
Fibre Reinforced Cement Composites

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<http://dx.doi.org/10.5772/intechopen.75102>

Abstract

Progression in cement-based technology has driven the development of fibre reinforced concrete (FRC) materials; such as concrete technology. Steel fibre and synthetic fibre are fundamental fibre types, which include glass, carbon, polyvinyl, polyolefin, waste fibre materials and polypropylene. The mechanical properties of FRC members are affected from these fibres individually and in hybrid aspects. The type, content and geometry of fibres are relied to these mechanical properties. A significant improvement in mechanical and dynamic properties of reinforced concrete members is enabled due to additional fibres into cementitious composites. Most mechanical properties are enhanced through intercept micro-cracks. The level of enhancement accomplished relied on the type and dosage of fibre as compared to plain concrete. Effective tensile strength, energy dissipation capacity and toughness are explained through FRC. The shear, punching and flexure are significantly increased through the level of enhancement accomplished. These fibres include polyvinyl, glass, carbon, polyolefin and polypropylene that improve the mechanical properties of concrete. The historical use of fibres and types of fibres are reported in this chapter. Similarly, the curing of steel, structural synthetic fibres, the mechanical properties of cement, the addition, placing, finishing and mixing are based on waste fibres, hybrid fibres, steel and structural synthetic.

Keywords: cement, steel fibre, synthetic fibre, hybrid fibre, waste fibre, concrete

1. Introduction

Advancements in cement-based technology, such as concrete technology, have led to the development of fibre reinforced concrete (FRC) materials [1]. Considerable research efforts have been made contributing to theoretical and technological knowledge about properties and behaviour of FRC across the globe. Applications of FRC are very common in civil and structural engineering.

There are numerous fibre types, in various sizes and shapes, available for commercial and experimental use. The basic fibre types are steel fibre; synthetic fibres, such as polypropylene, glass, carbon, polyolefin and polyvinyl; and waste fibre materials. Using these fibres individually as well as on hybrid basis has an effect on the mechanical properties of FRC members. These mechanical properties depend on the type, geometry, and content of fibres [2, 3] as described below.

The addition of fibres into cementitious composites enables considerable improvement in mechanical and dynamic properties of reinforced concrete members. The delay and control of tensile cracking in the composite material are the most considerable outcome of fibre associated with concrete [4]. Most mechanical properties of composite are enhanced using intercept micro-cracks. ACI/C [5] stated the reliance of the level of enhancement accomplished on the type of fibre and the dosage rate as compared to plain concrete. Thus, FRC demonstrates excellent tensile strength, toughness and energy dissipation capacity [6, 7]. It also increases significantly the shear [8–10], flexural [9, 11, 12], punching [13, 14], resistance and durability ([15, 16]; Kunieda et al., 2014) of concrete structures as well as superb resistance to cracking [17].

Those attractive properties allow the direct application of fibres in concrete. However, each fibre type could enhance specific concrete properties. Accordingly, the aim of this chapter is to investigate into the potential of using various types of fibres which include steel fibre and synthetic fibres such as polypropylene, glass, carbon, polyolefin and polyvinyl in enhancing the mechanical properties of concrete.

Recent researches have shown that waste fibres can also be a valuable reinforcement system to decrease significantly the brittle behaviour of cement-based materials, by improving their toughness and post-cracking resistance [18]. It also has beneficial environmental and economic impacts [19, 20]. The effect of using waste fibre in enhancing concrete properties is also reported.

The use of two or more types of fibres in a suitable combination showed a great potential to optimise the properties of concrete material as well as to improve the mechanical performance of reinforced concrete members. This combining of fibres, often called hybridization is currently used as the inclusion of single fibre in concrete cannot attain an optimal performance. The use of hybrid is commonly limited to two types. These are a mix of steel and polypropylene fibres and a mix of steel fibres with different geometry, shape and size. A further description on different fibre combinations is shown in the below sections. This chapter reported on the historical use of fibres; types of fibres; the addition, mixing, placing, finishing and curing of steel, polypropylene and structural synthetic fibres and the mechanical properties of cement-based composites reinforced with steel, polypropylene, structural synthetic, water fibres and hybrid fibres.

