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THE RESISTANCE OF HIGH STRENGTH CONCRETE WITH POLYPROPYLENE FIBER USING DIATOMACEOUS EARTH AS A CEMENT SUBSTITUTE AT HIGH TEMPERATURES

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ABSTRACT

High-strength concrete generally requires a large amount of cement to achieve high compressive strength. This study investigates the use of diatomaceous earth, which contains a high level of silica, as a partial replacement for cement, along with the addition of polypropylene fiber to improve the fire resistance of high-strength concrete. Concrete specimens were prepared with a 10% substitution of diatomaceous earth by weight of cement, 1.5% superplasticizer by weight of cement, and varying polypropylene fiber contents of 0.2%, 0.4%, 0.6%, and 0.8% by volume of concrete. The diatomaceous earth was calcined at 600°C for five hours before use. Concrete cubes measuring 5x5x5 cm were cured for 28 days and then exposed to elevated temperatures of 400°C, 500°C, and 600°C for 5 hours using a furnace in the Materials Laboratory of the Mechanical Engineering Department, Faculty of Engineering, Syiah Kuala University. Compressive strength was measured before and after heating. The results of the compressive strength showed that high-strength concrete with 10% diatomaceous earth substitution had the smallest decrease in compressive strength for each temperature variation and the variation of fiber addition with the largest residual compressive strength was obtained at a temperature variation of 400°C without the addition of fiber, which was 98,34% of the initial compressive strength. Meanwhile, the greatest residual compressive strength of high-strength concrete without diatomaceous earth substitution was obtained by concrete burned at a temperature of 400°C with 0,4% addition of polypropylene fiber, which was 81,01% of the initial compressive strength. Concrete with diatomaceous earth and polypropylene fibers better resisted high temperatures than concrete without diatomaceous earth.

1. INTRODUCTION

The increasing demand for infrastructure with high load-bearing capacity, such as skyscrapers, necessitates using high-strength concrete. This type of concrete usually requires the addition of materials to increase strength and workability. (Lu, 2023; Azzahra, 2019; Hilal et al. 2022). However, these additives also lead to increased cement consumption. To reduces the cement using in high strength concrete, diatomaceous earth represents a potential alternative for partially replacing cement (Hasan et al. 2020; Saidi and Hasan 2022). One potential alternative to partially replace cement is. Diatomaceous earth is a natural resource found in the Lampanah area of Aceh Besar, which is currently still rarely utilized. It contains a chemical composition consisting of 58.87% silica, 0.39% alumina, 12.2% lime, and 2.25% iron (Handayani,2018; Soraya et al. 2020).

According to the American Society for Testing and Materials C618 Class N, diatomaceous earth qualifies as a supplementary cementitious material that can be incorporated into concrete mixtures. One of the primary challenges of high-strength concrete is its resistance to elevated temperatures, particularly in fire scenarios. Fire exposure can severely degrade the structural integrity of concrete, leading to reduced compressive strength, surface deterioration, and explosive spalling (Maulani, 2016). Including polypropylene fiber, which melts at approximately 160°C and forms vapor release channels, can significantly mitigate spalling. When evenly distributed within the concrete matrix, these channels effectively reduce internal pressure and prevent explosive spalling (Aulia et al., 2020).

Shihada (2011) reported that concrete containing polypropylene fiber retained a higher percentage of its compressive strength after exposure to temperatures of 200°C, 400°C, and 600°C for 6 hours, compared to concrete without polypropylene fiber. The study concluded that using 0.5 % polypropylene fiber by volume significantly increased the residual compressive strength under thermal exposure. Similarly, Corpas et al. (2013) demonstrated that normal concrete without polypropylene fiber experienced a compressive strength loss of up to 73.8 % when exposed to 650°C. In contrast, adding 1 % polypropylene fiber by volume reduced this loss to only 36 %.

Bingöl and Atashafrazeh (2015) found that the addition of 0,12% of polypropylene fiber per m^3 of concrete improved relative compressive strength by 10.1% and 9.2% at temperatures of 300°C and 750°C, respectively, after 2 hours of exposure. Maulana (2020) investigated ultra-high-strength concrete using diatomaceous earth substitution at 0%, 5%, and 10% by weight of cement, combined with polypropylene fiber additions of 0% to 2.5% by volume. The highest compressive strength at 28 days, 111.18 MPA, was obtained from the mixture with no diatomaceous earth or polypropylene fiber.

