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Performance of Engineered Fibre Reinforced Concrete (EFRC) under Different Load Regimes: A Review

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Abstract

This review article presents a critical analysis by compiling the previous research studies with an emphasis on the optimization of fibre reinforced concrete to enhance its strength against different load regimes with a special focus on thermo-mechanical load conditions. The historical background, a description of the evolution of concrete as a material for advanced structures, and the fundamental principles of concrete production are provided as a preamble. Later, a discussion on FRC, fibre types and shapes, mixing methods and testing of properties is provided. A separate section describes how fibre mixing can affect fatigue and fracture behaviour, especially under different load regimes. Gaps in the existing research with possible new directions are discussed in the conclusion.

Keywords: Mechanical properties, Workability, Steel fibre, plastic fibre, reinforced.

Abbreviations

BPO	benzoyl peroxide
BF	Basalt fibre
CFRP	carbon fibre reinforced polymer
EFRC	engineered fibre reinforced concrete
ESF	engineering steel fibre
FRC	fibre reinforced concrete
FRP	fibre reinforced polymer
HSC	high-strength concrete
ISF	industrial steel fibre
PC	polymer concrete
PET	polyethylene terephthalate
PFRC	polymer fibre reinforced concrete
PP	polypropylene
RAC	recycled aggregate concrete
RSF	recycled steel fibre
SCC	self-compacting concrete
SF	steel fibre
SSF	short straight fibres
HF	Hooked Fibre
LSF	Long Straight Fibre
SFRC	steel fibre reinforced concrete
SFRCAC	steel fibre reinforced-recycled coarse aggregate concrete

SRAC	steel fibre recycled aggregate concrete
UHPC	ultra-high-performance concrete
UHP-FRC	ultra-high performance fibre reinforced concrete
WPF	waste plastic fibres
UHPCC	ultra-high performance cementitious composites
CRF	crumb rubber fibre
CW	CaCO3 whisker
RSM	response surface method.
OPC	ordinary Portland cement
PVA	polyvinyl alcohol fibre
HFRC	high-performance hybrid fibre-reinforced concrete
SPHFRC	steel-polypropylene hybrid fibre reinforced concrete

1. Introduction

The mixing of fibres in concrete began in the mid-1980s to improve its mechanical properties and the construction of structures [1–5]. Since then, considerable effort has been expended to demonstrate the success of concrete reinforcement with different types of fibres.[5]. However, a number of reinforcement optimization issues are still unaddressed, such as justification of a suitable fibre material, shape and proportion, technical feasibility of the mixing method and criteria to quantify the desired resultant properties; each of which requires comprehensive research [6]. The majority of the articles published have reported the performance of concrete structures under quasi-static conditions [5,7]. The performance investigations mainly involve tensile, compressive and flexural strength estimations of the reinforced structure. In tensile and compressive performance tests, applied quasi-static force is plotted against the deformation observed in the structure; while in the flexural case, the former is plotted against mid-structural deflection, as shown in Figure-1[8–10]. However, real concrete structures normally do not have ideal quasi-static load conditions and experience load changes with respect to time, which are termed dynamic load conditions. Moreover, in real applications, these changes in applied mechanical loads are coupled with thermal loads, as structures are mainly exposed to the outside environment during their working life [7,11–13].

Extensive review articles have been published describing investigations to evaluate the performance of fibre reinforced concrete (FRC). The description of these review articles demonstrates the significance and limitations of previous investigations without a particular emphasis on the issues of reinforcement optimization and structural performance following the reinforcement against real-world loads, such as coupled loads. This review article presents a critical analysis by compiling previous research studies with an emphasis on the optimization of RFC to enhance its strength against different load regimes, with a particular focus on coupled load conditions. The historical background, a description of the evolution of concrete as a material for advanced structures such as Multi Storied Building, Dams, Bridges, Industrial Structures, Retaining Wall, Hydraulic Structure and Marine Structure, and the fundamental principles of concrete production are provided as a preamble. Later, a discussion on FRC, fibre types and shapes, mixing methods and testing of properties is provided. A separate section describes how fibre mixing can affect fatigue and fracture behaviour, especially under different load regimes. Gaps in the existing research with possible new directions are discussed in the conclusion. In the published academic literature, little attention has been given to the performance estimations of concrete structures under coupled loads. It can be anticipated that the mentioned unresolved issues in fibre reinforcement will end in a complex zone of empirical results if the chosen structures are tested under coupled load conditions.

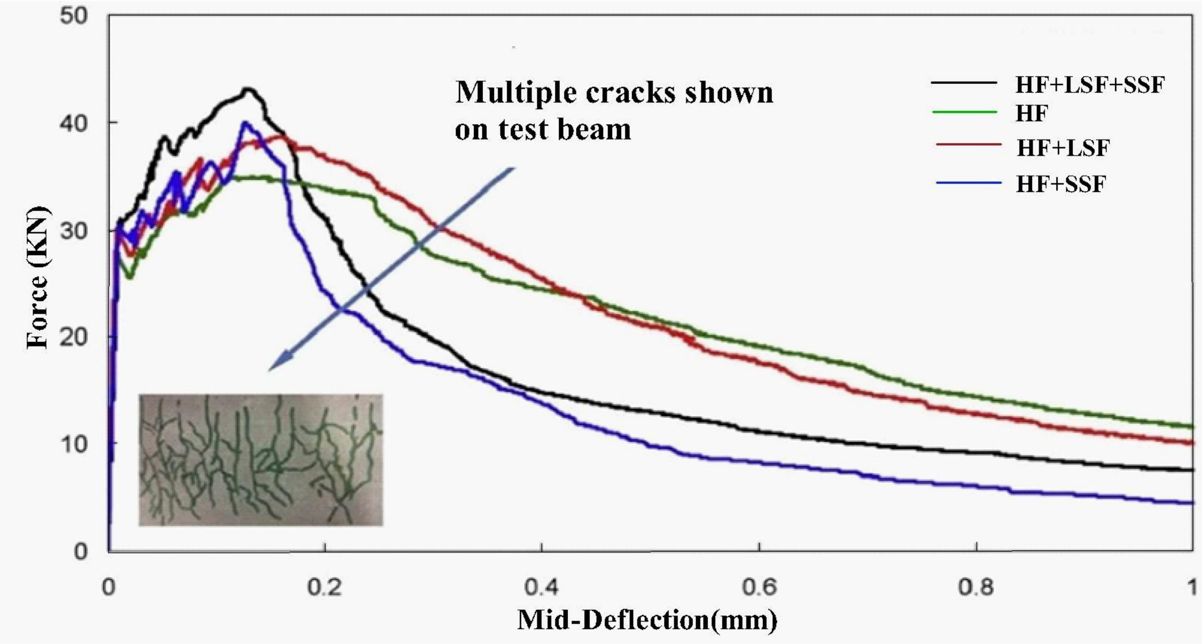


Figure-1 Impact of different type of FRC on the flexural behaviour of concrete[9].

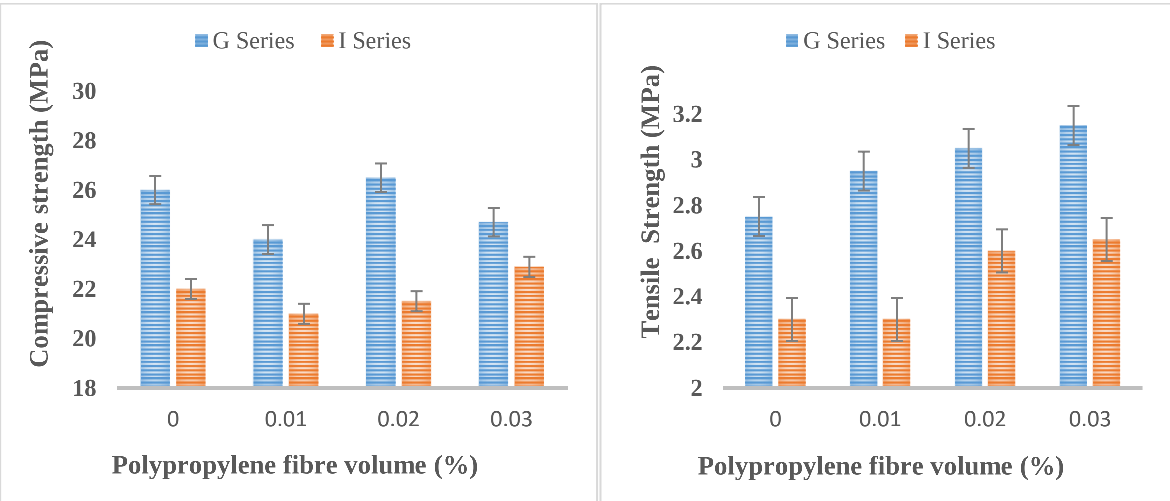
2. Historical Background of Engineered FRC

Concrete as a material of construction is widely adopted because it is economical and able to withstand the varied environmental conditions [14]. The Egyptians and the Romans both used concrete, but with the break-up and downfall of the Roman Empire, many of its technological secrets were lost, and the modern history of concrete extends for only two centuries. In 1824, Portland cement was patented, which later proved to be the most important concrete construction material [15,16]. Today, concrete is regarded as one of the most considerable and universal materials in building construction because of its ability to withstand compressive stress, its heat resistance, durability and enormous flexibility of shape [17]. Concrete is classified as a quasi-brittle material, and there are many small deformations before failure [18]. It works well under compression, but not as well against tensile loads. Published research indicates that concrete has relatively low flexural strength compared with compressive forces. The requirement to enhance tensile and flexural strengths led researchers to investigate materials that can be mixed with traditional concrete ingredients without a significant impact on other desired properties.

In the past, researchers investigated the extent to which the fibres of materials with good tensile properties could be used to reinforce concrete to obtain the required enhancement, as shown in Figure-2 [5,17]. Figure-2 shows the impact of polypropylene (PP) fibre reinforcement on the mechanical properties of concrete, whereby tensile and flexural strengths are significantly increased without any negative influence on compressive strength at the highest percentage of fibre volume (0.3%).

Design Guide AC1 544.4R issued by the American Concrete Organization specifies FRC “as concrete including separated randomly adapted fibres”[19]. Since the 1960s, extensive research has been carried out on FRC [20], beginning when Romualdi and Batson issued their empirical results regarding enhanced mechanical properties [21]. In addition to mechanical properties, fresh properties, such as workability and flow, have been investigated by researchers and their test results were used to enhance older construction codes for structural materials [22–24].

(a) (b)



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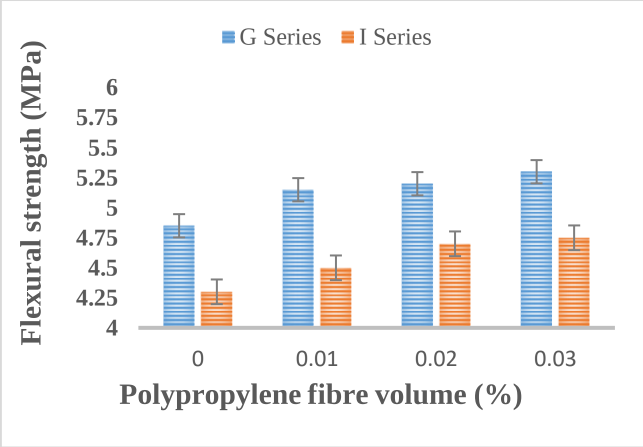


Figure-2 Effect of fibre on mechanical properties of concrete [5]. (a) Compressive strength of FRC; (b) tensile strength of FRC, (c) flexural strength of FRC.

Fresh concrete properties are mainly influenced by fibre material. According to GangaRao et al., the workability and strength of concrete can be enhanced if polymer can be used a fibre material with different admixtures [25]. Using the correct fibres in the correct mix can greatly increase the tensile strength of FRC. However, the final product may not always be appropriate for use in building applications due to the reduced workability of the concrete. Such concrete will be difficult to use due to the phenomenon of honeycombing [26]. It is more often the case, that as fibre is large in quantity, it can sharply reduce workability [27]. The use of FRC should be confined to those applications in which any decrease in splitting strength and crack dissemination is not significant, and where a mix of fibres and reinforcing bars could produce a synergistic outcome [28].