2. Fibres: origin and history

Fibres were used at least 3500 years ago to build the 57 m high hill of Aqar Quf near Baghdad through brittle matrix materials and sun-baked bricks [21]. Additionally, masonry mortar and plaster were reinforced through horsehair [22]. Similarly, cement products were reinforced through asbestos fibres for about 100 years ago. In contrast, alternate fibre types were instigated within the 1960s and 70s due to health issues related to asbestos fibres.

In the nineteenth century, the use of reinforcing rods in the tensile zone of the concrete was imposed for the low tensile strength and brittle character of concrete [23]. In addition, the incorporation of discontinuous steel reinforcing elements including metal chips, nails and wire segments into concrete was attempted through patents recently.

Romualdi and Baston [24] have investigated the steel fibres potential for steel reinforcing rods in concrete during the early 1960s in the United States. Afterwards, steel fibre reinforced concrete has been advanced through assorted experimentation, industrial application and research development. Similarly, Goldfein [25] conducted experiments with and without reinforcement using plastic fibres in concrete. Structural synthetic fibres were used explicitly by Japanese construction companies since 1997 as an alternate of steel fibre reinforcement. The expansion of structural synthetic fibres is attempted in Europe, North America and Australia.

Most applications suggest the use of fibre reinforced concrete such as refractory materials, concrete products, and road and floor slabs over the past 40 years [23].

3. Types of fibres

Fibre types are accessible for experimental and commercial use in assorted sizes and shapes. The basic fibre categories are steel fibre; synthetic fibres, such as polypropylene, glass, carbon, polyolefin and polyvinyl; and waste fibre materials. However, in structural cement-based elements, steel, polypropylene and structural synthetic fibre reinforced concrete as well as waste fibres are the main types of fibre, which are used as a replacement for conventional steel fabric reinforcement. Using these fibres individually as well as on hybrid basis has an effect on the mechanical properties of FRC members. These mechanical properties depend on the type, geometry and content of fibres [2, 3] as described below.

3.1. Steel fibres

Many efforts have been made in recent years to optimise the shape of steel fibres to achieve improved fibre-matrix bond characteristics, and to enhance fibre dispersibility in the concrete mix [26]. The classification for four general types is provided by ASTM A 820 on the basis of manufacturing products [22]. These products include cut sheet, melt extracted, cold-drawn wire and other fibres.

Figure 1 has shown other common types of steel fibres. By cutting and chopping wire, rounded and straight steel fibres, having a diameter between 0.25 and 1.0 mm are produced. Furthermore, shearing sheet of flattening wire produces flat and straight steel fibres of 0.15–0.41 mm thickness by 0.25–1.14 mm width. The production of crimped and deformed steel fibres is based on the full-length crimping or bent or enlarged at each side of the fibres. The bending or flattening process is used to deform fibres to expand bond and allow mixing and handling [28].

The handling and mixing process is facilitated through fibres being collated into bundles. The bundles are distributed into single fibres during the mixing process. Similarly, cold-drawn wire is used to produce fibres that are smooth for making steel wool. In addition, the melt extraction process is used to produce steel fibres [22].

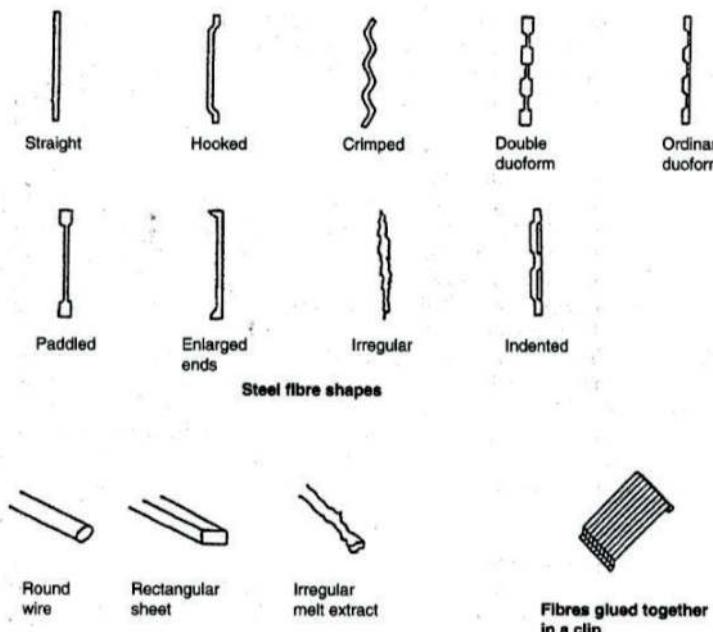


Figure 1. Different steel fibre types [27].

