SINTEF REPORT

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TITLE

COIN P2 Improved construction technology
SP 2.4 Workability

Concrete workability and fibre content

State of the art

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CLIENT(S)

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ABSTRACT

Parameters influencing the workability of fibre concrete and maximum fibre content are given in this state of the art report along with the range of fibre types available on today's market.

The study reveales that new placing techniques and production methods are crucial in order to increase fibre content and concrete strength. Achieving the same mechanical properties as traditionally reinforced concrete will probably also demand changes of the matrix.

Finally, recommendations for future work within COIN Project 2.2- Fibres are given.

KEYWORDS	ENGLISH	NORWEGIAN
GROUP 1	Materials technology	Materialteknologi
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Foreword

COIN - Concrete Innovation Centre - is one of presently 14 Centres for Research based Innovation (CRI), which is an initiative by the Research Council of Norway. The main objective for the CRIs is to enhance the capability of the business sector to innovate by focusing on long-term research based on forging close alliances between research-intensive enterprises and prominent research groups.

The vision of COIN is creation of more attractive concrete buildings and constructions. Attractiveness implies aesthetics, functionality, sustainability, energy efficiency, indoor climate, industrialized construction, improved work environment, and cost efficiency during the whole service life. The primary goal is to fulfill this vision by bringing the development a major leap forward by more fundamental understanding of the mechanisms in order to develop advanced materials, efficient construction techniques and new design concepts combined with more environmentally friendly material production.

The corporate partners are leading multinational companies in the cement and building industry and the aim of COIN is to increase their value creation and strengthen their research activities in Norway. Our over-all ambition is to establish COIN as the display window for concrete innovation in Europe.

About 25 researchers from SINTEF (host), the Norwegian University of Science and Technology - NTNU (research partner) and industry partners, 15 - 20 PhD-students, 5 - 10 MSc-students every year and a number of international guest researchers, work on presently 5 projects:

- Advanced cementing materials and admixtures
- Improved construction techniques
- Innovative construction concepts
- Operational service life design
- Energy efficiency and comfort of concrete structures

COIN has presently a budget of NOK 200 mill over 8 years (from 2007), and is financed by the Research Council of Norway (approx. 40 %), industrial partners (approx 45 %) and by SINTEF Building and Infrastructure and NTNU (in all approx 15 %). The present industrial partners are:

Aker Kværner Engineering and Technology, Borregaard LignoTech, maxitGroup, Norcem A.S, Norwegian Public Roads Administration, Rescon Mapei AS, Spenncon AS, Unicon AS and Veidekke ASA.

For more information, see www.sintef.no/coin

TABLE OF CONTENTS

1 Introduction

Fibres have been used in construction materials for several centuries. Since ancient times straw was used to reinforce sun-baked bricks, and horsehair was used to reinforce masonry mortar and plaster. Large scale commercial use of fibres in a cement paste matrix began with the invention of asbestos fibre production through the Hatschek process in 1898. Alternative fibres were, however, introduced throughout the 1960s and 1970s primarily due to the health hazards associated with asbestos fibres (ACI 544.1R-96 1997).

Reinforcing concrete structures is generally a rather expensive and time-consuming process, for designers as well as for constructors. The reinforcement design participates with about 50 % in the total design costs, and with around 30 % in the total work costs (Markovic et al 2003). Fiber reinforcement, on the other hand, has the advantage of being significantly less labour-intensive than rebar reinforcement, and thus meets both the demand for improved efficiency and future shortage of skilled workers. Future concrete might, therefore, be envisioned without traditional reinforcement.

The inclusion of fibres can enhance many of concrete's engineering properties such as fracture toughness, flexural strength, resistance to fatigue, impact, thermal shock and spalling. If the modulus of elasticity of the fiber is higher than the matrix (concrete or mortar binder), they help to carry the load by increasing the tensile strength of the material.

Under tensile stress, cracks develop in concrete. Fibres have been shown to be effective in reducing plastic shrinkage cracking. Fibres typically do not significantly alter free shrinkage of concrete, however at high enough dosages they can increase the resistance of cracking and decrease crack width (Shah et al 1998). Reinforcing steel bars in concrete have the same beneficial effect because they act as long continuous fibres. Short discontinuous fibres have the advantage, however, of being uniformly mixed and dispersed throughout the concrete.

One challenge is that fibres are generally distributed throughout the concrete cross section. Therefore, many fibres are inefficiently located for resisting tensile stresses resulting from applied loads. Depending on fabrication method, random orientation of fibres may be either two-dimensional (2-D) or three-dimensional (3-D). Typically, the spray-up fabrication method has a 2-D random fibre orientation where as the premix (or batch) fabrication method typically has a 3-D random fibre orientation. Also, many fibres are observed to extend across cracks at angles other than $90^{o}C$ or may have less than the required embedment length for development of adequate bond. Therefore, only a small percentage of the fibre content may be efficient in resisting tensile or flexural stresses. Efficiency factors can be as low as 0.4 for 2-D random orientation and 0.25 for 3-D random orientation. The efficiency factor depends on fibre length and critical embedment length (PCA 2002). Processing the concrete so that the fibres become aligned in the direction of applied stress will result in greater tensile or flexural strengths.

The mixture composition of fibre reinforced cementitious materials is a compromise between acceptable workability and improved efficiency in the hardened state. The fibre content of a concrete that is still workable depends on the mixture composition and the fibre type. High fibre contents create, however, a stiff internal structure which counteracts the flow. Fibers which are too long tend, moreover, to "ball" in the mix which again creates workability problems.

Fibre concretes are currently best suited for thin section shapes where correct placement of conventional reinforcement would be difficult. In addition, spraying of fibre concrete accommodates the fabrication of irregularly shaped products. Substantial weight savings can, moreover, be realized using relatively thin fibre concrete sections having the equivalent strength of thicker conventionally reinforced concrete sections (PCA 2002).

This literature study is written for COINs (Concrete Innovation Centre) fibre projects. COIN will investigate the possibilities of replacing traditional reinforcement with fibre in load carrying structures. The focus of the report has therefore been on workability of fibre reinforced concrete, material parameters of the fresh concrete, mix design and fibre types. Optimization of the maximum fibre content has been of special interest.

2 Fibres

Main parts of the following are taken from a report published by The Portland Cement Association (PCA) in 2002:
Fibres made from steel, plastic, glass and natural materials such as wood cellulose are available in a variety of shapes, sizes and thicknesses; they may be round, flat, crimped, and deformed with typical lengths of 6 mm to 150 mm and thicknesses ranging from 0.005 mm to 0.75 mm. The main factors that control the performance of the composite material are:

- Physical properties of fibres and matrix
- Strength of bond between fibres and matrix

Some properties of a number of selected fibre types can be found in Table 1

The amount of fibers added to a concrete mix is measured as a percentage of the total volume of the composite (concrete and fibers) termed volume fraction (Vf). The aspect ratio (l/d) is calculated by dividing fiber length (l) by its diameter (d). Fibers with a non-circular cross section use an equivalent diameter for the calculation of aspect ratio. The reinforcement index or the so-called "fibre factor", $V \cdot {}^{l}\!/\!_{d}$, were V is the fibre volume, is also used to characterize and compare the properties of different fibre-reinforced mixtures (Hughes and Fattuhi 1976).

Figure 1: Steel, glass, synthetic and natural fibres (ACI 544.1R-96 1997)

Table 1: Properties of selected fibre types (PCA 2002)

Fibre type	Relative density	Diameter (μm)	Tensile strength (MPa)	Modulus of elasticity (MPa)	Strain at failure (%)
Steel	7.80	100-1000	500-2600	210,000	0.5-3.5
Glass					
E	2.54	8-15	2000-4000	72,000	3.0-4.8
AR	2.70	12-20	1500-3700	80,000	2.5-3.6
Synthetic					
Acrylic	1.18	5-17	200-1000	17,000-19,000	28-50
Aramid	1.44	10-12	2000-3100	62,000-120,000	2-3.5
Carbon	1.90	8-0	1800-2600	230,000-380,000	0.5-1.5
Nylon	1.14	23	1000	5,200	20
Polyester	1.38	10-80	280-1200	10,000-18,000	10-50
Polyethylene	0.96	25-1000	80-600	5,000	12-100
Polypropylene	0.90	20-200	450-700	3,500-5,200	6-15
Natural					
Wood cellulose	1.50	25-125	350-2000	10,000-40,000	
Sisal			280-600	13,000-25,000	3.5
Coconut	1.12-1.15	100-400	120-200	19,000-25,000	10-25
Bamboo	1.50	50-400	350-500	33,000-40,000	
Jute	1.02-1.04	100-200	250-350	25,000-32,000	1.5-1.9
Elephant grass		425	180	4,900	3.6

The effectiveness of fibres in enhancing the mechanical performance of the brittle matrix is dependent to a large extent on the fibre-matrix interactions. Three types of interactions are particularly important:

1. Physical and chemical adhesion
2. Friction
3. Mechanical anchorage induced by deformations on the fibre surface or by overall complex geometry (e.g. crimps, hooks, deformed fibres)

The adhesional and frictional bonding between a fibre and cementitious matrix are relatively weak. They contribute, however, significantly in the case of composites having high surface area fibres (for instance carbon micro fibres) and for advanced cementitious matrices which are characterized by an extremely refined micro structure and very low porosity (i.e w/b < 0.3 (More information can be found in Chapter 5.3.)). Efficient reinforcement can, however, not be induced by adhesional and frictional bonding alone, and mechanical anchoring is required for conventional fibre reinforced concretes where the w/b is higher than 0.4 and the fibres are of a diameter larger than 0.1 mm (Bentur and Mindess 2007).

2.1 Steel fibres

Steel fibres are short, discrete lengths of steel with an aspect ratio from about 20 to 100. The fibre length varies, in general, from 12.7 mm to 63.5 mm. The most common fibre diameters are in the range of 0.45 mm to 1 mm. Modern steel fibres have shapes which include round, oval, rectangular, and crescent cross sections, depending on the manufacturing process and raw materials used (ACI 544.3R-2). Some steel fibres have hooked ends to improve the resistance to pullout from a cement-based matrix.

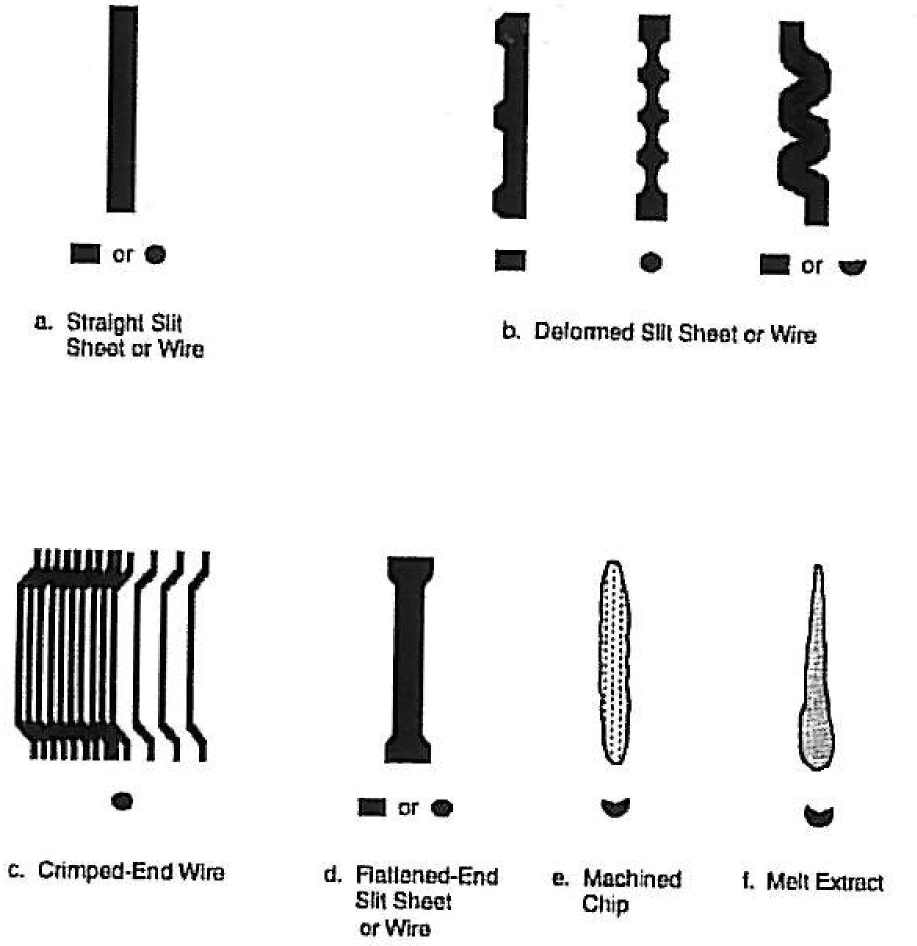

Figure 2: Various steel fibre geometries (ACI 544-1R-96 1997)

ASTM A 820 classifies four different types based on their manufacture.