3. Evolution in Concrete Materials for Advanced Structures

A multiscale structure, ranging from the macro- to the micro-scale of the traditional aggregate concrete structure, is shown in Figure-3. Typically, macro-level structures are considered for characterizing material behaviour. However, information at the multilevel, such as the meso level and micro scale, is also needed to have a concurrent multiscale model and accurate predictions of macroscopic properties. Conventional concrete structures are brittle in nature and continuous efforts have been made in the past to reinforce them with different types of fibre [29].

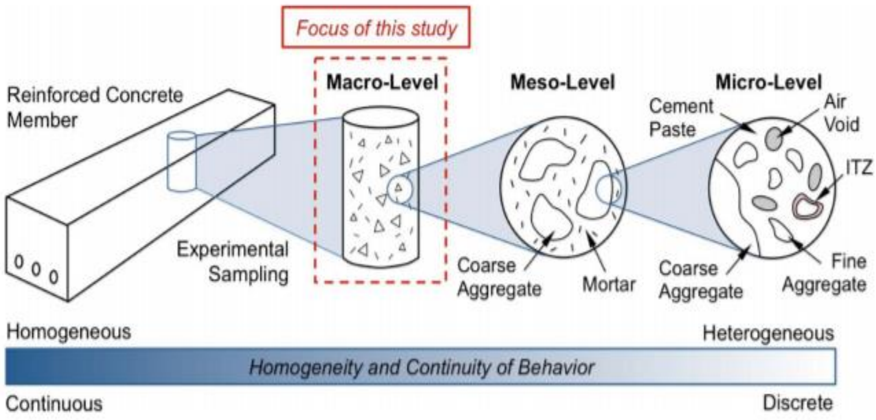


Figure-3 Scales of concrete adapted from ref [29].

In one study, a concrete beam reinforced with polymer fibre (polymer FRC [PFRC]) showed an increase in strength and stiffness when compared with a traditional concrete beam formed by mixing aggregate, water, and Portland cement[30]. The observed improvements in the brittle mode of concrete were not only due to the characteristics of the fundamental materials, but also because of their relative proportions, dimensions and crosswise arrangements[31–33]. According to previous research, fibres in concrete lead to durability, fire resistance and endurance against thermal stress. It is easy to use and, for this reason, has attracted the attention of the construction industry in gaining economic benefits [34–38].The concrete used in construction projects is reinforced with steel or macro synthetic fibres, which leads to exceptional material properties [39–42]. The addition of fibres in a concrete mix can reduce crack initiation and propagation. Fibres also offer greater flexibility in structures against crack propagation due to split obstruction and hence elongate the time to catastrophic fracture and enhance the mechanical properties of concrete[43]. It has been demonstrated that the presence of fibres not only influences concrete crack resistance, but also improves other properties [44]. The reason for this improvement is mainly due to the reduction of CO_2 and water content, as the fibres proportionally replace the amount of aggregate and cement [45,46]. Randl et al. investigated the flexural strength of ultra-high performance concrete (UHPC) beams reinforced with small volumes of fibre, and reported that adding high-grade steel fibres (2% by volume) gave an overall increase in load-bearing capacity of about 15% [47]. Other researchers observed that plastic fibres increased compressive strength and ductility[48,49], and Liu et al. demonstrated that the tensile strength of concrete improved by increasing the amount of steel fibre [50].

In addition to the investigations referred to above, several other significant research contributions have demonstrated the influence of fibres on concrete properties, as shown in Table-1. The majority of studies investigated the effect of fibre reinforcement on the fresh and mechanical properties of concrete. However, these investigations did not consider the influence of shape, type and amount of fibre during reinforcement. In the majority of the studies, ideal or lab-based loading conditions were used to determine the resultant properties. Very little effort has been made to investigate the performance behaviour of a reinforced structure under realistic loading conditions, such as coupled thermo-mechanical loads.

Table-1 Evolution of FRC.

Authors	Years	Contribution to knowledge	Limitations
Henager et al. [1-5]	1983 1984 1988 2009 2011	The mixing of fibres in concrete began in the mid-1980s to improve its mechanical properties and the construction of structures.	a number of reinforcement optimization issues are still unaddressed, such as justification of a suitable fibre material, shape and proportion, technical feasibility of the mixing method and criteria to quantify the desired resultant properties; each of which requires comprehensive research
Aldahdooh et al. [6]	2013	This article examined the Evaluation of ultra-high-performance-fiber reinforced concrete binder content using the response surface method.	The results showed that the prediction by using RSM was adequate to adjust the quantity of OPC and SF in the production of the material of UHP-FRC. Those values have to be further reduced.
Wille et al. [26]	2014	This paper investigated the stain hardening properties of ultra-high-performance FRC (UHP-FRC) under direct tensile loading.	The study was restricted to the tensile performance of small samples. They researchers recommended using large samples for future study to adopt their properties for specific practical applications.
Li et al. [27]	2016	This study examined the impact of superplasticizers on the fresh properties of concrete.	The use of coarse aggregate reduced compressive and tensile strengths.
Aslani et al. [28]	2019	The study investigated the effects of adding two types of fibre (i.e., steel and polypropylene) on workability and concrete hardening.	Proposed mixture of fibres and recycled aggregate self-compacting concrete was found to be suitable for only a few limited designs of concrete structure.
Long et al. [51]	2019	This paper investigated the impact of using cement-soil reinforced by coal gangue on mechanical and durability of foundations.	A mass loss of the resultant reinforcement was observed for a value of 4–7% of the original material due to the use of acidic immersion.
Sanjeewa et al. [52]	2017	This article examined the design aspects of a high-performance concrete mixture constructed from fly ash and silica fumes.	All mixes showed lower workability values than the control mixture.

Raad and Assaad. [53]	2021	This study investigated the impact of adding polymer plastic waste on the structural properties of concrete.	These types of fibre reduced the ultimate shear load and flexural strength of the reinforced concrete.
Li and Liu. [54]	2020	This paper investigated the impact of different percentages of steel fibre on the water permeability of concrete by using a controlled compressive load.	The increase in the permeability coefficient of the samples was not notable.

According to the above discussion on previous research, the evolution of concrete reinforcement was mainly influenced by mixing procedures and methods. To achieve optimal values of performance parameters, very good mixing is required. However, mixing procedures have their challenges, and it is important to understand these before holding any discussion of the optimization of reinforcement. The next section provides a brief discussion to cover these key challenges.

4. Challenges in Mixing Fibres

4.1 Selecting the Ratio of Mixing Materials

The making of a FRC mixture involves the determination of a suitable ratio of fibres to achieve the required characteristics. Mixing fibres can enhance and/or modify properties, such as durability, workability, crack resistance, elastic modulus, density and thermal conductivity [55,56]. However, the exact quantitative increase in these properties with the ratios of the fibres is not mapped comprehensively in the available literature. In the published literature, researchers have discussed the qualitative influence and impact on overall concrete performance with an increase and decrease in fibre ratio. Researchers have, for example, demonstrated that the strength of concrete can increase with the use of small size fibres [57,58].

4.2 Limiting Water Content in the Resultant Mix

The water ratio has a significant impact on the properties of concrete, especially on compressive strength and durability. However, due to fibre reinforcement, the mixing of water content can be challenging, as the fibres are often randomly distributed. Fibre addition reduces workability, as it limits the smooth mixing of water content in the concrete mixture. Compliance with flow and cohesion criteria are important in designing a concrete mixture. For example, in the design of self-compatible concrete mixes with reinforced fibres, it emerged, as anticipated, that they must also meet the criterion of a good flow of concrete [59,60].

4.3 Selection of the Correct Accelerator

Concrete production requires control of the water content, the selection of appropriate accelerators and the regulation of air retention. Accelerators have a significant influence on short- and long-term strengths of concrete, as they enhance early strength, decrease the bounce effect and overcome earth relaxation. Yun et al. observed that steel fibres incorporated with accelerators increased the strength of concrete in the long and short term. However, alkali-free accelerator was safer than cement mineral and aluminate for workers and the environment [61]. In another study, the use of accelerators had a great impact on the mechanical properties of FRC [62]. Other researchers have noted that polyolefin fibres and accelerators can significantly improve the properties of reinforced concrete, specially for marine structure applications [63]. The selection of the correct type of accelerator is very important and highly challenging. It has been observed that accelerators have a tendency to react chemically with the metallic fibres used during reinforcement. The impact of this reaction on the resultant concrete properties is still unexplored and hence makes selection difficult. Accelerators increase curing set-up time and, in the case of a chemical reaction with fibres, can be complex to quantify.

4.4 Controlling Air Bubbles

The stability of the air bubbles in fresh concrete is affected by numerous factors, such as mixing, air-entraining agents, temperature, chemical additives and atmospheric pressure [64,65]. The uneven distribution of air bubbles and fibres can adversely affect the homogeneity of the concrete, which can change mechanical characteristic and workability [66–71]. In the past, air bubbles and steel fibres were assumed to be uniformly and randomly distributed, respectively, in a concrete matrix. Moreover, in many case, UHPC was observed to have a random distribution for both [72,73]. Wang et al. demonstrated that adding a lower dosage of superplasticizer to UHPC can distribute air bubbles and steel fibre uniformly [74].

4.5 Controlling Undesired Chemical Reactions

Researchers have confirmed that a suitable quantity of fibres can delay the rate of carbonation in concrete with fibre compared with normal concrete because carbonation is associated with matrix porosity, permeability and pore structure. The optimal fibre ratio plays a significant function in carbonation. The true ratio and its relation to the rate of carbonation is still unexplored and challenging to quantify [75,76]. It has been found that alkali-aggregate reaction has a negative impact on the strength of FRC constructions [77]. In other work, the cracking onset produced by the corrosion of the steel used to reinforce UHPC is delayed by the reinforcement of the fibre [78]. Paewchompoo et al. explained that was associated with the resistance of FRC due to the stopping of micro-cracks by the fibres (mixing PP and steel) throughout the treatment [79,80].

The challenges relating to adding fibres to a concrete mixture could, if fully addressed, provide desirable properties. However, a great deal of research is still required to explore these challenges and their relative impact on resultant concrete properties. One of the key elements that can influence resultant concrete properties is the fibre material. A large number of academic articles have provided observations regarding how a fibre material can have an impact on fibre mixing and the resultant concrete properties. The following section provides a discussion based on these articles.

5. Influence of Fibre Material in the Reinforcement of Concrete and its Properties

The material of the fibres used to reinforce concrete is mainly responsible for changing the properties of the concrete. In the past, researchers used fibres from different materials and provided their observations. For example, Noaman et al. added crumb rubber for reinforcement and observed a negative impact on the mechanical properties of the resultant concrete. At the same time, however, the properties of the rubber increased the crack-resistant properties. They later added steel fibres to the same mix and found a good impact on the overall energy absorption of the resultant concrete[81,82]. Alsaif et al. reported a decrease in compressive strength and elastic modulus after reinforcing concrete with steel fibres and testing it after 28 days. They also found an improvement in these two parameters after 150 days of testing [83]. In contrast, Olivito and Zuccarello observed no increase in the aforementioned parameters after adding steel fibres [11]. The description of these articles demonstrates the significance and limitations of previous investigations without a special emphasis on reinforcement optimisation and structural performance against real-life load.

In their study, Islam et al. used polyethylene terephthalate (PET) in place of aggregate and found lesser bonding in the resultant concrete [84]. The researchers demonstrated the mechanical properties of UHP-FRC and found that fibres increased stress resistance. Similarly, other researchers replaced coarse, fine aggregates with fibres to enhance the mechanical properties of concrete [85–87]. Research has also indicated that FRC can improve post-cracking behaviour in comparison with standard concrete[88,89]. Alsaif et al. found that the density of concrete decreased after adding rubber due to the lower specific gravity of rubber in comparison with aggregate i.e., 0.8 for rubber and 2.65 for the aggregate [90]. Other researchers observed that steel fibre made from waste tyres enhanced the compressive strength and increased the crack resistance of concrete [91]. A number of investigations have examined the tensile strength characteristics of waste FRC. They found that waste fibres enhanced tensile strength [92–94].

Fibres obtained from a variety of forms of waste are appropriate for concrete reinforcement due to their various properties, as shown in Table-2. As shown in Table-2, we can divide such fibres into three categories: steel, plastic, waste material and Hybrid fibre. A detail discussion of these categories is provided in the next section.

