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ADVANCED FIBER REINFORCED CONCRETE(FRC): MULTISCALE MECHANICS, DURABILITY AND EMERGING PARADIGMS

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Abstract: This paper presents the results from an experimental program and an analytical assessment of the influence of test data for various mechanical properties of steel fiber-reinforced concrete have been presented. The various strength properties studied are cube and cylinder compressive strength, split tensile strength, modulus of rupture and post cracking performance, modulus of elasticity, Poisson's ratio, and strain corresponding to peak compressive stress. The variables considered are grade of concrete, namely, normal strength _35 MPa_, moderately high strength _65 MPa_, and high-strength concrete _85 MPa_, and the volume fraction of the fiber _Vf =0.0, 0.5, 1.0, and 1.5%_. The strength of steel fiber-reinforced concrete predicted using the proposed models have been compared with the test data from the present study and with various other test data reported in the literature. The proposed model predicted the test data quite accurately. The study indicates that the fiber matrix interaction contributes significantly to enhancement of mechanical properties caused by the introduction of fibers, which is at variance with both existing models and formulations based on the law of mixtures.

INTRODUCTION

Concrete is the world's most consumed construction material, valued for its high compressive strength, durability, and economy. However, its inherent brittleness, low tensile strength, and susceptibility to cracking severely limit its performance. While traditional steel and synthetic fibers successfully improve concrete's mechanical properties through fiber-bridging action across microcracks, these conventional materials present major drawbacks. Steel reinforcement is highly vulnerable to water and chloride ion attacks leading to corrosion—the primary cause of global infrastructure deterioration and massive repair costs. Meanwhile, synthetic fibers are expensive and energy-intensive to produce. Furthermore, the construction sector accounts for a massive depletion of non-renewable resources and 30% of global carbon dioxide emissions, driving an urgent regulatory push for sustainable, low-waste alternatives.

Natural fiber-reinforced concrete offers an eco-friendly, cost-effective solution to overcome the brittleness of plain concrete. Plant-based natural fibers—primarily composed of cellulose and lignin—are strongly preferred over animal or mineral variants due to their superior strength, stiffness, low density, and lack of associated health risks. Incorporating readily available fibers like sisal, coir, hemp, and sugarcane requires minimal extraction energy and significantly enhances the material's tensile strength, toughness, fatigue capacity, and impact resistance.

Among these alternatives, jute stands out as one of the most durable and affordable natural fibers. As the world's second most produced textile fiber, it offers high tensile strength, renewability, and biodegradability. Research indicates that adding specific aspect ratios and small volume fractions of jute fibers improves the compressive, tensile, and flexural strengths of concrete, while also enhancing its ductility and seismic resistance. Although challenges remain regarding the degradation of natural fibers in alkaline cement environments and their impact on the workability of fresh concrete, jute represents a highly promising, sustainable reinforcement agent for modern construction. [1]

It is known that concrete is a relatively brittle material.Reinforcement of concrete with randomly distributed short fibers may improve the toughness of cementitious matrices by preventing or controlling the initiation, propagation, or coalescence of cracks . The fibers used are mainly steel fibers, carbon fibers, and polymer fibers. Among the polymer fibers, polypropylene (PP) fibers have attracted most attention due to the outstanding toughness of concrete reinforced with them . However, concrete is a complex material with multiphases. The phases include large amount of C-S-H gel in micron-scale size, sands in millimeter-scale size, and coarse aggregates in centimeter-scale size. Thus,the properties of concrete will be improved in certain level,but not whole levels if reinforced only by one type of fiber. [2]

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SCOPE OF DISCUSSION

Intending to be as brief as is consistent with the goals of the presentation, the discussion is divided into four parts: Fiber-reinforced Portland cement concrete composite technology,Mechanics of behavior, Testing and performance evaluation, and Value-added applications.The breadth of FRC formulations and applications makes clear the fact that consideration of either the mechanics of behavior or the performance of FRC in a strictly generic sense, ie.fibers in concrete, is an unproductive over-simplification.Instead it is necessary to establish subcategories within the generic concept of FRC and to establish associated terminologies.

Even wh ile stressing the differences among types of FRC, both contemporary and historical thinking on the subject point to a somewhat unified, if not singular, notion as to how fibers act to improve the performance of brittle-matrix Portland cement concrete. Accordingly, the discussion seeks to integrate seemingly diverse FRC historical developments as a basis for understanding the mechanical behavior.

tion as well as the fiber material type, fiber geometry, fiber distribution, fiber orientation and fiber concentration.

