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Review Article

Investigation of mechanical and durability properties of concrete with hybrid polypropylene fiber (PPF): A review

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ABSTRACT
Concrete is the primary construction material used but it's brittle and has low tensile strength which make it subject to cracking and durability problems. In that regard as solution to these issues, fiber reinforced concrete has put forth itself as a good answer. As for the different fibers present their Polypropylene fiber (PPF) stands out because of its chemical stability, low density and cost efficiency. Recently hybrid fiber reinforcement has gained attention. This approach uses polypropylene fibers with other types and sizes of fibers to achieve better mechanical and durable performance. This paper reports on research which looks at mechanical and durability of concrete that includes hybrid polypropylene fiber used, we see how hybrid PPF affects compressive and tensile strength, flexural performance, strength, permeability, shrinkage control, and long-term durability of concrete. The key practices that improve performance are identified, and research gaps for future studies are noted.

1. Introduction

Due to its high compressive strength and versatility Concrete is the main construction material in the world. As for its traditional forms they do have some flaws which include low tensile strength, cracking and brittleness. These issues play a role in early cracking which in turn degrades a structure's performance and durability. We see this especially in cases of mechanical stress or when there are changes in temperature and environmental conditions. Microcracks that appear early will lead to larger cracks which in turn cause concrete to deteriorate at a faster rate as also increases the cost and frequency of repair and maintenance [1]. Fibers put into a concrete matrix are said to break up the crack initiation and also to improve tens tensile strength, ductility, and energy absorption capacity [1].

In order to improve concrete performance, discrete fiber reinforcement has been used as one of the effective methods to control cracking. Dispersed fiber matrices assist in the restriction of cracking, providing enhancement in tensile strength, ductility, energy absorption, and overall concrete matrix improvement [1]. From the different types of synthetic fibers, polypropylene fiber (PPF) stands out to be more preferable due to its resistance to corrosion, chemical inertness, high pliability, and control of cracking during the plastic shrinkage [2]. PPF also improves the performance of concrete by significantly minimizing early-age cracking and enhancing durability cracking.

Even out of the fact that nanofiber concrete systems do improve some strength related attributes of concrete we see that in practice it is not so which we attribute to the low stiffness of the polypropylene fibers. Also, as a result mono fiber concrete system have brought in hybrid fiber reinforcements which put polypropylene with other types of fibers or which use many different types of polypropylene (PPF) fibers of various lengths. For example, such hybrid systems are very much designed to target certain cracks which in turn improves the overall performance [3, 4].

This review reports on the study of mechanical and durability properties of concrete which we looked at via recent tests and also what issues will require more research in the future.

2. Hybrid fiber reinforcement concept

In hybrid fiber reinforced concrete two or more types of fiber are used in order to bring out the best in each type and also at the same time to reduce, if at all possible, what that fiber does poorly. In hybrid systems polypropylene micro-fibers (micro-PPF) are used mainly for early microcracking and plastic shrinkage. As opposed to that macro-fibers or the stiffer fibers are put in to improve post cracking strength, ductility and energy absorption [5]. Also, in regard to the different sized micro, macro and structural cracks. Also, which actually promote the better stress redistribution in the concrete structure.

Research reports that we see a great improvement from the use of hybrid fiber concrete as compared to mono-fiber concrete which we have in [6, 7]. We see that different length fibers which are used in this hybridization intercept at various stages of crack development which in turn produces a more ductile failure. Also, the increase in toughness and impact resistance is a result of what the fibers do together. Thus, it is that hybrid fiber concrete which is the best choice for pavements, industrial floors and structural elements that see dynamic loading [8].

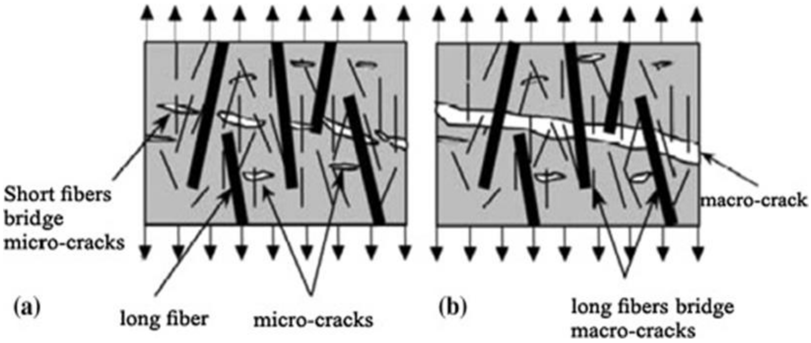

Figure 1: Hybrid fiber reinforcement system in concrete [35].

Figure 1 Schematic representation of fiber bridging mechanisms in fiber-reinforced concrete under tensile loading: (a) short fibers controlling micro-cracks, and (b) long fibers bridging macro-cracks, illustrating enhanced crack resistance and post-cracking behavior.