Table-2 Properties of different types of fibre [95]

Fibre type	Shape	Length (mm)	Diameter (mm)	Density (g/cm^3)	Tensile strength (MPa)	Elasticity modulus (GPa)
Steel		13	0.2	7.85	1000	210
Polypropylene		12	0.02	0.91	451	4.5
Glass		12	0.012	2.7	1850	65
Basalt		12	0.01	2.67	2100	79
Polyolefin		12	1.07	0.92	350	6

5.1 Steel Fibre Reinforced Concrete

Steel fibres (SF) have been used to reinforce concrete since the 1950s. Earlier studies showed that the flexural strength of concrete could be improved by using SF along with recycled aggregate concrete (RAC). The results revealed that either of these materials improved the bending, tensile and compressive strengths of concrete [96].

Wu and Ren observed that the dynamic spalling strength of ultra-high performance cementitious composites (UHPCC) was improved by adding micro-straight and hook-end SF. They found that micro-straight SF was more effective than hook-end SF for the dynamic compressive strength of UHPCC at the same strain rate [7]. A few pieces of research have indicated that SF can significantly improve the dynamic behaviour of UHTCC. In contrast, a few others have found that dynamic behaviour does not improve if SF is added in high volume [97,98]. The addition of glass or basalt fibres improved the bending strength to a certain extent, but slightly decreased the compressive strength[99]. Conventional aggregate concrete with SF showed a slight decrease in compressive strength. The strength of concrete was considerably affected by the interfacial bonding of the cement matrix and SF, and Figure-4 shows that a rise in the amount of rubber could cause a gradual reduction in compressive strength and elastic modulus. There were many reasons for a decrease in the strength of the concrete, some of which are provided below [100]:

1) Rubber has a high absorption level.
2) An increase in the porosity of concrete can cause a reduction in stiffness.
3) The concrete may be lower in strength due to the inclusion of rubber.

The above indicates that an increase in SF can increase the maximum load capacity. As shown in Figure-4, the maximum loading capacity was considerably affected by the recycled aggregate. It was shown the relationship between load and displacement of the concrete sample by adding different amounts of steel fibres and replaced the normal aggregate with recycled aggregate without transverse reinforcement. [101–103]. A more quantitative investigation observed an increase of 20% in maximum load capacity with an addition of 30 kg/m3 of SF. On the other hand, there was no significant effect on compressive strength behaviour. SF was found to be more effective with recycled aggregate in comparison with natural aggregate and hence could replace the design of mixed design [104]. Li et al. pointed out that steel FRC (SFRC) obtained an acceptable plastic strain, but this was low in comparison with conventional concrete [105]. Gao et al. indicated that an increase in the toughness index and modulus of SF reinforced-recycled coarse aggregate concrete (SFRCAC) with an increase in steel fibres [106]. The SFRCAC samples showed ductile failures and preserved their safety after shear failure [107].

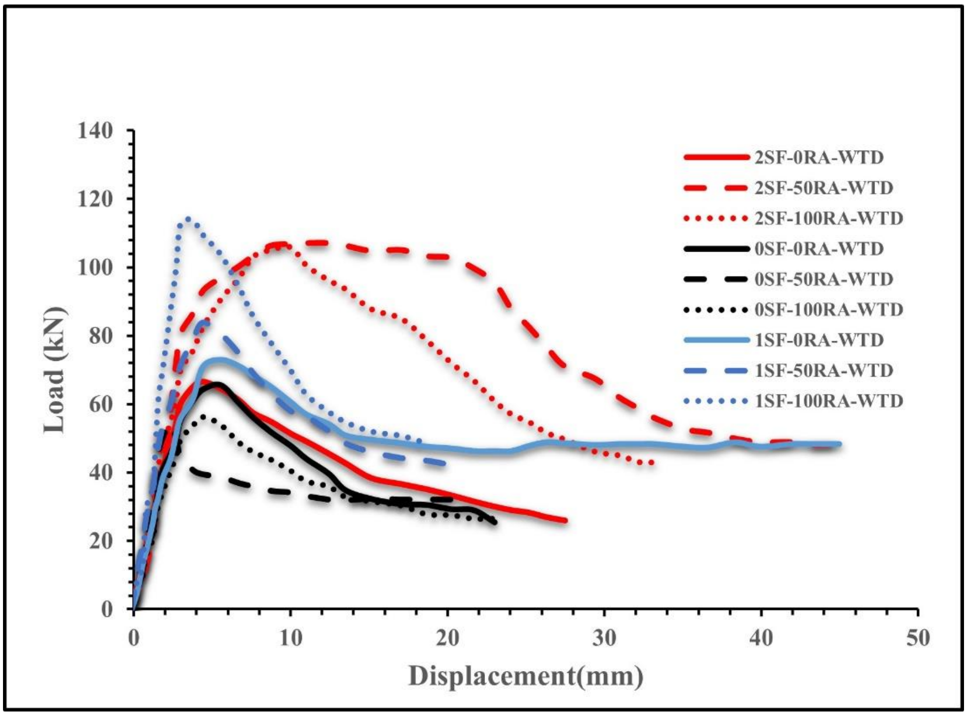


Figure-4 Load and displacement of samples with various recycled aggregates concrete, steel fibers with no transverse reinforcement [102].

A shear test on two types of steel fibres showed ductility in comparison with ordinary concrete [108]. However, the shear strength was high, which could be due to the small percentage and random distribution of the SF.

Benefits are offered by SFRC including lower maintenance cost, higher loading capacity, reduced loading limit through cracked concrete, and greater strength. In addition, fibre simplifies joint location, reducing the work involved on site in moving steel reinforcements. It is expected that future research could lead to methods for enhancing the brittleness characteristics of concrete, bringing benefits due to the widespread application possibilities.

5.2 Plastic Fibre Reinforced Concrete

Plastic fibre is widely used in a number of building applications, due to its excellent crack resistance [109–111]. Research has shown that the elasticity and compressive and bending resistance of concrete are increased by raising the proportion of polyester polymer [112]. Bulut and Şahin also pointed out that concrete that contains electronic plastic waste was more ductile than traditional concrete, although its mechanical properties were reduced with an increase in the percentage of such plastics [113]. Other researchers have indicated that density decreases with an increase in content when replacing PET with aggregate [84]. Zhang et al. demonstrated that polymer fibre bars enhanced the compressive strength and bonding behaviour of seawater sea-sand concrete [114]. In other work, Zhang et al. confirmed that basalt fibre reinforced polymer rebars increased shear capacity and flexural restraints [115,116]. Flexural and compressive strength were also found to be enhanced by adding waste plastic fibres

(WPF), as shown in Figure-5. It has also been observed that WPF reduced workability, but that V-funnel flow time and L-box height increased. Wet density decreased for the following two reasons, as shown in Figure-6 [117]:

1) The gravity of plastic is low compared with the gravities of cement and aggregate.
2) Plastic requires more water to develop density.

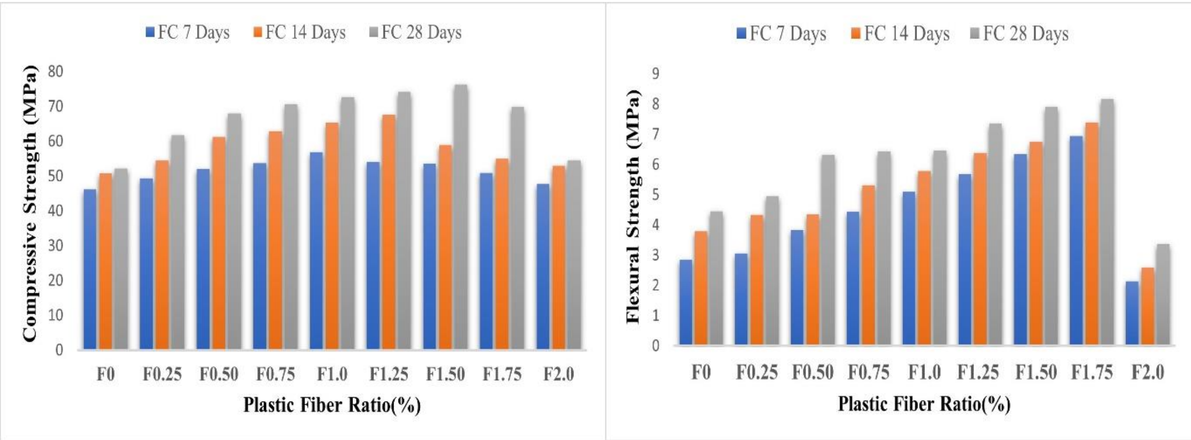


Figure-5 Effect of adding plastic fibre on the flexural and compressive strength of concrete [117].

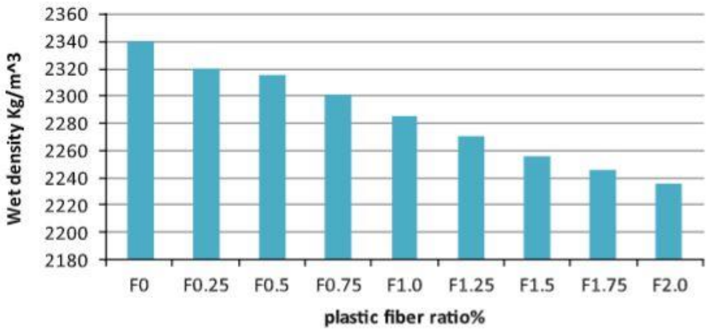


Figure-6 Plastic added to SCC requires more water to develop density [117].

Yang et al. found that the mechanical properties of concrete, including the split tensile, compressive and flexural strengths of self-compacting lightweight concrete, were improved by adding plastic fibres. However, elastic modulus, density and workability decreased [118]. Concrete with PET was also found to be more ductile in comparison with traditional concrete, with improved crack resistance [119]. During a freeze-thaw test, another study observed that the properties of concrete were improved by adding recycled PET fibre [120].

As demonstrated above, the addition of plastic fibre increases the performance of concrete, as different fibres have a high estimation for elastic modulus and improve various properties of concrete, such as: flexural strength, impact resistance, compressive properties, fatigue resistance, tensile strength, malleability, shear load of a structure, and abrasion and resistance against wear. As a result of such performance improvement, FRC has been used in a range of applications, such as water-driven structures, bridge decks, airfield pavements, uncompromising ground surfaces (industrial floors) and tunnel linings.

5.3 Waste Material as Fibre

In the literature, researchers have reported using waste materials as fibre to enhance the different properties of concrete, such as compressive and flexural behaviours [121,122]. Considerable improvement in flexural response was, for example, observed for concrete samples reinforced by adding waste tyres to the concrete mix [91]. The recycling of scrap tyres mainly involves separating the inner steel support from the rubber covering, and this waste material plays an important role in increasing the cracking resistance of RAC. For example, it was observed that the addition of waste fibre affected the initial cracking time, as shown in Figure-7 [123]. Carbon fibre waste added to concrete has a significant impact on mechanical properties, and, as a result, reduces maintenance requirements and thus improves the sustainability and durability of structures [124]. Kumar et al. observed that the combined impact of recycled steel fibres (RSF) and glass powder could also enhance the mechanical properties of concrete [125]. In similar research, it was found that the combination of fly ash and waste SF enhanced the density and mechanical performance of concrete, although the steel fibre reduced its workability [126]. Other researchers observed that the workability requirement could be satisfied by the smooth surface of waste plastic bag fibres [127].

In other studies, concrete density was reduced by increasing the quantity of PET bottle waste, because the density of a natural aggregate is higher than that of plastic. The mechanical properties of concrete containing PET bottle waste were lower than for standard concrete because it decreased the amount of natural aggregate, which is useful for strength [128,129]. Ghernouti et al. also demonstrated that PET increased the ductility of concrete and decreased cracking, and other researchers found that concrete could be made more structurally durable by using PET in strips to reduce the use of steel [128,130–132]. Tran and Ali demonstrated that fibres have another advantage in terms of the performance of FRC, such as the decreased cost of making the concrete and environmental benefits [133,134].