- Type I-Cold-drawn wire fibres are the most commercially available, manufactured from drawn steel
- Type II-Cut sheet fibres are sheared of steel sheets
- Type III-Melt extracted fibres are manufactured by a technique where a rotating wheel is used to lift liquid metal from a molten metal surface by capillary action. The extracted molten metal is then rapidly frozen into fibres and thrown of the wheel by centrifugal force. The resulting fibres have a crescent-shaped cross section
- Type IV-other fibres.

The usual amount of steel fibres is from 0.25 vol.% (20 kg/m^3) to 2 vol.% (157 kg/m^3). The low end of the range applies to lightly loaded slabs on grade, some precast applications, and composite steel toppings. The upper end of the range is common for security applications (safes, vaults, etc.) (ACI 544.3R-2). Volumes of more than 2 % steel fibres generally reduce workability and fibre dispersion and require special mix design or concrete placement techniques.

The addition of steel fibres significantly improves many of the engineering properties of mortar and concrete, notably impact strength and toughness. Flexural strength, fatigues strength, and the ability to resist cracking and spalling are also enhanced (ACI 544.3R-2). The compressive strength is only slightly affected by the presence of fibres. The addition of 1.5 % by volume of steel fibres can, however, increase the direct tensile strength by up to 40 % and the flexural strength up to 150 %.

Steel fibres do not affect free shrinkage. Steel fibres delay, however, the fracture of restrained concrete during shrinkage and improve stress relaxation by creep mechanisms (Altoubat and Lange 2001).

2.2 Glass fibres

The first research on glass fibres in the early 1960s used conventional borosilicate glass (E-glass) and soda-lime-silica glass (A-glass). Test results showed, however, that alkali reactivity between the E-glass fibres and the cement-paste reduced the strength of the concrete. Continued research resulted in alkali-resistant glass fibres (AR-glass) that improved long-term durability. Sources of other strength-loss trends were, however, observed. One acknowledged source was fibre embrittlement stemming from infiltration of calcium hydroxide particles into fibre bundles. Fibre modifications to improve long-term durability involve

- Chemical coatings to help combat hydration induced embrittlement
- Employment of a dispersed microsilica slurry to fill fibre voids and thereby reducing the potential for calcium hydroxide infiltration.

The single largest application of glass-fibre concrete has been the manufacture of exterior building façade panels.

2.3 Synthetic fibres

Synthetic fibre types used for concrete are: acrylic, aramid, carbon, nylon, polyester, polyethylene, and polypropylene. Synthetic fibres can reduce plastic shrinkage and subsequent cracking and may be beneficial after the concrete is fractured. Ultra-thin whitetopping often uses synthetic fibres for potential containment properties to delay pothole development. Problems associated with synthetic fibres include:

- Low fibre-to-matrix bonding
- Inconclusive performance testing for low fibre-volume usage with polypropylene, polyethylene, polyester and nylon
- Low modulus of elasticity for polypropylene and polyethylene
- High cost of carbon and aramid fibres

Polypropylene fibres, the most popular of the synthetics, are chemically inert, hydrophobic (do not absorb water) and lightweight. They are produced as continuous cylindrical monofilaments that can be chopped to specific lengths or cut as films and tapes and formed into fine fibrils of rectangular cross section. Used at a rate of at least 0.1 % by volume of concrete, polypropylene fibres reduce plastic shrinkage cracking and subsidence cracking over steel reinforcement. The presence of polypropylene fibres in concrete may, moreover, reduce settlement of aggregate particles and thus reduce capillary bleed channels.

Monofilament fibres are able to fibrillate during mixing if produced with both polypropylene and polyethylene resins. The two polymers are incompatible and tend to separate when manipulated. Therefore, during mixing each fibre turns into a unit with several fibrils at its end. The fibrils provide better mechanical bonding than conventional monofilaments. The high number of fine fibrils also reduces plastic shrinkage cracking and may increase the ductility and toughness of the concrete (Trottier and Mahoney 2001).

Acrylic fibres have been found to be the most promising replacement for asbestos fibres. They are used in cement board and roof-shingle production, where fibre volumes up to 3 % can produce a composite with mechanical properties similar to that of an asbestos-cement composite. Acrylic-fibre concrete composites exhibit high postcracking toughness and ductility.

Aramid fibres have high tensile strength and a high tensile modulus. Aramid fibres are two and a half times as strong as E-glass fibres and five times as strong as steel fibres. In addition to excellent strength characteristics, aramid fibres also have excellent strength retention up to 160^{o}C, dimensional stability up to 200^{o}C, static and dynamic fatigue resistance, and creep resistance. Aramid strand is available in a wide range of diameters.

Carbon fibres were developed primarily for their high strength and elastic modulus and stiffness properties for applications within the aerospace industry. Carbon fibres have high tensile strength and modulus of elasticity. They are also inert to most chemicals. Carbon fibres are typically produced in strands that may contain up to 12,000 individual filaments. The strands are commonly spread prior to incorporation in concrete to facilitate cement matrix penetration and to maximize fibre effectiveness. The manufacture of carbon fibres is expensive compared with most other synthetic fibres.

Nylon fibres are spun from nylon polymer and transformed through extrusion, stretching and heating to form an orientated, crystalline fibre structure. Nylon fibres exhibit good tenacity, toughness and elastic recovery. Nylon is hydrophilic with moisture retention of 4.5 % which increases the water demand of concrete. Nylon is relatively inert and resistant to a vide variety of organic and inorganic materials including strong alkalis

Instead of reinforcing concrete with randomly distributed short fibres, fibre mesh or textile reinforcement is being considered for various applications (Häuβler-Combe and Hartig 2007). As reinforcement materials, alkali resistant (AR) glass fibres are mainly used, but also carbon, aramid fibres and high modulus poylethylene fibres have their applications. The most important reason for reinforcement of concrete parts with textiles is that the concrete parts can be very thin as there is no risk of corrosion of the reinforcement materials. In addition the reinforcement is more flexible and the shape of the concrete elements can therefore be varied in a wide range (Hanisch et al. 2006). See Chapter 5.2 for more information about textile reinforced concrete.

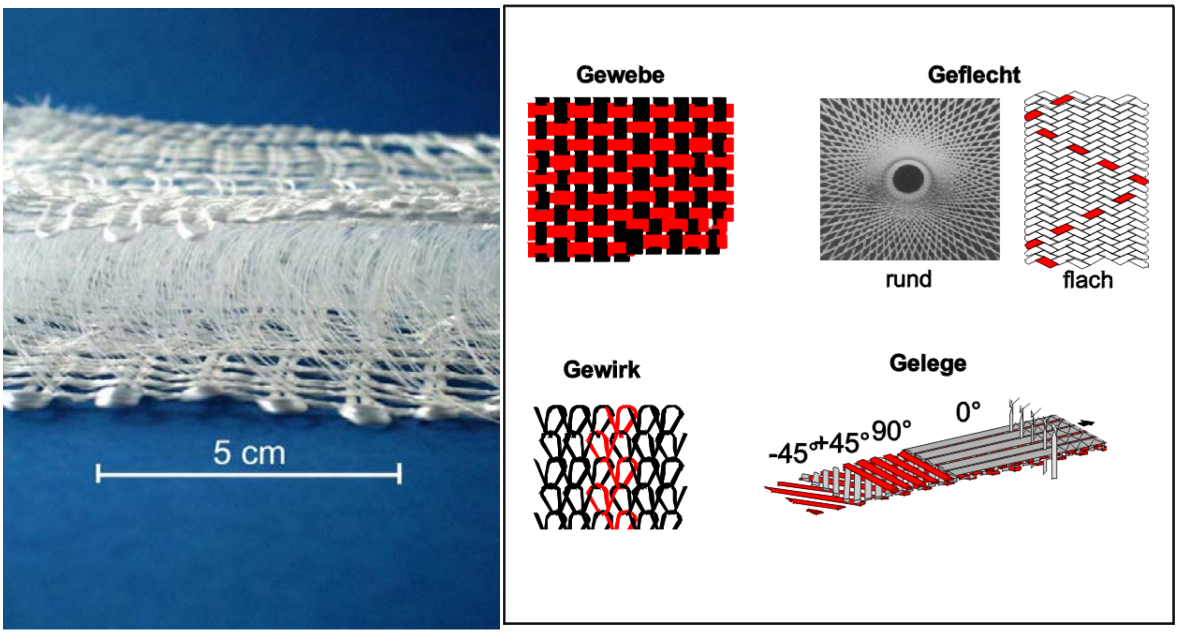

Figure 3: Examples of textiles for concrete (Brameshuber et al. 2002)

2.4 Natural fibres

Unprocessed natural fibres such as coconut coir, sisal, bamboo, jute, wood, and vegetable can successfully be used to make thin sheets for walls and roofs. The properties of wood cellulose fibres are greatly influenced by the method by which the fibres are extracted and the refining process involved. Wood cellulose fibres have relatively good mechanical properties compared to many manmade fibres such as polypropylene, polyethylene, polyester and acrylic. Designed cellulose fibres (lignin removed) can be produced with a tensile strength of up to approximately 2000 MPa for selected grades of wood and pulping processes. Fibre tensile strength of approximately 500 MPa can be routinely achieved using a chemical pulping process and the more common, less expensive grades of wood. Many of the natural fibres are, however, highly susceptible to volume changes due to variations in fibre moisture content. The fibre volumetric changes that accompany variations in fibre moisture content can drastically affect the bond strength between the fibre and the cement matrix. These types of concretes exhibit, thus, deficiencies in durability despite showing good mechanical properties.

Kaiping et al. (2004) tested the properties of brucite fibres. Brucite is a naturally occurring fibrous mineral with a main chemical composition of $Mg(OH)_2$. The fibres under study had a white grey fibrous morphology with a density of about 2.4 g/cm^3, tensile strength of 932 MPa and Young's modulus of 14.7-19.6 GPa. The dosage of fibre was 0.5 - 1.5 wt% corresponding to approximately 0.02 - 0.06 vol.% of the concrete. The results showed that the fluidity and the density of the concrete decreased while the water retentiveness increased with increasing fibre content. These effects were explained by the fibres having large surface areas and strong absorption capacities. Larger aspect ratios and smaller surface areas of the fibres were found to be beneficial for the workability and mechanical properties of the concrete. The effect of the fibres on the concrete strength was given by the collective interactions of the fibre reinforcement and the density reduction.

2.5 Optical fibres

The Hungarian architect Aron Losonczi developed in 2001 a new type of concrete that transmits light by adding "optical fibers" into the mix. The fibers are used to shift light at each end, producing a "see-through" effect. The concrete body only lets light through in one plane, namely in the direction in which the fibres are lying. The building material LiTraCon (Light Transmitting Concrete) comprises aggregate-free fine-grain concrete to about 96 vol.% and optic-glass fibres to about 4 vol.%. The thickness of the fibres used can vary depending on the particular requirement. Usually used are fibres of between 0.5 and 1 mm in diameter. The building material is a precast concrete part which is cut to the required thickness from a large block of material. This production method assures that each glass fibre starts at an edge of the stone (www.litracon.hu).

