Report number: ISI2013-15

Literature Review on Macro Synthetic Fibres in Concrete

Institute of Structural Engineering
Compiled by J Bothma

UNIVERSITEIT·STELLENBOSCH·UNIVERSITY
jou kennisvennoot·your knowledge partner

INSTITUTE OF STRUCTURAL ENGINEERING

1. Introduction

Fibre reinforced concrete (FRC) is not a new concept. Since biblical times fibers were used in cementing construction materials in the form of straw and horse hair (Brandt, 2008). In more recent times the asbestos fiber was used extensively in structural components like wall panels, roofs and gates to name a view. In the early 1960's the health risk of manufacturing and using asbestos fibers became apparent and alternative fibers were introduced as a replacement (Labib & Eden, 2004). After asbestos fibres, steel fibres was one of the first possible alternatives to steel bar reinforcing, with the first patent being applied for in 1874. It was however only in the early 1970's that the use of these fibres on a large scale was noticed in the USA, Japan and in Europe. Examples of existing structures build from steel and other fibre reinforced concretes include ground supported slabs, suspended slabs, pile supported slabs, tunnel panel segments (The Channel Tunnel Rail Link project) and various insitu concrete structures like a 210m long 6m high wall that is 310mm thick in Belgium to name a few (Concrete Society UK TR 63, 2007).

2. Fibre materials and types

The desired result of adding fibres to any concrete mix is to enhance its mechanical- and shrinkage properties. The improvements gained by using fibres depend on the properties of the fibre which include the fibre material as well as fibre length and geometry to name a few.

Various materials are used to produce fibres for use in concrete. Currently the main distinctly different categories are steel fibres, synthetic fibres, glass fibers and organic- or natural fibres. Table 2.1 shows some of the fibres from every category along with the basic material properties. Manufacturers produce fibers in different geometrical forms to improve the bond characteristics between fibre and the concrete matrix while trying to prevent fibre bundling from occurring during the mixing process. Figure 2.1 shows some of the most used fibre geometries for steel fibres.

All fibres are either categorised as macro- or micro fibres. The term structural fibres are often used for macro fibres which have lengths between 19-60mm. These fibres are expected to bridge cracks and provide structural support of the hardened state of concrete. Micro fibres on the other hand are included in a mix to help improve the fresh and early-age tensile- and flexural strength of concrete. These fibres provide the necessary resistance to tensile forces developed by drying shrinkage as well

UNIVERSITEIT STELLENBOSCH UNIVERSITY
Department of Civil Engineering (Room S310A) ◆ University of Stellenbosch
Private Bag X1 ◆ Matieland 7602 ◆ Stellenbosch ◆ South Africa
Web: http://www.civeng.sun.ac.za (Institutes)
Telephone: +27-(0)21-8084498 ◆ Fax: +27-(0)21-8084947

as plastic shrinkage. Micro fibres range between 2-10mm in length and nominal diameters of 0.1-1mm (Concrete Society UK TR 63, 2007).

Table 2.1: Properties of various fibre types (Zollo, 1995) (Shah, 1981).

	Specific gravity	Tensile strength (Mpa)	Elastic Modulus (GPa)
Acrylic	1.16-1.18	296-1000	14-19
Aramid I	1.44	2930	62
Aramid II	1.44	2344	117
Carbon I	1.9	1724	380
Carbon II	1.9	2620	230
Nylon	1.14	965	5
Polyester	1.34-1.39	228-1103	17
Polyethlene	0.92-0.96	76-586	5- 117
Polypropylene	0.9-0.91	138-690	3.0-5.0
Alkali-resistant	2.7-2.74	2448-2482	79-80
Non Alkali-resistant	2.46-2.54	3103-3447	655-72
Coconut	1.12-1.15	120-200	19-26
Sisal	-	276-568	13-26
Bagasse	1.2-1.3	184-290	15-19
Steel	7.8	1000-3000	200
Glass	2.6	2000-4000	80

The shapes of synthetic fibres are similar to that of steel fibres with the straight and crimped forms being the most common for macro fibres. Micro fibres for both steel and synthetic fibres are usually only available in short straight forms. Figure 2.2 shows an example of some polypropylene fibres, with micro fibres at the top and the packs in which macro fibres are produced at the bottom. In this project polypropylene fibres is used. These fibres could be produced as monofilaments, collated fibrillated filaments or continues films (Zheng & Feldman, 1995). Polypropylene is one of the most used synthetics is fibres for concrete. This is due to their light weight and relative low cost (Manolis *et. al*, 1995).

Polypropylene (PP) is made under low-pressure by using Ziegler-Netta catalysts. PP bares resemblance to polyethylene and also is a linear hydrocarbon. Polypropylene's micro-structure is arranged in a way that promotes the formation of crystals. This leads to a better balance of chemical resistance and heat stability which is influenced by molecular weight and polydispersity as with all thermoplastics. Fibres are produced by drawing the PP into thin film sheets and then slitting it in longitude to produce tapes which is then further worked into fine fibres that can either be collated or held together in their length. These tapes are twisted along its lengths to produce fibre bundles and these have a lower aspect ratio (Zheng & Feldman, 1995).