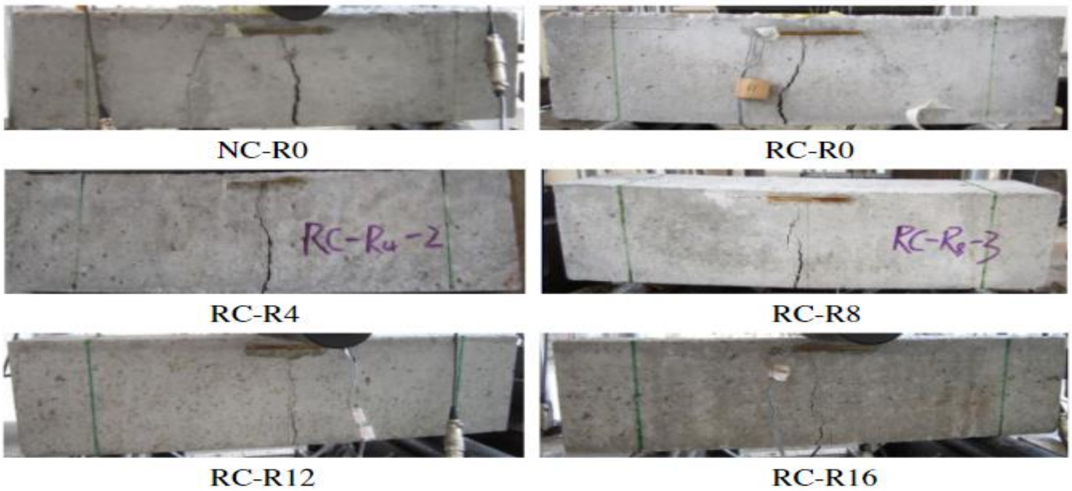


Figure-7 Flexural failure modes of rubber crumb and SF-reinforced RAC [123].

In summary, as demonstrated in the studies cited above, there are improvements that can be obtained from the use of waste materials as fibres, such as the lower cost of maintenance, development in load capacity and the mechanical properties of concrete, reduced cracking, and improved tensile strength.

5.4 Hybrid Fibre

Hybrid fibre is widely used in several construction applications, due to its excellent crack resistance and increase durability of concrete. Research has found that an improvement in the mechanical properties and resistance of concrete by adding the steel-polypropylene hybridization. It showed that the hybrid fibre with more steel content significantly increased the impact resistance with the amount of polypropylene at 0.2% as shown in Figure 8. However, large sample will be useful to check the impact of strength for more accurate conclusion [135]. In addition to the impact resistance, durability was investigated by the researchers and their test results were used to improve the compressive, bending and fracture strengths of structural materials. The research observed that the effect of abrasion improved by 10 % when added the hybrid fibre to concrete at 6kg/m^3[136,137]. Mehran and Mingli studied that the hybrid fibre has positive impact on fracture energy which has been considerably improved up to 258%. The researchers found that the best value of fibre hybridization was at 1% CW, 0.45% BF with 12mm length, and 0.35 % SF. This showed an improvement in concrete due to hybrid fibre in comparison with normal concrete[138–140]. Other findings showed a decrease in workability, density and compressive strength. They also observed an increase in spilt tensile and flexural strengths [141,142].

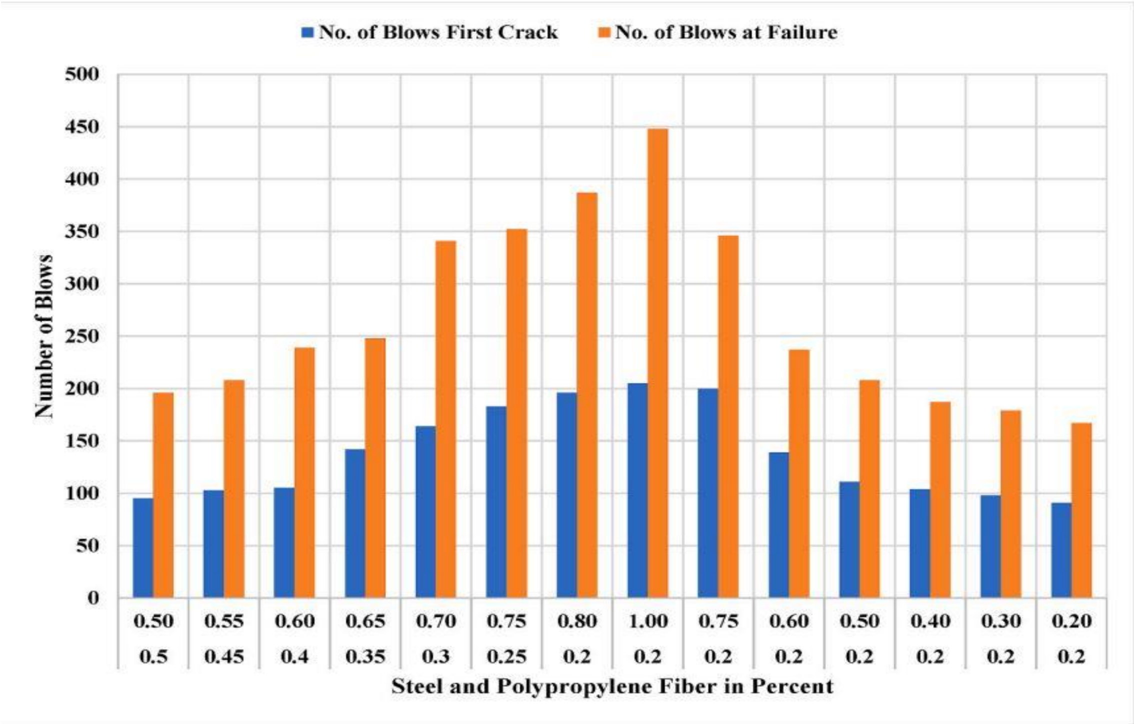


Figure-8 Hybrid effect on impact resistance[135].

Previous studies reported that the ductility of concrete was increased when added PVA with steel fibre. In contrast, the ductility reduced in the mix with Nylon-mono and steel fibre[143]. Zhishu and Wang observed that an improvement in compression deformation of HFRC. This improved brittleness and the dynamic strength. The hybrid fibre also reported to enable concrete resistance against crack initiation with improve fracture toughness[144]. Emad et al. found that rubber reduces the compressive and tensile strengths of concrete. However, by adding steel fibre with crumb rubber considerable improvements in fractal properties were achieved. The most significant improvement of reinforced concrete hybrid fibre observed for content with 1% PP and 0.9 steel fibre[145,146].

As per the above discussed past investigations, the addition of hybrid fibre enhances the performance of concrete. Properties like impact resistance, flexural strength, fatigue resistance, compressive properties, tensile strength, malleability and durability of structures were reported to be enhanced with inclusion of such fibres.

6. Optimization of Reinforced Concrete

6.1 Optimization of Concrete Using Different Shapes and Types of Fibre

The shape of the fibres added to concrete affects the properties of the material. Stereological standards have been set for the appropriate characteristics of fibres in terms of their size and boundary zones.

Symmetrical proficiency factors are also taken into account for 1D, 2D and 3D fibre divisions, which are combined to form an effective approach in the direct planar "Stroeven" framework method [147]. Different types of post-consumer plastics, such as PP, polycarbonate and glass reinforced plastic, have been used to reinforce concrete [148–150]. Research has also been conducted into high concrete performance that was consolidated with plastic bottle fibre portions of different volumes, shapes and lengths, and it was observed that tensile strength decreased with the additional content of fibres [151] and that both short and long steel fibres reduced the propagation of micro-cracks, as shown in Figure-9 [152]. The majority of researcher did not consider the shape, types and percentage together in their study of fiber to find the optimal value of fibre reinforced concrete.

Over 90% of the SF available is engineering steel fibre (ESF), with twisted finishes, treated surfaces, and bent, hooked end, and pleated fibres, as shown in Figure-10. The ESFs examined have been revealed to be significantly better than normal fibres. For example, the aspect proportion and other geometrical properties are not related to changes in the mechanical properties of ESFs [153].

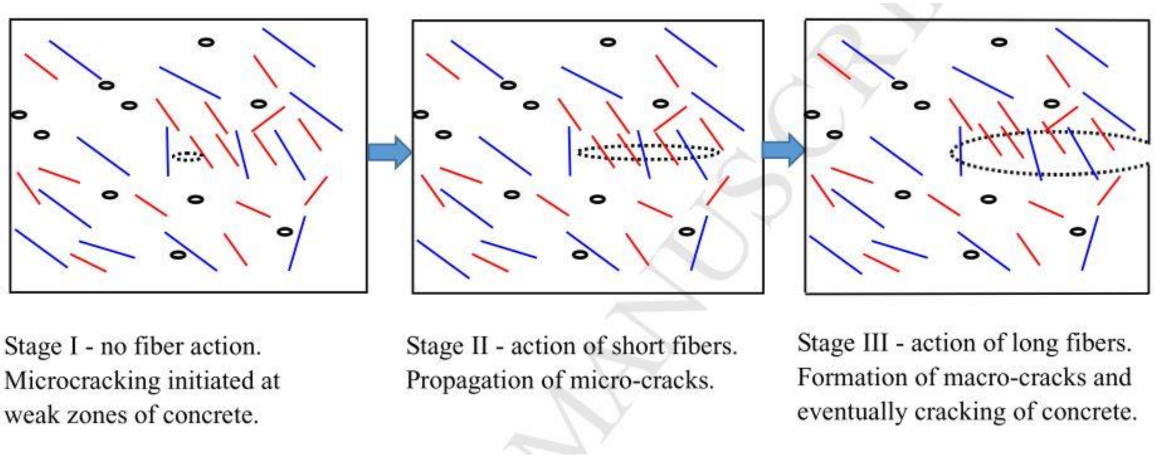


Figure-9 Crack restraint by adding hybrid SF reinforcements to UHPC [152].

According to Pereira et al., the load capacity of a natural concrete produced with PET fibres is better than that of traditional concrete. This is one of the areas in which the inclusion of fibres from PET containers to concrete has enhanced the mechanical properties of ordinary concrete in terms of tension, bending and compressive strength. The synergistic impact of variables relating to fibre volume and fibre length appears to have an effect on the tensile strength of concrete [154]. In other work, a bond resistance of 16 mm was higher than that of 20 mm WPF in all the examples examined. Figure-11 shows one of the plastic fibre types used[117].

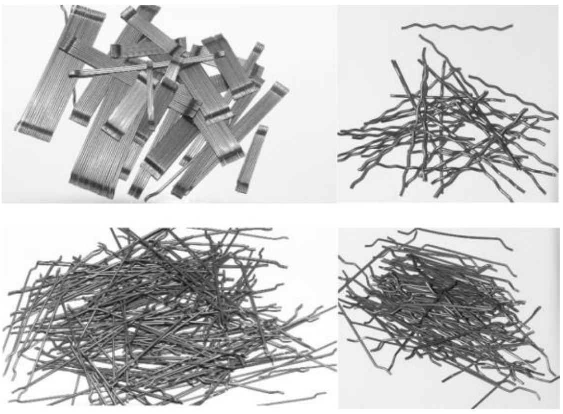


Figure-10 Examples of geometric shapes for commonly used ESF [79].

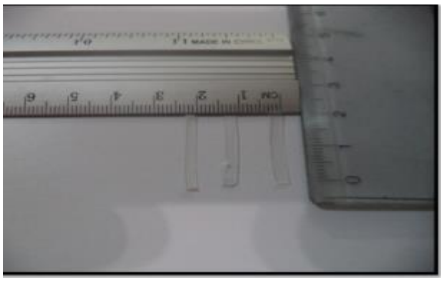


Figure-11 Shredded waste plastic[117] .

6.2 Optimization of Fibre Volume

Adding fibre at a particular volume fraction increases ductility and improves the properties of concrete. Researchers have tested various volume fractions to ascertain the optimal percentage of fibre for reinforced concrete [155]. Gao et al., for example, investigated the failure mode and mechanical properties of concrete with various amounts of steel fibre (0%, 0.5%, 1%, 1.5% and 2%) [107]. In other work, Youssf et al. studied the influence of FRP confined and unconfined crumb rubber concrete with a high amount of rubber on the mechanical proprieties of concrete, in which rubber replaced sand in the following percentages: 0%, 10%, 20%, 30% and 40% as shown in Figure-12 [156]. Another study showed that the addition of SF improved static and dynamic mechanical properties when using the optimal amounts of short and long steel fibres, which were 0.5% and 1.5%, respectively [157].In order to enhance fracture behaviour, the optimal volume of SF was found to be 1%, as shown in Figure-11. However, high-temperature exposure decreased the loading capacity of the sample [158]. In practical terms, a small proportion of short fibres used during blending (generally around 0.5-1.0% by volume) brings about improvements in toughness in the post-cracking of cementitious materials, as those fibres have a connecting impact over an opening crack and a positive effect on the distribution at that point [159].