The production method of LiTraCon is, however, costly. HeidelbergCement has, therefore, developed a semi-automatic production process of their product named Luccon. To produce Luccon individual textile pieces made of light-conducting fibres and fine-grain concrete are inserted alternately, at intervals of approximately two to five millimetres. The more densely the layers are packed, the more light the concrete allows through. A proportion of textile amounting to just a few percent is sufficient to produce this effect. The surface is polished, but the slabs can also be produced with semi-gloss or high-gloss polished surfaces. The strength of Luccon is comparable to that of high-strength concretes, as the number of light-conducting fibres is relatively small (www.luccon.de).

Figure 4: Example of Litracon in use

2.6 Multiple fibre systems

The fibre properties that are usually of interest are fibre concentration, fibre geometry, fibre orientation, and fibre distribution. Using a single type of fibre may improve the properties of fibre reinforced concrete to a limited level. The concept of hybridization with two different fibres incorporated in a common concrete mix can, however, offer more attractive engineering properties since the presence of one fibre enables the more efficient utilization of the potential properties of the other (Sahmaran et al. 2007, Yao et al. 2003, Kobayashi and Cho 1982). Although not investigated extensively, the use of two or more fibre types in the same concrete mix is considered promising. Banthia and Bindiganavile (2001) found for example that that a blend of macro- and microsteel fibres lead to a closer fibre-to-fibre spacing, which reduced the microcracking and increased the concrete tensile strength. More information about workability of multiple fibre systems can be found in Chapter 4.3.

3 Workability of fibre reinforced concrete

3.1 Factors influencing the workability of fibre reinforced concrete

Main parts of the chapter are taken from Grünewald (2004).

Steel fibres in a concrete mix act essentially as rigid inclusions with a large surface area and a geometry different from that of coarse aggregate. The fibre's long, elongated shape and/or higher surface area affect the workability of the concrete. The practical fibre content is limited since a sudden decrease of workability occurs at a certain fibre content depending on the mixture composition and the applied fibre type. The mixture composition of fibre reinforced concrete is, therefore, often a compromise between the requirements of the fresh and hardened state. Some define the optimum fibre content as the content of steel fibres beyond which fibre balling take place (Narayanan and Kareem-Palanjian 1982).

The effect of fibres on the workability is mainly due to four reasons:

- The shape of the fibres is more elongated compared with the aggregates and promote interlocking. The surface area of the fibres is, moreover, higher resulting in increased water demand.
- Stiff fibres change the internal concrete structure. Flexible fibres fill the space between the particles while stiff fibres push apart particles that are relatively large compared with the fibre length. This effect causes the porosity of the granular skeleton to increase.
- The surface characteristics of the fibres differ from that of cement and aggregates. Synthetic fibres might for instance be hydrophilic or hydrophobic. The surface area of flexible fibres is, moreover, often much higher that the area of steel fibres. Ando et al. (1990) found that the flow spread of fibre reinforced paste decreased markedly with increasing specific surface area of the fibre as illustrated by Figure 5.
- Steel fibres are often deformed (e.g. have hooked ends or are wave shaped) to improve the anchorage between a fibre and the surrounding matrix. The friction between hooked-end steel fibres and aggregates is higher compared with straight steel fibres.

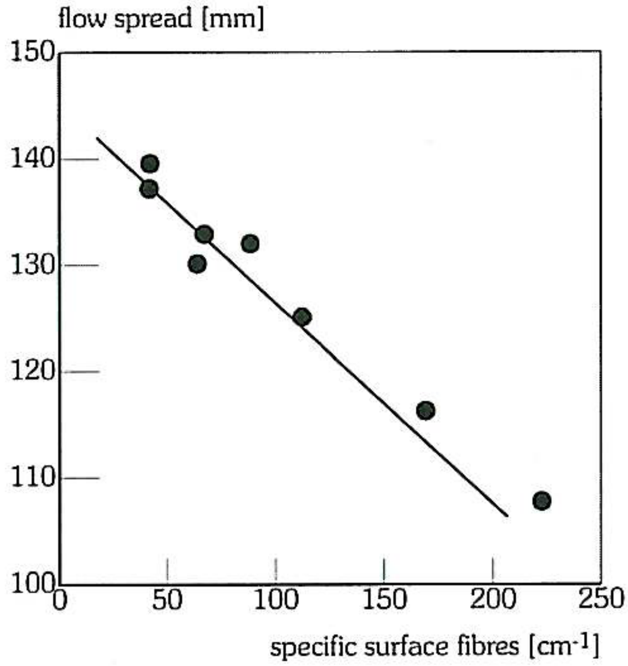

Figure 5: Effect of the specific surface area of carbon fibres on the flow spread of fibre reinforced paste (Ando et al. 1990)

The packing density of a granular skeleton determines the amount of cement paste that is required to fill the interstices. Any surplus of paste contributes to a better workability by reducing the friction between the fibres and aggregates. Minimising the porosity reduces material cost and affects paste-related aspects of concrete like shrinkage.

Swamy and Mangat (1974 a) found that the compactability of fresh fibrous concrete decreases linearly with increasing fibre aspect ratio. This finding was confirmed by studies made by Grünewald (2004) and is illustrated in Figure 6. The figure shows that the degree to which the packing density decreased depended on the aspect ratio of the fibres.

Edgington et al. (1978) performed, similarly, tests on the effect of aspect ratio and fibre concentration on the Vebe-time. Figure 7 illustrates that the maximum fibre volume fraction decreased with increasing aspect ratio.

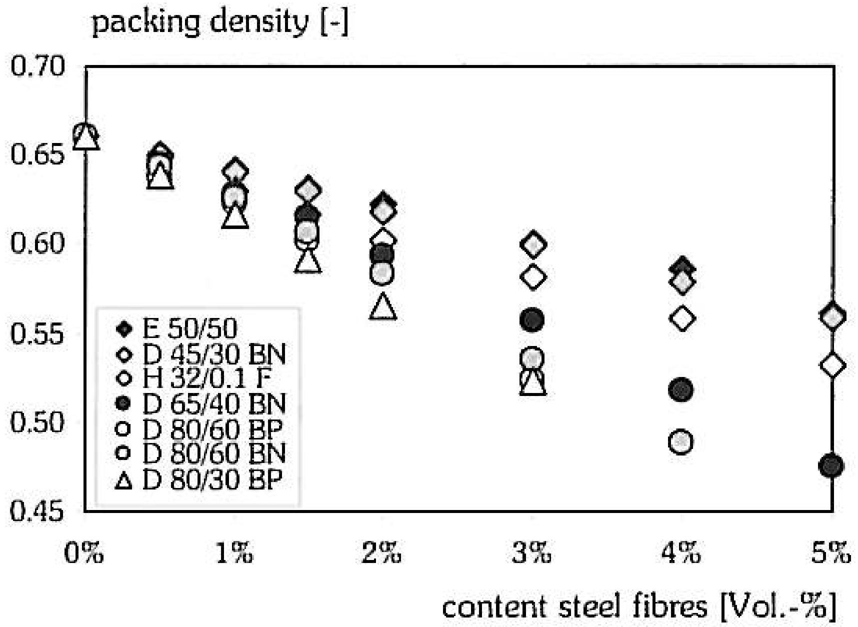

Figure 6: Packing density of concretes with round aggregates of 4-16 mm and different types and contents of steel fibres. The first fibre index represents the aspect ratio, while the second represents the fibre length (Grünewald 2004)

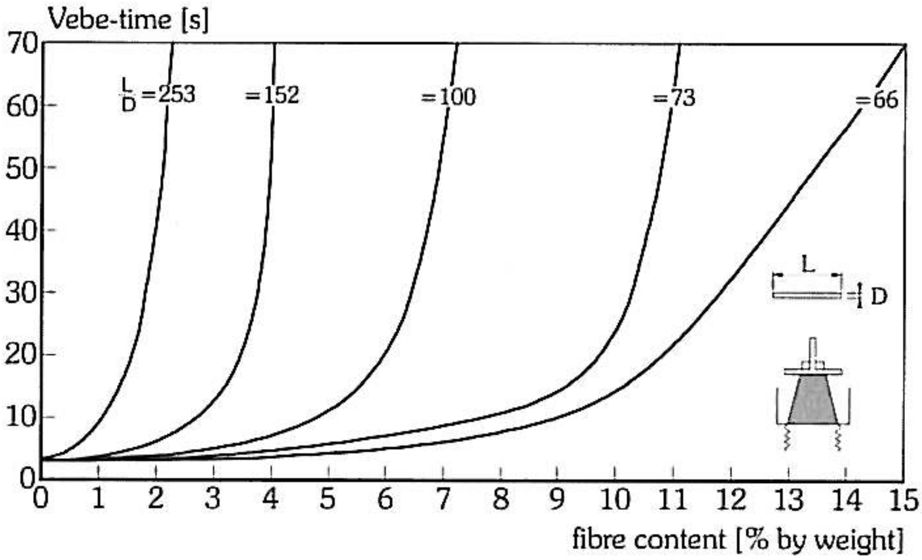

Figure 7: Effect of type and content of steel fibres on the Vebe-time of reinforced mortar with maximum grain size of 5 mm (Edgington et al. 1978)

Size, shape, content of coarse aggregates as well as geometry and volume of steel fibres affect the workability of concrete (Swamy 1975). Steel fibres increase for instance the porosity of the granular skeleton depending on the relative size of the aggregate grains to the fibre length as illustrated by Figure 8. To be effective in the hardened state it is recommended to choose fibres not shorter than the maximum aggregate size (Johnston 1996). Usually the fibre length is 2-4 times that of the maximum aggregate size.

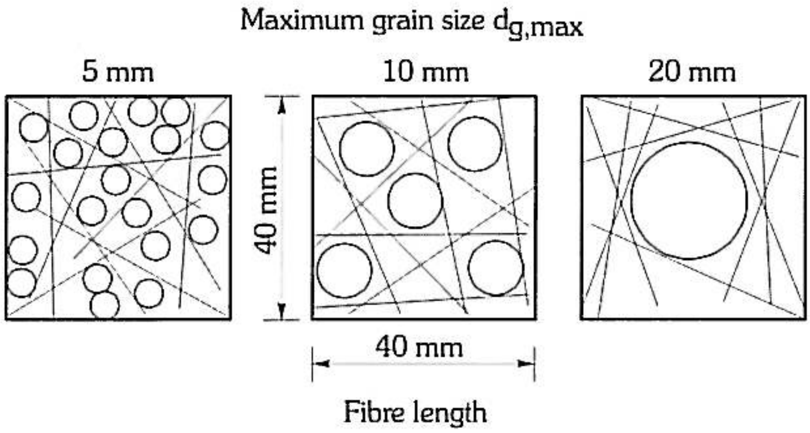

Figure 8: Effect of the aggregate size on the fibre distribution (Johnston 1996).

More fibres can be added as the fine aggregate content of the total aggregate is increased (ACI 1982, 1983). Figure 9 shows how the maximum content of steel fibres decreases at increasing coarse aggregate content. Steel fibres with a length of 25 mm and single sized aggregates (crushed) with a maximum aggregate size of 10 mm were applied in the investigation which was performed by Swamy and Mangat (1974). Note that the mixtures used were conventional concrete mixtures with no modern additives such as superplasticizers or mineral admixtures.

Narayanan and Kareem-Palanjian (1982) found, similarly, that the optimum fibre content increased linearly with increasing percentage sand of total aggregate. The optimum fibre content was defined as the content of steel fibres beyond which fibre balling took place. The maximum aggregate size was 14 mm. Different steel fibre types with lengths between 25-43 mm were tested. The established relation was independent of the ratios of aggregate to cement and water to cement, which means that balling occurred at a given fibre content independently of the concrete composition.

Figure 10 illustrates similar results reported by Hoy and Bartos (1999). The slope of the line in Figure 10 depends on the fibre type and geometry due to its effect on the packing density.