3. Mechanical properties of hybrid PPF concrete

Hybrid polypropylene fiber reinforcement which in turn changes the mechanical action of concrete by which it initiates and develops cracks also what happens post crack in concrete. It is a known fact that traditional concrete experiences sudden failure which is a result of rapid crack growth and crack formation, but what we see with hybrid PPF is better performance in terms of ductility and load transfer. At micro and macro scale levels these fibers play a role in crack control which in turn reports to better structural performance.

A. Compressive Strength

The effect for instance is that of hybrid PPF which in general does see a positive though small effect on compressive strength when fiber dosage and distribution is proper. Also, we note from several studies that the compressive strength either does not change from or at worst just outperforms plain concrete, which we see in reports to have an average gain of between 2% to 7% [9], [10] at this point it is very much from that the fiber's role in confinement which plays out to delay crack formation under compressive stress.

However, compressive strength is sensitive to fiber volume fraction. Too much polypropylene fiber can reduce workability and cause fiber balling. This leads to poor compaction and increased porosity [11]. As a result, compressive strength may drop beyond the optimal fiber dosage.

B. Tensile Strength

Split tensile strength has seen great improvement in hybrid PPF concrete as compared to that of traditional concrete. Polypropylene fibers which is what they do is to tie up microcracks and delay crack growth which in turn causes higher tensile resistance and better ductility [12]. In hybrid systems we see tenfold strength increase of 8% to 20% which is to say that results vary based on the type of fiber, dosage, and concrete mix [13]. That which we see is an improved tensile behavior is very helpful for crack width management and overall service performance.

C. Flexural Strength and Toughness

When we mix different types of polypropylene fibers with micro-PPF reinforcement what we see is an improvement in flexural strength and toughness. Micro-fibers play a role in the crack initiation and growth, out of which macro-PPF takes care of load support once cracks form [14]. Also, it is reported that we see an improvement of 25% in flexural strength. At the same time energy absorption and toughness post cracking see great improvement [15]. We see that there is an improvement in ductile flexural response and to resistance of catastrophic failure.

4. Durability performance of hybrid PPF concrete

A. Permeability and Water Absorption

Cracks are primary pathways for water and damaging ions to penetrate. Hybrid PPF systems reduce the extent and frequency of cracking, which in turn reduces permeability and water absorption [16]. Correctly designed hybrid fiber concrete tends to have an optimum fibrous composition that creates improved pore structure and reduces sorptivity. This increases resistance to the entry of chlorides and the occurrence of carbonation [17].

B. Shrinkage and Crack Control

Polypropylene fibers do a great job at controlling plastic shrinkage cracks as they put up well to tensile stress in the early stages. In Hybrid PPF systems we see that by using fibers of varying shapes and lengths we improve crack control [2, 6]. By reducing shrinkage cracking we improve surface finish and also prevent early age durability issues.

C. Long-Term Durability

Many studies have suggested hybrid fibre reinforced concrete provides better result in freeze-thaw cycles, improved abrasion resistance and decreases surface scaling. [18]. The fiber distribution and quality of curing impact how long hybrid PPFs are effective. Balanced hybrid systems in concrete reduce maintenance and improve the longevity of structures.

5. Literature review on hybrid fiber-reinforced concrete

Fibre reinforced concrete is the main focus of many studies which is due to its performance in solving issues like that of brittleness, cracking, and tensile strength in plain concrete. Recently researchers have reported greater interest in hybrid fibre reinforced concrete which is a mix of two or more types of fibers with different properties all of which aim to improve strength, ductility, durability and crack resistance.

A. Fiber–Matrix Interaction and Shrinkage Control

A large issue with Polypropylene fibers (PPF) is that they do not adhere well to cement materials which in turn does not allow for great strength improvement. To that end researchers started out with chemically modified polypropylene fibers which they designed to improve interaction with the matrix. We saw that surface treated polypropylene fibers improved wettability and also had better chemical bonding. This in turn reported better results in terms of compressive and tensile strength and also, we noted large scale reductions in drying and thermal shrinkage strains [20]. That which is put forth is that surface modification of fibers is a very good method to improve the performance of low modulus fibers in crack control applications.

Shrinkage control is also a large area of study in alternative binder systems. In Alkali Activated Slag concrete we saw that the addition of hybrid macro and micro polypropylene fibers reduced shrinkage greatly as compared to plain mixes. Also, it maintained good mechanical performance [24]. Also, it was found that hybrid systems outperformed single fiber systems due to the crack bridging which they do at micro and macro levels.

