Fibre reinforced concrete

1. Introduction

Concrete made with portland cement has certain characteristics: it is relatively strong in compression but weak in tension and tends to be brittle. The weakness in tension can be overcome by the use of conventional rod reinforcement and to some extent by the inclusion of a sufficient volume of certain fibres. The use of fibres also alters the behaviour of the fibre-matrix composite after it has cracked, thereby improving its toughness.

This leaflet aims to provide information on the properties of the more commonly available fibres and their uses to produce concrete with certain characteristics. Some new developments are discussed.

2. The concept of toughness

Toughness is defined as the area under a load-deflection (or stress-strain) curve. As can be seen from Figure 1, adding fibres to concrete greatly increases the toughness of the material. That is, fibre-reinforced concrete is able to sustain load at deflections or strains much greater than those at which cracking first appears in the matrix.

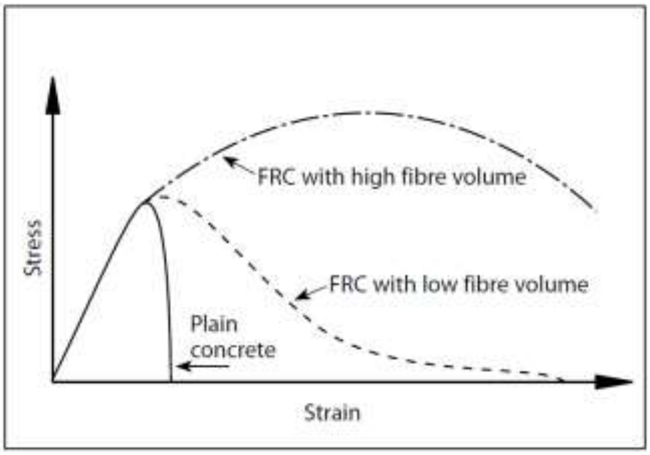

Figure 1: Typical stress-strain curves for fibre-reinforced concrete

3. The use of fibres

For the effective use of fibres in hardened concrete:

- Fibres should be significantly stiffer than the matrix, i.e. have a higher modulus of elasticity than the matrix.
- Fibre content by volume must be adequate.
- There must be a good fibre-matrix bond.
- Fibre length must be sufficient.
- Fibres must have a high aspect ratio, i.e. they must be long relative to their diameter.

It should be noted that published information tends to deal with high volume concentrations of fibre. However, for economic reasons, the current trend in practice is to minimise fibre volume, in which case improvements in properties may be marginal.

For the quantities of fibres typically used (less than 1% by volume for steel and about 0,1% by volume for polypropylene) the fibres will not have significant effect on the strength or modulus of elasticity of the composite. It is thus important to evaluate published test data and manufacturer’s claims carefully.

It must also be noted that high volume concentrations of certain fibres may make the plastic concrete unworkable.

4. Types of fibre

In this section each of the most commonly used fibre types is discussed, giving information on the manufacture of the fibre, its properties, fibre content in applications and the effects of the fibre type on concretes and mortars.

4.1. Glass

In the form first used, glass fibres were found to be alkali reactive and products in which they were used deteriorated rapidly. Alkali-resistant glass containing 16% zirconia was successfully formulated in the 1960's and by 1971 was in commercial production in the UK. Other sources of alkali-resistant glass were developed during the 1970's and 1980's in other parts of the world, with higher zirconia contents. Alkali-resistant glass fibre is used in the manufacture of glass-reinforced cement (GRC) products, which have a wide range of applications.

Glass fibre is available in continuous or chopped lengths. Fibre lengths of up to 35-mm are used in spray applications and 25-mm lengths are used in premix applications.

Glass fibre has high tensile strength (2 – 4 GPa) and elastic modulus (70 – 80 GPa) but has brittle stress-strain characteristics (2,5 – 4,8% elongation at break) and low creep at room temperature. Claims have been made that up to 5% glass fibre by volume has been used successfully in sand-cement mortar without balling.

