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Fly ash as a substitute for cement and polypropylene fibers in concrete mix design

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Abstract*– The research focused on analyzing the effect of fly ash (FA) and polypropylene fibers (PPF) on the mechanical properties of concrete with a compressive strength of f'c = 280 kg/cm². The objective was to determine the influence of adding FA and PPF on the mechanical properties of the concrete. Concretes with FA in proportions of 5%, 10%, and 15%, and PPF in amounts of 350 g/m³, 480 g/m³, and 530 g/m³ were analyzed, evaluating their compressive strength (CS) at 7, 14, and 28 days, and their indirect tensile strength (ITS) at 28 days. Regarding CS, the results showed that at 7 days, the concrete without additives reached 128.05 kg/cm², while with 10% FA and 480 g/m³ of PPF, the strength increased to 256.81 kg/cm². At 14 days, the concrete without additives achieved 155.80 kg/cm², improving to 280.88 kg/cm² with the additives. At 28 days, the concrete without additives reached 281.68 kg/cm², while with 10% FA and 480 g/m³ of PPF, the strength increased to 383.75 kg/cm². Regarding ITS, it was observed that with 10% FA and 480 g/m³ of PPF, the highest strength was obtained, with 49.57 kg/cm². In conclusion, the appropriate proportion of additives to improve the mechanical properties of the concrete is 10% FA and 480 g/m³ of PPF.

Keywords*-- Fly ash, polypropylene fibers, indirect tensile strength, compressive strength.

INTRODUCTION

Concrete is widely used in the construction of various civil works. In order to enhance its quality, several additives have been included in its mixture. In this context, fly ash (FA) and polypropylene fibers (PPF) stand out as viable alternatives to enhance the mechanical properties of concrete. In Peru and several developing countries, significant challenges exist in waste management and the construction sector. One of the most urgent issues is the inadequate handling of fly ash, a byproduct generated by coal-burning power plants and industries for energy production [1]. Improper disposal of this waste could contaminate soils and water sources, negatively impacting the health of local communities and the biodiversity of nearby ecosystems. Additionally, the release of toxic compounds found in fly ash, such as heavy metals and radioactive elements, poses a risk to both the environment and public health [2].

Numerous studies have investigated the impact of fly ash on concrete properties. It has been demonstrated that replacing 20% of cement with fly ash can increase concrete compressive strength by up to 24%, depending on the water/cement ratio used [3]. Additionally, replacing 30% of cement with fly ash can provide concrete with adequate compressive strength due to the pozzolanic reaction that enhances cement hydration [4]. These studies suggest that fly ash is a promising additive for improving concrete's mechanical properties.

Besides fly ash, polypropylene fibers have been extensively studied for their ability to enhance the strength and toughness of concrete. Reference [5] investigated the effect of these fibers in high-strength concrete and found that the addition of polypropylene fibers can significantly increase compressive strength. The fibers act as secondary reinforcement, redistributing stresses and enhancing material ductility, resulting in greater resistance to crack propagation and improved energy absorption before failure [6].

Research studies, such as those conducted by [7] and [8], have shown that the combination of fly ash and polypropylene fibers significantly enhances concrete properties. These studies demonstrate that compressive and tensile strength of concrete increases when these additive materials are incorporated, resulting in more durable and environmentally friendly concrete. Ongoing research aims to further explore these findings through rigorous experimental evaluation.

In a comprehensive study, the effect of fly ash on concrete mixtures with a specific strength of 350 kg/cm² was evaluated. The proportions of fly ash were varied from 0% to 50%. The results demonstrated that the addition of fly ash significantly improved the compressive strength of the concrete. Values ranged between 288 kg/cm² and 434 kg/cm², depending on the percentage of fly ash used in the mix. In conclusion, researchers affirmed that fly ash is a highly effective component for enhancing concrete properties [9].

Furthermore, theories of material strength and cement hydration provide a solid framework for understanding how the addition of fly ash and polypropylene fibers affects the mechanical properties of concrete. The theory of composite materials mechanics is also essential for evaluating how the combination of these additives can create a material with improved properties, optimizing both concrete strength and durability [10]. Cement hydration theory offers a fundamental perspective on how materials react at the molecular level. This deepens our understanding of how fly ash influences microstructure and, ultimately, the mechanical properties of concrete [11]. Additionally, the theory of composite materials mechanics plays a crucial role in assessing how the combination of different materials, such as fly ash and polypropylene fibers, can result in a composite material with enhanced properties. This conceptual approach allows us to explore the interaction of these components to optimize both strength and concrete durability [12].