Correspondingly, it is expected that more than one mechanical behavior theory could aptly model the performance of a particular FRC formulation. Likewise,while the phrase FRC is useful generic terminology, most often these materials do not permit simple generic descriptions when seeking to determine material properties needed for engineering analysis and design.Much of the discussion incorporates what has been reported in published state-of-the-art reports,“74 books,5-7 and special publications which are available worldwide. However, the discussion also contains concepts and a point of view based on experience through long association with the subject, especially on the matter of performance testing and evaluation. Finally, the section on applications is not intended to be exhaustive but selected applications are included as a means of demonstrating the utility of applying the energy concepts of the previous discussion. A complete compilation of potential applications is left to the imagination of the reader.The following terminology has been widely accepted as being useful when describing the great variety of FRC composites. [3]

EXPERIMENTAL PROGRAM

Materials : The cement used in all concrete mixes was normal Portland cement which corresponds to ASTM Type I. The sand used was local natural sand with specific gravity of 2.65. The coarse aggregate was crushed limestone with a maximum size of 15 mm and specific gravity of 2.70.Properties of the carbon, steel, and PP fibers are shown in Table 1. The carbon and PP fibers were smooth and straight,while the steel fibers were hooked end.

Table 1
Properties of carbon, steel, and PP fibers

	Carbon	Steel	pp
Length (mm)	5	30	15
Diameter (mm)	7	500	100
Density (g/cm3)	1.6	7.8	0.9
Modulus (GPa)	240	200	8
Elongation at break (%)	1.4	3.2	8.1
Tensile strength (MPa)	2500	1500	800

Table 2 presents the control concrete mix proportions used in the testing program. For the concretes containing fibers, the dosage of superplasticizer was increased properly to maintain the slump around 160 mm. The mixtures were batched in 30-l vertical axis concrete mixer. The cement,sand, and fibers were dry-mixed for 30 s. This was followed by the addition of coarse aggregate, water, and the super plasticizer, with a mixing time of 5 min. After pouring the mix into oiled molds, a vibrator was used to decrease the amount of air bubbles. The specimens were demolded after 1 day and then placed in a curing room with 90% relative humidity and 23 _C for 27 days of curing. For 12 h prior to the tests, the specimens were allowed to air dry in the laboratory.

Testing procedures:
For each mixture, nine specimens (six 100_100-mm cubes and three 100_100_500-mm beams) were prepared.The compressive and splitting tensile tests were carried out on the 100_100-mm cube specimens. The four-point loading flexural tests were carried out at a loading rate of 0.05 mm/min on the 100_100_500-mm beams according to the

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requirements of ASTM C 1018. During the flexural tests, the load and the midspan deflection were recorded on a computerized data recording system, and the load–displacement curve was drawn on a printer. [2]

Table 2
Concrete mix proportions

Material	Quantity
Type I cement (kg/m3)	490
Sand (kg/m3)	684
Crushed limestone (kg/m3)	1024
Water (kg/m3)	196
Superplasticizer (kg/m3)	2.5
Slump (mm)	160

MECHANICAL BEHAVIOR MODELS FOR FRC

Most often energy theories are only indirectly considered by design engineers. This may be due to valid criticism based on mathematical difficulties. However, qualitative application of energy concepts are useful in relation to modelling FRC behavior. By doing so the analyst can relate energy concepts to the more familiar classical methods of mechanics such as are applied in the analysis of conventional reinforced concrete.

Historical analytical development:
The development of FRC that began three decades ago was not based on the traditionalconcept of reinforced concrete. It was based on a fracture mechanics concept whereby the strength of a brittle Portland cement concrete could be improved by reinforcing the matrix with closely spaced continuous wires.' The operative term was closely spaced.

There was evidence that the improvement in strength of a filament-reinforced composite disappeared as the filament spacing increased. Initial tests were based on closely spaced continuous wire filament but further testing using discrete fibers produced the same result: no strength improvement with increased spacing.2 Fibers suitable for testing purposes, first steel and soon after polypropylene, were not readily available in the early stages of research. Sources were identified from diverse industries including the automobile tire manufacturing and textile industries. FRC was produced and laboratory experiments were conducted but there was little that could be done to control or vary the fiber geometry component of the concrete. The first fibers tested were relatively coarse, 6 to 10 mil (0.15 to 0.25mm) diameter, and were thus relatively stiff. Mixing and casting problems were evident. Coarse, stiff fibers could not conveniently, and sometimes not even inconveniently,be distributed in a batch mix concrete such that there would result a close enough spacing' of distributed fiber to produce the desired improvement in composite strength as fracture mechanics would predict. However,when suitable mixtures could be made in the laboratory, a statistically significant improvement in strength was found in both the pre- and post-cracking behavior of the composite.

The fiber spacing misnomer:
The phrase 'close enough as it refers to the spacing of fibers needs to be examined. The phrase is most naturally understood according to its literal implied spatial reference. While the fiber spacing concept was at the root of early FRC development, strict reference to spacing in its literal meaning is an over-simplification and somewhat misleading.The term Close enough spacing' is a misnomer because is does not consider factors affecting fiber efficiency other than fiber spacing.Close enough spacing for FRC in a broader interpretation is that which is required to guarantee that a propagating crack is affected so as to be stopped or at least slowed in its advancement.

Close enough spacing includes the probability that further energy input to the composite system will either be absorbed or redirected to areas of lesser fracture toughness. This behavior is truly a form of matrix strengthening. The matrix itself continues to conduct the load (stress) while on the ascending (strain hardening) or the descending (strainsoftening) portions of the material's load/deflection response.