Young's modulus is 205 MPa, aspect ratio varies from 30 to 100, ultimate tensile strength of steel fibre varies from 345 to 1700 MPa, and length varies from 19 to 60 mm for respective fibres.

The largest fibre producers offer a statistical analysis to claim the sale of 67% fibre based on the hooked type. Katzer (2006) explained that crimped fibre (8%), straight fibre (9%) and fibre with deformed wire (9%) are other most popular fibre types.

3.2. Synthetic fibres

Research and development reflect the efforts of man-made fibres in the form of synthetic fibres specifically in the textile and petrochemical industries. Organic polymers derive fibres for synthetic fibre reinforced concrete based on available formulations [22]. Acrylic, polyethylene, polypropylene, nylon, polyester, carbon and aramid are the concrete-based matrices for synthetic fibre types in Portland cement. However, there is a dearth of these fibres, but other fibres are found extensively in commercial applications [22]. Low modulus of elasticity and high elongation properties are found in synthetic and organic fibres. In contrast, high modulus of elasticity is found in steel, glass, carbon and asbestos and fibres [29]. Similarly, structural and polypropylene are emerged as synthetic fibres and extensively found in concrete ground floor-slabs.

3.2.1. Polypropylene fibres (*micro-synthetic fibres*)

The significance of polypropylene fibres emerged due to their high alkaline resistance and low price of the raw polymer material [30, 31]. Their formation is based on fibrillated or monofilament manufactured in an enduring process through polypropylene homopolymer resin extrusion. Micro synthetic fibres are used for reducing, plastic settlement cracking and plastic shrinkage cracking in ground-supported slabs based on 100% polypropylene. According to Perry [32], micro-synthetic fibres are usually 12 mm long by 18 µm diameter.

3.2.2. Structural synthetic fibres (*macro-synthetic fibres*)

During the last 7 years, the development of micro-synthetic fibres has expanded comprehensively. The potential of these fibres is evident in providing concrete with significant ductility. These fibres have potential to control cracking resultant from lasting drying shrinkage and thermal movements in concrete floors and slabs [33]. These macro-synthetic fibres vary from polypropylene micro-fibres due to their large and higher polymers even though they typically comprise few polypropylenes [32]. A significant level of post-crack control is provided from synthetic structural fibres to accomplish steel fibres and fabrics [34].

Steel fibres and polypropylene fibres as well as structural synthetic fibres are the most common types of fibres used in structural members. Therefore, the following section discusses the addition, mixing, placing, finishing and curing of steel, polypropylene and structural synthetic fibres. Also, they present the effect of adding these fibre types on the properties of fresh and hardened concrete. However, using waste fibres is relatively a new practice and it is not limited to one type of wastes. Therefore, there is no clear guidance for the addition, mixing, placing, finishing and curing of such fibres. On the other hand, using hybrid fibres is limited to the use of steel and polypropylene as well as using different types of steel fibres. Thus, the below practices of adding single steel or polypropylene fibres are applicable.

4. Fibre reinforced concrete addition, mixing, placing, finishing and curing

4.1. Steel fibre

4.1.1. Composition and quality

Higher cement, smaller aggregates and fine contents are generally combined in the fibre reinforced concrete as compared to plain concrete. The fibre content increases to decrease the extent of the slump [21, 22]. Therefore, a steel wire manufacturer signifies the following specification for acquiring steel fibre reinforced concrete [35].

4.1.2. Addition and mixing of steel fibre

It is deemed that 20–40 kg/m³ is usually the recommended dosage for steel fibres. According to Knapton, [27], the flexural strength of the concrete results in higher dosage rate. In general, the fresh concrete is combined with the fibres and; afterwards, these fibres are moved initially to the mixer. Newman and Choo [21] revealed that these fibres can be incorporated to the aggregated conveyor belt. The fibres might be dispensed directly regardless of any balling risk, when the aspect ratio of the fibre is less than 50. Particular packing techniques are employed by manufacturers for reducing the risk with higher aspect ratios [22]. On the contrary, the satisfactory outcome of visual inspection is evaluated for fibre distribution during pouring [27].