Fadillah (2020) evaluated the residual compressive strength of ultra-high-strength concrete containing 0%, 5%, and 10% diatomaceous earth, after heating to 400°C, 500°C, and 600°C for 5 hours at 28 days of age. The lowest strength reduction was observed in concrete with 10% diatomaceous earth, retaining 95.18%, 90.20%, and 87.84% of its original strength, respectively. Aulia et al. (2020) reported that high-strength concrete without polypropylene fiber experienced a decrease in compressive strength after fire exposure, by 0.81% at 7 days and 23.42% at 28 days. In contrast, adding 0.2% polypropylene fiber increased post-fire compressive strength by up to 25.52% and 10.44% at the same respective ages.

This study investigates the fire resistance of high-strength concrete using diatomaceous earth as a partial cement replacement and polypropylene fiber as an additive. The concrete specimens were exposed to temperatures of 400°C, 500°C, and 600°C for 5 hours. Compressive strength tests were conducted before and after heating. Concrete cubes measuring 5×5×5 cm were prepared using a water to cement ratio of 0.3. The diatomaceous earth used was ground, passed through a number 200 sieve, and calcined at 600°C for 5 hours. The replacement levels of diatomaceous earth were 0% and 10% by weight of cement, and the polypropylene fiber content varied from 0% to 0.8% by volume. Aggregates included crushed stone in the size ranges of 4.76–9.52 mm and 2.38–4.76 mm, and sand in the 0–2.38 mm range. A superplasticizer was used at 1.5% by weight of cement. Specimens were subjected to thermal exposure after 28 days of water curing and air drying at room temperature. All tests were conducted at the Civil Engineering and Mechanical Engineering laboratories of Syiah Kuala University.

2. MATERIALS AND METHODS

This study was designed to produce high-strength concrete using a water-to-cement ratio of 0.3, with a 10% substitution of cement by diatomaceous earth by weight, a superplasticizer dosage of 1.5% by weight of cement, and polypropylene fiber additions of 0.2%, 0.4%, 0.6%, and 0.8% by volume of concrete. The diatomaceous earth used in this study was first calcined at a temperature of 600°C for 5 hours to activate the silica content within the material. Concrete specimens were prepared as cubes with dimensions of 5×5×5 cm. For each variation, 3 specimens were made, resulting in 120 specimens for the entire experimental program. After 28 days of curing, the specimens were exposed to elevated temperatures of 400°C, 500°C, and 600°C for 5 hours using a furnace to evaluate the fire resistance of the high-strength concrete.

2.1 Materials

2.1.1 Portland Cement (PC)

This study used Portland cement type I. Based on SNI 2049:2015, Ordinary Portland Cement (OPC) Type I is the most commonly used Portland cement for various types of building construction because its use does not require special requirements as required for other types (sulfate resistance, hydration heat, and high early strength).

2.1.2 Coarse and Fine Aggregates

The coarse aggregate used in this study consisted of crushed stone (split) with particle sizes of 4.76–9.52 mm and 2.38–4.76 mm. Before use, the coarse aggregate was washed to remove impurities and clay content, then air-dried to achieve a Saturated Surface Dry (SSD) condition. The fine aggregate used was sand with a particle size of 0–2.38 mm, which was also washed and air-dried to reach SSD condition before mixing.

2.1.3 Diatomaceous Earth

The diatomaceous earth used in this study was sourced from Lampanah Village, Aceh Besar District. The diatomaceous earth's chemical compounds and physical properties are presented in Tables 1 and 2. The material was ground, passed through a No. 200 sieve, and calcined using a furnace.

Table 1. Chemical composition of diatomaceous earth

No.	Chemical Compound	Content (%)
1.	SiO_2	58.87
2.	Fe_2O_3	2.25
3.	Al_2O_3	0.39
4.	CaO	12.2

Source from Handayani (2018)

Table 2. Physical properties of diatomaceous

Physical property	Result
Bulk density	0.767 kg/l
Specific gravity	2.000
Absorption	6.535 %

Source from Handayani (2018)

2.1.4 Polypropylene Fiber

Polypropylene fiber is a type of plastic fiber specially produced using high technology. PT Fosroc Indonesia manufactured the polypropylene fiber used in this study. The fibers had a length of 12 mm, a diameter of 0.018 mm, and a tensile strength of 350 MPa.