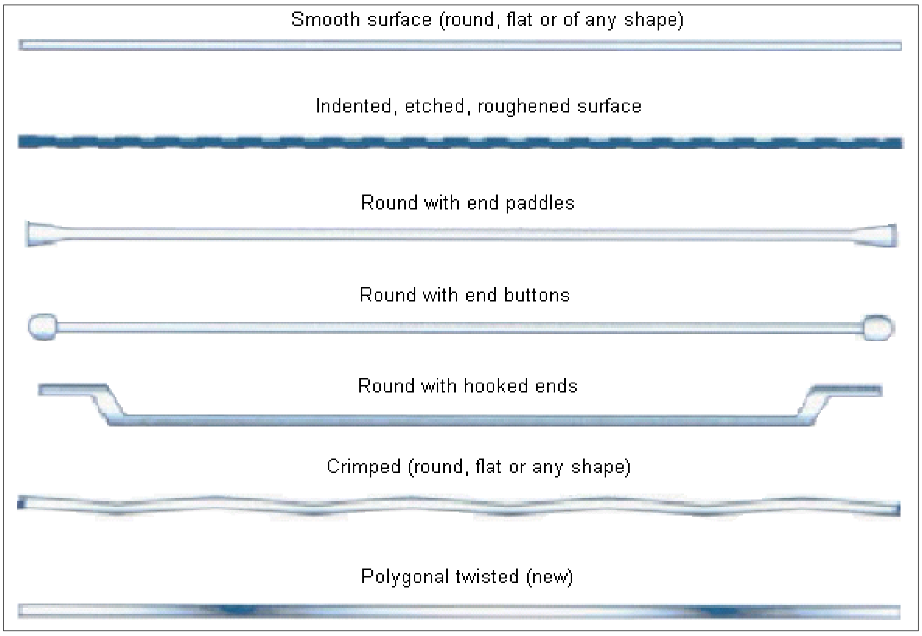

Figure 2.1: Steel fibre geometries (Concrete Society UK TR 63, 2007).

Figure 2. 2: Examples of polypropylene micro- and macro fibres.

3. Tests to determine concrete's performance

The compressive strength of concrete is used as a way to characterize or specify concrete e.g. a 30 MPa concrete, where 30 MPa is the design compressive strength of the concrete mix. The compressive strength of concrete is usually determined by performing a compression test on concrete cubes or cylinders. Methods commonly used to determine tensile strength of concrete is the splitting test as well as an inverse analysis on the data from flexural strength tests.

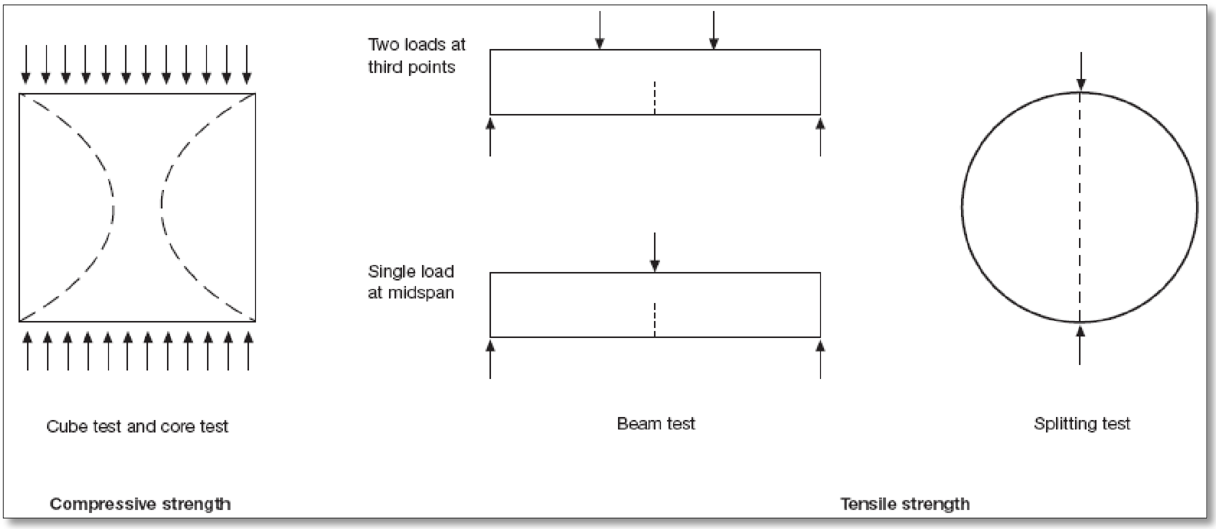

Figure 2.3: Tests to measure the strength of concrete (Fultons 9th edition, 2009).

Figure 2.3 shows conceptually the tests performed for compression strength, flexural strength (beam tests) and a splitting tensile strength test.

For beam specimens there are two different configurations of loading when performing a flexural test. The first being loading at third points where a constant bending moment is induced and consequently also a constant tensile stress in the area between the rollers applying the load.
The second method is loading at the centre point of a beam specimen. This produces a maximum bending moment as well as tensile stress at the centre of the beam. For both beam tests, flexural strength is plotted to deflection of the beam.

Panel specimens could also be used to determine flexural strength. It could be casted either as round panels or as squares. For squares simple support is provided at the corners and for round panels three simple supports are provided on the periphery of the panel. A point load is then applied at the centre of the panels and centre deflection to flexural strength is measured.

It has been stated that panel tests resembles the actual state of loading and structural performance of concrete's flexural strength more accurately than beam specimens. This is because the multi-axial state of stress discussed above is found in panel tests which are a better simulation of stresses found in applications like floors on grade and concrete pavements (Cengiz & Turneli, 2004). Figure 2.4 shows the setup for the European standard for testing panels of sprayed concrete (EFNARC).

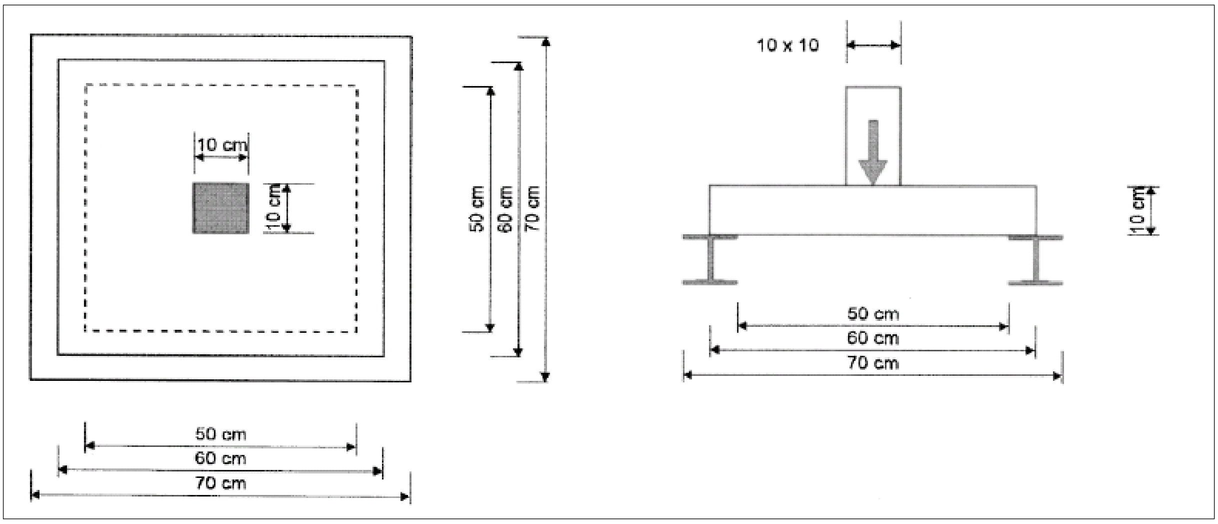

Figure 2.4 Test set setup for panel tests according to EFNARC (Ding & Kurnele, 1999).

