Fibre Reinforced Concrete

Contents

Introduction

The use of fibres to reinforce and enhance the properties of construction materials goes back at least 3500 years, when straw was used to reinforce sun-baked bricks in Mesopotamia. Cement-bound products have been reinforced by various types of fibre at least since the beginning of the last century, and steel and synthetic fibres have been used to improve the properties of concrete for the past 30 or 40 years. Fibres also improve the properties of many natural as well as engineered materials, e.g. motor vehicle tyres are made from fibre-reinforced rubber.

This Information Bulletin (IB) will outline:

- the different types of fibre commonly available on the New Zealand market,
- how fibres can be used to enhance the properties of concrete,
- the properties of concrete made using fibres,
- the manufacture and testing of fibre reinforced concrete (FRC), and
- typical applications of FRC.

The bulletin will review the use of discontinuous fibres in conventionally mixed concrete, but not in cement. In other words, it focuses on fibres added during the batching and mixing of concrete but excludes, for example, glass fibre reinforced cement (or concrete) – GRC, asbestos cement, and other specialised materials such as *ultra-high performance fibre reinforced* (or '*ductile*') *concrete*. Some synthetic fibres not commonly used in New Zealand, e.g. aramid, carbon, polyester, are also excluded from this bulletin.

Using this Document

In compiling this bulletin CCANZ sought input from a range of parties interested in advancing the use of fibre reinforced concrete in New Zealand. This included fibre manufacturers and suppliers, design engineers, testing professionals, and concrete engineers and specialists.

While every effort has been made to ensure accuracy, it was not possible to verify all claims made relating to proprietary or specialist products. As such, this bulletin seeks to provide *generic* information arrived at through consensus.

Users of this bulletin should seek independent verification or test results to satisfy themselves that their own specific requirements will be met in areas such as fibre type, fibre dosage, concrete properties, crack control, joint spacing and fire resistance.

It must always be remembered that no two fibres are the same and that comparisons of performance should only be made on a particular concrete dosed with a specific mass or volume of a particular fibre against a specific mass or volume of a different fibre used in the same concrete.

Steel Fibres

INTRODUCTION TO STEEL FIBRES

Although the concept of steel fibre reinforced concrete has been in existence for many years, it was not until the 1970's that commercial use took off, particularly in Europe, Japan and the USA.

Unreinforced concrete is a brittle material with low tensile strength. Traditional reinforcement in the form of either bars or mesh is used to provide load carrying capacity at a cracked section in the *ultimate limit state* and also to control cracking, deflections and rotations in the *serviceability limit state*. The high tensile strength of reinforcing bars and mesh is fully mobilised only when they are bridging macro or visible cracks in the concrete matrix. Short, discrete steel fibres provide discontinuous three-dimensional reinforcement that picks up load and transfer stresses at micro-crack level. This reinforcement provides tensile capacity and crack control to the concrete section prior to the establishment of visible macro cracks, thereby promoting ductility or toughness.

Initially, steel fibres were used as a substitute for secondary reinforcement or for crack control in less critical concrete elements. Nowadays, they are widely used as the main reinforcing for industrial floor slabs, shotcrete, and precast concrete products. They can also be used for structural purposes, e.g. for reinforcing slabs on piles, the full replacement of reinforcing cages for tunnel segments, and shear reinforcement in pre-stressed elements.

GENERAL CHARACTERISTICS

Steel fibres are manufactured from a number of different processes, are available in a range of shapes and sizes, and can be loose or collated (glued together in strips). Typically, they are between 18 and 60 mm long, with a tensile strength of between 600–2500 MPa with a modulus of elasticity of around 210,000 MPa. *Figure 1* shows some different shapes and sizes of steel fibres.

ASTM A820 classifies steel fibres into four groups according to the method of manufacture, as follows: cold-drawn wire, cut sheet, melt extracted, and others. EN 14889-1 uses a similar classification, but subdivides 'others' into *shaved cold drawn wire* and *milled from blocks*.

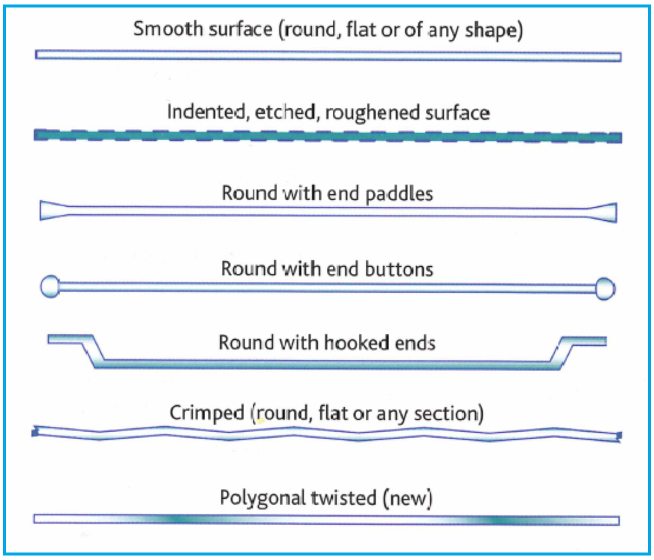

FIGURE 1: Types of steel fibres. (Source: CSTR 63)

The fibre dosage and the following physical characteristics of the fibre will influence the properties of the steel fibre reinforced concrete:

- fibre tensile strength
- anchorage mechanism; hook end, flat end, deformed or flat shape,
- aspect ratio.

Tensile Strength

Typical tensile strengths of steel fibres are in the range 600–2500 MPa. For concrete compressive strengths over 60 MPa, a fibre tensile strength greater than 1500 MPa should be used to prevent *embrittlement* – the loss of post-crack load and energy absorption capacity, as the strength of the concrete matrix increases with age.

The total force applied across a crack to prevent the crack from opening is the cumulative effect of the number of individual fibres bridging the crack and the tensile force developed in each. The number of fibres is the product of the fibre count (fibres/kg) and the fibre dosage (kg/m^3). To avoid brittle failure, the fibres bridging a crack must not snap easily. Fibres with a low tensile strength, and/or with an anchorage that develops too high a pull-out load, are prone to snapping. If that happens, their load carrying capacity is lost.

Fibre Anchorage

How a fibre anchors into the concrete will determine its ability to deform and slowly pull out, rather than break as the crack it is bridging becomes wider.

Aspect Ratio

The *Aspect Ratio* of a fibre is the ratio of its length to its 'equivalent' diameter.

As long as a fibre's basic shape, tensile strength, dosage and anchorage mechanism remain the same, a higher aspect ratio will result in a steel fibre reinforced concrete element having a higher post-crack load carrying capacity. This improved performance is due to the increased fibre count i.e. there are more fibres providing tensile capacity at each cracked section. The *Aspect Ratio* of the fibres chosen for a particular application is a function of economics and performance.

THEORY

Steel fibres do not significantly affect the compressive strength of the concrete that they are reinforcing, and the compressive strength is determined by standard cylinder tests in exactly the same way as for plain concrete. It is also generally accepted that steel fibres at *normal* doses do not significantly increase the tensile strength of concrete. In other words, steel fibre reinforced concrete will crack at approximately the same values of flexural or direct tensile stress as it would if it was unreinforced.