The crack arrest mechanism for FRC is similar to the manner in which aggregate fillers absorb energy and are known to arrest microcracks in concrete. It appears, however, that benefits attributable to fibers accrue to the brittle matrix in amounts exceeding that which is predicted by the law of mixtures. In addition to a fiber's strength and elastic properties,improved fiber efficiency is related to bond or anchorage and the potential for energy absorption through the accumulated effect of the number of fibers, their specific surface, and their orientation within the matrix.The number of fibers in a unit volume of matrix material, i.e. the fiber count, FC, is directly related to the statistical probability of cracks

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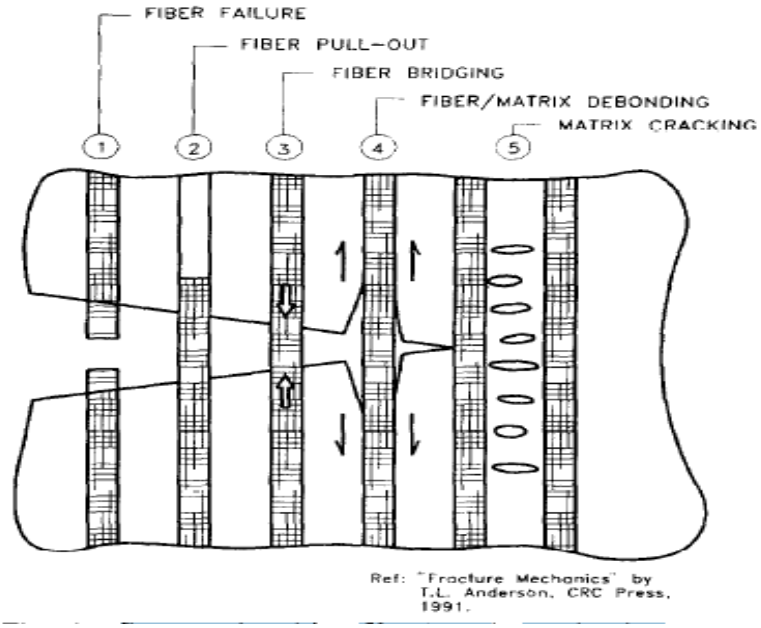
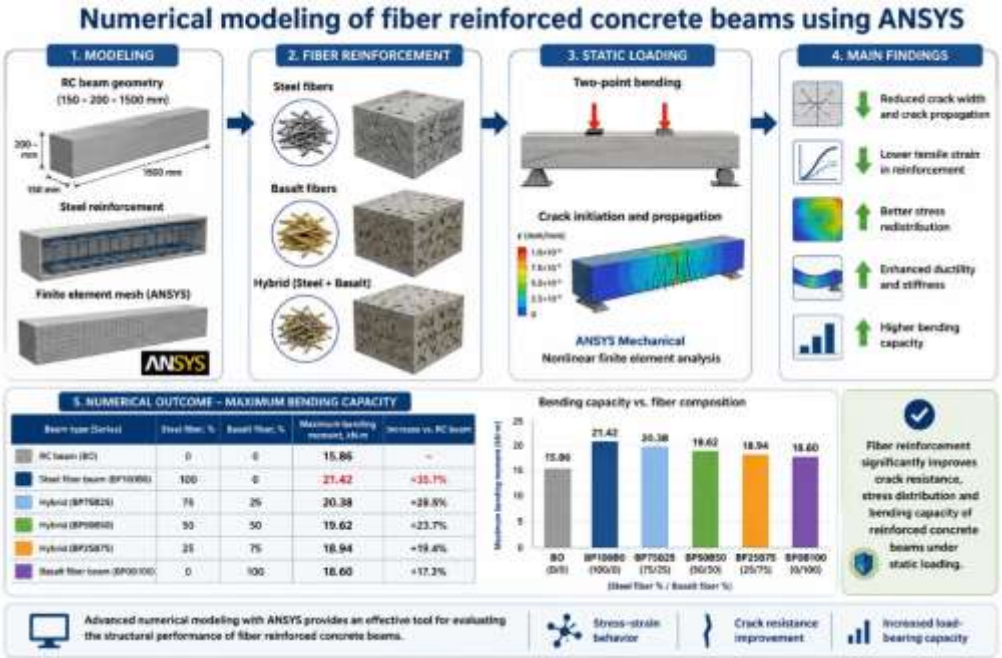
encountering fibers. The fiber specific surface, FSS, is directly related to the amount of energy that is absorbed in encounters between cracks and fibers. In this way weak brittle matrices can be improved, some would say strengthened, to provide a measure of postcracking toughness.