4.1.3. Placing finishing and curing

Approved mixing, quality control procedures, and finishing are required for good quality and economic construction of steel fibre reinforced concrete [22]. The placement of concrete through good concrete practice is affective in positioning during curing. The reduced flow characteristics allow positively the final placement of steel fibre reinforced concrete (Unwalla, 1982; [36]).

Placing, curing and finishing steel fibre reinforced concrete are satisfactorily used by traditional tools, procedure and equipment [36–39]. Antiwear products and cement are usually expanded on the concrete surface after levelling and compaction [27]. Same methods and techniques can be used for curing and protecting SFRC. Plastic and shrinkage cracking can be produced through insufficient curing methods in traditional concrete [36, 37, 39].

4.1.4. Mechanical properties of fresh steel fibre-reinforced concrete

The important problem produced during the steel fibre reinforced concrete is the accomplishment of sufficient workability. Fibres are included in the concrete mix with aspect ratio and fibre volume, which affect the workability [36, 40]. The steel fibres can mitigate the estimated

Element	Quantity
Cement	320–350 kg/m ³
Well-graded sharp sand	750–850 kg/m ³
Continuous aggregate grading	28 mm
Crushed stone	14 mm, 15–20%
Characteristic compressive strength	25 N/mm ²
Water/cement ratio	0.50–0.55

Table 1. Concrete mix design of steel fibre reinforced concrete.

composite slump as reported from the variations of volume fractions included in steel fibre reinforced concrete (0.25–1.5 vol%). Furthermore, the effects of vibration are suggested to assess workability of a SFRC mixture with the VB test because mechanical vibration is suggested in a number of SFRC applications as compared to traditional slump measurement. A good workability is maintained through the inclusion of superplasticiser. In contrast, the fibre balling should be ignored when considering above specifications.

4.2. Polypropylene fibre-reinforced concrete

4.2.1. *Addition and mixing (polypropylene)*

The addition of polypropylene fibres is at a recommended dosage of approximately 0.9 kg/m^3 (0.1% by volume) [27]; the fibre volume is so low that mixing techniques require little or no modification from normal practice [21]. The fibres may be added at either a conventional batching/mixing plant or by hand to the ready-mix truck on site [27].

4.2.2. *Placing finishing and curing (polypropylene)*

Polyproline fibres are comprised of concrete mixes that can be transformed by normal methods and; therefore, flow easily from the hopper outlet. The essential compaction might be used for providing traditional means of vibration and tamping. The traditional concrete can be considered strictly for curing procedures. The floating and trowelling of fibre-dosed mixes can be used for normal hand and poor tools [27].

4.2.3. *Mechanical properties of fresh fibre-reinforced concrete*

According to Ramakrishnan [4], proper design and application of fibre reinforced concrete mixes can be essentially considered on the basis of knowledge of the fresh concrete properties. The occurrence of polypropylene fibres is mechanically observed since a comprehensive impact is imparted on the concrete, cement hydration and delaying evaporation by holding water [27]. The polypropylene fibres did not affect the slump of fibre-dosed concrete. The properties of the fresh concrete are modified through the primary role of polypropylene. The movement of solid particles, the bleed of water chemicals and the homogeneity of the mix are stabilised, blocked and increased through polypropylene fibres. The bleed capacity of the concrete and plastic settlement is reduced, and decreases the rate of bleed through polypropylene fibres.

The plastic concrete is formed due to plastic cracking and drying shrinkage. The formation of plastic cracks took place in the first 24 h, when there is high evaporation rate and the concrete surface dries after the placement of the concrete [27]. The appearance of concrete along with its durability and physical and mechanical properties is affected through this high evaporation rate [41]. The width of plastic shrinkage cracks can be restricted due to the polypropylene fibres. In the initial phases, the post-cracking ductility of the concrete emerged from the fibres, increasing strain capacity and affecting plastic shrinkage cracking [21].

4.3. Structural synthetic fibres

For synthetic structural fibres, the dearth of available references and design guidelines are the considerable barriers for effective comprehension to add, mix, compact, finish, cure, and place within concrete properties. The information associated to these sources are mentioned in the following paragraph [32, 34, 42]. During the patching or mixing processes, the fibres can be incorporated to the concrete at any point.