Fly ash, a byproduct of coal combustion in thermal power plants and industries, can partially replace cement, enhancing the strength, durability, and workability of concrete [13]. This material, defined as a byproduct of coal combustion in various power plants or furnaces, consists of fine particles carried by air during combustion and subsequently captured in exhaust gas filters, preventing their release into the atmosphere [14]. Thus, its use not only promotes environmental impact reduction by reusing a potentially contaminating waste but also offers significant advantages in concrete properties.

Fly ash is generated in large quantities as a byproduct of coal combustion, presenting a significant ecological challenge. Improper disposal of fly ash can lead to soil, water, and air pollution. However, incorporating fly ash into concrete production not only mitigates these environmental issues but also offers technical benefits. The pozzolanic nature of fly ash allows it to react with the calcium hydroxide formed during cement hydration, resulting in the formation of compounds that enhance concrete strength and durability [15].

Polypropylene fibers have been extensively studied for their ability to improve concrete's resistance and fracture toughness. The inclusion of these fibers in concrete can significantly enhance its ability to resist crack propagation, leading to increased impact resistance and improved energy absorption capacity before failure. Additionally, polypropylene fibers can play a crucial role as secondary reinforcement in concrete, redistributing stresses and increasing material ductility [16].

Polypropylene fibers, a composite material consisting of monofilaments assembled in a plastic matrix, were added to concrete mixes to enhance their properties [17]. These fibers acted as secondary reinforcements within the concrete matrix, helping prevent crack propagation and increasing the concrete's energy absorption capacity before failure [16].

The incorporation of fly ash and polypropylene fibers in concrete mix design presents an efficient and sustainable solution. The proposed research aims not only to validate the technical benefits of these additives but also to promote more environmentally friendly practices in construction. By using recycled materials and industrial byproducts, it is possible to improve concrete properties and contribute to waste reduction and environmental protection. This study establishes the appropriate proportions of fly ash and polypropylene fibers to maximize the concrete's mechanical properties, providing a scientific basis for their application in the construction industry.

Optimizing concrete mixtures is a crucial approach to enhancing both mechanical properties and sustainability. Recent research has revealed that the proper combination of fly ash and polypropylene fibers can lead to significant improvements in compressive, flexural, and tensile strength of concrete while reducing its environmental impact through the use of recycled materials and industrial byproducts.

On the other hand, compressive strength represents a fundamental and essential property of concrete, serving as a key indicator of its quality and ability to withstand structural loads. The incorporation of fly ash and polypropylene fibers can have a significant impact on this crucial mechanical property, enhancing its capacity to resist and support compressive forces and vertical loads [12].

Similarly, indirect tensile strength is an essential property of concrete that determines its ability to withstand tensile forces, especially in applications where the material is expected to experience bending or tension loads. The inclusion of fly ash and polypropylene fibers can significantly influence this mechanical property, improving the concrete's ability to resist tension and reduce the risk of cracking [18].

MATERIALS AND METHODS

The objective of this study was to determine the influence of adding fly ash and polypropylene fibers on the mechanical properties of concrete with a compressive strength of f'c = 280 kg/cm². The aim was to identify suitable percentages of these materials that can be used in concrete mix design, improving strength while contributing to environmental mitigation through the reuse of fly ash, an industrial byproduct.

A. *Obtaining Fly Ash and Polypropylene Fibers*

The fly ash was obtained from the combustion of coal in a sugar industry plant. These particles are generally spherical and smooth, with color ranging from gray to black. Their average particle size is 23.0 µm, determined by laser diffraction testing, and their density varies between 2.1 to 2.6 g/cm³ [19]. The specific surface area typically falls between 200 to 600 m²/kg. In the research, we analyzed how the inclusion of fly ash influences the mechanical properties of concrete [16].

For the study, we used polypropylene fibers with an approximate density of 0.91 g/cm³. These white fibers were obtained from recycled materials and were selected based on several critical factors to ensure the effectiveness and quality of the final product. These factors included the quality of the recycled polypropylene, fiber length, and cleanliness [17]. We investigated how adding these 38 to 40 mm polypropylene fibers affects the concrete's mechanical properties in combination with fly ash, optimizing these variables to achieve high-quality concrete with a compressive strength of f'c = 280 kg/cm².

