Optimization of fiber reinforced polymer concrete mix design based on DBA

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Abstract

This paper investigates the behavior of fiber-reinforced concrete containing three polymer-based fibers, namely polypropylene, Barchip 48, and Forta-ferro, intending to optimize mix design using the DBA statistical approach. Two concrete mix designs were considered: a medium-strength mix and a high-strength mix. Fiber contents of 0.5% and 1% by concrete volume were used, and the specimens were tested at 7, 28, and 90 days. The study shows that the effect of fiber reinforcement depends strongly on fiber type, concrete strength class, and curing age. According to the results, Forta-ferro and Barchip generally improved compressive strength, while polypropylene reduced strength in some cases. The optimum combinations identified by DBA indicate that medium-strength concrete performs best with 0.5% polypropylene at 7 days, 0.5% Forta-ferro at 28 days, and 0.5% Barchip at 90 days; for high-strength concrete, 0.5% Forta-ferro was the best option at all ages. Overall, the findings confirm that polymer fiber selection plays a decisive role in the mechanical performance of concrete and that DBA can be used effectively for mix optimization.

KEYWORDS

Fiber concrete; compressive strength; tensile strength; flexural strength; polymer fibers.

Introduction

According to the definition provided by ACI Committee 544 of the American Concrete Institute, fiber-reinforced concrete is a mixture of cement, water, aggregates, and discrete fibers. The fibers must not exceed 76 mm in length and 1 mm in diameter [1].
In the present study, polymer-based fibers were used. Polypropylene fibers are manufactured from homopolymers, a type of polymer commonly employed in the textile industry. The principal characteristic of this fiber type is its adequate durability under alkaline–siliceous conditions, Where as its drawbacks include poor fire resistance, susceptibility to light and oxygen, low modulus of elasticity (0.5 to 8 GPa),

and weak bond with concrete [2]. BarChip fibers represent one of the most recent types of polymer-based fibers and can serve as a substitute for steel fibers. The surface of these fibers features protrusions that provide adequate mechanical interlock with the cement mortar. One recent application of this fiber type has been in tunnel segments, where it has been used as an alternative to steel fibers in precast tunnel segments [3].

Forta-Ferro fibers consist of a composite material made from a copolymer, formed into very fine twisted strands and a network of filament fibers. These fibers reduce plastic and drying shrinkage of concrete, enhance impact resistance, increase fatigue resistance, and improve concrete toughness [4].

In 2013, Ramezanianpour et al. conducted a study on the effect of polypropylene and steel fibers on concrete. Their research demonstrated that polypropylene fibers possess the ability to bridge micro-cracks but have little effect on the post-cracking strength of concrete. Furthermore, replacing steel fibers with a higher proportion of polypropylene fibers results in reductions in flexural strength, energy absorption, and impact resistance [5].

To date, numerous comparisons have been made regarding the effect of fiber size and volume fraction of various fiber types on the strength of normal- and high-strength concrete. However, a comprehensive comparison of the influence of different polymer-based fibers on the mechanical strength of normal- and high-strength concrete, along with the optimization of fiber-reinforced concretes using the DBA statistical method, has not yet been conducted. In this research, the effect of adding polymer-based fibers on the compressive, tensile, and flexural strengths of normal- and high-strength concretes has been investigated. Finally, employing the DBA statistical method and considering the cost of fiber procurement as a highly important parameter, the most optimal fiber-reinforced mix designs at ages of 7, 28, and 90 days are introduced for both normal- and high-strength concretes.

Methodology

The experimental program was organized around two concrete mix designs. The first mix was a medium-strength concrete designed according to ACI 544 guidance, and the second was a high-strength concrete mix with higher cement content and lower water-cement ratio. The first mix contained cement, water, sand, gravel, and no superplasticizer, while the second mix included more cement, less water, removal of coarse aggregate larger than 19 mm, and the use of a superplasticizer (102NPC) at 0.6% of cement weight. The mix details are given in **Table 1** of the paper.

Table 1. Mix design of the two concrete mixtures used in the study

Mix design	Cement	Water	Sand	Gravel	Superplasticizer
Mix 1	380	240	636	1079	No
Mix 2	500	234	871	718	0.6% of cement weight

The fiber types used in the study were polypropylene, Barchip 48, and Forta-ferro. Their basic properties, including density, length, tensile strength, and elastic modulus, are presented in **Table 2**. The corresponding fiber images are shown in **Figure 1**.

Table 2. Properties of fibers used in the research

Fiber type	Density	Length	Tensile strength	Elastic modulus
Polypropylene	910	12 mm	400 MPa	2700 Mpa
Barchip 48	910	48 mm	640 MPa	12000 Mpa
Forta-ferro	910	54 mm	660 MPa	9500 Mpa

Figure 1. Fibers used in the study
(a) Polypropylene (b) Barchip 48 (c) Forta-ferro

Specimens were prepared with fiber contents of 0.5% and 1% by volume of concrete. The mixing procedure differed slightly depending on fiber type. For Barchip 48, aggregates were first mixed with cement and water, and fibers were then added during the mixing process. For polypropylene and Forta-ferro, the aggregates were initially mixed, then fibers were added to avoid balling, followed by cement and water. In the high-strength mix, the reduced water-cement ratio and increased cement content were intended to improve the matrix quality and provide a more suitable environment for fiber action.
Compressive strength tests were conducted on 15 × 15 × 15 cm cube specimens at 7, 28, and 90 days, using the relevant ASTM and Iranian national standards cited in the paper. Specimens were water-cured and demolded after 24 hours. The study primarily focused on compressive strength, while the abstract also indicates that tensile and flexural behavior were considered in the broader discussion of fiber performance.