Fig,1 (T.L. Anderson 1991)

The schematic diagram of Fig, 1 demonstrates the ways in which fibers act to absorb energy and control crack growth. Starting from the leftmost fiber element in the figure and proceeding along the crack towards the right there is represented fiber rupture, fiber pull-out, fiber bridging by tension through the fiber, and debonding at the fiber/matrix interface,respectively. These mechanisms do not depend on fiber spacing and they are effective, albeit in insignificantly small amounts, even for a single fiber. It is the cumulative effect, however, of large numbers of fibers located in the restricted topography of the brittle paste phase of the typical concrete composite that has been shown to be significant [3]



Fig(Akmaljon Akhmedov)2026

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DURABILITY OF NATURAL FIBER

Durability of natural fi ber reinforced concrete is related to the ability to resist both external (temperature and humidity variations, sulfate or chloride attack, etc.) and internal damage (compatibility between fi bers and cement matrix, volumetric changes, etc). The degradation of natural fi bers immersed in Portland cement is due to the high alkaline environment that dissolves the lignin and hemicellulose phases,thus weakening the fi ber structure (Gram, 1983). Gram was the fi rst author to study the durability of sisal and coir fi ber reinforced concrete. The fi ber degradation was evaluated by exposing them to alkaline solutions and then measuring the variations in tensile strength. This author reported a deleterious effect of Ca 2+ elements on fi ber degradation. He also stated that fi bers were able to preserve their fl exibility and strength in areas with carbonated concrete with a pH of 9 or less. Filho et al. (2000) also investigated the durability of sisal and coconut fi bers when immersed in alkaline solutions. Sisal and coconut fi bers conditioned in a sodium hydroxide solution retained, respectively, 72.7% and 60.9% of their initial strength after 420 days. As for the immersion of the fi bers in a calcium hydroxide solution, it was noticed that the original strength was completely lost after 300 days. According to those authors, the explanation for the higher attack by Ca(OH) 2 can be related to a crystallization of lime in the fi bers' pores. Ramakrishna and Sundararajan (2005a) also reported degradation of natural fi ber when exposed to alkaline media. Other authors studied date palm reinforced concrete, reporting low durability performance that is related to fi ber degradation when immersed in alkaline solutions (Kriker et al. , 2008). Ghavami (2005) reported the case of a bamboo-reinforced concrete beam which was 15 years old and without deterioration signs. Lima et al. (2008) studied the variations of tensile strength and Young's modulus of bamboo fi ber reinforced concrete exposed to wetting and drying cycles, reporting insignifi cant changes, thus confi rming its durability. The capacity of natural fi bers to absorb water is another path to decreasing the durability of fi ber reinforced concrete. Water absorption leads to volume changes that can induce concrete cracks (Ghavami, 2005; Agopyan et al. , 2005). In order to improve the durability of fi ber reinforced concrete, the two following paths could be used:

Matrix modification:
Using low alkaline concrete and adding pozzolanic by-products such as rice husk ash, blast furnace slag, or f y ashes to Portland cement (Gutiérrez et al. , 2005;

Agopyan et al. , 2005; Savastano et al. , 2005a). Results show that the use of ternary blends containing slag/metakaolin and silica fume are effective in preventing degradation (Mohr et al. , 2007). But in some cases the low alkalinity is not enough to prevent lignin from being decomposed (John et al. , 2005).

Other authors reported that fast carbonation can induce lower alkalinity (Agopyan et al. , 2005). These results are confirmed by others that used artificial carbonation in order to obtain CaCO 3 from Ca(OH) 2 leading to increased strength and reduced water absorption (Tonoli, 2010a). The use of cement-based polymers can contribute to increased durability (Pimentel, 2006). D'Almeida (2009) used blends where 50% of Portland cement was replaced by metakaolin to produce a matrix totally free of calcium hydroxide in order to prevent migration of calcium hydroxide to the fi ber lumen, middle lamella and cell walls and thus avoid embrittlement behavior.

Fiber modification:
Coating natural fi bers to avoid water absorption and free alkalis . Use water repellent agents or fi ber impregnation with sodium silicate, sodium sulphite, or magnesium sulphate. Ghavami (1995) reported that using a water-repellent in bamboo fibers allowed only 4% water absorption. The use of organic compounds such as vegetable oils reduced the embrittlement process, but not completely (Filho et al. , 2003). Recent findings report that silane coating of fibers is a good way to improve the durability of natural-fiber reinforced concrete (Bilba and Arsene, 2008). Other authors mentioned that using pulped fi bers may improve durability performance (Savastano et al. , 2001). Some even reported that a fi ber extraction process can prevent durability reductions (Juárez et al. , 2007). The use of compression and temperature (120, 160 and 200°C) leads to an increase of fi ber stiffness and a decrease of fi ber moisture absorption (Motta, 2009). [4]

FIBER REINFORCED CEMENT AND CONCRETE (FRC) COMPOSITES

For practical purposes and mechanical modeling, as defined, fiber reinforced cement and/or concrete (FRC) composites are defined as composites with two main constituents, the fiber and the matrix (Fig.1). Generally the fiber is assumed to be discontinuous and, unless otherwise stated, randomly oriented and distributed within the volume of the composite. Both the fiber and the matrix are assumed to work together through bond, thus providing the synergism needed to make an effective composite. The matrix, whether it is a paste (cement mixed with water), mortar (paste with sand), or concrete (mortar with coarse aggregates) is assumed to contain all the aggregates and additives specified. A concrete matrix is

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supposed to contain large size aggregates, say with an equivalent diameter in excess of 8 mm (3/8 in). A mortar matrix generally contains sand (of mostly less than 3 mm (1/8 in)) but no large size aggregates. A cement paste may contain very fine sand, silica powder, fly ash, silica fume, and other fine additives. Air voids entrapped in the matrix during mixing are assumed to be also part of the matrix (Fig. 1). For simplicity, unless otherwise specifically noted, the term "concrete" will be generally used to represent a cementitious matrix whether it is a paste, a mortar or a concrete.

