University of
Stavanger

FACULTY OF SCIENCE AND TECHNOLOGY

BACHELOR'S THESIS

Study programme/specialisation:

Byggingeniør, konstruksjonsteknikk

Spring semester

Open / Confidential

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Programme coordinator:

Supervisor(s):

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Title of bachelor's thesis:
Effect of basalt minibars and steel fibers on the mechanical behavior of concrete.

Credits: 20 sp

Keywords:

Fiber reinforced concrete
Basalt fiber minibars
Steel fiber

Number of pages: 64

+ supplemental material/other: 17

Stavanger,
15/05/2021

Abstract

The use of steel reinforcement in the form of rebar has been used for many years to improve the tensile and flexural strength of concrete elements. The research and development within the field of concrete is ever expanding due to concrete being the most readily available and widely used construction material. The use of fibers in concrete is not an entirely new concept however increasing amounts of fiber types and materials are being introduced into the market. The mechanical behavior and properties of each of these fibers can drastically differ from each other and constant research is therefore being performed to better understand how different types of fiber reinforced concrete behave.

In this bachelor thesis tests were performed on two types fiber types, conventional steel hooked end smooth fibers and basalt fiber Minibars. The basalt fiber Minibars are a rather new technology which consist of many small micro-fiber basalt filaments that have been spun together to form large macro-fibers of length between 30-50 mm. These Minibars are supposed to act similar to traditional steel fibers by increasing the concretes flexural capacity through acting as tension bridges and limiting crack prorogation.

Volume fractions of 0.5% and 1% were tested for both fiber types and compared to plain concrete. The steel fibers showed a notable increase in compressive strength mean while the basalt fiber Minibars reduced the compressive strength proving to be insufficient at serving as compressive reinforcement. The steel fibers showed no significant increase or decrease when it came to the ultimate flexural strength of the concrete while the basalt fiber minibars caused a notable reduction in flexural strength. The fibers seemed ineffective at increasing the ultimate flexural strength of the concrete, they did however show exceptional post cracking behavior by increasing the concretes ability to carry loads past failure. Additionally, improved modes of failure were observed due to the significantly increase ductility of the fiber reinforced concrete.

Acknowledgments

We would like to thank our supervisor Yanyan sha for his exemplary support and supervision throughout the entire thesis. We would also like to thank Samdar Kakay for instruction us and supervising the use of the testing machines at the IMBM laboratory and Jarle Berge for helping us with the proportioning, logistics of preparing the necessary materials and mixing of all the concrete mixtures used in the tests.

15 May 2021, Stavanger, Norway

Nikolay Nikolov and Omed Sultani

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1. Introduction

1.1. Background

Concrete is a composite material that consists of a mixture of fine and coarse aggregates that are bonded together with cement paste which hardens (cures) over a period of time to give concrete its structural properties. Concrete is material used in the construction of structures and has been used for thousands of years and has seen extensive research and development to improve its use areas and mechanical properties. One of concrete's defining features is its ability to carry large compressive loads, however plain concrete is notoriously brittle and has poor ability to resist tensile loads. To counteract this weakness large steel reinforcement bars of varying diameters and lengths have been used since the mid-19th century. The steel rebar's purpose is to carry tensile loads in the concrete creating a more balanced composite which can equally resist compressive and tensile loads. The placement of steel rebar takes a lot of time and skill to achieve the appropriate spacings and rigidity as outlined in the structures design, this has led to more research and interest into the use of small fibers as a replacement to large rebar. Fibers of different sizes and materials have also seen use since ancient times in the form of straws or horse hairs. In modern day construction fibers are added to increase the ductility and to reduce or counteract crack propagation in concrete. Although fibers have proven to be able to increase the mechanical properties of concrete further research needs to be conducted to further optimize cost, strength, material use, sizing, and handling of fiber reinforced concrete (FRC). The use of fibers even at small doses has shown to have a drastic impact on the concrete's workability often requiring the use of superplasticizers to achieve sufficient flow and workability. Variation in FRC's mechanical properties is also largely dependent on the orientation of the fibers and how well the fibers are able to be distributed throughout the composite which are things that can often prove difficult to achieve due to the fibers tendency to ball or clump together in larger volumes. Heavier fibers such as steel can also sink to the bottom of the concrete mixture due to their high density. It is therefore a challenge to choose the right type of fiber to use as reinforcement as it has to fulfill both the mechanical and workability demands of the project.

