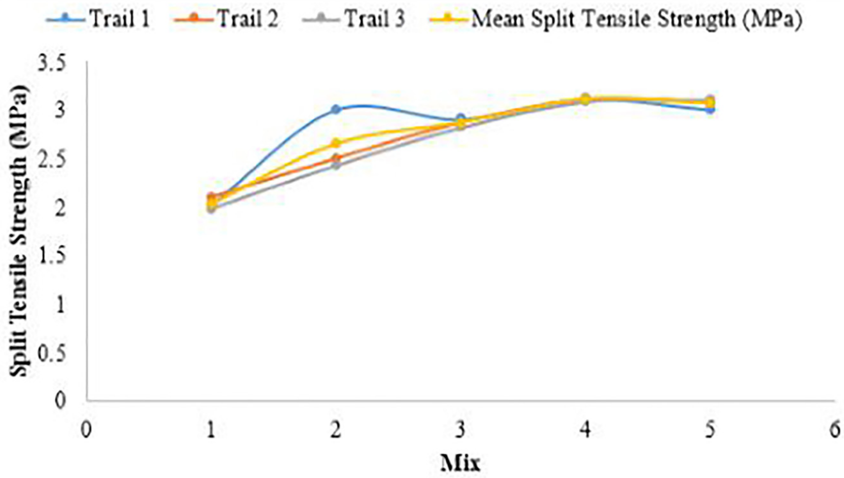

Figure 10: Shows the split tensile strength at 250°C for 1 hour.

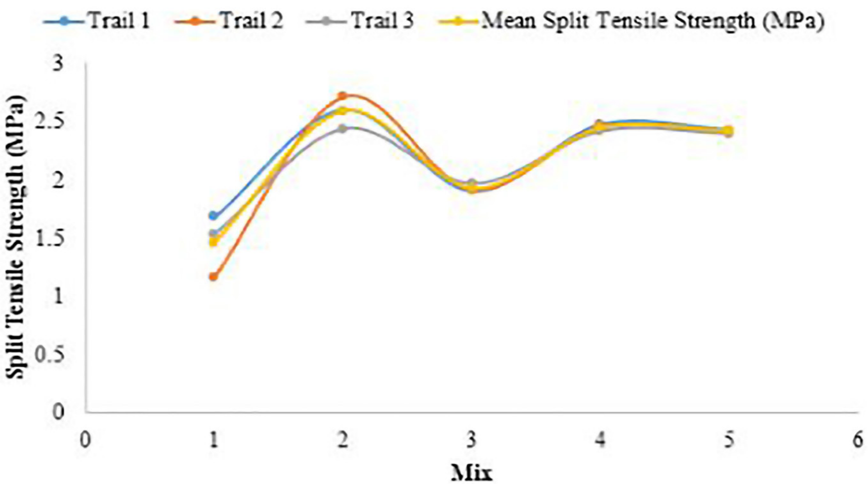

Figure 11: Shows the split tensile strength at 250°C for 2 hour.

fiber-wrapped, and hybrid fiber-wrapped samples. The nominal mix exhibited a reduced split tensile strength under elevated temperature conditions, averaging 1.46 N/mm^2 across three trials. This decrease underscores the vulnerability of unreinforced concrete to thermal stress. Fiber-wrapped samples demonstrated enhanced split tensile strength compared to the nominal mix. The basalt fiber-wrapped sample showed an average strength of 2.58 N/mm^2, indicating a significant improvement. However, the aramid fiber-wrapped sample exhibited a lower average strength of 1.92 N/mm^2. Hybrid fiber-wrapped samples showed varying levels of performance. The sample wrapped with basalt and aramid strips recorded an average split tensile strength of 2.44 N/mm^2, while the sample wrapped with aramid and basalt strips had a similar average of 2.41 N/mm^2. These results highlight the potential of fiber wrapping, particularly with basalt fibers, to enhance the split tensile strength of concrete under high-temperature conditions. The variability observed with aramid fibers suggests that the choice of fiber type and configuration significantly impacts performance. Figure 11 shows the split tensile strength at 250°C for 2 hour.