Glass-fibre products exposed to outdoor environment have shown a loss of strength and ductility. The reasons for this are not clear and it is speculated that alkali attack or fibre embrittlement are possible causes. Because of the lack of data on long-term durability, GRC has been confined to non-structural uses where it has wide applications. It is suitable for use in direct spray techniques and premix processes and has been used as a replacement for asbestos fibre in flat sheet, pipes and a variety of precast products. GRC products are used extensively in agriculture; for architectural cladding and components; and for small containers.

4.2. Steel

Steel fibres have been used in concrete since the early 1900s. The early fibres were round and smooth, and the wire was cut or chopped to the required lengths. The use of straight, smooth fibres has largely disappeared, and modern fibres have either rough surface, hooked ends or are crimped or undulated through their length. Modern commercially available steel fibres are manufactured from drawn steel wire, from slit sheet steel or by the melt-extraction process which produces fibres that have a crescent-shaped cross section. Typically, steel fibres have equivalent diameters (based on cross sectional area) of from 0,15 mm to 2 mm and lengths from 7 to 75 mm. Aspect ratios generally range from 20 to 100. (Aspect ratio is defined as the ratio between fibre length and its equivalent diameter, which is the diameter of a circle with an area equal to the cross-sectional area of the fibre).

Carbon steels are most commonly used to produce fibres, but fibres made from corrosion-resistant alloys are available. Stainless steel fibres have been used for high-temperature applications.

Some fibres are collated into bundles using water-soluble glue to facilitate handling and mixing.

Steel fibres have high tensile strength (0,5 – 2 GPa) and modulus of elasticity (200 GPa), a ductile/plastic stress-strain characteristic and low creep.

Steel fibres have been used in conventional concrete mixes, shotcrete, and slurry-infiltrated fibre concrete. Typically, content of steel fibre ranges from 0,25% to 2,0% by volume. Fibre contents in excess of 2% by volume generally result in poor workability and fibre distribution, but can be used successfully where the paste content of the mix is increased, and the size of coarse aggregate is not larger than about 10 mm.

Steel-fibre-reinforced concrete containing up to 1,5% fibre by volume has been pumped successfully using pipelines of 125 to 150 mm diameter. Steel fibre contents up to 2% by volume have been used in shotcrete applications using both the wet and dry processes. Steel fibre contents of up to 25% by volume have been obtained in slurry-infiltrated fibre concrete.

Concretes containing steel fibre have been shown to have substantially improved resistance to impact and greater ductility of failure in compression, flexure and torsion.

Similarly, it is reported that the elastic modulus in compression and modulus of rigidity in torsion are no different before cracking when compared with plain concrete tested under similar conditions. It has been reported that steel-fibre-reinforced concrete, because of the improved ductility, could find applications where impact resistance is important. Fatigue resistance of the concrete is reported to be increased by up to 70%.

It is thought that the inclusion of steel fibre as supplementary reinforcement in concrete could assist in the reduction of spalling due to thermal shock and thermal gradients.

The lack of corrosion resistance of normal steel fibres could be a disadvantage in exposed concrete situations where spalling and surface staining are likely to occur.

4.3. Synthetic fibres

Synthetic fibres are man-made fibres resulting from research and development in the petrochemical and textile industries. There are two different physical fibre forms: monofilament fibres, and fibres produced from fibrillated tape. Currently there are two different synthetic fibre volumes used in application, namely low-volume percentage (0,1 to 0,3% by volume) and high-volume percentage (0,4 to 0,8% by volume). Most synthetic fibre applications are at the 0,1% by volume level. At this level, the strength of the concrete is considered unaffected and crack control characteristics are sought.

Fibre types that have been tried in cement concrete matrices include: acrylic, aramid, carbon, nylon, polyester, polyethylene and polypropylene. Table 1 summarises the range of physical properties of some synthetic fibres.

4.3.1. Acrylic

Acrylic fibres have been used to replace asbestos fibre in many fibre-reinforced concrete products. In this process fibres are initially dispersed in a dilute water and cement mixture. A composite thickness is built up in layers using a pressure forming process and vacuum dewatering. Acrylic fibres have also been added to conventional concrete at low volumes to reduce the effects of plastic-shrinkage cracking.

4.3.2. Aramid

Aramid fibres are two and a half times as strong as glass fibres and five times as strong as steel fibres, per unit mass. Due to the relatively high cost of these fibres, aramid-fibre-reinforced concrete has been primarily used as an asbestos cement replacement in certain high-strength applications.

