CONCRETE
SikaFiber® REINFORCED CONCRETE HANDBOOK

BUILDING TRUST

Editor
Sika Services AG
Tüffenwies 16
CH-8048 Zürich

Authors
David Taylor BEng, Sika Services AG
Dr Carsten Rieger, Sika Services AG
Trevor Atkinson, Sika Europe Management AG (retired)

Layout
Sika Services AG
Corporate Marketing Service

Edition 2022

SikaFiber® Reinforced Concrete Handbook

FOREWORD

This handbook is intended to give guidance on the practical and technical merits of using fibre reinforcement in a variety of concrete applications.

Concrete is reported to be the most widely used substance on earth after water and recognized as a highly cost-effective versatile material used for the construction of housing, healthcare, education, transport, energy, industrial and many more applications. Without concrete many structures would simply be impossible to construct. Despite the versatility, concrete is affected with several drawbacks that are inherent to its composition. Whilst it has very high compressive strength, by generally accepted engineering standards concrete has a significantly lower tensile capacity and considered relatively brittle and lacking in flexural strength. Additionally, concrete tends to crack in both the plastic (early-age) and hardened (long-term) state.

Early-age cracks are defined as cracks that generally develop within the first hours and days after concrete placement and include plastic shrinkage and plastic settlement cracking. Long-term cracking, on the other hand, is in part caused by the shrinkage that transpires over several months, perhaps even years of drying that follows. In either case, these cracks can jeopardize the overall integrity of the concrete and not allow it to maintain or even attain its maximum performance capability.

The introduction of fibre reinforcement not only improves the flexural strength and toughness of concrete but also provides exceptional resistance to early and long-term cracking thus allowing concrete to achieve a long-term durability.

Whilst fibre reinforced concrete is now widely accepted in the construction and ready mixed concrete industry, there are many countries yet to be convinced of its practical, technical, and commercial benefits. Perhaps some still view fibre reinforcement as a relatively new and unproven technology when in fact it has been used for many centuries. Indeed, our ancient ancestors were the first to use similar technology by incorporating straw into clay blocks and animal hair into plasters/ mortars for the purpose of preventing cracking during the drying process.

Fibre technology was applied to concrete in the 1950's based on the idea of dosing steel reinforcement into the concrete mixer instead of fixing it within the formwork. Steel reinforcement was cut down into discrete discontinuous pieces to allow them to fit into the mixer, which became known as steel fibre reinforcement.

Since the 1950's a huge number of research activities have been carried out to develop new types of fibre reinforcement. In today's market the most widely used materials for fibres in concrete are steel, polypropylene, and other materials such as glass and naturally occurring materials such as cellulose.

Fortunately, design standards allowing the replacement oftraditional steel bar reinforcement with Fibre Reinforced Concrete (FRC) are now more prominent and countless documents online cover the merits of FRC, making it more acceptable to Engineers, Contactors, and Owners. The traditional method of reinforcing concrete with steel bars is predominantly taught in Civil Engineering schools but there is undoubtedly an increasing interest and research into the merits of FRC.

Neverthless, the usage of fibre reinforced concrete is still relatively low meaning that there is a huge potential growth in the FRC market.

With this handbook the reader has a guide to the most relevant topics relative to Fibre Reinforced Concrete. This will hopefully provide answers to questions relating to selection, benefits and usage of fibres, without going into too much of the respective scientific details.

Also in this series of Sika Handbooks:

Sika Concrete Handbook

Sika Sprayed Concrete Handbook

CONTENT

1 FIBRE BASICS

1

1.1 WHAT IS FIBRE REINFORCED CONCRETE

Fibre Reinforced Concrete (FRC) is a composite material combining concrete and discontinuous discrete fibres that are uniformly distributed throughout the concrete to create a 3-dimensional system of reinforcement. The inclusion of fibres in concrete and other cementitious materials, such as mortars and renders, improves many material properties including

- ductility
- toughness
- crack resistance
- strength
- reducing explosive spalling
- reduced permeability
- impact / shatter resistance
- fatigue resistance

Materials primarily adopted for FRC are steel, polypropylene, glass, and natural fibres.

In today's construction market FRC is often the first-choice reinforcement for many important applications including slab on ground or grade, composite metal decking and tunnel linings. It is often used as a cost-effective, easy-to-use alternative to traditional steel reinforcement, or to enhance other properties.

Fibres are easily added to the concrete/ mortar either at the batching plant or on-site. When used as a replacement for steel reinforcement, FRC removes the need to order steels bars or mesh and at the same time not having to store these bulky materials on site. FRC also reduces the labour-intensive process of cutting, placing, and fixing reinforcement. Overall concrete placement using fibres is faster, safer and will save money.

FRC is a growing interest for civil infrastructure owners in achieving greater concrete durability and longevity and has seen more and more projects move towards the use of high-performance concrete (HPC) and ultra -high performance concrete (UHPC).

The use of HPC/UHPC brings added risk of explosive spalling damage in the event of serious fire. Particularly in tunnel applications, polypropylene micro fibres are recognised as an effective measure to reduce dangerous explosive spalling. This increase in interest has drawn many Engineers to seriously consider the enhanced durability benefits of FRC either in combination with traditional steel reinforcement or as a replacement for certain applications.

1.2 FIBRE CHARACTERISTICS

There are several basic characteristics which influence the behaviour of fibres in concrete.

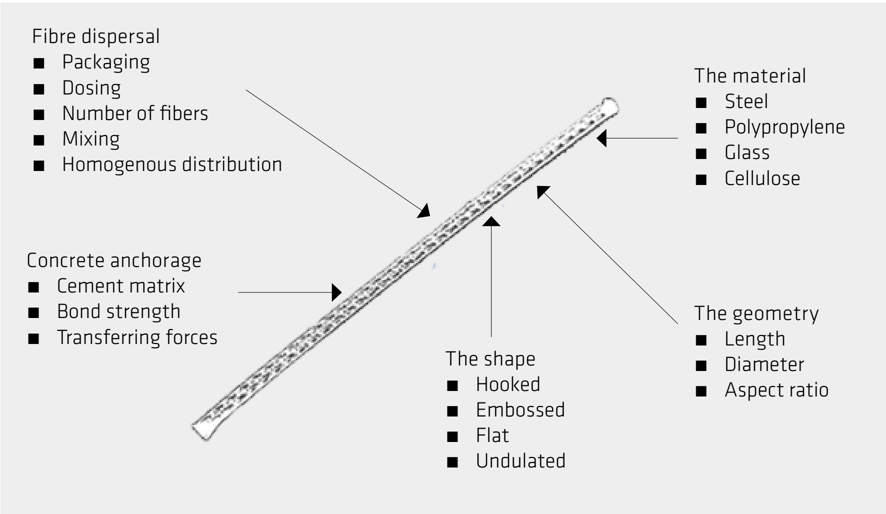


Figure 1.2: The basic characteristics of a fibre which determine performance in FRC

It is important to understand the performance of FRC is not solely dependent on one fibre characteristic, such as tensile strength, but also on the quality of the cement paste and number of fibres per cubic volume of material. In short, it is the performance of the composite material and not simply a fibre characteristic which are the driving criteria.

1.2.1 MATERIALS

A huge variety of fibres can be found on the market made of different materials with different geometries. The most used materials for fibres in concrete are steel, polyolefin (polypropylene, polyethylene, or a combination of), or other synthetic materials, glass (alkali-resistant) and natural materials like cellulose.
The main materials referred to in this handbook will be synthetic polypropylene fibres and steel.

Table 1.2.1.1: Main properties of materials commonly used to make fibres in concrete

Fibre Material	E-Modulus [kN/mm²]	Tensile Strength [N/mm²]	Strain to rupture [%]	Density [g/cm³]
Steel (normal)	210	400-2500	3 – 4	7.8
Steel (non-corrosive)	170	2100	3	7.8
Polypropylene (PP)	1-8	165-600	20	0.9 – 0.91
Polyvinyl alcohol (PVA)	30	880 -1600	6	1.31
Natural Sisal	9 -38	400 - 700	4	1.3 – 1.5
Vegetable fibres	4 - 40	0 - 1000	5 – 10	1.5
Glass fibres	80	2500	5	2.7
Carbon fibres	300	450 - 400	1.5	1.7

Polypropylene may sometimes also be referred to polyolefin. Polyolefins are a general term for polypropylenes and polyethylene's. According to ASTM D7508/D7508M polyolefin is any long-chain synthetic polymer composed of at least 85% by weight of ethylene, propylene, or other olefin units (monomers), except amorphous (non-crystalline) polyolefin.

Table 1.2.1.2: Main properties of the fibre matrix material

Matrix Material	E-Modulus [kN/mm²]	Tensile Strength [N/mm²]	Strain to rupture [%]	Density [g/cm³]
Cement stone	7 - 28	< 8	0.04	2.0
Mortar	20 - 45	< 6	0.01	2.3
Concrete	20 - 45	< 4	0.01	2.4

In principle, the material used for reinforcing another material should have a higher elastic modulus, a higher tensile strength, and a higher strain to rupture. However, in the case of fibre reinforced concrete this does not necessarily need to be fulfilled as:

- Fibre dosages used for normal FRC are generally too low to influence the tensile strength or the elastic modulus of the composite material.
- Fibres work at different stages of the hardening process of the concrete. The concrete in the first hours after placing has a much lower tensile strength and a much lower elastic modulus than after a few days.
- Fibres for concrete are designed to be pulled out of the concrete matrix and increase the resistance of the fibre reinforced concrete in the cracked state.

1.2.2 GEOMETRY

The geometry of the fibre plays a significant role for the anchorage of the fibre, especially the relationship between the length and the diameter of the fibre, this is called the aspect ratio.

$$\textbf{\textit{Aspect ratio}} = \frac{l_f}{d_f}$$

Experience shows that aspect ratios between 40 and 80 have a good performance.

The aspect ratio is an important factor for the behaviour of the fibres in the fresh and hardened concrete state. For example, a very long and thin fibre (high aspect ratio) would generally show better performance in the hardened concrete due to fact that it has a longer embedded length and more fibres over the crack. However, this may create difficulties with mixing of the fibres and may tend to ball together resulting in poor distribution. The other extreme would-be fibres with a too small aspect ratio. For example, a very short and thick fibre may provide good distribution in the cement paste but would not embed well into the matrix meaning that the performance in the hardened state concrete would be reduced.

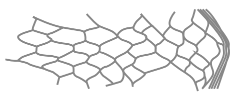
1.2.3 SHAPE

Many different types of fibres can potentially be used for FRC, the main type are:

1. SYNTHETIC MICRO-FIBRES
- Straight monofilament fibres
- Fibrillated fibres

Polypropylene (PP) Micro mono-filamented

Polypropylene (PP) fibrillated



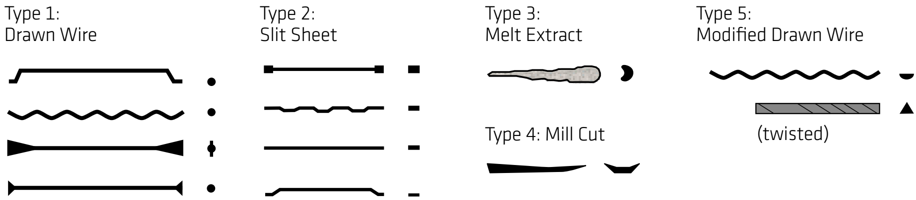
2. SYNTHETIC MACRO-FIBRES
- Straight embossed stiff fibres
- Undulated stiff fibres with smooth surface
- Soft flat or oval fibres
- Soft, thin twisted fibres

Embossed PP Macro

Undulated PP Macro

3. STEEL MACRO-FIBRES

- Hooked end
- Flat end
- Undulating (Continuously deformed)
- Straight fibres



1.2.4 ANCHORAGE

To transfer forces between the cracked concrete and the fibre it is important to demonstrate there is sufficient anchorage, or bond, between the fibre and matrix material. This can be done in different ways.

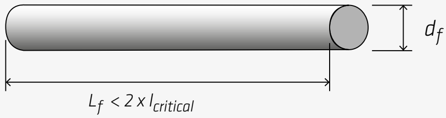
a) a rough embossed surface
b) rigid undulating shapes
c) soft and flexible
d) hooked end

A chemical bond can be applied to the surface of PP fibres to promote chemical interaction with the concrete. Typically, many steel fibres have hooked or flat ends for a better anchorage or they may be undulated (continually deformed) for an increased pull-out resistance.

For a good anchorage and a good performance in the hardened concrete a long and thin fibre would be ideal. The fibre would be nicely embedded and would not slip out. However, if the fibre to matrix bond is too good it can result in fibre rupture. Fibre rupture is when the tensile strength of the fibre is exceeded.

Knowing the relationship of bond strength between fibre and matrix, the critical length of the fibre can be calculated in relation to the diameter and the fibre tensile strength. The critical length is the length of the fibre where the bond strength is equal to the tensile strength of the fibre. When bridging a crack, a maximum of half of the fibre length is expected to be embedded in the concrete.

$$l_{critical} = \frac{d_f}{4} \times \frac{f_{tf}}{\tau_{fm}}$$



where: f_{tf} = Tensile strength of fibre (MPa)
τ_{fm} = Shear strength between fibre and matrix (MPa)

Figure 1.2.4.1 Calculating for the critical length

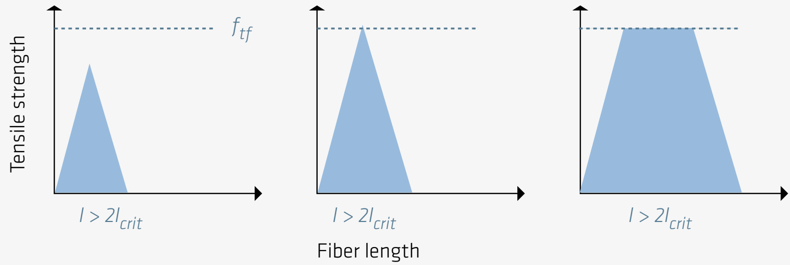


Figure 1.2.4.2 The critical length of the fibre depends on the tensile strength of the fibre material.

The critical fibre length of smooth fibres can result in fibre lengths that cannot be mixed into the concrete as they tend to ball from aspect ratios above 100. Decreasing the fibre length will help disperse the fibres more easily.

1.2.5 DISPERSION

In addition to having a good anchorage in the hardened concrete, it is essential to achieve complete distribution of the fibres to achieve a homogeneous mix, and to benefit from the full performance benefits of FRC. Full dispersion of fibres can be influenced by the correct selection of fibre according to the concrete/mortar mix and the mixing process. The addition/mixing of fibres may vary depending on the fibre type used i.e., steel, synthetic micro, or synthetic macro-fibres and for loose and collated (glued fibres) products.

Long and thin fibres may tend to ball together and cause problems with mixing, resulting in poor distribution and much lower performance characteristics. Short and thick fibres generally tend to show few problems with mixing and have much better dispersion qualities, although the overall performance will be impacted since the fibre is likely to be much lower than the critical length. Fibres show a good performance in hardened concrete with an aspect ratio of between 40 – 80. The primary objective is to ensure that fibres are fully dispersed as quickly as possible in the parent material without balling (fibre hedgehogs).

Packaging is also very important for a fast and homogeneous distribution of the fibres. Many manufacturers state that fibres should be added to the mixer as the first material. However, where fibres are supplied in small pucks, which are bound together with a water-soluble film, the pucks may be included to the mixer once all other materials (including water) are added.

Fibres may be supplied in degradable bags or boxes. Fibres packed in degradable bags are added directly into the mix, slowly. Where fibres are supplied loose, in boxes, the contents must be emptied slowly and uniformly into the concrete, and boxes discarded.

Mixing time for FRC ultimately depends on the efficiency and shearing action of the concrete mixer. High quality forced action pan mixers will offer quicker mixing periods. Truck mixing is sometimes less efficient, and as a general guide fibre-concrete should be mixed for a minimum of 5 minutes at full mixing speed once all the concrete ingredients have been added. Or adding 1 minute per cubic meter mixing time if the fibres are added after the concrete has been mixed.

The performance of degradable bags may be affected by certain concrete admixtures e.g., liquid micro-silica. Therefore, it is important to check compatibility with the manufacturer.

In all situations it is important the manufacturer's recommendations for addition and mixing of fibres are fully adhered to. Should difficulties be encountered when following such instructions, it is advised to seek assistance and further guidance from the fibre manufacturer.

1.2.6 CEMENT MATRIX

The quality of the cement matrix is an important influencing factor for the bond strength with the fibre and ultimately the FRC performance. The same fibre may show a very different performance when embedded into a porous matrix compared to embedding into a dense matrix.

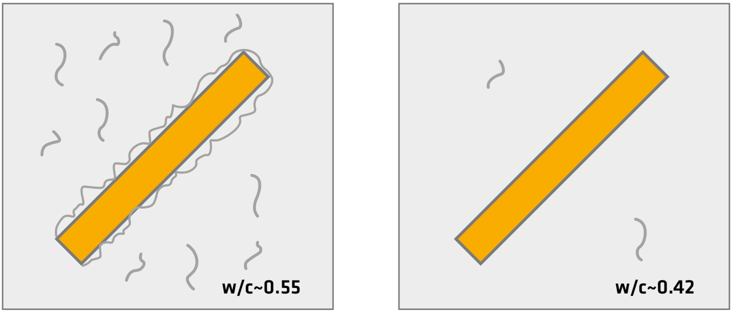


Figure 1.2.6: Fibre in relationship to the matrix material

Concrete strength is essentially a measurement of the porosity, which can also be related to the fibre bond strength within the concrete. This means that a specific fibre may not have the same performance in different types of concrete. Usually, a fibre will have an optimum performance with a certain concrete strength, and it is entirely possible that the same fibre performance could be lower when a higher strength concrete is used.

If the concrete strength reduces the anchorage of the fibre to the matrix also decreases making it easier for the fibre to pull out. When the concrete strength increases the fibre anchorage can be too good and the fibre will rupture before the fibre can be pulled out. Both result in a lower performance of the fibre-reinforced concrete.

1

2 SUSTAINABILITY

2.1 SUSTAINABILITY

As environmental sustainability is becoming more relevant and urgent every day, the building industry is addressing this topic by becoming more efficient is key areas:

- Improving energy and resource efficiency
- Reducing water demand
- Building efficient building and infrastructure
- Using hazard-free and safe products

The LCA study presented in this chapter concludes that fibres reinforced concrete offers sustainability benefits compared to traditional reinforced concrete with steel wire fabric solutions.

Life Cycle Assessment (LCA) provides a method to quantify and evaluate potential environmental impacts throughout the product's life cycle. In this study, raw materials for two concrete slab mixtures were assessed. It contains cradle-to-gate impacts for each component in the mix-design. Impacts from concrete mixing and application are excluded from the study, as well as use phase impacts, end-of-life treatment, recycling and to final disposal.

PRODUCT PROOF
Life Cycle Assessment (LCA) is a standardized method to assess and compare the inputs, outputs and potential environmental impacts of products and systems over their life span. LCAs are recognized as a convenient way to evaluate the sustainability performance.

The LCAs conducted by Sika are performed according to ISO 14040. The impact assessment methodology used is CML 2001. The data for Sika LCAs are based on public databases such as ecoinvent, GaBi by Sphera and specific data collected from Sika production plants and products.

Software and Database: GaBi 10 software, ecoinvent 3.7.1 and Sphera CUP2021.2
LCIA Method: CML 2001 Method (CML 2001 - Aug. 2016)

2.2 LIFE CYCLE ASSESSMENT

For the fibre reinforced concrete example, three impact categories are used as indicators to rate the environmental effect.

- Global warming potential (GWP 100 years)
- Cumulative energy demand (CED)
- Photochemical ozone creation potential (POCP)

In this example, a fibre-reinforced concrete slab on ground, with light loading and a good bearing stratum is being compared with a traditional steel reinforcement solution, comprising of mesh or mat sheets. Only raw materials for each concrete slab are assessed, and impacts from the application are not considered.

2

The concrete slab size is the same for both scenarios and is taken to be rectangular or square area of 1000 m² x 150 mm thick. The basic process of casting the slab is to firstly to prepare the ground and install the ancillary services etc. In this example penetrations, re-entrant corners etc are not considered. For purposes of the LCA the example is to cast the concrete on the ground using two techniques.

1. Concrete containing 4 kg/m³ of SikaFiber® Force-50
2. Concrete reinforced with a light mesh in the top of the slab.

Light mesh is open to interpretation and for this example it is assumed to be 3.0 kg/m² with an additional 10 % for lapping, therefore 3.10 kg/m². For estimating the impacts of the steel mesh, a dataset for steel wire rod was used.
The concrete performance is the same, with the exception in the case of FRC, the superplasticiser has been adjusted to have the same workability as a non-fibre concrete solution.

Table 2.2.1: Concrete mix designs for the LCA analysis

Parameters	Fibre reinforced concrete		Traditional steel reinforcement	
Mix design	Cement	350 kg/m³	Cement	350 kg/m³
	Water content	182 litres	Water content	182 litres
	Sand	857 kg/m³	Sand	857 kg/m³
	Gravel	1007 kg/m³	Gravel	1007 kg/m³
	Sika® ViscoCrete®	4.2 kg/m³	Sika® ViscoCrete®	2.8 kg/m³
Additives	SikaFiber® Force-50	4 kg/m³	None	
	Total amount	600 kg		

Global Warming Potential [kg CO_2-eq.], CML 2001
Potential contribution to climate change due to greenhouse gases emission

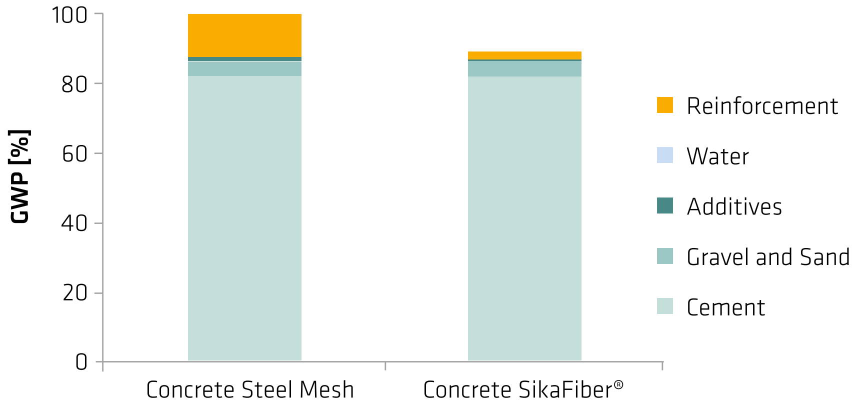


Figure 2.2.1: Global Warming Potential with and without SikaFiber®

Cumulative Energy Demand [MJ]
Total amount of primary energy from renewable and non-renewable resources

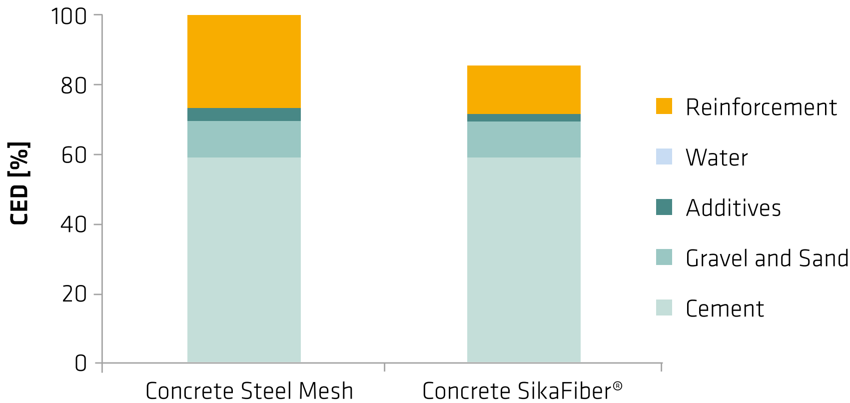


Figure 2.2.2: Cumulative energy demand with and withoutt SikaFiber®

Photochemical Ozone Creation Potential [POCP]

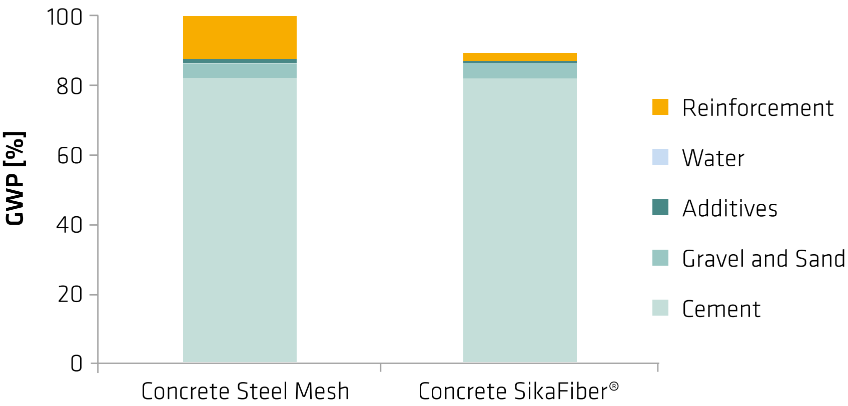


Figure 2.2.3: Photochemical Ozone Creation Potential with and withoutt SikaFiber®

2.3 EXCESS MATERIAL

Excess material should not be disposed into waterways, drains or sewers and shall be disposed responsibly through a licensed waste disposal company in accordance with the relevant legislation and local/regional authority requirements.

Fibres can be extracted from excess fresh concrete using suitable filtering equipment. Polypropylene fibres will float on water and can be removed, while the heavier particles sediment downwards. Polypropylene fibres are non-hazardous materials and in theory can be recycled as plastics, if they are clean and are accepted by the relevant recycler. Steel fibres can be removed using magnetic equipment. Steel fibres can also be recycled if also they are accepted by the relevant recycling plant.

2.4 DURABILITY

Durability may be defined as the ability to last a long time without significant deterioration. Throughout history, concrete has proven itself to be a most flexible and durable construction material. Modern day building and civil engineering projects rely heavily on the usage of concrete. However, conventional concrete is susceptible to cracking because it has relatively low tensile capacity and ductility. Cracks are pathways for gases, liquids, and deleterious solutions entering the concrete, which lead to the early onset of a deterioration process in the concrete and reinforcing steel where present.

The main durability enhancing feature of Fibre Reinforced Concrete (FRC) is its ability to both minimize and control cracking. This effectively limits the rate at which deleterious substances such as water, chlorides, and carbon dioxide can enter concrete elements, thereby prolonging the service life of the structure. Micro and macro fibres are both best suited to help provide this long-term durability.

An advantage of synthetic fibres is their high resistance to acidic and alkaline environments, therefore are unaffected by alkalis in cement paste. They are not attacked by salts or chlorides in aggressive environments and therefore are corrosion free. Synthetic fibres will soften and melt at high temperatures around 150 to 160 °C, thus losing their mechanical properties. While this may be a problem for macro synthetic fibres in structural applications, where there is a risk of fire, micro synthetic fibres were found to help reduce the potential for explosive spalling and are later described in this manual.

Steel is known to be susceptible to corrosion. If steel fibre reinforced concrete is placed in a corrosive environment, then the contribution of fibres located at the surface usually must be ignored. Particular attention is required when considering the use of steel fibres in very corrosive environments e.g. marine, de-icing salts; where the concrete may expect to crack e.g. sprayed concrete. The corrosion process will especially accelerate if the concrete is under tension. In some situations, the overriding factor are the staining effect of the corroding fibres on the surface, which may be aesthetically unpleasing. Generally, steel fibres are protected by the high alkalinity of the cement paste, like traditional steel reinforcement. Unlike steel reinforcement, the small volume of fibre is considered unlikely to produce sufficient stresses to cause major cracking issues, unless the concrete sections are very thin. As the concrete carbonates, consideration must be given as the steel fibres are no longer protected in a passive environment. In the presence of air and water these fibres too have the potential to corrode. Since the fibres are discontinuous, galvanic corrosion should not be an issue.

2.5 ASSOCIATIONS

Sika is working around the world with different Concrete and Admixtures Associations, to support and promote increasingly sustainable development using concrete admixture technologies.

2.5.1 EFCA

Sika is a member of EFCA, the European Federation of Concrete Admixtures Associations. EFCA was formed in 1984 from a partnership of 12 National Admixture Associations, and now represents all major admixture manufacturers. EFCA represents the interests of the members with increasing European construction legislation and standardisation.