1.2. Objective of research

This thesis aims to firstly provide a general understanding of different types of fibers that are commonly used today and their different mechanical properties and effects on both fresh and hardened concrete. Basalt fibers and more specifically Minibars are a rather new innovation within the field of FRC. The aim of this thesis is therefore to investigate the effect of basalt Minibars and steel fibers on the mechanical behavior of concrete.

2. Fibers and fiber reinforced concrete

2.1. What are fibers

Fibers are small pieces of material used to increase structural integrity by acting as reinforcement. A wide variety of fibers have been used for construction throughout the past decades, ranging from horsehair in mortar and hey straws in mud bricks. Material scientists and researchers have adopted this technique in modern-day construction through the development of newer fiber types with more desirable properties. The different types of fibers that are commonly used are SF-Steel fiber, GF-Glass fiber, BF-Basalt fiber, SN-Synthetic fiber, NF-Natural Fiber. Fibers are used as a type of reinforcing material and commonly come in either as monofilament, fibrillated fibers or woven mats as show in *figures 2-1 and 2-2*; these fibers have the effect of increasing the material properties of concrete. Concrete is a composite material with a low tensile strength and low strain limit. By mixing basalt fiber, steel, glass, synthetic or other organic fiber into the concrete mix we improve the engineering properties such as durability, tensile strength, crack control, better impact and abrasion resistance longevity under various loads and types of exposure. [1]

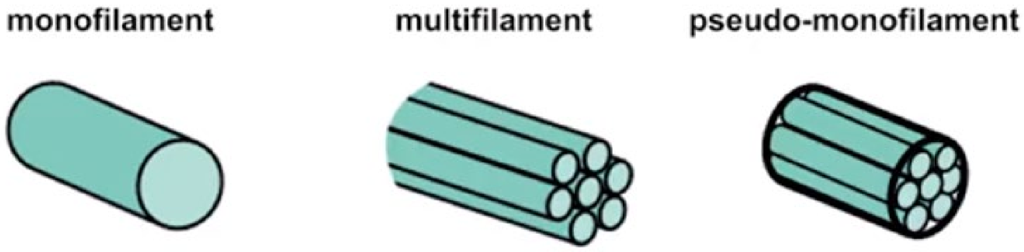


Figure 2-1: Structural difference between monofilament, multifilament and pseudo-monofilament