The particular application and intended properties relied on the additional rate, which differs from 1.8 to 7 kg/m³. Careful attention is required for their additional rate within both batching procedures and mix design to accomplish optimum consequences. The required workability is accomplished by ensuring the adjustments into the mix design. Afterwards, the fine aggregate contents include a slight increase for coating the fibres comprehensively. The concrete is assisted with efficient finishing and rapid placing. In contrast, medium to high level of workability is accomplished through the inclusion of a superplasticiser. It is evident that the position of structural synthetic fibres is appropriately similar according to the normal concrete. Moreover, concrete must be compacted adequately to assure the surface placement with the easy finishing. An easy float is typically transformed over the concrete for patching the surface after compaction. The fibre reinforced is enabled to cure effective concreting practice once it is levelled, floated and compacted. Structural synthetic fibre mostly relies on surface friction to achieve anchorage across a crack. It controls plastic shrinkage cracking and cracking due to drying shrinkage of the concrete. Moreover, it improves concrete properties including ductility, fracture toughness, impact and fatigue resistance.

5. Effect of using single type of fibres on concrete mechanical properties

5.1. Steel fibres

Steel fibre is becoming an important type of concrete reinforcement due to the numerous advantages that it offers for concrete. Compared to traditional fabric reinforcement, steel fibres have a tensile strength typically two to three times greater and a significant greater surface area to develop a bond with the concrete matrix [5]. Over the past three decades, the potential of using steel fibre reinforced concrete (SFRC) to improve the performance of structures has been investigated [43]. The available literature on the subject shows that steel fibre reinforcement can increase significantly the compression, tension, flexure, impact and toughness, shear and punching resistance, as well as the energy dissipation capacity and durability of concrete structures.

The occurrence of fibres affects the compressive strength as it varies from 0 to 15%. In contrast, the order of 30–40% fibres is increased with direct tension. There are little data dealing strictly with the torsion and shear even though they are usually increased [22, 44]. Moreover, steel fibre has a noteworthy effect on the residual tensile strength and flexural strength, with increase of more than 100% being reported [45, 46]. The most important part of the commercial use of steel fibre is the post-crack flexural performance, which is based on the steel fibre

concrete and sections subjected to point or flexure load. The flexural behaviour of concrete reinforced with straight and hooked end steel fibres was studied by Pajak and Ponikiewski [26]. It was found that the increase of fibre volume ratio increases the flexural tensile strength. The fracture energy increases with the increase of fibre dosage and is higher for hooked end steel fibres than for straight ones. Steel fibres continue to carry stresses after matrix failure. This is also confirmed by many researchers [9, 11, 12].

According to Hauwaert et al. [47], impact strength and toughness are significantly increased, which is defined as energy absorbed to failure. Under the load deflection curve, the toughness increases resulting in tension and flexure due to the increase in area [21]. A claim is usually made due to fatigue and increased resistance to dynamic load. The resistance of increased resistance to dynamic loading highly emerged as it is associated with the fibre distribution in concrete [48].

In studying the effect of steel fibres on the shear capacity of concrete, some investigations were carried out for evaluating the performance of beam–column sub assemblages. Susetyo et al. [10] undertaken experimental investigations on concrete panels based on pure-shear monotonic loading conditions for assessing the steel fibre effectiveness to meet minimal shear reinforcement requirements for concrete elements. Ductile behaviour, good crack control attributes and sufficient shear strength are exhibited through the test results. Minimum extent of traditional shear reinforcement is accomplished through the level of performance. The role of steel fibres in enhancing the shear strength of concrete was also confirmed by many researchers [8, 9, 49].

Labib (2008) conducted experimental investigations on concrete slab-column connections reinforced with hooked end steel fibres failing in punching; it was found that the inclusion of steel fibres significantly increases the load carrying capacity of tested specimens and is strongly dependent on the fibre dosage. Moreover, the crack opening restraint provided by the reinforcement mechanisms of steel fibres bridging the crack surfaces leads to a significant increase in terms of load carrying capacity and energy absorption capability of concrete structures. This was also confirmed by [13, 14].

In particular, steel fibre possesses a positive impact on the shrinkage behaviour of concrete that mitigates the extent and organises the cracks width, as compared to plain concrete [22, 28]. The fibres will corrode quickly in exposed situations, if the concrete compacts the fibre corrosion under the surface. The deterioration caused due to freeze-thaw cycling and the permeability of cracks can be reduced from the fibres [22, 50].