2.5.2 LEED

LEED stands for Leadership in Energy and Environmental Design and originates from the USA in 1993. The first LEED v1.0 was published in 1998 and latest update v4.1 was released in 2019. The objective of LEED is to provide a framework for healthy, efficient, and cost-saving green buildings, and a LEED certification is accepted in many countries. LEED covers all building types, building phases and is relevant to new construction, refurbishment, and maintenance.

2.5.3 MFSA

MFSA stands for the Macro Synthetic Fibre Association and is a group of companies who came together to advance the knowledge of macro synthetic fibre (MSF) concrete reinforcement.

Since the beginnings two distinct groups have emerged which the MFSA have brought together. These are mainly the fibre manufacturers and the various fibre user groups. The aims are to promote the benefits, the safe and responsible use of MSF, as well as developing relevant Standards, codes, and guidelines.

2.5.4 FRCA

The Fiber Reinforced Concrete Association is focused on furthering the development, knowledge and market of fiber reinforced concrete (FRC), both synthetic and steel fibers. It consists of major manufacturers, suppliers and marketers of the world's most popular FRC solutions in the concrete industry.

3 STANDARDS

This section identifies many of the guidance documents which are available to understand fibres and fibre reinforced concrete.

The main Standards related to performance referred to in this handbook are from European-EU & North American-ASTM.

DOCUMENT REFERENCE	PUBLISHER	TITLE	USE
EN 14889-1	European Standard	Fibres for concrete – Part 1- Steel Fibres	Definitions, specifications, and conformity
EN 14889-2	European Standard	Fibres for concrete – Part 2- Polymer Fibres	
ASTM A820 / A820M	American Society for Testing and Materials	Standard Specification for Steel Fibres for Fibre-Reinforced Concrete	Materials, manufacture, properties, workmanship certification and packaging
ASTM D7508 / D7508M	American Society for Testing and Materials	Standard Specification for Polyolefin Chopped Strands for Use in Concrete	

3.1 GUIDANCE

There are numerous other documents relevant to fibres and fibre reinforced concrete. Some documents may originally have been drafted for steel fibres although have since been adopted for synthetic fibres. Some of these documents will be referred to also in this handbook.

The aim of these documents is to give practical advice about the types of fibres, material properties, test methods for characterisation, design concepts, mixing placing and application. In using these documents, the reader should have experience with conventional steel reinforcement.

American Concrete Institute

DOCUMENT REFERENCE	PUBLISHER	TITLE	USE
ACI 209.2R	American Concrete Institute	Guide for Modelling and Calculating Shrinkage and Creep in Hardened Concrete	Used for slabs-on-ground/grade
ACI 318M	American Concrete Institute	Building Code Requirements for Structural Concrete	General aspects of FRC
ACI 360R	American Concrete Institute	Guide to Design of Slabs-on-Ground	Design, specification, and construction methods
ACI 506.1R	American Concrete Institute	Guide to Shotcrete	Products, application, equipment, labour
ACI 544.4R-18	American Concrete Institute	Guide to Design with Fibre-Reinforced-Concrete	Design and specification

3

National Standards

DOCUMENT REFERENCE	PUBLISHER	TITLE	USE
CNR-DT 204/2006	Italian National Research Council Advisory Committee on Technical Recommendations for Construction	Guide for the Design and Construction of Fibre-Reinforced Concrete Structures	Materials, design concepts, construction,
DAfStB	German Committee for Reinforced Concrete	Part 1: Dimensioning and construction Part 2: Definition, properties, manufacture, and conformity Part 3: Instructions for execution	FRC design using steel fibres
JSCE-SF 4	Japanese standard	Flexural strength and toughness of fibre reinforced concrete	Test method
NZS 3101	New Zealand Standard	Concrete Structure Standard	SFRC design and fire resistance
SIA 162/6	Swiss Standard	Testing and design basics	SFRC design
SS 812310	Swedish Standard	Fibre Concrete - Design of Fibre Concrete Structures	FRC design

European References

DOCUMENT REFERENCE	PUBLISHER	TITLE	USE
Eurocode 2: EN 1992-1-1:2004	European Standard	Design of concrete structures Part 1-1: General rules and rules for buildings	Principles of concrete design
Eurocode 2: EN 1992-1-2:2004	European Standard	Design of concrete structures – Part 1-2: General rules – Structural fire design	Passive fire resistance using fibres
EN 14487-1	European Standard	Sprayed concrete - Part 1: Definitions, specifications, and conformity	Fibres for sprayed concrete

Additional Guidance

DOCUMENT REFERENCE	PUBLISHER	TITLE	USE
fib Model Code for Concrete Structures	International Federation of Structural Concrete	Chapter 5 Materials: 5.6 Fibres/fibre Reinforced Concrete	FRC design
ITAtech Report N°7/ April 2016	The International Tunnelling and Underground Space Association	Guidance for Precast Fibre Reinforced Concrete Segments – Vol 1 Design Aspects	FRC for precast concrete tunnel segments
RILEM TC 162-TDF	The International Union of laboratories and Experts in Construction Materials, Systems and Structures	Reinforced concrete – Test and design methods for Steel fibre	FRC design and testing

Concrete Society Technical Reports

DOCUMENT REFERENCE	PUBLISHER	TITLE	USE
Technical Report 34	The Concrete Society, UK	Concrete Industrial Ground Floors – A Guide to Design and Construction	Key aspects about industrial slabs-on-ground
Technical Report 63	The Concrete Society, UK	Guidance for the Design of Steel-Fibre-Reinforced Concrete	SRFC design
Technical Report 65	The Concrete Society, UK	Guidance on the use of Macro-synthetic-fibre Reinforced Concrete	Synthetic FRC design
Technical Report 66	The Concrete Society, UK	External In-situ Concrete Paving	Key aspects about external slabs-on-ground

3.2 CERTIFICATION

Since 1985, a European CE marking represents a manufacturer's declaration that product placed in any EU country complies with an EU directive. The Conformitè Europëenne (CE) Mark was set-up by the European Union (EU) for regulating goods sold within the European Economic Area (EEA). All defined goods produced or entering must have a mandatory conformity marking before they can be sold.

By displaying a CE logo, the manufacturer confirms the good's conformity with European health, safety, and environmental protection standards.

In contrast, North America has the ASTM Standards whereby the manufacturer declares conformity on the product documentation according the requirements stated in the Standard.

3.2.1 EN 14889: PARTS 1 AND 2

EN 14889-1 and EN 14889-2 were approved and released in 2006. Both Standards relate to structural and non-structural use of fibres in concrete, mortar, or grout. Part 1 specified the requirements for steel fibres and Part 2 for polymer fibres. The Standard structure is divided into definitions, requirements, and conformity.

Table 3.2.1.1: Main contents of EN 14889: Parts 1 and 2

SECTION	CONTENT	DESCRIPTION
	Foreword	Information to member states
1	Scope	Content of the standard
2	Normative references	Cross references to other relevant Standards
3	Terms and definitions	Clarification of specific wording
4	Symbols	Clarification of abbreviations
5	Requirements	How to define the fibre group, geometric, performance and safety
6	Evaluation and conformity	Definition of the initial type testing and factory production control
Annex ZA	Informative	Relationship with EU Constructions Product Directive (89/106/EEC)

The Standards referred to in EN 14889-1 /-2 required for purposes of the CE.

STANDARD	TITLE	Steel	Polymer
EN 10002-1 [1]	Metallic materials – Tensile testing – Part 1: Methods of test at ambient temperatures	✓	✓
EN 10218-1	Steel and wire products – General – Part 1: Test methods	✓	
EN 12350-3	Testing fresh concrete – Part 3: Vebe test	✓	✓
EN 13392	Textiles – Monofilaments – Determination of linear density		✓
EN 14845-1	Test methods for fibres in concrete – part 1: Reference Concrete	✓	✓
EN 14845-2	Test methods for fibres in concrete – Part 2: Effect on Concrete	✓	✓
EN ISO 2062	Textiles – Yarns from packages – Determination of single-end breaking force and elongation at break (ISO 2062:1993)		✓
EN ISO 6892[2]	Metallic materials – Tensile testing – Part 1: Method of test at room temperature (ISO 68921:2019)	✓	✓
ISO 11357-3	Plastics – Differential scanning calorimetry (DSC) – Part 3: Determination of temperature and enthalpy of melting and crystallisation		✓

[1] This Standard has been withdrawn, is still referred to in EN 14889-1:2006 and EN 14889-2:2006 and will be replaced by EN ISO 6892:2016

[2] Will supersede EN 10002-1 in the next update of EN 14889-1 and 2

In addition, the required test method is specified in EN 14845-1

STANDARD	TITLE	Steel	Polymer
EN 14651	Test method for metallic fibred concrete – Measuring the flexural strength (limit of proportionality) (LOP), residual	✓	✓

SYSTEMS

Fibres in EN 14889 Parts 1 and 2 are designated AVCP system 1 or system 3, according to table ZA.2.

System 1 are defined as structural fibres and the manufacturer must engage the services of a Notified Body to assess the performances of the initial type testing, factory production control and continuous surveillance of the process.

Non-structural fibres are defined as system 3. A notified body is responsible for assessing the performances of the initial type testing, whilst the manufacturer is responsible for their own factory production control and continual assessment.

Table ZA.2 from EN 14889:1 and 2

Product(s)	Intended use(s)	Level s or classe(s)	Attestation of conformity system(s)
Polymer / steel fibres	for structural uses in concrete mortar or grout	see Table ZA.1	1
Polymer / steel fibres	for other uses in concrete mortar or grout	see Table ZA.1	3

System 1: See Directive 89/106 EEC (CPD) Annex III.2.(i), without audit testing of samples
System 3: See Directive 89/106 EEC (CPD) Annex III.2.(ii), Second possibility

Table ZA.1 of a Standard summarises the scope and characteristics of the product which are relevant for the CE marking, lists the essential characteristics and relevant clauses. There are three main tests required to be performed for the CE.

DESCRIPTION	RELEVANT STANDARDS	FIBRE TYPE
Tensile properties (tenacity) and modulus of elasticity	EN ISO 2062	Class I – micro
	EN 10002-1 (evt. EN ISO 6892)	Class II – macro
Effect on consistence (Vebe Test)	EN 14895-2	Class I and II
Effect on strength of concrete (Beam Test)	EN 14845- 1 /-2 EN 14651	Class II

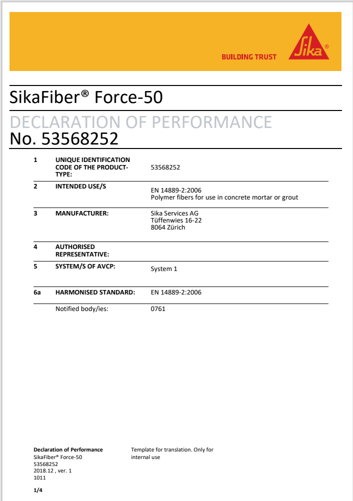
Table ZA.1 from EN 14889 Part 2 Scope and relevant clauses

Product / **Intended use**	**Polymer fibres in concrete mortar or grout**		
Essential Characteristics	Requirement clauses in this or other European Standard. (This standard unless otherwise stated)	Mandated level(s) and/or class(es)	Notes
Tensile properties / Modulus of elasticity	5.4 and 5.5	none	declared values
Effect on consistence (workability) of concrete	5.7	none	declared value
Effect on strength of concrete	5.2, 5.3 and 5.8	none	declared values
Release of dangerous substances	5.10 and ZA.1	none	requirements are dependent on regulations in the place of use
Durability	-	-	Durability relates to the concrete incorporating fibres

TOLERANCES

Tolerances are an important aspect for fibres to maintain a level of quality. Table 1 of EN 14889 stipulates tolerances for length and (equivalent) diameter which shall not deviate from the declared value. Samples are taken from the production for purposes of initial type testing and factory production control and the fibre manufacturer must comply with the requirements.

Once the requirements of the annex in the Standards are achieved, for system 3 the manufacturer can produce a Declaration of Performance (DOP) and affix a CE marking to the product in accordance with ZA 2.2 and ZA.3. For system 1 products the certification body will issue a Certificate of Conformity to the manufacturer, which entitles the manufacturer to affix the CE marking and produce a DOP.



BUILDING TRUST

SikaFiber® Force-50

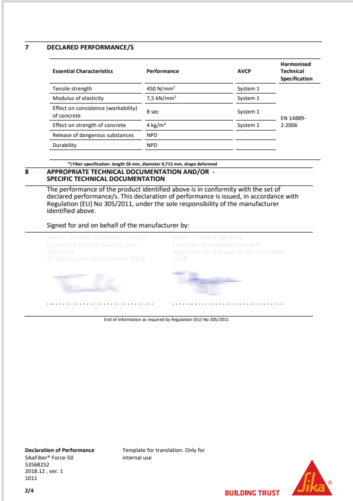
DECLARATION OF PERFORMANCE
No. 53568252

1	**UNIQUE IDENTIFICATION CODE OF THE PRODUCT-TYPE:**	53568252
2	**INTENDED USE/S**	EN 14889-2:2006 Polymer fibers for use in concrete mortar or grout
3	**MANUFACTURER:**	Sika Services AG Tüffenwies 16-22 8064 Zürich
4	**AUTHORISED REPRESENTATIVE:**	
5	**SYSTEM/S OF AVCP:**	System 1
6a	**HARMONISED STANDARD:**	EN 14889-2:2006
	Notified body/ies:	0761

Declaration of Performance
SikaFiber® Force-50
53568252
2018.12 , ver. 1
1011

Template for translation. Only for internal use

1/4



7 DECLARED PERFORMANCE/S

Essential Characteristics	Performance	AVCP	Harmonised Technical Specification
Tensile strength	450 N/mm²	System 1	EN 14889-2:2006
Modulus of elasticity	7,5 kN/mm²	System 1	
Effect on consistence (workability) of concrete	8 sec	System 1	
Effect on strength of concrete	4 kg/m³	System 1	
Release of dangerous substances	NPD		
Durability	NPD		

*) Fiber specification: length 50 mm, diameter 0,715 mm, shape deformed

8 APPROPRIATE TECHNICAL DOCUMENTATION AND/OR - SPECIFIC TECHNICAL DOCUMENTATION

The performance of the product identified above is in conformity with the set of declared performance/s. This declaration of performance is issued, in accordance with Regulation (EU) No 305/2011, under the sole responsibility of the manufacturer identified above.

Signed for and on behalf of the manufacturer by:

Name : Tomasz Gutowski Function: Corporate Standardization and Approvals At Warsaw on 06 December 2018

Name : Tatiana Ageyeva Function: Standardization and Approvals At Warsaw on 06 December 2018

....

End of information as required by Regulation (EU) No 305/2011

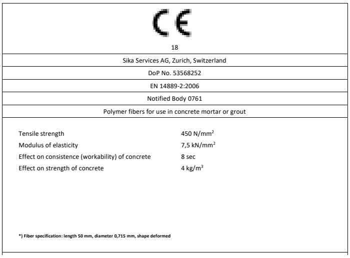
Declaration of Performance
SikaFiber® Force-50
53568252
2018.12 , ver. 1
1011

Template for translation. Only for internal use

2/4

BUILDING TRUST

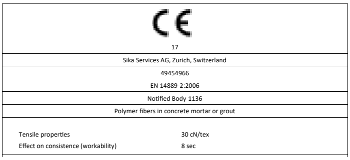
Example DOP SikaFiber® Force-50



18
Sika Services AG, Zurich, Switzerland
DoP No. 53568252
EN 14889-2:2006
Notified Body 0761
Polymer fibers for use in concrete mortar or grout

Tensile strength	450 N/mm²
Modulus of elasticity	7,5 kN/mm²
Effect on consistence (workability) of concrete	8 sec
Effect on strength of concrete	4 kg/m³

*) Fiber specification: length 50 mm, diameter 0,715 mm, shape deformed



17
Sika Services AG, Zurich, Switzerland
49454966
EN 14889-2:2006
Notified Body 1136
Polymer fibers in concrete mortar or grout

Tensile properties	30 cN/tex
Effect on consistence (workability)	8 sec

Example of the CE marking for SikaFiber® Force-50 and SikaFiber® PPM-12

3.2.2 ASTM D7508/D7508M

ASTM D7508/D7508M Standard Specification for Polyolefin Chopped Strands covers the requirements for polyolefin chopped strands fibres in concrete. It was developed in accordance with principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee. All polyolefin chopped fibres used in concrete must also comply with the specification given in ASTM C1116/C1116M.

Table 3.2.2.1: Main contents of ASTM D7508/D7508M

SECTION	CONTENT	DESCRIPTION
	Foreword	Information to member states
1	Scope	Content of the standard
2	Referenced documents	Summary to other relevant Standards
3	Terminology	Definitions used in the Standard
	SPECIFICATIONS	
4	Chopped strands for FRC	Information to manufacturers
5	Summary	Summary of testing procedures
6	Significance and use	Acceptance and correlation testing
7	Sampling and number of specimens	Guidance notes
8	Fibre length and permissible variations	Guidance notes
9	Linear density, cross sectional area, equivalent diameter of FRC strand and finish content	Procedures
10	Tensile and tenacity Properties	Procedures
11	Conformance	Quality control guidance

The additional Standards referred to ASTM D7508/D7508M, are either test methods or further guidance.

STANDARD	CONTENT	DESCRIPTION
ASTM C1116/ C1116M	Guidance	Specification for fibre-reinforced concrete
ASTM D123	Guidance	Terminology relating to textiles
ASTM D1776	Guidance	Practice for conditioning and testing textiles
ASTM D1577	Denier	Test method for linear density of textile fibres
ASTM D1907	Linear density	Linear density of yarn by Skein method
ASTM D2256	Tenacity Tensile Elongation Initial Modus	Test method for tensile properties of yarns by single-strand method
ASTM D2257	Finish content	Test method for extractable matter in textiles
ASTM D2258	Guidance	Practice for sampling yarn for testing
ASTM D3218	Acceptance testing	Specification for polyolefin monofilaments

3

TOLERANCES

Product tolerances are defined from testing 30 representative fibres from 10 randomly selected grab samples from different set intervals. The tolerances are defined in section 8 of ASTM C1116/C1116M.

CONFORMANCE

Conformance can be defined between the purchaser or supplier or using table 1 in the Standard. A delivery is deemed valid when the test results conform to these agreed tolerances.

Table 3.2.2.2 Table 1 from ASTM D7508/7508M

Chopped Strands Attributes	Micro Chopped Strands	Macro Chopped Strands	Hybrids Chopped Strands
Compliance with Specification C1116/C1116M, Type III	Required	Required	Required
Denier Finish Content	580 or less 1.5 % max.	581 or greater 1 % max.	As Designated - Must be stated 1.5 % max. on Micro Portion 1 % max. on Macro Portion
Tensile Strength	N/A	Greater than 344.4 MPa [50 000 psi]	Micro Portion N/A Macro Portion - Greater than 344.4 MPa [50 000 psi]
Cut Length	3 - 50 mm	12 - 65 mm	As Designated - Must be stated

Fibres must also comply with the requirements of Annex B of ICC ES AC32 for alkali resistance.

3.2.3 ASTM A820/A820M

ASTM A820/A820M is the Standard Specification for Steel Fibres for Fibre-Reinforced Concrete and covers the minimum requirements for five types of steel fibres.

Table 3.2.3.1: Main contents of ASTM A820/A820M

SECTION	CONTENT	DESCRIPTION
	Foreword	Information to member states
1	Scope	Content of the standard
2	Referenced documents	Summary to other relevant Standards
3	Terminology	Definitions used in the Standard
4	Classification	Types of steel fibre
5	Ordering information	Information required
6	Materials and manufacture	Guidance notes
7	Mechanical properties	Testing procedures
8	Dimensions and permissible variations	Procedures
9	Workmanship, finish, and appearance	Guidance notes
10	Inspection	Guidance notes
11	Rejection and rehearing	Guidance notes
12	Certification	Guidance notes
13	Packaging and package marking	Guidance notes

The additional Standards referred to in ASTM A820/A820M, are either test methods or further guidance.

STANDARD	TITLE
ASTM A370	Test methods and definitions for mechanical testing of steel products
ASTM A700	Guide for packaging, marking, and loading methods for steel products for shipment
ASTM C1116/C1116M	Specification for fibre-reinforced concrete

In ASTM A820/A820M, there are references also to documents produced by the American Concrete Institute (ACI).

DOCUMENT	TITLE
ACI 506.1R	Guide to fibre-reinforced shotcrete
ACI 544.1R	Report of fibre-reinforced concrete

4 FIBRE PROPERTIES

4.1 TERMINOLOGY

Fibre types

Monofilament / Multifilament fibres	Single fibre strand which may be circular or irregular in cross section
Embossed fibres	Fibres which have been pressed with indentations into the surface
Fibrillated fibres	Fibres when stretched out have a branch or net structure

Fibre characteristics

Length	Distance between outer ends or length of a deformed fibre after straightening without deforming the cross section	mm / inch
Equivalent Diameter	Diameter of a circle with an area equal to the mean cross section	mm / inch
Aspect ratio	Length/equivalent diameter	ratio
Linear density	Mass per unit length filament 1 denier = 1g/9000m	Denier
Linear density	Mass per unit length filament 1 tex = 1g/1000m	Tex
Breaking force	Maximum force a fibre can resist	kN, cN, lb, k
Tensile strength	Maximum force divided by the mean cross-sectional area	MPa/Psi
Tenacity	Breaking force divided by linear density	cN/tex
Elongation	Ratio of length change to initial length	%
E-modulus	Initial slope of the tensile strength versus elongation curve or slope of the tensile stress versus tensile strain curve	GPa

Fibre Testing

Peak flexural strength or modulus of rupture MOR	The maximum flexural tensile stress in a beam test	MPa/ksi
Limit of proportionality	The point where on the load/deflection or stress/strain graph, the curve departs from the initial linear response.	MPa/ksi
Residual flexural strength	The post crack strength measured from a bending test after the peak flexural strength has been exceeded	MPa/ksi
R_{e3}	The equivalent flexural strength ratio determined from a beam test up to a deflection of 3 mm	%
CMOD	Crack Mouth Opening Displacement and determined from beam tests. It is the opening distance between the opposite faces of a notch which is cut into the bottom of a beam.	mm/inch
Energy absorption	Ability of a FRC to sustain loads after cracking and determined from a load-deflection concrete panel test	Joules
Deflection	The measure linear displacement of a specimen subject to a loading	mm/inch

Fibre application

Balling	Clumps or clusters of fibres that have formed due to various reasons
Fibre count	The number of fibres in a unit volume of concrete

Figure 4.1.1: Fresh concrete without balling

Figure 4.1.2: Fresh concrete with balling

4.2 CLASSIFICATION

EN 14889 PARTS 1 and 2

European Standard EN 14889-Part 2 characterises fibres according to their diameter. The length of the fibre is not considered in the classification.

Class Ia:	Micro-fibres:	< 0,30 mm in diameter; Monofilament
Class Ib	Micro-fibres:	< 0,30 mm in diameter; Fibrillated
Class II	Macro-fibres:	> 0,30 mm in diameter

Micro-fibres having a diameter less than 0.3 mm are further sub-divided according to their form, these being monofilament or fibrillated. Class II macro fibres are not further sub-divided.

ASTM D7508/D7508M

ASTM D7508/D7508M also defines fibres into two categories based on their denier and diameter.

(a) Macro polyolefin fibre which has linear density greater than or equal to 580 deniers (equivalent diameter ≥ 0.3 mm)
(b) Micro polyolefin fibre which has a linear density of less than 580 denier (equivalent diameter < 0.3 mm)

The standard also defines hybrid fibres which include a combination of macro polyolefin and micro polyolefin fibres, multi-length fibres, which consist of chopped strands of various lengths of fibre and graded fibres which consists of a gradation of multiple lengths and multiple denier fibres.

4.3 PHYSICAL PROPERTIES

4.3.1 LENGTH

The length of the fibre must be declared and is measured from the extremity of each end.

4.3.2 DIAMETER

The cross section of a fibre can be round, elliptical, rectangular, or irregular. Circular, elliptical, or rectangular cross sections are determined with optical measuring equipment for fibre diameters less than 0.3 mm and using a micrometre, to a precision of 0.001 mm, for fibres greater than 0.3 mm.

Fibres with an irregular cross section are said to have an *equivalent diameter* and must be determined from the fibre length, weight, and material density.

EN 14889-2 METHOD OF DETERMINING EQUIVALENT DIAMETER

Procedure for determining an equivalent diameter

1. The mass of the strand shall be determined to an accuracy of 0.001 g
2. The length of the strand shall be determined to an accuracy of 0.01 mm
3. The equivalent diameter shall be determined from the following equation [1]
4. The cross-sectional area shall be determined according to equation [2]

Equation [1] $$d_e = \sqrt{\frac{4\, m_f \cdot 10^3}{\pi \cdot l_d \cdot \rho}}$$ equivalent diameter

Where $\rho = 0.9 g/cm^3$
m_f = Mass (g)
l_d = developed length in mm

Equation [2] - Refer to 4.3.3)

D7508/D7508M METHOD OF DETERMINING EQUIVALENT DIAMETER

For strands with a rectangular cross section, the width and thickness are measured and equivalent diameter is calculated.

$$d = \sqrt{\frac{4\,wt}{\pi}}$$

Where d = equivalent diameter in mm
t = measured thickness of strand in mm
w = measured width of strand in mm

For irregular cross section fibres, the equivalent diameter is calculated from the linear density (tex or denier).

$$d = \sqrt{\frac{4\left(\frac{tex}{1000}\right)}{\pi\rho}} \quad \text{or} \quad d = \sqrt{\frac{4\left(\frac{denier}{9000}\right)}{\pi\rho}}$$

Where
d = equivalent diameter in mm
ρ = unit density of polyolefin g/cm^3

4.3.3 CROSS SECTIONAL AREA

Equation [2] π x d/4 cross-sectional area

4.3.4 DENSITY

The nominal density of polypropylene is 0.905 g/cm^3 and for steel it is generally given by the steel fibre supplier in kg/m^3.

4.4 STRENGTH

The main strength tests for fibres are tensile strength and the E-modulus.

CLAUSE	STANDARD	TEST STANDARDS
5.3 and 5.4	EN 14889-1 (steel)	EN 10002-1[1]
5.4 and 5.5	EN 14889-2 (synthetic)	EN ISO 2062 / EN 10002-1[1]
7	ASTM A820/A820M (steel)	ASTM A370
10	ASTM D7508/D7508M (synthetic)	ASTM D1776 / D2256 / D3218

[1] Withdrawn Standard but still referred to in EN 14889-Parts 1 and 2: 2006

The methods used in these standards to determine tensile strength and E-modulus are very different and leave room for interpretation. As a result, potentially all fibre manufacturers test their products using different test methods and machine settings. For this reason, the declared values for tensile strength and E-modulus in product data sheets are not always comparable. Equally a declared value does not always reflect the quality of the fibre, or performance in the concrete

4

4.4.1 TENSILE STRENGTH

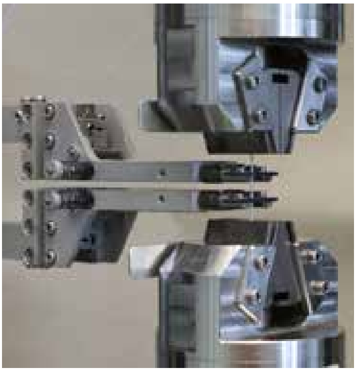


Figure 4.4.1.1: Universal Testing Machine with a flat-faced clamping system, incorporating a tactile extensometer for very precise determination of the strain

The tensile strength of a micro or macro fibre is the maximum stress it can withstand while being stretched or pulled before breaking. This value is divided by the cross-sectional area of the fibre and is measured as force per unit area (N/mm^2 / ksi). Often fibres are not perfectly round, square, or rectangular, therefore, the equivalent cross-sectional area must be determined from the weight, length, and density of the fibre.

Tensile strength is usually tested using a Universal Testing Machine. To prevent slippage, the equipment can be fitted with clamps consisting of two flat-faced jaws which are adjusted for the fibre length and apply a strain until the specimen ruptures. (Figure 4.4.1). There are also snubbing type clamps also referred to as capstan or drums as shown in figure 4.4.2. The use of a flat-faced clamp with a tactile extensometer or snubbing-type clamping system are recommended to correct the imprecision of the elongation. Flat-faced clamps may often be associated with testing thin fibres, whereas the snubbing clamps can be used to prevent slippage for thicker fibres, with a high breaking force.