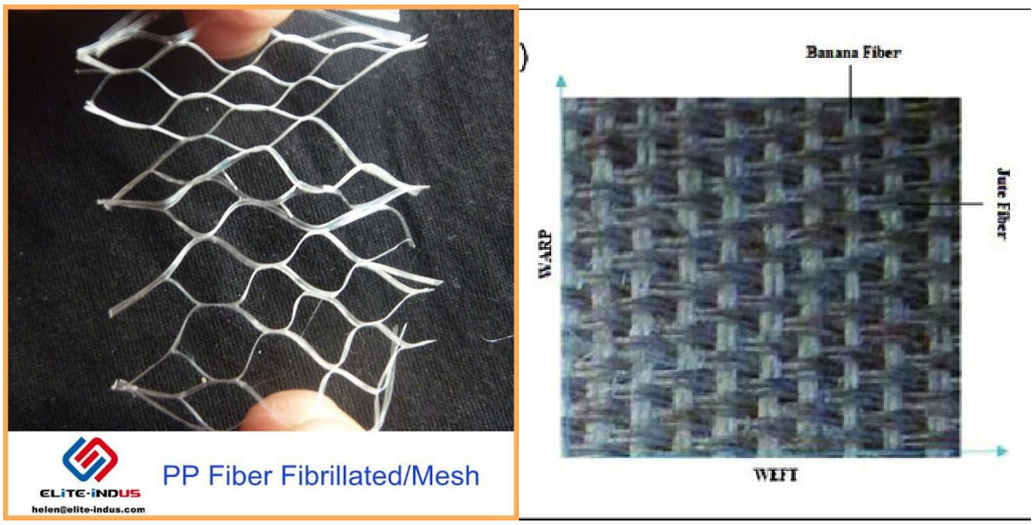


Figure 2-2: a) Fibrillated polypropylene (PP) mesh/fibers, a) Fiber woven mat,

2.2. Classification and sizes

2.2.1. sizes and geometry

The geometry and size of fibers plays a large role when it comes to how efficient the fibers are. An efficient fiber is a fiber that fails by breaking in two rather than by pull-out. For conventional macrofibers (diameter 0.1 mm or greater) the friction between the fibers surface and the cement matrix is often not enough to prevent fiber failure by pull-out resulting in an inefficient reinforcement of the composite. To solve this issue different types of geometrical deformations have been employed to give the fibers a complex shape. The complex shape of the fibers will provide anchoring effects which have been shown to achieve a much better fiber-matrix bond than interfacial effects. Several tests have been performed to assess the effectiveness of geometrical deformations and anchoring mechanisms on the fibers' pull-out strength and can be seen in *figure 2-3*. Additional tests were performed where the fiber surface was coated with grease as to neutralize the additional bonding effects caused by adhesion and friction between the fiber and the cement matrix. The results showed that deformed fibers exhibit a high level of anchoring in the post-peak zone. There are many different ways of manufacturing the fibers such as crimped, coiled, end hooks, twisted etc. to achieve a sufficient level of anchoring, examples of these geometrical deformations can be seen in, *figure 2-4.* [2]

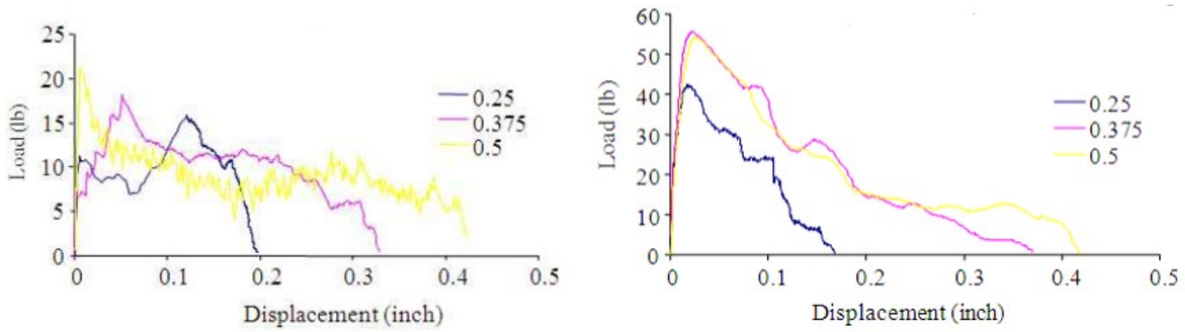


Figure 2-3: a) Pull out strength of smooth fibers (left), b) Pull out strength hooked fibers (right) at different embedment lengths. (Abu-Lebdeh, 2010)

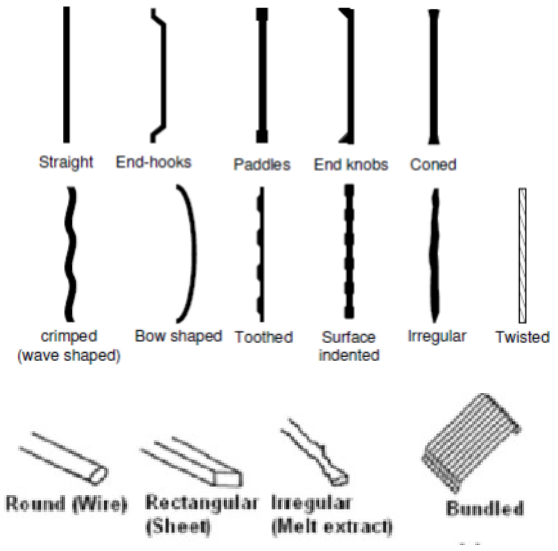


Figure 2-4: Different types of fiber geometries and cross sections

2.2.2. classifications

Fibers can first be organized into two main categories, natural fibers, and manufactured fibers, see *figure 2-5*. The determining factor of whether a fiber is considered natural or manufactured is its chemical origin. Natural fibers are fibers that are directly obtained from sources like plants, mineral or animal sources. These fibers can be obtained as continues filaments or elongated discrete pieces comparable to thread. Natural fibers are then often spun into cloth, yarn or other nonwoven fabrics such as felt or paper. Natural fibers are in abundance in nature and could be a more environmentally friendly alternative to manufactured fibers, but extensive research has yet to be conducted regarding natural fiber reinforced concrete (NFRC). Kavitha reported improvement in crack resistance, ductility and flexural strength [3], the mechanical properties of NFRC need to be explored further and solutions to issues such as fiber decay over time have to be developed. [4]. Manufactured or manmade fibers are produced through a series of controlled chemical reactions, these types of fibers are much more extensively used due a large amount of research and innovation within the field of FRC. Fibers can further be divided into macro and microfibers. Macro-fibers are defined as fibers with a length, l, that exceeds the maximum aggregate size and a diameter, d, that is much greater than the cement's diameter (~50 µm). Micro-fiber must have length less than that of the maximum aggregate size used and a diameter the same or less than that of cement. [5]