Table 1: Selected synthetic fibre types and properties*

Fibre type	Equivalent diameter µm	Relative density	Tensile strength MPa	Elastic modulus GPa	Ultimate elongation %	Ignition temperature °C	Melt, oxidation, or decomposition temperature °C	Water absorption per ASTM D 570, % by mass
Acrylic	13 - 104	1,16 - 1,18	270 - 1 000	14 - 19	7,5 - 50,0	-	220 - 235	1,0 - 2,5
Aramid I	12	1,44	2 900	60	4,4	high	480	4,3
Aramid II†	10	1,44	2 350	115	2,5	high	480	1,2
Carbon, PAN HMΔ	8	1,6 - 1,7	2 500 - 3 000	380	0,5 - 0,7	high	400	nil
Carbon, PAN HT§	9	1,6 - 1,7	3 450 - 4 000	230	1,0 - 1,5	high	400	nil
Carbon, pitch GP**	10 - 13	1,6 - 1,7	480 - 790	27 - 35	2,0 - 2,4	high	400	3 - 7
Carbon, pitch HP††	9 - 18	1,8 - 2,15	1 500 - 3 100	150 - 480	0,5 - 1,1	high	500	nil
NylonΔΔ	23	1,14	970	5	20	-	200 - 220	2,8 - 5,0
Polyester	20	1,34 - 1,39	230 - 1 100	17	12 - 150	600	260	0,4
PolyethyleneΔΔ	25 - 1 000	0,92 - 0,96	75 - 590	5	3 - 80	-	130	nil
PolypropyleneΔΔ	-	0,90 - 0,91	140 - 700	3,5 - 4,8	15	600	165	nil

Notes
* Not all fibre types are currently used for commercial production of FRC
† High modulus
Δ Polyacrylonitrile based, high modulus
§ Polyacrylonitrile based, high tensile strength
** Isotropic pitch based, general purpose
†† Mesophase pitch based, high performance
ΔΔ Data listed is only for fibres commercially available for FRC

4.3.3. Carbon

Carbon fibre is substantially more expensive than other fibre types. For this reason, its commercial use has been limited.

Carbon fibres are manufactured by carbonizing suitable organic materials in fibrous forms at high temperatures and then aligning the resultant graphite crystallites by hot stretching. The fibres are manufactured as either Type I (high modulus) or Type II (high strength) and are dependent upon material source and extent of hot stretching for their physical properties. Carbon fibres are available in a variety of forms and have a fibrillar structure similar to that of asbestos.

Carbon fibre made from petroleum and coal pitch is less expensive than the conventional carbon fibre made from fibrous materials. The Type I and II carbon fibres produced by carbonizing suitable organic materials other than petroleum-based materials are 20 to 40 times stronger and have a modulus of elasticity up to 100 times greater than the pitch-based carbon fibre.

Carbon fibre is available as continuous strands or as individual chopped fibres. Continuous strands are normally pre-placed and aligned to provide the optimum fibre orientation during fabrication. Chopped fibres are generally incorporated during the mixing process and are therefore orientated randomly throughout the mix. A satisfactory mix of chopped carbon fibre, cement and water is difficult to achieve because of the large surface area of the fibre. Research has shown that uniform dispersion of discontinuous low-modulus carbon fibre has been achieved using an omnimixer and admixture. Carbon fibre has high tensile strength and modulus of elasticity and a brittle stress-strain characteristic. Additional research is needed to determine the feasibility of carbon-fibre concrete on an economic basis. The fire-resistance properties of carbon-fibre composites need to be evaluated, but ignoring economics, structural applications appear promising.

4.3.4. Nylon

Nylon is a generic name that identifies a family of polymers. Nylon fibre's properties are imparted by the base polymer type, addition of different levels of additive, manufacturing conditions and fibre dimensions. Currently only two types of nylon fibre are marketed for concrete. Nylon is heat stable, hydrophilic, relatively inert, and resistant to a wide variety of materials.

Nylon is particularly effective in imparting impact resistance and flexural toughness and sustaining and increasing the load carrying capacity of concrete following first crack.

