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Natural and Artificial Fibre Reinforced Concrete: A State-of-art Review

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A B S T R A C T

The Fibre reinforced concrete (FRC) has become popular in construction industry in last few decades. Various natural and artificial fibres are added in concrete to enhance the crack resistance property by developing some bonding between fibre and concrete. FRC is not only performs better than conventional concrete but also the fibre reinforced concrete (FRC) has become popular in construction industry in last few decades. FRC is not only performs better than conventional concrete but also it reduces environmental pollution. Actually in many rural area, people are not concerned about the pollution and hygiene. The unused portion of sugarcane fibre, banana fibre, jute fibre are thrown into pond/ lake. After few days they decompose and rotten, that causes pollution in waterbody and disturb the ecosystem. The fibres can be used as additive in concrete to enhance their overall performance as well as to reduce environmental pollution. In this paper, a state-of-art review has been investigated on FRC and its different benefits. Different fibres such as jute fibre, coconut fibre, polypropylene, basalt, areca leaf, glass, mask, plastic, carbon and steel fibre were incorporated in concrete by several researchers in the past decades that have been highlighted in detail in this paper. The performance has been evaluated in terms of load displacement hysteretic pattern, stiffness, ductility, energy dissipation, crack resistance, durability and workability of FRC. The virtue and limitations of FRC have also been discussed. From the existing literature, it is found that the performance of FRC under dynamic load, Damage assessment, Time dependent assessment of damage, Effect of fibre in high-performance concrete (HPFRC) and Life cycle assessment are found as major literature gap that needs to be fulfilled. A case study on damage assessment of FRC has also been conducted in this paper. From the result it is found that the Carbon fibre reinforced concrete (CFRC), Steel fibre reinforced concrete (SFRC) and Areca leaf sheath fibre reinforced concrete (ALSFRC) are experiencing lesser damage in compared to normal concrete without fibre. Based on the existing literature the future scope and probable direction of research of FRC have also been highlighted.

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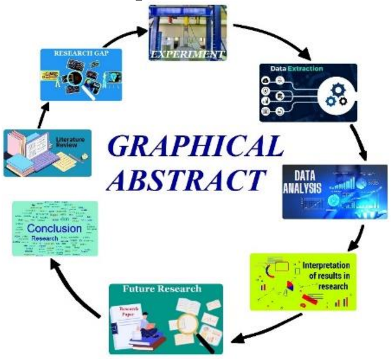
Graphical Abstract



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1. INTRODUCTION

Concrete is a popular choice for construction purposes, typically combined with deformed steel reinforcing bar (rebar) due to its high compressive strength. Steel reinforcements are utilized only in regions where there is a chance of tensile or shear stress, resulting in the development of reinforced concrete (RC). These types of concrete have improved tensile and shear resistance, making them ideal for structural elements subjected to quasi-static loading conditions. However, in recent times, structures have been exposed to harsh loading conditions like blasts, and fire from various sources, including terrorist attacks. While reinforced concrete (RC) and Prestressed concrete (PSC) structures are efficient under static conditions, they prove inadequate under extreme loads due to concrete's poor energy absorption capacity and brittle nature, which causes it to break apart.

Fibre Reinforced Concrete (FRC) is a type of composite material that enhances the structural strength and integrity of concrete by incorporating fibrous materials. According to ACI, FRC refers to concrete that contains randomly dispersed fibres. Due to its inherent brittleness and poor tensile strength, concrete tends to crack easily, resulting in issues such as freeze-thaw damage, scaling, discoloration, and steel corrosion. To address these problems, fibres are added to concrete to control the formation and growth of cracks. Various synthetic and natural fibres are commonly utilized in concrete to manage cracking and its propagation caused by plastic and drying shrinkage.