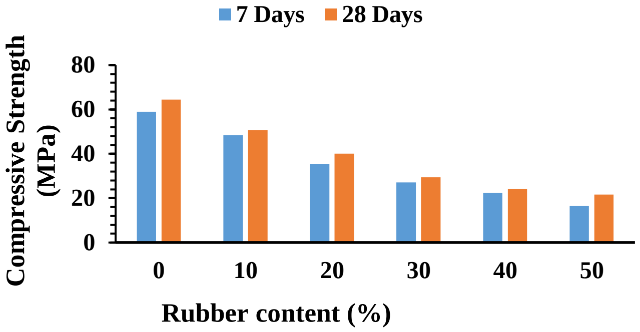


Figure-12 Effect of rubber content on compressive strength [156].

The optimum ratio of fibres per quantity of concrete has been found to be between 0.5% and 1%. Depending on the type of fibre, previous work has investigated the effect of the percentage of fibres based on the workability and flexural, split tensile and compressive strengths of the concrete produced. However, still a comprehensive effort is required to investigate the effect of content fibres on more realistic loads such as thermo-mechanical and dynamic load.

7. Testing the Optimization of FRC Properties

7.1 Workability

Studies have reported the various factors that must be considered in the optimal casting of concretes. A collapsed slump and a zero slump are, for example, both external to the range of the types of workability that can be included in a workability test, as shown in Figure-13 [160]. The factors that must be considered include construction type, the standards to use and the methods that should be followed. In addition to the basic structures, there are complexities in the casting and the finer points of construction that have an impact on the extent of the reinforcement of the structure. As the structural use of concrete grows to encompass auxiliary execution, a greater need has arisen for high-flow cement for form-filling. These elements may be challenging to reconcile, as there are constraints to poker vibration and the force needed to fill an area optimally.

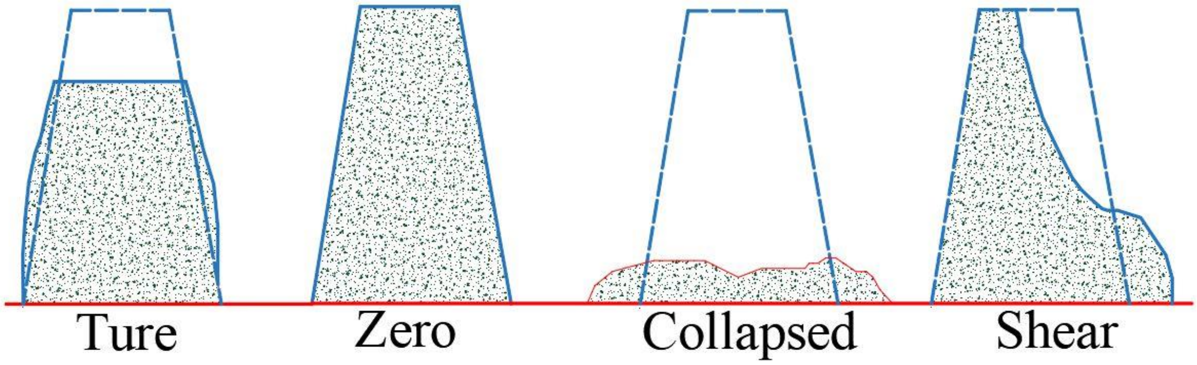


Figure-13 Types of workability [160].

As this type of general concrete has a high level of fluidity, over-vibrating it can cause it to separate, distort and fail in the spreading space between reinforcements. Thus, workers are required to have a strong level of skill and a strict focus on quality standards in order to ensure that the concrete cast is homogenous and adequate pressure is attained. This requires effort and time, and testing processes must be available that can rapidly measure workability, with further work needed to develop this area. Current testing procedures provide a foundation for the discussion of theories and models that have not been fully developed and which could inform further testing strategies [160]. Recent research attention has turned to workability in assessing fibre concrete production possibilities, and various researchers have applied slump tests, as these appear to be reliable and simple in their application. In [28], the authors report decreases in workability with an increased fibre content of the concrete sample, and another study found reduced fresh concrete workability when either of two kinds of SF were added [161]. It has also recently been reported that both rubber and SF additions caused workability to decrease [83]; this was also found in [90], in which the authors suggest that this could be due to reductions in free water due to the added rubber. Leone et al. found that a good workability level was found with the addition of either industrial or recycled short SF. Workability was reported not to show an impact with a small amount of added SF [108]. Adding WPF to concrete also reduced the workability of fresh concrete, as shown in Figure-14[117].

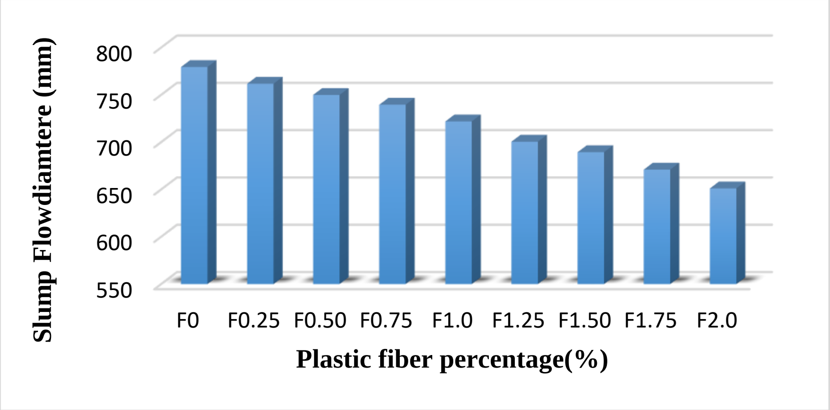


Figure-14 Impact of plastic fibre on the workability of fresh concrete [117].

Concrete workability was also found to reduce as the level of low-grade SF additions increased [104]. Decreases in workability with increased SF use could be due to low levels of superplasticizer, in which the added fibres also reduced workability. This might be mitigated by adding superplasticizer [162,163]. In comparison with a control sample, concrete containing PET aggregate concrete displayed greater workability [84]. Other researchers found that slump values were enhanced at plastic levels below 20%, with slump loss reductions of as much as 30% [118]. Workability was also found to decrease when PET was added, which was attributed to the sharpness of PET increasing the water requirements of the concrete [164]. They found that all types of fibre reduced the workability, but they can avoid this issue by adding materials improve the workability such as superplasticizer for Concrete vibrating equipment.

Based on recent studies, the shape and ratio of the fibres added have a great impact on concrete flow and the degree of skill that workers require to produce high-quality concrete structures. Investigating greater levels of cement or fine aggregate or fibre additions could be beneficial in this area, as increasing fibre additions may change sample responses and lead to development in which the shape of fibres is modified to target greater workability [93,147].

7.2 Mechanical Properties

7.2.1 Quasi-Static Loads

7.2.1.1 Compressive strength

An essential attribute of concrete when managing quality is compressive strength and, therefore, work to develop and improve different concrete types and classes should involve investigation of this characteristic [166]. A calculation of the compressive strength of a sample is determined by dividing the highest load applied to the sample during the test by the cross-sectional area, determined by the mean dimensions of the section, and recorded to the closest kg per cm^2. Recently, various researchers have contributed to a comprehensive review of the mechanical properties of concrete, including its compressive strength. As noted, compressive strength decreases as the proportion of fibres increases in the concrete [28]. Moreover, compressive strength was found to be reduced with an increase in WPF values because the fibre lowered the workability of the mix, which grew porous [167]. However, other researchers reported that the addition of silica fume to steel fibre RAC (SRAC) after exposure to high temperature achieved significantly improved compressive strength, toughness and elastic modulus [10,168].A slight effect on compressive strength was reported after adding two types of SF [108]. Similar effects on compressive strength were also found in both SFRCAC and standard concrete [169]. Other results have suggested that the compressive strength of concrete using recycled tyre steel fibres and recycled tyre steel cords was greater than for SFRC [170]. Other researchers found that the compressive strength of RAC was about 72.26% of natural aggregate concrete but, after adding silica fume, the compressive strength of concrete with recycled PET increased slightly (by about 3.6-9%), as shown in Figure-15 [171]. The effect of steel and plastic have been investigated by past researcher. the steel fibre increased but not very significant .in case of plastic fibre, no impact has been observed.in addition, they did not consider the long-term impact of fibre on compressive.

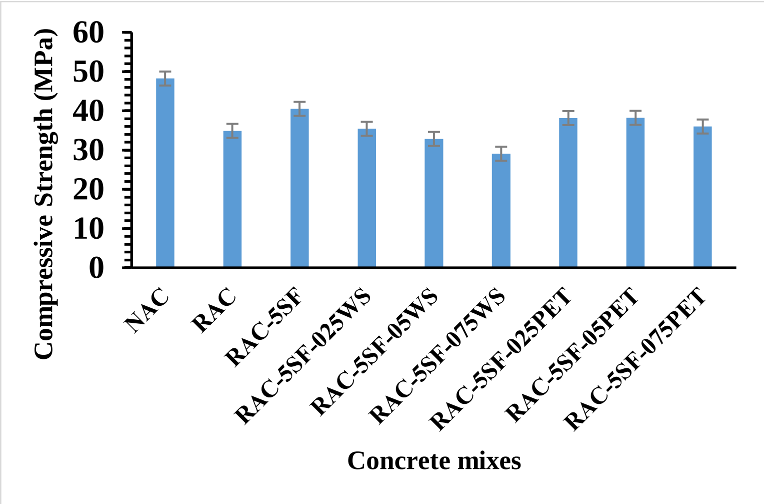


Figure-15 Compressive strength of concrete mixtures [171].

Furthermore, with the addition of SF, compressive strength increased for two aggregates (normal and recycled), by about 12% after 28 days [104]. However, in another study, the compressive strength of the concrete was too low. Two potential reasons were identified: when RAC replacement increases, it reduces the water-cement ratio and has effects either due to the shape or volume of the steel fibres [107]. An increasing amount of rubber was also found to reduce compressive strength in two mixes [172]. Other results indicate that compressive strength increased slightly with a greater amount of both types of SF. However, the compressive strength, elastic modulus and toughness of SFRAC decreased when exposed to a temperature of around 400 °C, although the addition of silica fume was found to enhance the compressive strength properties of SRAC [173]. Other findings show a decrease in compressive strength with the addition of e-plastic due to the replacement of the aggregate with plastic [113].

Compressive strength was affected only with greater volume fractions of fibre added to the concrete. The standard models created could be adopted to predict the compressive strength value [154].

Su et al. indicated that the addition of SF to UHPC increases compressive strength, as shown in Table-3 [174]. Other researchers found no significant effects on compressive strength with the use of SF[175–177] . The addition of waste PET was also found to reduce compressive strength because the concrete had a low water-to-cement ratio and high workability and the amount of PET added to the concrete as aggregate, because the surface of a natural aggregate had a stronger bond than PET [84].

Table-3 Experimental results of different formula UHPC under compressive load [174].

Fibre type	MF15	MF06	TF03	TF05
Strength (MPa)	145.12	114.51	132.29	113.05

In other work, the compressive strength of lightweight SCC was found to decrease by approximately 12% compared with concrete without SF [178]. However, Caggiano et al. reported that compressive strength appeared not to be affected when adding steel and PP fibres to concrete, as shown in Figure-16[179]. Noaman et al. found that compressive strength increased with the addition of SF up to 0.50% [180]. A high value for SF was also associated with a decrease in the mechanical properties in comparison with standard concrete [181]. Other researchers ascertained that the elastic modulus and compressive strength of polymer concrete (PC) produced with benzoyl peroxide (BPO) were less than for PC with methyl ethyl ketone peroxide (MEKP) [182].