However, when steel fibres are present, a number of them intercept micro-cracks as they form and continue to provide tensile capacity across the cracks. The level of tensile capacity provided across these cracks is typically evaluated in the laboratory using standard beam or panel tests and is expressed in terms of residual post-crack strength or energy absorption. This compares to traditional reinforcing that becomes effective only when macro-cracks have developed, as seen in *Figure 2*.

In most structural applications, traditional reinforcing is provided to ensure that the load bearing capacity of the cracked section exceeds the capacity of the plain concrete. At dosages of up to approximately 40 kg/m^3 dependent on the aspect ratio of the fibres used, the post crack flexural capacity provided by the steel fibres is typically less than the capacity of the uncracked concrete, this type of behaviour is described as strain softening – see *Figure 3*.

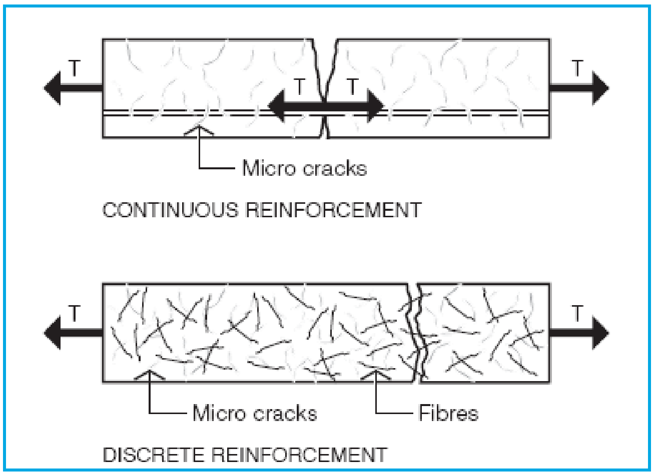

FIGURE 2: Reinforcement in a concrete matrix

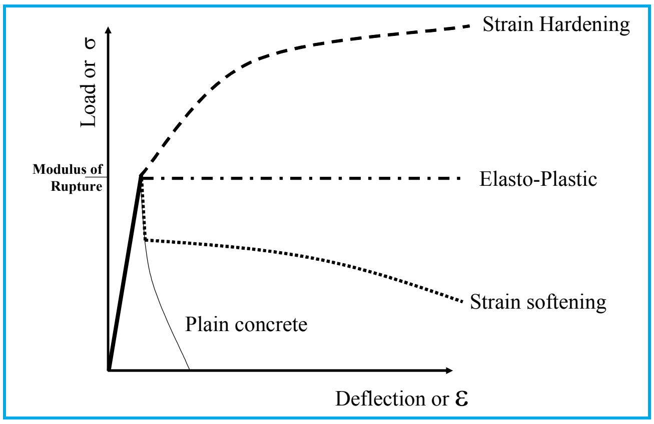

FIGURE 3: Typical load/ deflection (stress/ strain) plots of fibre reinforced concrete

This strain softening characteristic means that at a crack the moment carrying capacity is less than in the adjacent uncracked concrete and the crack is effectively a plastic hinge. In elements where a single crack forming is enough to turn the element into a mechanism i.e. a simply supported, or statically determinate beam, the post cracked load carrying capacity will be less than for the uncracked element. However, in statically indeterminate elements, where more than one crack is required to create a mechanism i.e. a built-in or continuous beam, in which moment redistribution can take place, the load carrying capacity will increase even as cracking occurs, right up until the last crack forms and the element becomes a mechanism. Once the mechanism is complete the load carrying capacity will then fall away.

Consequently, steel fibres are generally used as sub-critical reinforcing in statically determinate structures such as beams, columns, suspended slabs etc. However, in applications that are statically indeterminate where load redistribution is possible, e.g. ground supported slabs, shotcrete etc., steel fibres have the ability to increase the load carrying capacity of the concrete element.

The tension provided by steel fibres across cracks as they continue to open allows load versus deflection curves to be plotted for fibre reinforced test samples. The area under such *curves* has the units Nm or Joules and measures the energy that can be absorbed by the element. When fibre reinforced sections are able to absorb significant levels of energy they are said to possess ductility or toughness, and load/deflection tests are commonly referred to as 'Toughness Tests'.

DESIGN OF STEEL FIBRE REINFORCED CONCRETE

The most important consideration when working with steel fibre reinforced concrete is to ensure that the fibres form an effective network within the concrete matrix that will effectively intersect any developing cracks. If this is achieved, crack growth will be resisted and localised stresses redistributed. This provides a ductile failure mode. The following should be considered:

- minimum fibre length - Industry best practice suggests the fibre length should be 2.0 to 3.0 times the nominal maximum aggregate size
- minimum dosage to achieve sufficient fibre overlap – Brite EuRam suggests that the average spacing between fibres should not exceed 45 percent of the fibre length
- dosage based on performance (from test results) - residual or equivalent strength values, or energy absorption.

The fibre dosage required to achieve an effective 3-D network will depend on the fibre length, tensile strength, distribution and number of fibres per kilogram (fibre count). Designs are then carried out based on the toughness requirements of the steel fibre reinforced concrete.

The use of steel fibres in structural applications has evolved as the result of research in order to understand and quantify the material properties. Since October 2003, RILEM TC 162-TDF - *Test and design methods for steel fibre reinforced concrete,* has provided recommendations for design rules for steel fibre reinforced concrete in structural applications. These recommendations form the basis of the design methods provided for steel fibre reinforced concrete in NZS 3101:2006 *Concrete Structures Standard*.

Design guides for specific applications are also available, such as CSTR 34 *Concrete industrial ground floors: A guide to design and construction* covering ground supported slabs. These also use the post-crack strengths determined by testing, and have explicit design equations suitable for ground supported steel fibre reinforced concrete slabs.

Other publications providing guidance on the design of steel fibre reinforced concrete include:

- Technical Report 63 – CSTR 63: Guidance for the design of steel fibre reinforced concrete, The Concrete Society, Camberley, Surrey, UK.
- DIN N62 Steel fibre concrete, Deutsches Institut für Normung, Berlin, Germany.
- EN 14487-1:2005 – Sprayed concrete. Definitions, specifications and conformity, British Standards Institution, London, UK
- ACI 544.4R-88 (Reapproved 1999), Design considerations for steel fibre reinforced concrete, American Concrete Institute, Farmington Hills, MI, USA.
- Concrete Roundabout Pavements - A Guide to their Design and Construction, NSW RTA, Sydney, Australia. 1998.
- Brite EuRam, Design Methods for Steel Fibre Reinforced Concrete, A State-of-the-Art Report, RILEM, France. 2000.

PROPERTIES OF STEEL FIBRE REINFORCED CONCRETE

The ability to provide capacity and control cracking at micro-crack level – see *Theory* – has a positive effect on the concrete matrix, improving attributes such as:

- toughness,
- residual (post-cracking) flexural strength,
- crack control,
- impact resistance,
- fatigue, and
- shear resistance.