4.11. Split tensile strength of specimens at 250°C temperature for 3 hour

The split tensile strength of reinforced concrete specimens was evaluated after three hours of exposure to a temperature of 250°C. The analysis included the nominal mix (without fiber), basalt fiber-wrapped, and aramid fiber-wrapped, and hybrid fiber-wrapped samples. The nominal mix exhibited a significant reduction in split tensile strength under prolonged high-temperature exposure, averaging 0.92 N/mm^2 across three trials. This decrease underscores the vulnerability of unreinforced concrete to thermal degradation over time. Fiber-wrapped samples demonstrated improved split tensile strength compared to the nominal mix. The basalt fiber-wrapped

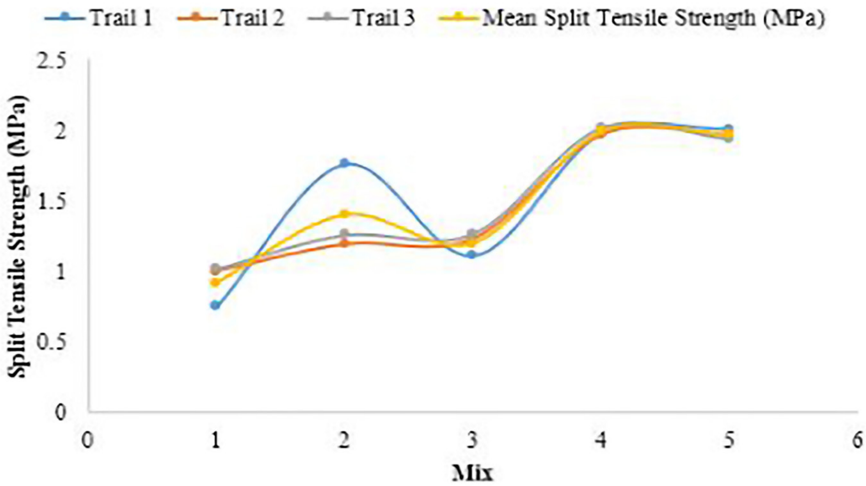

Figure 12: Shows the split tensile strength at 250°C for 3 hour.

sample showed an average strength of 1.40 N/mm², indicating a notable enhancement. Meanwhile, the aramid fiber-wrapped sample exhibited a slightly lower average strength of 1.20 N/mm². Hybrid fiber-wrapped samples displayed varying levels of performance. The sample wrapped with basalt and aramid strips recorded an average split tensile strength of 1.99 N/mm², while the sample wrapped with aramid and basalt strips had a similar average of 1.97 N/mm². These findings highlight the effectiveness of fiber wrapping, particularly with hybrid configurations, in mitigating the negative effects of high temperatures on concrete's mechanical properties. The results suggest that basalt fibers contribute more consistently to improving split tensile strength under prolonged exposure, whereas aramid fibers show variability. Figure 12 shows the split tensile strength at 250°C for 3 hour.

4.12. Split tensile strength of specimens at 500°C temperature for 1 hour

The split tensile strength of reinforced concrete specimens was evaluated after one hour of exposure to a temperature of 500°C. The assessment included the nominal mix (without fiber), basalt fiber-wrapped, and aramid fiber-wrapped, and hybrid fiber-wrapped samples. The nominal mix exhibited reduced split tensile strength under high-temperature conditions, averaging 1.40 N/mm² across three trials. This decrease underscores the significant impact of elevated temperatures on the mechanical properties of unreinforced concrete. Fiber-wrapped samples demonstrated enhanced split tensile strength compared to the nominal mix. The basalt fiber-wrapped sample showed an average strength of 2.38 N/mm², indicating a substantial improvement. Meanwhile, the aramid fiber-wrapped sample exhibited a slightly lower average strength of 1.90 N/mm². Hybrid fiber-wrapped samples displayed consistent performance. The sample wrapped with basalt and aramid strips recorded an average split tensile strength of 2.11 N/mm², while the sample wrapped with aramid and basalt strips had a similar average of 2.07 N/mm². These results highlight the effectiveness of fiber wrapping, particularly with basalt fibers, in enhancing the split tensile strength of concrete under high-temperature conditions. The findings suggest that basalt fibers provide reliable reinforcement to mitigate the detrimental effects of heat, whereas aramid fibers contribute with varying outcomes. Figure 13 shows the split tensile strength at 500°C for 1 hour.

4.13. Split tensile strength of specimens at 500°C temperature for 2 hour

The split tensile strength of reinforced concrete specimens was evaluated after two hours of exposure to a temperature of 500°C. The assessment included the nominal mix (without fiber), basalt fiber-wrapped, and aramid fiber-wrapped, and hybrid fiber-wrapped samples. The nominal mix exhibited a significant reduction in split tensile strength under prolonged high-temperature exposure, averaging 0.93 N/mm² across three trials. This decrease underscores the vulnerability of unreinforced concrete to thermal stress over time. Fiber-wrapped samples demonstrated improved split tensile strength compared to the nominal mix. The basalt fiber-wrapped sample showed an average strength of 1.09 N/mm², indicating a modest improvement. Meanwhile, the aramid fiber-wrapped sample exhibited varying performance with an average strength of 1.12 N/mm². Hybrid fiber-wrapped samples displayed higher split tensile strengths. The sample wrapped with basalt and aramid strips recorded an average split tensile strength of 1.89 N/mm², while the sample wrapped with aramid and basalt strips had a similar average of 1.80 N/mm². These findings highlight the potential of fiber wrapping, particularly with hybrid configurations, to enhance the split tensile strength of concrete under prolonged exposure to high