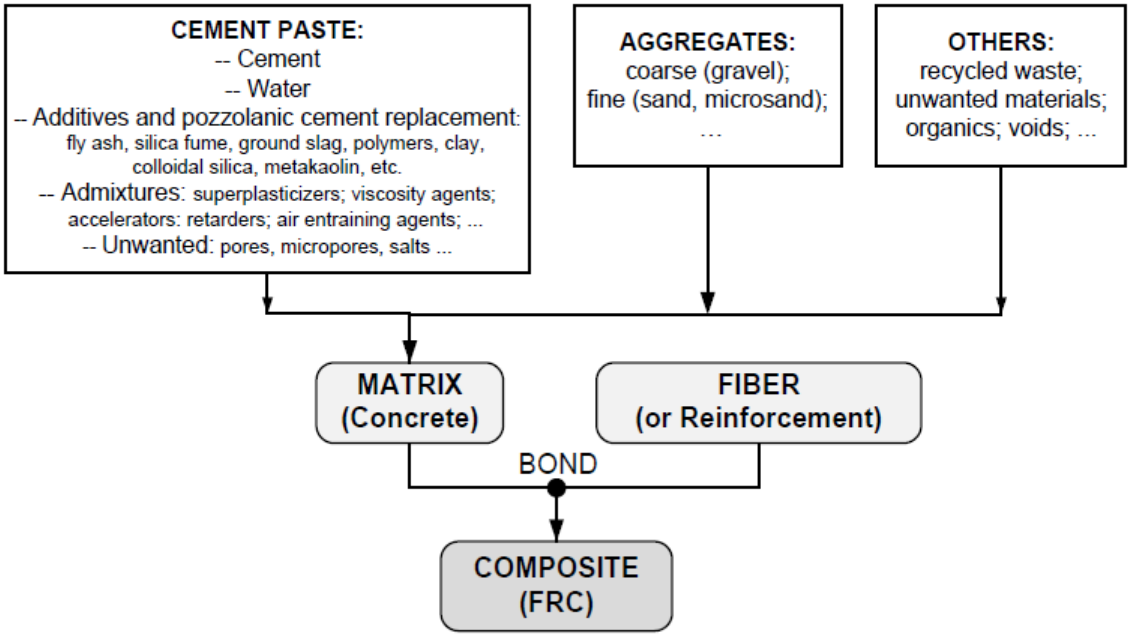

Fig .2(a)[Naaman,2018]

Thus from the broadest perspective, fiber reinforced concrete can be defined as follows:

Fiber reinforced concrete (FRC) is concrete with suitable discontinuous fibers added to it for the purpose of achieving a desired level of performance in a particular property (or properties).

If the fibers are continuous, a different terminology is used to describe the composite such as ferrocement, textile reinforced concrete (TRC), or laminate cementitious composites which use continuous reinforcements made out of continuous wires, textiles, or meshes. Reinforced and prestressed concrete (RC and PC) are also considered composites with continuous reinforcements mostly made out of steel rebars or prestressing strands, but other reinforcing materials (such as fiber reinforced polymer (FRP) reinforcements) are also used.

It illustrates how the combination of a concrete matrix with reinforcement, be it continuous or discontinuous, leads to various structural composites developed since the mid nineteenth century; these include the most broadly used structural materials worldwide, namely reinforced and prestressed concrete.

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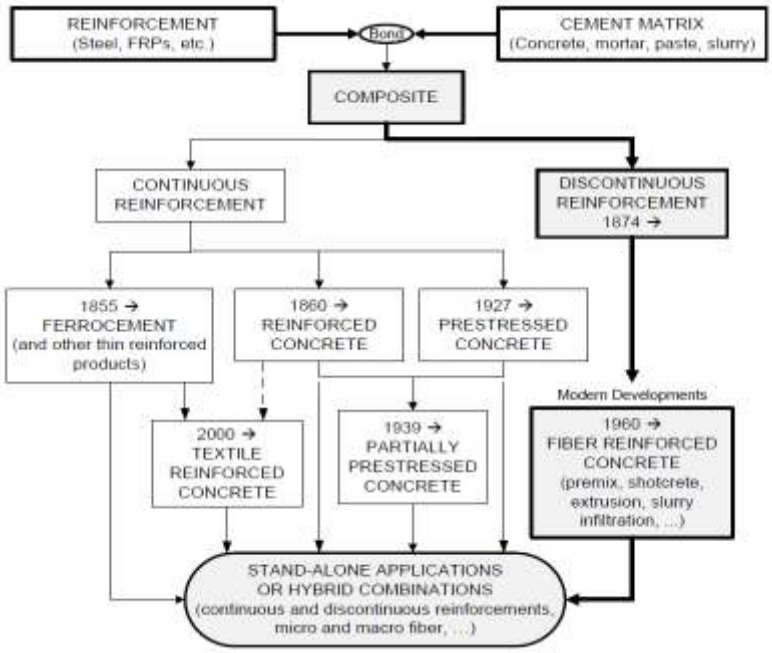