Not All Fibres Are the Same

Different fibre types give quite different post-crack strengths. In this regard, clause C5.5 of NZS 3101:2006: Part 2: Concrete Structures Standard – Commentary states:

> *'The design properties of steel fibre reinforced concrete are dependant on the post-cracking toughness of the composite material. The properties of the fibre, such as its aspect ratio (length/diameter), ultimate tensile strength and end anchorage have a significant influence on the performance of the fibre reinforced concrete. Different fibre properties will result in different fibre dose rates to meet specific design properties. Designs must be based on the test data supplied by the fibre manufacturer, or confirmed by tests. The design method of Appendix A to Section 5 may be used.'*

The purpose of this clause is to emphasise that even fibres that look the same, but are supplied from a different source, will give different properties to the fibre reinforced concrete. Therefore, designs should be based on the fibre reinforced concrete properties provided by the fibre supplier, or on the properties obtained through testing. Care should be taken by the engineer to specify the properties used in design, as opposed to, for example, a *generic* fibre dosage.

CE Approved Fibres Manufactured to EN 14889-1

The properties of fibre reinforced concrete are more critical than the properties of the fibres on their own. For this reason, the European Standard EN 14889-1 *Fibres for concrete: Steel fibres – Definitions, specifications and conformity* is a 'performance specification' insofar as it requires manufacturers to declare a fibre dosage to achieve a minimum performance level (residual post-crack flexural strength) in a reference concrete. This enables the user to equitably compare the expected performance of different fibre types. This information along with the fibre description, tensile strength, E-modulus, and how the minimum dosage effects consistence (workability) is included on labelling attached to every bag. Engineers can then specify compliance with EN 14889-1 in project documentation, and the CE label used to check that the correct fibres and appropriate dosage are used for the designed application.

It should be noted that there are two types of classification, Class 1 for structural use (i.e. where the addition of fibres is designed to contribute to the load bearing capacity of the concrete element) and Class 3 for non structural use. A CE marked fibre for structural use in sprayed concrete, flooring and precast should not be used at a lower dosage than the declared minimum value mentioned on the CE label.

Durability/Corrosion

According to the UK Concrete Society, corrosion of steel fibres in well compacted concrete is restricted to the surface of the concrete. Staining may be unsightly and should be accounted for in architectural applications and when appearance is important.

Long-term Performance - Creep

Steel fibre reinforced concrete exhibits good creep properties which are critical in applications, such as container and racking loads typical on industrial slabs, where loads are to be established, or sustained, over long periods.

Embrittlement

Notwithstanding the long-term performance/ creep of steel fibre reinforced concrete, high tensile strength steel fibres should be used if there is a concern about *embrittlement* – refer section on *Tensile Strength* on page 2 – due to high, long term strength development of the concrete.

Crack Control (Combined Reinforcing)

Steel fibres used in combination with conventional reinforcing can significantly reduce the quantity of the latter required, whilst also providing the concrete with tighter crack control through controlled multiple fine cracking. This enhances the durability of the concrete.

MIX DESIGN/PROPORTIONING

Typically, steel fibres are used at a dosage rate between 15 and 45 kg per cubic metre of concrete.

Similar mix design methods for *ordinary* concrete can be used to proportion steel fibre reinforced concrete, with the fibres being considered as coarse aggregate.

However, depending on the overall aggregate grading and the volume and type of steel fibre used, it may be necessary to increase the fines content of the mix, both to improve fibre dispersion and to make the concrete easier to compact and finish. An increased fine material content will increase the water demand of the mix, which can be compensated for by using a water reducing admixtures.

USING STEEL FIBRES

Batching and Mixing

Most commercially available steel fibres can be readily added to the fresh concrete as part of the normal concrete batching process. The fibres may be dispersed on to the aggregate conveyor, or into the weigh hopper at the batching plant, or directly into the back of the concrete truck. The most common way in New Zealand is directly into the back of the truck; by hand from either the slump stand or a specially constructed platform, or via a conveyor belt. Collated fibres are glued together with water soluble glue that dissolves during mixing. These fibres should be added as the last component to the truck at a maximum rate of 40 kg/minute, and *never* as the first ingredient of a mix. Seek advice on adding loose fibres to a mix from the manufacturer.

Health and safety aspects are an important consideration in adding steel fibres directly into the back of a concrete truck; their weight should be taken into account and appropriate procedures adopted.

During the mixing process the truck drum should be turning on full speed, and for approximately five minutes after the last mix constituents are loaded.

Placing and Finishing

All conventional concrete placing, compacting and finishing techniques can be used. For flat formed surfaces, generally no special attention is needed to avoid fibres on the surface when the dosage rate is less than around 30 kg/m^3. A vibrating screed used on slabs helps the coarse aggregates and fibres to settle, with a 3-5 mm surface 'paste' usually being sufficient to effectively cover, protect and hide the fibres. Floors constructed with higher fibre dosages may require a quartz-based dry shake topping to minimize surface fibres, if this is an issue. See also *Durability/Corrosion* on page 5.

The experience of the concrete placer has a significant affect on the quality of the surface finish. The type of finish (for example, power float, trowelled or brushed) will depend on the particular application and the client's requirements. Curing should be handled in exactly the same way as traditionally reinforced concrete.

Pumping

Pumping of steel fibre reinforced concrete does not require specialist equipment and, provided a pump mix is used, there should be little change to the concrete mix design. Talk to the fibre supplier if a high fibre content mix or a high aspect ratio fibre is required. This might require reducing the coarse aggregate content of the mix, and a pumping trial might be needed. Normally, it is recommended that the length of the fibre should not exceed 70% of the internal diameter of the delivery pipe or hose.

TESTING AND QUALITY CONTROL

Testing for SFRC Properties

Properties of steel fibre reinforced concrete for use in structural design are determined by *statically determinate* beam or panel tests. Beam tests are deflection controlled up to approximately 3.5 mm, and can be used to determine either the average or the equivalent load carrying capacity up to a nominated deflection value or distinct residual strength values at nominated deflection values. The Round Determinate Panel (RDP) test is deflection controlled up to 40 mm and is typically used to determine the post-crack performance, expressed in joules, for shotcrete.

Properties obtained from these tests include:

- Equivalent flexural strength – average flexural stress up to a specified deflection, in excess of the deflection required to cause cracking,
- Residual flexural strength – flexural stress at a specified deflection,
- $R_e$value – equivalent flexural strength value for the post-cracked steel fibre reinforced concrete divided by the flexural tensile strength of the parent concrete. (The R_{e3} value is the equivalent flexural strength ratio determined up to a deflection of 3 mm - and should be greater than 0.3, otherwise the concrete is considered as unreinforced).

Statically indeterminate plate tests are used to determine toughness in terms of energy absorption. These tests allow multiple cracking and load redistribution and are commonly used to evaluate shotcrete performance. In these tests, the plate can be considered to simulate the behaviour of a shotcrete layer under rock pressure when supported by a central anchor bolt. However, because the tests are statically indeterminate, they cannot be used to determine material properties.

In Australasia, fibre type and dosage are typically based on manufacturers' literature to give the specified properties to the concrete.

Testing for Fibre Properties

For projects such as segmental tunnel linings or shotcrete, the project specifications may also include compliance testing on the steel fibres for tensile strength, diameter, and minimum and maximum length.

Testing for Fibre Quantity and Distribution

A visual inspection is common practice to determine whether or not a homogeneous distribution has been achieved. Under no circumstances should fibre clumping or balls be observed.