2.1.5 Superplasticizer

The superplasticizer used was Sika Viscocrete, produced by PT. Sika Indonesia. This admixture had a specific gravity of 1.06 g/cm³. It was applied to adjust the concrete’s workability. This type of SP can be categorized as a high-range water reducer admixture.

2.2 Method

2.2.1 Calcination Process of Diatomaceous Earth

The diatomaceous earth, which had been ground and passed through a No. 200 sieve, was calcined using a furnace at 600°C to activate its silica content. The material was placed in an aluminum container and inserted into the furnace. This process was carried out for 5 hours at the Materials Engineering Laboratory, Department of Mechanical Engineering, Faculty of Engineering, Syiah Kuala University.

2.2.2 Concrete Mix Design

The high-strength concrete mix was designed based on ACI 211.4R–93. In this study, diatomaceous earth was used as a partial replacement for cement at proportions of 0% and 10% by weight of cement. The water-cement ratio (w/c) used was 0.3, and a superplasticizer was added at 1.5% by cement weight. Polypropylene fibers were incorporated in varying volumes of 0.0%, 0.2%, 0.4%, 0.6%, and 0.8% of the concrete volume. The detailed mix proportions are shown in Table 3, and the fiber variations are presented in Table 4.

Table 3. Concrete mix proportions per m^3

No.	Material (kg)	Diatomaceous Earth Percentage	
		0%	10%
1.	Cement	600	540
2.	Diatomaceous Earth	0.00	60
3.	Coarse Aggregater (4.76 - 9.52) mm	763.43	763.43
4.	Coarse Aggregater(2.38 - 4.76) mm	276.14	276.14
5.	Fine Aggregate (0 - 2.38) mm	584.76	584.76
6.	Water	180.00	180.00
7.	Superplasticizer	9.00	9.00
	Total	2413.33	2413.33

Table 4. Additional polypropylene fiber weight per m^3 of concrete

Polypropylene Fiber Percentage	0%	0.2%	0.4%	0.6%	0.8%	Total
Weight (kg)	0.00	1.82	3.64	5.46	7.28	18.20

2.2.3 Specimen Preparation

The coarse and fine aggregates were prepared in a Saturated Surface Dry (SSD) condition, while the cement was ensured to be free of lumps to prevent any alteration of the water content in the mix. All materials were weighed according to the proportions of the designed concrete mix. The ingredients, including cement, aggregates, polypropylene fibers, superplasticizer, and water, were mixed for 10 to 15 minutes. Once a homogeneous mixture was achieved, a flow test was conducted to evaluate the consistency of the mortar.

Cube molds measuring 5×5×5 cm were coated with oil, filled with the fresh concrete mix, and compacted by tapping the sides with a rubber mallet. After leveling the surface, the specimens were left undisturbed for 24 hours before demoulding.

2.2.4 Specimen Curing

After the concrete mixture hardens, the concrete is removed from the mold and cured by immersing the test specimens in a protected tank filled with fresh water. This curing process is carried out until the specimens reach the age of 28 days, by the standard procedure for compressive strength testing. Once the specimens reach this age, they are taken out of the curing tank and air-dried for 24 hours. This drying process is important to remove excess water from the surface of the concrete before accurate weighing and dimensional measurements are conducted.

2.2.5 Specimen Heating

After being air-dried for 24 hours at room temperature and measured, the specimens were heated in an electric furnace. The internal dimensions of the furnace were 320 mm × 270 mm, and it could accommodate up to 25 specimens at once. The specimens were placed directly inside the furnace without trays or containers. Heating was conducted at planned temperatures of 400°C, 500°C, and 600°C for 5 hours.

2.2.6 Specimen Observation and Testing

The visual inspection process involved observing physical changes in the concrete, such as color transformation, surface edge cracking, and alterations in surface texture after exposure to high temperatures. This observation was conducted by comparing the visual appearance of the high-strength concrete specimens before and after being exposed to elevated temperatures for 5 hours.

The initial weight of each specimen was recorded on day 28 after curing in fresh water, before high-temperature exposure, and served as the control. Weight measurements were then repeated 24 hours after heating. The recorded mass was compared to the initial mass for specimens heated at 400°C, 500°C, and 600°C.