fig.2(b)[Naaman,2018]

modern fiber reinforced concrete started in the early 1960s; here, modern implies the use of a scientific approach to better understand the fundamental properties of the composite. At time of this writing, fiber reinforced concrete has gained a place of its own in the family of structural concrete materials. Figure 2 illustrates its position within that group. It can be observed that fiber reinforced concrete can be used on its own or in combination with reinforced concrete (RC), prestressed concrete (PC), or ferrocement, thus leading to a hybrid composite containing both discontinuous fibers and continuous reinforcements. Hybrid composites also include the use of fibers of different materials and/or different geometric and mechanical properties (not addressed in this paper). [5]

DEVELOPMENT OF FIBERS FOR CONCRETE AND FIBER REINFORCED CONCRETE

Two distinct time periods seem to characterize the pace of development of fibers specifically intended for concrete. The first period, prior to the 1960's, corresponds to a slow pioneering phase with many ideas but almost no applications, while the second period, since the early 1960's corresponds to a phase of more rapid and modern developments paralleled by increasing applications.

The first period (1874-1960) can be considered a dormant period during which many patents were submitted on the subject but were not technically convincing since they claimed an increase in tensile or bending resistance by addition of fibers, but only deflection softening behavior was observed from limited experimental tests . The second time period termed modern development started with a scientifically based study by Romualdi et al. in the early 1960's; while it also claimed the increase in tensile strength of the composite by fiber addition, it mainly brought awareness of the increase in fracture resistance of the composite. This became a starting point for an intense number of fundamental analytical and experimental studies on the mechanics and behavior of the composite. This second phase was accompanied by the increasing use of modern scientific methods to better understand the reinforcing mechanisms of the fibers, the role of bond, and the contribution of the two main constituent materials. Eventually not only the significant increase in fracture toughness was discovered as the most important benefit of fiber addition, but also researchers were able to develop composites with tensile and bending strengths way higher than those of the matrix alone; thus in effect satisfying what early patents have claimed but could not achieve due to lack of fundamental research. The right side of is to be correlated with below where additional details (SS, SH, DS, DS) are explained.

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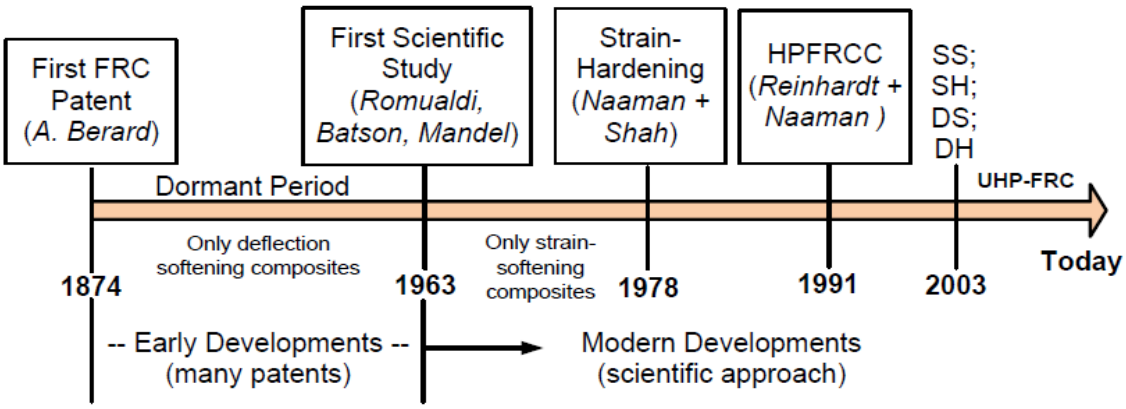

Fig 3(Naaman ,2018)

Numerous patents on fiber reinforced concrete have been granted. They generally address one or a combination of the following: the fiber itself, the fiber reinforced concrete mix, the production process, and the application. A selective number is reviewed and summarized next to illustrate the underlying idea behind each patent and the evolution of new ideas with time.