EN 14488 include details of a test to determine the fibre content of sprayed concrete (shotcrete), but the same approach can be used for conventional concrete.

Standards and Specifications

In Australasia, steel fibres are generally specified to confirm to either ASTM A 820 or EN 14889.1.

ASTM C 1116 is a standard specification for fibre reinforced concrete, and references the applicable testing standards. In Europe, EN 14845 stipulates test methods for fibres in concrete.

APPLICATIONS

The most common applications for steel fibres have traditionally been in systems where moment redistribution and consequent load carrying capacity increases can be achieved at relatively low dosages for applications such as ground supported slabs and shotcrete. However research and a better understanding of SFRC technology has resulted in the development of various design guides and standards, which have given engineers the confidence to design SFRC into a diverse range of structural applications, including:

- ground supported slabs,
- sprayed concrete (shotcrete),
- pile supported slabs,
- precast beams and panels,
- precast storage tanks, pipes etc.,
- segmental tunnel linings,
- composite steel decks,
- combined reinforcement for crack control,
- seismic beam/column joints.

Macro Synthetic Fibres

INTRODUCTION TO MACRO SYNTHETIC FIBRES

Macro synthetic fibres became commercially available in the late 1990's. They are used to control cracking in concrete due to drying shrinkage, thermal movements or both, and to provide post-cracking energy absorption capacity or toughness.

GENERAL CHARACTERISTICS

Most macro synthetic fibres have dimensions broadly similar to steel fibres, and are from materials with a specific gravity in the order of 0.9. They maintain their mechanical properties in alkaline as well as in acidic environments. Typical 'equivalent' diameters of macro synthetic fibres range from 0.5 to 1 mm, with tensile strengths between 350 to 700 MPa. The modulus of elasticity of these fibres is typically around 3,000 to 10,000 MPa.

Macro synthetic fibres are made from a wide variety of organic polymers. They are generally 40-60mm in length with aspect ratios ranging from 70-90. The shape of some fibres is cylindrical, and are often 'crimped' or 'ribbed', while others are thin and flat.

Examples of macro synthetic fibres are shown in *Figure 4* (page 8).

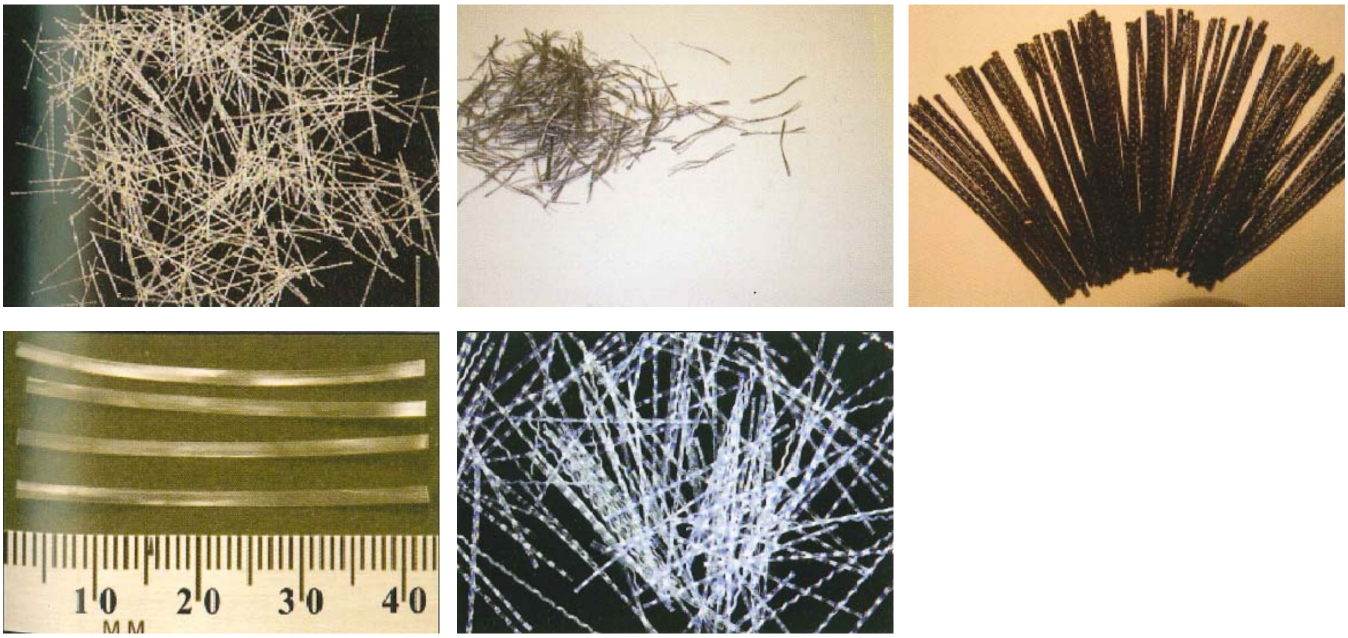

FIGURE 4: Examples of macro synthetic fibres.
*(*Source: TR 65 *Guidance on the Use of Macro Synthetic Fibre Reinforced Concrete*, Concrete Society, UK*).*

THEORY

Macro synthetic fibres rely on sufficient bond to the cement paste (which can be improved with the addition of fly ash or silica fume). 'Flat' shaped fibres are designed in part to increase area by providing a larger surface area to volume ratio.

For optimum fibre efficiency, the elastic modulus of a fibre should closely match the elastic modulus of the hardened cement paste in which the fibre is embedded. This allows the fibres to transfer stresses across a crack after cracking has begun.

As the elastic modulus of macro synthetic fibres is much less than hardened concrete – a typical elastic modulus value of concrete used for slab on grade is around 23,000 MPa - they are generally designed to fail when the fibres break (whereas the failure mode of SFRC is when the fibres *pull out* of the cemented matrix). This should be taken into consideration in the intended application: macro synthetic fibres are generally used in shotcrete for ground support applications and in concrete for slabs on grade where wider cracks (i.e. cracks wider than about 0.4 or 0.5 mm) can be accommodated and/or closer joint spacing is provided. It should however be noted that NZS 3101 recommends maximum surface widths of cracks at the serviceability limit state above 0.4 mm only for benign exposure classifications when the load category is IV (i.e. permanent loads plus infrequent combinations of transient loads).

The key to efficient fibre performance is the bond between the fibre and the hardened cement paste. Some fibres have surface irregularities to strengthen the bond with the cement paste, whereas others rely on the physical bond between the fibre surface and the hardened cement paste.

Macro synthetic fibres are particularly beneficial when larger crack widths, say >0.5 mm, can be accommodated in the concrete as they need to elongate or 'stretch' before they are able to transfer significant amounts of stress across the cracks.

DESIGN OF MACRO SYNTHETIC REINFORCED CONCRETE

The material properties of macro synthetic fibre reinforced concretes such as residual tensile strength are determined by beam tests (e.g. ASTM C1609-06, ASTM C1550 and JSCE-SF4). The results from these tests can be used to calculate the capacity of the concrete element, but where the in-service performance relies on the post-cracking capacity of the concrete and where the fibres are subjected to sustained higher levels of stress, creep is a significant design consideration.