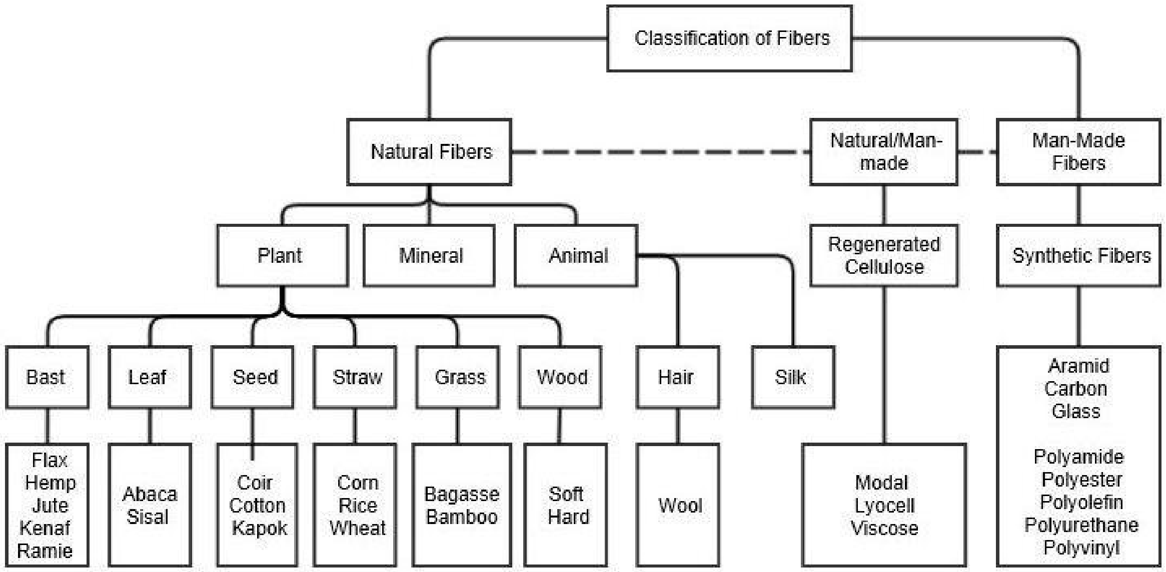


Figure 2-5: Example of how fiber can be split up into different classifications

2.3. types of fiber materials

2.3.1. basalt fibers

Basalt is an igneous rock that has been formed by the rapid cooling lava. Basalt is regarded as the most common rock on earth although the basalt rocks characteristics can vary depending on the source of the lava, cooling rate and exposure to the elements. The abundance of basalt makes it a viable alternative to other composites such as carbon or glass fiber. Basalt rocks have a general composition as shown in *Table 2-1*. As we can see the main chemical compounds are 48.64% SiO_2, 14.88% Al_2O_3, 14.85% Fe_2O_3 and 10% CaO. Basalt rock with a high acidity (SiO_2 content over 46%) and low iron content is the most desirable when it comes to the production of basalt fibers [6].

Table 2-1:Chemical composition of basalt rock. (Shrivastava, 2016)

		Elements	
$\mathbf{SiO_2}$	48.64	**Si**	17.26
$\boldsymbol{TiO_2}$	2.83	**Ti**	0.59
$\mathbf{Al_2O_3}$,	14.88	**Al**	5.51
CaO	10.02	**Ca**	2.51
$\mathbf{Fe_2O_3}$	14.85	**Fe**	2.65
$\mathbf{K_2O}$	0.34	**K**	0.08
MgO	5.77	**Mg**	2.37
$\boldsymbol{Na_2}\mathbf{O}$	2.77	**Na**	1.2
$\boldsymbol{P_2}\mathbf{O_5}$	0.19	**P**	-

The basalt rock with desirable chemical properties is used and subsequently crushed before being melted down at around 1500°C (~2700°F). The basalt fibers are made with a process very similar to glass fibers, the molten basalt rock is extruded though small nozzles which produce a large continues filament of basalt fiber [7]. The three main techniques that are used to manufacture basalt fibers are centrifugal-blowing, die-blowing and centrifugal-midroll. The resulting fibers have a filament diameter ranging from 9-13 µm [8]. The use of basalt rock is rather attractive due to its relatively low raw material cost and ease of filament production. Basalt textile products (weaves, knitted forms, sheets etc.) can sustain extremely cold temperatures (around -200°C) and temperatures all the way up to 700-800°C [9]. Compared to glass fiber the basalt fibers have a simpler processing because basalt fibers have a less complex composition. While additional additives are often required to make glass fibers, basalt rock is the only needed material to make basalt fibers. This makes basalt fibers a more environmentally benign alternative to other types of fibers [7].