4.3.5. Polyester

Polyester fibres are available in monofilament form and belong to the thermoplastic polyester group. They are temperature sensitive and above normal service temperatures their properties may be altered. Polyester fibres are somewhat hydrophobic. Polyester fibres have been used at low contents (0,1% by volume) to control plastic-shrinkage cracking in concrete.

4.3.6. Polyethylene
Polyethylene has been produced for concrete in monofilament form with wart-like surface deformations. Polyethylene in pulp form may be an alternate to asbestos fibres. Concrete reinforced with polyethylene fibres at contents between 2 and 4% by volume exhibits a linear flexural load deflection behaviour up to first crack, followed by an apparent transfer of load to the fibres permitting an increase in load until the fibres break.

4.3.7. Polypropylene
Polypropylene fibre was first used to reinforce concrete in the 1960s. Polypropylene is a synthetic hydrocarbon polymer, the fibre of which is made using extrusion processes by hot - drawing the material through a die. Polypropylene fibres are produced as continuous monofilaments, with circular cross section that can be chopped to required lengths, or fibrillated films or tapes of rectangular cross section.

Polypropylene fibres are hydrophobic and therefore have the disadvantages of poor bond characteristics with cement matrix, a low melting point, high combustibility, and a relatively low modulus of elasticity. Long polypropylene fibres can prove difficult to mix due to their flexibility and tendency to wrap around the leading edges of mixer blades.

Polypropylene fibres are tough but have low tensile strength and modulus of elasticity; they have a plastic stress-strain characteristic.

Monofilament polypropylene fibres have inherent weak bond with the cement matrix because of their relatively small specific surface area. Fibrillated polypropylene fibres are slit and expanded into an open network thus offering a larger specific surface area with improved bond characteristics. Polypropylene fibre contents of up to 12% by volume are claimed to have been used successfully with hand-packing fabrication techniques, but volumes of 0,1% of 50-mm fibre in concrete have been reported to have caused a slump loss, of 75 mm.

Polypropylene fibres have been reported to reduce unrestrained plastic and drying shrinkage of concrete at fibre contents of 0,1 to 0,3% by volume.

4.4. Fabric and composite fibre reinforcement
South African manufacturers have been extremely innovative in developing versions of fibre for use with concrete.

To overcome the bond and elastic modulus problem of polypropylene fibres, one development has been that of a composite of a core fibre (which can be polypropylene or a stiffer material such as acrylic, Kevlar, glass, or carbon fibres) around which is spun a fluffy coating of polypropylene or cellulose. The coating can be bonded to the core at intervals to enhance the composite behaviour.

These composite strands can be woven into a textile or cut into appropriate lengths for a range of applications, especially thin elements such as permanent forms and decorative cladding units.

Table 2: Typical properties of natural fibres

Fibre type	Coconut	Sisal	Sugar cane bagasse	Bamboo	Jute	Flax	Elephant grass	Water reed	Plantain	Musamba	Wood fibre (Kraft pulp)
Fibre length, mm	50 - 100	N/A	N/A	N/A	175 - 300	500	N/A	N/A	N/A	N/A	2,5 - 5,0
Fibre diameter, mm	0,1 - 0,4	N/A	0,2 - 0,4	0,05 - 0,4	0,1 - 0,2	N/A	N/A	N/A	N/A	N/A	0,025 - 0,075
Relative density	1,12 - 1,15	N/A	1,2 - 1,3	1,5	1,02 - 1,04	N/A	N/A	N/A	N/A	N/A	1,5
Modulus of elasticity, GPa	19 - 26	13 - 26	15 - 19	33 - 40	26 - 32	100	5	5	1,5	1,0	N/A
Ultimate tensile strength, MPa	120 - 200	275 - 570	180 - 290	350 - 500	250 - 350	1 000	180	70	90	80	700
Elongation at break, %	10 - 25	3 - 5	N/A	N/A	1,5 - 1,9	1,8 - 2,2	3,6	1,2	5,9	9,7	N/A
Water absorption, %	130 - 180	60 - 70	70 - 75	40 - 45	N/A	N/A	N/A	N/A	N/A	N/A	50 - 75

Notes
N/A Properties not readily available or not applicable.