Macro synthetic fibres can be used to replace steel mesh for shrinkage control in ground supported floors, and also as rock support when used in shotcrete. Macro synthetic fibres are not designed to replace steel bars or mesh where either is used for structural reasons. However, because the inclusion of macro synthetic fibres can provide concrete with post cracking capacity, they can be used in some designs based on plastic analysis such as some ground supported slabs and rock support.

If macro synthetic fibres (or steel fibres) are used as a replacement for shrinkage and temperature control steel it is important that the fibre type and dose rate provides a similar level of direct tensile capacity as the reinforcement they replace. This will ensure that crack control is provided, but due consideration should be given to maximum acceptable *serviceability limit state* crack widths.

According to CSTR 34, certain types and dosages of macro synthetic fibres will give acceptable equivalent flexural strength ratio values, which should be determined by testing (as for steel fibres). The dosage of fibres should be sufficient to give an equivalent flexural strength of at least 0.3; otherwise the concrete should be treated as plain.

Guidance on the use of macro synthetic fibre reinforced concrete – including design approaches - can be found in the UK Concrete Society's Technical Report, CSTR 65. However, this document points out, *'where the in-service performance relies on the post-cracking capacity of the concrete and where the fibres are subjected to sustained higher levels of stress, creep will be a significant design consideration'* and *'design using macro synthetic fibres is still in its infancy and there are no universally accepted methods'*.

PROPERTIES OF MACRO SYNTHETIC FIBRE REINFORCED CONCRETE

Hardened concrete containing macro synthetic fibres can generally be described as having post-crack energy absorption capacity. At normal fibre addition levels, the fibres should not themselves have any adverse effect on the compressive strength of the concrete. However, as previously mentioned, strength and durability will be compromised if a reduction in workability due to the fibres is recovered through the addition of extra water.

At higher fibre dosages, some types of macro synthetic fibre may cause the plastic concrete to appear stiff and harsh. In some cases, it may be necessary to increase the slump of the concrete through the use of chemical admixtures in order to avoid any placement and/or compaction issues. In situations where coarse sand must be used, increasing the sand content may not be sufficient to overcome the harsh nature of the fibre reinforced concrete. In these cases, a higher cement content and/or the addition of a small amount of entrained air (2-3 percent) will create a workable fibre reinforced concrete mix.

According to CSTR 65, there is limited information on how the physical properties of macro synthetic fibres change over time and therefore how the long-term structural performance of the concrete may be affected. The modulus of elasticity and creep of the fibres should be kept in mind.

Macro synthetic fibres will soften when subjected to fire, and melt above around 150°C. They lose their mechanical properties and will no longer provide any structural capacity when they melt. It may be necessary to use passive fire protection (e.g. thermal barriers) to limit the temperature rise in the concrete.

CE Approved Macro Synthetic Fibres Manufactured to EN 14889-2

In Europe, macro synthetic fibres can have a CE label for structural use, certifying compliance with EN 14889-2, Class II, i.e. fibres >0.3 mm in diameter.

Macro synthetic fibres (for structural use) should not be used at a lower dosage than the declared minimum value stated on the CE label. See also general information on CE labelled fibres under *Properties of Steel Fibre Reinforced Concrete/CE Approved Fibres* on page 4.

It is important to emphasise that EN 14889-2 is a product manufacturing standard and not a design standard. The suitability of a particular fibre for a particular application will depend on appropriate design rules being followed, and – inter alia - an assessment of long term properties – see *Theory*, *Design* and *Properties* on pages 8 and 9.

MIX DESIGN/PROPORTIONING

Typical dosage rates of macro synthetic fibres range between 2 and 7 kg per cubic metre of concrete, i.e. about 0.25 to 0.75% by volume. The dosage rate needed to achieve the desired residual flexural strength will vary depending on fibre type (i.e. material and fibre dimensions). Increasing the dosage of fibres to achieve a certain toughness performance target is likely to have a negative impact on the workability of the concrete and/or on the ease by which the surface of a floor can be finished. To overcome this, the addition of a superplasticising admixture is recommended to maintain the strength, durability and other properties of the concrete mix design.

As with other fibre additions, the concrete mix must be designed to accommodate the inclusion of macro synthetic fibres. Generally, this means an increase in the volume of the wet cement paste needed to help coat the surface area of the fibres. This can be achieved either through a modest increase in the cement content, and/or through an increase in the sand content by approximately 5 percent. The reduction in workability must be recovered – not by adding extra water – but either by additional water-reducing admixture or by adding a superplasticising admixture.

For external applications, air entrainment may be required to ensure the surface durability of concrete slabs exposed to freezing. The inclusion of macro synthetic fibres may require a slight increase in the dosage of the air entraining agent, primarily because of the increased surface area of the fibre in the concrete mix.

USING MACRO SYNTHETIC FIBRES

Batching and Mixing

Macro synthetic fibres can be added to the empty ready mixed truck prior to loading the concrete constituents or ready-mixed concrete, therefore minimising the time the truck has to spend in the concrete plant. Some macro synthetic fibres, however, are added to the concrete truck at arrival on site. In this instance checks should be made to ensure adequate fibre dispersion throughout the concrete.

In each case the concrete should be mixed for at least five minutes at maximum mixing speed to disperse the fibres throughout the load of concrete.

As previously mentioned, any reduction in workability due to the fibres can be restored by adding additional water-reducing or super-plasticising admixtures.

Placing and Finishing

Concrete containing macro synthetic fibres can be placed and compacted using the same methods as for *plain* concrete, but the concrete should be finished to minimise the appearance of fibres on the surface. An excessive number of fibres *floating* on the surface may indicate inadequate mix design/proportioning, fibre type and physical properties, dosage, and placing/finishing techniques. In some instances, a *fibre suppressant dry shake* topping may be required.

For outdoor applications, a broom finish or "panned" non-slip finish is normally applied. In this case, some of the macro synthetic fibres are likely to be seen on the surface of the concrete pavement. These will not harm the environment, since they will quickly wear off due to abrasion.

Pumping

Generally the inclusion of macro synthetic fibres in a concrete mix does not significantly affect its pumpability.

SAMPLING, TESTING AND QUALITY CONTROL

No special requirements for the sampling and testing of macro synthetic fibre reinforced concrete mixes should be necessary. In the case of casting fibre reinforced concrete for flexural beam performance testing, care must be taken to fill the beam moulds in the specified manner. Failure to do so will result in significant variances in test results, due to changes in fibre alignment within the mould.

Some manufacturers of macro synthetic fibres offer test methods for determining the dosage in plastic concrete. Generally, these methods use flotation to separate the fibres from the concrete. Advice should be sought from the supplier on whether a recommended method is available.

Generally, it is extremely difficult to determine the fibre content of hardened concrete, where fibre separation is near impossible.

Standards and Specifications

In Australasia, macro synthetic fibres are generally specified to confirm to either ASTM C 1116 or EN 14889.2.

ASTM C 1116 is a standard specification for fibre reinforced concrete, and references the applicable testing standards. In Europe, EN 14845 stipulates test methods for fibres in concrete.

APPLICATIONS

The primary applications for macro synthetic fibres are in shotcrete as ground support in underground works, concrete for footpaths, and for some ground supported slabs. They have also been used in marine/coastal applications, precast concrete (including paving slabs, pipes, and ancillary products), and for non-magnetic applications such as track slabs.