It is essential to define the specific parameters before testing and to make sure these are included in the test report.

- Strain rate (%/min) [1]
- Test speed (mm/min)
- Gauge length (mm)

[1] derived from the test speed divided by the gauge length multiplied by 100%

Figure 4.4.1.2: Snubbing clamp referred to ASTM D 2256–02

Testing is normally carried out on a minimum 30 strands. From the spread of results the manufacturer can decide which value to declare, although the relevant Standards (EN14889-1 /-2 and ASTM D7508/D7508M and A820/A820M) defines a maximum allowable difference between the declared value, and the upper and lower values. The manufacturer will also define from where in the production process the strands are removed for testing. For example, tensile tests are typically carried out on the embossed fibre (the finished product) whereas for undulated or crimped fibres the test is better carried out on the pre-undulated or crimped fibre. The reason for this is because the initial elongation to straighten an undulated or crimped fibre affects the result interpretation.

4.4.2 E-MODULUS

The E-modulus is a measure for the stiffness of a material. At near-zero stress and strain, the stress–strain curve is linear which means that stress is proportional to strain. The higher the E modulus, the more stress is needed to reach the same degree of elongation in this region.

In tensile testing of plastics, E-modulus typically is determined as a secant modulus. This means that a line is drawn through the points at 0.05% and 0.25% elongation on the stress-strain curve and E-Modulus is determined from the line of the slope. The two points at 0.05% and 0.25% elongation are chosen for the determination of the secant modulus, as in this range of deformation plastics show linear-viscoelastic behaviour. Linear-viscoelastic behaviour means, that elongation is reversible. Most plastics show non-linear-viscoelastic behaviour with irreversible deformations at a strain of greater 0.3%.

4.4.3 ELONGATION

Elongation of fibers is a measure of the deformation that occurs before material eventually breaks when subjected to a tensile load. Elongation is measured as a percentage (%) of stretch from the material's original length to the point of failure. It is fair to say that polymer fibers generally have a higher elongation percentage when compared to steel fibers. However, the selection of fiber reinforcement material should not be based solely on this property.

4.4.4 CREEP

Typically, steel fibres do not exhibit a creep behaviour in normal service conditions below 370°C (700°F). Synthetic fibres are visco-elastic and therefore may be susceptible to long term creep due to high stresses. But for slabs on ground/grade or shotcrete where the stresses are lower and with continuous support, creep has not been considered a determining factor for synthetic fibres.

4.5 SYNTHETIC CHEMICAL PROPERTIES

4.5.1 TEMPERATURES

Melting Point of commercially available homopolymer polypropylene (PP) generally has a range from 160 – 165 degrees Celsius. (320 – 329 degrees Fahrenheit). Polypropylene fibres soften under heat at around +140 to +150°C (+284 to +302 degrees Fahrenheit) and at temperatures up to +120°C (+248 degrees Fahrenheit) PP-fibres mostly retain all their normal mechanical properties.

Melt Flow Index is the rate of extrusion of thermoplastics through a specified orifice/dye size at a prescribed temperature and load. Melt Flow Index has significantly more influence in the production of extruded plastic fibers than it does in their usage as concrete reinforcement. It provides a means of measuring the flow of molten material and can differentiate grades of polypropylene or other plastic materials. Melt Flow Index refers to the amount of polymer that is extruded through the specified orifice/dye and is expressed as a quantity in grams/ 10 mins. Variations in melt flow properties can have a detrimental effect on the productivity and end quality of fibers.

Decomposition Temperature often described as thermal degradation is the breaking down of the chemical compound into small components as a result of heating and does not recombine on cooling. Depending on the product and environment polypropylene has a decomposition temperature in the range of 250 – 425 degrees celsius (482 - 797 degrees Fahrenheit).

In **Cold Temperatures** polypropylene fibres keep their flexibility until 5°C (41 degrees Fahrenheit), and at sustained temperatures below 0°C (32 degrees Fahrenheit) the exposed fibres become brittle.

4.5.2 MOISTURE / ABSORPTION

Polypropylene (PP) is a hydrophobic polymer, which reflects the negligible amount of water absorbed by PP-fibres. As PP-fibres do not absorb moisture the fibres do not change their volume or dimensions in different humidity, or when wet. In a 24-hour soak test, the material absorbs less than 0.01% of its weight in water.

4.5.3 CHEMICAL RESISTANCE

Polypropylene (PP) is resistant to all non-oxidising inorganic-based acids solvents and chemicals, which also means it is alkali resistant. PP has no long-term resistance to fuels and some organic solvents but is resistant to many polar liquids such as alcohols, organic acids, esters, ketones, aqueous solutions of inorganic salts.

4.5.4 UV RESISTANCE

Polypropylene (PP) is not UV resistant and needs to be stored and protected from direct sunlight. UV rays can degrade PP when exposed sustained direct sunlight. However, with macro and micro synthetic (PP) fibres the materials are completely embedded in the concrete where UV light cannot penetrate, meaning that UV degradation is not an issue. Furthermore, good quality synthetic fibre will generally have an UV stabilizer in their composition so that even near-surface fibres do not suffer deterioration.

4.5.5 SURFACTANT COATINGS

A surfactant coating is an agent used in the manufacturing process of synthetic fibers which essentially reduces the surface tension between the molten polymers and the extrusion equipment, thereby ensuring continuity and quality of the extrusion process.
A surfactant coating can also enhance the dispersion qualities of the fibers when introduced into a concrete or cementitious mix. Careful selection of a surfactant coating is necessary in the production of synthetic fibers as some types are known to entrain higher levels of air content in mixed concrete.

5 FIBRE TYPES

5.1 MICRO FIBRES

Synthetic micro-fibres have been used in construction for many years and originate from the carpet manufacturing industry. These fibres were found to have a positive effect on the fresh concrete properties, as well as increasing durability, and led to a large early increase in the usage of this type of fibre. Nowadays, synthetic micro-fibres are often a standard stocked item with ready-mixed concrete suppliers.

Often cost/performance is an overriding factor when selecting micro fibres, therefore the most common materials are polypropylene (PP).

The two main different types of synthetic micro-fibres.

Monofilament fibres [1]

Fibrillated fibres

[1] Sometimes referred to multifilament by the textile industry because of the process of extruding fibres through a multi-headed dye head

5.1.1 TYPES OF SYNTHETIC MICRO-FIBRES

Numerous types of synthetic micro-fibre materials are now available to the construction market including, acrylic, aramid, carbon, nylon, polyester, polyethylene, and polypropylene. Additionally, there are many naturally occurring products including coconut, sisal, jute, and bamboo which are creating interest. The selection of materials can be dependent on the specific application, benefits required and of course availability of material.

Where there is a need to reduce plastic shrinkage and settlement cracking in concrete the most widely used material is polypropylene. This is largely because the material is readily available and commercially viable. For crack bridging and load transfer a fibre type with a higher tensile strength and E-Modulus is required e.g., glass, basalt, or carbon. For fire protection and reduction of explosive spalling a fibre material with a low melting point is required e.g., polypropylene or PVA.

5.1.2 IMPACT ON FRESH CONCRETE

Micro-fibres will impact the workability of fresh concrete, depending on the fibre type and dosage. Introducing fibres increases the surface area that needs to be covered by the cement paste. If nothing is changed to the original mix design the concrete will generally only feel more cohesive. Whilst this cohesiveness can reduce the slump of the concrete, it is not necessarily an indication of reduced workability and is purely a thixotropic effect caused by the fibres which can be corrected with the use of admixtures.

Table 5.1.2.1 compares the number of fibres per kg in relation to the length and equivalent diameter of PP-fibres. The fibre deniers used in this table represent the most commonly available products in the marketplace. Usually, fibres are dosed by weight per cubic meter/cubic yard of concrete or mortar. Depending on the fibre geometry the same dosage weight can lead to different concrete properties.

Table 5.1.2.1: Monofilament fibres per kg dosage according to fibre length and denier

Fibre Length (mm)	Fibre Count / kg			
	18 Micron	22 Micron	32 Micron	34 Micron
	2.1 denier	3.1 denier	6.6 deniers	7.4 denier
6	718,349,627	480,878,676	227,290,312	201,336,747
12	344,867,821	230,821,764	109,099,350	96,641,638
19	226,847,251	151,856,424	71,775,888	63,580,025

The fibre with the lowest diameter and length will provide the highest fibre count per kg dosage. This can be a key feature/characteristic of the synthetic micro-fibre when used to prevent early age cracking and can be used in lower dosages as a result. Whilst this seems to be a reasonable argument the specifier must also consider the impact of very fine fibres on the workability of the fresh concrete. This is because a higher fibre count will invariably increase the total surface area of the fibres and for them to function correctly in the mix the fibres need to be fully coated with cement paste.

It follows that very fine materials will have a greater water-cement paste demand. The effect on air content should also be checked as fibres with high fibre counts and, therefore, surface area may have an impact on entrapped air in the mix which can influence target strengths of the concrete.

In a flow-table test to EN 12350-5, the addition of 600g 12 mm long x 32µm fibres reduced the workability of a reference concrete by 10%. The air content in the same reference concrete increased by 30%, from 1.75% to 2.3%. While this may not be dramatic it illustrates why it is recommended to pre-check these parameters.

5

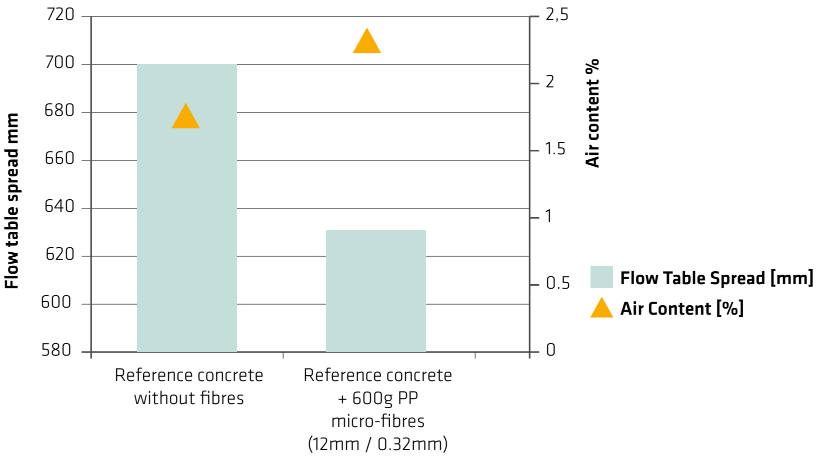


Figure 5.1.2.1: Impact on fresh properties of a reference concrete with PP micro-fibre addition

When concrete is vibrated fibres tend to release their grip on the cement paste and the concrete will flow normally. This cohesive effect is often misunderstood by concrete operatives and may wrongly lead to additional water being added to the concrete. This should be avoided as it will reduce mechanical strengths and may cause bleeding. If there is an unexpected loss in workability, then the adjustments should be made with the mix design.

5.1.3 INFLUENCE ON CRACKING

The tendency for concrete to crack has for years been accepted as natural to its use. The main reason cracks occur in concrete are because internal stresses exceed the concrete strength. Stresses from external forces can be offset by providing higher compressive strengths. However, intrinsic stresses caused by chemical reactions/shrinkage within the newly placed concrete itself have historically been a problem to control because of their unpredictability.

Table 5.1.3.1: Shrinkage stages can lead to cracking

INTRINSIC STRESSES THAT CAUSE CONCRETE CRACKING		
Type	PRIMARY CAUSE (Excluding Restraint)	TIME OF APPEARANCE
Plastic settlement	Excess bleeding/change in volume	10 min. – 3 hrs.
Plastic shrinkage	Rapid early drying	30 min. – 6 hrs
Early thermal contractions	Excess heat and temperature gradients	1 day – 2 or 3 weeks
Long-term drying shrinkage	Inefficient joints	Several weeks or months

5.2 PP MICRO BENEFITS

PP micro-fibres influence the concrete characteristics during the early stages of the strength development when the concrete is hardening, and they also offer passive fire resistance.

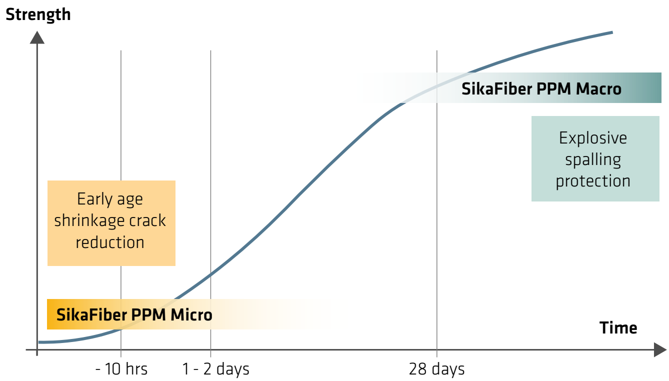


Figure 5.2.1: Showing benefits of using micro-fibres in relation to time and strength development

5.2.1 REDUCING PLASTIC SETTLEMENT CRACKING

Plastic settlement cracking is caused by a change in volume of a concrete section and is influenced by the degree of bleeding that may occur for a given concrete mix. Bleeding is the action of water rising to the surface of the concrete shortly after placement and is caused by heavier particles gravitating downwards and displacing fine particles and water. Bleed water is seen on the concrete surface only if the rate of evaporation is less than the rate of bleeding.

Bleeding can be reduced with proper concrete mix design containing a well-balanced aggregate sieve curve and/or the use of the right admixture technology to stabilize the concrete mix. However, synthetic micro-fibres also have a dramatic effect on reducing bleeding because they act as an internal suspension system effectively supporting the coarse aggregates in the mix thus inhibiting bleeding and settlement.

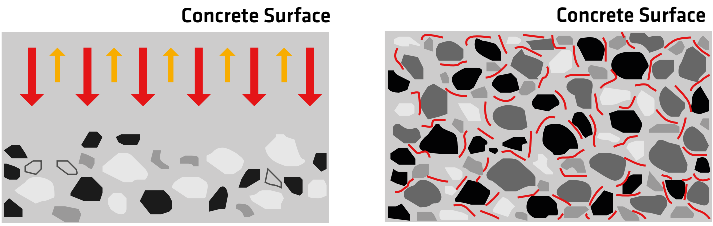


Figure 5.2.1.1: Reducing concrete bleeding using synthetic micro-fibres

Settlement cracks will invariably form over reinforcement, which is fixed in position near the top of the concrete. These cracks will be detrimental to the long-term durability of the steel reinforcement and the concrete itself.

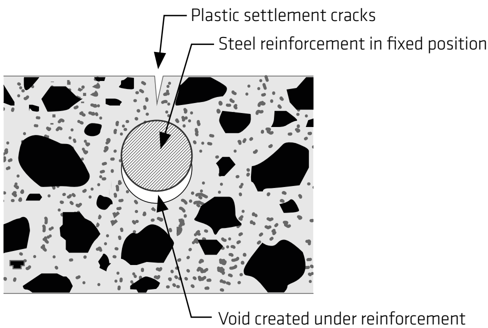
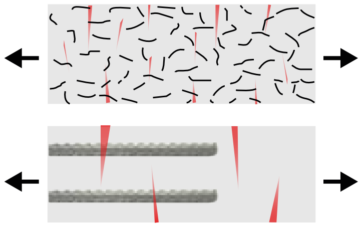


Figure 5.2.1.2: Plastic settlement under a reinforcing bar

5.2.2 REDUCING PLASTIC SHRINKAGE CRACKING

Plastic shrinkage cracks occur within a few hours after placing concrete, although they may not be noticed until the following day. They are most common in floor slabs but can also occur in other exposed concrete surfaces. Although plastic cracks may be wide on the surface they will quickly diminish with depth. However, plastic cracking will generally pass through the full depth of the slab.



The key reason for the formation of plastic cracking is that for several hours after placement the concrete has little or no tensile strength. Where the concrete surface is exposed to rapid drying, moisture on the surface will quickly evaporate and this creates the tensile strain on the surface of the concrete. Cracks occur when these stresses exceed the tensile strength of the concrete.

When plastic cracks occur in concrete with steel reinforcement, air and moisture can penetrate through the open crack together with other aggressive agents such as chlorides and other harmful soluble substances. This will inevitably lead to steel corrosion and a reduce the durability of the concrete.

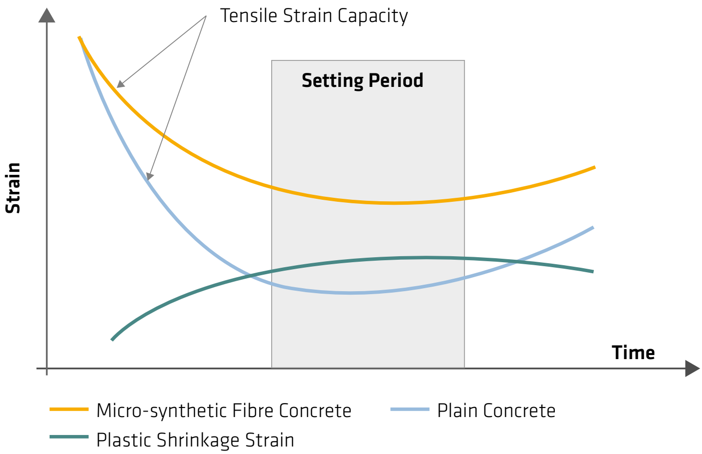


Figure 5.2.2.1: Principal of tensile strain in early-age concrete

A major benefit of using synthetic micro-fibres in concrete is the ability to increase the early age tensile strength of the concrete. This means when there are strains on the concrete surface, due to drying or fast evaporation of moisture, they generally will not exceed the tensile strain capacity of the fibre reinforced concrete. The benefit of using micro-fibres is to reduce or eliminate the plastic shrinkage cracking.

DOSING

PP micro-fibres inhibit early age plastic shrinkage cracking and are generally dosed between 0.6 – 0.9 kg/m³ (1 to 1.5 pcy). This dosing range is dependent on the fibre denier, the sand grading, and the ambient conditions. If significant cracks are to be avoided, or at least reduced, then concrete exposed to high temperatures and drying winds are at greater risk of early age plastic shrinkage cracking. In these situations, it is advisable to use a higher dosage amount. Similarly, concrete subject to low temperatures and moderate winds are less at risk and can require the lower dosage amount.
Mix designs with a higher number of small fractions such as mortars and wet screeds, require a higher fibre dosage of around 0.9 – 1.8 kg/m³ (1.5 to 3 pcy). Care must always be taken to pre-check the fresh properties when using high dosages of micro fibres.

Table 5.2.2.1: Example of micro-fibre dosing to reduce plastic shrinkage control.

	Reference Concrete	Concrete for plastic shrinkage reduction
Cement	320 kg/m³	320 kg/m³
w/c-ratio	0.5	0.5
Aggregates	0 – 32 mm	0 – 32 mm
Sika® ViscoCrete®	0.8 %	0.9 – 1.1 %
SikaFiber® PPM	–	0.6 – 0.9 kg/m³

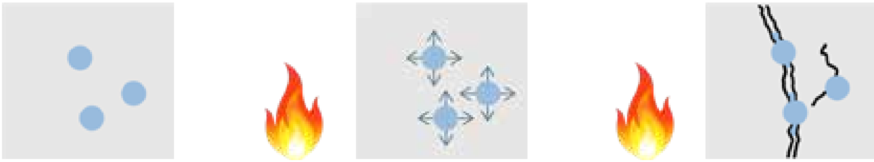
5.2.3 EXPLOSIVE SPALLING RESISTANCE

The addition of suitable polypropylene (PP) monofilament micro-fibres into concrete is now widely accepted to control explosive spalling in cast/precast concrete and sprayed concrete. This type of protection is termed as "passive fire protection", which means that it is an integral part of the concrete structure and does not require external activation in the event of a fire. Since the first usage of PP micro-fibres in the Channel Tunnel Rail Link Project (2007), the technology has been incorporated into many world-wide tunnel projects, including: Gotthard Base Tunnel, Switzerland; Doha Metro, Qatar; London Crossrail, UK; Copenhagen Metro, Denmark; Los Angeles Metro System and Hong Kong MTR.

Explosive spalling can present a severe risk to the structural integrity of a structure due to a loss in concrete section and/or the yielding of embedded steel reinforcement when exposed to high temperatures. In all cases, there is potential for explosive spalling to lead to complete structural failure.

There is a simple theory why PP micro-fibres prevent explosive spalling in the event of fire this is because well distributed PP micro-fibres melts at a temperature of 160°C (360 degree F) creating tiny channels within the concrete which permit the escape of super-heated moisture. This reduces the internal pressures and minimises explosive spalling damage.

Mechanism leading to explosive spalling in a high-density concrete

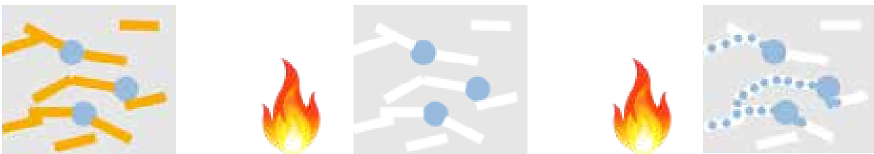


Moisture present in concrete

When a rapidly rising heat source occurs the moisture within the concrete quickly tries to escape. In high density concrete this becomes a major obstacle and the water quickly heats and transforms to super-heated steam.

This creates a significant build-up of internal stresses. When the tensile capacity of the concrete is exceeded spalling of the concrete will inevitably occur.

Mechanisms of Passive Fire Resistance



Moisture in concrete and a well distributed dosing of PP micro-fibre

When the rising heat source reaches a temperature of 160°C (360 degree F), the PP micro-fibres melt.

The new pathways release the moisture and super-heated steam.

Later research has shown that this is an oversimplification of the true mechanisms contributing to the influence of PP micro-fibres on explosive spalling.

Alternative Passive Fire Theory

In 2001, Prof P.J.E. Sullivan, City University London presented an alternative theory based on the different thermal expansion of synthetic polymer and concrete. The work concluded that PP micro-fibres when exposed to increased temperature will initially expand and exert stresses onto the cement matrix which initiates the formation of micro-cracks.

Coefficient of thermal expansion for concrete	= 6 to 12 x 10^{-6}/K
Coefficient of thermal expansion for polypropylene	= 86 x 10^{-6}/K

This thermal expansion of polypropylene was estimated to be 7 – 14 times greater than concrete and Saka et al, 2009 also reported significant stresses are created by a single polypropylene fibre embedded in a mortar matrix when subjected to a temperature increase of 140°C (284 degree F).

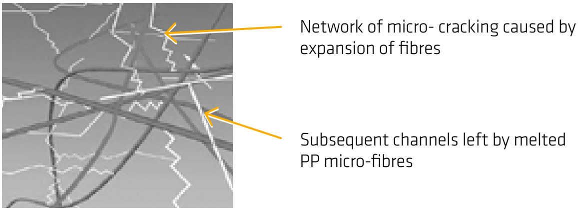


Figure 5.2.3.1: Micro-cracking Network

5

As the temperature continues to increase the fibres melt and further create small channels which combine to provide a pressure release system to alleviate the potential for explosive spalling.

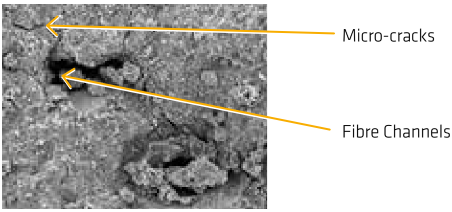


Figure 5.2.3.2: Microscopic photo highlighting formation of channels and micro-cracking after fire

Work carried out in 2004 by Dehn & Willie in Leipzig confirmed the presence of micro-cracking and fibre channels after exposure to high temperature fire tests.

5.2.4 REDUCING PERMEABILITY

Synthetic micro-fibres can inhibit the formation of internal intrinsic micro cracking, which if left unchecked can increase moisture absorption. The reduction of these micro cracks with fibres means that the concrete is less permeable. This can also help to improve the freeze-thaw resistance of concrete in external applications.

5.2.5 ABRASION RESISTANCE

The reduction of bleeding and settlement, achieved with PP micro-fibres, means that more coarse aggregates particles are retained at and near the surface. It is the increased coarse aggregates at the surface which provides longer durability to abrasion resistance.

5.2.6 IMPACT / SHATTER RESISTANCE

PP micro-fibres, particularly the fibrillated types are exceptionally good in distributing localized stresses as they effectively act as tiny shock absorbers within the concrete. When concrete is exposed to impact loads fibres distribute the stress over a wider area and therefore significantly reduce impact damage. Fibrillated fibres are also very good at holding concrete together after the formation of a cracks.

5.3 PP MACRO-FIBRES

PP Macro-fibres have been commercially available for more than 20 years. The main applications for this type of fibre are shotcrete, slabs on ground and for precast concrete elements. Unlike synthetic micro-fibres, which have their main benefits/influences within plastic state concrete, synthetic macro and indeed steel-fibres are used primarily to provide benefits in the hardened state concrete.

Synthetic macro-fibres can be made of the same materials as micro-fibres but tend to be coarser and stiffer. The most widely used synthetic macro-fibres are made of polypropylene as this material shows the best properties in terms of durability and resistance against an alkaline environment, such as concrete.

Synthetic macro-fibres are now available in several different geometries; the main types of fibres in terms of shape are as follows:

- Straight embossed fibres
- Undulated fibres
- Soft flat fibres
- Twisted

Figure 5.3.1: : a) Straight embossed fibres   b) Undulated fibres   c) Soft flat fibres

The straight embossed fibres are considered to have better advantages in high strength concrete where the porosity is lower around the fibre and the embossing results in a higher pull-out resistance. Due to the fibres being straight, there is much less tendency for balling during mixing with high fibre dosages.

Undulating fibres are sometimes considered to have better advantages in low strength concrete where the large porosity around the fibre is overcome with the undulation, and results in a larger pull-out resistance.

The advantage of a soft fibre is the high fibre count, especially at low dosages the performance can be better than the other fibre geometries. Soft fibres deform during mixing, twist around the aggregates and this, together with high fibre numbers, increase the crack resistance. Soft fibres, generally have low dosages as with high dosages the concrete workability decreases.

5.3.1 PLASTIC SHRINKAGE CRACKING

Whilst synthetic macro and steel-fibres may reduce the early age plastic shrinkage cracks, they are not present in sufficient numbers to have the same high level of reduction as PP micro-fibres.

5.3.2 IMPACT ON FRESH CONCRETE

PP macro-fibres will impact on the workability of concrete like micro-fibres, depending on the fibre type and dosage. The demand on cement paste generally makes the concrete more cohesive. This cohesiveness can reduce the slump of the concrete. However, a loss in slump is not necessarily an indication of reduced workability, it is a thixotropic effect caused by the fibres.

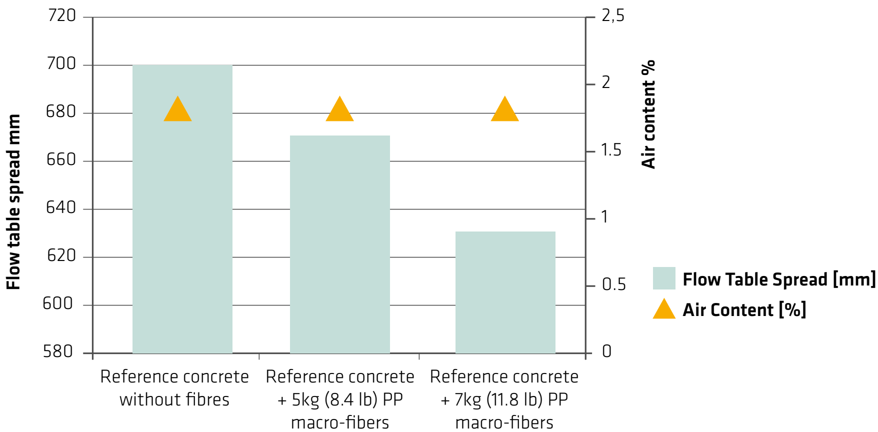


Figure 5.3.2: Impact on fresh properties of a reference concrete with PP macro-fibre addition

In a flow-table test to EN 12350-5, the addition of 5 kg / 8.4 lb PP macro-fibres reduced the workability of a reference concrete by 4%. With the addition of 7 kg / 11.8 lb PP macro-fibres the workability reduced by 11%, compared to the reference. The air content practically remained the same with the addition of PP macro-fibres.