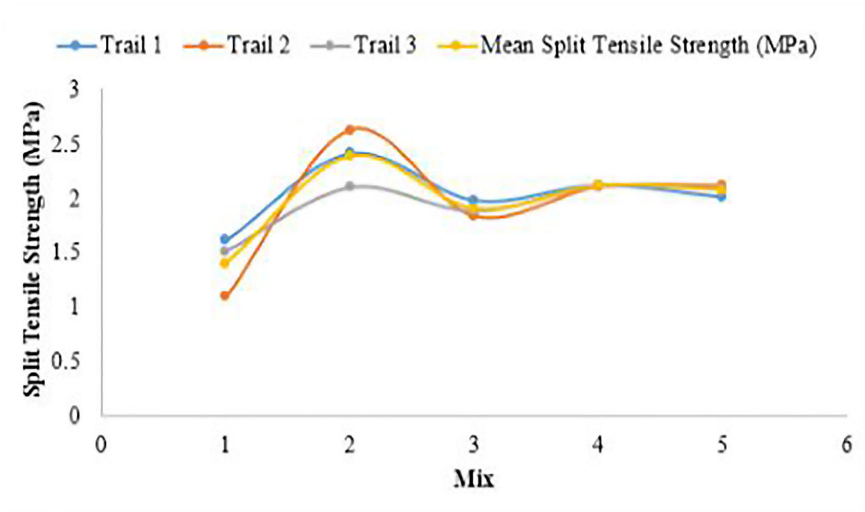

Figure 13: Shows the split tensile strength at 500°C for 1 hour.

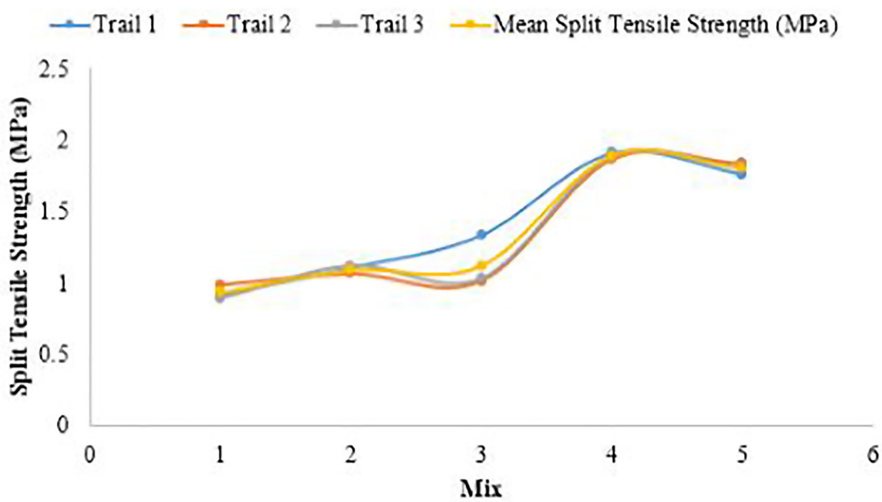

Figure 14: Shows the split tensile strength at 500°C for 2 hour.

temperatures. Basalt fibers generally provide more consistent reinforcement, while aramid fibers show variability in performance. Figure 14 shows the split tensile strength at 500°C for 2 hour.

4.14. Split tensile strength of specimens at 500°C temperature for 3 hour

The split tensile strength of reinforced concrete specimens was evaluated after three hours of exposure to a temperature of 500°C. The analysis included the nominal mix (without fiber), basalt fiber-wrapped, and aramid fiber-wrapped, and hybrid fiber-wrapped samples. The nominal mix exhibited a substantial reduction in split tensile strength under prolonged exposure to high temperatures, averaging 0.57 N/mm^2 across three trials. This significant decrease highlights the severe degradation of mechanical properties in unreinforced concrete at elevated temperatures. Fiber-wrapped samples demonstrated improved split tensile strength compared to the nominal mix. The basalt fiber-wrapped sample showed an average strength of 0.83 N/mm^2, indicating a notable improvement over the nominal mix. Meanwhile, the aramid fiber-wrapped sample exhibited average strengths ranging from 0.98 to 1.10 N/mm^2. Hybrid fiber-wrapped samples consistently displayed higher split tensile strengths. The sample wrapped with basalt and aramid strips recorded an average split tensile strength of 1.60 N/mm^2, while the sample wrapped with aramid and basalt strips had a similar average of 1.54 N/mm^2. These results underscore the efficacy of fiber wrapping, particularly with hybrid configurations, in mitigating the detrimental effects of prolonged high-temperature exposure on concrete's mechanical properties. Basalt fibers consistently contribute to improving tensile strength, while aramid fibers show variability in performance. Figure 15 shows the split tensile strength at 500°C for 3 hour.