2.3.2. steel fibers

Steel fibers are small pieces of steel wire that are between 0.3 to 1.1 mm in dimeter and can vary in length from 10 to 50 mm. Steel fibers have for a long time been the most common fiber type that is used to reinforce concrete and are used to replace steel mesh [10]. Steel fibers original intended use was in concrete slabs, tunnel linings and pavement for crack control. The use for steel fiber has expanded over the years to include other structural elements both on their own and in conjunction with regular steel reinforcement bars to act as secondary reinforcement.

The use of steel fibers has been so widespread due to the fibers' many favorable physical and mechanical properties. The main advantages of using steel fiber to reinforce concrete are increased impact strength, improved shrinkage behavior, longer service life, significant increase of resistance to cracks and deflections. The relation between fiber volume and the average crack width can be seen in *figure 2-6*. Steel has been the material of choice due to its relatively high modulus of elasticity and high strength. The steel fibers are also protected by the alkaline environment produced by the cement matrix. The surface of the steel can also easily be manipulated to increase the bond strength between the fibers and the matrix. This can be achieved by surface roughness or by mechanical anchorage [11]. As stated by a steel fiber producer, Tanis.by, Steel fibers also have many economic benefits such as decrease in construction time, decreased labor costs, easy manual and machine laying, reduction of coat thickness (Tanis.by, 2021).

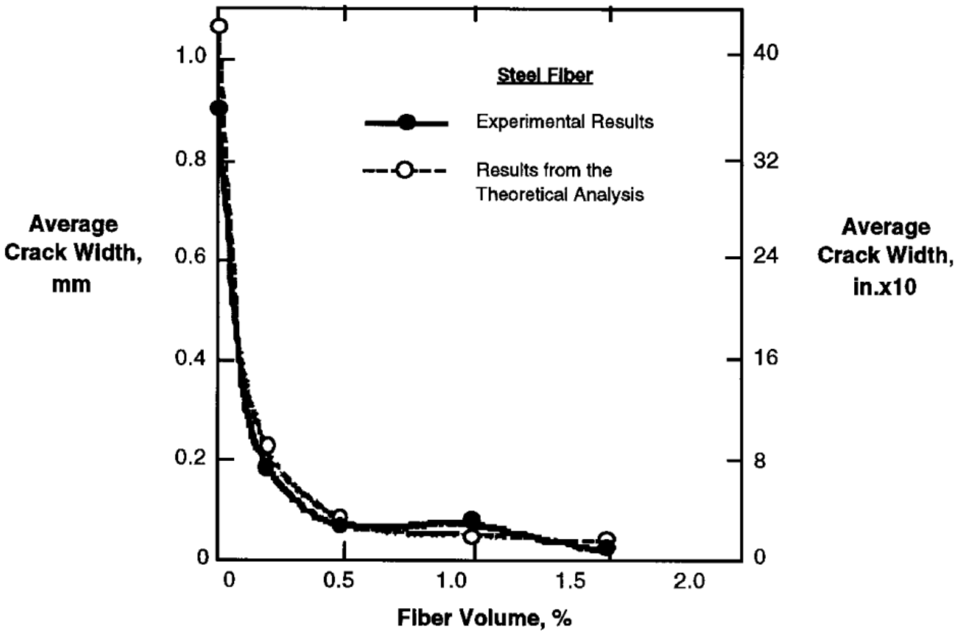


Figure 2-6: Average crack width vs. fiber volume %. (James I. Danie, 2002)

As with most other fibers, steel fiber reinforced concrete (SFRC) does not exhibit any major improvements to its compressive strength. The steel fibers effect can most clearly be seen in crack prevention and crack minimization due to changes in relative humidity or temperature. The figure bellow *figure 2-7* shows how steel fibers increase SFRC's post cracking carrying capacity and some modest benefits to compressive strength at high fiber volumes.
In Norway steel fibers are produced in accordance to the Norwegian standard NS-EN 14889-1. The steel fibers are typically manufactured from stainless steel or carbon steel with tensile strength varying from 345 to 2100 MPa. [12]