4. Performance of FRC

The performance of FRC can often be compared to that of steel bar or steel mesh reinforcement. This is because of the level of confidence that designers and contractors use the conventional method to improve the concrete's tensile and flexural resistance. In literature there have been many experimental investigations into finding an alternative to this type of reinforcement. In the following paragraphs some of the most relevant findings from literature are documented to compare the performance of various types of FRC for their structural use. Although different fibre types will be discussed, steel- and polypropylene fibre reinforced concrete is the main focus of this research.

Fibres begin to function in a structural supportive manner when the concrete matrix starts to crack. The fibres then provide ductility and support by bridging cracks and thus providing post crack strength to the concrete. When performing a load deflection test of any kind, it can be noticed that by adding fibres to a mix there exists a strain softening behaviour of FRC where some loads can be supported after the concrete first begins to crack. Strain hardening is encountered, when a higher load is reached after the concrete cracks for the first time, by the fibres bridging the cracks. This only occurs if the reinforcing provide by the fibres is sufficient. Figure 2.5 demonstrates this strain softening and hardening behaviour. Typically only high performance fibre reinforced concretes (HPFRCC) show strain hardening. The toughness and thus the energy which could be absorbed by the addition of fibres could be computed by determining the area under a stress-strain curve (from flexural strength tests). It is essential to understand that the first crack strength of a fibre reinforced specimen will not necessarily give higher values than plain concrete. The effect of pull-out forces which is generated as the fibres gradually slip out of the matrix causes the improved toughness. It is thus preferred that pull-out of the fibres do occur instead of fibres breaking which is the result of too large bond strength between fibres and the surrounding matrix. In order to achieve optimum efficiency of the fibres, the bond strength between fibres and the matrix needs to be as close as possible to the same value as the tensile strength of the fibres, but still less (Banthia, 2012).

Steel fibres are currently one of the most used fibres in concrete to improve structural performance. At the time of writing this is the only type of fibre for which there exists design guidelines and frameworks on an international level. The Concrete Society of the United Kingdom documented guidelines for the use of Steel fibre reinforced concrete (SFRC) in their technical report No. 63 in 2007. In this report they provide a framework for the design of structures like slabs on various support structures, linings for tunnel construction and the design of insitu concrete members. Table 2.2 shows the performance enhancing capabilities that steel fibers can provide compared to unreinforced concrete according to the mentioned reference.