5.3.3 INFLUENCE ON STRENGTH

Synthetic macro-fibres, in general dosages, do not normally increase the compressive strength of concrete. The effect they have is on the cohesiveness of the concrete, which may improve the density and a slight increase in final strengths.

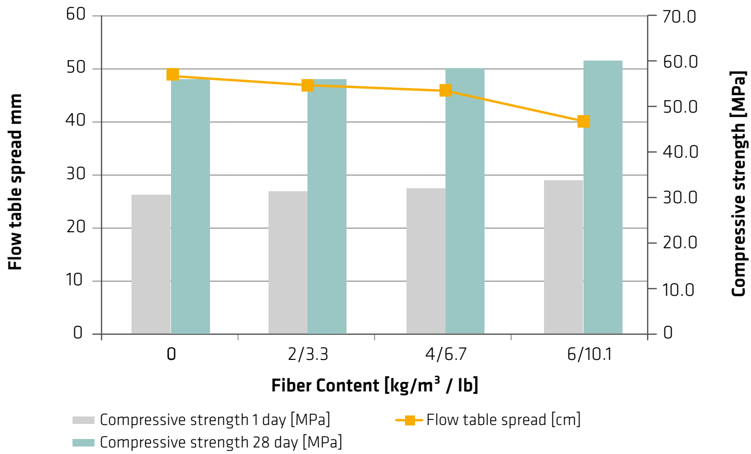


Figure 5.3.3: SikaFiber® Force-60 - 320kg/m³ CEM i 42,5 - w/z: 0.46 -0/32

5.4 STEEL MACRO FIBRES

Steel fibres are well known in the market and have been used for >40 years in the construction industry. Steel fibres are mainly used for slabs on ground or shotcrete applications but often used in several other applications such as pre-cast elements, structural elements, foundations, and others.

For some Engineers the move from traditional steel wire mesh to steel fibres may be an easier step to take than from wire mesh to synthetic fibres, despite the fact both steel and synthetic fibres work very similarly in concrete and both are covered by European Standard performance requirements.

EN 14889-1 classifies steel fibres into five groups

- Group I: Cold-drawn wire
- Group II: Cut sheet
- Group III: Melt extract
- Group IV: Shaved cold drawn wire
- Group V: Milled from blocks

ASTM A820/A820M classifies steel fibres into five general types

- Type I: Cold-drawn wire
- Type II: Cut sheet
- Type III: Melt extract
- Type IV: Mill cut
- Type V: Modified cold-drawn wire

5

MAIN TYPES

Group I or type I fibres are the most widely type used steel fibre in concrete. These fibres are often suppled as straight or deformed and in a loose or glued format. Cold Drawn wire fibres may also be coated for corrosion protection, but this often leads to increased costs.

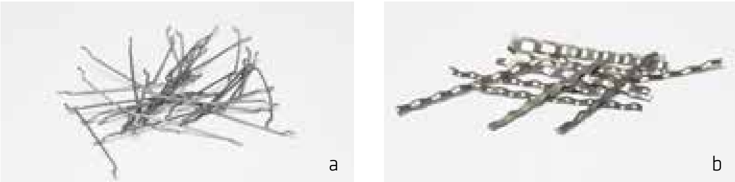


Figure 5.4: ***a)*** *group I cold drawn wire* ***b)*** *group V modified cold drawn*

5.4.1 IMPACT ON FRESH PROPERTIES OF A REFERENCE CONCRETE

As with synthetic micro and macro-fibres the influence on workability and air content for steel-fibre concrete should be carefully assessed prior to supply.

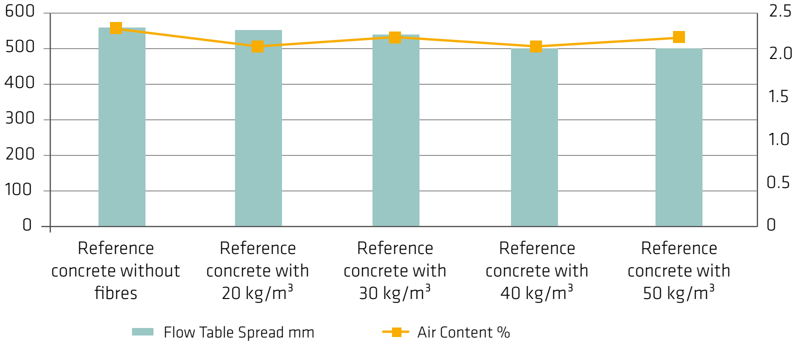


Figure 5.4.1.1: Impact on Fresh Properies of a Reference Concrete using SikaFiber® Steel Fibers in Different Dosages

5.4.2 IMPACT ON STRENGTH OF A REFERENCE CONCRETE

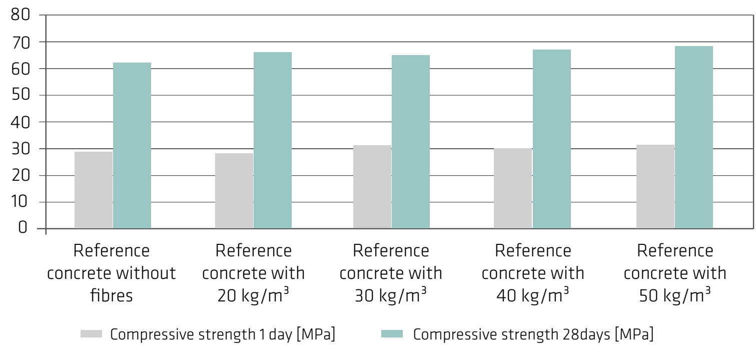


Figure 5.4.1.2: Impact on Strength of a Reference Concrete using SikaFiber® Steel Fibers in Different Dosages

5.5 MACRO BENEFITS

Macro-fibres mainly influence the concrete characteristics in the hardened concrete such as increasing the mechanical strength, ductility and reducing the construction time

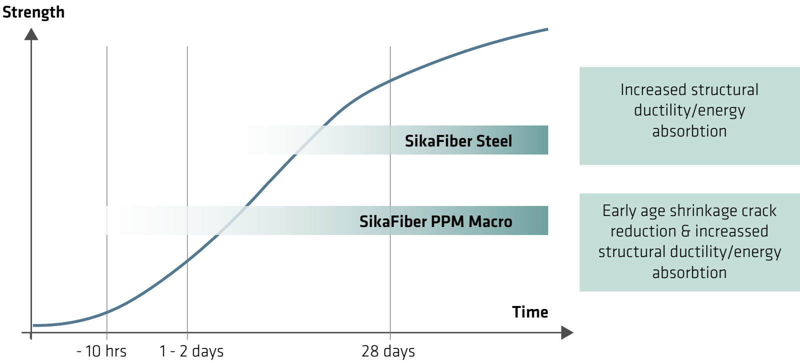
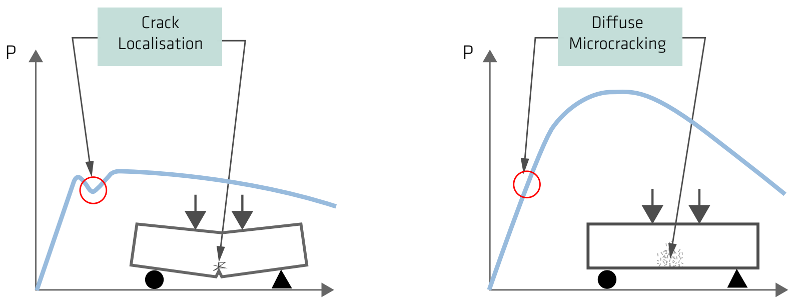


Figure 5.5.1: Macro-fibres influences

5.5.1 INCREASING MECHANICAL STRENGTH

The addition of macro-fibres to concrete can significantly improve the ductility and flexural capacity (toughness) of concrete. A three or four-point beams are tested in flexure to obtain the post crack response, known as the residual flexural strength. This data is used for characterising the performance of FRC.

The concrete's toughness is improved with the addition of fibres. For optimum efficiency, the bond strength between the fibre and the concrete matrix needs to be as close as possible to the tensile strength of the fibre. It is better fibres pull-out of the matrix rather than fibres breaking. When fibres break the anchorage is too strong.



5.5.2 INCREASING CONCRETE DUCTILITY

Ductility is the ability of a material to absorb energy and sustain loads beyond the yield point, which defines the elastic behaviour. This is also the point in concrete where cracks start to appear. Plain concrete is brittle and will exhibit a complete loss of strength past the elastic limit.

Synthetic macro and steel-fibres can significantly increase the impact and shatter resistance of concrete because of their ability to distribute and absorb localized stresses.

5.5.3 REPLACING TRADITIONAL REINFORCEMENT

A major benefit of macro fibres is they can replace certain steel reinforcement. The steel mesh has a design purpose and FRC can also be proven, with calculations, to do the same job.

5.5.4 REDUCING CONSTRUCTION TIME

Handling heavy steel reinforcement, lifting, placing, and fixing in the correct position is often back-breaking and hazardous work.

Where fibres can replace the steel reinforcement, much time will be saved in the in the construction process. Fibres are simply added to the concrete at the batching plant and delivered ready-mix to the construction site. When FRC is used as an alternative to steel reinforcement there may be no access issues for the concrete trucks, which facilitates a much quicker turn around on site and the need for pumping equipment is often avoided.

5.6 FIBRE APPLICATION GUIDE

Different fibre types can be used for different types of applications. The following table shows where PP micro- and macro-fibres, steel fibres and glass fibres are typically used.

Application / Fibre Type	Steel fibre <35 mm	Steel fibre >50 mm	Macro- fibre <48 mm	Macro- fibre >48 mm	Micro-fibre monofilament	Micro-fibre fibrillated	Glass fibre	Blend
Shotcrete	x			x		x [1]		
Slabs on ground		x	x		x	x		
Roads		x	x		x	x		x
Early age shrinkage			x		x	x		
Fire protection					x			
Precast	x		x	x	x	x		
Screeds						x	x	
Mortars					x	x	x	
Topping slabs	x		x					

[1] rebound control

Fibre reinforcement is often incorporated into many other different types of products and applications essentially to limit cracking and to enhance durability qualities of the parent material. These include,

- Mortars & Renders
- Sand/Cement Floor Screeds
- Cementitious Pump Screeds
- Refractory Products
- Garden Products (Pots & Ornaments)
- Architectural Concrete
- Pattern imprinted concrete
- Exposed aggregate concrete
- 3D Concrete Printing
- Ultra-thin white topping

5.7 MINIMUM FIBRE DOSAGE

While the fibre dosing shall be stated on the manufacturer's Product Data Sheet (PDS), there is a minimum amount to provide ductility or provide crack control and is referred to in EN 14487-1.

A minimum fibre dosing was suggested by McKee as a spacing theory.

The three-dimensional representation shows a single fibre in a unit volume. The theory suggests in one-unit volume of concrete there are several cubes with a dimension of s which is equal to the number of fibres in total volume. If the size of the cube containing one fibre is reduced, then fibre overlap will occur.

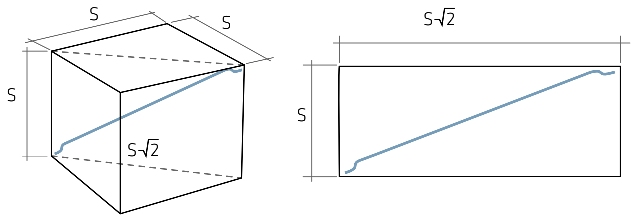


Figure 5.7.1: Minimum fibre dosage based on an overlap concept

The average distance between fibres, s, can be estimated where l_f is the length of the fibre, d_f is the diameter of the fibre and ρ_f is the percentage of fibre by volume.

$$s = \sqrt[3]{\frac{\pi \cdot d_f^2 \cdot l_f}{4\,\rho_f}}$$

where d_f = equivalent diameter in mm
l_f = length in mm
ρ_f = percentage of fibre by volume

The formula can be transposed to determine the dosage based on the geometry of the fibre, aspect ratio, and the volume fraction of the fibre concrete.

$$Dosage\,(min) = \left[\frac{1}{\left(\frac{l_f}{\gamma\sqrt{3}}\right)^3}\right] \Big/ \left[\frac{4}{\pi\, d_f^2\, l_f\, \rho_f}\right]$$

[1] The properties of expansive cement mortar reinforced with random wire fibres, PhD Thesis, University of Illinois, Urbana, 1969. Documented in ACI committee 544 report State of the art report on fibre reinforced concrete 1982.

Example with SikaFiber® Force-50:

Fibre length	= 50 mm
Equivalent fibre diameter	= 0.72
Aspect ratio	= 0.69
Material density	= 910 kg/m^3

Y	Minimum dosage	
1	$s < 0.58\ l_f$	1 kg/m^3 / 2 pcy
1.35	$s < 0.45\ l_f$	2 kg/m^3 / 3 pcy
1.45	$s < 0.40\ l_f$	3 kg/m^3 / 5 pcy
1.70	$s < 0.29\ l_f$	4 kg/m^3 / 7 pcy

In sprayed concrete EN 14487-1 suggests the average distance between fibres, s, should be lower than $0.45l_f$ and for applications it may be suggested s should be taken as lower than 0.4.

6 FIBRE REINFORCED CONCRETE

6.1 STARTING

Fibre reinforced concrete design is often a niche technology and may not be included in any learning curriculums. Currently, there are no harmonised global standards for FRC, meaning that design methods come from available pre-normative publications such as fib Model Code 2010, section 5.6 and the RILEM TC 162-TDF: Test and design methods for steel fibre reinforced concrete.

For design, the material is considered in the Ultimate Limit State (ULS) and Serviceability Limit State (SLS). Numerous studies and published reports have undertaken to correlate the tensile and flexural response in the post-crack region. This is not the subject of this handbook and further information can be found in the following documents.

There are several approaches to FRC design, but not limited to the following examples.

- American Concrete Institute 544.4R Guide to Design with Fibre-Reinforced Concrete
- The Concrete Society Technical Report 63 – Guidance for the Design of Steel-Fibre Reinforced Concrete
- The Concrete Society Technical Report 65 – Guidance for the Design of Steel-Fibre Reinforced Concrete

Specifically, for tunnel segments

- The International Tunnelling and Underground Space Association ITAtech Report N°7/April 2016

For slabs on ground/grade

- American Concrete Institute ACI 360R – Guide to Design of Slabs-on-Ground
- The Concrete Society Technical Report 34 – Concrete Industrial Ground Floors

Chapter 3 of this handbook contains some more references and there may also be some national Standards in your country.

6.2 PHILOSOPHY

Structural Engineers typically design reinforced concrete in a way that all tensile forces are carried by continuous steel bar or mesh reinforcement. It is always assumed that steel reinforcement is firmly fixed in position and unable to move, the steel reinforcement may start to yield although, it is not designed to slip out of the concrete. Structural concrete design provides a detailed specification of concrete geometry, material properties, size, and location of steel reinforcement. These are usually expressed as a bar bending schedule and detailed drawings.

In comparison, FRC in normal concrete, utilises the slip-out principle as part of the design philosophy and the emphasis is on how the tensile capacity is calculated. This means FRC elements are based on post-cracking residual strength. Generally, fibres used at standard dosage do not directly influence the tensile or bending strength of the concrete in the same way as steel reinforcement. This is until the concrete cracks and the fibres restrain the size of the crack opening. Once a crack has occurred fibres take over and support the applied forces. Fibres are said to improve the behaviour in the SLS by reducing plastic shrinkage cracking and improve the behaviour in ULS where they can partially or totally replace traditional steel reinforcement. An advantage of FRC is that the distance between fibres is very small, and that the fibres fill corners and edges. Steel bars are spaced apart and have a cover distance to the concrete surface.

Crack bridging principle

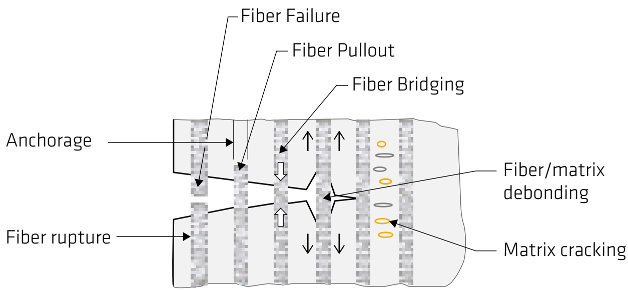


Figure 6.2.1: Principle of fibres bridging cracks in concrete changing it from a brittle to a ductile material

The stages of FRC failure or residual stress starts with the crack forming in the cement matrix. As the crack opens there is a debonding between the fibre and the cement matrix. If the fibre can bridge the crack there is no failure, but as the load or stress increases the crack size increases and there is frictional sliding along the fibre, or deformation of the anchorage. Eventually, with higher stresses the fibre pulls out of the cement matrix or there is a fibre rupture under tension.

The most important property of FRC when considering a structural element is this post-cracking and the residual tensile or flexural strength. Fibres start to work as soon as the first micro-crack forms in the concrete. As the crack mouth opens the fibres begin to resist the tensile forces by bridging and transmitting the stresses across the crack. In doing so the fibres provide resistance to the crack widening and extending through the concrete. It means the concrete will not fail and there is some residual strength in the concrete after the first crack appears.

Most important in the design approach is the performance of the composite material, which is measured as the residual tensile strength. The parameters are determined from beam testing to find the residual flexural strength at defined beam deflections. These results are inserted into equations to determine the load bearing capacity of the element being considered.

6.2.1 STRAIN-SOFTENING AND STRAIN-HARDENING

When a material is reinforced it generally implies that there will be a strength improvement. As concrete is already strong in compression the implied improvement is in the weaker characteristics such as an increase in tensile strength, an increase in tensile strain, an increase of the elastic modulus or a combination of these influences. The design of structural fibres compared to traditional steel mesh/bar reinforcement is different and assumes that the fibre slips out of the concrete under sustained loading.

In standard concrete, fibre dosages of 4 - 8 kg/m^3 / 6.7 - 13.5 lb PP macro or 20 – 40 kg/m^3 / 33.6 - 67.2 lb steel, will not increase the tensile strength or bending strength of the concrete. Additionally, fibres at these dosages do not influence the peak load of the composite material but will effectively bridge cracks once they have occurred. This is described as the post crack concrete performance resulting in increased toughness and increased energy dissipation/ absorption properties.

Whilst FRC has the potential to produce a strain hardening effect with much higher dosages of high tensile steel fibres, in most cases performance of fibres leads to a strain-softening behaviour. This simply means a reduction in stress beyond the peak value with an increase in the deformation.

With a strain hardening behaviour, the tensile strength increase is due to the reinforcement. With increasing strain, a higher stress can be applied before the peak load is reached. When the peak load is reached, usually a distributed cracking will be observed again leading to crack localisation with a strain-softening behaviour.

An example of strain-hardening can be in ultra-high-performance concrete (UHPC or UHPFRC) using steel fibres or Engineered Cementitious Composite (ECC) using synthetic fibres.

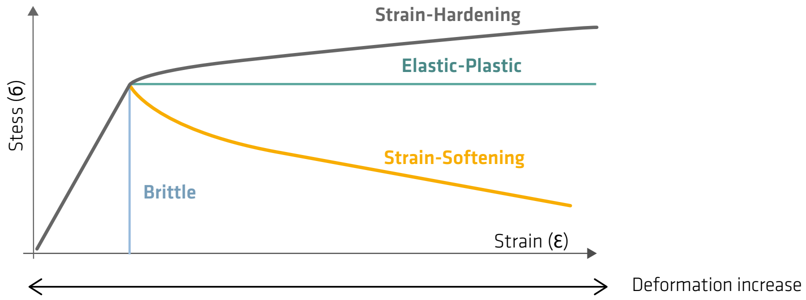


Figure 6.2.1.1: Illustration of strain-softening versus strain hardening

The mechanism of fibre behaviour can be illustrated on a three-point bending test (fig. 6.2.1.2). A load is applied on a concrete beam in the centre and the stress is increased (1) until it reaches a point at which the load-deflection curve departs from the initial linear response. This is known as the limit of proportionality (LOP). Up until this point the stress is acting on an un-cracked mid-span section. If the beam is un-reinforced and the applied load continues the beam will break (4).

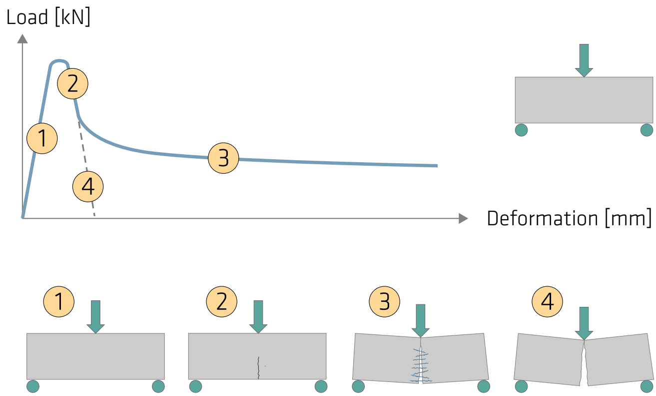


Figure 6.2.1.2: Performance of a fibre reinforced concrete beam in a 3-point bending test compared with unreinforced concrete

When the concrete is reinforced with macro-fibres, the fibres will bridge the crack and exhibit a strain-softening behaviour. The post cracking strength is lower than the strength after first crack (2) and as the fibres bridge the crack, they also are supporting the applied load (3). This is when the fibre material, geometry, shape, anchorage, dispersion, and matrix material now play a vital role.

6

A fibre with a too high tensile strength, too high elastic modulus or with poor anchorage will not transfer the force from the concrete to the fibre and ultimately will pull out. This will result in poor structural behaviour of the fibre reinforced concrete.

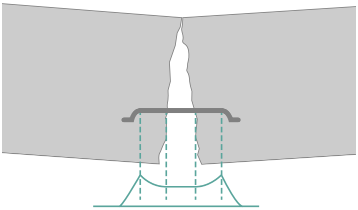


Figure 6.2.1.3: Stress distribution of a steel fibre bridging a crack in a cementitious matrix

To utilize the high strength and high elastic modulus, steel fibres are usually produced with hooked ends. The hooks prevent the fibres from slipping out too early and help to transfer as much of the forces as possible from the concrete to the fibre before the fibres slip out. It is desirable to have an anchorage failure before the tensile strength of the fibre is reached otherwise the result is a fibre rupture and a sudden failure of the concrete.

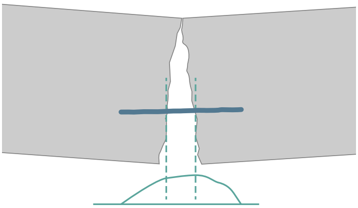


Figure 6.2.1.4: Stress distribution of a synthetic macro-fibre bridging a crack in a cementitious matrix

The anchorage of synthetic macro-fibres works differently. Macro-fibres are usually manufactured with an undulation or with an embossed surface which results in a constant resistance during the pull-out of the fibre from the concrete.
The different anchorage behaviour can be observed with single fibre pull-out test. This is a single fibre embedded into a cementitious matrix and then pulled-out in the direction of the fibre.

6.3 MECHANICAL PROPERTIES

6.3.1 STRUCTURAL AND NON-STRUCTURAL

Synthetic micro-fibres offer key benefits in the plastic state concrete and are used a relatively low dosage. As such, these fibres have little or no effect on the compressive, tensile, or flexural strength of hardened concrete and are generally described as non-structural fibres. Synthetic macro and steel fibres are designed to show best performance in the hardened concrete state. This means the performance of fibre reinforced concrete is usually tested after 28 days. EN 14889 describes structural fibres as those added to concrete to contribute to the load bearing capacity of a concrete element.

6.3.2 STRUCTURAL ACCORDING TO EUROPEAN STANDARDS

Fibres classified as structural according to EN 14889 must be proven to achieve certain performance criteria in beam tests. A three-point beam test is used to determine the residual flexural strength of the beam. The performance requirements are defined in clause 5.8 of EN 14889-1 and EN 14889-2.
The reference concrete is defined in another Standard EN 14845-1 and is broadly intended to compare fibre performances in a similar way. The reference concrete is usually different to the project concrete and in such cases the beam test can be repeated to reflect the project requirements, and to optimise the design.

CLAUSE 5.8 EFFECT ON STRENGTH OF CONCRETE

The effect on strength is determined in accordance with EN 14845-2 using a reference concrete conforming to EN 14845-1. The unit volume of fibres in kg/m^3 is declared by the manufacturer to achieve an average residual flexural strength of at least 1.5 MPa at 0.5 mm CMOD (equivalent to 0.47 mm central deflection) and an average residual flexural strength of at least 1 MPa at 3.5 mm CMOD (equivalent to 3.02 mm central deflection).

6.3.3 STRUCTURAL ACCORDING TO AMERICAN STANDARDS

ACI 360R recommends the minimum R_{e3} residual strength should be greater than 30% for designing a slab-on-grade using the yield line method. This is on the basis the analysis accounts for redistribution of moments and formations of plastic hinges in the slab.

6.4 DESIGN CONCEPTS

6.4.1 REINFORCED CONCRETE DESIGN

The design of reinforced concrete for flexure using stress block theory shows when the concrete cracks the compression force is carried by the concrete and the tensile force is carried by the reinforcing bar. The tensile capacity of plain concrete is not considered. The design moment capacity of the reinforced section shall be greater than the factored moment of the section.

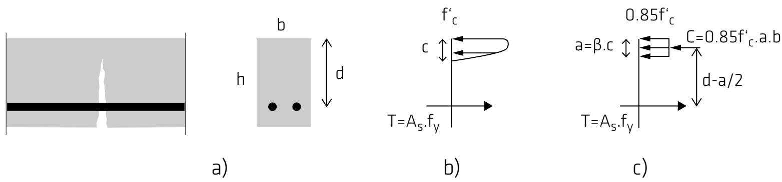


Figure 6.4.1.1: Schematics of stress block for a cracked reinforced concrete flexural member without fibres:
***a)** reinforced concrete beam section; **b)** actual distribution of normal stresses; **c)** simplified distribution of normal stresses.*

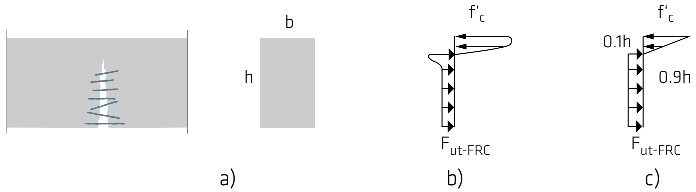


Figure 6.4.1.2: Schematics of stress block for a cracked FRC flexural member:
***a)** FRC beam section; **b)** actual distribution of normal stresses; **c)** simplified distribution of normal stresses.*

ASTM C1609/C1609M

The moment capacity of a FRC section is determined using the same stress block method determined by the RILEM TC 162-TDF (2003) and Vandewalle (2003). The bending moment for FRC section is determined from formulations contained in the ASTM C1609/C1609M. For ultimate limit state, the ultimate tensile strength of cracked concrete is taken as 0.37 multiplied by the residual strength $f_{\frac{150}{D}}$ or $f_{e,3}$. These parameters are determined from ASTM C1609/C1609M beam tests. $f_{\frac{150}{D}}$ or $f_{e,3}$, corresponds to the FRC flexural residual strength at a deflection of L/150. L being the span of the beam. Depending on design and serviceability requirements, the FRC can be designed using a smaller deflection in the beam test using $f_{\frac{600}{D}}$ for smaller crack widths and SLS.

The equivalent flexural strength $f_{e,3}$ is the total energy absorption, or flexural toughness, and is used instead of $f\frac{150}{D}$ for designing continuously supported sections.

To satisfy the design, the design moment capacity of the FRC shall be greater than the factored moment capacity of the section.

TUNNEL SEGMENTS

Precast segments can be designed using the finite element method from recommendations contained in fib Model Code 2010. Another design guidance available is the ITAtech Guideline for Precast Fibre Reinforced Concrete Segments – Volume 1: Design Aspects (ISBN: 978-2-9701013-2-1). The aim of the ITAtech document is to assist tunnel Engineers, contractors, and owners to understanding more the benefits and limitations of using FRC for precast concrete segments.