Results and Discussion

This study employed the DBA (Distance from Best Available) method to optimize fiber-reinforced concrete mixes. Four attributes were considered: compressive, tensile, and flexural strength, as well as fiber cost per cubic meter of concrete. In the DBA framework, the worst condition for each attribute among all alternatives was assigned a value of zero in the criterion matrix. For strength properties (where higher is better), other values were calculated as the absolute difference from the worst performance. For cost (where lower is better), the zero value represented the most expensive fiber in that group, and other values indicated the cost difference from that worst economic condition. All values were then standardized using Z-scores, and the Compound Distance (CD) to the ideal condition was calculated. The mix with the lowest CD was selected as optimal.
The results show that in normal-strength concrete, the optimal fiber type varies with age. Polypropylene 0.5% performs best at 7 days (CD = 1.09), likely due to its early-age bonding characteristics despite its overall poor adhesion. At 28 days, Fortaferro 0.5% becomes optimal (CD = 1.82), and at 90 days, Barchip 0.5% shows the best performance (CD = 1.60). This shift suggests that different fiber types activate their reinforcement mechanisms at different stages of concrete hardening.
In high-strength concrete, Fortaferro 0.5% is the optimal mix across all ages (CD = 1.21, 0.92, and 0.90 at 7, 28, and 90 days, respectively). This consistency indicates that the improved matrix strength enhances fiber-matrix bonding, allowing Fortaferro fibers to perform effectively from early to late ages. Polypropylene fibers, in contrast, showed poor bonding and led to strength reductions of up to 15% in compressive strength and 12% in tensile strength. Barchip fibers displayed mixed results, increasing early strength but sometimes reducing later-age strength, depending on the mix design.

From an economic perspective, the DBA cost analysis identified the most expensive fibers (zero cost value) as Barchip 1.0% and Fortaferro 1.0%, while the most economical acceptable mix was Polypropylene 0.5%. For high-strength concrete, despite its higher cost, Fortaferro 0.5% remains the most efficient choice due to its superior and stable mechanical performance.
Overall, the DBA method successfully integrates mechanical and economic criteria, providing clear, age-specific recommendations for fiber selection in both normal and high-strength concrete.

Conclusion

According to the results, increasing the concrete strength leads to enhancements in the compressive, tensile, and flexural strengths of polymer-based fiber-reinforced concrete, owing to the improved bond performance between the cement paste and the fibers. The findings of this study can be summarized as follows:

1) Increasing the strength of the concrete matrix improves fiber-matrix bonding. This leads to higher compressive, tensile, and flexural strength in polymer-based fiber-reinforced concrete.
2) Fibers have a minimal effect on compressive strength in normal-strength concrete and may even reduce it in some cases. In contrast, for high-strength concrete, fibers significantly improve compressive strength compared to normal-strength concrete.
3) Polypropylene fiber exhibits poor bonding with the cement matrix. It reduces compressive strength by up to 15% and tensile strength by 12%, and is only acceptable at early ages (7 days) in normal-strength concrete.
4) Barchip fiber shows mixed performance depending on the mix design and age. It increases early-age strength by approximately 10% but may reduce later-age strength by 11% in some mixes. However, Barchip 1.0% consistently increases 90-day strength by up to 29%.
5) Fortaferro fiber achieves the highest compressive strength among all fibers, averaging approximately 60 MPa. It increases early-age strength by about 20% in one mix design, while in another mix design, Fortaferro 1.0% increases strength by up to 20% across all ages.
6) In normal-strength concrete, the optimal fiber type varies with concrete age. Polypropylene 0.5% is optimal at 7 days (CD = 1.09), Fortaferro 0.5% at 28 days (CD = 1.82), and Barchip 0.5% at 90 days (CD = 1.60).
7) In high-strength concrete, Fortaferro 0.5% is the optimal mix at all ages. It achieves CD values of 1.21, 0.92, and 0.90 at 7, 28, and 90 days, respectively.
8) In the DBA method, a zero value in the cost column indicates the most expensive fiber in that group. The most expensive mixes are Barchip 1.0% and Fortaferro 1.0%, while the most economical acceptable mix is Polypropylene 0.5%.
9) For normal-strength concrete, fiber type should be selected based on the target age. Polypropylene is recommended for early-age applications, while Fortaferro or Barchip are better for later ages.
10) For high-strength concrete, Fortaferro 0.5% is the most efficient and robust choice for all ages. This recommendation is consistent across all mechanical and economic criteria considered in the DBA analysis.

References

[1] ACI Committee 544, State-of-the-art report on fiber reinforced concrete (ACI 544.1R-96), American Concrete Institute, Detroit, 1996, pp. 2-3.
[2] A. Bentur, S. Mindess, Fibre reinforced cementitious composites, CRC Press, 2014.
[3] A.G. Nitschke, R. Winterberg, Performance of macro synthetic fiber reinforced tunnel linings, in: Proceedings of the 2016 World Tunneling Congress, 2016.

[4] F. Hasan-Nattaj, M. Nematzadeh, The effect of Forta-Ferro and steel fibers on mechanical properties of high-strength concrete with and without silica fume and nano-silica, Construction and Building Materials, 137 (2017) 557-572.
[12] A.A. Ramezanianpour, P. Rashid Dadash, Polypropylene-steel fiber reinforced concrete, Journal of AUT, 44 (2013) 75-83. (In Persian)