B. *Characterization of Aggregates*

Concrete with a compressive strength of 280 kg/cm² was used, composed of fine and coarse aggregates with the characteristics shown in Table I, water, and cement. An experimental concrete was also included, with partial replacement of cement by fly ash and the addition of polypropylene fibers, while maintaining the same aggregates of sand, gravel, and water.

TABLE I
CHARACTERISTICS OF FINE AND COARSE AGGREGATES FOR CONCRETE PRODUCTION

Lekersa quarry	Fine Aggregate	Coarse Aggregate
Maximum size (in.)	0.187	0.50
Specific gravity	2.73	2.62
Loose unit weight (kg/m^3)	1464	1587

Compacted unit weight (kg/m^3)	1674	1798
Moisture Content (%)	1.20	0.53
Absorption (%)	1.71	0.64
Fineness modulus	2.92	6.54

C. *Specimens for Testing*

A control group and fifteen experimental groups were used. The control group, consisting of plain concrete, did not contain any fly ash or polypropylene fiber additives. The experimental groups included combinations of fly ash in proportions of 5%, 10%, and 15%, and polypropylene fibers in amounts of 350 g/m³, 480 g/m³, and 530 g/m³. A total of 192 specimens with dimensions of 100 mm x 200 mm were prepared. For the compressive strength test, 144 cylindrical specimens were used at 7, 14, and 28 days of curing, with 48 specimens for each curing period. For the indirect tensile strength test, an additional 48 specimens were used at 28 days of curing.

D. *Mix design*

The control and modified mix designs, in which cement is replaced with fly ash and polypropylene fibers are added, were carried out following the ACI 211 method. The water-cement ratio was 0.45, with a slump between 3 to 4 inches and a design strength of 280 kg/cm², as shown in Table II.

TABLE II
STANDARD AND MODIFIED MIX DESIGN

Materials	Mix Proportion for 1 m³			
	CONTROL	5% FA	10% FA	15% FA
Cement (kg)	478	454.1	430.2	406.3
Water (l)	220	220.0	220.0	220.0
Coarse aggregate (kg)	1103	1103	1103	1103
Fine aggregate (kg)	509	509	509	509
Fly ash (kg)	0	23.9	47.8	71.7
Polypropylene fiber (g)	0	350	480	530

E. *Statistical analysis*

Normality testing and analysis of variance (ANOVA) wer e used to determine the differences between groups. Tukey's te st was then used for multiple comparisons between control and experimental groups at a 5% significance level.

RESULTS

A. *Slump*

Fig. 1 shows the average slump and percentage variation of the standard concrete and the modified concrete with fly ash and polypropylene fibers. It is evident that as the percentage of fly ash increases, the slump increases due to its spherical shape and fine size, facilitating placement and finishing. However, it is also evident that as the amount of polypropylene fibers increases, the slump decreases because it increases the cohesion and viscosity of the mix, making the concrete less fluid and more difficult to handle. Additionally, the proportion of 10% FA and 480 g/m³ PPF, which provides the best compressive strength, has a slump of 4.2 inches, considered a workable concrete.

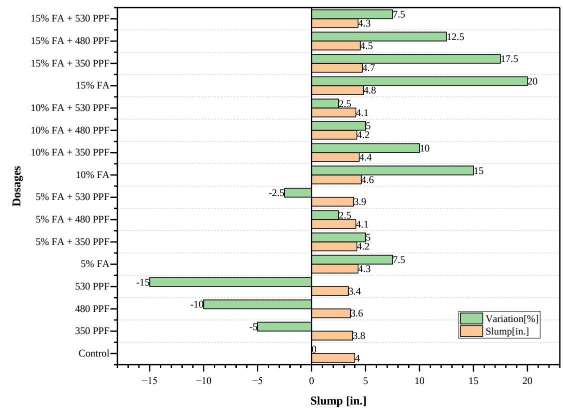

Fig. 1 Percentage variation of Slump

B. *Compressive strength*

The average compressive strength (CS) results of the concrete at 7 days are presented in Table III, showing the different percentages of fly ash used as a partial replacement for cement and the polypropylene fibers added to the concrete mix.

TABLE III
AVERAGE COMPRESSIVE STRENGTH AT 7 DAYS OF CURING.