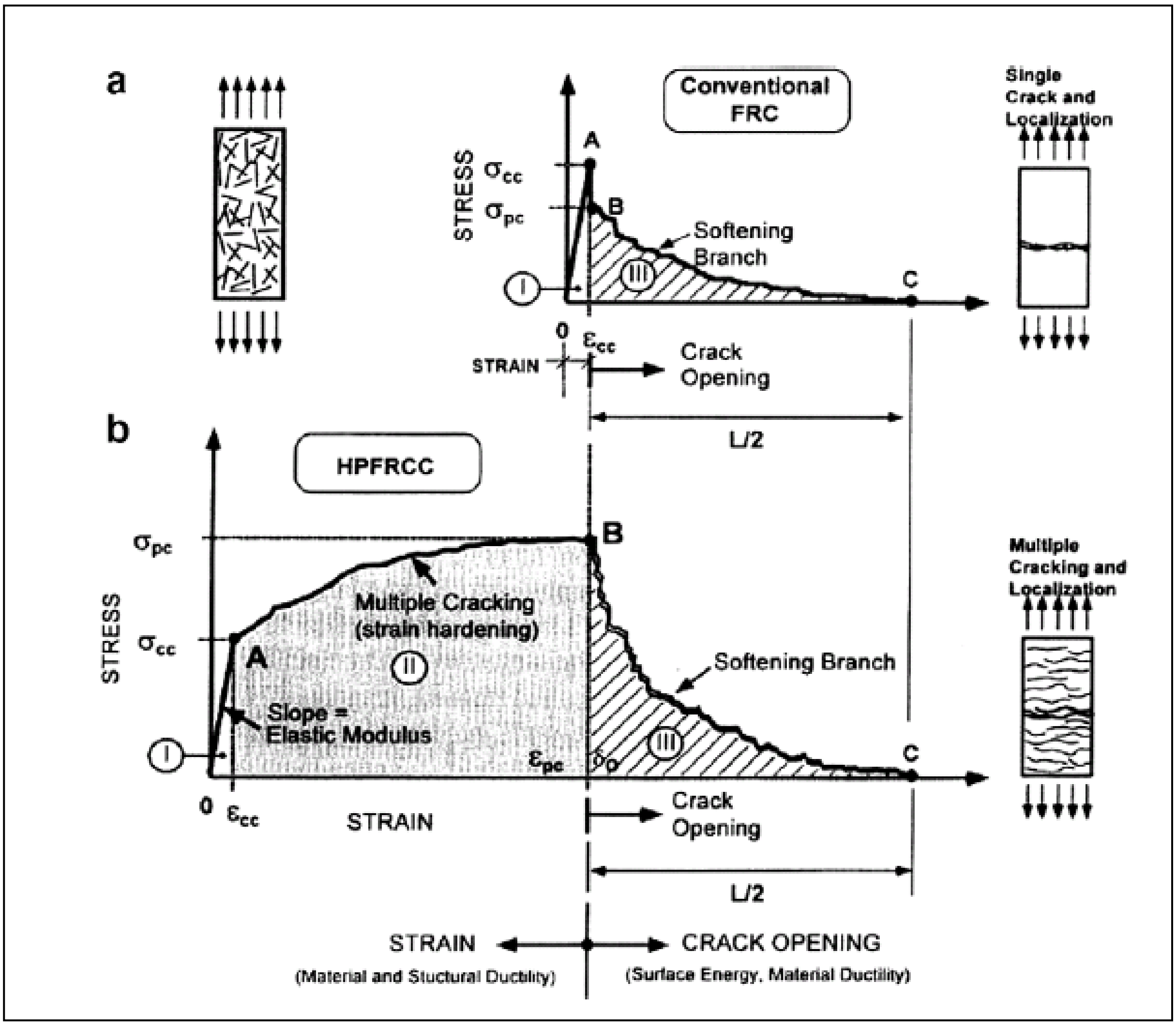

Figure 2 5: Strain hardening and strain softening behaviour of different FRC's (Brandt, 2008).

Table 2. 2:The performance of SFRC compared to unreinforced concrete (Concrete Society UK, 2007).

Property	Comment
Abrasion resistance	Improvement may be achieved as a result of reduced bleeding.
Compressive strength	Little change.
Electrical resistance	No significant change at fibre dosages generally used.
Fatigue resistance	Improvements even at low dosages.
Flexural strength	Little change in first crack strength at dosage rates commonly used.
Freeze-thaw resistance	Can reduce the deterioration caused by freeze-thaw cycling.
Impact resistance	Major improvements.
Modulus of elasticity	No significant change at fibre dosages generally used.
Restrained shrinkage	Even at low dosages, better distribution of stresses can reduce crack widths.
Shear strength	Improvements even at low dosages can be achieved in combination with reinforcing bars.
Spalling resistance	Being dispersed throughout the matrix, steel fibre reinforcement gives superior protection to exposed areas such as the joint arris.
Thermal shock resistance	As with impact resistance, there are improvements even at low dosage rates, a typical application being foundry floors.
Toughness	Major improvements, even at low dosages.

Researchers found varying results surrounding the performance of various FRC's. Typically the standard properties tested are compressive strength, flexural strength and indirect tensile strength.

4.1 Flexural and shear strength of FRC

In a study Ding & Kurstele (1999) found that the early age flexural and shear strength of SFRC greatly out performs that of unreinforced concrete of the same age and is can replace steel mesh reinforcement. The flexural panel tests were conducted in accordance to the European standard for panel tests for sprayed concrete (EFNARC, Figure 2.4).

The tests were conducted from an age of 10h and up to 48h and found that the optimal dosage of fibres is 40kg/m³ to improve flexural and shear capacity. It was also found that from a dosage of 20kg/m³ fibres the failure mode for a panel test changed from punching shear as for steel mesh reinforcement (SRC) to flexural failure for SFRC. The research concluded from their test results that the influence of SFRC is most contributing in the early ages, green state, than it is for hardened concrete. This was found by comparing the load deflection curves for 20, 40 and 60kg/m³ of steel fibres in a mix to that of minimum steel reinforcement needed (mesh) for ages 10h, 18h, 30h and 48 hours. They found that the 20kg/m³ dosage outperformed SRC at the age of 10 hours for its energy absorption capacity. But from an age of 18 hours the SRC exceed the capacity provided by the fibres (Ding & Kurstele, 1999). Figure 2.5 shows the load to deflection curves obtained in their study for an age of 48 hours of the concrete panels.

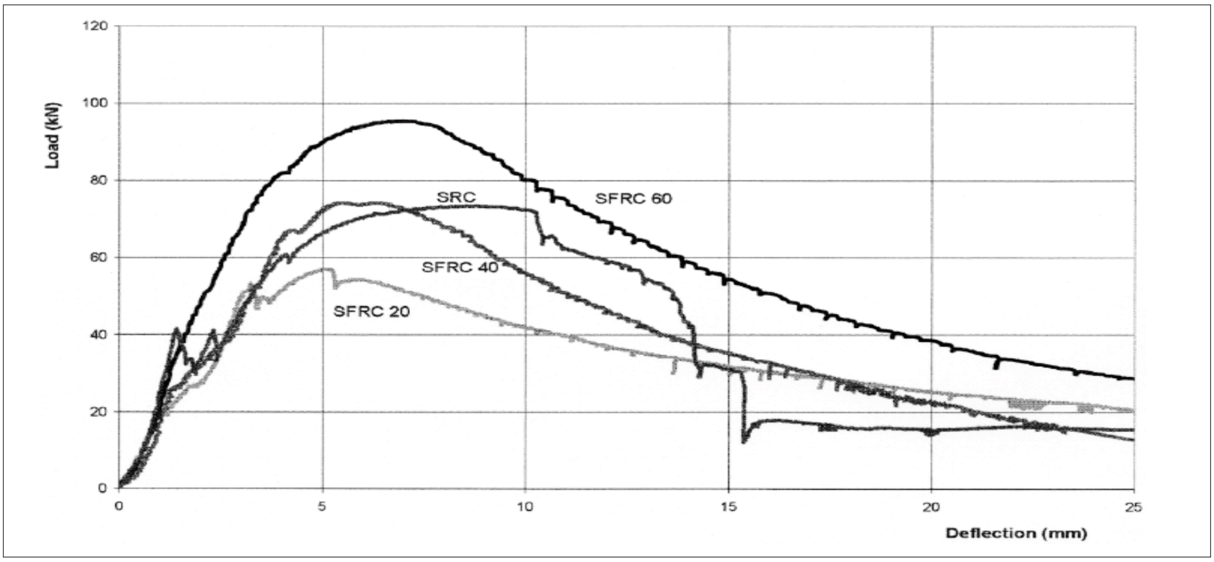

Figure 2.6 Comparison of SRC to SFRC for different fibre dosages at an age of 48h (Ding & Kurnele, 1999).