The role of fibres in bridging the crack opening and enhancing the load capacity and post-peak behaviour leads to better concrete durability and structural integrity ([15, 16]; Kunieda et al., 2014). This was also confirmed by the experimental results of Stephen (2001) which showed that the introduction of steel fibres into the concrete can arrest the early spalling of the concrete cover and increase the load capacity as well as the ductility of the columns over that of comparable non-fibre reinforced specimens. Similar observations were reported more recently by Lee et al. [49], Joao (2010), and Röhm and Arnold [51]. Steel fibres improve the ductility of concrete under all modes of loading.

5.2. Synthetic fibres

Synthetic organic fibres have low modulus of elasticity and high elongation properties [29]. Therefore, they have the potential to provide concrete with significant ductility. As a result, when added to concrete, these fibres are able to control cracking caused by thermal movements and long-term drying shrinkage [33] and improve the performance of concrete by negating its disadvantages such as low tensile strength, low ductility and low energy absorption capacity (Lakshmi et al., 2010; [52]; Mu et al., 2000; [53, 54]). Glass, polyvinyl, polypropylene, polyolefin and carbon are concrete-based matrices used in the synthetic fibre types in Portland cement.

Synthetic fibre types that have been tried in Portland cement concrete-based matrices are: polypropylene, glass, carbon, polyolefin and polyvinyl. For many of these fibres, there is little reported research or field experience, while others are found in commercial applications and have been the subject of extensive reporting [22]. Among these materials, polypropylene fibres are one of the most widely used for construction applications such as blast-resistant concrete and pavements (Mwangi, 2001).

Polypropylene fibres are gaining significance due to the low price of the raw polymer material and their high alkaline resistance [30, 31]. Their formation is based on fibrillated or monofilament manufactured in an enduring process through polypropylene homopolymer resin extrusion. Micro-synthetic fibres are used for reducing, plastic settlement cracking and plastic shrinkage cracking in ground-supported slabs as based on 100% polypropylene. Polypropylene fibres are used extensively in concrete for the purpose of reducing, plastic shrinkage cracking and plastic settlement cracking [32].

Mazaheripour et al. (2011) investigate the effect of polypropylene fibre inclusion on fresh and hardened properties of concrete. The results obtained have shown that the polypropylene fibres did not influence the compressive strength and elastic modulus; however, applying these fibres at their maximum percentage volume increased the tensile strength and the flexural strength of concrete.

Fire still remains one of the most serious risks for tunnels, buildings and other concrete structures. Thereby, the risks related with increased temperatures should be considered by engineers when designing concrete structures, including explosive spalling due to adverse concrete deterioration (Phan et al., 2002; Horiguchi et al., 2004).

It has been widely shown that polypropylene fibres are very effective in mitigating spalling in concrete exposed to elevated temperatures. Bangi et al. (2012) conducted an experimental study for investigating the fibre type effect and maximum pore pressure amount in fibre reinforced high-strength concrete. It uses different lengths of steel fibres, polyvinyl and polypropylene. The pore pressure reduction in heated concrete is contributed through pore pressure measurements based on organic fibres. The most effective maximum pore pressure development is polypropylene fibres as compared to polyvinyl alcohol fibres. On the contrary, there is a low effect found on the steel fibres. This result has been proved by studies from different researchers. These studies found that the complex mechanism of porosity variations in concrete at elevated temperatures, enriched with polypropylene fibres (Khoury, 2008; [55, 56]; Zeimi et al., 2006; Muzzucco et al., 2015).

On the other hand, polypropylene fibres can improve not only mechanical properties of concrete but also its durability due to reduced crack width by fibre bridging effect. Therefore, it could be considered as solution to extend lifecycle in terms of improvement of durability (Kunieda et al., 2014). The polypropylene fibres enhance the resistance to frost attack and the surface of abrasion resistance. The protection of the steel reinforcement is increased through these aspects alongside corrosion and mitigates the concrete water permeability. Knapton [27] states that the chemical resistance of concrete is not changed in this process. In particular, polypropylene fibres are usually more durable as compared to plain concrete [28].