Fly ash (FA)	Polypropylene fiber (PPF)			
	0_PPF (g/m^3)	350_PPF (g/m^3)	480_PPF (g/m^3)	530_PPF (g/m^3)
CONTROL	128.05	167.43	193.83	156.74
5%FA	153.64	182.12	203.85	167.30
10%FA	191.71	217.68	256.81	202.40
15%FA	147.53	183.77	217.13	180.33

Fig. 2 shows that adding 10% fly ash with 480 g/m³ achieves the highest strength with a value of 256.81 kg/cm². These values are suitable for use in replacing cement and adding polypropylene fibers.

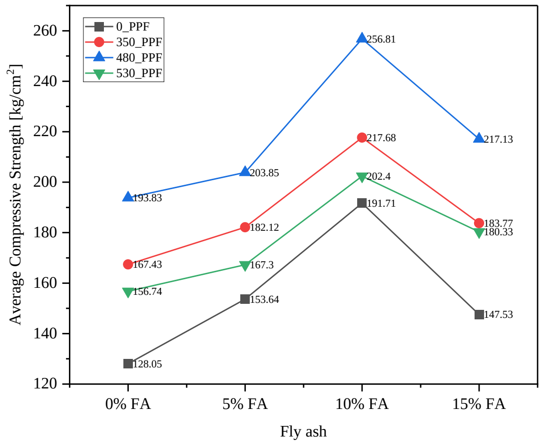

Fig. 2 Compressive strength (CS) at 7 days of Curing.

The results of the average compressive strength of the concrete at 14 days are presented in Table IV, showing the different percentages of fly ash used as a partial substitute for cement and the amounts of polypropylene fibers.

TABLE IV
AVERAGE COMPRESSIVE STRENGTH AT 14 DAYS OF CURING.

Fly ash (FA)	Polypropylene fiber (PPF)			
	0_PPF (g/m^3)	350_PPF (g/m^3)	480_PPF (g/m^3)	530_PPF (g/m^3)
CONTROL	155.80	202.74	219.00	189.50
5%FA	181.86	207.28	235.55	193.02
10%FA	222.86	245.73	280.88	237.03
15%FA	179.23	205.67	244.59	211.06

Fig. 3 shows that adding 10% fly ash with 480 g/m³ results in the highest strength, with a value of 280.88 kg/cm². These values are suitable for replacing cement with fly ash and adding polypropylene fibers to the concrete.

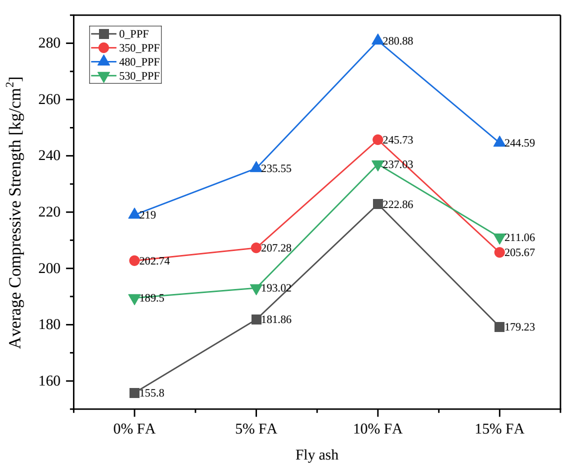

Fig. 3 Compressive strength (CS) at 14 days of Curing.

The results of the average compressive strength of the concrete at 28 days are presented in Table V, showing the different percentages of fly ash used as a partial substitute for cement and the amounts of polypropylene fibers.

TABLE V
AVERAGE COMPRESSIVE STRENGTH AT 28 DAYS OF CURING.

Fly ash (FA)	Polypropylene fiber (PPF)			
	0_PPF (g/m^3)	350_PPF (g/m^3)	480_PPF (g/m^3)	530_PPF (g/m^3)
CONTROL	281.68	290.81	312.16	301.50
5%FA	291.23	308.93	338.94	306.09
10%FA	338.47	354.60	383.75	357.52
15%FA	302.22	329.37	341.40	306.30

Fig. 4 shows that adding 10% fly ash with 480 g/m³ results in the highest strength, with a value of 280.88 kg/cm². These values are suitable for replacing cement with fly ash and adding polypropylene fibers to the concrete.