B. Mechanical Performance of Hybrid Fiber Systems

The stiffness, geometry, and dosage of the fibers play a role in the mechanical behavior of hybrid fiber-reinforced concrete. We looked at fibers in terms of their Young's modulus which we found to be that high modulus fibers mainly contribute to the load carrying capacity of the concrete also we saw that low modulus fibers improve toughness, impact resistance and crack growth. Hybrid fiber systems put into play many bridge mechanisms at different crack widths which in turn we see to improve the strength to ductility ratio.

Research reports on hybrid basalt and polypropylene fiber systems which showed great improvements in flexural strength, performance after cracking, and energy absorption when compared to plain concrete [32]. In recycled aggregate concrete we saw that micro-basalt and macro-polypropylene fibers increased tensile and flexural strengths. This was despite the strength penalties associated with recycled aggregate replacement [25]. From these studies it is reported that post cracking behavior is improved by use of hybrid fiber systems which in turn compensates for the defects of recycled aggregate concrete.

C. Hybrid Fibers in Recycled and Sustainable Concrete

In the rise of sustainability and circular economy issues we have seen great research into hybrid fiber reinforcement in Recycled Aggregate Concrete (RAC). We noted that hybrid systems of steel and polypropylene fibers did outperform in terms of flexural strength, water absorption, and chlorides permeability which in turn presents a more eco-friendly and economic option to single steel fiber reinforcement [23]. Also, we saw that the use of stiff steel fibers in combination with flexible polypropylene fibers improved crack resistance which at the same time addressed issues related to permeability.

More in the research we see that which mix of hybrid basalt and rebar polypropylene fibers performs best reports greater results in terms of mechanical and durability performance. These results put forth their value in sustainable structural concrete [22]. Also, it is brought to light once again the value of hybrid fiber systems in the structual recycling of materials.

D. Dynamic and Impact Behavior of Hybrid Fiber-Reinforced Concrete

Specific studies have concentrated on the effects of dynamic loading of hybrid fiber reinforced concrete and protective and marine structures. Hybrid basalt and polypropylene fiber reinforced coral aggregate concrete showed increased dynamic compressive strength, impact toughness and strain capacity under higher strain rate conditions [33]. Different fibers modified the failure mechanisms because of fiber pull out at lower strain rates and fiber rupture at higher strain rates, which caused better energy dissipation.

Concrete in the case of steel and polypropylene hybrid fibers saw a transformation from brittle to plastic failure modes with impact loading. We noted that at high strain rates concrete had higher peak stress, peak strain, and energy absorption [34]. Also, it was put forth by researchers that we develop a better dynamic model which will pay attention to the performance of hybrid fiber systems in rapid loading and also that which increases the impact resistance of these systems.

E. Structural Applications and Rehabilitation

Beyond the material level studies, in structural elements hybrid fiber reinforced concrete has been looked at. In the addition of hybrid polypropylene fibers we see that flexural strength, ductility, and post-peak response of concrete beams that are reinforced with innovative hybrid bars has improved [19]. Also seen was better crack healing and energy dissipation which in turn brought about behavior similar to that of steel reinforced beams but we saw also that it provided better corrosion resistance. resistance.

There has also been suggested the use of hybrid fiber reinforced concrete has for structural rehabilitation and seismic strengthening. Hybrid synthetic fiber reinforced concrete for example, showed increased compressive, flexural, and tensile strength, and even greater toughness and energy absorption. This demonstrates positive potential for the repair and retrofitting of damaged infrastructure [31].

6. Discussion

Although extensive research confirms the benefits of hybrid fiber-reinforced concrete, some gaps remain. There are few long-term durability studies examining combined mechanical and environmental loading, especially for chemically modified polypropylene fibers and sustainable binder systems. Furthermore, existing design codes and predictive models do not effectively account for the complex behavior of hybrid fiber systems, particularly under dynamic loading conditions [24,30]. Future research should concentrate on standardized mix design methods, lifecycle performance assessment, and code integration to support large-scale structural applications.

Table 1: Summary of literature review.