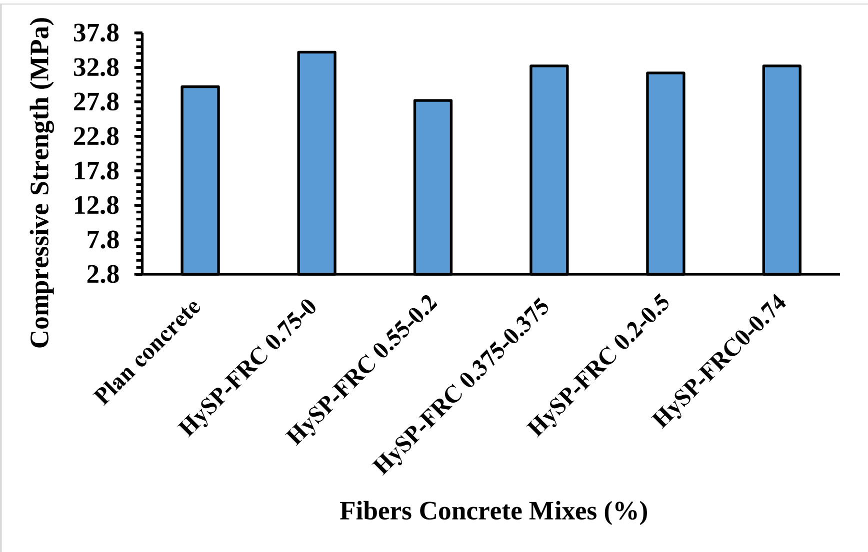


Figure-16 Compressive strength of HySP-FRCs[179].

7.2.1.2 Tensile strength

The tensile strength of concrete is increasingly becoming a consideration, due its impact on structure durability, load capacity and fracture properties [183]. The previous study reported that ductility was improved by adding fibres and that tensile strength increased in two types of SF added to concrete, as shown in Figure-17 [184]. Similarly, tensile strength and ductility were shown to increase by raising the WPF content, due to greater ultimate applied load and decreased internal stresses, [167]. Moreover, tensile strength was found to increase with SF and RAC without fibres by 9-16.6%. The elastic modulus of RAC was shown to reduce with an increased value of recycled woven plastic sack waste as shown in Figure-18 [185]. In their study, Leone et al. indicated that there were no significant effects on tensile strength with the use of SF, finding only slight effects on tensile strength through SF added to both types [108].

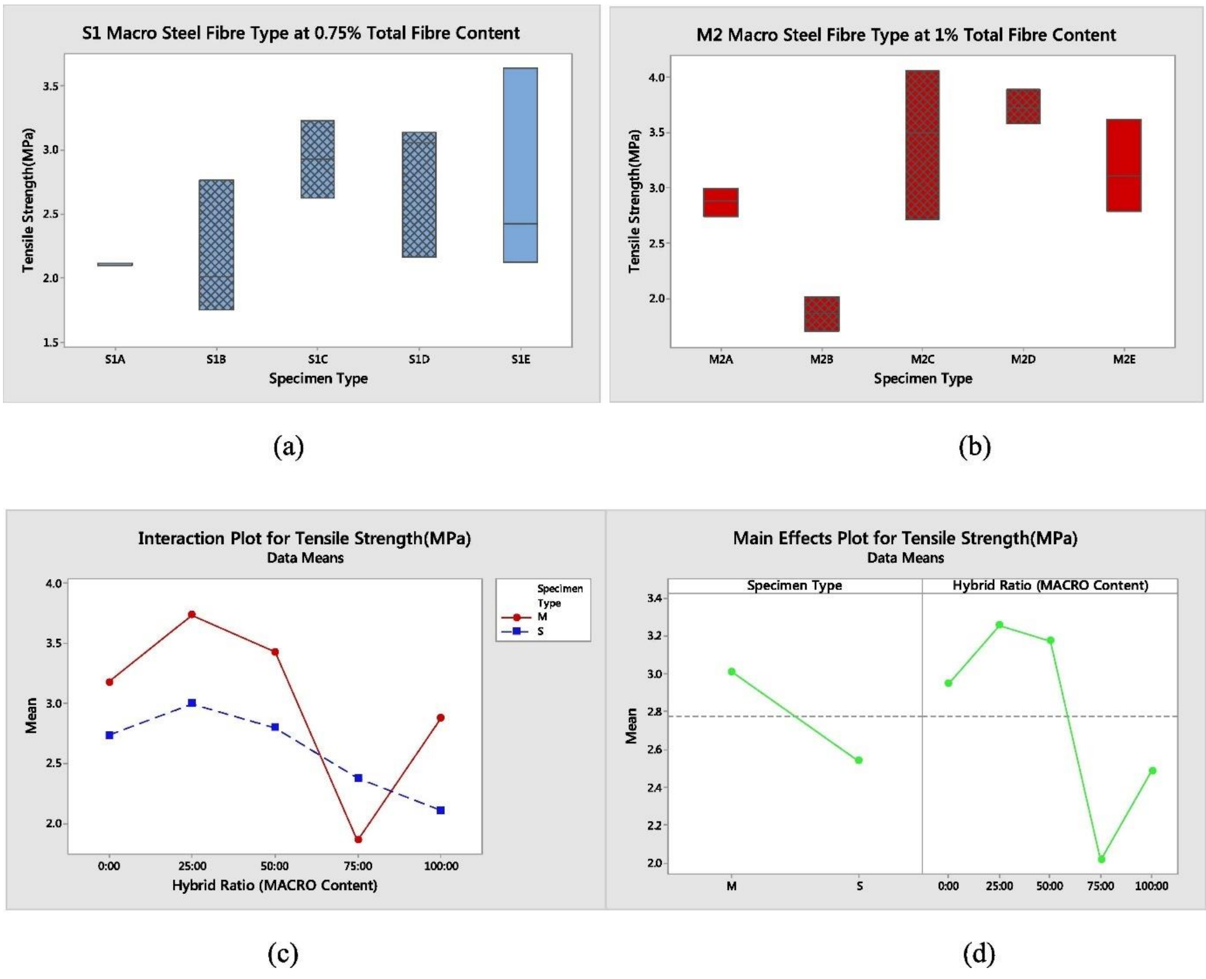


Figure-17 Increase in tensile strength with two types of SF [184].

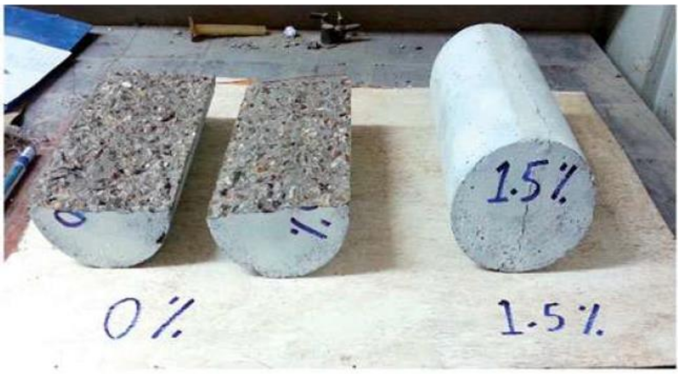
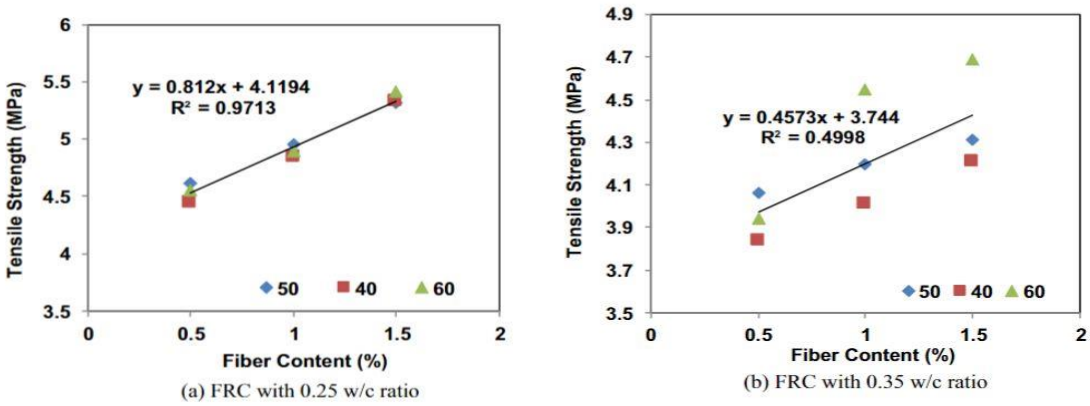
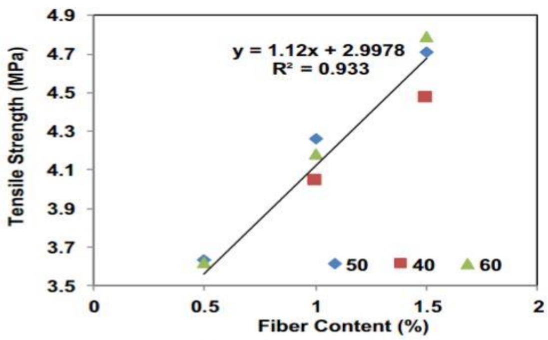


Figure-18 Comparison between specimens with the highest PET fiber percentage directly after the test[185].

According to Pereira et al., there was a significant influence on the tensile strength of concrete with fibre compared with the reference concrete [186]. The researchers suggested that a decrease in tensile strength with the addition of e-plastic was due to the replacement of the aggregate with e-plastic. However, an increase in tensile properties with a higher percentage of e-plastic waste was attributed to the increased ratio of resin resulting in better moistening and encasement of the gaps in the materials [113]. Abbass et al. demonstrated that the tensile strength increases with the addition of steel SF content. However, one configuration was found to have a lower water-to-cement ratio and showed a reduction in tensile strength, as shown in Figure-19[10,187,188]. However, an overall effort is still needed to study the effect of content, percentage and type.





(c) FRC with 0.45 w/c ratio

Figure-19 Lower water-to-cement ratio showing a decrease in tensile strength[10].

7.2.1.3 Flexural strength

Flexural strength is a measure that is often applied in relation to structural concrete. it is tested the bending based a method of third-point loading as in ASTM-C78 (2010) by using the prism specimen test, or on centrally positioned loads, as set out in ASTM C293 (2015), until failure. The second method is the one most frequently applied and is mainly accepted as offering greater value in comparison with other approaches[189,190]. The impacts from flexural strength are considered an important measure for the design of basic structural components, such as shafts and cantilevers:

Previous studies have reported that adding steel and plastic fibres to standard concrete improves crack resistance and reduces cracking Flexural strength increased as two types of steel fibres were added to concrete as shown in Figure-20[184]. In one study, flexural strength enhancement of reinforced RAC was found to be approximately 43% by adding waste fibre [191]. Yap et al. found that SF additions improved mechanical properties, including resistance to cracking and toughness[192], and Monteiro et al. showed that hooked-end SF was more effective in increasing resistance to crack growth due to its geometrical properties and material [193]. A study reported by Iqbal et al. found an increase in flexural strength and tensile strength of around 110% and 37%, respectively [161].