Cengiz & Turanli (2004) performed similar panel tests to compare the performance of steel mesh reinforcement to that of steel fibre reinforcement, high performance polypropylene fibre reinforcement and a hybrid mix of both steel- and polypropylene fibres. Their most important conclusions obtained were that PP fibres greatly enhanced the flexural ductility, toughness and load carrying capacity of the concrete matrix. They further discovered that a hybrid polypropylene- and steel fibre mix can be used alternatively to steel mesh and steel bars in shotcrete applications to gain improvements in mechanical properties efficiently. Figure 2.6 shows the comparison of a hybrid fibre reinforced mix to that of high performance polypropylene fibres (HPPFR) of different dosages for a panel load-deflection shotcrete test. 30kg/m³ of steel fibres and 5 kg/m³ of polypropylene fibres were used in the hybrid fibre mix and 10 kg/m³ and 7 kg/m³ were used for the polypropylene mix (Cengiz & Turanli, 2004).

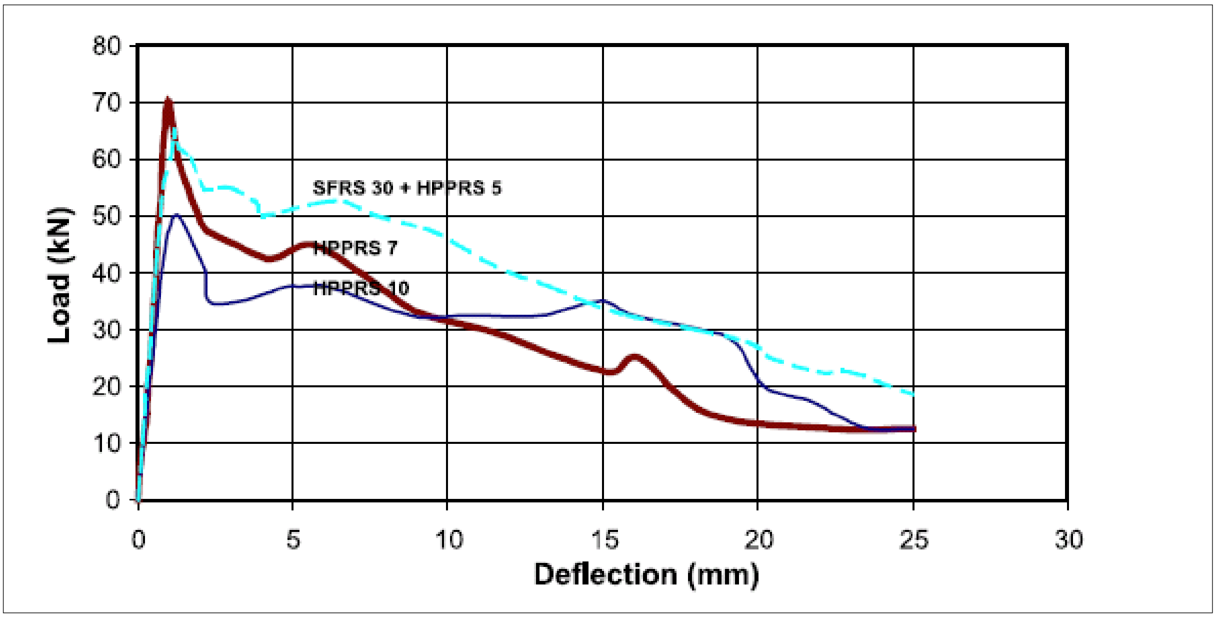

Figure 2.7: Comparison of hybrid fibre reinforcement to HPPFR (Cengiz & Turanli, 2004).

The flexural strength of SFRC increases as the temperature decreases as were found in a study which tested the flexural strength on to different dosages of fibres under temperature below freeze point. *Pigeon & Cantin (1998).* conducted a four point flexural test on beam specimens with water:cement (w/c) ratios of 0.45 and 0.3 respectively. The research found that for both normal strength concrete (w/c of 0.45) and a more high performance one (w/c of 0.3) flexural strength of the concrete increased for temperatures under 0°C. Two different fibre dosages were used: 40 and 60kg/m³ respectively. This increase in flexural strength was noticed first at a temperature of -10°C but was quit significant at -30°C (Pigeon & Cantin, 1998).

An increase in flexural toughness was witnessed by Alhozaimy *et al. (1995)* in their research by performing flexural strength tests on concrete specimens reinforced with polypropylene fibres. They found that for volume fractions of 0.1%, 0.2% and 0.3% of fibres the flexural toughness increased by 44%, 271% and 386% respectively over that of plain unreinforced concrete for the same mix compositions.

4.2 Tensile strength of FRC

The splitting tensile strength of concrete can be increased by adding fibres to a concrete mix. During their research Choi *et al.* found that glass fibre reinforced concrete (GFRC) and polypropylene fibre reinforced concrete (PFRC) have a splitting tensile strength of 20-50% more than that of unreinforced concrete (Figure 2.7). They also concluded that the splitting tensile strength of these composites ranged between 9-13% of their compressive strengths (Choi & Yuan, 2004).