Authors	Fibers / Hybrid	Key Findings	Ref.
Cao et al. (2024)	Graft-modified polypropylene	UV-grafted amide groups enhanced fiber-cement bonding; increased compressive str. by 6.56%, tensile by 4.94%, reduced shrinkage (drying 25.55%, thermal 13.16%), reduced rebound modulus 7.42%.	[22]
Pham (2025)	Various (steel, carbon, PP)	Classifies fibers by Young's modulus; high-modulus gives tensile strength, low-modulus gives impact resistance; hybrid systems improve toughness/ductility; eco-economic strategies suggested.	[30]
Paing Htet et al. (2023)	Macro PP + Micro basalt	Hybrid improved mechanical properties; 6 kg/m³ PF + 6 kg/m³ BF optimal; increased split tensile strength 17.5%, increased flexural 23%; higher RCA reduces quasi-static strength.	[25]
El Ouni et al. (2022)	Steel + PP (0.85% SF + 0.15% PPF optimal)	Hybrid SF-PPF improved flexural strength by 26%, reduced water permeability; more environmentally friendly than SF alone.	[23]
Shi et al. (2020)	Basalt + macro PP (0.1% BF + 1% PP optimal)	Hybrid increased compressive (~10%) and flexural (~20%) strengths; new post-cracking behaviour observed; energy absorption improved.	[32]
Zhang & Niu (2024)	Basalt + PP	Hybrid mitigated failure under dynamic loading; increased dynamic compressive strength and modulus with strain rate; critical strain and impact toughness maximized at 0.2% BF + PF.	[33]
Zhang et al. (2025)	Steel + PP	Hybrid fibers shifted failure from brittle to plastic; increased peak stress, strain, energy absorption; strain rate dependent.	[34]
Hassan et al. (2024)	Macro + micro PP	Hybrid reduced shrinkage up to 15%; increased flexural & tensile strength;	[24]
Abdel-Karim et al. (2023)	Hybrid PP	Improved peak strength, ductility, bending stiffness; post-peak response enhanced due to fiber bridging; validated simplified flexural capacity formula.	[19]
Shahid et al. (2022)	Kevlar + Glass	Best mix (0.75% Kevlar + 0.75% Glass) enhanced compressive, flexural, tensile strengths; improved toughness and energy absorption; suitable for structural rehabilitation.	[31]

7. Conclusions

This review has examined recent progress in the field of hybrid fiber-reinforced concrete, with a particular focus on polypropylene-based hybrid systems combined with steel, basalt, recycled, and synthetic fibers. Across the research reported we see that hybrid fiber reinforcement has great benefits over single fiber systems. By way of many crack --scaling mechanisms which they engage in, hybrid fibers improve crack resistance, report better post cracking response, and present a more balanced set of strength and ductility.

Also, it is put forth by many studies that fiber matrix interaction is key to overall performance. We see that surface modification and chemical activation of polypropylene fibers greatly improves their bonding with cementitious matrices which in turn results in better stress transfer and reduced shrinkage cracking. Also, it is noted that the use of hybrid of macro and micro-polypropylene fibers does very well in controlling shrinkage which we have seen in for instance in systems of alkali activated slag concrete. These findings underline the potential of hybrid fiber systems to address early-age cracking and volumetric instability, which continue to be critical durability challenges in modern concrete construction.

In terms of mechanics hybrid fiber reinforced concrete in general sees similar improvements in tensile strength, flexural strength, toughness, and energy absorption from static and dynamic loading. High modulus fibers mainly put in play the load carrying capacity, at the same time low modulus polypropylene fibers play key role in improving ductility and crack control. This we see in particular in recycled aggregate concrete which hybrid fiber reinforcement has proven to do the job of in part making up for strength losses which go along with the use of recycled materials also at the same time we see an improvement in related durability properties.

Studies that look at dynamic and impact loading show that hybrid fiber systems do in fact greatly assist in which the materials fail better in some cases we see brittle behavior transform into more ductile and energy dissipating responses. Also, we see that improvements in strain capacity, impact resistance, and strain rate sensitivity report very good potential for the use of hybrid fiber reinforced concrete in impact resistant, marine, and protective structures. Also, at the same time it is a key step to create constitutive models for hybrid fiber systems in order to better predict their performance at high strain rate.

At the structural level it is reported that the use of hybrid fibers greatly improves the flexural performance, ductility, and post-peak behavior of reinforced concrete elements. Also, we see that the synergy between hybrid fibers and also conventional and modern reinforcement systems improves crack control and energy dissipation which in turn makes these materials a great choice for new construction as well as structural repair works which includes areas in large seismic zones.

We see potential in what we have achieved thus far but we still see large gaps in our research. In terms of long-term durability which includes a wide range of environmental and mechanical loading issues we are mostly in the dark, especially for chemically treated polypropylene fibers and low carbon or sustainable binder systems. Also, at present our design codes and analysis models do not do enough in terms of presenting what we see in the field the complex performance of hybrid fiber reinforced concrete in dynamic loading or the use of recycled materials. To close in on these issues, we will need a coordinated effort in the fields of experiment, analysis and numerics as also the development of standard mix design procedures and proper codal provisions.

Overall, in many settings Hybrid fiber reinforced concrete proves to be a very flexible and promising material which is seeing great demand in terms of durability, sustainability and structural performance in modern construction. Going forward research as well as development and implementation of appropriate codes will be key to see that its proved benefits are put into wide scale reliable engineering practice.

Authors' contributions

All authors contributed equally to the conception, design, experimental work, data analysis, interpretation of results, and preparation of the manuscript. All authors reviewed and approved the final version of the manuscript for publication.

Conflicts of interest

The author declares no conflict of interest.

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Data availability

No new data were created.

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