Suresh et al. (1) investigated the strength of concrete infused with glass and jute fiber as a natural and artificial fiber combination. The workability and compressive strength of the concrete with 1% of fiber content with cement weight is more than 2% of fiber content. However, it reduces the crack width under different loading (1). Chloride diffusivity is reduced when the concrete is infused with PPF, and the diffusivity of chloride is increased when the concrete is infused with steel fibre. However, the mixture of these two fibres shows improvement in the concrete properties and decreases the drying shrinkage (2). The physical characteristics of fresh and durability properties of dried concrete made with PPF concrete and compared with conventional concrete. The result shows that the usage of fiber quantity affects the properties of fresh concrete. Among different volume fractions of fiber used in the concrete, 0.8% of fiber utilized mix shows a positive effect in durability aspect. An increment of the volume fraction of fiber exhibits the heterogeneous dispersion of fibers in concrete. Due to this, floccule formed in the mixes, leading to more voids forming (3). The mechanical and physical properties of concrete infused with steel fibre were compared with conventional concrete. Under loading, the conventional concrete shows a typical advancement crack pattern, but on the contrary, in FRC, the crack ceased due to the ductile property of steel fibre. The compressive strength of the concrete increases as SF increases; on the contrary, the workability decreases when SF increases (4). The workability and mechanical property of the self-compacting HPC with PPF and M-sand was studied. Results show that around 25% increment was found in compressive strength compared to self-compacting PPC (5). Krishna et al. (6) have investigated the ductility and load-carrying capability of concrete made with coir and sisal fiber. The coir fiber in concrete controls the tensile crack and improves the ductility energy absorption capacity. Microstructural morphology of PPF concrete was carried out by using non-destructive technology. It is evident that the micro-crack develops during hydration are emerges on the interfacial zone along the close vicinity of aggregates. The maximum voids were found at the interfacial transition between cement paste and fibre or coarse aggregate. It is evident from the result that the volume of pores is proportionate to the fibre volume fraction (7). The durability of concrete made with polypropylene, glass, and hybrid fibre was studied by rapid chloride penetration and rapid chloride migration test. From the result, it is evident that the hybrid fibre shows better mechanical and durability properties. Compared to glass fibre, polypropylene fibre depicts better strength and durability (8). The effect of the fraction of polypropylene fibre and its geometry effect on ultra-high performance concrete (UHPC). It was evident that the length and dosage of fibre strongly influence permeability. The permeability does not increase once the fibre aspect ratio is less, even though the fibre dosage is increased. However, the authors proposed a mathematical model to select and optimize the fibre content to avoid the spalling of concrete (9). The mechanical, rheological, and microstructure of self-compacting lightweight concrete (SCLC) is analyzed by incorporating the combination of steel, PPF fibre, and silica fume. It is evident that a significant improvement in the mechanical properties by adding fibre and silica fume. Different mixes of SCLC show good flowability, passing ability, and viscosity (10). A study on the effect of the length of PPF on the emerging stage in High-Performance Concrete (HPC) was performed. Autogenous shrinkage value, temperature drop at a cracking time, and the value of specific tensile creep are reduced when the PPF length is increased. The ratio of cracking stress to axial tensile strength and the value of stress reserve is also reduced when the length of PPF increases. From the study, it was evident that the length of the fibre is another critical parameter (11). It was concluded that PPF did not alter cement's density, rheology, and free water property when infused with cement. The cement thickening time was reduced significantly. The 0.5% of PPF from the total weight of cement added to the cement can enhancement in compressive stress is 17.8%, and the PPF of 0.75% of the total weight of cement increases the tensile strength of concrete by around 18% (12). The mechanical, durability, and microstructure of PPF concrete was studied with different utilization ratio. The fiber volume fraction varied from 0 to 0.5%; among this, the specimen with 0.3% PPF showed the highest flexural strength. The result of dry-wet cycles shows that the specimen with 0.1% of PPF is the lowest water absorption among others, and it is evident that the optimum fiber content helps to improve the compactness of concrete, thus helping to reduce the porosity. In the freeze-thaw test, the specimen with 0.5% PPF shows better resistance against salt freezing. However, in a chloride environment, the specimen with 0.1% PPF performs better in the freeze-thaw and wet-try tests (13). Jia et al. (14) confirmed that the interfacial adhesive strength between the cement matrix to PPF was increased when PPF was