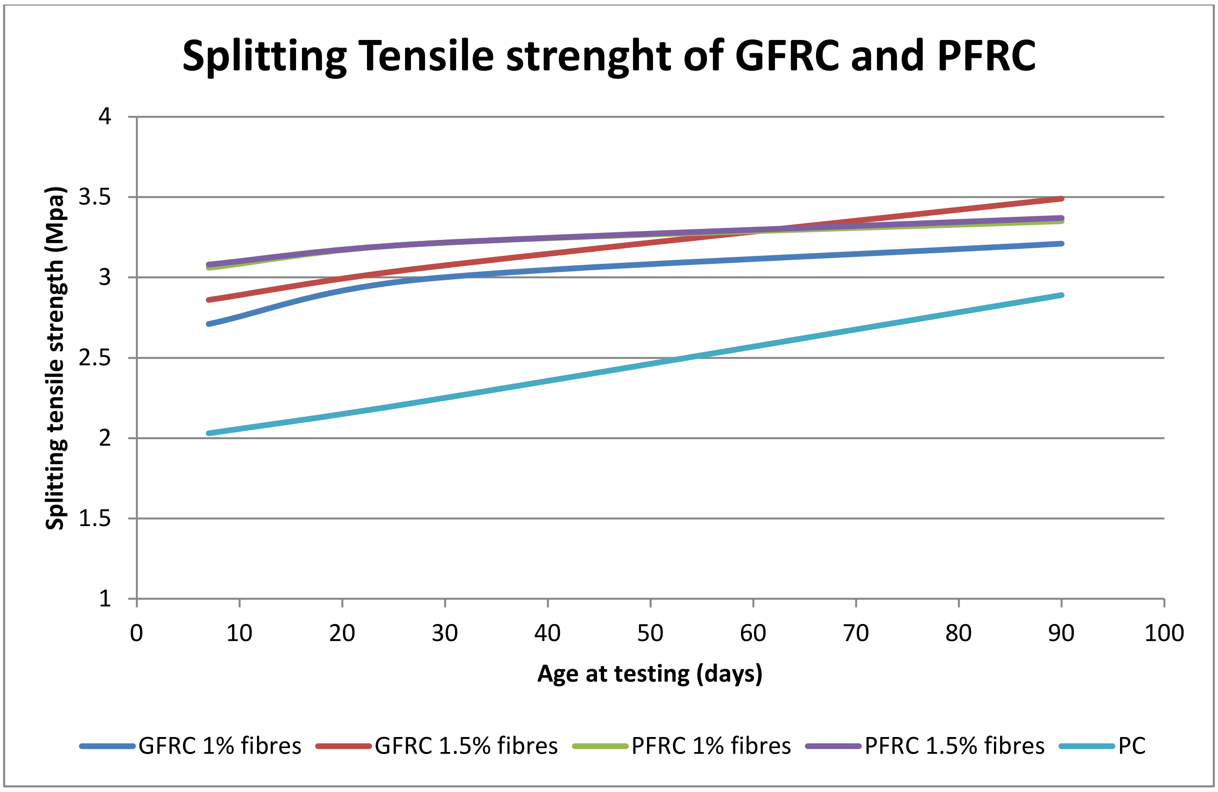

Figure 2.8: Comparison of splitting tensile strength of GFRC and PFRC with unreinforced concrete after Choi & Yuan (2004).

4.3 Compressive strength of FRC

Since the compressive strength of concrete is one of its main attributes and the reason for adding any reinforcing material is in most cases to improve other characteristics, little focus has been put on the compressive strength of FRC. Because compressive strength tests measure the load until failure (first cracks) and since fibres only contributes to the structural integrity of concrete by bridging cracks after cracks begins to form, the effect on compression strength is not its main attribute. By bridging cracks, fibres stops or limits the propagation of cracks and also limits crack widths. These attributes not only contributes to structural integrity, but also improves the durability of structures made from such materials.

Different and often contradicting results on compression strength tests were found in literature. Alhozaimy *et al. (1995)* found in their research that the addition of low volumes (0.1%) of polypropylene fibres to a concrete mix has no significant effect on the compressive strength of conventional concrete*.* Previous research suggests that the compressive strength of concrete containing synthetic fibres (0 – 0.3%) is less than that of plain concrete (Zollo, 1984). Other studies found that by using 0.5% fibres by volume, the compressive strength could be increased by as much as 25% (Mindess, S. & Vondran, 1988). The addition of supplementary materials such as silica fume or slag in combination with the use of fibres could yield some improvement in compressive resistance of the composite as Figure 2.8 shows for specimens of conventional concrete and that of mixed binder type with and without 0.1% fibres by volume (Alhozaimy *et. al,* 1995*)*.

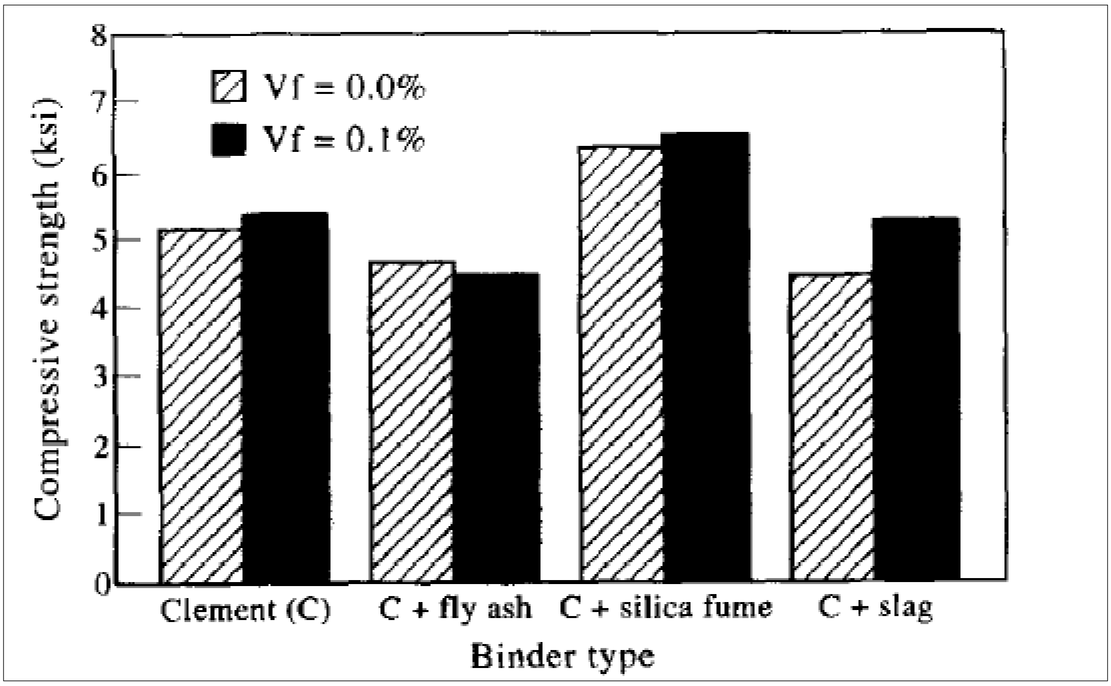

Figure 2.9: Compressive strength of different concrete mixes comprising of plain and fibre reinforced concrete (Alhozaimy *et. al,* 1995*)*

4.4 Fire resistance

Polypropylene fibres perform well as a measure to improve fire resistance of concrete since it has a low melting point (107 - 141 °C), which is a desirable attribute during a fire in a building. During fires, high temperatures cause the trapped water particles, still present in the concrete, to turn into vapour and this result in pressures within the concrete, which tends to cause brittle failure. When polypropylene fibres are present, they melt and provide channels through which the vapour could escape.