Compressive strength testing was conducted using a compressive loading machine at 28 days of age. Several compressive strength results were obtained based on the heating temperatures of 400°C, 500°C, and 600°C. For each temperature condition, three specimens were tested. The average compressive strength was then calculated from these three samples. Post-heating compressive strength values were compared against the control specimens cured in water for 28 days. The tests were performed 24 hours after the heating process for the post-heated specimens.

3 RESULT AND DISCUSSION

3.1 Result

The study produced several findings, including physical changes observed visually and mechanical changes identified through compressive strength tests.

3.1.1 Visual Changes

Visual observations were conducted on 28-day-old concrete specimens before and after exposure to high temperatures of 400°C, 500°C, and 600°C for 5 hours using a furnace. The purpose of visual observation was to compare the physical appearance of concrete after exposure to specific temperature levels to assess whether visible changes, such as cracking or deterioration, occurred. Figures 1 through 5 present the visual appearance of high-strength concrete without diatomaceous earth, while Figures 6 through 10 show the visual appearance of high-strength concrete containing 10% diatomaceous earth.

(a) (b) (c) (d)

Figure 1. High-strength concrete without diatomaceous earth and with 0% fiber content: (a) at room temperature, (b) after heating at 400°C, (c) after heating at 500°C, (d) after heating at 600°C.

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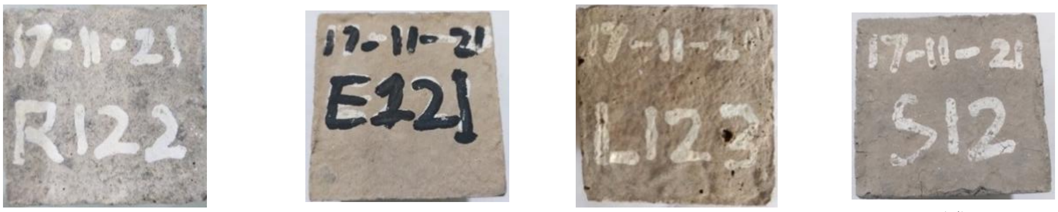


(a) (b) (c) (d)

Figure 2. High-strength concrete without diatomaceous earth and with 0,2% fiber content: (a) at room temperature, (b) after heating at 400°C, (c) after heating at 500°C, (d) after heating at 600°C.

(a) (b) (c) (d)

Figure 3. High-strength concrete without diatomaceous earth and with 0,4% fiber content: (a) at room temperature, (b) after heating at 400°C, (c) after heating at 500°C, (d) after heating at 600°C.

(a) (b) (c) (d)

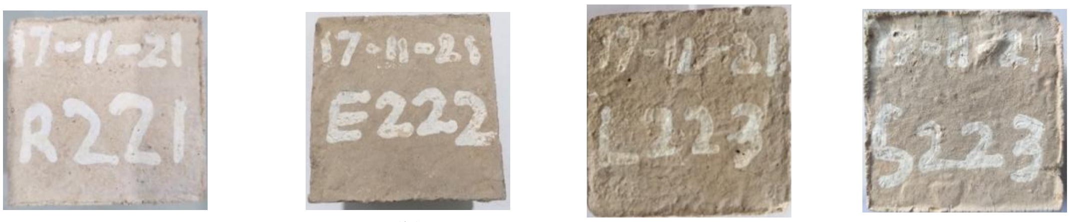
Figure 4. High-strength concrete without diatomaceous earth and with 0,6% fiber content: (a) at room temperature, (b) after heating at 400°C, (c) after heating at 500°C, (d) after heating at 600°C.

(a) (b) (c) (d)

Figure 5. High-strength concrete without diatomaceous earth and with 0,8% fiber content: (a) at room temperature, (b) after heating at 400°C, (c) after heating at 500°C, (d) after heating at 600°C.

(a) (b) (c) (d)

Figure 6. High-strength concrete with 10% diatomaceous earth substitution and 0% fiber content: (a) at room temperature, (b) after heating at 400°C, (c) after heating at 500°C, (d) after heating at 600°C.



(a) (b) (c) (d)

Figure 7. High-strength concrete with 10% diatomaceous earth substitution and 0.2% fiber content: (a) at room temperature, (b) after heating at 400°C, (c) after heating at 500°C, (d) after heating at 600°C.