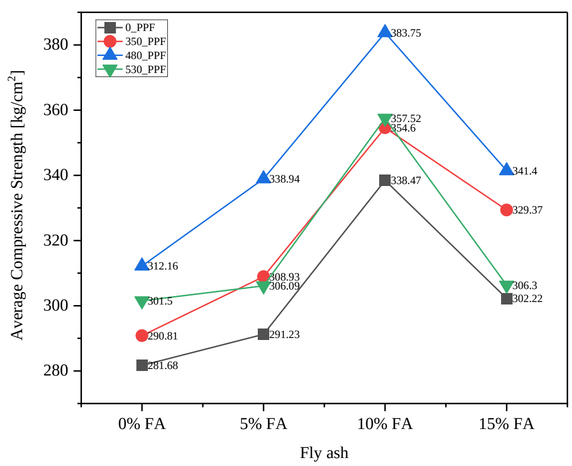

Fig. 4 Compressive strength (CS) at 28 days of Curing.

C. *Indirect Tensile Strength*

The results of the average indirect tensile strength (ITS) test of the concrete at 28 days are presented in Table VI, showing the different percentages of fly ash used as a partial substitute for cement and the amounts of polypropylene fibers.

TABLA VI
AVERAGE INDIRECT TENSILE STRENGTH (ITS) AT 28 DAYS OF CURING.

Fly ash (FA)	Polypropylene fiber (PPF)			
	0_PPF (g/m^3)	350_PPF (g/m^3)	480_PPF (g/m^3)	530_PPF (g/m^3)
CONTROL	28.50	32.72	35.91	31.93
5%FA	30.27	36.93	42.48	35.52
10%FA	31.71	40.41	49.57	35.29
15%FA	27.10	35.67	39.37	32.49

Fig. 5 shows that adding 10% fly ash with 480 g/m³ results in the highest strength, with a value of 49.57 kg/cm². These values are suitable for replacing cement with fly ash and adding polypropylene fibers to the concrete.

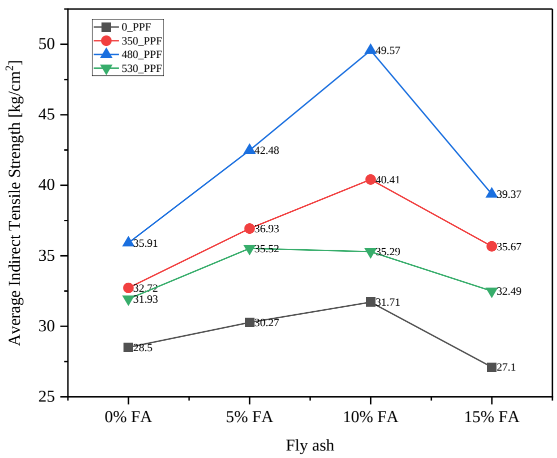

Fig. 5 Indirect Tensile Strength at 28 days of Curing.

D. Statistical analysis of results

The data on compressive strength and indirect tensile strength showed a normal distribution (p>0.05), except for the 530PPF group at 7 and 14 days, and the 5%FA + 530PPF group at 14 days. An analysis of variance and Tukey's multiple comparison test were then performed, with the results shown in Tables VII and VIII.

TABLE VII
ANALYSIS OF VARIANCE (ANOVA) FOR COMPRESSIVE AND INDIRECT TENSILE STRENGTHS ACCORDING TO THE AGE OF CONCRETE SPECIMENS.

Age of specimens	**F**	**Significance (p)***
Compressive strength		
7 days	8613.694	0.000
14 days	723.213	0.000
28 days	7597.949	0.000
Indirect tensile strength		
28 days	3238.467	0.000

* The difference in means is significant at the 0.05 level (p<0.05).

TABLA VIII
MULTIPLE COMPARISON (TUKEY) BETWEEN SAMPLES OF CONCRETE SPECIMENS ACCORDING TO AGE, FOR COMPRESSIVE AND INDIRECT TENSILE STRENGTH.

Age of specimens	**Significance (p)***	**Result**
Compressive strength		
7 days	0.000	Significant difference between control group and all experimental groups. Except group PPF530.
14 days	0.000	Significant difference between control group and all experimental groups. Except groups PPF530 and 5%FA + 530PPF
28 days	0.000	Significant difference between control group and all experimental groups.
Indirect tensile strength		
28 days	0.000	Significant difference between control group and all experimental groups.

* The difference in means is highly significant at the 0.01 level (p<0.01).