Tunnel segments are typically designed to support compression loads. This is because tunnel segments, in service, are essentially in compression unless ground conditions dictate there are tensile or bending moment forces. Where there is only compression, steel reinforced is generally included to control shrinkage cracking and to strengthen the segment demoulding, transportation, and placement.

Advantages for the precast manufacturer in the production of the tunnel segments without steel mesh reinforcement.

- No detailed drawings or bending schedules were required
- No fabrication of the steel reinforcement
- No need for bulky storage
- Less risk of handling injuries
- Time saving fixing reinforcement
- Faster production of segments
- Less vibration required
- A good surface finish with fibres

6

To use FRC for the purpose of structural bearing in tunnel segments the FRC must satisfy several criterial based on the limit of proportionality and residual strengths. These values are taken from the beam tests according to EN 14651.

$f_{R1k}/f_{Lk} > 0.4$ and $f_{R3k}/f_{R1k} > 0.5$

Although it is not possible to completely replace the steel reinforcement with just fibres, full scale 1:1 testing can be used to verify a structural design. Research tests show a reduced steel reinforcement in combination with fibres leads to an increase in ductility when compared to a reinforcement only option.

In addition, there are several advantages to use PP macro-fibres as partial replacement with a reduced amount of reinforcement.

- Increase of structural performance combining PP macro-fibres and traditional steel reinforcement
- Faster mould filling and easier compaction especially in the center of the segment
- Better protection of edges during transport of the segments
- No significant effect on surface treatment

SLABS ON GROUND

Traditionally ground-supported floor slabs have been designed by elastic methods, using equations developed by Westergaard in the 1920s and this is still widely adopted. These design methods tend to be conservative and produce slab designs that are relatively thick, meaning that assessment of deflections and other in-service requirements may not be considered necessary.

As plastic methods of analysis have developed, slabs have become thinner and other factors such as deflections, load transfer across joints and crack control must be considered as well as the load capacity of the slab.

Technical Report 34 and ACI360R give concise guidance relative to the design procedures of slabs on ground, however in general the design of such slabs primarily depends on the following.

- Ground conditions (k-value)
- Slab properties (geometry, joints, material properties)
- Loads (static, dynamic, uniformly distributed, point loads)

A concrete slab bearing on a stiff ground needs to transfer much fewer static moments than a slab based on a weak ground. A usual precondition for a slab is a well compacted ground resulting in an increased stiffness. This will result in fewer cracks caused by applied loads but does not take into consideration shrinkage, temperature, or joint positions.

6.5 SikaFiber® SOFTWARE

SLAB ON GROUND TOOL

Sika® provides a proprietary software tool for designing ground supported slabs reinforced with synthetic or steel fibres. The software has been developed in accordance with two publications.

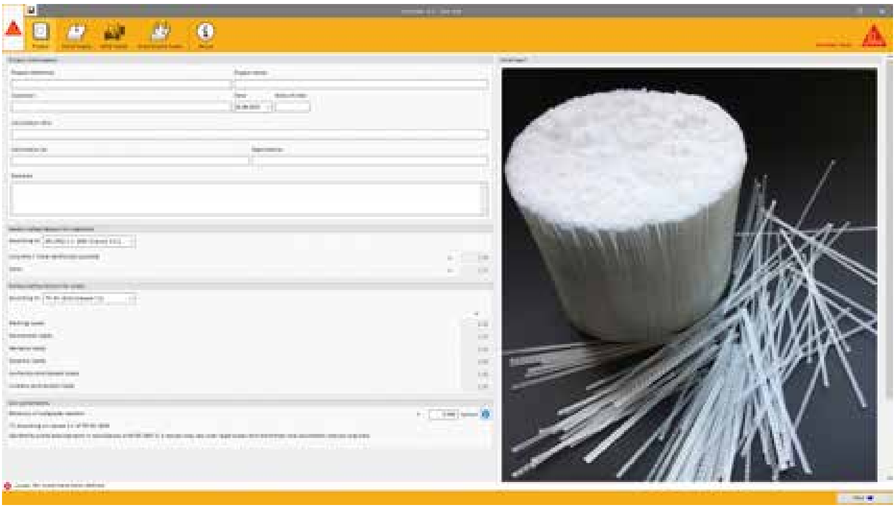
- ✓ The Concrete Society Technical Report 34 Concrete Industrial Ground Floors – A guide to design and construction
- ✓ The American Concrete Institute ACI 360R Guide to Design of Slabs-on-Ground

After adding the project information, ground conditions and loadings, the software tool will help the designer determine the optimum fibre dosage for the required slab thickness and concrete grade.

TOOL FEATURES

- Simple step by step procedure
- Global SikaFiber® selection
- Multiple languages
- Metric or imperial units (ACI 360R)
- Helpful graphics
- Useful information prompts
- Print-out in a short or detailed format

6



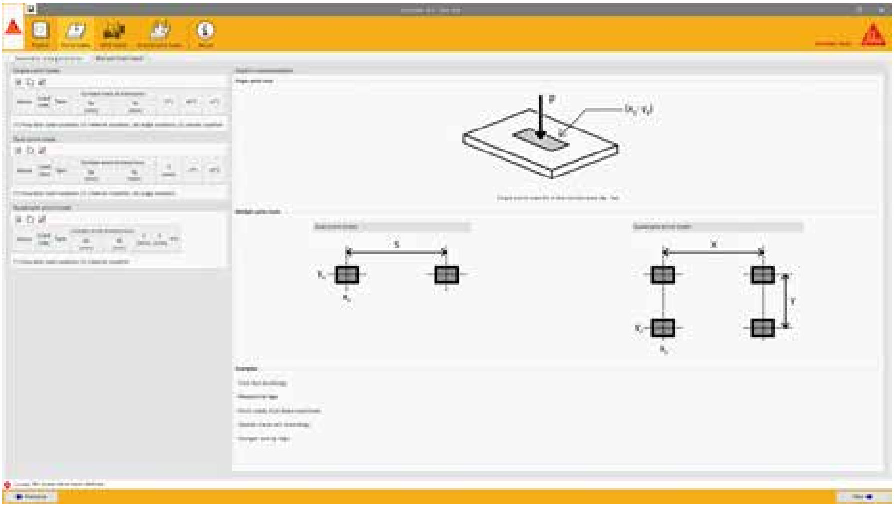
TOOL OPTIONS

There are several options to allow the user to tailor make specific designs.

- Standard or user defined partial safety factors
- Adjustable soil parameter (k-factor)
- Load check at proximity to a joint or free edge
- Changeable load transfer values at edge and corner joints
- Optional joint spacing check
- User defined concrete class
- Option to add light reinforcement
- Option to print a summary or long print-out

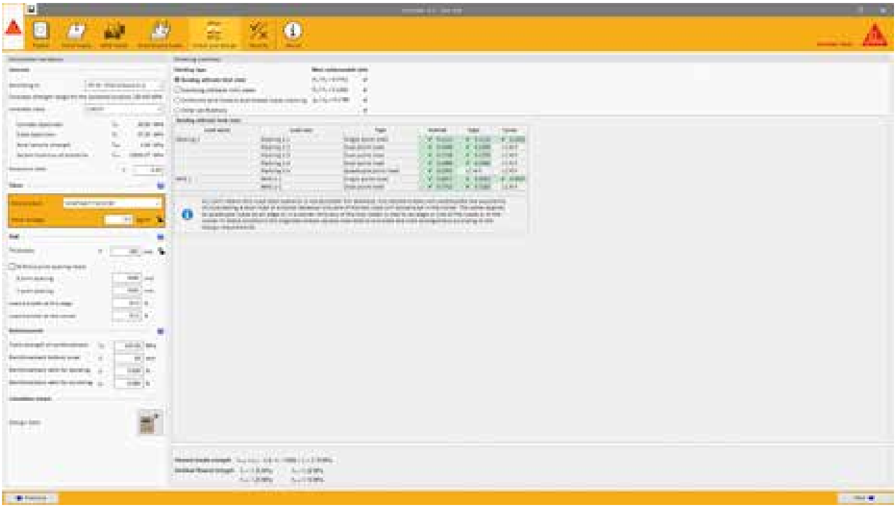
LOADINGS

Select options from multiple point loads, material handling equipment (MHE), uniformly distributed or line loads with the additional option to define a load in proximity to a joint.



CHECKING SUMMARY

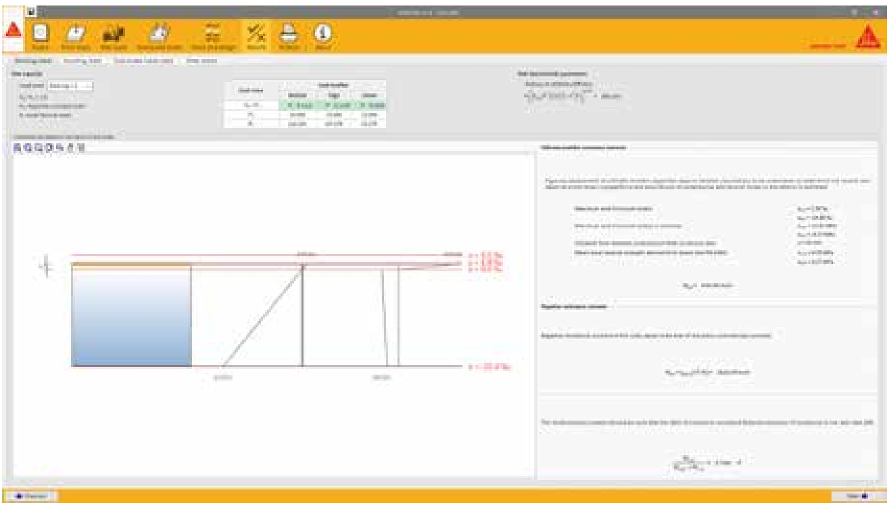
The check summary screen provides a quick and easy overview of the results, clearly indicating where the slab exceeds the design capacity (red) or where the design fulfils the design criteria (green).
The User can optimise the slab design by adjusting the design parameters such as slab thickness, concrete quality, load transfer or fibre type or dosage.



6

RESULTS

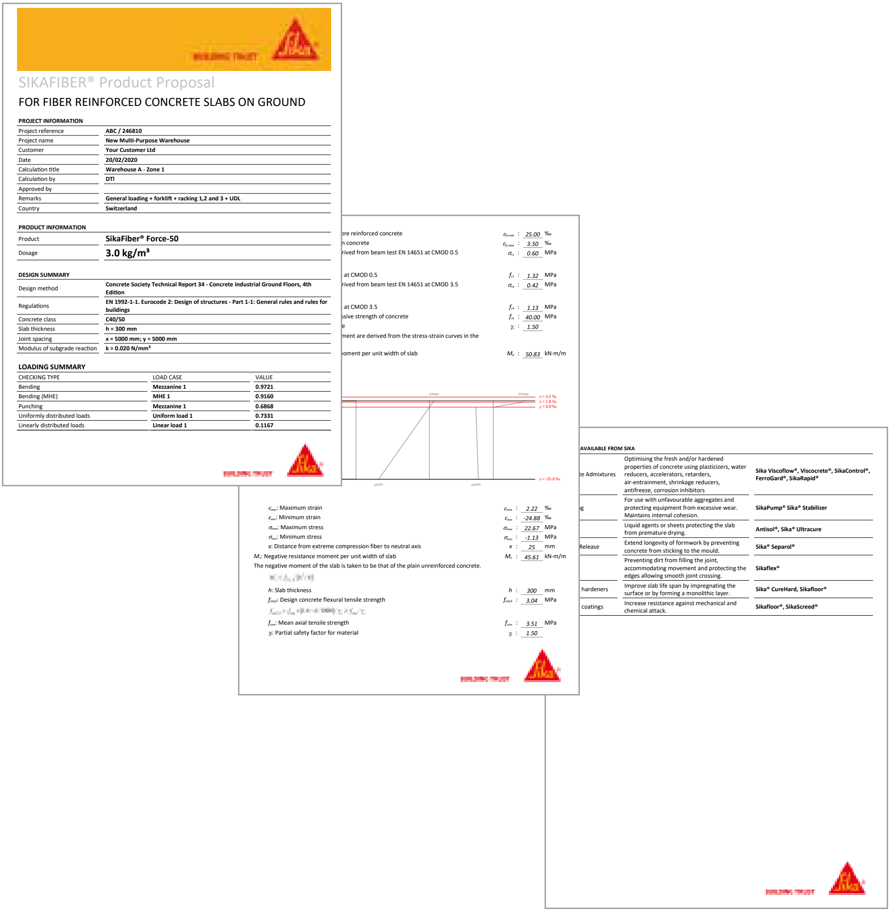
With a valid design, the results are available for viewing or printing and the figures for each load case can be viewed in more detail.



PRINT OUT

The software tool has the option to print a summarised or detailed version of the design. It will display the

- Project information
- Input loadings
- Calculations for the worst load case
- SikaFiber® type and dosage



7 CONCRETE APPLICATION

7.1 SLABS ON GROUND / GRADE

Slabs on ground, slabs on grade, ground bearing slabs and ground supported slabs all have one thing in common, and that is the ground directly under the slab is the foundation. It is a similar principle to a traditional wall foundation where the loads are transferred through the concrete into a suitably stable ground. Slabs on ground are not to be confused with suspended slabs, post-tensioned, floating or raft foundations where the design concepts are different. Whilst there may be ground under these types of slabs, the ground may be susceptible to settlement or movement or may not sufficiently strong enough to support the loadings. There are different understandings of floating slabs and screeds, so, ultimately the definition of a slab on ground depends on the structural design concept and how the loads are being transferred to a suitable bearing stratum.

USES

- Domestic, commercial, or Industrial floors
- Agricultural slabs
- Pavements and hard standings
- Roads
- Screeds and overlays

BENEFITS

Fibre reinforced concrete is an ideal alternative to traditional steel reinforcement in ground supported slabs where the purpose of the reinforcement is to control plastic shrinkage cracking. No matter where the first crack appears the fibres are always in the correct location. There are several key reasons why the use of fibre reinforced concrete has increased over the last decades.

- To simplify the construction process
- To shorten construction times
- To improve health and safety
- To make significant cost savings
- 3-Dimensional reinforcing

FIBRE SELECTION

The choice of fibres may also depend on availability of the product.

Fibre Type	Micro - monofilament	Micro – fibrillated	Macro PP	Macro steel
Slab Type	Non & structural	Non & structural	Non & structural	Structural
Considerations	Temperatures Humidity Wind	Temperatures Humidity Wind	Loadings Ambient conditions	Loadings Ambient conditions
Application Guide	Residential Light commercial	Residential Commercial	Commercial Industrial	Heavy Industrial
Product	SikaFiber®-618 PPM SikaFiber®-1218 PPM SikaFiber®-6 PPM SikaFiber®-12 PPM	SikaFiber®-6 PPF SikaFiber®-12 PPF	SikaFiber® Force-50	Refer to local Sika Organisation
Guidance Dosage [1]	0.6 – 1.0 kg/m^3 1.0 – 1.5 lb/yd^3	0.9 – 1.2 kg/m^3 1.5 – 2.0 lb/yd^3	3 – 6 kg/m^3 5 – 10 lb/yd^3	20 – 40 kg/m^3 34 – 67 lb/yd^3

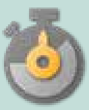
[1] refer to relevant Product Data Sheet for guidance

APPLICATION

The cost of a cubic of FRC concrete is going to be higher than a non-fibre concrete, so there is the additional cost of the concrete from producer to consider, which will depend on several factors.

- The fibre type and quantity
- Dosing method
- Mix design
- Handling charges

Main steps	Structural Design	Ordering	Transportation	Unloading
				
Steel Reinforcement	Calculations and concrete specification. Drawings and bending schedule	Order placed with steel manufacturer. Lead times.	Bulky heavy steel may require more than one truck delivery to job site.	Storage reinforcement on site. Lifting equipment required.
Fibre reinforced concrete	FRC calculation	Order concrete with batching plant		



50% TIME SAVING

20% COST SAVING

Typical savings on a project

- Design & detailing fees
- Transportation costs
- Labour costs
- Pumping equipment

It may be necessary for the concrete producer to adjust the sieve curve or add some additional plasticizer to compensate the workability. The concrete producer may also add a handling charge if the fibres are added in the plant, or if the fibres are added on site there may be a surplus if the trucks stay longer on site. The major savings changing from a traditional reinforcement design to FRC is mainly on job site, where the additional cost of concrete is offset by eliminating the need for handling, laying, and fixing the steel bars and mesh, as well as reducing the amount of labour. The main savings of using FRC will be on the construction site, where there is no heavy steel mats.

EXAMPLE

Replacing «light» mesh reinforcement weighing 3 kg/m^2 measuring 2.4 x 4.8 m.

- → Slab thickness is 150 mm
- → Slab size 1000 m^2
- → Weight per mat ~35 kg
- → 3.10 kg/m^2 reinforcement required allowing for lap lengths
- → 3,100 kg total bulky steel reinforcement required
- → 4 kg/m^3 PP fibre dosage
- → 600 kg total fibres required

Preparation	Placing	Concrete	Finishing
			
Skilled labour required to measure, cut, and bend steel reinforcement. Chairs and ancillary fixings.	Lift mesh into place. Ensure correct concrete cover. Lap and tie steel.	Concrete trucks cannot drive on prepared reinforcement and pumping equipment may be required. Working around placed steel.	Scrap excess material or return unused reinforcement to works.
		Manoeuvre concrete truck to the point of placement.	

Other advantages

- Fibres fill edges, corners, and difficult shapes
- Better concrete cohesion and less bleeding
- Better strain distribution in the slab
- Storage area for steel reinforcement not required on the construction site
- 3-Dimensional reinforcing

SLAB JOINTS

When it comes to the spacing of movement joints every country may have their own rules, guidance, requirements, and most importantly experience. In principle the aim of joints is to accommodate shrinkage, expansion movement and to minimise the risk of unwanted visual cracking. A joint must also be capable of transferring load from one slab to another. The type of joint and spacing depends on several factors, including but not restricted to.

- Concrete mix design
- Amount of drying shrinkage in the concrete/volume change
- Temperature changes/thermal movement
- The slab size and layout
- Planned loads/use & degree of trafficking
- Design method
- Slab thickness
- Slab restraints (e.g., slab thickenings, re-entrant corners, etc)
- Subgrade moisture
- Construction process
- Curing

The width of a joint is influenced by the concrete shrinkage, joint spacing and thermal movement. Extended joint spacing may result in higher movement at each joint, and therefore a risk of mid-panel cracking and wider joints. There are different types of joints which can be used to minimise the potential for cracking. The design, selection and positioning of joints are the responsibility of the Engineer or designer. They are not within the scope of this manual and various guidance documents exist where the reader can find more information.

- → Technical Report 34, Concrete Industrial Ground Floors, A Guide to Design and Construction - Chapter 11
- → American Concrete Institute ACI 360R Guide to design of slabs-on-Ground Chapter 6
- → American Concrete Institute ACI 223R Standard Practice for the Use of Shrinkage-Compensating Concrete

A high drying shrinkage is one of the main reasons for cracking. The use of Sika shrinkage reducing admixtures SikaControl® SRA, together with fibres are used to obtain a low-shrinkage concrete.

7.2 TUNNEL LININGS

Over last 30 years a series of severe tunnel fires have highlighted the weaknesses of high strength concrete when exposed to high temperatures. Subsequent investigations into such fires and research have revealed that during exposure to high temperatures, high strength concrete was extremely susceptible to explosive spalling damage caused by the build-up of internal vapour pressures.

Concrete spalling is generally described as pieces, fragments or layers breaking off concrete when exposed to the high and rapidly increasing temperatures, experienced during fires. Concrete spalling can be categorized into three main types.

1. SURFACE SPALLING

Surface spalling affects aggregates on the concrete's surface whereby small pieces of concrete up to 20 mm in size are gradually and non-violently dislodged from the surface during the early part of the fire. This is usually caused by the fracture of pieces of aggregate due to physical or chemical changes at high temperatures. In the case of surface spalling, the degradation of the concrete is relatively slow and involves the dehydration of the cement matrix followed by the loss of bond between aggregate and matrix.

2. CORNER BREAK-OFF

In the latter stages of heat exposure when concrete has cracked, the weakened corners and edges of concrete start to break off.

3. EXPLOSIVE SPALLING

This is unquestionably the most dangerous form of spalling and occurs during the first 20 – 30 minutes of a fire when the temperature in the concrete is in the range of 150 - 250°C. Theories as to how and why explosive spalling occurs are predominantly based upon moisture movement. As the temperature of the concrete increases, the moisture in the concrete changes to steam vapour. If it is unable to escape from the concrete mass, this vapour creates a dramatic increase in pressure within the concrete. As this process continues, the vapour pressure increases to the point where it exceeds the tensile capacity of the concrete, causing large pieces of concrete to be violently and explosively dislodged from the element. As the subsequent remaining concrete is presented to the fire, progressive explosive spalling deep into the concrete structure can occur.

FACTORS INFLUENCING SPALLING

Many factors influence the degree of explosive spalling in concrete. Today's construction often requires far higher concrete strengths to those used 40 years ago. Whilst, high-strength concrete provides a higher compressive strength, a higher modulus of elasticity, a higher tensile strength and greater durability, than normal-strength concrete, it also increases the density of the concrete. This increased density is one of the key reasons explosive spalling has become more prominent in the last 30 years. Where more permeable concrete is used, and a fire occurs, moisture can quickly escape from the heat source due to its higher porosity and the build-up of vapour pressures are minimised.

In high strength/dense concrete the escape of moisture is blocked due to the changes in pore structure, moisture is effectively trapped and begins to generate super-heated vapour and increased internal stresses that contribute to explosive spalling. This is the main reason why PP micro-fibres are specified for many high strength concrete applications and pre-cast structures today.

Other contributory factors to the spalling potential of concrete include:

- Rate of heating
- Presence of continuous reinforcement
- Loadings
- Expansion properties of the aggregates

All the above should be carefully considered when specifying a concrete mix design. In many major tunnelling projects, the choice of aggregate is often limited to readily available materials in a specific location meaning that it is not possible to specify an aggregate with low thermal expansion properties.

FIBRE SELECTION

The use of PP micro-fibres for passive fire protection is either specified based on experiences from similar projects, available Standards or 1:1 scale testing. The correct dosage of PP micro-fibres for passive fire protection must take into consideration the concrete specification and a fire risk assessment.

Large scale fire tests are often considered the only way to determine the correct fibre dosage for a specific concrete mix design. European Standard EN 1992 Eurocode 2 Section 6.1 refers to the use of 2 kg/m^3 of monofilament polypropylene PP micro-fibres to control explosive spalling in high strength concrete. Many Engineers may follow this recommendation to negate the need for expensive fire testing in the knowledge this has proven performance in many completed projects.

This does not stop the use of specifying lower dosages, but careful consideration of the requirements and full-scale testing are required. Where such testing has been carried out dosage rates of between 1.0 and 1.5 kg/m^3 have proved satisfactory for some specific tunnel projects.

Initial small scale fire testing will provide some indicative performance data, useful in making the initial selection of materials. It must be decided if such a scenario will fully replicate the situation in a real fire and provide the quality or range of data that will be provided by the full-scale test.

All components of the concrete mix design need to be carefully selected. The overall effect of fibre type and dosage on concrete workability, air-content and strength should also be carefully evaluated prior to carrying out the fire testing.

Concrete testing should be caried out a minimum 90 days after preparing the specimens, so that most of the water has been used in the hydration process.

Table 7.2.1: Example concrete mix design with passive fire resistance

	Reference Concrete	Concrete for passive fire protection
Cement	320 kg/m^3	320 kg/m^3
w/c-ratio	0.5	0.5
Aggregates	0-32 mm	0-32 mm (limestone, no quartz)
Sika® ViscoCrete®	0.8 %	1.1 %
SikaControl® AER (optional)		0.2 %
SikaFiber®-12 PPM		2.0 kg/m^3

APPLICATION

Full scale fire tests are used to verify the structural performance of concrete elements under fire and load conditions. In addition to heat, the concrete is structurally loaded to replicate in-place service conditions.

For major projects full-scale fire tests are typically required in a project specification.

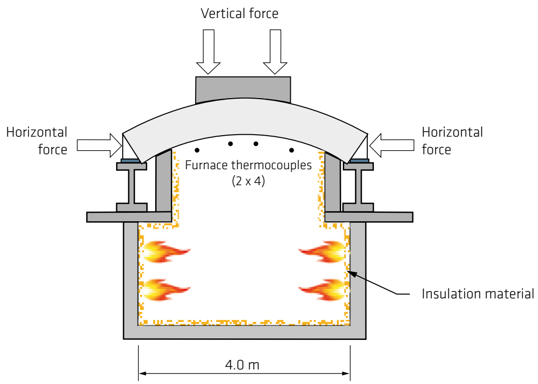


Figure 7.2.3: Typical test setup for testing tunnel segment in fire loaded conditions

The results of a fire test are interpreted on,

- An optical check if there is explosive spalling on the concrete surface
- Measurement of the depth of the surface spalling
- Time until first spalling occurs
- Temperature development at different levels inside the specimen (including temperature at embedded steel rebar)

Table 7.2.2: Summary of the fire test results on a tunnel segment using SikaFiber®-12 PPM

Specimen	Maximum spalling in 20 x 20 cm grid	Average spalling depth in 20 x 20 cm grid	Average spalling depth over all specimen
Reference without fibres	20 mm	15 mm	18 mm
Reference concrete with 2.0 kg/m³ SikaFiber®-12 PPM	0 mm	0 mm	0 mm

In tests, plain concrete exhibited significant loss in section due to explosive spalling due to rapid heat penetration through the concrete. The use of 1.5 kg/m³ dosage of PP micro-fibres reduced the spalling depth and heat penetration. Whereas with 2 kg/m³ of SikaFiber®-12 PPM there was no spalling of the concrete and the maximum temperature recorded at 50 mm depth from the surface was 170°C after 60 minutes.

Temperature in Concrete at 50 mm from surface

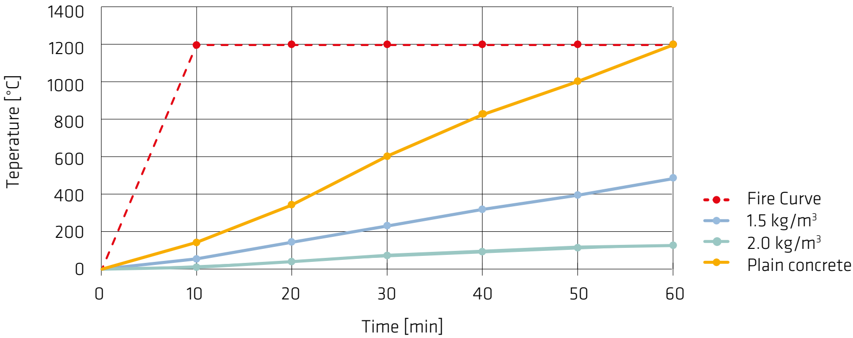
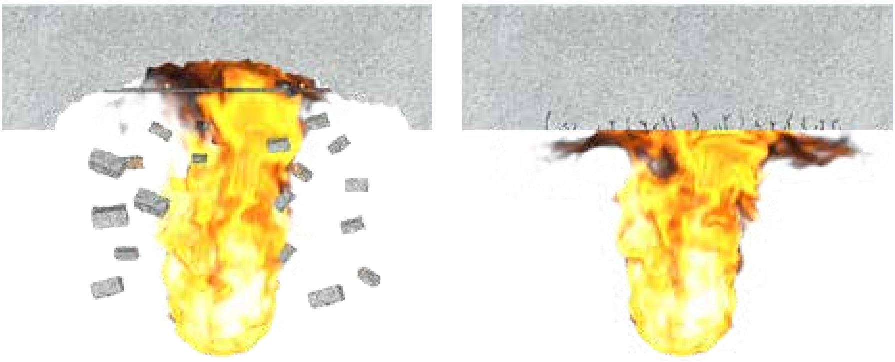


Figure 7.2.4 Temperature measurements from the same concrete at 50 mm depth when exposed to a RABT-ZV (Train) fire curve

Results of spalling depths and heat penetration can vary dramatically depending on concrete quality and fire load curve. Therefore, it is essential that all major projects clearly specify a suitable fire curve according to risk assessments and clear performance parameters such as permissible maximum spalling depths and temperature development.