4.5 Impact resistance of FRC

Impact resistance refers to the strength provided by the concrete when exposed to an increase in strain rate. Fibre reinforced concrete is known to have an increased resistance to impact loading over that of unreinforced concrete. In literature there is no unique standard or specific test that can be performed to determine impact resistance. The method that is mostly used for testing is to subject a concrete sample to a dynamic load from a drop weight system. Other methods include the use of a pendulum to subject an impact load or to use high velocity projectiles. The testing method that is chosen depends on the conditions under which the concrete will be used in the field. For concrete structures like warehouse floors, the drop weight system should be sufficiently accurate in simulating loading conditions. For more extreme loading like impacts through high velocity projectiles like bullets or explosive fragments, other methods should be used to simulate the actual conditions.

Mindess & Vondran (1988) found in their research that polypropylene fibres with a length of 19.1mm which were added in volume fractions from 0.1% to 0.5% increased impact resistance and fracture energy of the concrete. The experimental method used was a 345kg drop hammer released from 0.5m above the concrete specimen. Beam specimens of 1200mm in length, 100mm wide and 125mm deep were used. From the tests they found that an increase in fracture energy and impact resistance occurred as the volume fraction of fibres in the mix increased. At a dosage of 0.5% fibres a maximum bending load, as a measure of impact strength, was obtained which was 40% higher that of plain concrete. They also noticed that the fracture energy doubled at this volume of fibres. The primary mode of failure was fibre rupture rather than fibre pull-out.

In another similar study the effect of adding polypropylene fibres as well as steel fibres were tested to determine whether an increase in impact resistance can be achieved. For this study beam specimens was tested under a dynamic load from a drop hammer (60.3kg). Figure 2.10 shows the schematic test setup. This study found that polypropylene fibres improved impact loading resistance marginally (21% increase at 0.5% volume). When steel fibres were used at the same volume fraction an increase of 41% in impact resistance was noticed. This study also concluded that the mechanism of failure changed from fibre rupture to fibre pull-out as the volume fraction approached the region of 0.5% to 0.75%. Below this region rupture of the fibre is the dominating mode of failure for greater volumes of fibres a pull-out mechanism occurs (Wang & Mindess & Ko, 1996).

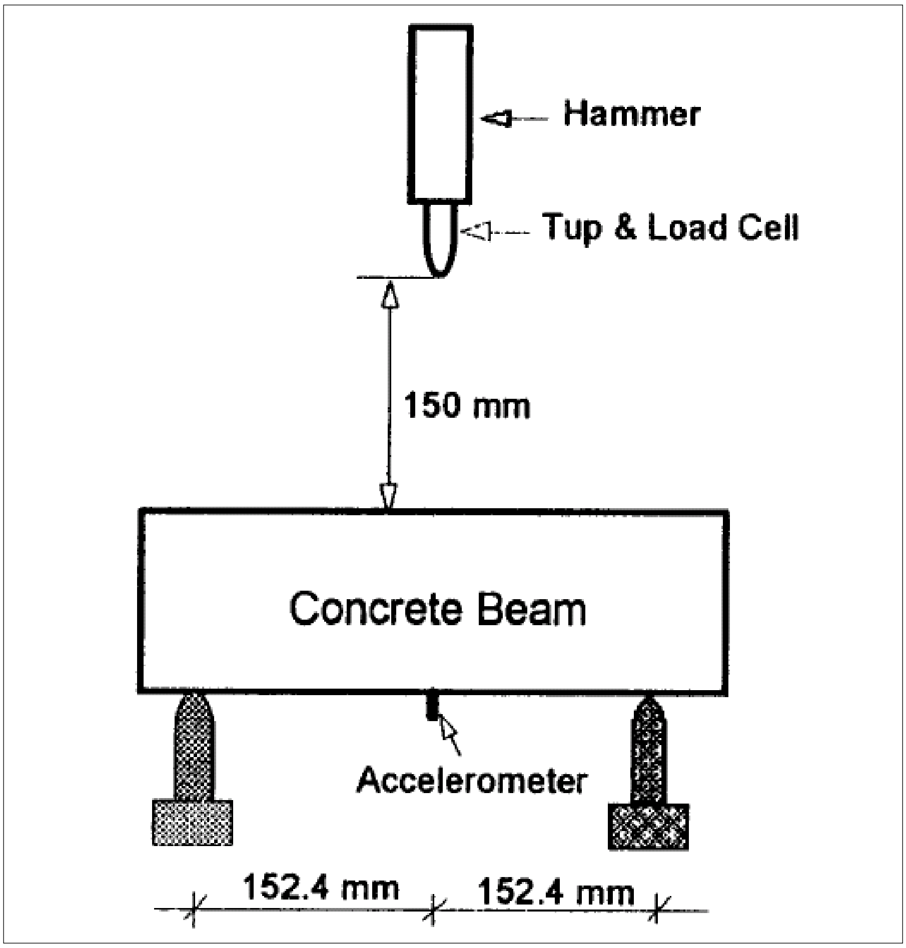

Figure 2.10: Impact load test setup (Wang & Mindess & Ko, 1996).

Buildings are increasingly designed to withstand impact loading from either seismic loading, wind loading or resistance to impacts caused by projectiles. In a study where high performance concrete reinforced with steel-, polyethylene- or polypropylene fibres were tested, results shown that an optimum impact resistance can be obtained by using 0.75% steel fibres and 0.25% polypropylene fibres in combination or just 1% steel fibres. This result was obtained by testing concrete specimens under high velocity projectile blows. The projectile is shown in Figure 2.11, weighs 15g and the impact velocities ranged from 610m/s to 710m/s. Concrete specimens had compressive strengths at 28 days from 46.3 MPa to 129.7 MPa. Results shown that fibres reduced the size of the crater created by the projectile, but that penetration depth only depended on the compressive strength of the concrete and thus on the water to cement ratio as well as aggregate size (Zhang & Sharif & Lu, 2007).