DISCUSSION OF RESULTS

In the context of the research, the compressive strength of concrete was determined at different curing ages, specifically at 7, 14, and 28 days. At 7 days of curing, the concrete without fly ash or polypropylene fibers showed a strength of 128.05 kg/cm². Incorporating 10% fly ash (480 g/m³) significantly increased the strength to 256.81 kg/cm². On the other hand, the addition of 530 g/m³ of polypropylene fibers, without fly ash, resulted in a strength of 156.74 kg/cm². At 14 days of curing, additional increases in strength were observed. The concrete without fly ash or polypropylene fibers reached 155.80 kg/cm². With the inclusion of 10% fly ash, the strength improved to 280.88 kg/cm². In the case of concrete with 530 g/m³ of polypropylene fibers and no fly ash, the strength was 189.50 kg/cm². At 28 days, the compressive strength of the concrete showed a notable increase. Without additives, the concrete reached 281.68 kg/cm². With the addition of 10% fly ash, the strength rose to 383.75 kg/cm². Finally, the mix with 530 g/m³ of polypropylene fibers, without fly ash, achieved a strength of 301.50 kg/cm². These results align with the research conducted referenced [7], which demonstrated the effectiveness of using polypropylene fibers and fly ash in the concrete mix, suggesting that strength values can improve up to 350 kg/cm² compared to the design strength of 280 kg/cm². In the research referenced [15], the results indicate that at 28 days, the average strengths were 221 kg/cm² for normal concrete; 223 kg/cm² for concrete with 2.5% fly ash; 231 kg/cm² for concrete with 5.0%; 200 kg/cm² for concrete with 10.0%; and 192 kg/cm² for concrete with 15% fly ash, demonstrating that the appropriate percentage for replacing cement with fly ash should be less than 10% as higher percentages negatively affect concrete strength and quality control. Additionally, the study referenced [8] considers that polypropylene fiber improves compressive strength by 3.6%, with an amount of 450 g/m³. In summary, these findings indicate that both fly ash and polypropylene fibers are viable alternatives to effectively improve the mechanical properties of concrete.

The indirect tensile strength (ITS) was evaluated at 28 days of curing. It was observed that adding 0% fly ash and 0 g/m³ of polypropylene fibers resulted in a value of 28.50 kg/cm². Additionally, incorporating 10% fly ash with 480 g/m³ of polypropylene fiber achieved the highest strength, with a value of 49.57 kg/cm². These values are suitable for improving the mechanical properties of concrete. On the other hand, adding 0% fly ash with 530 g/m³ resulted in the lowest strength, with a value of 31.93 kg/cm². Comparing these results with the study by [21], which reports an indirect tensile strength of 3.57 MPa (36.40 kg/cm²) for the GCV/ESC mix at 28 days of curing, we find that the values exceed by 113% and

143% those of GCV/OPC and GCV concretes, respectively. Furthermore, these findings align with the research by reference [8], which demonstrated that the addition of 450 g/m³ of polypropylene fiber significantly improves the indirect tensile strength of concrete by 14%. This amount is similar to the dosage of 480 g/m³ used in the present research, along with fly ash. Additionally, reference [20] determined that the splitting tensile strength (indirect tensile strength) at 180 days increases from 2.1 MPa to 2.6 MPa due to the decrease in w/c ratios from 0.4 to 0.34.

It was also determined that the appropriate percentage of fly ash is 10% and the appropriate amount of polypropylene fiber is 480 g/m³, as both significantly improve the mechanical properties of concrete with a design strength of f'c=280 kg/cm². These results are consistent with the study by reference [22], which indicates that the influence of fly ash on the achieved strength is most notable between 2.5% and 10%, identifying this range as suitable for improving compressive strength. Similarly, reference [23] determined that the most appropriate replacement percentage is 10% fly ash for cement, as higher percentages negatively affect compressive strength. Additionally, reference [8] demonstrated that polypropylene fiber improves compressive strength by 3.6%, with an appropriate amount of 450 g/m³. These findings align with the results of the present research, highlighting that both fly ash and polypropylene fibers are highly beneficial materials for improving the properties of concrete.

CONCLUSIONS

Based on the most significant results of this experimental research on the behavior of concrete with the incorporation of fly ash and polypropylene fiber, the following conclusions are presented:

- The workability of the concrete is not affected by the incorporation of FA and PF in different percentages, with the proportions of 5% FA and 10% FA achieving the best workability, and their values are within the range of 3 to 4 inches.
- The compressive strength and indirect tensile strength of the concrete are improved with the addition of 10% FA and 480 g/m³ of PF, surpassing all tested dosages.
- Increasing FA and PF above 10% and 480 g/m³ tends to decrease the strength of the concrete, indicating that beyond this limit, both materials are detrimental to the concrete and limit the capacity of the cement matrix.

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