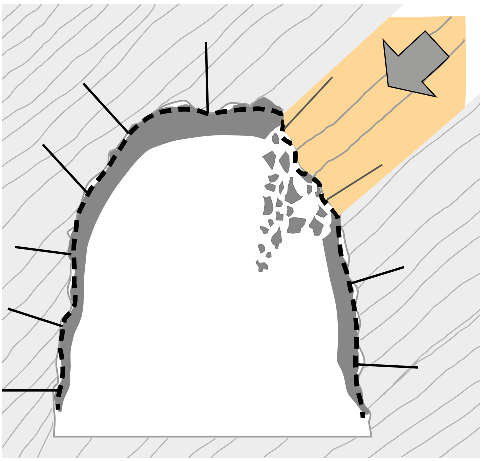


7.3 ROCK SUPPORT

Sprayed concrete, or shotcrete, refers to a method of projecting concrete onto a surface at high velocity. Sprayed concrete can be used in a wide variety of applications including swimming pools, slope stabilisation, silos and irrigation channels.

In tunnelling and mining it is mainly used as rock and slope stabilisation. The key advantages of sprayed concrete are the concrete hardens in a short time, and no need for formwork.

Traditional steel wire fabric (SWF) is typically used for reinforcing rock or slopes, but this needs to be painstakingly cut and fixed into position before the concrete can be sprayed. Additional attention is required by the nozzleman to ensure the SWF is completely encased by the sprayed concrete. If this is not achieved the shotcrete will not perform as required and the long-term durability may be reduced.



It is well known from simple structural mechanics concrete is weakest in tension and needs reinforcement to support any increase in tensile load capacity. A ground slope or excavated surface is not perfectly smooth or contoured. SWF is fixed to a substrate as best as possible, sometimes fixed directly on or away from the surface. This means if tensile forces from ground movement in the concrete is in the front face of the concrete, and mesh is located at the back, then the concrete and SWF are not going to perform compositely. The sprayed concrete is going to crack and break away, sometimes causing a dangerous hazard for overhead applications.

7

Fibre reinforcement has been used in sprayed concrete for more than fifty years and since that time technology and performance has improved hugely, especially in the field of PP macro-fibres, which are now considered a practical, safe, and economic alternative to SWF. Fibre reinforced sprayed concrete provides good performance benefits and allows construction operations to advance far more quickly than installing traditional SWF. Fibres have the benefit of being evenly distributed throughout the entire concrete cross-section, meaning when uneven stresses are applied to the concrete, there will always be fibres in the zone of weakness.

BENEFITS

The use of fibres in shotcrete is widely accepted as Engineers, Contractors and Owners recognise the advantages of fibres to replace or partly replace the SWF. There are numerous benefits of using fibres instead of SWF for ground support, tunnelling and mining applications.
The benefits of using fibres

- Safer working conditions
- Faster application process
- Fibres are distributed homogenously in the concrete
- Fibres are added into the concrete in the batching plant
- Reduction in rebound
- Reduction in waste
- Reduction of voids

The cost savings associated with changing from SWF to fibres.

- ***Transportation*** – No need to order and transport SWF to the job site
- ***Storage*** – No need for areas around the job site to be reserved for storing the SWF
- ***Labour*** – Depending on local factors such as project location, steel, and labour costs etc. approximately 25% labour savings from not having the challenges of fixing SWF to a substrate.
- ***Time*** – Not having to fix sheets of SWF to the substrate
- ***Rebound*** - The amount of rebound caused by sprayed concrete vibrating the SWF is approximately 20% higher than applying FRC. This means typically 20% more concrete is required for SWF and the other 20% needs to be removed as waste.
- ***Materials*** – The sprayed FRC concrete requires no minimum SWF cover thus allowing the sprayed concrete to follow the contours of the substrate.

FIBRE SELECTION

Steel fibres have been used in tunnelling and mining for many years and efficiency has been improved with the use of fibre dosing systems. However, there are disadvantages for using steel fibres.

- Abrasion –steel fibres increase wear costs on mixing and spraying machinery
- Sharp edges – protruding steel fibres can damage waterproofing layers
- Sharp edges – manual handling steel fibres cause skin injuries
- Corrosive – exposed steel corrodes in presence of air and water
- Performance - magnetic fibres can lead to problems in mining

PP macro-fibres are an ideal alternative because they are lighter, dosed in lower quantities and can achieve similar performance criteria to steel fibres. In normal dosages, PP macro-fibres can sustain loads at greater deformations. This provides an important safety factor in tunnelling and mining when cracks start to open in the concrete. There are some good reasons to consider PP macro-fibres, as an alternative.

- Handling – less weight to transport to mixing plant
- Handling – easy to handle, light pucks wrapped in a soluble film
- Handling – pucks work on dosing equipment
- Abrasion – less wear on machinery
- Non-corrosive – will not corrode
- Performance - protruding fibres are not a hazard to waterproofing layers
- Performance – higher sustained loadings at wider deformations

The quantity of fibres is based on a test which determines the amount of energy absorbed by a concrete plate and is measured in Joules. The number of joules required by a test must first be determined from geotechnical calculations.

There are two main test methods for determining the energy absorption.

- EN 14488-5 Testing sprayed concrete. Determination of energy absorption capacity of fibre reinforced slab specimens
- ASTM C1550 Flexural Toughness of Fibre-Reinforced Concrete

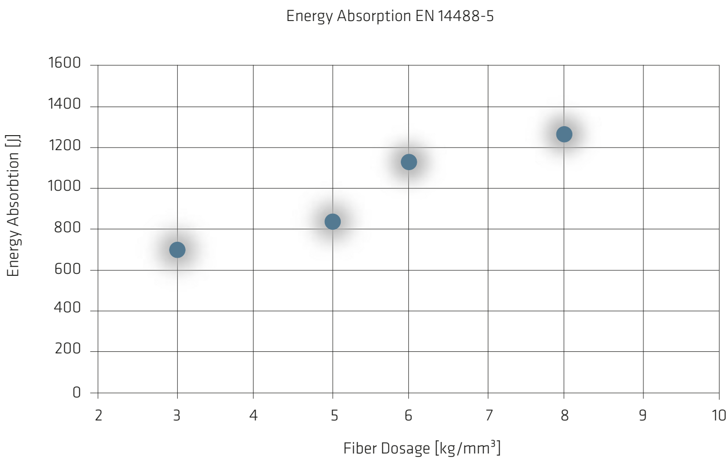


Figure 7.3.1: Example dosages of SikaFiber® Force-60 with a sprayed concrete mix design to achieve classes of energy absorption according to EN 14488-5T-ZV (Train) fire curve

Table 7.3.1: Indicative fibre dosage of synthetic and steel fibres to achieve EFNARC energy absorption classes

Energy Absorption Class	Joules (25 mm Deflection)	Fibre Dosage (kg/m^3)	
		PP Macro-fibres	Steel fibres
E 500	500	3 to 4	20 to 25
E 700	700	5 to 6	25 to 35
E 1000	1000	> 7	> 35

When specifying energy absorption, it is important to understand the degree of crack opening required for the application and relate this to the results. For example, if there is a final lining it may be important to minimize the crack opening width. Therefore, the type and dosage of fibres needs to carry higher loads at small deformations. In mining or tunnelling, or for rock support, it may be more important to have an improved ductile behaviour of the sprayed concrete, therefore the type and dosage of fibres needs to carry higher loads at wider crack openings. Due to the different anchorage characteristics, numbers of fibres and higher elastic modulus, steel fibres show higher performance at small crack openings and PP macro-fibres show much better load capacity at larger crack openings.

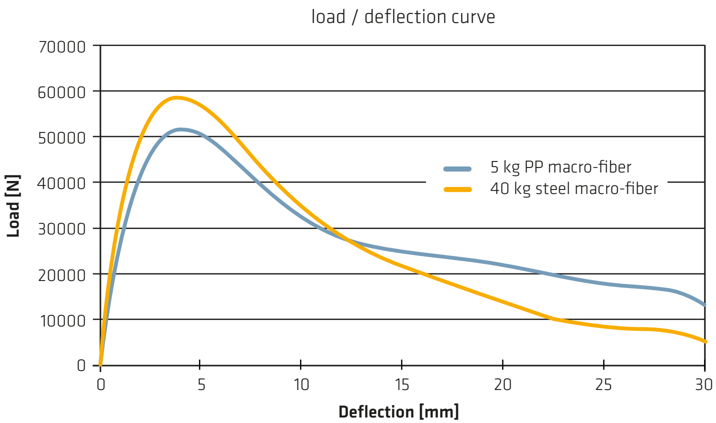


Figure 7.3.2: Typical load deflection behaviour of PP and steel macro-fibres in a EN14487-5 energy absorption test

Table 7.3.2: Examples mix design for sprayed concrete.

	Reference concrete	Concrete for sprayed concrete
Cement	400 - 500 kg/m^3	400 - 500 kg/m^3
w/c-ratio	0.45 - 0.5	0.45 - 0.5
Aggregates	0 - 8 mm	0 - 8 mm
Sika® ViscoCrete®	0.8 - 1.2 %	1.0 - 1.5%
Sika® Sigunit®	5 - 8% (Alkali free)	5 - 8% (Alkali free)
SikaFiber® Force-60		4 - 8 kg/m^3

For more information consult the
Sika Sprayed Concrete Handbook

7.4 PRECAST CONCRETE MANUFACTURING

Precast concrete is an efficient way of building structures because the elements can be prefabricated in a quality process and delivered to the construction site in time to be installed. Fibres are ideal for improving the manufacturing process because they provide resistance to cracking, replace or partially replace steel reinforcement and increase durability. This can lead to significant cost savings from steel fixing and help reduce the number of rejected elements, damaged during formwork removal and transportation.

USES

- Wall Panels
- Paving slabs
- External Cladding
- Walls
- Railway sleepers
- Jersey blocks
- Concrete Pipes and ancillary products
- Box Culverts
- Septic Tanks
- Piles
- Tunnel Segments

BENEFITS

There are multiple benefits of using FRC in precast concrete industry

FABRICATION

- Increase early green strengths allowing early removal of formwork
- Reduce vibrating and application times
- Reduction of shrinkage cracks
- Replacing steel reinforcement in light precast elements
- Partially replacing steel reinforcement for structural elements
- Streamline productivity

SERVICE LIFE

- Increasing abrasion and impact resistance
- Reducing permeability
- Increasing durability

TRANSPORTATION

- Protecting edges and corners during transport, handling, and storage

FIBRE SELECTION

Replacing secondary or light mesh with FRC has many advantages. From a cost saving perspective fibre reinforced concrete removes the need for cutting, bending, placing, and fixing steel reinforcement. This has the overall advantage of increasing productivity.

PP micro-fibres are an easy and economic option for adding value for the precast manufacturer.

Steel fibres can be used to increase mechanical strength and ductility. However, exposed fibres on the surface open to air and water will start to corrode. This can lead to unsightly staining on the surface.

PP macro-fibres can be used to increase mechanical strength and ductility and have the additional benefit of not corroding.

APPLICATION

Replacing traditional steel reinforcement very much depends on purpose that the reinforcement was originally specified. Whilst fibre reinforcement can influence the moment capacity of concrete it does not have the same effect as structural steel reinforcement. For this reason, where precast elements are subject to high bending moments it is unlikely that steel reinforcement can be totally replaced with FRC. Although, there is potential to use the moment capacity achieved with FRC to reduce the cross-sectional area of steel, by using fibres the concrete will benefit from several FRC advantages, such as impact resistance and extended durability.

7

Secondary reinforcement, such as steel welded wire fabric (SWF), is used to minimise crack widths due to thermal expansion, contraction, and shrinkage. Secondary reinforcement is essentially used to hold the concrete together once cracks have occurred and is not considered to contribute to the structural performance of the concrete element. In such cases, it is entirely feasible to replace this reinforcement with a fibre only solution. Care must still be taken where precast elements have re-entrant corners, openings or lifting sockets as these are locations where cracks are more likely to occur and may still need a steel reinforcement solution.

The preparation of steel reinforcement in precast elements can very time consuming and often causes significant costs as the geometry of many units can be quite complex. Additionally, steel reinforcement can cause problems with placement and compaction of concrete into the moulds. These complications can lead to poor quality concrete including unwanted surface defects and corrosion where there is insufficient cover to the steel.

7.5 PUMPED CONCRETE

Pumped concrete is generally used where it is not possible for truck mixers to discharge concrete to a point of application, or where large pours of concrete are required in a restricted time frame. Fibre-reinforced concrete can generally be pumped but requires a suitable FRC mix to prevent segregation or clogging in the equipment or pipes. The type of equipment may limit the number of fibres which can be dosed.

USES

- Sprayed concrete tunnels and mining
- Sprayed concrete soil stabilisation
- Pumping concrete to a point of application

BENEFITS

- Faster application process
- Improve efficiency

FIBRE SELECTION

The passing of the fibre concrete through the grill above the pump's hopper, together with the pipe diameter, limits the maximum length of the fibres and maximum dosage. As a rule of thumb, the length of the fibres should be more than half the hose diameter, since longer fibres will orientate along the course of the hose, whereas smaller ones are able to rotate which can result in balling of the fibres and pipe blockages. It is possible to dose high amounts of PP macro-fibres with a suitable mix design.

MIX DESIGN

Refer to chapter 6.2 of the Sika® Concrete Handbook

7.6 ULTRA HIGH PERFORMANCE FRC

Ultra-High Performance Fibre Reinforced Concrete (UHPFRC) is produced from cement, additions (powders), hard fine particles, water, admixtures, and high amount of relatively short steel fibres. The densely packed structure of UHPFRC results in a waterproof concrete with extremely high compressive strengths, typically over 150 MPa. In tension, UHPFRC shows significant hardening and softening behaviour, and the tensile strength is about 7 to 15 MPa.

Fibre selection is a key factor for the optimum design of UHPC, and it has a strong influence on the strength, ductility, and costs. Ductility is particularly important because a minimum amount of ductility is usually required.

BENEFITS

- Increase ductility
- Control cracking
- Increase durability

FIBRE SELCTION

There are different types of materials, although high tensile stainless steel is the most common.

The minimum fibre length is usually 3-times the maximum grain size, although kept as short as possible bearing in mind the required performance requirements in the concrete. A suitable aspect ratio shall be specified to avoid balling during mixing. Fibres may be easy to bend during mixing with a high aspect ratio and low yield stress. This may be a reason why fibres with a high yield strength are required, typically >2 GPa.

Table 7.6.1: Typical mix design for UHPFRC in comparison with normal fibre reinforced concrete

	UHPFRC	Normal FRC
Cement content	1000 kg/m^3	350 kg/m^3
Max aggregate size	< 1 mm	32 mm
Water/cement ratio	< 0.2	< 0.5
SikaFiber®	>100 kg/m^3 (l=12 mm steel fibres)	5 kg/m^3 PP macro-fibres or 25 kg/m^3 steel fibres (l= 50 mm)

8 TESTING

8.1 BEAM TESTING

There are different types of beam tests and the choice of which beam test will depend on the application, the specification requirements, or the design method. Beam tests are not always the same and vary for different reasons.

- 3-point or 4-point bending
- Beam size
- With/without a notch
- Equipment specification/settings
- Method of measurement
- Reference concrete

8.1.1 EUROPEAN BEAM TESTING

The relevant European Standards for beam testing FRC

Reference	TITLE	RELEVANCE
EN 14889-1	Fibres for concrete – Part 1- Steel Fibres	Performance requirements
EN 14889-2	Fibres for concrete – Part 2- Polymer Fibres	Performance requirements
EN 14845-1	Test methods for fibres in concrete – Part 1: Reference concretes [1]	Composition and characteristics of reference concrete
EN 14845-2	Test methods for fibres in concrete - Part 2: Effect on concrete	Method for determining residual flexural strength
EN 14651	Test method for metallic fibred concrete – Measuring the flexural tensile strength (limit of proportionality) LOP, residual	Test preparation and procedure
EN 14488-3	Testing sprayed concrete – Part 3: Flexural strengths (first peak, ultimate and residual) of fibre reinforced beam specimens	Method for determining flexural strength

EN 14845-1

Test methods for fibres in concrete – Part 1: Reference Concretes

Content

This Standard defines the composition and characteristics of four reproducible reference concretes which can be used to evaluate the fibre performance in concrete. One of the reference concretes is mandatory to test, while the remaining three reference concretes are optional. The reference concrete(s) are selected according to the type of product or system and their characteristics are defined by a minimum flexural tensile strength value, maximum grain size and maximum cement content.

Aggregates

Natural, uncrushed, silica based with <2% by mass water absorption. The aggregate grading shall conform to EN 1766: Annex A with the exception for 16 mm and 20 mm aggregates >0.25 mm shall be 5 % to 10 % (not 3 % to 8 % as indicated in EN 1766).

Mixing water

According to EN 1008 classifies different types of water coming from different sources. Generally, the water used for testing is potable drinking water which does not need further testing. Other types of water may be used but must be checked.

Cement

Portland type CEM I class 42.5 R according to EN 197-1

Admixtures

A plasticizer or superplasticizer, in accordance with EN 934-2, can be used to control workability. The standard describes two options for determining the concrete consistence.

- Vebe class V3 EN 12350-3
- Compaction class C2 EN 12350-4

Fibres

The manufacturer shall use fibres in accordance with EN 14889 part 1 or part 2 and can define the mixing sequence to ensure even distribution in the concrete.

Preparation

Specimen preparation is described in the standard with also reference to EN 14845. Concrete sampling shall be according to EN 12350-1.

Requirements

Table 1 from EN 14845-1 Four reference concrete mix requirements

Flexural tensile strength (MPa)	Water/cement ratio		Maximum cement content (kg/m³)
	Maximum aggregate size		
	8 mm or 10 mm	16 mm or 20 mm	
4.3 ± 0.3 (25/30)[c]	0.55[b]	0.55[a]	350
5.8 ± 0.4 (40/50) [c]	0.45[b]	0.45[b]	400

a Mandatory mix
b Optional mixes
c Equivalent compressive class according to EN 1992-1

Table 1 from EN 14845-1 describes the four mandatory mixes to determine the effect on consistence of a concrete. One mix is mandatory although the fibre manufacturer has the option to make further tests using one of the other three reference concretes.

Report

A record of the reference concrete(s) information should contain.

- Mix composition
- Mixing procedure
- Fibre type according EN 14889 and dosage
- Date and time of production
- Consistence: Vebe time or degree of compactability
- Curing and storage
- Results -limit of proportionality strength (average and individual values)
- Reference to the Standard
- Any deviation to the Standard

BEAM TESTS

EN 14845-2

Test methods for fibres in concrete – Part 2: Effect on concrete

Content

This Standard gives a method for determining the effect of steel or polymer fibres on one or more reference concretes with the objective to achieve a minimum specified value of residual flexural strengths, which are related to a defined amount of deformation.

Description

Twelve notched beams measuring 550 x 150 x 150 mm cast from the mandatory reference concrete with fibres, and any additional optional reference concrete, are tested at 28 days on a three-point beam test spanning 500 mm according to EN 14651.

Results
The name and dosage of fibres shall be declared by the manufacturer that achieves a residual strength of ≥1.5 MPa at 0.5 mm CMOD and ≥1.0 MPa at 3.5 mm CMOD.

Report
A record of the reference concrete(s) specimens should contain.
- Fibre type according EN 14889 and dosage
- Mix composition according to EN 14845-1
- Details of test specimens
- Preparation procedure, date and time of production
- Curing history and moisture conditions at test
- Testing procedure, date of testing
- Results, limit of proportionality and residual flexural strengths (average and individual values)
- Reference to the Standard
- Any deviation to the Standard

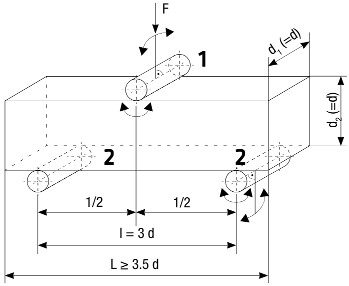
EN 14651
Test method for metallic fibre concrete – Measuring the flexural tensile strength (limit of proportionality (LOP), residual)

Content
The Standard details the test method for measuring the flexural tensile strength of the FRC on a defined test specimen, to determine the limit of proportionality (LOP) and set of residual flexural tensile strength values. Originally intended for metallic fibres ≤60 mm, the method can be used for a combination of metallics and other fibres, as well as being referred to in EN 14889-2 for polymer fibres.

Description
The tensile behaviour of the FRC is evaluated by a three-point loading test on a beam from EN 14845-2, which is notched on the underside by means of wet saw cutting. The load is applied in the centre of the beam and the residual flexural tensile strength values measured from one of two methods. Tests are rejected if a crack propagates outside of the notch.

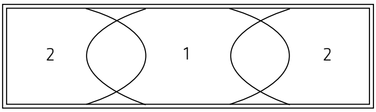
i) A displacement curve determined from measurements recorded in the notch when the crack mouth opening displacement are equal to 0.5 mm, 1.5 mm, 2.5 mm and 3.5 mm
ii) The load-deflection curve is determined from deflection measurements taken at the mid-span equivalent to the CMOD (Crack Mouth Opening Distance); 0.08 mm (0.5 mm CMOD), 1.32 mm (1.5 mm CMOD), 2.17 mm (2.5 mm CMOD), 3.02 mm (3.5 mm CMOD) and 3.44 mm (4 mm CMOD)

For reproducibility, the Standard describes the method for preparing, filling, and curing the specimens in compliance with EN 12350-1 and EN 12350-2.



Arrangement of the loading test specimen

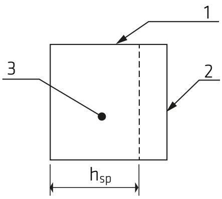
1 Supporting roller
2 Loading roller



1 and 2 order of filling

Filling must be consistent since it will influence the fibre orientation and therefore the results.

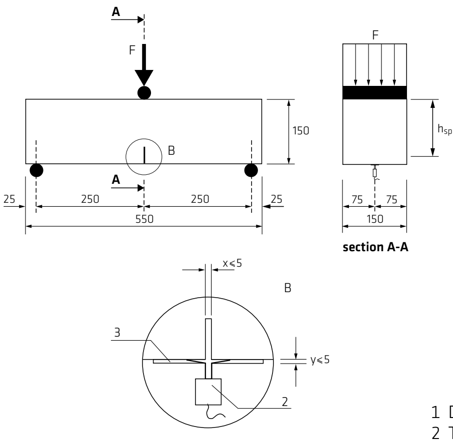
The Standard describes how the mould should be filled and FRC compacted.



1 Top surface during casting
2 Notch
3 Cross-section of test specimen

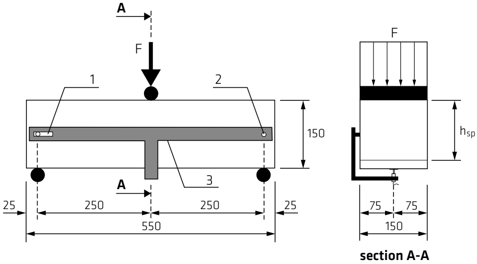
After preparation the beams are rotated 90° and a saw cut is made through the width of the specimen.

The Standard gives specific instructions when the beam is to be sawn and curing conditions in compliance with EN 12390-2.



Measuring the CMOD is made by mounting a displacement transducer at mid-span of the beam. The machine starts at a constant rate so that the CMOD increases at 0.05 mm/min until the CMOD reaches 0.1 mm when the CMOD increases to a constant rate of 0.2 mm/min. For the first 2 minutes the values of load and corresponding CMOD are recorded at a rate ≥5 Hz which may be reduced to a rate ≥ 1 Hz. The test is stopped when the CMOD ≥ 4 mm.

1 Detail (notch)
2 Transducer (clip gauge)
3 Knife edge



1 Sliding fixture
2 Rotating fixture
3 Rigid frame

Deflection is measured by mounting a displacement transducer on a rigid frame at mid-height over the supports. One end of the frame is mounted to the beam with a sliding fixture and the other end with a rotating fixture. The deflection method is like the CMOD except the CMOD parameters are transformed into deflection.

Results
The results are expressed as load-deflection diagrams and the Standard gives formulations to determine the equivalent deflection from the CMOD measurement, which are summarised in table 1 in EN 14651.

CMOD (mm)	**δ** (mm)
0.05	0.08
0,1	0,13
0,2	0,21
0,5	0,47
1,5	1,32
2,5	2,17
3,5	3,02
4,0	3,44

The limit of proportionality and residual flexural tensile strengths are derived from expressions in Annex A of the Standard, and can be summarised.

Limit of Proportionality (LOP)

$$f_{ct,L}^{f} = \frac{4 F_L l}{2bh^2_{sp}}$$

where

$f_{ct,L}^{f}$ is the LOP, in Newton per square millimetre;
F_L is the load corresponding to the LOP, in Newton;
l is the span length, in millimetres;
b is the width of the specimen, in millimetres;
h_{sp} is the distance between the tip of the notch and the top of the specimen, in millimetres

8

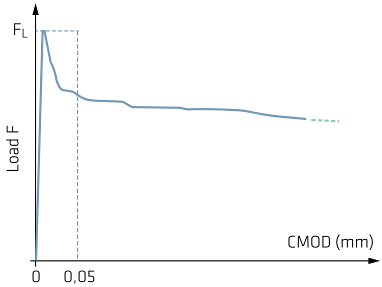
Residual flexural tensile strength ($f_{R,j}$)

$$f_{Rj} = \frac{3 F_j l}{2bh^2_{sp}}$$

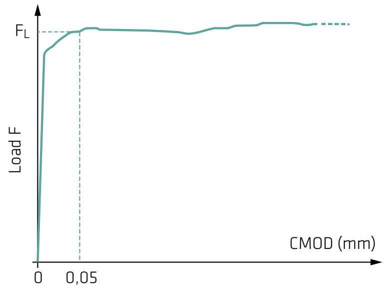
where f_{Rj} is the residual flexural tensile strength corresponding with $CMOD = CMOD_j$ or $\delta = \delta j$ (j = 1,2,3,4), in Newton per square millimetre
F_j is the load corresponding with CMOD = $CMOD_j$ or $\delta = \delta j$ (j = 1,2,3,4), in Newton (see Figure 7)
l is the span length, in millimetres;
b is the width of the specimen, in millimetres;
h_{sp} is the distance between the tip of the notch and the top of the specimen, in millimetres

The load value F_L is determined by the load value at 0.05 mm CMOD.

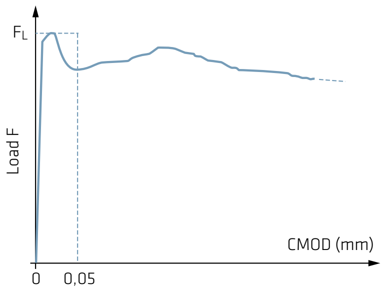
Strain softening

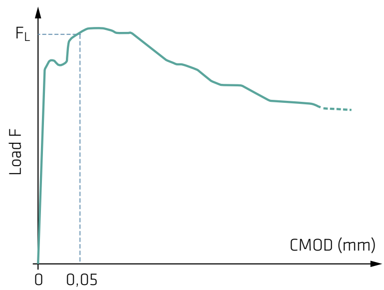


Strain hardening

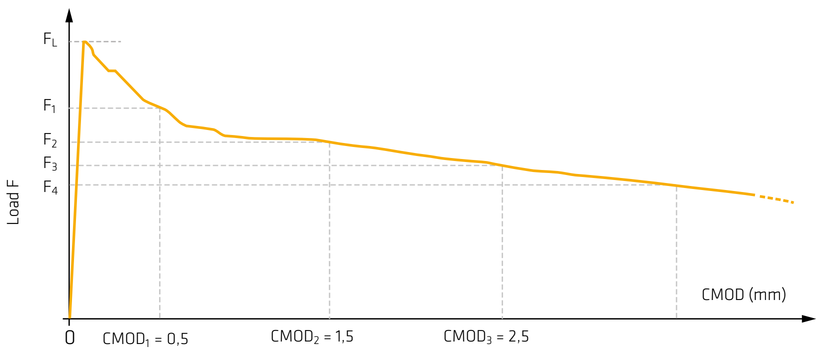


Typical of a normal steel fibre concrete





Typical of a PP macro-fibre concrete

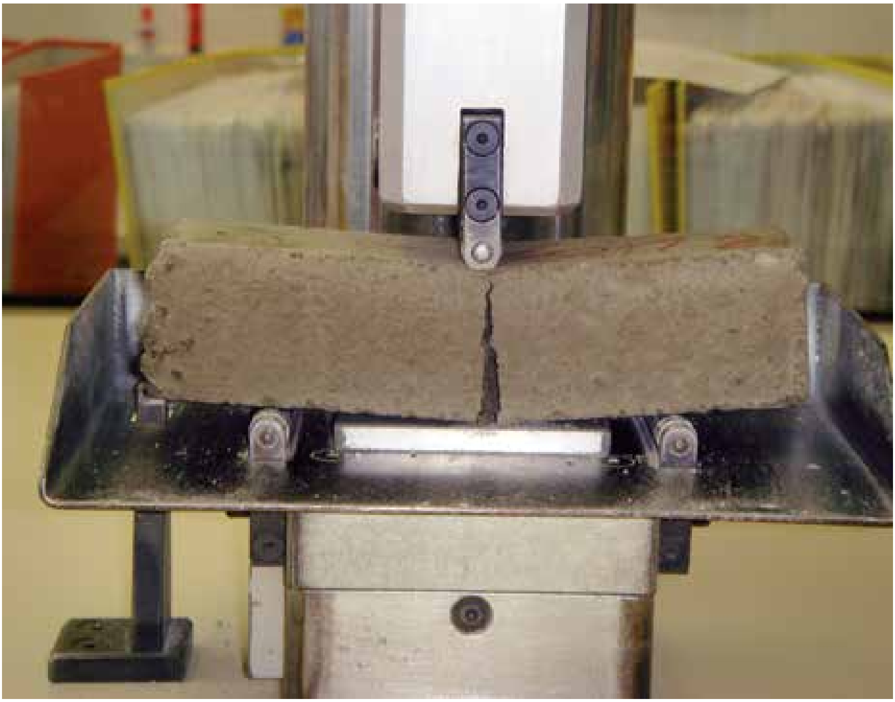


The load-CMOD is expressed as load corresponding with CMOD at:

- 0.5 (FR1)
- 1.5 (FR2)
- 2.5 (FR3)
- 3.5 (FR4)

Report
The test report may be summarised.