As stated previously, while polypropylene is extensively used in concrete, other synthetic fibres such as glass, carbon, polyolefin and polyvinyl had little reported research or field experience. Barhum et al. (2012) studied the impact of the dispersed and short fibres of carbon and alkali resistance on the textile-reinforced concrete's fracture behaviour. The strength, fracture behaviour and deformation of the study are performed through a series of deformation-controlled and uniaxial tension tests. Pronounced enhancement of first-crack stress was achieved due to the addition of glass and carbon fibres. While more and finer cracks were observed on the specimens with short fibres added, a moderate improvement in tensile strength was recorded.

The formation of polyolefin fibre reinforced concrete is based on the employment of polyolefin fibres since they are lighter and possess a final lower cost and not chemically stable. They have been proved to be suitable for structural uses. Moreover, in some cases, they have substituted steel fibres (Behfarnia et al., 2014; Pujadas et al., 2014; Alberti et al., 2015). On the other hand, polyvinyl alcohol organic fibres and nylon are also effective in mitigating spalling, while others like polyethylene fibres are not so effective. Investigations from Laura et al. (2014) indicated that the use of synthetic fibre reinforced concrete can enhance the ductility and energy dissipation capacity of concrete.

5.3. Waste fibres

The use of waste fibres plays an important role in sustainable solid waste management. It helps to save natural resources, decreases the pollution of the environment and saves energy production processes. It has beneficial environmental and economic impacts; therefore, wastes and industrial by-products should be considered as potentially valuable resources merely awaiting appropriate treatment and application [19, 20]. Therefore, the addition of waste to concrete corresponds to a new perspective in research activities, integrating the areas of concrete technology and environmental technology.

Steel fibres originated from the industry of tyres and plastic wastes are among these wastes; their disposal has harmful effects on the environment due to their long biodegradation period, and therefore one of the logical methods for reduction of their negative effects is the application of these materials in other industries.

Recent research is showing that steel fibres originated from the industry of tyre recycling and can be a valuable reinforcement system to decrease significantly the brittle behaviour of cement-based materials, by improving their toughness and post-cracking resistance. Recycled steel fibre reinforced concrete is therefore becoming a promising candidate for both structural

and non-structural applications [18]. Zamanzadeh et al. [43] compared the characterisation of the post-cracking properties of recycled steel fibre reinforced concrete and industrial steel fibre reinforced concrete, on its use as shear reinforcement. Although the results indicated that the fibre reinforcement mechanisms for relatively small crack width levels were not as effective in the recycled steel fibres as the industrial steel fibres, it was verified that both fibres have similar trend in the post-cracking behaviour.

Much research effort has focused on reusing waste materials from plastic industries in concrete. Different works have analysed the effect of the addition of recycled polyethylene terephthalate (PET) to the properties of concrete (Choi et al., 2005; Jo et al., 2007; Robeiz, 1995). The reinforced concrete with PET bottles has been analysed by Foti (2011). The study has found that there is a great influence on post-cracking performance of simple concrete elements, when incorporating little amount of recycled fibres from PET bottle wastes. The sample's toughness and the concrete plasticity are enhanced and increased, respectively, through these fibres. Moreover, fibres are used from recycled PET bottles in reinforced mortar by De Oliveira et al. (2011). The findings have shown that a significant enhancement on compressive strength of mortars is shown from these PET fibres on their toughness and their flexural strength. The possibility of recycling PET fibres is explored by Foti (2013) as acquired from waste bodies with assorted shapes. The ductility of concrete is increased through these tests and PET fibres in a concrete mixture. At the end, as limited research has been carried out in this area, therefore, more studies could be carried out on the effect of using the previously mentioned wastes on the mechanical properties of concrete to prove the above results and to further examine different mechanical properties. In addition, the effect of using other types of wastes on the mechanical properties of concrete could be investigated.

6. Effect of using hybrid fibres

It is noteworthy to examine that the concrete failure is based on a multi-scale and a gradual process even though the research mentioned above have convinced us that remarkable improvement in mechanical performance can be achieved by using single fibre type in concrete. Therefore, significant attempts are made toward fibre combinations with different functions and constitutive responses and dimensions into cementitious composite. Potential advantages can be offered through hybrid combinations of steel and non-metallic fibres to enhance concrete properties and to reduce the entire cost of concrete production (Bentur and Mindess, 1990). Fibre fractions result in a uniform and a denser fibre distribution within the concrete as it enhances post-crack strength of concrete and reduces shrinkage cracks. This combination of low- and high-modulus fibres can arrest the micro- and macro-cracks, respectively, which could be also achieved by using a combination of long and short fibres as different lengths of fibres would control different scales of cracking.