mixed with Micro-silica (MSi), which acts as a hydrophilic modifier. The effect of the inclusion of hybrid fibre, including PPF and Latex powder have been studied in concrete to evaluate their mechanical properties. The specimen at the initial days of the drying period shows significant shrinkage deformation; however, the shrinkage rate after 45 days of drying periods decreased. The shrinkage model shows a strong interrelation between shrinkage rate to polymer latex fibre. The optimum utilization value of fibrous materials to develop overlay materials for CC pavement is 0.2% of 9 mm length PP fibre with 2.5% of both latex and silica powder (15). The tribological and rheological properties of fresh concrete made with PPF were studied by Bentegri et al. (16). The effect of fibre, such as shape (fibrillated twist and wave fibre), length, and dosage in the fresh concrete with superplasticizers, was analyzed. The fibre length does not affect the plastic viscosity. However, the plastic viscosity and segregation (tribological) of the concrete show a negative effect when the fibre dosage increases, but it could improve with superplasticizers. The rheological and tribological properties and workability were improved for the concrete with superplasticizers. Combining fibres reduces plastic viscosity and constant viscosity compared to a single fibre (16). The mechanical and durability of hybrid fiber reinforced foam concrete (HFRFC) was investigated by Raj et al. (17). Flexural and split strength, the compressive strength of the concrete infused with fiber is improved compared to plain foam cement concrete; however, the synthetic fiber (ploy vinyl alcohol) shows better results than the natural (Coir) fiber. The chemical and physical properties of concrete infused with polypropylene fibre were discussed in detail. The amount of fibre is another critical parameter. If it is added more than its requirement, it may reduce the workability of the concrete. Adding polypropylene fibre can enhance the strength of the concrete, but it can produce negative results if it is more than the optimum dosage (18). The durability of concrete can be increased when it is infused with polypropylene fibres (PPF), as it optimizes the opening of the pores in concrete. It helps to reduce the entry of ions and water, which is detrimental. When the combination of PPF and steel fibre is mixed in concrete, further enhancement in the durability of concrete is achieved. PPF shows weak bonding with cement matrix and does not disperse completely in concrete; however, it can be overcome when the fibre is treated with the chemical (19). Moreover, the abrasion and impact resistance of concrete are improved in addition to other mechanical properties. However, the hybrid fiber shows better results than the mono fiber. The researchers found the optimum dosage of hybrid fiber as 0.3% of PVA and 0.2% coir (20). Islam et al. (21) have investigated the mechanical and rheological properties of concrete with nylon, iron, and coir as steel, synthetic and natural fiber. The result shows that the addition of fiber causes a significant reduction in the workability of concrete. Among these three fibers, steel fiber shows a significant increment of compressive and flexural strength. However, these three fiber shows lower compressive strength at the beginning (3-7 days) days due to weak bonding of materials. From the study, it was evident that the addition of fiber enhanced the ductility after the crack and the capacity of energy absorption (21). The physical, mechanical, and durability properties of different natural and synthetic fiber-infused concrete were examined by More and Subramanian (22). The results show that water absorption of natural fiber is more than that of artificial fiber. However, the artificial fiber is more efficient compared to natural fiber. Under acidic exposure, the weight loss of fiber concrete is higher, but the weight loss is less under an alkaline environment. Split tensile strength, ductility, and post-cracking resistance were improved (22). Amir et al. (23) have analyzed flexural capacity by static analysis. The result shows that compared to conventional shear reinforcement, spiral reinforcement increases flexural performance. The crack pattern, punching shear, and load displacement of slap with steel fiber were analyzed. Ahmed et al. (24) have reviewed the mechanical, physical, and durability of coir fiber concrete. The flexural strength of concrete with coir fiber is significantly improved compared to compressive strength, as mentioned by previous researchers. Ahmed et al. (24) mentioned that the optimum dosage of coir fiber was 2 to 3%. However, Krishna et al. (6) mentioned that the optimum percentage of coir fiber was 1.5%. Effiong and Ede (25) have reviewed the techniques of Near Surface Mounted (NSM) and Externally Bonded (EB) for strengthening reinforced concrete beams by using natural fiber polymer composite. In the NSM technique, synthetic fiber shows failure by flexural rupture, pull-out driven by intermediate crack, and end pull-out. However, these failure mechanisms of the concrete beam with natural fiber reinforcement still need to be explored fully. Burst cycles and break solidity of sisal fiber need to be studied mentioned that more data is needed for the design and performance of steel fiber concrete (25-27).