- Place, date, name of testing institute and person and operator responsible for testing
- Fibre type according EN 14889 and dosage
- Mix composition according to EN 14845-1
- Details of test specimens - dimensions, condition
- Specimen preparation date and time of production
- Curing history and moisture conditions at test
- Testing procedure, date of testing (rate of increase of CMOD or deflection and any deviation)
- Results –
  - → Load-CMOD curve or Load-deflection curve
  - → Limit of proportionality
  - → Residual flexural tensile strengths corresponding to CMODj (average and individual values)
- Reference to the Standard
- Any deviation to the Standard
- Optionally, observations of uniformity of fibre distribution
- Declaration from person responsible for the test, that the testing was in accordance with EN 14651, except for declared deviations



EN 14488-3

Testing sprayed concrete – Part 3: Flexural strengths (first peak, ultimate and residual) of fibre reinforced beam specimens

Content

This Standard classifies the residual strength of fibre reinforced sprayed concrete (FRSC) for a strength level at a certain deformation. The deformation classes are defined in EN 14487-1 according to the deformation range D1 (low), D2 (normal) and D3 (high), and strength level.

For example, a class D2S2 means the residual strength ≥ 2 MPa and deflection is between 0.5 and 2 mm.

Table 2 from EN 14487 defines the residual strength classes

Deformation range		Strength level (minimum strength, MPa)			
	Deflection mm	S1	S2	S3	S4
D1	0.5 to 1	1	2	3	4
D2	0.5 to 2				
D3	0.5 to 4				

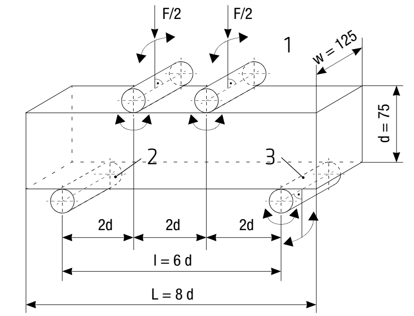
There are two described methods A and B which can apply to metallic, synthetic, other fibres or a combination of different fibres. The test is usually carried out on a sprayed concrete sample, unless specified otherwise.

i) Method A – four point bending test on a sawn cut beam (without notch)
ii) Method B – three point bending test on a square panel with notch

Method A Description

The specimens are loaded using a test machine (EN 12390-4) through two upper and two lower rollers to produce a bending moment which is used to determine the first peak, ultimate/maximum and residual flexural strengths from the load/deflection curve. The span between the two lower rollers is 450 mm.

Specimens measuring 75 mm deep x 125 mm wide x 500 mm (minimum) long according to EN 12390-1 are sawn from a test panel that has been applied with sprayed concrete in accordance with EN 14488-1. Beams are tested with the uncut mould face in tension, unless specified otherwise. The top face may be put in tension, although it must not be sawn to avoid cutting the fibre anchorages. Testing is performed after 28 days and the Standard details the requirements for storage while curing.

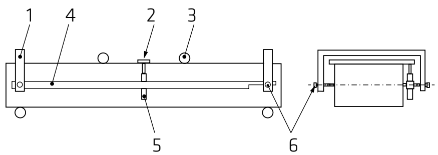


Bending deflection is measured using an electronic transducer mounted at mid-span on a yoke located in the neutral axis on mid-height of the beam. Two transducers located on each side are preferable to only one. The procedure for preparing, positioning, and loading the specimens are given in the Standard. The test is finished when the mid-span deformation exceeds 4 mm, or the specimen fractures.

where

1 loading roller (capable of rotation and of being incliend)
2 supporting roller
3 supporting roller (capable of rotation and of being incliend)

F is the load (P_{fp} or P_{ult}), defined above in N
l is the span
w is the average beam with
d is the beam height
L is the beam length



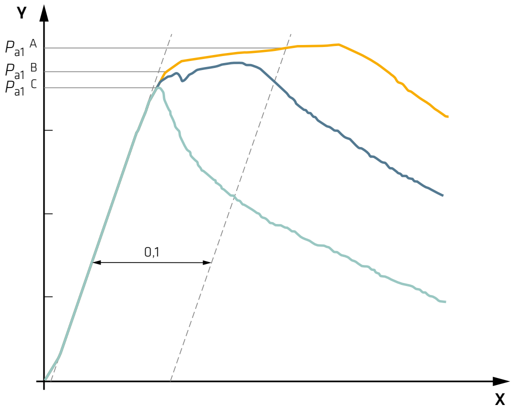
Arrangement of the yoke for measuring bending-deflection

where

1 cramp
2 reference bar (clamped or glued)
3 loading roller
4 yoke
5 transducer
6 locating screw

Method A Results

The distance from the crack centre on the tensile face to the nearest support shall be recorded. The first peak flexural strength is calculated from the load-deflection curve, depending on the curve type (refer to Standard).



Examples of load/deflection curves to determine the first peak load.

where

X central deflection in mm
Y load in kN
P_{a1}A is the first peak load (P_{fp}) for curve A
P_{a1}B is the first peak load (P_{fp}) for curve B
P_{a1}C is the first peak load (P_{fp}) for curve C

flexural strength in MPa = $P \times l/(w \times d^2)$

The ultimate flexural strength is then determined from the maximum recorded load using a formulation.

where

P is the load (P_{fp} or P_{ult})defined above in N
l is the span (450 mm)
w is the average beam width at the fracture plane (nominally 125 mm)
d is the average beam width at the fracture plane (nominally 75 mm)

The residual flexural strengths are calculated from the minimum loads from the flexural stress/ load-deflection curve between 0.5 mm, 1 mm, 2 mm and 4 mm.

f_{r1} is calculated from minimum load P_{r1} recorded between midspan deflections at 0.5 mm and 1.0 mm

f_{r2} is calculated from minimum load P_{r2} recorded between midspan deflections at 0.5 mm and 2.0 mm

f_{r4} is calculated from minimum load P_{r4} recorded between midspan deflections at 0.5 mm and 4.0 mm

The residual flexural strength is calculated as an equivalent elastic tensile strength using the previous formulation.

Method A Report

The test report may be summarised.

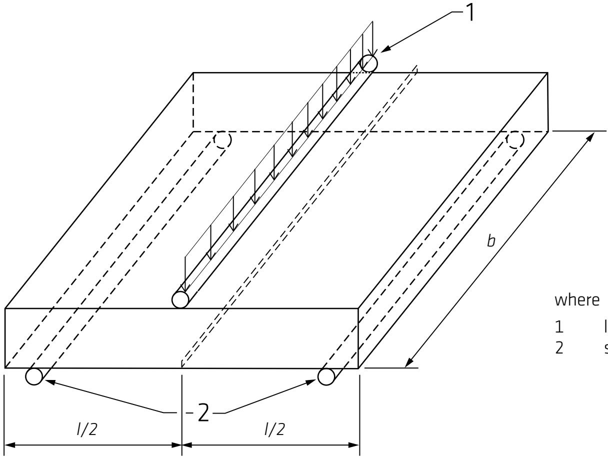
- Place, date, name of testing institute and person and operator responsible for testing
- Fibre type according EN 14889 and dosage
- Identification of mix composition
- Specimen application date and time, identification, and place of production
- Condition of specimens at receipt for storage
- Details of test specimens, number of, dimension and preparation
- Curing history and moisture conditions at test
- Age of specimen when tested
- Test machine and setup
- Results –
  - → Load (or stress)-deflection curve
  - → First peak, maximum, and residual loads
  - → First peak, maximum and residual flexural strengths
  - → Distance centre of crack to nearest support
  - → Visual appearance of concrete
- Reference to the Standard
- Any deviation to the Standard
- Observations of uniformity of fibre distribution (must be requested)
- Declaration from person responsible for the test, that the testing was in accordance with EN 14488-3, except for declared deviations

Method B Description

A panel specimen is loaded using a test machine (EN 12390-4) through one upper and two lower rollers to produce a bending moment which is used to determine the first peak, ultimate/maximum and residual flexural strengths from the load/deflection curve. The distance between the two lower rollers (panel span) is 500 mm.

Specimens measuring 100 mm deep x 600 mm wide x 600 mm long according to EN 12390-1 are produced spraying concrete into a panel in accordance with EN 14488-1. A notch, measuring 10 mm deep x 5 mm wide is wet sawn through the width of the panel at mid-span on the face in contact with the bottom of the mould during spraying. The panels are cured in accordance with EN 12390-2 3 days after sawing until <3 hours before testing, unless specified otherwise. Testing is performed after 28 days.

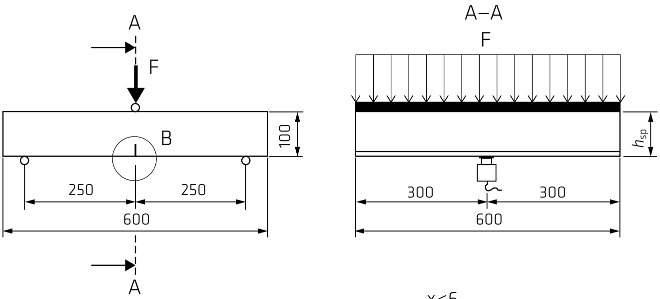
The test is carried according the relevant parts of EN 12390-4 for bending tests and operating in a controlled manner.

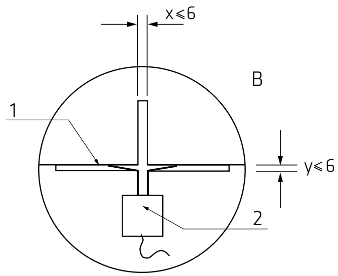


where

1 loading roller
2 supporting roller

Deflection can be measured using the CMOD (Crack Mouth Opening Distance) method or deflection method.

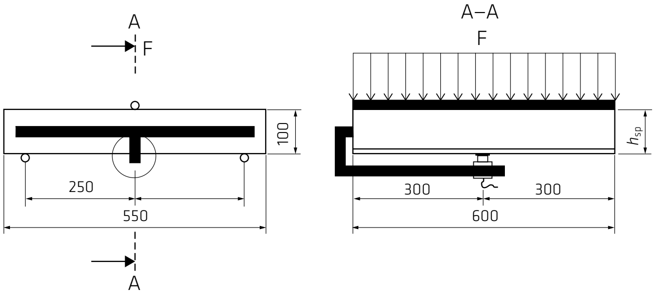


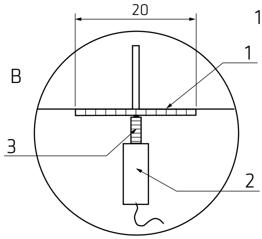


where

1 knife edge
2 transducer (clip gauge)
B detail (notch)

Measuring the CMOD is made by mounting a displacement transducer at mid-span of the beam. The machine starts at a constant rate so that the CMOD increases at 0.05 mm/min until the CMOD reaches 0.2 mm when the CMOD increases to a constant rate of 0.2 mm/min. For the first 2 minutes the values of load and corresponding CMOD are recorded at a rate ≥5 Hz which may be reduced to a rate ≥ 1 Hz. The test is stopped when the CMOD ≥ 5 mm. If cracks start outside of the notch the specimen shall be rejected.





where

1 1 mm thick aluminium plate
2 transducer (linear variable differential transformer)
3 spring shaft
B detail (notch)

Deflection is measured by mounting a displacement transducer on a rigid frame at mid-height over the supports. One end of the frame is mounted to the beam with a sliding fixture and the other end with a rotating fixture. The deflection method is like the CMOD except the CMOD parameters are transformed into deflection.

Method B Results

The results are expressed as load-deflection diagrams and the Standard gives a formulation to determine the equivalent deflection from the CMOD measurement in relation to the LOP and residual flexural strength (summarised in table 1 of EN 14488-3.

LOP/Residual flexural strength	CMOD (mm)	Deflection (mm)
F_L	0.05	0.08
$f_{R_s},1$	0,5	0,631
$f_{R_s},2$	1,5	1,894
$f_{R_s},3$	2,5	3,156
$f_{R_s},4$	3,5	4,420

The LOP is given by the expression where the load value F_L is determined from drawing a line at distance 0.005 mm and parallel to the load axis of the load-CMOD diagram, taking F_L as the highest load value.

$$f^{f}_{cts,L} = \frac{3 F_{Ls}\, l}{2bh^2_{sp}}$$

where

$f^{f}_{cts,L}$ is the LOP, in N/mm;

F_{Ls} is the load corresponding to the LOP, in N;

l is the span length, in mm;

b is the width of the specimen, in mm;

h_{sp} is the distance between the tip of the notch and the top of the specimen, in mm

Residual flexural tensile strength ($f_{R,j}$) is given by

$$f_{Rs,j} = \frac{3 F_{s,j}\, l}{2bh^2_{sp}}$$

where

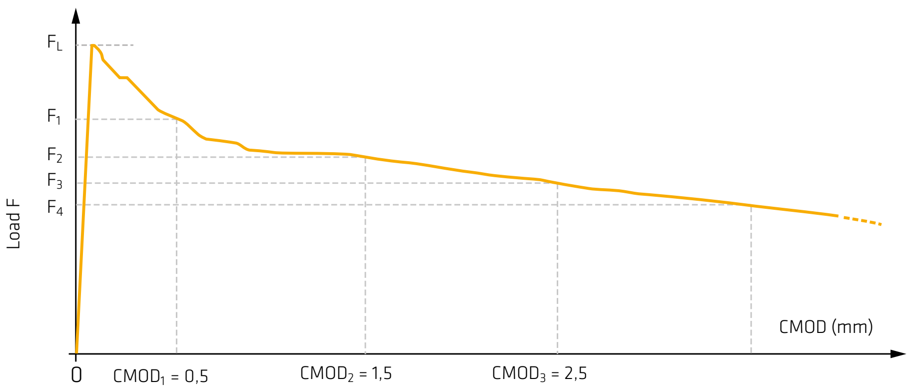
$f_{Rs,j}$ is the residual flexural tensile strength corresponding with $CMOD = CMOD_j$ or $\delta = \delta j$ (j = 1,2,3,4), in N/mm²;

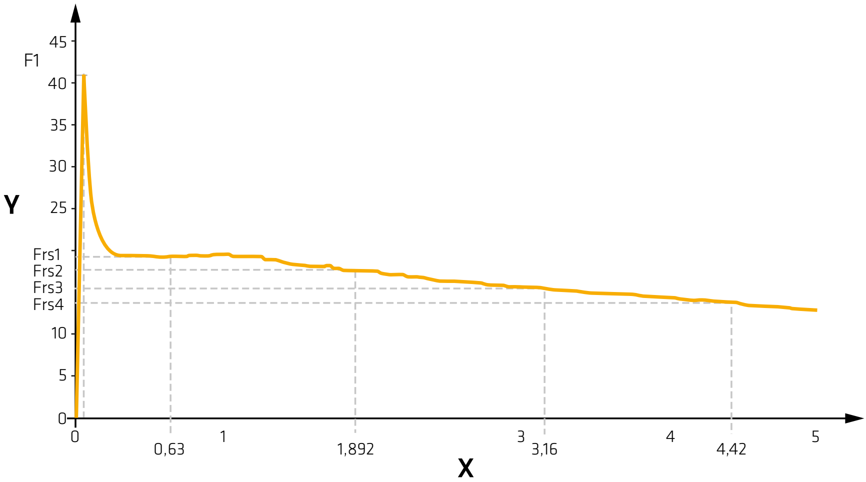
$F_{s,j}$ is the load corresponding with CMOD = $CMOD_j$ or $\delta = \delta j$ (j = 1,2,3,4), in N (see Figure 7);

l is the span length, in mm;

b is the width of the specimen, in mm;

h_{sp} is the distance between the tip of the notch and the top of the specimen, in mm





The load-CMOD is expressed as load corresponding with CMOD at 0.5 (F_{R1}), 1.5 (F_{R2}), 2.5 (F_{R3}) and 3.5 (F_{R4})

Method B Report

The test report may be summarised.

- Place, date, name of testing institute and person and operator responsible for testing
- Fibre type according EN 14889 and dosage
- Identification of mix composition
- Specimen application date and time, identification, and place of production
- Condition of specimens at receipt for storage
- Details of test specimens, number of, plate and notch dimensioning, and preparation
- Curing history and moisture conditions at test
- Age of specimen when tested
- Test machine and setup
- Results –
  - → Load-CMOD curve or load-deflection curve
  - → Limit of proportionality
  - → Residual flexural tensile strengths corresponding to CMODj (average and individual values)
  - → Visual appearance of concrete
- Reference to the Standard
- Any deviation to the Standard
- Observations of uniformity of fibre distribution (must be requested)
- Declaration from person responsible for the test, that the testing was in accordance with EN 14488-3, except for declared deviations

8.1.2 ASTM BEAM TESTING

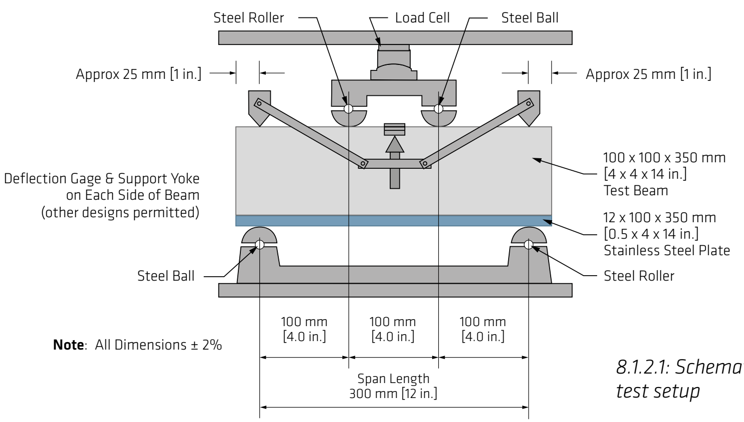
The relevant North American Standards for beam testing

Reference	TITLE	RELEVANCE
ASTM A820/820M	Steel Fibres for Fibre-Reinforced Concrete	Minimum requirements
ASTM D7508/7508M	Standard Specification for Polyolefin Chopped Strands for Use in Concrete	Specification requirements
ASTM C78/C78M	Test Method for Flexural Strength of Concrete (using simple beam with third-point loading)	Test preparation and procedure
ASTM C1399/1399M	Standard Test Method for Obtaining Average Residual-Strength of Fiber-Reinforced Concrete	Method for determining residual flexural strength
ASTM C1609/1609M	Standard Test Method for Flexural Performance of Fibre-Reinforced Concrete (Using Beam with Third-Point Loading)	Test preparation and procedure

ASTM C1399/C1399M
Standard Test Method for Obtaining Average Residual-Strength of Fiber-Reinforced Concrete

Content
A test method to determine the residual strength of a FRC test beam.

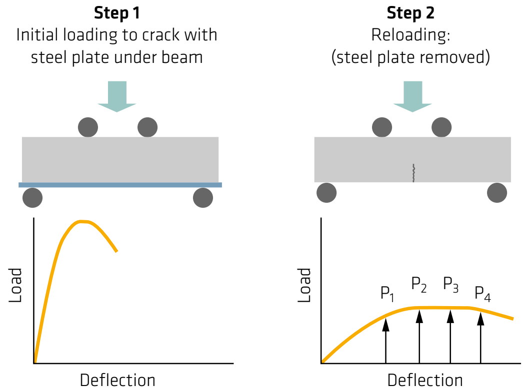
Description
A minimum 5 test beams cast in moulds, or cut from larger specimens, measuring 100 x 100 x 350 mm (4 by 4 x 14 in.) or as defined, are tested in flexure using a four-point bending equipment according to ASTM C78. A steel plate is placed on the underside of the beam and load applied until the beam cracks. Load is applied until the deflection reaches a maximum 0.20 mm, when the beam shall have cracked. At this point the test is paused while the steel plate is removed. The beam is then re-loaded to a maximum deflection of 1.25 mm (0.05 in) obtain the load-deflection curve.



8.1.2.1: Schematic drawing of the test setup

Results

The average residual strength for each beam using the loads determined from reloading the beams and curve deflections for 0.50, 0.75, 1.00, and 1.25 mm [0.020, 0.030, 0.040, and 0.050 in.] are calculated from the formulation given in the Standard.



8.1.2.2: Schematic drawings of the loading procedure

Report

The test report shall contain a minimum amount of information as listed in the Standard, which can be summarised.

- Concrete mix proportions
- Name and dosage of fibres
- Beam
  - → Reference numbers
  - → Preparation
  - → Beam span
  - → Dimensions
  - → Age at testing
  - → Curing history
  - → Test conditions
  - → Visual aspect
- First peak load, strength, and deflection
- Residual loads and strengths at f^{600}_{D} and f^{150}_{D}
- Toughness at T^{150}_{D} min Joule or in.lb
- Equivalent flexural strength $f^{D}_{e,600}$
- The rate of increase of net deflections
- Load-deflection graph
- Equivalent flexural strength ratio $R^{D}_{T,600}$
- If required, the residual loads corresponding to the residual strengths
- Example of parameter calculations (when peak load is greater than first peak load)

ASTM C1609/C1609M

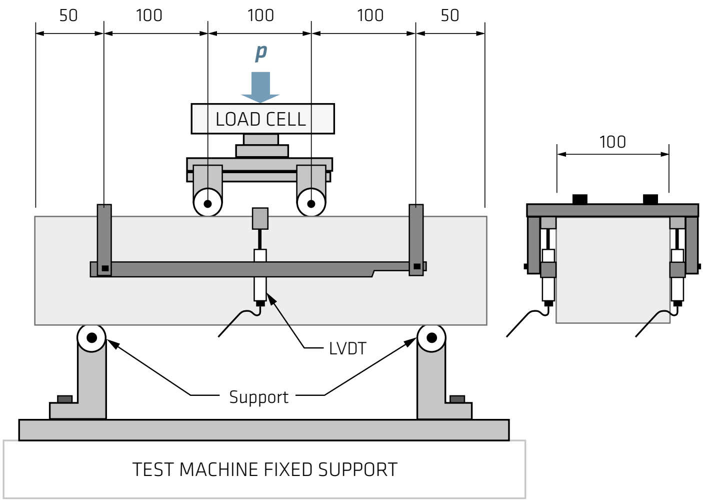
Standard Test Method for Flexural Performance of Fibre-Reinforced Concrete (Using Beam with Third-Point Loading)

Content

A closed-loop test is conducted on a simply supported beam subject to third point loading to obtain a load-deflection curve. The load-deflection curve is used to assess the flexural strength of a fibre-reinforced concrete under loading.

Description

Beams cast in moulds, or cut from larger specimens, measuring 100 x 100 x 350 mm (4 by 4 by 14 in.); 150 x 150 x 500 mm (6 by 6 by 20 in.) or as defined, are tested in flexure using equipment according to ASTM C1812/C1812 M and E4 practices for force verification of testing machines. The span for the two beam sizes are adjusted according to the specimen size. For 100 x 100 x 350 mm beams the span is 300mm span, and for 150 x 150 x 500 mm beams the span is 450mm. The beam is un-notched and placed on two supports with loads applied on top in the third points of the beam. The displacement of the beam is measured with extensometers and the testing machine is controlled according to the measured displacement of the beam. Load and deflection are recorded to an end deflection a minimum 1/150 of the span.



8.1.2.3: Schematic drawing of the test setup

Results

- The first peak load is determined where the slope of the load deflection curve is zero, or the maximum load value.
- The first peak strength is determined from equation (1)

$f = PL \quad bd^2$

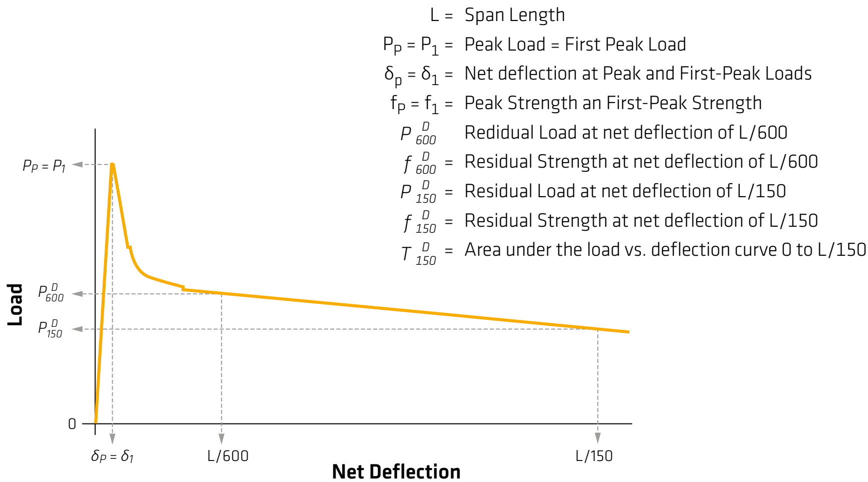
where f = strength MPa (psi)
P = the load N (lbf)
L = the span
b = beam width
d = beam depth

- Determine the residual loads at P_{600}^{D} and P_{150}^{D}
- Determine the residual strengths f_{600}^{D} and f_{150}^{D} using equation (1)
- The toughness T_{150}^{D} for the beam depth is calculated from the total area under the load-defelction curve up to a net deflection 1/150
- The equivalent flexural strength $f_{e,150}^{D}$ is determined from:

$$f_{e,150}^{D} = \frac{150 . T_{150}^{D}}{b . d^2}$$

- The equivalent flexural strength ratio $R_{T,150}^{D}$ is determined from the following equation and expressed as a percentage.

$$R_{T,150}^{D} = \frac{f_{e,150}^{D}}{f_1} \cdot 100\%$$



Report

The test report shall contain a minimum amount of information and if it is not known it shall be clearly stated "unknown".

- Concrete mix proportions
- Name and dosage of fibres
- Beam
  - → Reference number
  - → Preparation
  - → Dimensions
  - → Age at testing
  - → Curing history
  - → Test conditions
  - → Visual aspect
- Record load at 0.50 to 1.25 mm deflection at increments of 0.25 mm
- Individual residual flexural strength values for each beam
- Mean average residual flexural strength from set of beams
- Load-deflection graph

8.2 ENERGY ABSORPTION

There are different types of energy absorption tests, depending on the specification requirements, or the design method. Energy absorption tests are not always the same and vary for different reasons.