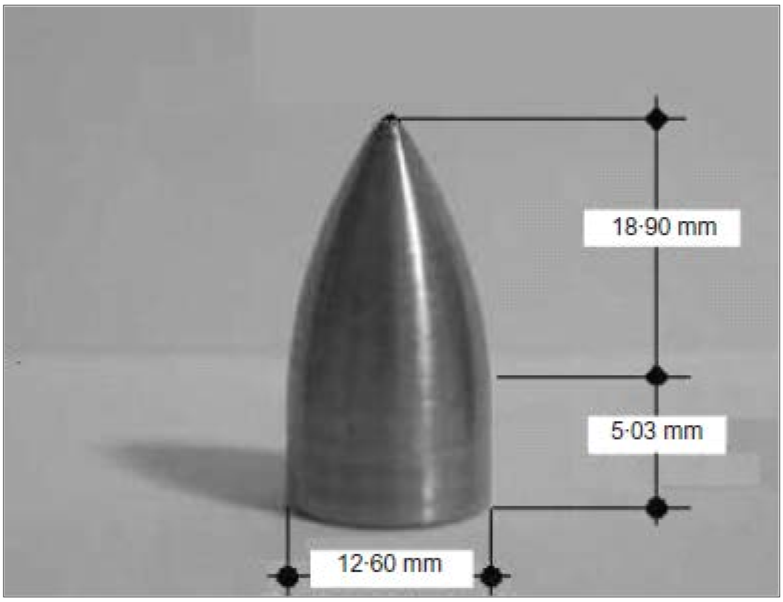

Figure 2.11: Projectile for impact testing (Zhang & Sharif & Lu, 2007).

References

ACI Committee 360. 1997. *Design of Slabs on Grade.* American Concrete Institute. USA

Banthia, N. 2012. watancon.com/.../technical/Banthia_-_Fibre Reinforced_Concrete.pdf

Alhozaimy, A. M. Soroushiad, P. MirzaC, F. 1995. *Mechanical Properties of Polypropylene Fiber Reinforced Concrete and the Effects of Pozzolanic Materials*. Cement & Concrete Composites. Great Britain.

Brandt, A.M. 2008. *Fibre reinforced cement-based (FRC) composites after over 40 years of development in building and civil engineering*. Institute of Fundamental Technological Research, Polish Academy of Sciences, Warsaw, Poland.

Concrete Society Technical Report No. 34. 2003. *Concrete Industrial Ground Floors – A guide to design and construction 3rd edition*. The Concrete Society UK.

Cengiz, O. Turanli, L. 2004. *Comparative evaluation of steel mesh, steel fibre and high-performance polypropylene fibre reinforced shotcrete in panel test.* Department of Civil engineering, Middle East Technical University, METU06531 Ankara, Turkey. Elsevier Ltd.

Choi, Y. Yuan, R.L. 2004*. Experimental relationship between splitting tensile strength and compressive strength of GFRC and PFRC. Cement and Concrete Research 35 (2005) 1587– 1591.* Department of Civil and Environmental Engineering, University of Texas at Arlington, Arlington, TX, USA .Department of Civil Engineering, Lamar University, Beaumont, TX, USA

Ding, Y. Kusterle, W. 1999. *Comparative study of steel fibre-reinforced concrete and steel mesh-reinforced concrete at early ages in panel tests.* Institute of Building Materials and Material Testing, University of Innsbruck, Technikerstr Innsbruck, Austria.

Hannant, D.J. 1998. *Durability of polypropylene fibres in portland cement-based composites: eighteen years of data*. Department of Civil Engineering, University of Surrey, Guildford. United Kingdom.

Kayali, O. Haque, M.N. Zhu, B. *Some characteristics of high strength fiber reinforced lightweight aggregate concrete*. Cement & Concrete Composites 25 (2003) 207–213, Australia.

Knapton, J. 2005. *Design of Ground Bearing Concrete Slabs.* African Concrete Code Symposium-2005. John Knapton Consulting Engineers, UK.

Luca, G. Sorelli, Alberto Meda, and Giovanni A. Plizzari. 2006. *Steel Fiber Concrete Slabs on Ground: A Structural Matter. ACI Structural Journal, V. 103, No. 4.* American Concrete Institute.

Marais, R. Pierre, D. 1993. *Concrete Industrial Floors on the Ground*. Portland Cement Institute. Midrand, South Africa.

Mindess, S. & Vondran, G. *Properties of concrete reinforced with fibrillated polypropylene fibers under impact loading*. Cement and Concrete Research, 18 (1988) 109-15.

Manolis G.D. Gareis P. J. Tsonos A. D. Neal J. A. 1995. *Dynamic Properties of Polypropylene Fiber-Reinforced Concrete Slabs.* Civil Engineering, Aristotle University, Thessaloniki, Greece. Department of Civil Engineering, State University of New York at Buffalo, USA.

Owens, G. 2009. Fulton's concrete technology. Cement and concrete institute. South Africa.

Pigeon, M. Cantin, R.1998. *Flexural Properties of Steel Fiber-reinforced Concretes at Low Temperatures.* Cement and Concrete Composites 20 (1998) 365-375. Centre de recherche interuniversitaire sur le b&on (Sherbrooke-Laval), UniversitC Laval, Sainte-Foy, QuCbec, Canada.

SHAH, S.P. 1981. *Fibre reinforced concretes, a review of capabilities*. University of Illinois at Chicago Circle.

Zhang, M.H. Sharif, S.H. Lu, G. 2007. *Impact resistance of high-strength fibrereinforced Concrete.* Magazine of Concrete Research, 2007, 59, No. 3, April, 199–210

Zheng, z. Feldman, d. 1995. *Synthetic fibre-reinforced concrete*. Concordia University, Montreal, Quebec H3G 1M8. Pergamon. Great Britian.

Zollo, R. F., Collated fibrillated polypropylene fibers in FRC. Fiber reinforced Concrete International Symposium. Special Publication (SP 81-19), 1984.