PIONEERING DEVELOPMENTS: 1874 – 1960

The first patent (1874) on fiber reinforced concrete seems to be due to A. Berard from California who suggested the use of granular waste iron in a concrete mix to create an artificial stone. A similar idea suggesting the use of steel shavings and metal scraps was patented by J.C. Seailles in France, in 1920. In 1911, G.M. Graham (US) suggested the use of steel fibers (short cut steel wires) in addition to conventional reinforcement to increase the strength and stability of reinforced concrete

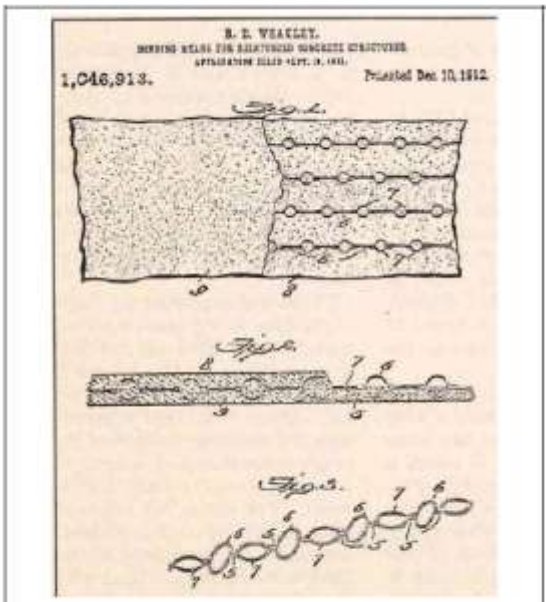

Figure 4 *Weakley*'s two-dimensional steel fiber made out of two wires (US Patent 1912).

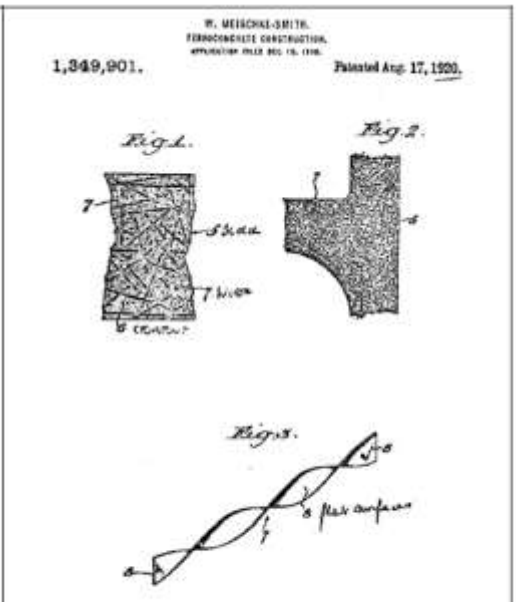

Figure 5 *Meischke-Smith* flat twisted steel fiber (US Patent 1920).

A French patent dated 1918 by H. Alfsen describes a process to improve the tensile strength of concrete by uniformly mixing small longitudinal bodies (fibers) of iron, wood or other materials. It also suggests that the surface of these fiber elements must be rough or roughened and, if possible, their ends bent in order to provide better adherence to the concrete

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R. Weakly (Missouri) obtained a patent in 1912 for using steel fibers made out of two wires and containing loops to secure a durable bond with concrete (Fig. 4). Weakly's fibers were two-dimensional; a tridimensional steel fiber is described farther below.

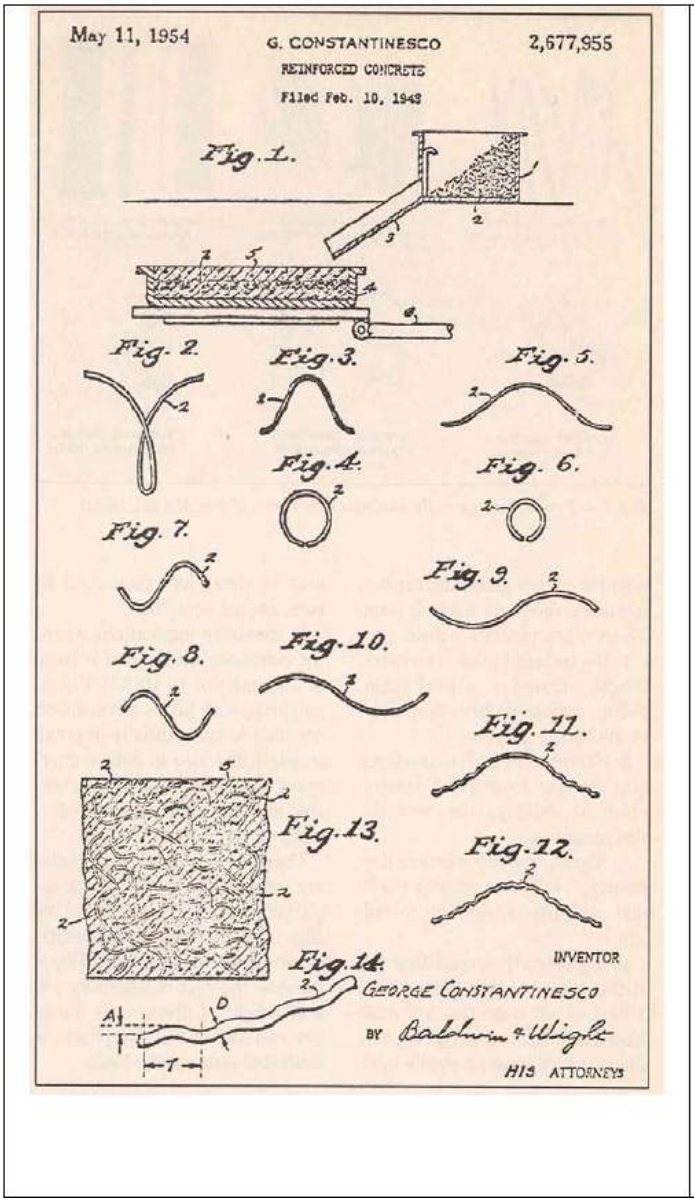

Fig. 6 (martin)