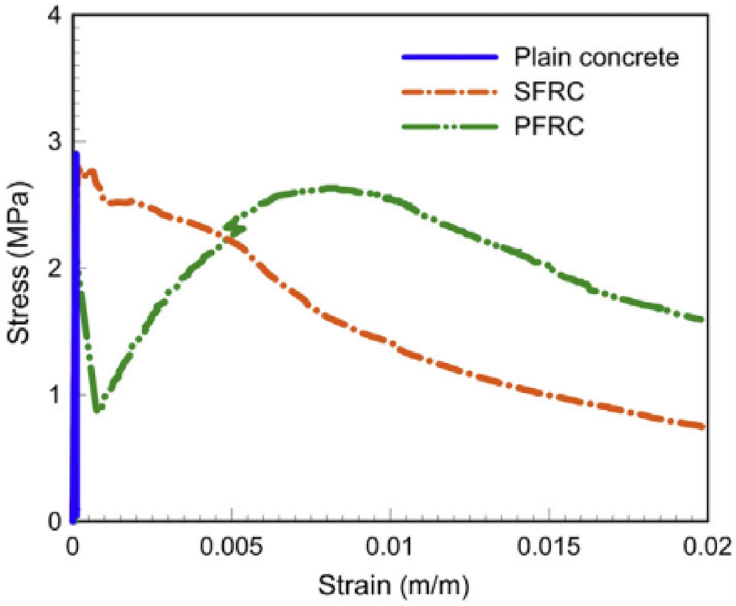


Figure 2-7: Post cracking behavior of SFRC compared with plain concrete and PFRC. (Choun, 2015)

Steel fibers have also shown to increase the tensile strength of SFRC. However, it is important to note that only fibers aligned in the same direction as the tensile stress contribute the most to the tensile strength. Correctly aligning the steel fibers is rather difficult as they are often randomly distributed throughout the composite, this leads to a typical tensile strength increase ranging from 0 – 60%. Therefore, using steel fibers to only increase tensile strength has been deemed not cost effective. Due to the steel fibers random distribution throughout the matrix a non-homogenous distribution can occur for small amounts of fiber volume (0.3%>). This can cause a lot of variation in the mechanical properties of different specimens with the same fiber volume and therefore a minimum fiber content (0.4-0.5%) has been established to achieve a homogenous distribution. [13]

Fiber efficiency is something to consider when talking about SFRC. Fiber efficiency refers to the resistance of the fibers to pull out from the matrix. Theoretical research has shown that fiber efficiency increases along with an increasing aspect ratio (fiber aspect ratio is defined as length divided by diameter). Fiber geometry is also important when it comes to fiber efficiency and post-cracking behavior as it determines the pull-out force vs. displacement of the fibers. [14] Examples of how different geometries affect the pull-out strength of the fibers can be seen in *table 2-2.*

Table 2-2: Pull-out strength for fibers with different geometries. [15]

Fiber type	**Diameter (µm)**	**Length (mm)**	**Fiber strength (Mpa)**	**Mean bond stress (Mpa)**
Plain straight	0.3	Various	1205	4.17
Indentions straight	0.5	30	955	8.10
Plain, Hooked end	0.4	40	1355	4.93
Plain, weak crimped	0.35	30	1295	5.25
Plain, heavy crimped	0.4	25	1615	13.4
Plain, enlarged ends	0.3 x 0.4	14.5	510	7.27

2.3.3. glass fibers

Glass fibers are produced in a similar way as basalt fibers, both types of fibers are composed of different oxides that compose a large crosslinked molecule with primary bonds. Due to this defining feature they can both be considered a special type of polymer. Glass and basalt fibers also share similar densities of 2.5-2.6 g/cm^3 and 2.6-2.7 g/cm^3 respectively. In glass fiber production overhead gas burners are most often used to heat the melt, the resulting glass melt is then rolled into a continuous or chopped roving or alternatively into a woven mat (*figure 2-8*) [16]. The first types of glass fibers that were ever used as concrete reinforcement were E-glass and A-glass fibers. While basalt fibers thrive in a high alkaline environment, E and A-glass fibers were found to be particularly sensitive to a such environment. This is problematic as the cement matrix causes rapid deterioration of the glass fibers due to the high alkalinity. Although glass fibers have a low alkaline resistivity, they are better at withstanding strong acids [16]. This led to the research and development of new types of glass fiber that could withstand the high alkaline environment of concrete. The result was the creation of AR- glass fibers that had a higher alkaline resistivity. This improved the long-term durability of glass fiber reinforced concrete (GFRC) but a loss of strength in other areas was observed. Long term aging is the main concern when it comes to GFRC [17].