From the literature it has been observed that Performance of FRC under dynamic load, Damage assessment of FRC, Time-dependent assessment of damage of FRC, Effect of fibre in high performance concrete (HPFRC), life cycle assessment of FRC have not been performed. In the above literature review a detailed scenario on FRC has been presented. Different virtue and limitations are found from the literature and portrait in this paper. Based on the literature the research gap has been discussed. The probable future research direction has been explained based on the existing review.

2. RESEARCH SIGNIFICANCE

The natural and artificial fibres have their own properties based on which they help to improve the performance of concrete. On the other way the fibre also reduce the workability of concrete. A state-of-art review on FRC have been highlighted on existing literature in this paper. It shows different properties of fibre and their performance in concrete in terms of load displacement hysteretic pattern, stiffness, ductility, energy dissipation, crack resistance, durability and workability. This review also reveals the virtue and limitations of FRC. Based on the existing literature the research gap and probable future direction of research have been highlighted in this paper.

3. CLASSIFICATION OF FIBRE REINFORCED CONCRETE

Different types of natural and artificial fibres are available for FRC shown in Figure 1

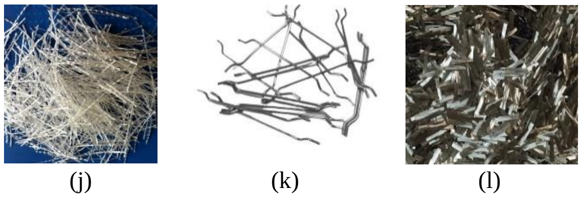


Figure 1. Different types of fibre (a) Coconut fibre (b) Jute fibre (c) Nylon fibre (d) Glass fibre (e) Polypropylene fibre (f) Carbon fibre (g) ALS fibre (h) Banana fibre (i) Sugarcane fibre (j) Plastic fibre (k) Steel fibre (l) Basalt fibre

4. CLASSIFICATION OF FIBRE

There are several types of fibres are available round the globe. They can be classified as per the following Figure 2 (28). A flow chart has been presented in Figure 3.

5. PROS AND CONS OF FRC

In this study an overview of commonly used fibres are discussed. The FRC has virtue and limitations have been discussed in Table 1.

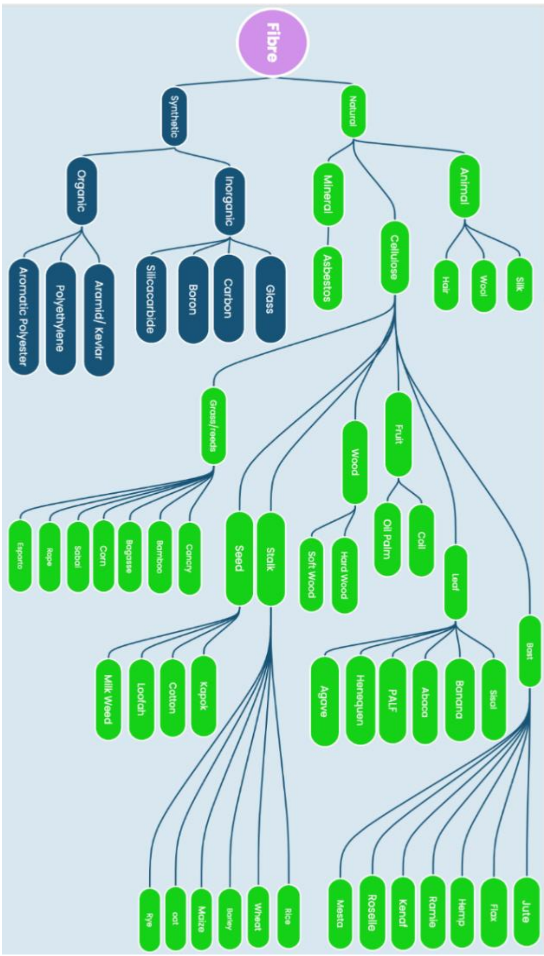


Figure 2. Classification of existing fibre [28]

Figure 3. Flow chart of the research

TABLE 1. The virtue and limitations of FRC

Sl. No.	Virtue	Limitations
1.	From the above literature it is found that the FRC has many pros and cons. Firstly, the FRC is highly crack resistance while it is incorporated in concrete. Secondly, it increases tensile strength, compressive strength, shear capacity, ductility, stiffness, impact load resistance capacity, freeze-thaw resistance, shrinkage crack resistance.	Apart from many pros, there are few cons are associated with FRC. Firstly fibre reduces the workability of concrete, especially with steel fibre. Moreover there is a chance of fibre ball formation in concrete that may affect adversely. Secondly, due to corrosion the steel FRC may deteriorate early. Moreover, maximum FRC is costly with compared to normal concrete although the extra cost can be set off by reducing the cement consumption or other factors.

6. CASE STUDY

A case study has been conducted on fibre reinforced beam-column joint under cyclic load. In this study an uncommon natural fibre i.e. Areca leaf sheath (ALS) fibre, steel and carbon fibre have been used. For this purpose an Areca leaf sheath fibre reinforced concrete (ALSFRC) beam-column joint (BCJ), steel fibre BCJ and carbon fibre BCJ have been casted and tested under cyclic load in actuator shown in Figure 4. The performance has been assessed by Ghobarah et al. (29) stiffness damage index (DI). A beam-column joint without fibre has been tested as control specimen to compare the performance of FRC. The estimated DI is compared with Park-Ang DI in Figure 5. It has been observed that the present study estimates the similar DI with Park et al. (30) DI.