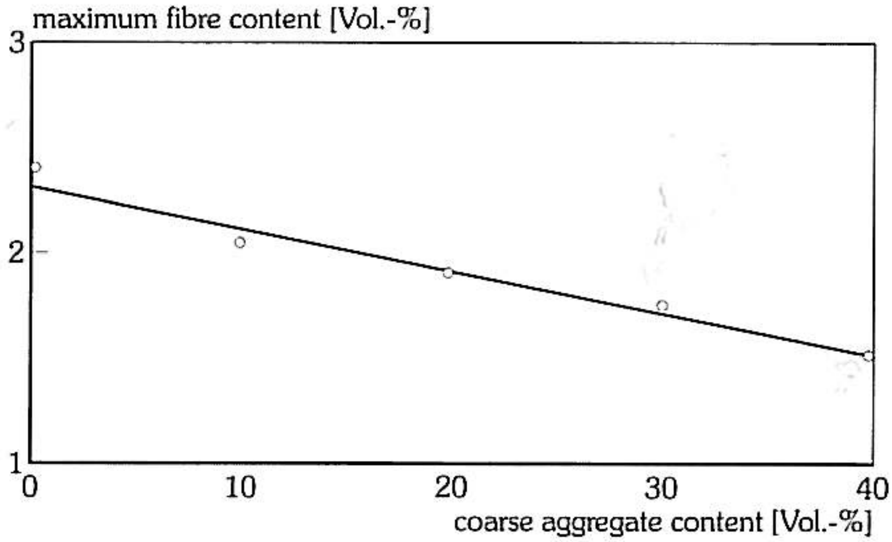

Figure 9: Effect of the coarse aggregate content on the maximum content of steel fibres. Steel fibres with aspect ratio of 100 (length: 25.4 mm and diameter 0.254 mm) and crushed aggregate with maximum size of 10 mm were applied in the study (Swamy and Mangat 1974)

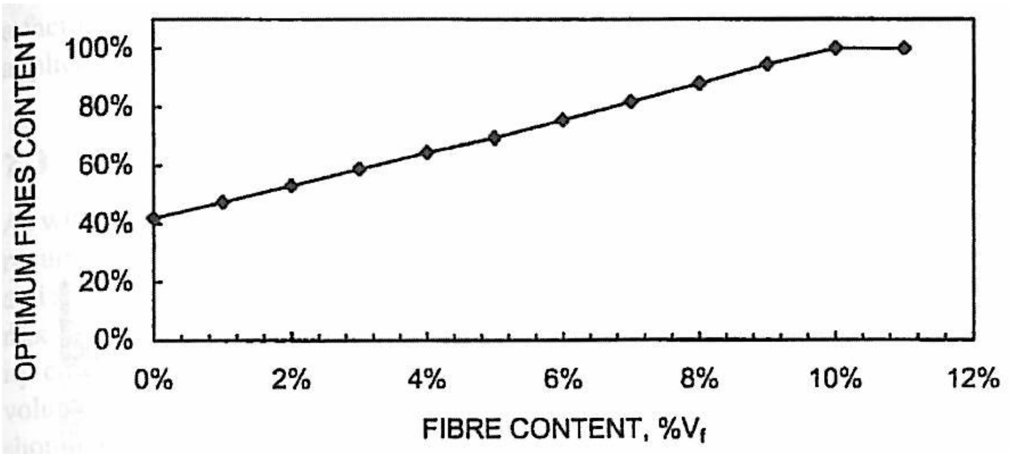

Figure 10: Fines content versus fibre content for determination of optimum packing density (Harex fibres, 32 mm long, 0.9 mm dimater) (Hoy and Bartos 1999)

Rossi and Harrouche (1990) proposed a design method to optimise the granular skeleton of fibre reinforced concrete that was based on the Baron-Lesage method. They assumed that the most workable concrete is obtained when the granular skeleton is optimised. The optimised granular skeleton was, moreover, assumed to be independent of the nature and volume of cement paste. The content and composition of the paste were, therefore, kept constant. The characteristics of fibre reinforced concrete in the fresh state were determined with a LCL-Workabilitymeter which determined the flow time by applying external vibration. Figure 11 shows how the optimum workability of the fibre reinforced concrete depended on the sand content.

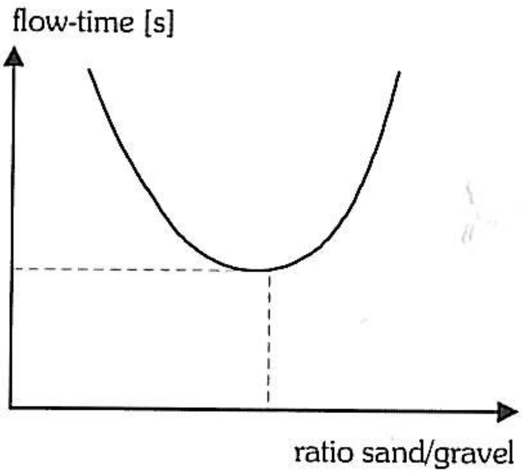

Figure 11: Fibre reinforced concrete – optimisation of the granular skeleton (Rossi and Harrouche 1990)

Figure 12 shows the effect of different sand contents on the packing density as given by Grünewald (2004). The figure illustrates that the effect on packing density is more pronounced at high aspect ratios and low sand contents. The same packing density was obtained for all mixes when the content of sand increased beyond 75 vol.%. Also the relative size between the fibre and the aggregate affects the packing density. Figure 12 shows that the maximum packing density decreases and shifts towards higher sand contents as the aspect ratio increases. Thus, the mixture composition must be adjusted by increasing the content of grains that are relatively small to the fibre length to compensate for the effect of the fibres.

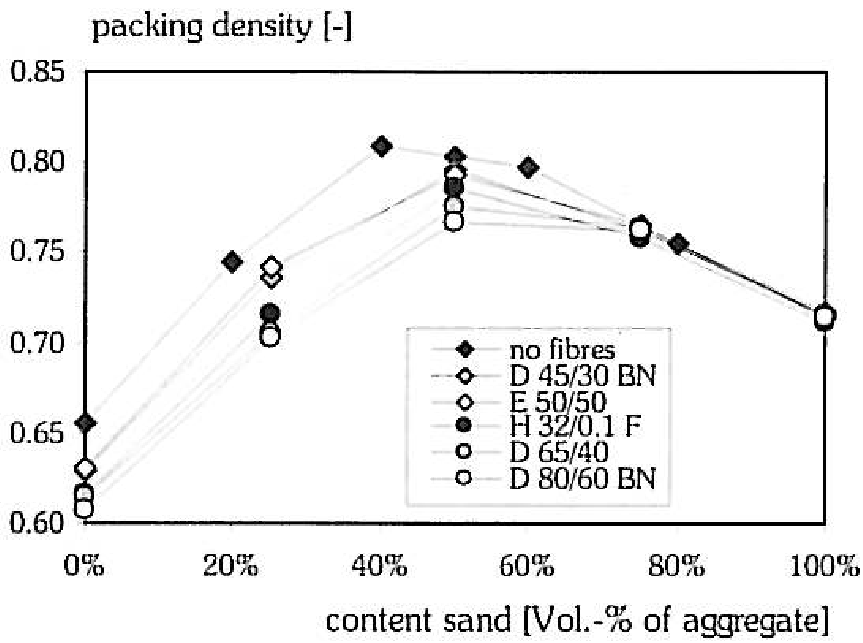

Figure 12: Effect of sand content and type of steel fibres (at 0.93 vol.%) on the packing density. The first fibre index represents the aspect ratio, while the second represents the fibre length (Grünewald 2004)

Hoy (1998) performed experimental and numerical studies on the packing density of the granular skeleton of steel fibre reinforced concrete. Various methods were tested in order to include steel fibres into the Solid Suspension Model (SSM) (packing program developed by De Larrard and Sedran (1994)). Hoy assumed that the most workable mixture would be the one with the highest packing density. The optimum composition of the granular skeleton was obtained from simulations with the SSM. Input parameters of the simulations were the characteristics of the components (steel fibres, sand and coarse aggregate). Figure 13 shows the results from the numerical parameter study. It shows that the required optimum sand content increases with the content of steel fibre. It is important to note that practical considerations limit the applicability of Figure 13 since steel fibre contents larger than 2 vol.% cause a significant decrease of workability.

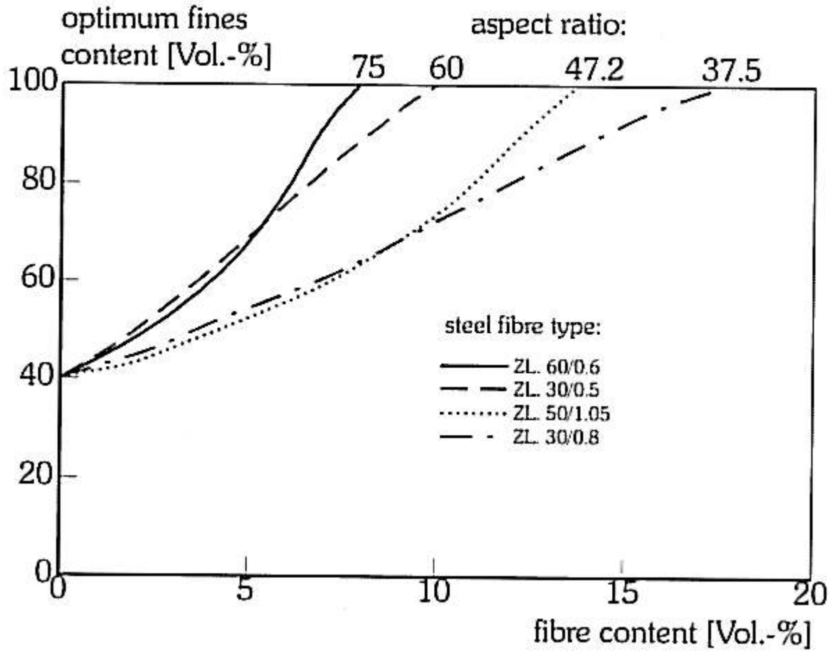

Figure 13: Theoretical effect of the type and content of steel fibres on the optimum sand content (Hoy 1998)

Edgington et al. (1978) studied different reference mixtures which all contained a steel fibre with aspect ratio of 100 and differed in maximum aggregate size (20, 10, 5 mm and cement paste). Figure 14 illustrates how the workability (measured as Vebe-time) and maximum fibre content increased with decreasing aggregate size. The authors proposed an equation to estimate the critical percentage of fibres which can just make the steel fibre reinforced concrete (SFRC) unworkable:

$$PW_{crit} = 75 \cdot \frac{\pi \cdot SG_f}{SG_c} \cdot \frac{d}{l} \cdot K \tag{1}$$

where PW_{crit} is the critical percentage of fibres (by weight),
SG_f and SG_c are the specific gravity of the fibres and concrete respectively and d/l the inverse aspect ratio. K is the factor $W_m/(W_m+W_a)$ where W_m is the weight of the mortar fraction (particle size < 5 mm) and W_a is the weight of the aggregate fraction (particle size > 5 mm). The authors recommended that the fibre content should not exceed 0.75 PW_{crit} in order to permit proper compaction.