4.5 Natural fibres

Natural reinforcing materials can be obtained at low cost and low levels of energy using local manpower and technology. Utilization of natural fibres as a form of concrete reinforcement is of particular interest to less developed regions where conventional construction materials are not readily available or are too expensive. Sisal-fibre reinforced concrete has been used for making roof tiles, corrugated sheets, pipes, silos and tanks. Elephant-grass-reinforced mortar has been used for low-cost housing projects. Wood-cellulose-fibre reinforced cement has commercial applications in the manufacture of flat and corrugated sheet and non-pressure pipes. Typical properties of natural fibres are shown in Table 2.

Natural fibres can be either unprocessed or processed.

4.5.1 Unprocessed natural fibres

Products made with unprocessed natural fibres such as coconut coir, sisal, sugarcane bagasse, bamboo, jute, wood, and vegetable fibres have been tested in a number of countries. Problems have been reported with the long-term durability of some of the products.

The properties of concrete made using unprocessed natural fibres depend on a number of factors including the type and length of fibre as well as the volume fraction. To show some improvement in mechanical properties, the minimum fibre content is of the order of 3% by volume.

4.5.2 Processed natural fibres

Wood cellulose is the most frequently used natural fibre. It is most commonly obtained using the Kraft process. This process involves cooking wood chips in a solution of sodium hydroxide, sodium carbonate and sodium sulphide. Different grades of wood-cellulose fibre containing more or less of the three main constituents, cellulose, hemicellulose and ligna can be obtained by bleaching.

Wood-cellulose fibre has relatively good mechanical properties compared with many man-made fibres such as polypropylene, polyethylene, polyester and acrylic.

De-lignified cellulose fibre can be produced with tensile strengths up to approximately 2,0 GPa from selected grades of wood and using suitable pulping processes. Fibre tensile strengths of 500 MPa can be routinely obtained using a chemical pulping process and the more common, less expensive, grades of wood.

Using conventional mixing techniques, the amount of fibre that can be incorporated into the cement matrix at low water contents is limited by the capacity of the fibres to be mixed uniformly into the matrix. Fabrication techniques that involve mixing fibre with the matrix at initially high-water contents and then using dewatering procedures are therefore effective and common.

Wood-cellulose fibre that has not been de-lignified can adversely affect the curing of the cement matrix. This is because leaching of sugar and other organic impurities into the cement matrix can retard or completely inhibit cement set. Results obtained from autoclaved wood-cellulose cement composites indicate that such products can be sensitive to moisture content.

Published information on the performance of wood-cellulose fibre composites is conflicting. However, Bentur and Mindess state: "Although the strength and other properties of the cellulose-pulp fibre are inferior to those of many other fibres, such as asbestos, they are highly cost effective. This, combined with their compatibility with processes for producing asbestos cement, makes the cellulose-pulp fibres an attractive alternative to asbestos. As a result of intensive research and development, cellulose-pulp fibres are now used in some places as partial or full replacement for asbestos in cement composites."

4.6 New Developments

A development of the last few decades has been significant research activity and increasing application of high-performance fibre-reinforced cement-based composites (HPFRCC). This has led to design recommendations being proposed for these materials recently in Japan. Particular classes are ultra-high performance (UHPFRC) and strain-hardening (SHCC) fibre-reinforced cement-based composites. These composites are designed for particular applications varying from the requirement of high strength to that of high ductility. For instance, UHPFRC have been designed for and applied in thin bridge decks or bridge deck overlays, with compressive strengths in the range 120 to 180 MPa and flexural strengths in the range 20 to 40 MPa. On the other hand, the requirement of energy dissipation in earthquake-resistant buildings has led to the use of highly ductile SHCC in coupling beams of cores of high rise reinforced concrete buildings in Japan. Other uses of SHCC include direct exploitation of its tensile deformability in bridge deck movement joint replacement, and protection of reinforced concrete structures by its multiple, fine cracking nature, which significantly retards the ingress of moisture, gas and chlorides. An example of this application is a thin SHCC overlay of an existing dam face.

5. Further reading

1. ACI 544.1R-96, **State-of-the-art report on fibre rein-forced concrete**, Farmington Hills, Michigan: American Concrete Institute, 1996.
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