A further application is in concrete for composite floors with profiled sheeting. However, as discussed previously, due consideration must be given to the serviceability requirements of such applications.

Micro Synthetic Fibres

INTRODUCTION TO MICRO SYNTHETIC FIBRES

Micro synthetic fibres are manufactured from man-made materials, and are specifically designed for concrete. Their primary function is to modify the properties of fresh concrete. They increase the homogeneity, reduce bleeding, and reduce plastic settlement and plastic shrinkage cracking.

The effect of micro synthetic fibres on the properties of hardened concrete is limited, but they can reduce permeability, and increase resistance to impact, abrasion and shatter, and can reduce spalling of concrete in fire situations. They can also provide some resistance to damage caused by frost.

In shotcrete, they are also used to reduce sloughing and rebound.

GENERAL CHARACTERISTICS

Micro synthetic fibres are characterised by their small size – typically 5-30 mm in length, with a diameter of a few tens of microns.

Micro synthetic fibres used in New Zealand are most commonly made from polypropylene (but they can also be made from nylon, polyester, acrylic or glass), and are classified as either mono filament or fibrillated – see *Figure 5*. Mono-filament fibres are hot drawn through a circular cross section die. Fibrillated fibres are thicker than mono filament fibres. They are manufactured from extruded rectangular films, which are slit longitudinally and fibrillated to produce a lattice network.

The tensile strength and elastic modulus of polypropylene micro synthetic fibres are around 30 MPa and 2,000 MPa, respectively.

The melting point of polypropylene is in the region of 150-160°C.

Micro synthetic fibres should be inert and alkali-resistant to ensure they are not affected by the high alkalinity of the concrete.

FIGURE 5: Examples of monofilament and fibrillated micro synthetic fibres. (Source: Advanced Concrete Technology edited by Newman and Choo).

THEORY

Micro synthetic fibres work by evenly distributing tens to hundreds of millions of fibres, providing reinforcement throughout the mass of the concrete in all directions to control cracking of concrete in its plastic state. Their physical properties are designed to match the properties (e.g. the modulus of elasticity) of fresh concrete.

They are used to increase the tensile strain capacity of the plastic concrete by intersecting micro-cracking that occurs when the concrete shrinks. The fibres provide enough extra strength to prevent micro-cracks from widening.

The effect of the fibres is sufficient to restrict the formation of plastic shrinkage cracking during the two to four hours after the concrete is placed, at which time the concrete tensile strain capacity is at its lowest – see *Figure 6.* Fibrillated micro synthetic fibres offer longer term crack resistance than mono filament fibres, due to their structure and greater physical dimensions.

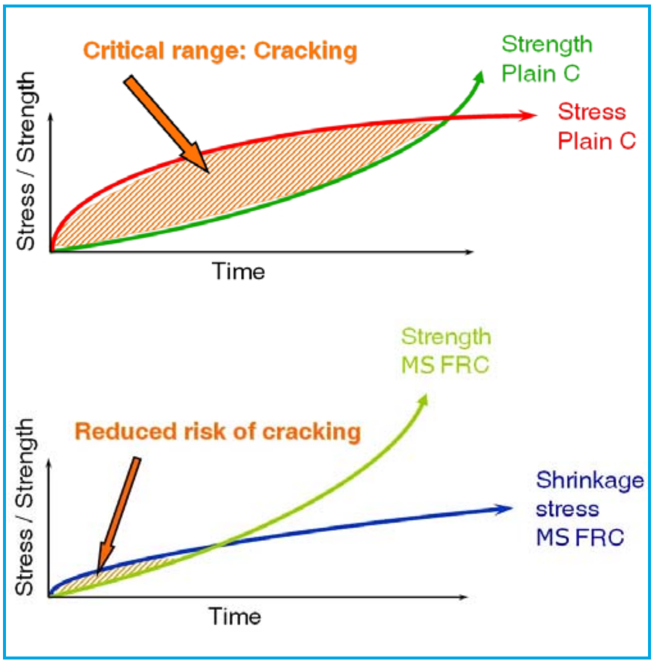

FIGURE 6: Risk of plastic cracking in plain concrete vs. micro synthetic fibre reinforced concrete

Plastic shrinkage cracking results from rapid early drying of concrete. Plastic settlement cracking of concrete occurs when excess water in the mix rises as the heavier materials settle over obstructions. Early thermal cracking occurs when there are excess thermal gradients in unrestrained concrete. See *Table 1*.

It should be stressed that micro synthetic fibres do not replace proper curing of the concrete once finishing operations are completed.

Mono filament polypropylene fibres reduce spalling surface of concrete in fire situations because they melt and vaporise at 160°C, providing channels for water vapour to escape.

The ability of micro synthetic fibres to inhibit bleeding in fresh concrete assists to enhance the surface properties of hardened concrete, as less bleed water at the surface results in a lower water:cementitious material ratio.

They are used in shotcrete to reduce *rebound*, and increase *build* thickness.

DESIGN OF MICRO SYNTHETIC FIBRE REINFORCED CONCRETE

Micro synthetic fibre reinforced concrete should be designed in accordance with the fibre manufacturer's recommendations.

Some micro synthetic fibres manufacturers claim that their fibres offer some longer-term crack mitigation during the drying and shrinkage phase of the hardened concrete, allowing increased joint spacing to be permitted in concrete slabs. However NRMCA CIP 24 specifically advises against increasing control joint spacing beyond recommended guidelines.

PROPERTIES OF HARDENED MICRO SYNTHETIC FIBRE REINFORCED CONCRETE

In addition to reducing or eliminating plastic settlement and plastic shrinkage cracking, micro synthetic fibres can improved the following properties of hardened concrete:

- improve explosive spalling resistance in fire,
- reduce permeability,

TABLE 1: Examples of Cracking in Slabs on Grade Due to Intrinsic Stresses in Early Age Concrete

Type	Cause	Time of Appearance
Plastic settlement	Excess bleeding and/or rapid early drying/differential settlement	10 min – 3 hours
Plastic shrinkage	Rapid early drying/low rate of bleeding	30 min – 6 hours
Early thermal contractions	Excess heat & temperature gradients	Overnight – 2 or 3 weeks

- increase impact, abrasion and shatter resistance, and

- improve resistance to deterioration by freeze-thaw cycles.

Micro synthetic fibres do not provide any appreciable amounts of *residual strength* to concrete, i.e. they do not significantly increase the ability of concrete to carry a load after it cracks, so they should NOT used be used to:

- control cracking due to external stresses and loads,

- reduce the thickness of a concrete slab,

- replace any moment-resisting or structural steel reinforcement, or

- increase joint spacing above NZS (or other recommended) guidelines.

CE Approved Micro Synthetic Fibres Manufactured to EN 14889-2

In Europe, micro synthetic fibres can have a CE label for non structural use, certifying compliance with EN 14889-2 for either Class Ia (Mono-filament) or Class Ib (Fibrillated) fibres <0.3mm in diameter.

MIX DESIGN/PROPORTIONING OF MICRO SYNTHETIC FIBRE REINFORCED CONCRETE

In most cases, mix design/proportioning of low to moderately dosed micro synthetic concrete (i.e. a fibre dosage of less than approximately 2.2 kg per cubic metre of concrete, or 0.25% by volume) is similar to that for conventional concrete, although an adjustment to the water content, or preferably an increase in water-reducing admixture, may be required to maintain workability.