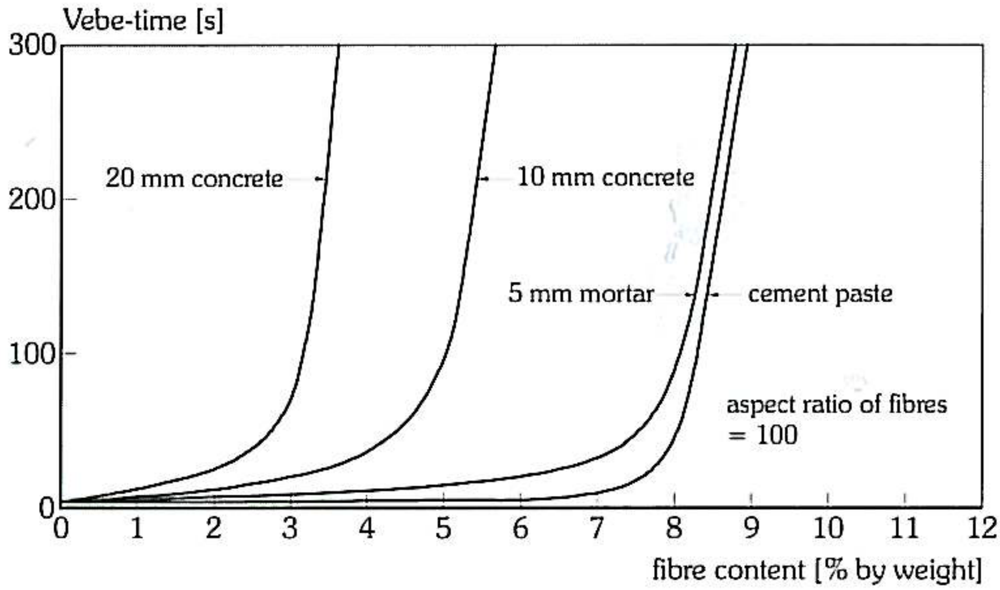

Figure 14: Effect of the mixture composition and the fibre content on the Vebe-time (Edgington et al. 1978)

Fibres tend to stiffen a concrete mix, and make it seem harsh when static, though it may still respond well to vibration. Under vibration, the stiffening effect of the fibres tends to disappear, and so a properly designed FRC mix can be placed and pumped readily with standard placement practices (ACI 544 1993, Johnston 2001). Vibration is encouraged to increase the density, decrease the air void content and to improve the bond with the reinforcement bars. It is important to note that workability tests based on static conditions, such as the slump test are not very useful and can be quite misleading, since the concrete is in fact workable when vibrated. Thus, in order to assess the workability of fresh FRC mixes, it is recommended that dynamic tests are used (Bentur and Mindess 2007).

3.2 Effect of method of fibre addition on fibre balling

Fibre balling can occur even before the fibres get into the mixture: Adding fibres first to the mixer will cause the fibres to fall on each other and form balls since they have nothing to keep them apart. Once the fibres get into the mixture ball-free, they nearly always stay ball-free. Adding fibres too fast to a mixture which is not fluid enough or workable enough to enable the fibres to get mixed in fast enough will cause them to pile up on each other in the mixer. Using equipment with worn-out mixing blades is yet other cause of fibre balling.

Balling will also occur when the critical fibre content is surpassed as discussed in Chapter 3.1. The most common causes of wet fibre balls are over-mixing and using mixtures with too much coarse aggregate (more than 55 % of the total combined aggregate by absolute volume) (ACI 544.3R-93 1998).

3.3 Fibre orientation and distribution

The reinforcing ability of the fibres depends on how the fibres are dispersed throughout the material. Poorly dispersed fibres provide little or no reinforcement in some regions, which then act as flaws in the composite material. Controlling fibre dispersion characteristics is generally difficult and new methods are needed. Convenient methods are also needed for evaluation of fibre dispersion since most methods currently used are both destructive and time consuming. Alternating current-impedance spectroscopy (AC-IS) has been proposed to define fibre dispersion characteristics. AC-IS has been reported to be effective for monitoring various fibre dispersion issues such as fibre orientation, segregation and clumping.

AC-IS is an electrical characterization method that consists of applying an excitation voltage over a range of frequencies to a specimen and thereby recording the current response. AC-IS can only be used for fibre dispersion monitoring when the fibres are conductive. The experimental configuration may, moreover, depend on the size/geometry of the fibres and the specimen. An alternative method to AC-IS is image analysis whereby the fibres of a cross-section are counted (Ozyurt et al 2006, 2007).

Ozyurt et al (2007) obtained fibre distributions for concretes with varying degrees of vibration (0, 2 and 8 minutes) and a SCC. Mix designs with viscosity modifying admixtures appeared to be more resistant to segregation even when vibration was applied. Concretes with 6 mm long fibres had less segregation compared with concretes with 40 mm long fibres. The SCC mix had some segregation, but not as severe as the concrete which had been vibrated for 8 minutes.

4 Fibre reinforced SCC

4.1 Characteristics in the fresh state

The addition of fibres into self-compacting concrete may take advantage of its high performance in the fresh state to achieve a more uniform fibre dispersion. Fibres will, however, reduce the flowability of a SCC due to their long shape and high specific surface compared with aggregate of the same volume. While keeping a stable mixture, the slump flow of the reference mixture without fibres should, therefore, be as high as possible to compensate for their effect (Grünewald and Walraven 2001).

Fibres need to be homogeneously distributed and clustering of fibres must be counteracted in order to optimise the performance of the fibre. The critical fibre content is surpassed when a stiff structure of the granular skeleton makes flow under concretes' own weight impossible (Balaguru and Najm 2004, Grünewald 2004).Workability and maximum fibre volume are governed by parameters such as

- maximum aggregate size
- the type and content of the fibres used
- the matrix in which the fibres are embedded
- the properties of the constituents of the matrix on their own
- fibre addition and mixing process

4.2 Mix design

Generally, the resistance to flow has been found to increase with increasing fibre factor (V·l/d), increasing coarse aggregate content and decreasing paste content (Groth 2000, Khayat and Roussel 1999). Grünewald and Walraven (2001, 2003) observed increased internal interference with increasing fibre content. This was explained by increased internal porosity of the granular skeleton, decreased layer thickness around each particle and increased friction. The influence of stiff fibres on the packing density was found to be most pronounced for mixtures with the lowest paste and the highest coarse aggregate content. The difference in packing density of different types of steel fibres was, accordingly, found to decrease with increased sand content.

The paste is often in focus when a self-compacting concrete is proportioned since it is the vehicle for the transport of the aggregate. The volume of the paste must, therefore, be greater than the void volume created by the aggregate so that all individual aggregate particles are fully coated and lubricated by a layer of paste (see Figure 15). The coarse to fine aggregate ratio in the mix is normally reduced so that individual aggregate particles are fully surrounded by a layer of mortar. This reduces aggregate interlock and bridging when the concrete passes through narrow openings. A certain yield stress and plastic viscosity of the cement paste is, moreover, required in order to avoid segregation. Paste volume, composition and particle size distribution of the aggregates will also influence the concrete stability (Ferrara et al. 2007).

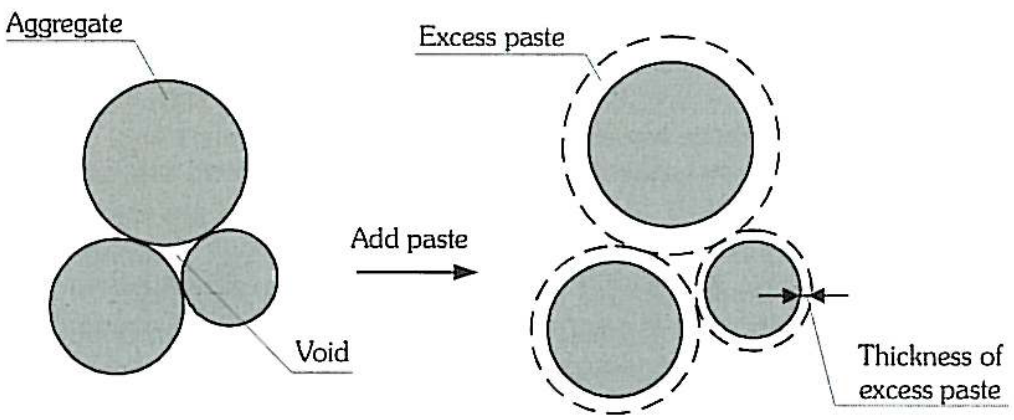

Figure 15: Excess paste layer around aggregates (Oh et al 1999)

Oh et al (1999) created a material model describing how the amount and characteristics of the paste determine the rheological properties of the concrete. The model expresses plastic viscosity and yields stress as follows:

$$\eta_{pl} = \eta_{paste} \cdot \left(a_\eta \cdot \Gamma^{-b\eta} + 1\right) \tag{2}$$

$$\tau_0 = \tau_{0,paste} \cdot \left(a_\tau \cdot \Gamma^{-b\tau} + 1\right) \tag{3}$$

were
η_{pl} is the plastic viscosity of concrete
η_{paste} is the plastic viscosity of the paste
τ_0 is the concrete yield stress

τ_{0paste} is the yield stress of the paste
Γ is the relative paste thickness around the aggregates
a_τ, a_η, b_τ and b_η are constants depending on the production facility

The parentheses in equation (2) and (3) will reach unity and the rheological properties of the concrete will be identical to the paste as the paste thickness (Γ) around the aggregates increases. Oppositely, both yield stress and plastic viscosity will increase towards infinity as the paste layer thickness decreases towards zero.

The amount of surplus paste is according to the model crucial for the concrete workability. The model assumes that surplus paste is distributed in a thin layer on the surface of all aggregate particles which is proportional to the aggregate diameter as given by equation (4):

$$\Gamma = \frac{t_{paste}}{d_{aggregate}} \qquad (4)$$

were t_{paste} is the thickness of the paste layer and $d_{aggregate}$ is the diameter of the respective aggregate as illustrated by Figure 15.

The paste surplus can be calculated with the aid of the aggregate volume fraction, φ, and the maximum aggregate compactability, φ^*:

$$\varphi = \frac{V_{aggegate}}{V_{total}} \qquad (5)$$

$$\varphi^* = \frac{V_{aggegate}}{V_{aggregate+paste}} \qquad (6)$$

$$V_{total} = V_{paste\ surpluss} + V_{aggregate\ and\ paste} \qquad (7)$$

$$V_{pastesurpluss} = V_{total} - \frac{V_{aggregate}}{\varphi^*} \qquad (8)$$

The following is achieved by dividing equation (8) with the unit volume V_{total}

$$V_{pastesurpluss} = 1 - \frac{\varphi}{\varphi^*} \qquad (9)$$

The model assumes that the surplus paste is distributed with a constant thickness *t* over a spherical aggregate with a diameter *d*, and surface area *A*:

$$\text{Paste surpluss} = A_{sphere} \cdot t = (\pi \cdot d_{sphere}^2) \cdot (\Gamma \cdot d_{sphere}) \qquad (10)$$

giving

$$\Gamma = \frac{Pastesurpluss}{6 \cdot V_{sphere}} \qquad (11)$$

Inserting equation (8) into (10) and dividing by the reference volume V_{total} gives

$$\Gamma = \frac{V_{pastesurpluss}}{6 \cdot \varphi} = \frac{1 - \frac{\varphi}{\varphi^*}}{6 \cdot \varphi} = \frac{1 - \frac{\varphi}{\varphi^*}}{\frac{f}{k} \cdot \varphi} \qquad (12)$$

were f/k is a factor which describes the particle shape, 6 being a perfect sphere. The factor is increasing with increasing asymmetry of the particle.

Ferrara et al. (2007) based their concrete proportioning on models made for SCC. Their proportioning was initiated by defining the average diameter of the solid particle skeleton as:

$$d_{av} = \frac{\sum_i d_i m_i}{\sum_i m_i} \qquad (13)$$

where d_i is the average diameter of aggregate fraction *i* and m_i is the mass of the given fraction.

Fibres were handled as an "equivalent spherical particle" fraction with 100 % passing at an equivalent diameter, $d_{eq\text{-}fibers}$, defined as

$$d_{eq-fibres} = \frac{3L_f}{1 + 2\frac{L_f}{d_f}} \frac{\gamma_{fibre}}{\gamma_{aggregate}} \qquad (14)$$

where L_f and d_f are the length and diameter of the fibres, respectively, γ_{fibre} is the specific weight of the fibres and $\gamma_{aggregate}$ is the weighed average specific weight of all the aggregates.