Figure 2-8: a) Glass fiber woven matt, b) Continues roving, c) Chopped roving

Figure 2-9 shows the effect that GF has on the tensile strength of concrete beams. The tests concluded that the optimum volume of GF was 1% with other volumes such as 0.5% and 2% giving a modest increase meanwhile fiber volumes upwards of 3% resulted in a decrease of ultimate flexural strength. GFRC beams also experienced increased the ductility, this resulted in the beams experiencing a ductile failure compared to the brittle failure of the reference concrete. [18]

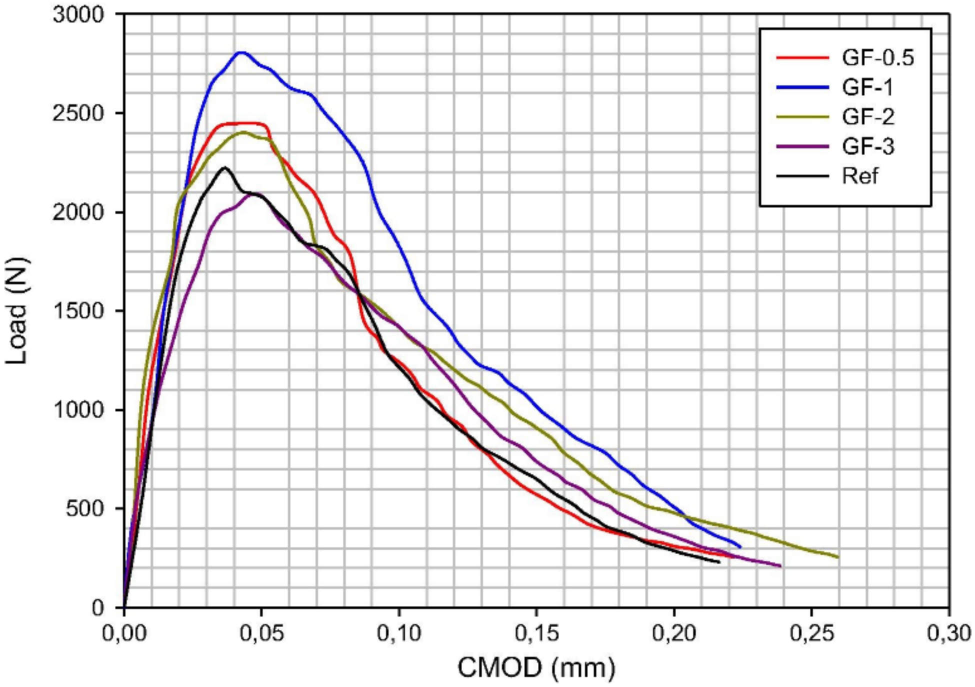


Figure 2-9: Load carrying capacity of 0.5%,1%,2% and 3% GF volume. [18]

2.3.4. synthetic fibers

Synthetic fibers have been gaining increasing attention over the past 2 decades. Different types of fibers have been developed to be used as reinforcement both as a replacement for steel or in situations where the use of steel reinforcement is not feasible. The mechanical properties of these synthetic fibers vary greatly and therefor the appropriate type must be picked out for the situation at hand. One of the most important factors to consider is the modulus of elasticity that the fibers have. The fibers are required to have a modulus of elasticity greater that of the matrix if they are to increase the strength of the composite. The modulus of elasticity of cementitious materials can range from 15 all the way up to 45 GPa. This critical condition has shown to be difficult to satisfy with synthetic fibers. This has led to the development and research of high tenacity fibers, “high tenacity” refers to a high modulus of elasticity and high strength. Even though high tenacity fibers are optimal for use as reinforcement in concrete, fibers with a low modulus of elasticity can still serve to benefit the structural integrity of concrete elements. Both theoretical and applied research have concluded that these lower grade fibers still lead to considerable improvements in strain capacity, toughness, impact resistance and crack control of FRC. In addition to a low modulus of elasticity early synthetic fibers were observed to have poor bonding with the matrix. These issues stemmed from the fiber’s chemical composition and surface properties. Advances have since been made with in this field, especially regarding polypropylene fibers. The use of synthetic fibers in cement and concrete applications only became feasible after the realization that specific properties had to be researched and developed. It is important to note that many of these modifications of the fibers are often patented and exclusive to the companies that have developed them. Therefore, in depth information on the fiber structures is not available in the open literature. This can result in a difference in behavior within the same “family” of fibers. Some changes that can be observed are fiber geometry, modulus of elasticity and alkaline resistivity [2].