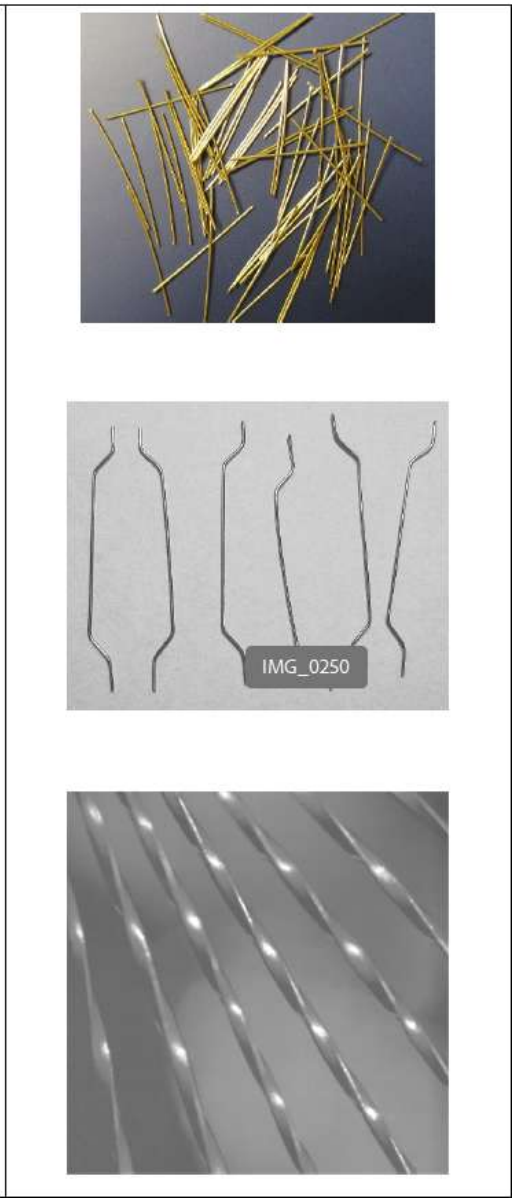

Fig 7(H.Etheridge)

In 1920, A. Kleinlogel from Germany filed a patent for mixing a relatively large volume of iron particles (up to 50% of 2 mm long steel fibers) with concrete in order to produce a moldable mass capable of being chilled, turned, sawed, and filed similarly to an iron mass.

Two relevant patents were granted in California in the 1920's. Meischke-Smith's patent (Fig. 5) describes the use of flat twisted pieces of wires as fiber reinforcement for concrete mixtures. Martin's patent (Fig. 6) describes the use of plain or crimped pieces of steel wires mixed with concrete to strengthen concrete pipes The idea of improving the shape of the fiber to increase its contribution was pushed one step further by H. Etheridge (New Jersey, 1933) who proposed adding "annuli" fibers (Fig. 7) of different sizes and diameters to improve the crack resistance and fatigue of concrete for use in railway ties. He wrote: "The object that I have in view is the prevention of local cracks and fractures and I accomplish such object by mixing with the plastic concrete a mass of metal annuli in sufficient quantity to effect coupling of what I may term the 'stitching' together of the adjacent masses of concrete...". [5]

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CONCLUSION

Two time periods mark the history of fiber reinforced concrete. The pioneering period started in 1874 and claimed strengthening of concrete (in tension or bending) by addition of fibers; but that claim could not be confirmed by test results. Thus the first period saw little progress for almost a century and can be described as technically dormant. The modern period started in the 1960's whereas initial attention focused on the claim that fibers increase the fracture energy of the composite. This drew enormous interest from the technical profession. Fundamental studies and research led to a better understanding of the effect of fibers on energy absorption capacity and all other properties, eventually leading to the development of FRC composites with tensile and bending resistance higher than those of the matrix. It also led to a simple classification of all FRC composites based on their tensile response leading to the qualifiers: "strain-softening" or "strain-hardening", and consequently "deflection-softening" or "deflection-hardening." With the increasing penetration of ultra-high performance concrete (UHPC) and fiber reinforced concrete (UHP-FRC) and the introduction of enhanced fiber materials, progress will continue. "The engineering dream and challenge that started in the 1870's, that is, to mix fibers into concrete like sand or aggregates to create an isotropic, homogeneous, moldable, strong, ductile and durable composite for construction applications with comparable strength and ductility as reinforced concrete, is today closer than ever"

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