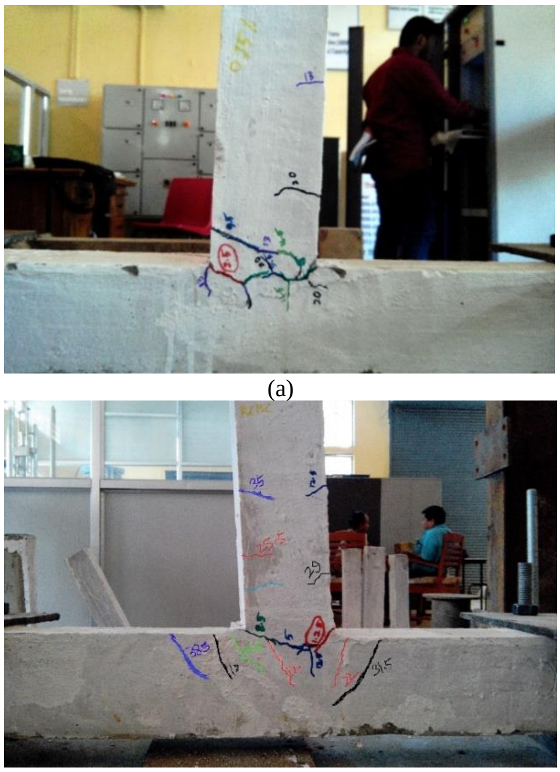
$$DI = 1 - K_f / K_i \quad (1)$$

where, DI = Damage index of the member, K_i = Initial stiffness, K_f = final stiffness

The performance of the specimens are determined in terms of DI. Using the Eq. 1 the DI of the BCJs are determined. The DI is plotted with different displacement level to compare the performance among ALSFRC, Steel FRC (SFRC), Carbon FRC (CFRC) and BCJ without fibre presented in Figure 5. In this figure the ALSFRC, SFRC and CFRC are experiencing lower damage with compared to the BCJ without fibre. Moreover the CFRC achieved lowest DI due to its highest strength.

7. RESULTS AND DISCUSSIONS

In this article the state-of-art review has been examined. The performance of FRC have been discussed in terms of tensile strength, compressive strength, dissipated hysteretic energy, stiffness, ductility, crack resistance, creep and shrinkage. Apart from the existing research there are many other important aspects are required to discuss given below.



(a)

(b)

Figure 4. (a) ALSFRC BCJ (b) BCJ without fibre

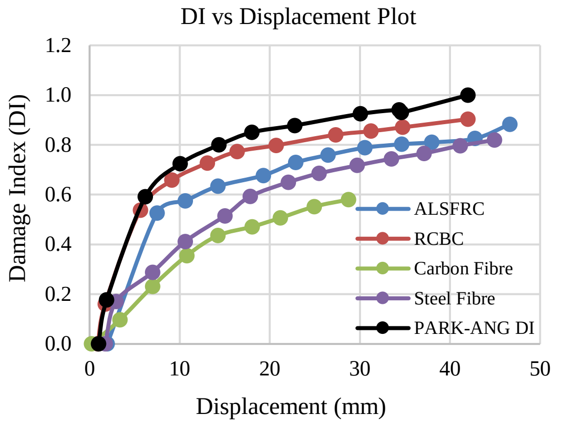


Figure 5. Comparison of DI between ALSFRC and BCJ without fibre

7. 1. Performance under Dynamic Load From the existing literature it is found that the performance of concrete has been carried out under static load. Whereas non-linear dynamic analysis of FRC is not explored yet. The performance of FRC under seismic and wind load may reveal new outcomes and it may introduce new direction of research.

7. 2. Damage Assessment The structural damage assessment of FRC has not been explored yet. It is very essential to determine the damage index (31-38) of FRC for different percentage of fibre under different types of static and dynamic load. The investigation results from damage assessment may explore new important direction of research.

7. 3. Time-dependent Assessment of Damage Ageing, operational circumstances, materials utilization, geometric shape, repeated loads, increased mean load, and environmental factors all are responsible for structural degradation. Other factors that contribute to the slow decay of structures include humidity and chemical substances like sulphur and chloride. Environmental consequences and structural deterioration have not been explored significantly. Future research will compare various environmental elements and degradation mechanisms for hazard function.