(a) (b) (c) (d)

Figure 8. High-strength concrete with 10% diatomaceous earth substitution and 0.4% fiber content: (a) at room temperature, (b) after heating at 400°C, (c) after heating at 500°C, (d) after heating at 600°C.

(a) (b) (c) (d)

Figure 9. High-strength concrete with 10% diatomaceous earth substitution and 0.6% fiber content: (a) at room temperature, (b) after heating at 400°C, (c) after heating at 500°C, (d) after heating at 600°C.

(a) (b) (c) (d)

Figure 10. High-strength concrete with 10% diatomaceous earth substitution and 0.8% fiber content: (a) at room temperature, (b) after heating at 400°C, (c) after heating at 500°C, (d) after heating at 600°C.

3.1.2 Changes in Average Compressive Strength

The compressive strength tests were conducted after the specimens were subjected to different heating temperatures, 400°C, 500°C, and 600°C, for 5 hours, and the results were compared with unheated concrete specimens used as controls. The test results show a comparison of the compressive strength of concrete maintained at room temperature versus that of concrete subjected to heating at 400°C to 600°C, where a reduction in strength was observed. However, the degree of reduction varied depending on the conditions. Detailed results can be found in Tables 5 and 6.

Table 5. Compressive strength test results of concrete without diatomaceous earth

Polypropylene Fiber Percentage	At room temperature	Heated at 400°C	Heated at 500°C	Heated at 600°C
(%)	(MPa)	(MPa)	(MPa)	(MPa)
0.0%	73.67	58.78	56.57	50.06
0.2%	72.15	56.71	53.04	48.08
0.4%	68.82	55.75	51.62	46.64
0.6%	67.74	53.76	49.87	45.21
0.8%	66.62	52.19	48.85	44.07

Table 6. Compressive strength test results of concrete with 10% diatomaceous earth

Polypropylene Fiber Percentage	At room temperature	Heated at 400°C	Heated at 500°C	Heated at 600°C
(%)	(MPa)	(MPa)	(MPa)	(MPa)
0.0%	62.23	61.20	59.39	54.70
0.2%	58.28	57.60	56.08	51.95
0.4%	57.45	56.00	55.23	49.97
0.6%	56.51	54.97	53.02	47.19
0.8%	55.50	53.41	51.43	45.90

3.2 DISCUSSION

Based on visual observations from Figures 1 to 10, the concrete specimens exhibited noticeable color changes after heating. Before heating, the concrete was dark grey. After being exposed to 400°C, the color lightened, and at 500°C to 600°C, it turned into a brownish-grey hue. Concrete containing diatomaceous earth showed less significant color change, as it was already brownish.

Regarding physical damage, no major deterioration was observed at 400°C; only minor surface changes were visible. At 500°C, surface cracking began to appear. The most severe damage occurred in the specimens without diatomaceous earth and polypropylene fibers when heated at 600°C, where extensive cracking and surface spalling were observed. In contrast, concrete with 10% diatomaceous earth and 0.2% polypropylene fibers exhibited the least damage, with only fine surface cracks visible.

According to the data in Tables 5 and 6, high-strength concrete without diatomaceous earth substitution experienced a significant reduction in compressive strength due to high-temperature exposure. This reduction increased with higher percentages of polypropylene fiber. On the other hand, concrete containing 10% diatomaceous earth demonstrated better resistance, as indicated by less drastic strength loss and higher residual compressive strength at all tested temperatures. These findings suggest that diatomaceous earth improves the thermal resistance of high-strength concrete.

Combining diatomaceous earth (DE) and polypropylene (PP) fibers in concrete produces a denser, more heat-resistant structure. DE undergoes a pozzolanic reaction with calcium hydroxide to form compounds that fill the pores. At the same time, PP fibers, which melt at elevated temperatures, create vapor channels that help prevent excessive internal pressure. The interaction of these two mechanisms reduces thermal damage, resulting in a smaller decrease in compressive strength after heating compared to concrete without these additives.

The relationship between residual compressive strength percentage and fiber content at each temperature is illustrated in Figure 11.