- Panel size and shape
- Panel support in the machine
- Load application
- Equipment specification / settings
- Method of measurement
- Sprayed concrete

The two main tests are commonly referred to as the square or round panel test. Results from square and round panel test methods are difficult compare directly as their geometry and testing conditions are quite different. However, studies show there is a correlation between the results and suggests a factor of 2.5 between the ASTM C1550 energy absorption at 40 mm deflection and the EN 14488-5 energy absorption at 25 mm deflection. It is uncertain if this basic correlation can be relied upon for all mix designs.

Table 8.2.1: Comparison of the round and square panel test method

Characteristic	Square Panel Test EN 14885	Round Panel Test ASTM C1550
Geometry	Square (600 x 600 x 100 mm deep)	Round (800 mm diameter x 75 mm)
Support Conditions	Continuous edge support	Supported at 3-points
Stress Type	Flexure & Punching Shear	Flexure
Behaviour Type	Material & Structure	Material
Cracking Pattern	Variable	Determinate
Deflection	Up to 25 mm	Up to 40 mm
Disadvantage	Test method susceptible to having perfect support conditions	Not the best simulation of the actual real-life situation
Advantage	Better simulation of the real-life performance	Robust and repeatable

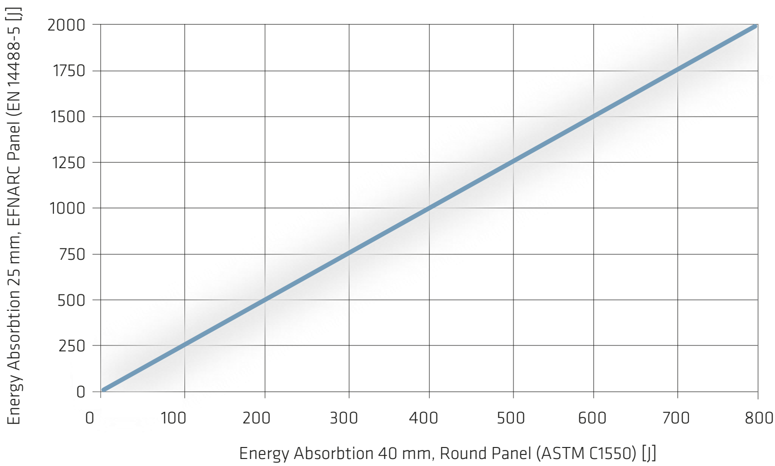


Figure 8.2.1: Approximate correlation of square round panel test methods for energy absorption

8.2.1 SQUARE PANEL TEST

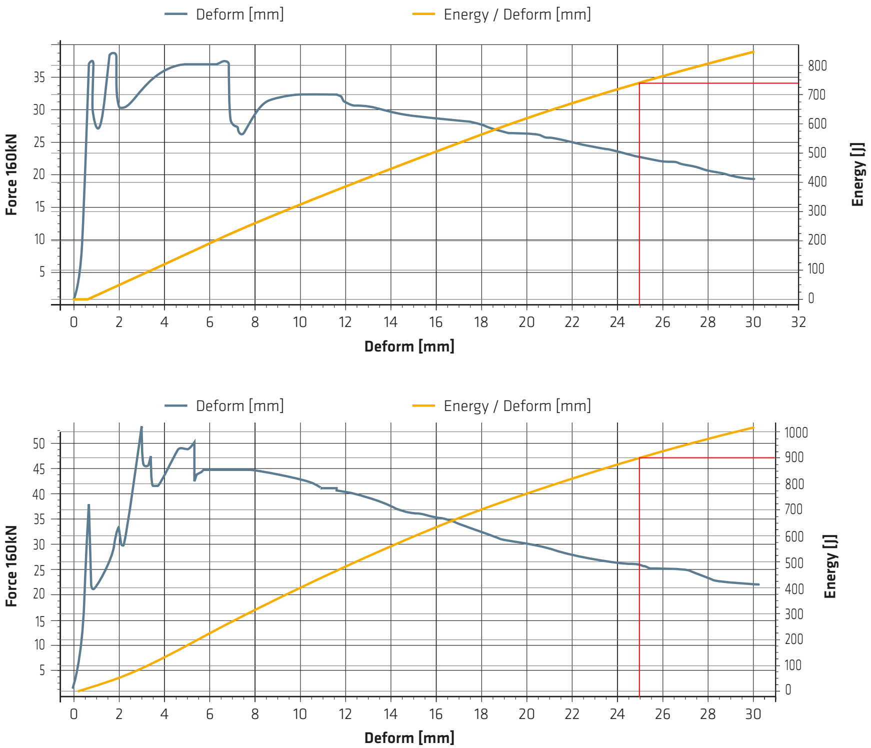
8.2.1.1: Relevant documents for determing energy absorption

Reference	TITLE	RELEVANCE
EN 14889-1	Fibres for concrete – Part 1- Steel Fibres	Performance requirements
EN 14889-2	Fibres for concrete – Part 2- Polymer Fibres	Performance requirements
EN 14488-1	Sprayed concrete – Part 1: Definitions, specifications, and conformity	Performance requirements
EN 14488-5	Testing sprayed concrete – Part 5: Determination of energy absorption capacity of fibre reinforced slab specimens	Test preparation and procedure

8

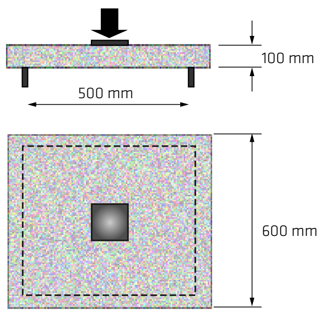
EN 14488-5
Testing sprayed concrete – Part 5: Determination of energy absorption capacity of fibre reinforced slab specimens

Content
This Standard specifies a method of determining energy absorption by applying a load on the top-centre of a specimen and measuring the load/deflection. From the load/deflection curve a second curve can be calculated giving energy absorption as a function of the deflection.



Figures 8.2.1.1: Examples of load/deflection diagrams to determine energy absorption

Description



FRC is sprayed into a panel form using the concrete mix design, for the project. The panel is removed from site and delivered to a test institute where it will be prepared for testing and cured according to EN 12390-2. The test is normally carried out at 28 days. The specimen for the test is cut down to measure 600 mm x 600 mm x 100 mm thick and is placed on a rigid square support frame in a machine according to EN 12390-4. A point load is applied on the top surface of the panel by a 100 x 100 square loading block. Electronic transducers are used to measure the specimen deflection as the load is being applied. The test is finished when the deflection exceeds 30 mm. The energy absorption capacity of the concrete in joules is determined from the area under the load-deflection curve between 0 - 25 mm.

Results

The energy absorption diagram related to the displacement is calculated from the load-deflection curve.

Definitions of energy absorption classes are given in EN 14488-1: Table 3.

Energy absorbtion class	Energy absorbtion in J for deflection up to 25 mm
E500	500
E700	700
E1000	1000

Report

- Place, date, name of testing institute and person and operator responsible for testing
- Fibre type according EN 14889 and dosage
- Identification of mix composition
- Specimen application date and time, identification, and place of production
- Condition of specimens at receipt for storage
- Details of test specimens, number of, dimension and preparation
- Curing history and moisture conditions at test
- Age of specimen when tested
- Test machine and setup
- Results –
  - → Load-deflection curve
  - → Maximum load (kN)
  - → Calculated energy-deflection diagram
  - → Energy absorption capacity
  - → Sketch or photograph of the specimen showing number and location of cracks
- Reference to the Standard
- Any deviation to the Standard
- Declaration from person responsible for the test, that the testing was in accordance with EN 14488-5, except for declared deviations

Figure 8.2.1.2: Underside view of tested square panels

8.2.2 ROUND PANEL TEST

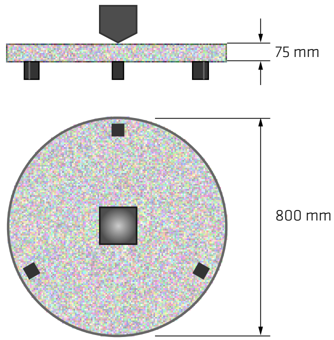
ASTM C1550-20

Standard Test Method for Flexural Toughness of Fiber Reinforced Concrete (Using Centrally Loaded Round Panel)

Content

This Standard specifies a method of determining flexural toughness, expressed as energy absorption, by applying a load on the top-centre of a specimen and measuring the central deflection with the onset of load. From the load/deflection curve a second curve can be calculated giving energy absorption as a function of the deflection.

Description



FRC is sprayed into a panel form using the concrete mix design, for the project. The panel is removed from site and delivered to a test institute where it will be prepared for testing and cured in accordance with the Standard. The specimen for the test measures 800 mm diameter x 75 mm thick and is placed moulded face onto three symmetrically arranged pivots. A point load, in the form of a steel hemispherical ball, is applied in the centre of the panel. The rate of deflection is controlled and applied at a constant rate. The test is finished when the deflection exceeds 45 mm. The energy absorption capacity of the concrete in joules is determined from the area under the load-deflection curve between 0 - 40 mm.

Results

The adjusted load-deflection curve is used to identify the load capacity at first peak and corrected using the given formulation. In the standard the energy absorption is determined from the area under the load-net deflection curve between the corrected origin and 40 mm net deflection. In addition, toughness can be defined at central deflections of 5, 10 and 20 mm.

Figure 8.2.2.1: Standard Test Method for Flexural Toughness of FRC

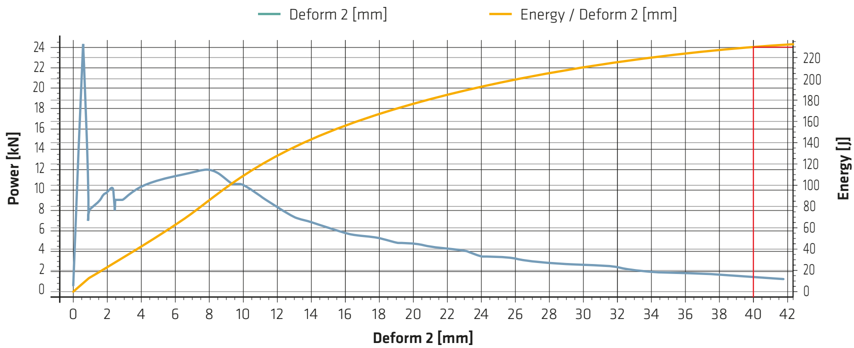


Figure 8.2.2.2: Top and underside views of tested square panels

Report

- Specimen application (cast or sprayed)
- Identification reference
- Type of fiber and dosage rate
- Average thickness and standard deviation
- Average diameter
- Curing history
- Age of specimen at test
- Record any defects in specimen

Results

- Description and number of radial cracks
- Uncorrected and corrected peak load
- Uncorrected and corrected values of energy absorptions
- Graph of the load-net deflection

Figure 8.2.2.3: Specimen set up result reporting according to ASTM C-1550 round panel test

8.3 FIBRE STRENGTH

The tensile and E-modulus test procedures mentioned in the global standards differ greatly from each other and sometimes do not specify the precise test conditions.

EN 14889-2:2006 does not define performance requirements for tensile strength or E-modulus, although the manufacturer's values must be declared. There are two methods for determining the tensile strength of a synthetic fibre, depending on if the fibre is classified as a micro or macro fibre.

Macro-synthetic fibres are currently tested according to EN 10002:1 with the additional requirements that the test speed may not be higher than 10 mm/min and testing must be done on strands of at least 20 mm in length. This means, that no specific strain rate is given, however, EN 10002-1:2001 gives a maximum strain rate of 0.008 s^{-1}, which is approximately 50%/min.

EN 10002-1:2001 was withdrawn in 2009, however is still referred to in EN 14889:1 and 2 until these Standards are updated. EN 10002-1:2001 will be replaced by ISO 6892-1:2009 Metallic materials – Tensile testing – Part 1: Method of test at room temperature.

Testing is normally carried out on a minimum 30 strands. From the spread of results the manufacturer can decide which value to declare, although Standards will define the maximum allowable difference between the declared and upper and lower values. The manufacturer will also define from where in the production process the strands are removed for testing. For example, tensile tests are typically carried out on the embossed fibre (the finished product) whereas for undulated or crimped fibres the test is better carried out before the undulation or crimping process. The reason for this is because the initial elongation to straighten an undulated or crimped fibre will strongly affect the results.

Micro-synthetic fibres are tested according to EN ISO 2062:2009, with a gauge length of either 250 or 500 mm and a test speed of 250 and 500 mm/min respectively which translates into a strain rate of 100%/min. EN ISO 2062:2009 further states, that all preconditioning and testing must be done in standard atmosphere at 20°C and 65% relative humidity. Although this test method only applies to micro-synthetic fibres, it is not uncommon to also test macro-synthetic fibres using this method.

ASTM D7508/D7508M-10 (2015) only specifies the determination of the tensile strength and gives a minimum required value of 50,000 PSI (~344.4 MPa).

Tensile strength is tested according to ASTM D2256 in ambient conditions of +21°C and 65% relative humidity. The strain rate in D2256 specifies the breaking force shall be reached within 20 seconds. As most polypropylene based macro-synthetic fibres usually have an elongation at break between 5 and 15%, this translates into strain rates between 15 and 45%/min. However, according to D2256 it is also possible to test with a strain rate of 120%/min. D2256 also gives two methods for calculating the E-modulus. One is called initial modulus, the other chord modulus. However, these two methods leave plenty of room for interpretation and can therefore provide many different values for the same fibre.

The E-modulus is defined as secant modulus determined by making a line through the points at 10% and 30% of maximum force, on the stress-strain curve. Albeit precise, the method is not ideal. The point on the stress strain curve corresponding to 30% of maximum force always exhibits a deformation of greater 0.3%, which means, that this point already lies outside the region where the material exhibits linear-viscoelastic behaviour so that the deformation is irreversible. The point corresponding to 30% of maximum force even lies beyond the yield point, at which the stress-strain curve levels off and plastic deformation begins. This means, fibres with lower values of maximum force, the two points at 10% and 30% of maximum force, move closer together leading to a steeper slope of the line for the secant modulus and thus seemingly higher values for the E modulus for a weaker fibre.

Table 8.3.1: Overview over the main standards governing tensile testing procedures for macro-synthetic fibres for use in concrete.

	EN 14889-2		ASTM D7508/D7508M
Tensile strength	macro fibres EN 10002-1	micro fibres EN ISO 2062	ASTM D2256
Strain rate	< 50%/min	100%/min	ca. 15-45%/min or 120%/min
Gauge length	≥ 20 mm	250 mm or 500 mm	250 mm (10 inch)
Test speed	≤ 10 mm/min	250 mm/min or 500 mm/min	20s to break or 300 mm/min
E-modulus	EN 10002-1 slope of the line going through the points at 10% and 30% of maximum force on the stress-strain curve		not required however, ASTM D2256 gives different options for its calculation: ■ initial modulus ■ chord modulus

STRAIN RATE

The strain rate in the tensile testing plays a major influence on the declared values. Values for tensile strengths are strongly dependent on testing parameters, namely the strain rate and for synthetic fibres the testing temperature. The strain rate is the speed of the moving cross head in relation to the test specimen's original length between the clamps. Strain rate and the temperature at which the tensile test is performed strongly influence the 'shape' of the stress-strain curve of macro-synthetic fibres. In general, the higher the strain rate and thus the test speed, the higher the resulting values for tensile strength. Lowering the testing temperature has the same effect as increasing the strain rate.

E-Modulus is not required according to D7508

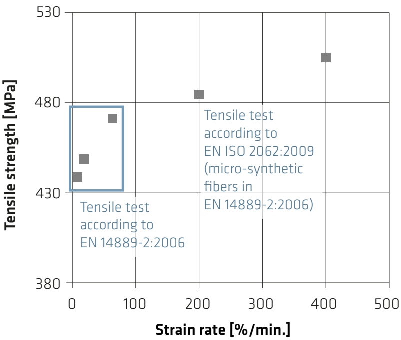


Figure 8.3.1: Tensile strength of a macro-synthetic fibre in relation to the strain rate in the tensile test.

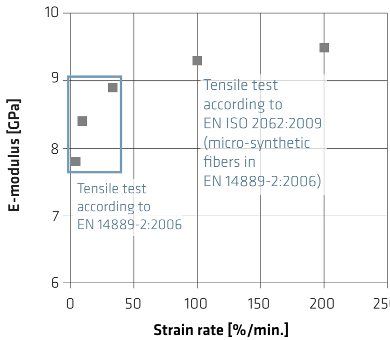


Figure 8.3.2: E-modulus of a macro-synthetic fibre in relation to the strain rate in the tensile test.

RECOMMENDATION FOR MACRO FIBRE TENSILE TEST

A minimum 30 strands measuring ~400 mm long will be required.

Embossed	The embossed strands shall be tested i.e., finished product
Crimped/undulated	The uncrimped strands shall be tested

For EN 14889-2:2006 all tensile and e-modulus values must be tested using a Universal Testing Machine with a flat-faced clamping system incorporating a tactile or optical extensometer.

Strain rate [1]	33%/min (derived from test speed/gauge length *100%)
Test speed [2]	10 mm/min
Gauge length	30 mm ±2 mm
Distance of tactile extensometer	10 mm ±1 mm

[1] Determined from the test speed and gauge length
[2] Given in the Standard

The equivalent area and cross section area are determined using the irregular cross section method.

Tensile strength is determined from the maximum breaking force [N] / cross sectional area [mm^2]

The E-Modulus is determined from the stress strain curve between the determine values at 10% of f_{max} and 30% of f_{max} from the maximum breaking force and using the equation:

$$\frac{(30\%F_{max} - 10\%\ F_{max})/\text{cross sectional area}}{(\text{elongation at }30\%\ F_{max} - \text{elongation at }10\%\ F_{max})}$$

8

9 PACKAGING AND DOSING

9.1 PACKAGING

The effectiveness of fibre reinforced concrete (FRC) in providing resistance to cracking and enhancement of material properties is entirely dependent on the uniform three-dimensional distribution of fibres throughout the concrete.

FRC cannot be described as a 3-dimensional system of reinforcement if fibres are present in one part of the concrete and not another. Therefore, to achieve complete and uniform distribution it is essential the chosen fibre is compatible with the selected concrete or cementitious mix and that the recommended mixing procedure is followed.

Depending on the manufacturer, fibres are available in different packaging types and sizes. Typically, the packaging types are degradable bags for easy dosing, cardboard boxes, or the larger bags/sacks.

PP MICRO-FIBRES

PP micro-fibres are supplied as loose fibres and generally packaged in 0.6 kg or 0.9 kg degradable paper bags. These bags are designed to be added directly into the concrete mix without opening the bag itself. It is normal to add these bags once all other materials, including water have been added to the mixer. Bags will degrade in the mix due to the mechanical action of the aggregates. Care should always be taken to add the individual bags slowly and uniformly into the concrete and not simply all at once. Once added, the concrete should be mixed until all the fibres have homogenously distributed in the concrete. Mixing times can be influenced by the age and efficiency of the mixing equipment, and whether it is a forced action static or tumble mixer. Mixing times vary depending on the volume of the concrete mixed, w/c-ratio and type of mixer. Always consult the Product Data Sheet.

There are automated systems on the market for introducing small, bagged materials into the concrete. However, where PP micro-fibres are used in large quantities, for example in tunnel applications, they are often supplied in big bags to facilitate the use of automated dosing machinery.

PP MACRO-FIBRES

PP macro-fibres are generally supplied in degradable paper bags, cardboard boxes and depending on the manufacturer in big bags. The degradable bags are designed to be added unopened into the concrete, whereas boxed fibres must be opened and introduced slowly into the concrete. Some types of PP macro-fibres are supplied as loose materials, such as the soft tape types. PP micro-fibres are also generally supplied as “pucks” which are essentially large amounts of single fibres wrapped in a soluble film.

These pucks help with the uniform dispersion of fibres in the concrete and allow other-wise bulky material to be efficiently packed for transportation. PP macro-fibres should be added slowly and uniformly into the concrete. When the bags have quickly degraded the “pucks” will evenly distribute into the concrete. The film around the pucks will then dissolve allowing the fibres to homogenously distribute in the concrete.

PP macro-fibres can be supplied in big bags and will generally be used in combination with an automated dosing equipment.

STEEL MACRO-FIBRES

Steel fibres are available as a loose or glued collated clip and generally supplied in cardboard boxes or large bags/sacks for major projects. Cardboard box sizes vary depending on the manufacturer and typically may be supplied as 10 kg, 20 kg, or 25 kg sizes. Steel fibres may also be supplied in degradable bags depending on the weight, glued or loose and size of fibres. Degradable bags can be strengthened to support the additional weight, but this will influence the degrading time in the mixer. Regularly checks should be made to make sure the bags have completely degraded.

Steel fibres with high aspect ratios are typically glued together to form clips of fibres as this will improve the fibre distribution in the concrete.

Steel fibres are added to the freshly mixed concrete and never as the first component. Mixing time will depend on the size and efficiency of the mixing equipment. The mixing time is generally recommended as 5 minutes as a minimum, or an extra 1-minute mixing for every cubic meter in the mixer. Steel fibres can generally be supplied in a ~1 tonne big bag for use with automated dosing equipment.

9.2 DOSING

9.2.1 MANUAL DOSING

Dosing is linked to the quantity of concrete to be used. Where relatively small quantities of fibres are required then these will normally be dosed manually. Where large quantities of concrete are to be used then the preference may be to use automated dosing equipment.

9.2.2 AUTOMATED DOSING EQUIPMENT

For large projects, the best method of dosing fibres is to use an automated dosing equipment. These systems are generally suitable for all fibre types and are selected according to the fibre type, feeding capacity, tray content and accuracy requirements. Typically, the equipment has a cylindrical tray with a spirally shaped feeder coil on the inside which is mounted onto a rigid framework with vibrating motors attached. When activated, manually or automatically fibres work their way upwards on the spiral and discharge into the mixer or onto secondary delivery belts. Automated dosing equipment can be used as a stand-alone system or linked directly to the concrete batching computer system which accurately measures and records fibre dosage for each batch

CONVEYOR BELT
Mobile conveyor belts are a very simply way of transporting PP or steel micro or macro-fibres directly to the concrete mixer. Fibres are manually placed at the bottom of the moving conveyor belt. The fibre quantities going into the mixer are controlled manually and it is recommended to make a record of the dosing for each concrete batch. Ribbed belts are recommended when using pp macro-fibres supplied in pucks.

BLOWING EQUIPMENT
Blowing systems can be used for various types of fibres. They are more commonly used by specialist contractors for undulating steel fibres. This is because the wave-like shape of the fibre can cause balling issues when introduced as a loose material from the box tape packaging or from a conveyor belt.

BUCKET ELEVATORS
Bucket elevators are for the vertical conveyance of fibres. They have a series of small buckets attached to a moving belt which move all types of fibres from a ground to an elevated position. Bucket elevators can be integrated into more intricate delivery methods such as automated fibre dosing system, the conveyor belts and other weighing systems.

10 CONCRETE FINISHING

10.1 GOOD CONCRETE PRACTICE

Where FRC is to be exposed, the quality of surface finish is often a measurement of success. For example, precast elements and for exposed insitu cast concrete such as floor slabs. To achieve a good surface finish is necessary to pay careful attention to the concrete mix design, placing timing, and the finishing technique. The constituents of the mix design places and important role of the finishing charcteristics.

- Fines content
- Aggregate content
- Water/binder-ratio
- Use of admixtures
- Finishing aids

It is also making sure there is sufficent paste to coat the fibres. Long stiff fibres can protrude out of exposed concrete, whereas soft fibres will bend down on the surface. Exposed steel fibres can start to corrode and leave unsightly stains on the concrete. Therefore, the right fibre selection is also about the concrete application and desired surface appearance. Whilst, fibres are distributed homogenously in the concrete it is inevitable that some may be visable on the surface.

FRC can be placed using conventional methods such as concrete chutes, and buckets. FRC can also be extruded or projected onto a surface using specialist pumping and spraying techniques. The desired workability will influence the surface aspect depending on if there was high or low workability at the time of placement, and the degree of compaction. Over vibrating FRC can align fibres in a similar direction and will affect the concrete performance. FRC can look drier than a normal concrete, but it has the same workability when vibrated into place. This is due to the fact the fibres need to be coated with cement paste and means the concrete may become more cohesive.

Apparent slump or slump-flow loss is a characteristic of FRC and in most instances the addition of water is unnecessary. Many factors affect the workability of concrete; therefore, it is important to analyse the FRC mix design prior to placing the concrete. As with all concrete, do not expect the best results with a mix with high w/c-ratio.

When finishing the concrete, timing is important as are having the right tools. Brooms, hand trowels or power trowels are a few examples. Do not commence finishing operations too early. Let all bleed water evaporate from the surface before finishing. It is very important not to overwork the surface, especially FRC where there may be fibres on the surface.

BLEEDING

Bleeding is the movement of water within the concrete to the surface due to gravitational displacement of the cement and aggregate prior to the initial set. Plain concrete can form puddles of bleed water on the surface in areas where large capillaries have formed. Inconsistency of concrete quality and supply rates can cause further issues with variable bleed and concrete finishing.

Finishing operations performed while bleed water is present on the surface can cause serious crazing, dusting, or scaling problems. Sprinkling water on the surface to facilitate finishing can also cause these problems.

FRC will exhibit less bleed water than the equivalent plain concrete due to the internal support mechanism fibres provide to the aggregates. Where bleed does occur, it will generally be more uniform meaning that the risk of “puddling” is significantly less than that of plain concrete.

10.2 FINISHING METHODS

Fibres are compatible with most finishing and surface treatments including pattern stamping, exposed aggregate, brooming and hand or power trowelling. Steel fibres are not recommended for pattern stamping or exposed aggregate finishes. Dragging burlap over the surface is not recommended because they can get caught on a fibre and lift it from the surface.

STRIKE-OFF OR BULLFLOATING

Manual, vibratory or laser screeds can be used during the strike off operation. Laser guided screeds and vibratory screeds ensure surface vibration, which brings paste to the surface and limits the possibility of exposed fibres. Magnesium floats are recommended to establish a smooth, level surface and can close any tears or open areas that occur during the strike off operation. As with finishing any concrete, overworking the surface should be avoided as this will simply bring excessive fines and fibres to the surface

MACHINE TROWELLING

Timing is everything and there may be a tendency for inexperienced operators to start FRC finishing too early.

This because the fibre reinforced concrete will look stiffer and exhibit less surface water than plain concrete. It is important to understand that fibres do not influence the concrete hydration process. Therefore, concrete which appears ready for finishing is probably not, because the concrete is not setting any faster.

Fibres will add cohesion and support to the concrete meaning there is less bleed water. This should be taken into consideration when operators use on site tests to ascertain readiness for finishing operations.

Premature trowelling will exhibit more surface fibres since the cement paste has not sufficient time to adhere to the fibre. This results in fibres being moved around the surface. It will also draw more fibres to the surface making quality finishing more difficult. If fibres do appear to be drawn to the surface, stop, wait ten to fifteen minutes, and try again. Correct timing will produce a smooth, even finish with minimal fibre exposure.

Good practice is to start floating the surface with a pan-trowel or with the power blades laid flat. This floating operation will consolidate the surface, remove surface imperfections, and prepare the surface for further finishing operations. Continue with the pan or flat blades for as long as possible then slowly increase the angle of the blades until the desired concrete finish is obtained.

RAKE & BROOM FINISHING

Brooming and raking is best accomplished by pulling the broom or rake in one direction. There may be some fibres at the surface, but this is normal and the PP fibres can be cut or burnt off later, however if left they will wear away in time. Steel fibres can be removed by clipping the fibre from the surface with offset pliers or wire cutters. These steps are rarely necessary with experience FRC operators.

PRECAST ELEMENTS

There are few problems associated with FRC in precast elements when the concrete is cast in formwork. However, care should be taken to produce a good quality concrete and not to over vibrate. Exposed surfaces will need to be hand trowelled at a suitable time. Protruding fibres can be cut or in the case of PP, the fibres can be burnt if necessary.

11 INDEX

11

FOR MORE REINFORCED CONCRETE INFORMATION

WE ARE SIKA

Sika is a specialty chemicals company with a leading position in the development and production of systems and products for bonding, sealing, damping, reinforcing and protecting in the building sector and the motor vehicle industry. Sika's product lines feature concrete admixtures, mortars, sealants and adhesives, structural strengthening systems, flooring as well as roofing and waterproofing systems.

SIKA SERVICES AG
Tüffenwies 16
CH-8048 Zürich
Switzerland

Contact
Phone +41 58 436 40 40
www.sika.com

BUILDING TRUST