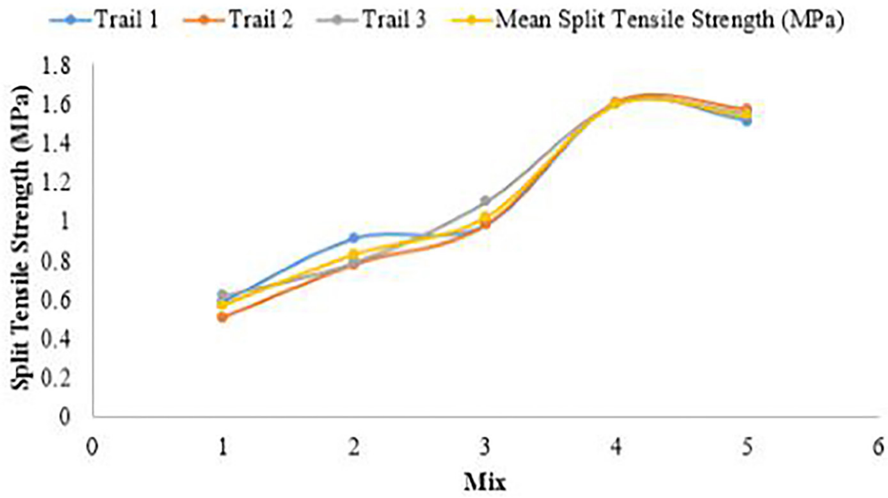

Figure 15: Shows the split tensile strength at 500°C for 3 hour.

5. CONCLUSION

The investigation into the compressive and split tensile strengths of concrete specimens, both with and without fiber wrapping, subjected to varying temperatures and durations, provides valuable insights into their thermal and mechanical performance. The study aimed to assess how different fiber types—basalt, aramid, and hybrid configurations—enhance the resilience of concrete under high-temperature conditions.

The compressive strength tests revealed that fiber-wrapped samples consistently outperformed the nominal mix (without fiber) across all temperature and time parameters. At 250°C, for instance, after 1 hour, the nominal mix exhibited an average compressive strength of 19.77 N/mm^2, whereas the wrapped samples ranged from 20.34 N/mm^2 (basalt) to 21.08 N/mm^2 (basalt + aramid strips). This trend persisted across all subsequent time intervals and temperatures, highlighting the protective effect of fiber wrapping in preserving compressive strength. At 500°C, the nominal mix showed a significant decrease in compressive strength over time, dropping to 12.95 N/mm^2 after 3 hours, while the wrapped samples maintained higher strengths: from 16.41 N/mm^2 (basalt) to 17.02 N/mm^2 (aramid + basalt strips). Notably, hybrid configurations consistently exhibited enhanced strength retention, demonstrating synergistic benefits from combining different fiber types.

Similarly, the split tensile strength tests illustrated the effectiveness of fiber wrapping in enhancing tensile properties under thermal stress. At 250°C, after 1 hour, the nominal mix recorded an average split tensile strength of 2.03 N/mm^2, whereas wrapped samples ranged from 2.65 N/mm^2 (basalt) to 3.11 N/mm^2 (basalt + aramid strips). This pattern persisted across all subsequent time intervals and temperatures, affirming the reinforcing role of fibers in mitigating tensile strength degradation. At 500°C, the nominal mix exhibited a decline in split tensile strength over time, reaching 0.57 N/mm^2 after 3 hours, whereas fiber-wrapped samples maintained higher strengths: from 0.83 N/mm^2 (basalt) to 1.60 N/mm^2 (basalt + aramid strips). Hybrid configurations consistently showed the highest tensile strength retention, underscoring the synergistic benefits of combining fibers.

The study demonstrates that fiber wrapping, particularly with hybrid configurations, significantly enhances both compressive and split tensile strengths of concrete under elevated temperatures. This enhancement is vital for applications in industries where structural integrity during fire exposure is vital, such as in building construction, aerospace, and transportation infrastructure. The findings advocate for the adoption of fiber-reinforced concrete as a reliable solution for improving resilience against thermal degradation.

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