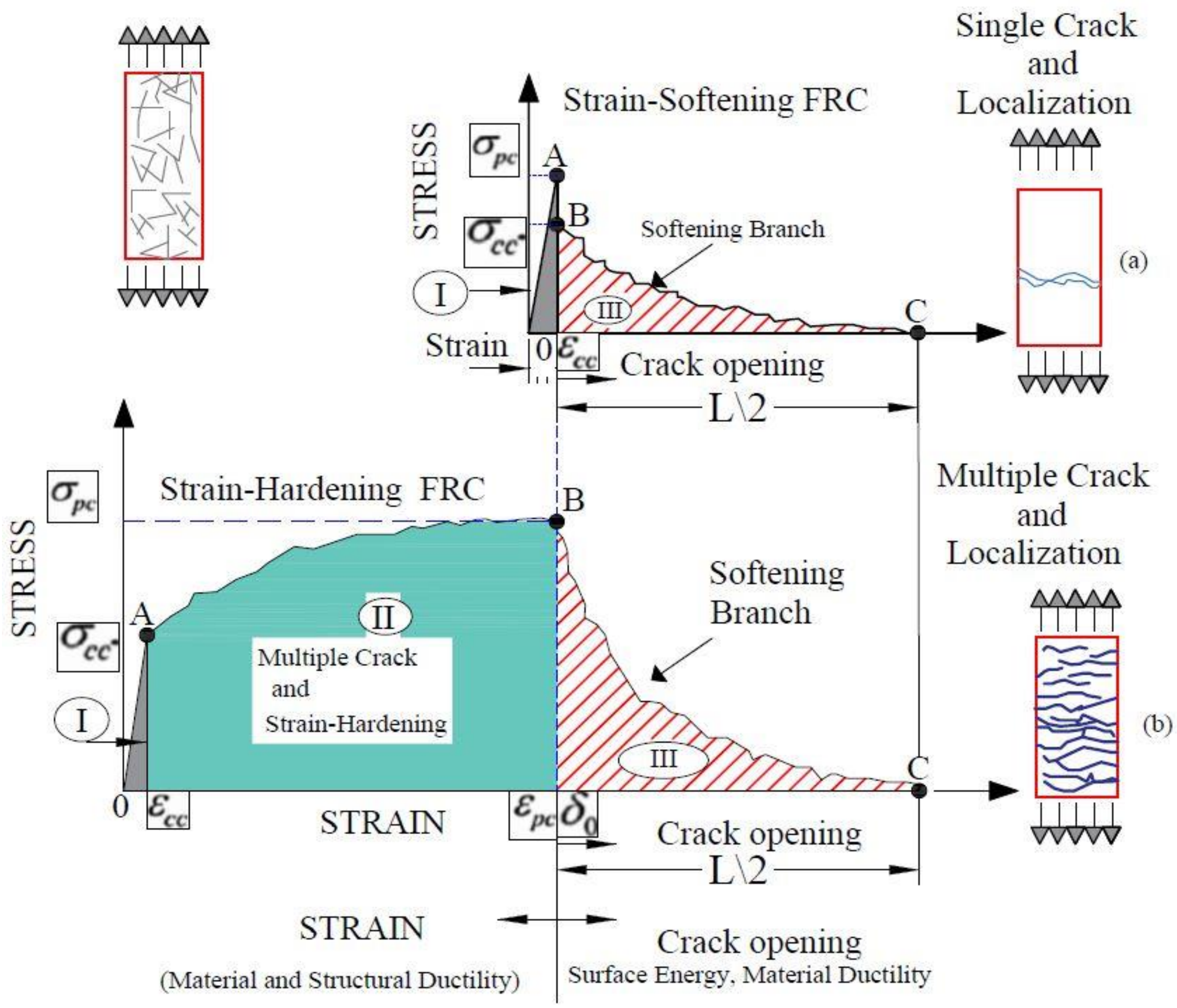


Figure-20 Increased flexural strength in two types of steel fibre [184].

Another study findings supported the approach of increasing flexural strength by raising PP fibre content, as this showed flexural performance improvement in both equivalent flexural strength and toughness with an increase in the proportion of SF used[194,195]. Moreover, there was a significant positive correlation between the type of FRP added to concrete. A positive correlation was also found between steel and PP after adding different volumes to concrete, which enhanced the post-cracking behaviour of the cement material[196].According to above investigation the fibre was increased the flexural ,but an overall effort is still needed to study the effect of content, percentage and type.

However, an increased strain rate was found to cause a higher amount of cracking. The transverse reinforcement spacing was 100 mm to affect flexural strength when adding the steel fibre [102]. On the other hand, flexural capacity was developed by using 200 mm spacing, and increasing the SF improved the failure mode from shear to bending. The addition of industrial SF (ISF) and RSF improved flexural strength behaviour [108]. Flexural strength was increased by less when using a volume of below 0.5% SF, and between 0.5% and 1.0% content of SFRCAC, but the toughness and flexural strength rose slightly [169]. Papastergiou et al. demonstrated that cracks were more significant in hollow beams without fibres. However, by adding SF to the hollow beams, cracking was reduced and the load capacity increased. Furthermore, the flexural strength of recycled SFRC is reported as being considerably higher (about 103%) than for concrete with ISF. Flexural strength performance develops with increases in the value of RSF [170]. Ductility was also shown to be improved by adding fibre, which significantly enhanced flexural strength. Post-cracking was improved by using both ISF and RSF [108]. Furthermore, the number of cracks in hollow beams has been shown to be lower than for traditional concrete. This may be due to bending influences in the tensile area being reduced by entering an empty longitudinal hole [197]. For both plain reactive powder concrete and SF-reinforced reactive powder concrete, the compressive strength increased with a rise in strain rate [198].

Li et al. reported that the concrete in their study had a considerably increased flexural strength, and that a useful shear crack mode could be achieved with SFRC compared with standard concrete [105]. Other results indicate, however, that there were no significant effects on flexural strength of the use of SF, and that this may be due to the amount and type of fibres used [199]. There was no apparent cracking in concrete samples with 20% rubber [172]. Bending was found to be highly influenced by using ISF and RSF reinforced concrete, which reduced cracking. However, ISF reinforced concrete showed slightly reduced toughness and ductility, especially for the opening of small cracks. The reason for this was probably the amount and diameter of the fibre [173].

Another study shows considerably improved both initial crack and ultimate failure, and found that SFRP and crumb rubber fiber (CRF) together improved dynamic concrete properties [180]. Experimental testing has also shown a significant influence on bending behaviours by adding fibre [91]. According to an investigation by Abbas et al., an increase in mechanical properties also occurred with a rise in the volume of SF [200]. Furthermore, a mix incorporating short SF enhanced flexural strength compared with the same mix and volume of long SF [178]. Another study found that the mode of concrete changed from brittle to ductile and there was a significant impact on post-cracking and a reduction in cracking [11]. The bond strength of PC made with MEKP was also found to be higher than for concrete with BPO. However, increasing PET to PC with MEKP from 1:1 to 2:1 decreased the bond strength of the PC [182]. Flexural and tensile strengths were improved compared with the control concrete. However, compressive strength was not affected after 28 days [127]. Other results found a decrease in flexural strength with the addition of e-plastic due to replacement of the aggregate with plastic [113]. In another study, flexural strength increased because recycled WPF improved crack resistance, developing ductility and controlling crack size [171]. Other researchers found that flexural strength increased and obtained a higher peak load when increasing the content of the fraction, but post-cracking with a short fraction was smaller than with a larger fraction [201]. Further results show that flexural strength increased for two lengths of fibre (20 mm and 50 mm), as illustrated in Figure-21, compared with standard concrete [202]. The control concrete failed in brittle mode, whereas concrete with recycled WPF failed in ductile mode. Finally, cracking was reduced significantly for all lengths and volume fractions tested [203].

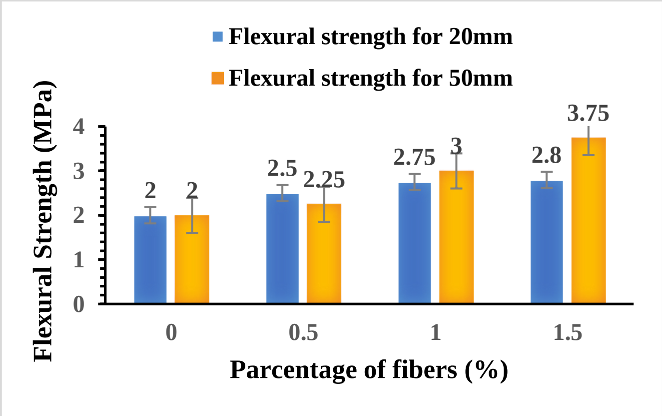


Figure-21 Comparison of flexural strength for mortar mixtures [202].

7.2.1.4 Fracture energy

The fracture energy of concrete is a fundamental property required for the accurate estimation of brittle failures of concrete construction [204]. The fracture zone of concrete is shown in Figure-22[205]. Raj et al. investigated the impact of SF and rubber additions to concrete. When added at approximately 1% SF and 15% rubber, the fracture energy improved by 90%. However, when 0.3% PP fibre was added, the fracture energy was enhanced by only 47% [206]. Fracture energy was found to increase with SF hybridization of up to 70%, but decreased when using just macro SF [184]. Other researchers found that fracture energy increased by approximately 37% when adding 25% rubber, and 0.5% hooked-end SF raised fracture energy by nearly 152% [207]. Figure-22 shows the association between two fracture energies for the fibre types examined (Fig.23 a, b) [208].

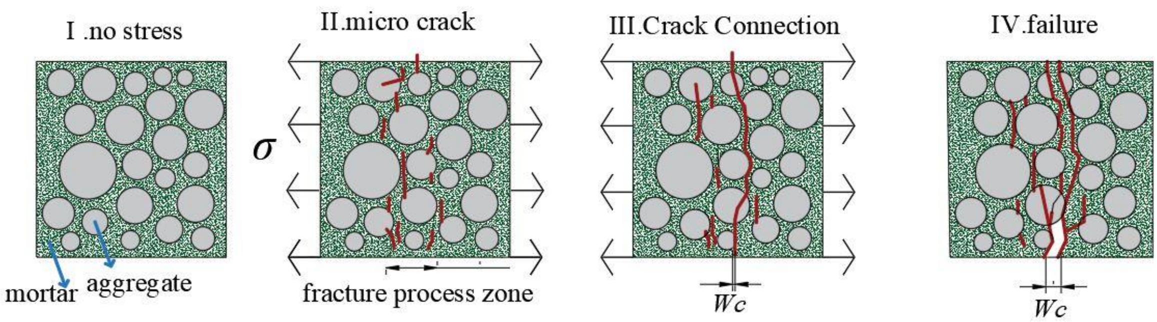


Figure-22 Fracture energy zone of concrete [205].

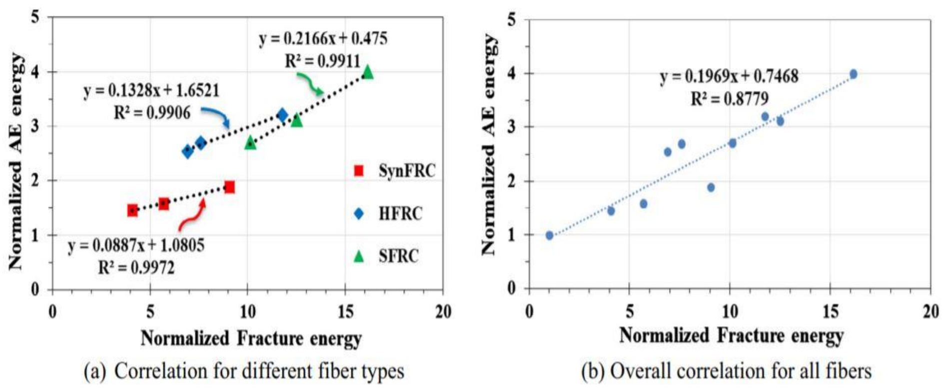


Figure-23 Relationship between normalized fracture energy and normalized acoustic emission energy [208].

In their study, Noaman et al. demonstrated an improvement in fracture energy through the consolidation of rubber chips as a partial substitution for aggregate [207]. The highest measure found for fracture energy (Gf) was 12%, which brought about an improved retained fracture and energy model when contrasted with standard concrete (PC) [209]. Depending on the requirements, studies suggest restricting the content of morsel elastic aggregates to up to 10% of the volume of fine and coarse rubber aggregates to improve fracture energy and reduce decreases in bending strength [210]. Utilizing rubber from destroyed tyres with steel wire belts was found to be an excellent solution compared with those without steel wire belts [211].

7.2.1.5 Fatigue life of FRC

Fatigue is challenging, as the bond joining carbon fibre reinforced polymers (CFRP) and steel is essential. Bonding failure is the predominant failure in SF systems, although this is not the case in concrete-FRP structures [212–217]. Depending on the fatigue performance of concrete and FRP support, long-term serviceability may be influenced by both non-strengthened and reinforced concrete beams [218]. Other researchers have stated that numerous structural parameters of concrete elements, for example, tensile and compressive strengths, fatigue life, and Young's modulus, among numerous others, show basic dispersal. Investigation of concrete fatigue life typically yields test results that can differ by two sets of extent, when ‘identical’ solid examples subject to ‘identical’ cyclic loads are considered. Dissipated impacts are seen in plain concrete, as well as in FRC [219]. Banjara and Ramanjaneyulu found that the fatigue life of FRC can be assessed according to the portion of the fibre content fraction, as shown in Figure-24 [220].