Equation (14) was derived under the assumption that the surface area of an equal mass of fibres to the unit volume of concrete corresponds to the surface area of an equal mass of spheres having the same specific weight as aggregates. For the fibre-reinforced skeleton, the "average equivalent diameter of solid particles" was then expressed as:

$$d_{av} = \frac{\sum_i d_i m_i + d_{eq-fibres} m_{fibres}}{\sum_i m_i + m_{fibres}} \qquad (15)$$

Ferrara et al. (2007) defined the average aggregate spacing d_{ss} as twice the thickness of the excess paste covering the aggregates:

$$d_{ss} = d_{av}\left[\sqrt[3]{1 + \frac{V_{paste} - V_{void}}{V_{concrete} - V_{paste}}} - 1\right] \qquad (16)$$

The aggregate spacing factor can be regarded as an indicator of the "degree of suspension" of the solid skeleton.

The void ratio, V_{void}, of the graded solid fraction including fine and coarse aggregates and fibres was measured according to ASTM C29/C29M05. The average solid particle spacing d_{ss} could then be calculated through equation (16). The final stage of the design consisted in combining a cement paste with given rheological properties with the suitably graded particles of the solid skeleton. The paste volume governs the average spacing between the solid particles. The spacing factor will consequently influence the required rheological properties of the paste to obtain a concrete with the desired flowability and stability characteristics.

Markovic et al (2003) applied the so-called “Excess paste Model”, developed for conventional self-compacting concrete, for the self-compacting fibre concrete. According to this model, the necessary amount of the cement paste in self-compacting concrete, consists of two components. The first one is the minimum paste amount (V_p), which fills the voids in a dry packed mixture of aggregates and fibres. The second one is the additional paste amount (V_{pa} + V_{pf}) which covers all aggregate particles (V_{pa}) and all fibres (V_{pf}), in order to “lubricate” them and to create a flowable viscous mixture. The composition of the fibre concrete mixture with dry packing density PD, which consists of m fractions of aggregate and n types of fibres, may be represented as:

$$V_a + V_{pa} + V_f + V_{pf} + V_p + V_{air} = 1 \text{, which equals} \qquad (17)$$

$$V_a + \sum_{i=1}^{m} n_i \cdot V_{pa,i}^{(1)} + V_f + \sum_{j=1}^{n} n_j \cdot V_{pf,j}^{(1)} + (1 - PD) + V_{air} = 1 \qquad (18)$$

where $V^{(1)}_{pa,i}$ and $V^{(1)}_{pf,i}$ represent the volume of excess paste around a single aggregate particle and single fibre respectively. Assuming a spherical shape of the aggregate particles and a constant thickness of the cement paste layers (c_a and c_f) these volumes may further be expressed as

$$V_{pa,j}^{(1)} = \pi / 6 \cdot (6 d_{a,i}{}^2 c_{a,i} + 12 d_{a,i} c_{a,i}^2 + 8 c_{a,i}^3) \text{, and} \qquad (19)$$

$$V_{pf,j}^{(1)} = \pi \cdot l \cdot (d_{fj} c_{fj} + c_{fj}{}^2) \qquad (20)$$

From the known dry packing density of the aggregate-fibre mixture (PD), one may obtain the minimum necessary paste volume (V_p). The authors computed the additional paste volume, which is necessary to cover all particles and fibres for a given volume and grading of the aggregate, and amount and types of fibres. The total paste content was obtained by summing-up the minimum and the additional paste volume.

The following additional assumptions were made in order to be able to use the model:

1) The thickness of the paste layer is proportional to the diameter of the particle (i.e. diameter and length of the fibre) with the proportionality factor k, so that

   $c_a = k \cdot d_a$ and (21)

   $c_f = k \cdot d_f \cdot l_f^m$ (22)

   where *m* is a parameter which should be calibrated using the results of the experiments;

2) No entrapped air is present in the fresh mixture

The procedure for estimation of maximum applicable aggregate content for self-compacting fibre concrete was thus:

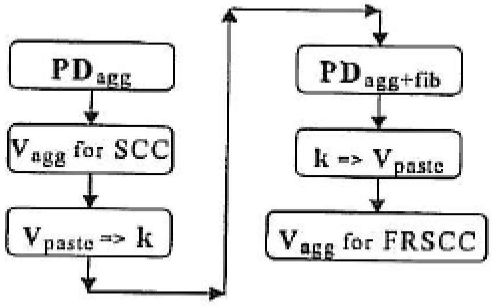

Figure 16: Flow chart for proportioning of SCC with the Excess Paste Model given by Markovic et al (2003)

The model was applied on concrete mixes with two different "Dramix" fibre types, namely straight OL 6/0.16 (l = 6mm, d = 0.16 mm) and long hooked-end fibres RC-80/60-BP (l = 60 mm, d=0.70mm). The maximum applied fibre volume content was 4 vol.% in a dry mixture, which corresponds to 3 vol.% in the wet concrete mixture. A maximum grain size of *1 mm* was selected. The maximum applicable content of fibre was obtained experimentally by mixing and compared to the values estimated by the model. The results showed that the model was applicable for the short fibres and that it worked well for contents of long fibres up to 1 vol.%. It was according to the model, possible to apply higher fibre volumes than 1 vol.% with a decrease in the aggregate content. Higher fibre contents caused, however, clustering of the long fibres and unsuccessful application of the model.

The authors achieved surprisingly higher packing densities of fibre and aggregate mixtures when large 80/60 fibres were applied than with sand on its own as illustrated by Figure 17. On the contrary, the presence of short fibres decreased the packing density. The rheological measurements showed that the short, straight fibres did not have a significant influence on the workability, except in case of fibre volume contents larger than 4 %. No significant decrease in the volume content of aggregate was necessary in order to keep the workability at a satisfying level. Best fit for the calibration factor *m* was in this case 0.5 - 1.0.

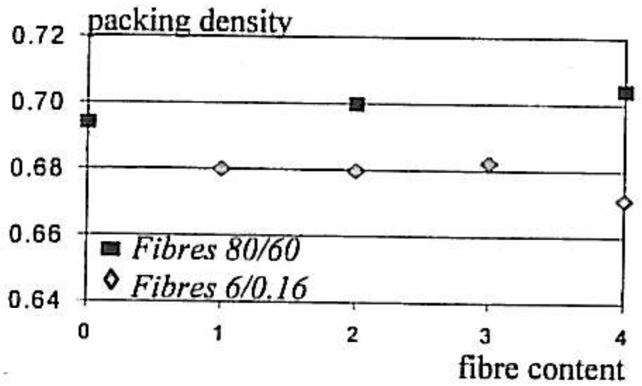

Figure 17: Relation between applied fibre volume and packing density for pastes with maximum aggregate size of 1 mm as derived by Markovic et al (2003)

Barragan et al (2005) showed that self-compactability could be obtained with the incorporation of 40 kg/m^3 steel fibres (corresponds to 0.5 % when ρ = 7800 kg/m^3). High strength SCC was fabricated with a CEM I 52.5 R cement, limestone filler with a Blaine of 620 m^2/g, 10 % by weight of the cement microsilica, and crushed limestone aggregates; 0-5 mm sand and 5-12 mm gravel. The water-cement ratio was 0.45. A polycarboxylate-based superplasticizer was utilized.

The steel fibres were hooked-ended Dramix RC-80/30 BP, with a length of 30 mm and a diameter of 0.5 mm. The authors used Marsh cone and mini slump tests to determine the optimal superplasticizer dosage and filler-cement ratio rendering adequate flowability and a high level of internal cohesion. A superplasticizer saturation dosage of 0.3 % as solid content was determined for pure paste by aid of marsh cone measurements, while the optimum filler-cement ratio was determined to be 0.40.

To obtain the best packing of the aggregates an experimental method based on the ASTM C29/C29M standard was used. The weight of dry aggregate mixes was determined with different sand/gravel ratios without compaction. The ratio that gave the highest unit weight, corresponding to the minimum void content, was considered the optimum. The optimal particle packing was achieved by a sand/gravel=1.5, giving a void content of 39 %. Finally, tests were performed on concretes with varying paste volumes, starting from a threshold corresponding to the void content of the skeleton. The minimum paste content providing adequate flowability, passing ability and resistance to segregation was then considered to be the optimum. In this case, the optimal paste volume was 46 %. The final mix composition is given in Table 2

Table 2: Mix composition developed by Barragan et al (2005)

COMPONENTS	**kg/m^3**
Cement CEM I 42.5 R	489
Microsilica	49
Limestone filler	195
Limestone sand 0-5 mm	882
Limestone gravel 5-12 mm	585
Water	212

4.3 Workability of hybrid fibre reinforced SCC

Sahmaran et al (2005) prepared hybrid fiber reinforced SCC of the two fibre types Dramix ZP 305 and Dramix OL 6/16. The total fibre content was 60 kg/m^3 for all mixes while the ratio between the two fibre types was varied. The fibre characteristics are given in Table 3.

Table 3: Fibre parameters for the study performed by Sahmaran et al (2005)

	Fibre Type	
	ZP 305	**OL 6/16**
Shape	Cylindrical, hooked	Straight
Length (mm)	30	6
Aspect ratio	55	37.5

The viscosity (measured by t_{500} and V-funnel) decreased as the volume fraction OL6/16 increased and the fraction of ZP 305 decreased. No significant effects were, however, seen for the slump flow. Multivariable analysis was used to correlate results from V-funnel and t_{500} measurements. The fibres had to be treated as separate factors due to different geometry and surface roughness using the fibre factor as the variable. The authors recommend increased paste amount in order to retain high level of workability with fibre reinforcement. Increased cement content, increased fine aggregate content or using pozzolanic admixtures were suggested as alternative solutions.

The highest split tensile strength occurred for the concrete in which the fibres were proportioned equally. On the other hand, the densities of the hardened concrete, measured by ultrasonic pulse velocities, did not seem to be affected by the fibre composition. This finding indicated that all concrete matrixes were uniform.

Aydin (2007) used carbon (isotropic pitch based) and steel (cylindrical straight type, Dramix OL 6/16) fibres in combination. The fibre characteristics are given in Table 4.

Table 4: Properties of the fibres used by Aydin (2007)

	Fibre Type	
	Carbon	**Dramix OL 6/16**
Specific gravity	1.6	7.17
Tensile strength (MPa)	690	1100
Length (mm)	5	6
Diameter (μm)	15	16

The total fibre content vas kept constant at 2 vol % while the ratio between the steel and carbon content was varied. The results showed that increased volume ratio of steel fibre volume resulted in a more workable concrete (increased slump flow and decreased t_{500} and V-funnel values). Increased compressive, flexural and splitting tensile strengths were, moreover, observed as the steel fibre content was increased.

4.3.1 Blocking

The long elongated shape of the steel fibres might increase the bar spacing required to avoid blocking. The blocking tendency might be investigated by the use of the J-ring. For the J-ring, blocking is defined as when the difference between the heights of the concrete in- and outside of the ring is larger than 10 mm.

Grünewald and Walraven (2001 b) found that stiff steel fibres caused blocking in the V-funnel. A new funnel was, therefore, designed with a square cross section of the opening gap of about twice the length of the longest fibre used in the study.

5 Alternative fibre technologies

5.1 Slurry Infiltrated (Mat) Concrete, SIFCON and SIMCON

The fibre volume fraction of conventional fibre reinforced concrete is generally limited to 1 - 3 % due to interlocking of the fibres. SIFCON (slurry infiltrated fibre concrete) and SIMCON (slurry infiltrated mat concrete), on the other hand, may be produced with fibre volume fraction values between 5 % and 30 %. SIFCON is produced by preplacing the fibres in the mould until it is completely filled. The fibre network of SIFCON is then infiltrated by cement-based slurry. Maximum fibre volume is a function of several parameters, such as the shape, diameter, and aspect ratio of fibres; their orientation; the method used in packing; mould size; and the extent of vibration (Lankard 1984, Mondragon 1987).

Figure 18: Placing of steel fibres before cement slurry is added in order to produce slurry infiltrated steel fibre concrete (ACI 544.1R-96 1997).