A number of studies indicated the overall benefits of using combinations of steel fibres and polypropylene fibres (Xu et al., 2011; Sivakumar, 2011; Chi, 2014; Ding et al., 2010; Sahoo et al., 2015), while limited research was carried out on the effect of using steel fibres and other types of fibres such as glass and polyethylene (Banthia et al., 2014) or using a mix of short and long steel fibres [11].

Xu et al. (2011) found that the tensile strength of steel-polypropylene hybrid fibre reinforced concrete. The results indicated that the tensile strength of conventional concrete can be dramatically improved by mixing with hybrid steel-polypropylene fibres. The enhancing effect of hybrid fibre is better than that of single fibre, and the volume fraction of steel fibre is observed to have a great impact on the tensile strength. The same results were found by Sivakumar (2011) who studied the flexural strength, toughness, and ductility of concrete specimens containing individual steel fibres and hybrid combinations of steel and non-metallic fibres such as glass, polyester and polypropylene. He found that the ability of non-metallic fibres to bridge smaller micro-cracks was suggested as the reason for the enhancement in flexural properties compared to individual steel fibre.

The effect of inclusion hybrid steel-polypropylene fibre reinforced concrete on triaxial compression was developed by Chi (2014). The results showed that the steel fibres mainly contribute to the composite's triaxial strength that was observed to improve significantly when both the volume fractions and aspect ratios of steel fibre were increased. On the other hand, the polypropylene fibres were found to have considerable effect on improving the tensile meridian rather than compressive meridian.

Ding et al. (2010) analysed the influence of various fibre types, including steel macro-fibre and hybrid fibre (macro-steel fibre and macro-plastic fibre) on the shear strength and shear toughness of reinforced concrete beams. The results indicated that hybrid fibres can evidently enhance both the shear toughness and the ultimate shear bearing capacity.

Sahoo et al. (2015) studied the influence of using both high-modulus (steel) and low-modulus (polypropylene) fibres on the shear strength of reinforced concrete beams. A better post-peak residual strength response is noticed in the case of all FRC beam specimens due to multiple cracking associated with the fibre bridging action. The main parameters investigated are shear strength, failure mechanism and displacement ductility. The FRC specimens with combined steel and polypropylene fibres showed that the shear resistance and deformability values are improved significantly; multiple cracks of smaller crack width are noticed at the failure stage of the specimens indicating the better fibre bridging action of combined metallic and non-metallic fibres.

Banthia et al. (2014) used hybrid fibres by using two types of macro-steel fibres and a micro-cellulose fibre. Flexural and direct shear tests were performed, and the results were analysed to identify the degree of enhancement in the mechanical properties associated with various fibre combinations.

7. Conclusion

This chapter reported on the historical use of fibres; types of fibres; and the addition, mixing, placing, finishing and curing of steel, polypropylene and structural synthetic fibres. This chapter also discussed the potential of using various types of fibres in reinforced concrete to optimise the properties of concrete material as well as to improve the mechanical performance of reinforced concrete members. The reviewed literature highlighted the role of fibres

in enhancing the concrete tensile strength, flexure strength; shear strength, punching shear strength, toughness, energy dissipation capacity, resistance to cracking and durability. The reviewed literature also indicated that, in most cases FRC contains individual type of fibres, which includes steel, polypropylene, glass, carbon, polyolefin and polyvinyl. Although extensive research is conducted on the FRC, the reviewed literature showed a dearth of research conducted on waste fibre. The reviewed literature highlighted that the research conducted on the use of waste fibre in concrete is limited to the effect of waste fibre on toughness, flexural strength, compression strength and post-peak behaviour of concrete elements. In addition, this chapter reported on the use of two or more types of fibres in a suitable combination which has proved the potential to improve the mechanical properties of concrete. Numerous studies on hybrid fibre reinforced concrete have been performed. The reviewed literature showed that combination of fibres is commonly limited to two types of mixes, a mix of steel and polypropylene fibres and a mix of steel fibres with different geometry, shape and size. It is recommended that more mixes should be analysed to identify the degree of enhancement in the mechanical properties associated with various fibre combinations.

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