7. 4. Effect of Fibre in High Performance Concrete (HPFRC) The fibres are generally used in normal concrete found from literature. A few literature are available on HPFRC. It is necessary to know the effect of fibre in high performance concrete and its performance.

7. 5. Life Cycle Assessment The life cycle assessment (LCA) is one of the important aspect in sustainable development. The LCA of FRC is essential to know its safety and serviceability. This investigation may help the future probable direction of research.

8. CONCLUSIONS

In this paper a detailed review has been discussed. The virtue and limitations of FRC have been discussed. The probable future scope of FRC has also been highlighted. Although several researchers have explored the properties and utilities of various types of FRC still it is not yet commercialized in large scale. The following conclusions can be drawn from this study:
1. The CFRC is experiencing lowest DI and RCBC is experiencing highest DI among all the specimens.
2. The structural damage assessment of FRC is essential to know the performance in high seismic region and its range of application.
3. FRC deteriorates due to ageing, operational circumstances, materials utilization, geometric shape, repeated loads, increased mean load, and environmental substances. This deterioration is called time-dependant damage assessment that is essential for FRC.
4. The effect of fibre in high performance concrete and LCA may be another important future direction of research.
5. Incorporation of fibre improves the mechanical properties of concrete such as tensile strength, compressive strength, ductility, stiffness and energy absorption capacity significantly and reduces the workability of concrete.
6. The creep deformation decreases and crack resistance property increases with higher aspect ratio and higher length of fibre.
7. Similarly, irregular, hooked or crimped shaped fibres perform better than regular shaped fibres due to better grip.

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Persian Abstract

چکیده

بتن مسلح با الیاف (FRC) در چند دهه اخیر در صنعت ساختمان سازی رایج شده است. الیاف طبیعی و مصنوعی مختلفی به بتن اضافه می شود تا با ایجاد پیوند بین الیاف و بتن، خاصیت مقاومت در برابر ترک را افزایش دهد. FRC نه تنها عملکرد بهتری نسبت به بتن معمولی دارد، بلکه بتن مسلح با الیاف (FRC)نیز در چند دهه اخیر در صنعت ساختمان سازی رایج شده است. FRC نه تنها عملکرد بهتری نسبت به بتن معمولی دارد بلکه باعث کاهش آلودگی محیط زیست نیز می شود. در واقع در بسیاری از مناطق روستایی، مردم نگران آلودگی و بهداشت نیستند. بخش استفاده نشده از الیاف نیشکر، فیبر موز، فیبر جوت در حوضچه/دریاچه ریخته می شود. پس از چند روز تجزیه شده و پوسیده می شوند که باعث آلودگی آب و اختلال در اکوسیستم می شود. الیاف را می توان به عنوان افزودنی در بتن برای افزایش عملکرد کلی آنها و همچنین کاهش آلودگی محیط زیست استفاده کرد. در این مقاله، یک بررسی پیشرفته در مورد FRC و مزایای مختلف آن بررسی شده است. الیاف مختلفی مانند الیاف جوت، الیاف نارگیل، پلی پروپیلن، بازالت، برگ آرکا، شیشه، ماسک، پلاستیک، کربن و الیاف فولادی توسط چندین محقق در دهه‌های گذشته در بتن گنجانده شده‌اند که در این مقاله به تفصیل مورد اشاره قرار گرفته‌اند. عملکرد از نظر الگوی هیسترتیک جابجایی بار، سختی، شکل پذیری، اتلاف انرژی، مقاومت در برابر ترک، دوام و کارایی FRC ارزیابی شده است. مزیت و محدودیت های FRC نیز مورد بحث قرار گرفته است. از ادبیات موجود، مشخص شده است که عملکرد FRC تحت بار دینامیکی، ارزیابی خسارت، ارزیابی آسیب وابسته به زمان، اثر الیاف در بتن با عملکرد بالا (HPFRC)و ارزیابی چرخه حیات به عنوان شکاف اصلی ادبیات یافت می‌شوند که نیاز به برآورده شود. یک مطالعه موردی در مورد ارزیابی آسیب FRC نیز در این مقاله انجام شده است. از نتایج مشخص شد که بتن مسلح با الیاف کربن (CFRC)، بتن مسلح با الیاف فولادی (SFRC) و بتن مسلح با الیاف غلاف برگ Areca (ALSFRC) در مقایسه با بتن معمولی بدون الیاف آسیب کمتری را تجربه می‌کنند. بر اساس ادبیات موجود، دامنه آینده و جهت احتمالی تحقیق FRC نیز برجسته شده است.