Lankard (1985) showed that it is possible by aid of SIFCON to increase the flexural strength and toughness by more than an order of magnitude, compared with the unreinforced matrix or to a matrix reinforced with a low fibre volume (Figure 19).

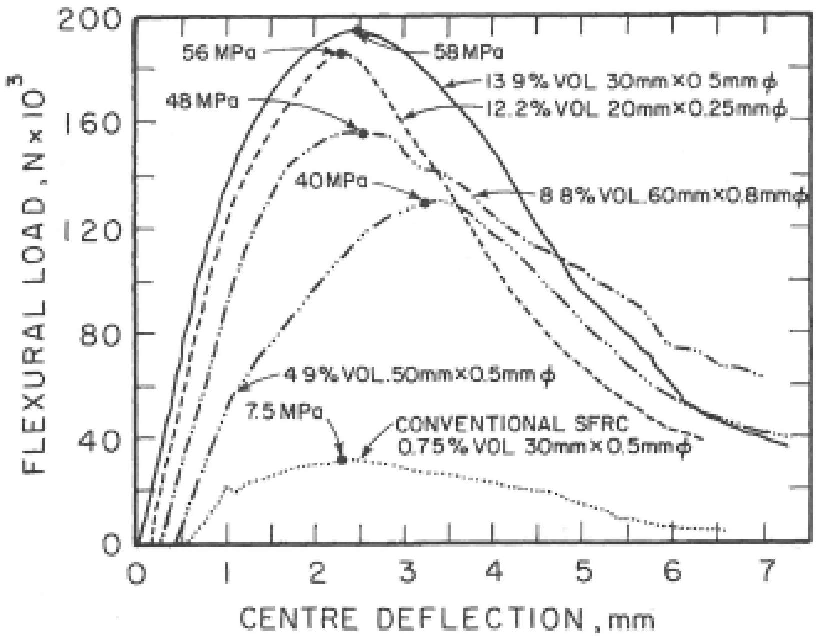

Figure 19: Effect of fibre content in SIFCON on the load-deflection curve of the composite (Lankard 1985)

Fibre alignment greatly affects the behaviour of a SIFCON product. Fibres can be aligned normal, parallel to the loading direction or can be placed randomly. The ultimate strength, residual strength, ductility and energy absorption properties are all affected by the fibre alignment. It is difficult to obtain uniformly distributed fibres due to the manual sprinkling process. However, the alignment of fibres can be controlled by using special sieves.

The use of SIFCON in real construction has been concerned with producing this material as simply as possible. From this point of view, SIFCON has a great problem with the infiltration of slurry among fibres and generally requires intensive vibration (Lankard 1984, Mondragon 1987). Vibration might, however, be omitted by the use of self-consolidating slurry. A statistical approach to optimize the self-compacting SIFCON slurry incorporating silica fume or limestone powder in terms of workability, rheology, penetrability, bleeding and compressive strength has been studied by Sonebi et al. (2004). It was found that limestone powder had a positive effect on the fluidity and penetrability of the cement slurry through the fibre mass. On the other hand, compressive strength of hardened slurries decreased by the incorporation of these mineral admixtures.

SIMCON, developed by Hackman et al. (1992), is fabricated by placing a factory-prepared random two-dimensional steel-fibre mat in a mould and infiltrating the cement-based slurry with external vibration to enforce uniform slurry distribution.

The main difference between SIFCON and SIMCON is the fibre type. The use of short fibres is the general practice in SIFCON, while a mat with long fibres is the main reinforcement in SIMCON. Thus, fibre alignment can be easily controlled in SIMCON. Laboratory test data have shown that SIMCON exhibits equivalent or superior strength and ductility properties to those of SIFCON (Balaguru and Najm 2004).

Figure 20: SIMCON (CNN)

With a high volume fraction of steel fibres, both SIMCON and SIFCON exhibit dramatically improved strength and ductility compared to conventional steel fibre-reinforced concrete (Homrich and Naaman 1987). These products are, however, relatively expensive. Only applications requiring very high strength and toughness have, therefore, so far benefited from their use. These applications include impact and blast resistant structures, refractories, protective revetments, bridge deck renovation and pavement repairs (ACI 544.1R, Schneider 1992). In a retrofit situation continuous SIMCON fibre-mats, delivered in large rolls, can be easily installed by wrapping around members to be rehabilitated. In new construction of high-performance composite frames SIMCON is well suited for manufacturing high strength, high ductility, and thin stay-in-place formwork elements that eliminate the need for secondary and most of the primary reinforcement.

5.2 Textile reinforced concrete

Textile reinforced concretes were developed as a result of the observation that fibres distribute randomly in concrete. As a result the strength of the fibres is not fully used and a comparatively high degree of reinforcement is needed. Textiles on the other hand are oriented in line with the occurring stresses. Textiles are usually made of alkali resistant (AR) glass fibres, but carbon and aramid fibres can be used as well.

Brameshuber and Brockmann (2001) optimized a matrix which offered chemical compactability with the textile materials as well as a suitable consistency, rapid hardening and high early strength. Self-compactability, stability and ability to fill the formwork were emphasized. Ensuring adequate stability was especially important as the concrete was cast through close-meshed textiles (width < 5 mm). A lack of stability could result in segregation at the reinforcement and cause blockage flow. The chosen parameters and the range of variation for optimization of the mixture are given in Table 5. The optimized mix with the best rheological properties is given in Table 6.

Table 5: Range of parameters used by Brameshuber and Brockmann (2001) for the optimization of fibre reinforced concrete

Parameter	Variation
Binder content (kg/m^3)	600 - 900
w/b ratio	0.35 - 0.50
Type of plasticizer	Polycarboxylate-melamine-lignosulphonate
Content of plasticizer (mass% of binder)	0-3 - 3.0
Ratio fines/sand	0.4:1-0.5:1-0.7:1
Maximum grain size of sand (mm)	0.5 - 2.0
Fly ash, fineness (cm^2/g)	2600 - 8600
Ratio cement/fly ash/silica fume	70:30:0-70:23:7-70:25:5-30:50:20-30:65:15
Additives	Polymers, stabilizer etc.

Table 6: Optimized mixture composition for textile reinforced concrete developed by Brameshuber and Brockmann (2001)

Materials	Content
CEM I 52.5 (kg/m^3)	490
Fly ash (kg/m^3)	175
Silica Fume (kg/m^3)	35
Water	245
Polycarboxylate (mass % of binder)	1
w/b ratio	0.40
Fines (kg/m^3)	500
Aggregates 0-0.6 mm	714

The tensile strength of alkali-resistant glass fibres has been found to be reduced by the alkalinity of the concrete as a function of time. Büttner et al. (2006) improved, however, the load bearing capacity and durability of textile reinforced concrete components by impregnating the textiles with epoxy resins.

The advantage of textile reinforced concrete is that it has no need for corrosion protection which renders reduced required cover thickness. Nevertheless, this material will not displace or replace the ordinary steel reinforced concrete. Its application is only useful in extremely thin and slender structures or for repair and strengthening of existing structural members. However, to use the full potential of this new composite, fundamental questions regarding the failure and damage processes, durability aspects, production processes, supplementary applications as well as the bonding characteristics have to be solved (ACI).

Figure 21: Textile reinforced concrete as a rhomb framework with a span of 10 m. Height and width of each rhomb is 16 cm and 25 mm respectively (Hegger et al 2007)

5.3

Ultra-High Performance Fibre Reinforced Concrete (UHPFRC)

Achieving the same mechanical properties as traditionally reinforced concrete will probably demand changes of the matrix composition in line with ultra high performance concretes. High performance concretes obtain compressive strengths higher than 80 MPa and contain

- good quality aggregates
- ordinary Portland cement; 450-550 kg/m^3
- silica fume; 5-15 % by mass of the cementitious material
- other cementitious materials such as fly ash or ground granulated blast furnace slag
- superplasticizer; 5-15 l/m^3
- water cement ratio 0.20-0.35

High performance concrete is placed in the structure by conventional methods, although particularly good wet curing is required (Aitcin and Neville 1993).

Ultra-High Performance Fibre Reinforced Concretes (UHPFRC) are cementitious composites also known as reactive powder concretes (Richard and Cheyrezy 1995) which exhibit compressive strength >150 MPa, tensile strength >8 MPa and strain-hardening behaviour under uniaxial tension. The mix design of UHPFRC differs significantly from that of normal and high strength concretes: UHPFRC mix compositions are characterized by high cement, superplasticizer and silica fume contents. Furthermore, the water-binder ratio is lower than 0.20. The size of the coarsest aggregate used in UHPFRC generally lies between 0.5 and 4 mm. Aggregates are thus replaced by crushed quartz and sand in order to improve the compactness and homogeneity of the concrete. Strain-hardening behaviour is achieved by incorporating more than 2 vol.% steel fibres. Examples of mix designs are given in Table 7.

Table 7: Example of mix designs for UHPFRC developed by Habel et al (2006) and Richard and Cheyrezy (1995). Weights are given relative to the cement mass.

	Habel et al (2006)		**Richard and Cheyrezy (1995)**	
Constituent	**Type**	**Weight**	**Type**	**Weight**
Cement	CEM I 52.5 N	1	Portland	1
Sand	Quartz, diameter < 500 µm	0.70	150-600 µm	1.1
Silica fume	Spec. surf.: 12 m^2/g	0.26		0.25
Steel fibres	Straight (10 mm, 0.2 mm)	0.45	12 mm	0.175
Superplasticizer	Chryso Optima 175	0.03	Polyacrylate	0.02
Total water		0.18		0.17

6 Other ongoing projects about fibre reinforced concrete

RILEM's Technical Committee 208-HFC named "High performance fibre reinforced cementitious composites" started its activity in 2004. The committee works with structural design, material property characterization and testing, and field execution. The focus is on High Performance Fibre Reinforced Cementitious Composites (HPFRCC) in structural applications. Estimated time needed for the work is 4-5 years.

7 Conclusions and recommendations for future work

Workability and maximum fibre volume are governed by parameters such as
- maximum aggregate size
- the type and content of the fibres used
- the matrix composition, amount and workability
- the properties of the matrix constituents
- mixing and placing process

There is a gap in the knowledge about flow properties and simulation of flow of fibre reinforced concrete. Systematic studies need to be made upon the influence of fibre type and fibre combination on concrete flow.

The paste thickness around the particles determines the degree of concrete flowability until the critical fibre content is reached and fibre balling occurs. The maximum fibre content is governed by fibre inter-lock and workability loss due to the long shape and high surface area of the fibre. The literature indicates that the critical fibre content is 2 - 4 vol.% for traditional concretes and SCC. Increasing the fibre content above 2 % seems to demand new casting techniques or a change of the fibre reinforced concrete concept as exemplified by SIFCON and textile reinforced concrete.

Achieving the same mechanical properties as traditionally reinforced concrete will probably demand changes of the matrix's materials in line of high performance concrete and better control over fibre distribution. Some structural applications of fibre reinforced concrete have already been made possible using special high-performance fibre-reinforced composite materials such as DUCTAL®. However, further research is required for a comprehensive understanding and a more widespread use of fibre-reinforced cement-based materials. Quality assurance and quality control systems are needed to be able to further commercialize these composites. Fresh and hardened state properties should be well monitored. Combinations of high performance concrete and new production techniques should be interesting topics for further study.

The market offers a multitude of different fibre types. The development of an inexpensive, strong and flexible fibre which do not interfere with aggregate particle packing and has good bond to the binder phase would, however, bring fibre concrete a giant leap forward.