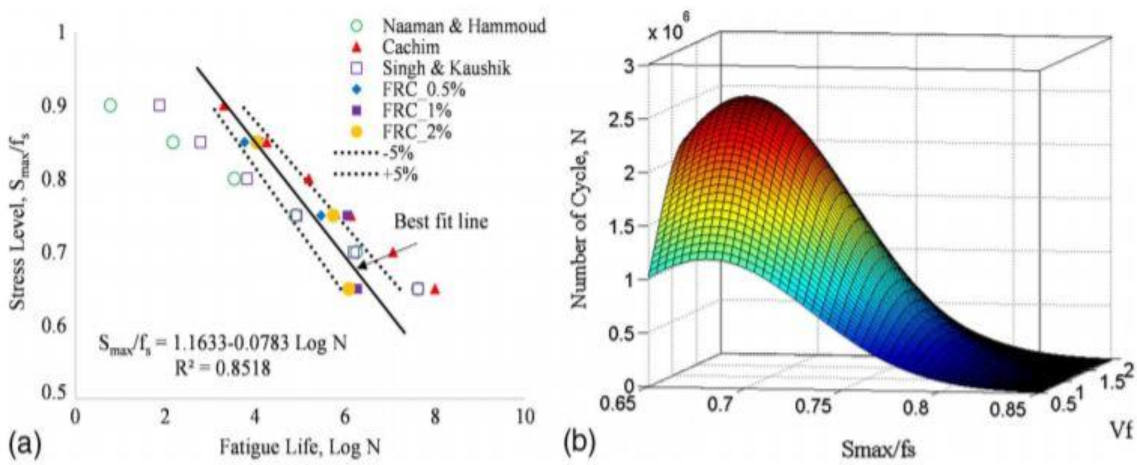


Figure-24 Shows S-N curves for FRC using flexural fatigue loading: (a) comparison of S-N models for FRC; and (b) impact of the FR volume on the S-N curve [220].

CFRP reinforcement in strengthening concrete beams seems appropriate as an intelligent system for setting the fatigue life of a reinforced concrete beam that has failed tensile steel, or as a way to increase fatigue life [221]. FRP composites were found to bring about higher resistance from fatigue in comparison with other design materials [222,223]. Matsumoto investigated the impact of FRC on fatigue life using a theoretical investigation via a fracture mechanics-based model and found that FRC increases the fatigue life [224]. The addition of SF was found to be significant in improving the strength of concrete and its fatigue life, as it avoided the open crack area [225]. According to above investigation the fibre was improve the fatigue life, but an overall effort is still needed to study the effects of content, percentage and type.

8. Testing Fibre Reinforced Concrete Properties under Thermo-Mechanical Loads

FRC has been investigated in recent decades for increased crack control. Further significance is found when fibres are combined with a naturally brittle material: for instance, high-strength concrete (HSC), the utilization of which has expanded gradually, is not simply due to its higher load-bearing capacity [226]. Therefore, because of the increase in service life and durability, the higher load-conveying boundary of HSC is commonly accompanied by progressively more brittle behaviour, which can be mitigated by the consolidation of fibres. Various investigations on the degradation of concrete when subject to high temperatures have been conducted. Concrete structures could be subject to high temperatures, coincidental causes or the attributes of auxiliary application and, as a result, concrete changes, which may affect its mechanical properties [227]. Different researchers have considered the influence of adding polymeric fibres to concrete under thermo-mechanical loads [228–230].

Several researchers have studied the impact of thermo-mechanical loads on FRC. According to [231], there was an explicit reduction in compressive strength at high temperature compared with ambient temperature. However, 3D and 5D SF added to increases in compressive strength compared with 1D SF concrete, at about 75 kg/m^3 and 45 kg/m^3, respectively. Moreover, there was a small loss of density in the concrete due to its reduced water content, as similarly reported by [232]. Therefore, there was no change in the compressive strength and elastic modulus of concrete with and without fibres. However, there was a significant increase in tensile and bending strength when adding both steel and PP fibres at between 40% and 150%. Treviño et al. demonstrated that the conductivity, due to the thermal process for standard concrete and FRC, was reduced by about 7%. Electrical resistivity was not an influencing parameter when checking the damage accrued by using microwaves in the method used. The results indicate that flexural strength decreased by around 50% and 32% at 320 s and 240 s microwave heating, respectively, as shown in Figure-25[233]. Moreover, researchers have indicated that adding PP to mixes reduced the spalling of concrete at high temperatures. The density of all the samples considered was decreased by approximately 2375 kg/m^3, 2325 kg/m^3, 2275 kg/m^3 and 2225 kg/m^3 by increasing the temperature to 20 °C, 200 °C, 400 °C and 600 °C, respectively. Compressive and tensile strengths sharply decreased when the temperature increased, as shown in Figure-26[234].

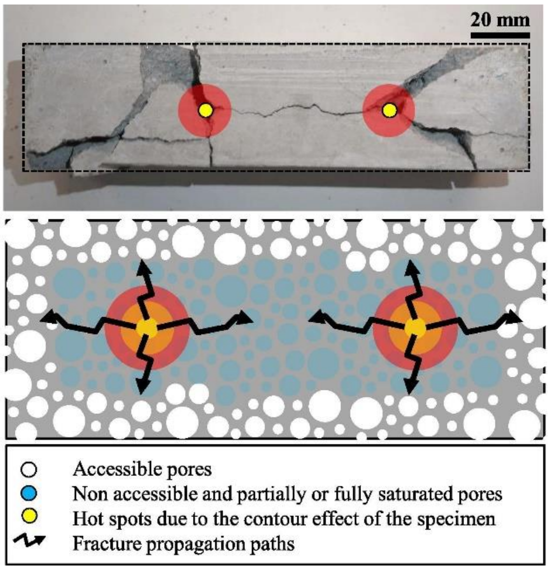


Figure-25 Reshaped intermittent reference mortar after a microwave circle of 300–400 s and cracks beginning and spreading on a prismatic sample [233].

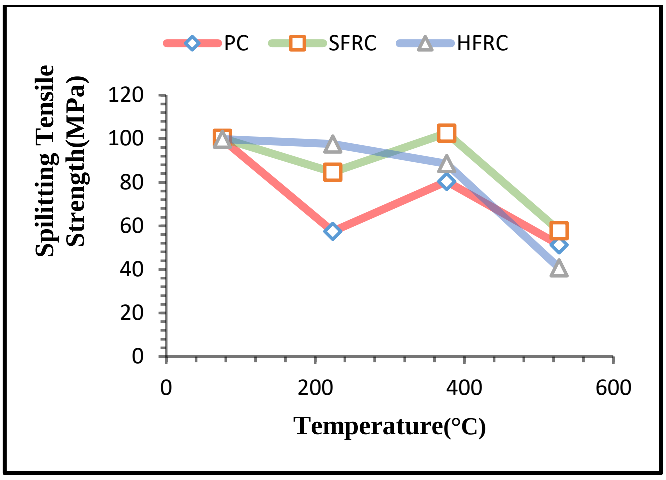
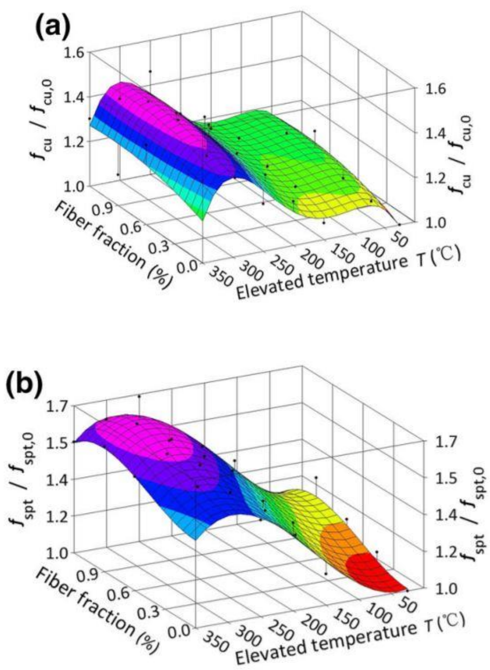


Figure-26 Split tensile strength of concrete at high temperature [234].

Researchers have identified the most convenient FRP composites among the possibilities investigated in order to achieve the best fatigue performance in comparison with concrete without FRP under exposure to high temperature. A spalling mechanism was employed using an electric furnace, and scanning electron microscopy tests were performed to determine the microstructure of polypropylene-fibre reactive powder concrete (PPPRC). Wang et al. observed that severe spalling decreased as the fibre content in the samples was increased the compressive strength. They found that flexural and tensile strengths did not reduce with increased temperatures due to the PPRPC added to the concrete, which enhanced mechanical properties when compared with standard concrete. The results showed that peak bond stress, stress–slip and elastic modulus reduced when the temperature increased. The bond strength of glass FRP and basalt FRP bar samples dramatically decreased when increasing the temperature, as shown in Figure-27 [235].



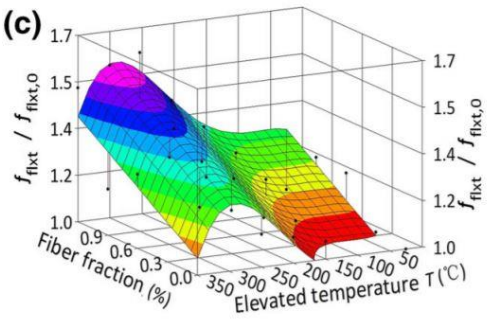


Figure-27 Effects of temperature on the mechanical properties of RFC at temperature[235].

According to Ozawa and Morimoto, concrete that contains fibre reduced the build-up of the vapour pressure of the water inside the concrete, and decreased the spalling of concrete exposed to high temperature [236]. The control concrete, critically dropped, and the maxim in spelling was about 7 mm. Other researchers observed FRP composites as the most convenient among the possibilities investigated, as these additions enable the best fatigue performance in comparison with concrete without FRP under exposure to high temperatures [225]. The majority of researchers have studied the impacts of high temperatures on mechanical properties, but all constructions are exposed to thermo-mechanical and dynamic loads.

9. Conclusions and Current Challenges

This review provides an understanding about the behaviour of EFRC. The following are the key findings from a critical analysis of the existing research.

- EFRC increases tensile strength, improves ductility, shrinkage properties, impact, fatigue properties, post-cracking resistance, cavitation, toughness, and erosion resistance, and the serviceability of concrete.
- SFRC shows low maintenance costs, an expansion in load capacity, low load limits through cracks, and increased tensile strength.
- Plastic fibre reinforcements show a high estimation of flexible modules with an improvement in various mechanical properties.
- Waste fibre reinforced concrete shows an increase in load capacity and crack resistance and a rise in tensile strength with a low overall cost.
- In general, workability was shown to decrease after an increase in the number of fibres in concrete. A possible solution is to use superplasticizers to overcome reductions in workability.
- The compressive strength of a control concrete without fibre was more than with fibres.
- With an addition to the ratio of fibre in the concrete mixture, there has been notable development in the flexural strength of concrete.

To obtain the optimum values of the performance parameters, a very good mixing is necessary. However, mixing processes have their challenges, and it is important to understand them before discussing how to optimize improvement. The challenges of adding fibre to a concrete mix can, if fully addressed, provide desirable properties. However, much research remains to be done to look at these challenges and their relative impact on the resulting concrete properties. Moreover, real concrete structures normally undergo dynamic loads with a coupling of mechanical and thermal conditions. The sole aim of using fibre is to modify the mechanical properties of concrete to increase its suitability for constructing a range of structures. A great deal of effort has been made in reinforcing concrete with different types of fibre. However, there are still various unaddressed challenges related to the optimization of the proportion of fibre, the shape of the fibre and the mixing method, and the properties achieved demand comprehensive research. In addition, the evolution of concrete reinforcement has been mainly influenced by mixing processes and methods. Hence, comprehensive research with an emphasis on the optimization of FRC, in particular to enhance its strength against thermo-mechanical dynamic loads, is still required.

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Performance of engineered fibre reinforced concrete (EFRC) under different load regimes: a review

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