A typical dosage of monofilament polypropylene fibres – 0.7 kg/cubic metre of concrete – distributes tens to hundreds of millions of fibres throughout the concrete mix.

Typical dosages rates for fibrillated fibres (generally around 0.9 kg/cubic metre of concrete) are higher than for monofilament fibres as they are usually much thicker, so a higher dosage is required to provide the desired fibre count.

USING MICRO SYNTHETIC FIBRE REINFORCED CONCRETE

Batching and Mixing

Micro synthetic fibres are packaged in water soluble packaging (typically bio-degradable bags) that facilitate the addition of the fibres directly into the concrete mix at either the batching plant or on site in the concrete truck.

Placing and Finishing

Monofilament fibres are very hard to see in the finished concrete, and the finishing techniques are the same as those for plain concrete. Because of their very fine construction, monofilament fibres are especially useful in exposed aggregate concrete.

More attention is required when placing concrete reinforced with fibrillated fibres, as a result of their structure and larger size. However, conventional equipment and minor adjustments to techniques and workmanship are generally sufficient.

Pumping

Concrete reinforced with micro synthetic fibres, at *normal* addition rates, can be pumped as readily as plain concrete, and sometimes more readily provided any loss of consistence is compensated for by a water-reducing admixture.

SAMPLING, TESTING AND QUALITY CONTROL

There are no special sampling techniques necessary for micro synthetic fibre reinforced concrete.

Standards and Specifications

In Australasia, micro synthetic fibres are generally specified to confirm to either ASTM C 1116 or EN 14889.2.

ASTM C 1116 is a standard specification for fibre reinforced concrete, and references the applicable testing standards. In Europe, EN 14845 stipulates test methods for fibres in concrete.

APPLICATIONS

Micro synthetic fibres may be used in a wide range of concrete applications to improve the plastic and hardened properties of concrete. Typical applications (dependent on fibre type and dosage) include:

- slabs-on-grade,
- stucco,
- exposed aggregate concrete,
- coloured and imprinted concrete,
- composite metal decks,
- shotcrete, and
- precast applications.

Cellulose Fibres

INTRODUCTION TO CELLULOSE FIBRES

Cellulose fibres are a class of fibres belonging to the *natural fibres* family, i.e. fibres that originate from wood and plant materials. These fibres vary tremendously in size, shape, purity and fibre strength, but they all contain some cellulose, an organic polymer of glucose. On a molecular level, celluloses can vary substantially in their degree of polymerisation and in their crystalline structure. It is important to understand that all cellulose fibres are not created equal and therefore it is important to select a fibre for concrete that can achieve the intended properties.

The use of unprocessed cellulose fibres for reinforcement in building materials dates back well over 2000 years. Their usefulness was first recognized by the ancient Greeks, who used straw fibres to reinforce mud bricks. Today, processed, refined and engineered cellulose fibres are used in building materials and concrete applications.

Their primary function in concrete is to modify its fresh properties to mitigate plastic cracking, although they can enhance some properties of hardened concrete such as improved frost and impact resistance, and reduced permeability.

GENERAL CHARACTERISTICS OF CELLULOSE FIBRES

Wood fibre, jute, sisal, flax and coconut hair are examples of cellulose fibres used to reinforce concrete. Typically, they come in small discrete square tabs about 5 mm x 5 mm and 1 mm thick. Each of these tabs (see *Figure 7*) holds tens of thousands of individual fibres, which break up when they are mixed with concrete. The average length of a fibre is about 2mm with a diameter of about 16 microns (about one-sixth the diameter of a human hair).

At a dosage rate of 0.9 kg/m^3 there can be over 1.3 billion fibres in a cubic metre of concrete.

Cellulose fibres, being natural, come from renewable resources.

Cellulose fibres should be treated to make them alkaline resistant.

FIGURE 7: Tabs of cellulose fibres.

THEORY

Cellulose fibres can enhance the properties of concrete by interfering with the processes of micro-crack propagation and cracking in concrete. Plastic cracking is mitigated in much the same way as it is in micro synthetic fibres.

With a modulus of elasticity higher than that of fresh concrete, the closely-spaced cellulose fibres resist the concentration of strains near crack tips and also at the edge of reinforcing bar deformations. With their relatively close spacing and high surface area they inhibit crack propagation by lengthening the route of potential cracks.

The fineness of the fibres allows them to reinforce the mortar fraction of the concrete, delaying crack formation and propagation. This fineness also inhibits bleeding in the concrete, thereby reducing permeability and improving the surface characteristics of the hardened surface.

DESIGN OF CELLULOSE FIBRE REINFORCED CONCRETE

Cellulose fibre reinforced concrete should be designed in accordance with the fibre manufacturer's recommendations.

Cellulose fibres should not be used for longer-term crack mitigation during the drying and shrinkage phase of hardened concrete, e.g. to increase recommended joint spacing in concrete slabs.

PROPERTIES OF CELLULOSE FIBRE REINFORCED CONCRETE

Typically, fresh concrete reinforced containing cellulose fibres will be more cohesive than plain concrete, and plastic cracking will be reduced.

Additionally, the following hardened concrete can be improved:

- improve resistance to deterioration by freeze-thaw cycles.
- increase impact, abrasion and shatter resistance, and
- reduce permeability.

MIX DESIGN/PROPORTIONING OF CELLULOSE FIBRE REINFORCED CONCRETE

The quantity of cellulose fibres used varies according to the properties required from the concrete. As a guide, the following are some typical dosages used for different properties:

Increased freeze/thaw resistance	0.9 kg/m^3
Reduced plastic shrinkage cracking	up to 1.8 kg/m^3
Increased impact, abrasion, and shatter resistance	up to 2.7 kg/m^3
Reduced permeability	up to 5.5 kg/m^3

A plasticiser or superplasticiser may be necessary to maintain the desired water/cementitious material content ratio and workability.

USING CELLULOSE FIBRE REINFORCED CONCRETE

Batching and Mixing

Cellulose fibres should be stored in a dry environment and be clean and free from any deleterious materials before use.

The mixing of cellulose fibres into concrete is a straightforward process when done at the batching plant, and degradable bags can be introduced directly into the mixing drum with the other materials and mixed at full speed for a minimum of three minutes.

If the batch plant has an automated fibre dispensing system installed, the dispenser is turned on during or immediately following the addition of the initial water.

When the cellulose fibres are mixed with concrete they are not readily seen because of their small size and because they are dispersed throughout the concrete. When mixed properly, cellulose fibres should not ball, clump or give a hairy finish to the concrete, but this should be checked in trial mixes. Finishing methods are the same as those used with ordinary concrete.

Cellulose fibres are generally compatible with normal concrete materials and admixtures and should not affect their performance.

Placing and Finishing

Placing and finishing methods are the same as those used with ordinary concrete, but early curing may be necessary as the fibres cause the concrete to bleed less than normal concrete.

Pumping

Concrete reinforced with cellulose fibres, at *normal* addition rates, can be pumped as readily as plain concrete provided any loss of consistence is compensated for by a water-reducing admixture.