8 References

ACI Committee 544, State of the art report on Fibre Reinforced Concrete, ACI 544 IR-82, *Concr. Int.* **4** (1982) 9-30

ACI 544.3R-93 Guide for specifying, proportioning, mixing, placing and finishing steel fibre reinforced concrete, (1998)

ACI Committee 544, Guide for specifying, proportioning, mixing, placing and finishing steel fibre reinforced concrete, *ACI Mater. J.* **90** (1993) 94-101

Aitcin P.-C., Neville A., High-performance concrete demystified, *Concr. Int.* **15** (1993) 21-26

Altouat S.A., Lange D.A., Creep, Shrinkage, and cracking of restrained Concrete at Early age, *ACI Mat. J.,* July (2001) 323-331

Ando T., Sakai H., Takahashi K., Hoshjima T., Awara M., Oka S., Fabrication and properties of a new carbon fibre reinforced cement product, Thin-Section Fiber Reinforced Concrete and Ferrocement, American Concrete Institute Special, publication SP-124 (1990), pp. 39-60

Aydin A.C., Self compactibility of high volume fiber reinforced concrete, *Construction and Building Mater.,* **21** (2007) 1149-1154

Balaguru P., Najm H., High-Performance Fiber-reinforced Concrete Mixture Proportions with High Fiber Volume Fractions, *ACI Materials Journal,* **101** (2004) 281-286

Banthia N., Bindiganavile V., repairing with Hybrid-Fiber-reinforced Concrete, *Concr. Int.* June (2001) 29-32

Barragan B., Gettu R., de la Cruz C., Bravo M., Development and application of fibre-reinforced self-compacting concrete, Proceedings of the Young Reserchers' Forum, Dundee, Scotland, UK (2005) 165-172

Bentur A., Mindess S., Fibre Reinforced Cementitious Composites, 2nd ed. Modern Concrete Technology 15, Taylor & Francis, London and New York 2007

Brameshuber, W., Brockmann, T., Hegger, J., Molter, M. Textilbeton - Betontechnologie und Tragverhalten, Untersuchungen zum Textilbewehrten Beton, *Beton* **9** (2002) 424-429

Brameshuber, W., Brockmann, T., Development and Optimization of cementitious matrices for textile reinforced concrete elements, in proceedings: 12th GRCA International Congress, 14-16 May 2001, Dublin - Republic of Ireland, 2001

Büttner, T., Raupach, M., Orlowsky, J., Dilthey, U., Schleser, M., Epoxy-impregnated textiles in concrete - Load bearing capacity and durability, in proceedings: ICTRC 2006 1st International RILEM Conference on Textile Reinforced Concrete, 2006

De Larrad F., Sedran T., Optimization of Ultra-High-Performance Concrete by the use of a packing model, *Cem. Concr. Res.* **24** (1994) 997-1009

Edgington J., Hannant D.J., Williams R.I.T., Steel fibre reinforced concrete, Fibre reinforced materials, The Construction Press, Lancaster, England, (1978) pp. 112-128

Edgington J., Hannant D.J., Williams R.I.T., Steel fibre reinforced concrete, Current Paper CP69074, Building Research Establishement, Garston, Watford, 1974, 17 pp.

Ferrara L., Park Y.-D., Shah S.P., A method for mix-design of fiber-reinforced self-compacting concrete", *Cem. Concr. Res.* **37** (2007) 957-971

Groth P., Fibre reinforced concrete – Fracture mechanics methods applied on self-compacting concrete and energetically modified binders, PhD-thesis, Department of Civil and Mining Engineering, Luleå University of Technology (2000 a)

Groth P., Nemegeer D., The use of steel fibers in self-compacting concrete, First International RILEM symposium on self-compacting concrete, Stockholm, Sweden, (1999) 497-507

Grünewald S., Performance-based design of self-compacting fibre reinforced concrete, PhD thesis 2004, DUP Science, Delft, ISBN 90-407-2487-3

Grünewald S., Walraven J.C., Rheological measurements on self-compacting fibre reinforced concrete, 3rd International Symposium on Self-Compacting Concrete, Reykjavik, Iceland (2003) 49-58

Grünewald S., Walraven J.C., Rheological study on the workability of fibre-reinforced mortar, The Second International Symposium on Self-Compacting Concrete, Tokyo (2001) 127-136

Grünewald S., Walraven J.C., Parameter-study on the influence of steel fibers and coarse aggregate content on the fresh properties of self-compacting concrete, *Cem. Concr. Res.,* **31** (2001 b) 1793-1798

Grünewald S., Walraven J.C., Maximum content of steel fibres in self-compacting concrete, The Second International Symposium on Self-Compacting Concrete, Tokyo (2001) 137-146

Habel K., Viviani M., Denarié, Brühwiler E., Development of the mechanical properties of an Ultra-high performance Fiber Reinforced Concrete (UHPFRC), *Cem. Concr. Res.* **36** (2006) 1362-1370

Hackmann L.E., Farell M.B., Dunham O.O., Slurry infiltrated mat concrete (SIMCON), *Concrete Int.* **December** (1992) 53-56

Hanisch V., Kolkmann A., Roye A., Gries T., Yarn and textile structures for concrete reinforcements, in proceedings: FERRO8, Bangkok, Febuary 6th, 2006

Häuβler-Combe U., Hartig J., Bond and failure mechanisms of textile reinforced concrete (TRC) under uniaxial tensile loading, *Cem. Concr. Comp.* **29** (2007) 279-289

Hegger J., Will N., *SFB 532 - Textilbewehrter Beton*, Deutscher Beton- und Bautechniktag 2007 Institut für Massivbau (2007) http://sfb532.rwth-aachen.de

Hegger, J., Bruckermann, O., Voss, S., Brameshuber, W., Brockmann, T., Decentralized wastewater treatment plants made of textile reinforced concrete, in proceedings: Techtextil Symp., 7.-10. April 2003, Frankfurt

Homrich J.R., Naaman A.E., Fiber Reinforced Concrete Properties and Applications, ACI SP-105, Detroit, MI (1987) 244

Hoy C.W., Mixing and Mix Proportioning of Fibre Reinforced Concrete, PhD-thesis, Advanced Concrete and Masonry Centre, University of Paisley (1998)

Hoy C.W, Bartos P.J., Interaction and packing of fibres: Effects of the mixing process, in Reinhardt H.W. and Naaman A.E. (Eds.) High Performance Fibre reinforced Cement Composites (HPFRCC 3), RILEM Proceedings PRO 6, RILEM Publications, Bagneux, 1999, pp. 181-191

Hughes B.P., Fattuhi N.I., The workability of steel-fibre reinforced concrete, *Mag. Concr. Res.,* **28** (1976) 157-161

Johnston C.D., (2001) Fiber-Reinforced Cements and Concretes, Gordon and Breach Science Publishers, Amsterdam, ISBN: 9056996940

Johnston C.D., Proportioning, mixing and placement of fibre-reinforced cements and concretes, Production Methods and Workability of Concrete, Edited by Bartos, Marrs and Cleland, E&FN Spon, London, (1996) pp. 155-179

Kaiping L., Hewei C., Jing'en Z., Investigation of brucite-fiber-reinforced concrete, *Cem. Concr. Res.,* **34** (2004) 1981-1986

Kareem-Palanjian A.S., Naranyanan R., The workability of steel-fibre-reinforced concrete: Part 1, *Concrete* **16** (1982) 45-48

Kareem-Palanjian A.S., Naranyanan R., The workability of steel-fibre-reinforced concrete: Part 2, *Concrete* **17** (1983) 42-44

Khayat K.H., Roussel Y., Testing and performance of fiber-reinforced self-consolidating concrete, First International RILEM symposium on self-compacting concrete, Stockholm, Sweden, (1999) 509-521

Kobayashi K., Cho R., Flexural Characteristics of Steel Fiber and polypropylene Fiber Hybrid Reinforced Concrete, *Composites* **13** (1982) 164-168

Lankard, D.R., Highly reinforced refracting concrete with 4-20 volume % of steel fibers. U.S. (1982) Patent 4, 366,255

Lankard D.R., Slurry infiltrated fiber concrete (SIFCON): Properties and applications. In: Young J.F., (Ed.), Very high Strength Cement-Based Materials, **42**. Symposium held November 27-28, 1984, Boston, MA. Materials research Society, Pittsburg, PA, 227-286

Lankard D.R., Properties, applications: Slurry infiltrated Fiber Concrete (SIFCON), *Concr. Int.* **6** (1984)

Lankard D.R., Lease D.H., Highly reinforced precast monolithic refractories. *Ceram. Bull.* **61** (1982) 728-732

Lankard D.R., Preparation, properties and application of cement-based composites containing 5 to 20 percent steel fibre, in S.P Shah and Å. Skarendahl (eds) *Steel Fibre Concrete*, Proceedings US-Sweden Joint Seminar, Elsevier Applied Science Publishers, Barking, essex, 1985, pp. 199-217

Markovic I., Walraven J.C., van Mier J.G.M., Self-compacting hybrid-fibre concrete – mix design, workability and mechanical properties, 3rd International Symposium on Self-Compacting Concrete, Reykjavik, Iceland (2003) 763-775

Mondragon R., SIFCON in Compression, *Fiber Reinforced Concrete Properties and Applications,* SP-105, Shah S.P., Batson G.B (Eds.) American Concrete Institute, Farmington Hills , Mich., (1987) 269-281

Murakimi H., Zeng J.Y., Experimental and analytical study of SIMCON tension members, *Mechanics of Materials* **28** (1998) 181-195

Narayanan R., Kareem-Palanjian A.S., Factors influencing the workability of steel-fibre reinforced concrete, *Concrete,* (1982) Part 1 **16** 45-48, Part 2 **17** 43-44

Oh S. G., Noguchi T., Tomosawa F., Towards mix design for Rheology of self-compacting concrete, 1st International Symposium on SCC, Stockholm (1999) 361-372

Ozyurt N., Mason T.O., Shah S.P., Correlation of fiber dispersion, rheology and mechanical performance of FRCs, *Cem. Concr. Comp.* **29** (2007) 70-79

Ozyurt N., Mason T.O., Shah S.P., Non-destructive monitoring of fiber orientation using AC-IS: An industrial-scale application, *Cem. Concr. Res.* **36** (2006) 1653-1660

PCA Portland Cement Association, *Concrete Information*, IS532 (2002)

Richard P., Cheyrezy M., Composition of reactive powder concretes, *Cem. Concr. Res.,* **25** (1995) 1501-1511

Rossi P., Harrouche N., Mix design and mechanical behaviour of some steel-fibre-reinforced concretes used in reinforced concrete structures, *Materials and Structures* **23** (1990) 256-266

Sahmaran M., Yaman I.O., Hybrid fiber reinforced self compacting concrete with a high volume of fly ash, *Construct. Build. Mater.* **21** (2007) 150-156,

Sahmaran M., Yurtseven A., Yaman I.O., Workability of hybrid fiber reinforced self-compacting concrete, *Building and Environment* **40** (2005) 1672-1677

Schneider B., Development of SIFCON through applications. In Reinhardt H.W., Naaman A.E. (Eds.), High Performance Fiber-Reinforced Cement Composites. (1992) RILEM Publishing, London, 177-194

Shah, S.P., Weiss M.J., Yang W., Shrinkage Cracking – Can it Be Prevented?, *Concr. Int.* ACI April (1998) 51-55

Sonebi M., Svermova L., Bartos P.J.M., Factorial Design of Cement Slurries Containing Limestone Powder for Self-Consolodating Slurry-Infiltrated Fiber Concrete, *ACI Materials Journal*, **101** (2004) 136-145

Swamy R.N., Fibre reinforcement of cement and concrete, *Materials and Structures* **8** (1975) 235-254

Swamy R.N, Mangat P.S, Influence of fiber geometry on the properties of steel fiber reinforced concrete, *Cem. Concr. Res.* **4** (1974 a) *451-465*

Swamy R.N, Mangat P.S, Influence of fibre-aggregate interaction on some properties of steel fibre reinforced concrete, *Materials and Structures* **7** (1974) 307-314

Trottier J.-F., Mahoney M., Innovative Synthetic Fibers, *Concr. Int.* June (2001) 23-28

Yao W., Li J., Wu K., Mechanical properties of hybrid fibre reinforced concrete at low fibre volume fraction, *Cem. Concr. Res.* **33** (2003) 27-30

Yazici H., Yigiter H., Aydin S., Baradan B., Auticlaved SIFOC with high volume Class C fly ash binder phase, *Cem. Concr. Res.* **36** (2006) 481-486