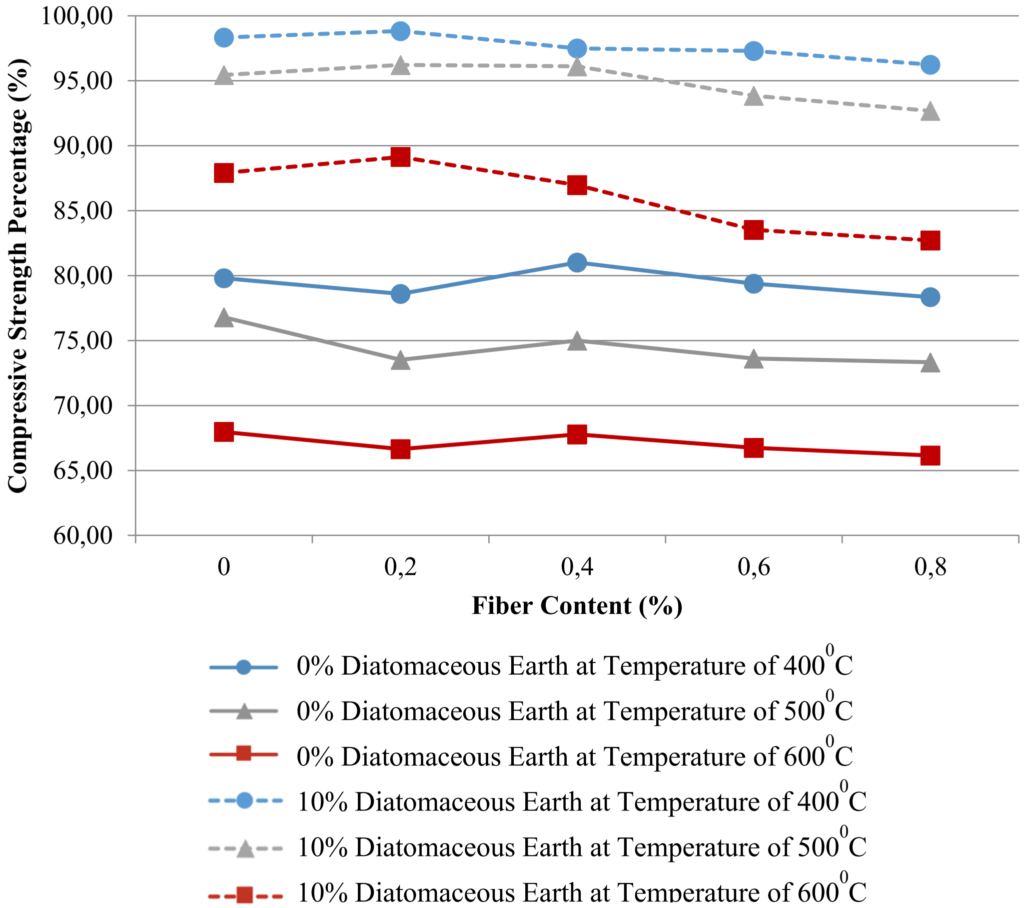


Figure 11. Graph of the Relationship Between Residual Compressive Strength Percentage and Fiber Content at Each Temperature

4 CONCLUSION

Visual observation of concrete after heating at 400°C, 500°C, and 600°C revealed surface damage, including cracking and slight spalling. Cracks began to appear at 500°C and became most severe at 600°C. Adding 10% diatomaceous earth and 0.2% polypropylene fiber effectively reduced cracking, with only fine surface cracks observed. In contrast, concrete without diatomaceous earth and polypropylene fibers exhibited extensive cracking and surface spalling.

The highest residual compressive strength was recorded in high-strength concrete containing 10% diatomaceous earth without polypropylene fibers, which retained 98.34% of its original strength after being heated at 400°C. In comparison, concrete without diatomaceous earth but with 0.4% polypropylene fiber retained only 81.01% of its initial strength after exposure to the same temperature. These results indicate that the combination of diatomaceous earth and polypropylene fiber provides better thermal resistance than concrete without diatomaceous earth.

The findings of this study are expected to contribute to the advancement of concrete technology and its practical applications in the field. Future research should pay closer attention to mixing methods to ensure uniform fiber distribution, explore a broader range of high-temperature exposures for more comprehensive data, evaluate different polypropylene fiber dosages, and examine concrete of varying strength classes.

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