SAMPLING METHODS, TESTING, AND QUALITY CONTROL

There are two methods to check that the fibres tabs have been broken up and the fibres evenly dispersed in the concrete mix:

1. Take a sample of mixed concrete from the truck and place it into a bucket. Add sufficient water to fill the bucket, and then stir until the aggregate settles and the fines are left in suspension. The fibres will also remain in suspension as they are heavier than water. Drain the water through a sieve to capture the fibres.

2. Set aside a handful of concrete and leave until initial set. Break the sample to expose the fibres.

Standards and Specifications

Cellulose fibres can be specified to conform with ASTM D 7357. ASTM C 1116 references the applicable testing standards for testing fibre reinforced concrete.

APPLICATIONS

Typical areas of use include:

- slabs on grade,
- exposed aggregate concrete,
- polished and decorative concrete,
- toppings to precast floors, and suspended floors using tray deck assemblies,
- precast applications,
- shotcreting.

Fibre Blends

INTRODUCTION

Concrete can be reinforced with conventional steel bars, and/or blends of steel and/or synthetic and/or cellulose fibres. The reason for using fibre blends is to enhance the properties of concrete by combing the benefits that each particular fibre type can impart.

THEORY

There is no fibre type that can encompass all the desired properties of fresh and hardened concrete in terms of, for example, providing load bearing capacity at cracked sections, crack control, spalling resistance at elevated temperatures, improved abrasion, impact and frost resistance. However, appropriate blends of fibres, with or without, traditional reinforcing bars can lead to synergetic effects, i.e. combinations of different fibre types can enhance concrete in both its fresh and hardened states.

PROPERTIES OF FIBRE BLENDS REINFORCED CONCRETE

Steel/Steel Fibre Blends

Small steel wire fibres are effective in micro-crack bridging, leading to an increased fractural energy and higher flexural strength. Their use, when blended with larger steel wire fibres, can dramatically increase the peak load and post-cracking performance of concrete. In other words, by combining steel fibres that are effective in both micro-cracking and in macro-crack bridging, synergetic effects will increase the fractural energy absorption capacity and toughness of the concrete.

Steel/Micro Synthetic Fibre Blends

Steel fibres do not contribute significantly to the performance of plastic concrete, because their strength and stiffness differs too much from the properties of concrete at an early age. Micro polypropylene fibres are better suited to take up stresses in plastic concrete due to their lower elastic modulus. Furthermore, their ability to interfere with the capillary forces by which water bleeds to the surface of concrete reduces the risk of plastic settlement due to water evaporation. Consequently, a blend of large steel fibres and micro polypropylene fibres can combine structural reinforcement with plastic crack control. The micro synthetic fibres in the concrete also increase its resistance to spalling in fire situations.

Synthetic/Synthetic Blends

As previously mentioned, micro synthetic fibres have been used for many years to effectively control plastic shrinkage cracking as well as plastic settlement cracking in concrete floors and slabs. However, once the concrete has set and begun to gain strength, there are no benefits with respect to crack control. Macro synthetic fibres are dimensionally much bigger than micro synthetic fibres and therefore they provide very few benefits to the plastic concrete (although there are some commercially available macro synthetic fibres that are claimed to perform a similar role to that of micro synthetic fibres).

The main role of synthetic/synthetic blends is to control plastic cracking (in fresh concrete) and drying shrinkage cracking (in hardened concrete), and to improve post-cracking toughness, subject to the previously mentioned provisos on the long-term properties of macro synthetic fibres. Micro synthetic fibres also increase resistance to spalling in fire situations (although the mechanical properties of macro synthetic fibres can be lost at elevated temperatures – see section on *Properties of Macro Synthetic Fibre Reinforced Concrete* on page 9).

USING FIBRE BLENDS

The applications for fibre blends are those where concrete with one type of fibre is not able to fulfil all the design requirements. For example, in flooring slabs or initial linings of shotcrete in underground works, steel fibres could provide the reinforcement needed for the required toughness and crack control of the hardened concrete, but micro synthetic fibres may be required to control plastic cracking. Micro synthetic fibres are also used to reduce the risk of explosive spalling under fire conditions.

A potential application for concrete containing blends of different fibres is in segmental tunnel linings, when the design calls for high water tightness in order to improve micro-crack resistance, and for high residual strength.

DESIGN

Steel fibre reinforced concrete is generally used for its load-bearing capacity, even at larger crack widths, since it can provide high equivalent flexural tensile strength and/or residual strength.

Established design standards may stipulate post-crack performances. For example, the *Yield Line Theory*, which forms the basis of slab on ground design in CSTR 34 *Concrete industrial ground floors: A guide to design and construction*, refers only to post-crack performance at larger deflections. Less attention is paid to micro-cracking, despite its importance to durability. The design criterion for serviceability limit state in TR 34 is at a mean crack width or crack mouth opening displacement (CMOD) of 0.5 mm. This is larger than the crack width limits according to Eurocode 2 which specifies a maximum of 0.4 mm, depending on the exposure class.

The use of an appropriate dosage and type of micro synthetic fibres, in addition to, for example steel fibres, will assist in controlling plastic and drying shrinkage cracking.

MIX DESIGN/PROPORTIONING

There are no special mix proportioning requirements for concrete reinforced with fibre blends, apart from the general requirements of an appropriate cement or binder content, water: cementitious material content ratio, and an appropriate combined aggregate grading.

Concretes with very high fibre dosages sometime require more fines to ensure that the fibres are properly embedded in the matrix of the concrete. These additional fines have an increased surface area that needs to be balanced with an increased binder paste. Consequently, the plastic concrete becomes stiffer and more difficult to handle. An appropriate countermeasure is the addition of suitable admixtures, such as water reducing and/or superplasticising admixtures.

The use of special dosing equipment (that is, mechanical or pneumatic fibre dispensers), eases the introduction of fibres into concrete, especially when using fibres with high aspect ratios.

SAMPLING, TESTING AND QUALITY CONTROL

There are no well-established standards or specifications per se for blends of fibres for concrete or for concrete reinforced with blends of fibres. However, generally, the different fibres used in a blend will comply with a specification for that particular fibre type, and some testing methods and standards used for other types of fibre reinforced concrete may be applicable for determining specific properties of FRC containing mixed fibres.

The fibre manufacturer's recommendations, and good engineering judgement, should be adopted in this regard.

APPLICATIONS

Fibre blends can be used for most applications that the individual fibre types can be used for, but they are best suited to applications where there are specific requirements on the properties of concrete in both the plastic and hardened state, e.g. concrete slabs-on-grade.

Summary/Conclusions

This Information Bulletin has looked at various general types of fibres – steel, macro synthetic, micro synthetic, and cellulose – and how they should be used to reinforce and enhance the properties of concrete. Each general fibre type contains various categories, each with different physical and mechanical characteristics, and each capable of imparting different beneficial properties to the concrete that it reinforces.

The theory, properties, and typical applications of concrete reinforced with the various fibres have been described.

As 'no two fibres are the same', it is imperative to note that fibre types and categories are not interchangeable simply by direct substitution of a dosage rate (mass by mass or volume by volume).

A knowledge of the theory of the different fibre types and categories is necessary to understand the appropriate testing and degree of quality control/assurance necessary to ensure that design requirements are satisfied.

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