2.3.4.1. Polypropylene fibers

Homopolymer Polypropylen resin is the main ingredient that is used in the production of Polypropylen fibers. The fibers can be produced in many different shapes and sizes and can have varying mechanical properties. The biggest advantage of polypropylene fibers is their relatively high alkaline resistance, low cost of production and relatively high melting point of around 165°C. The down sides of these fibers are their poor bond with the matrix, poor fire resistance, low modulus of elasticity (1-8 GPa) and a high sensitivity to oxygen and sunlight compared to other types of materials. The disadvantages of polypropylene fibers can often be negated, specifically through the enhancement of their mechanical properties to increase the modulus of elasticity and bond strength. The chemical structure of the fibers makes them hydrophobic resulting in the aforementioned lack of bond strength. To overcome this most polypropylene fibers undergo surface treatment to improve the wetting of the fibers. [19] Poor fire resistance and reactivity to sunlight and oxygen are not critical as the fibers are often embedded in a concrete cover and are thus protected from outside elements. Polypropylene fibers are produced in three main geometries, monofilaments, extruded tape and film, all of which serve the purpose of reinforcement for cementitious matrices. Alternatively, polypropylene fibers can be produced in continuous mats. The modulus of elasticity and tensile strength of commercially available monofilaments and mats are in the range of 3-5 GPa and 140-690 MPa respectively. [20] [21]

Krenit fibers are a type of high tenacity polypropylene fibers that have been developed in Denmark. The fibers are first produced in an extruding tape which is subsequently mechanically split into single rectangular fibers. This splitting process results in the edges of the fibers becoming uneven and frayed and therefore creating a better bond with the cement matrix. This mechanical process of splitting the fibers can be controlled to adjust the degree of fraying to match the desired application. The classification of the Krenit fibers as high tenacity is due to their relatively high modulus of elasticity and tensile strength of 7-18 GPa and 500-1200 MPa respectively. Due to the fibers modulus of elasticity still being below that of the matrix their main use is control of plastic shrinkage cracking. [22]

2.3.4.2. Polyester fibers

Polyester fibers generally have slightly higher mechanical strength than polypropylene fibers with an elastic modulus and tensile strength ranging from 10-18GPa and 280-1200MPa respectively. Polyester fibers are available in the form of monofilaments, however the fibers are not considered stable in an alkaline environment and are therefore not suitable for use in FRC. [2]

2.3.4.3. Nylon fibers

Nylon fibers have a history of being used as a replacement to polypropylene fibers in FRC. These fibers are stable in an alkaline environment and are therefore suitable for use as concrete reinforcement. The nylon fibers are manufactured as a type of high tenacity yarn that is then cut to a desired length. Unlike polypropylene fibers, nylon fibers are both light and heat stable and also have an elastic modulus and tensile strength of 4GPa and 800 MPa respectively. It is important to note that the fibers are hydrophilic meaning they can absorb up to 4.5% of water, hence this must be considered when using large volumes of nylon fibers. [23]

2.3.4.4. Polyethylene fibers

Polyethylene fibers are of considerable interest when it comes to their use in FRC, they can be easily mixed using conventional batching techniques. These fibers can be mixed in rather large volume of up to 4% or alternatively in a continuous network of fibrillated fibers where around 10% of the composite is composed of fibers. The main use for these fibers is to increase post cracking load bearing capacity. The effect of discontinues shot fibers on load deflection can be seen in *Figure 2-10*, the best effect can be observed at 1.25% fiber volume. Polyethylene monofilaments circumvent the problem of poor bond strength seen in other synthetic fibers such as nylon and polypropylene by having “wart like” surface deformations. Polyethylene fibers manufactured for use in FRC typically have an elastic modulus of 5 GPa and a tensile strength of 80-600 MPa, however newer polyethylene fibers have been developed with a much higher elastic modulus of around 15-32 GPa, similar to that of cement matrices. [24]

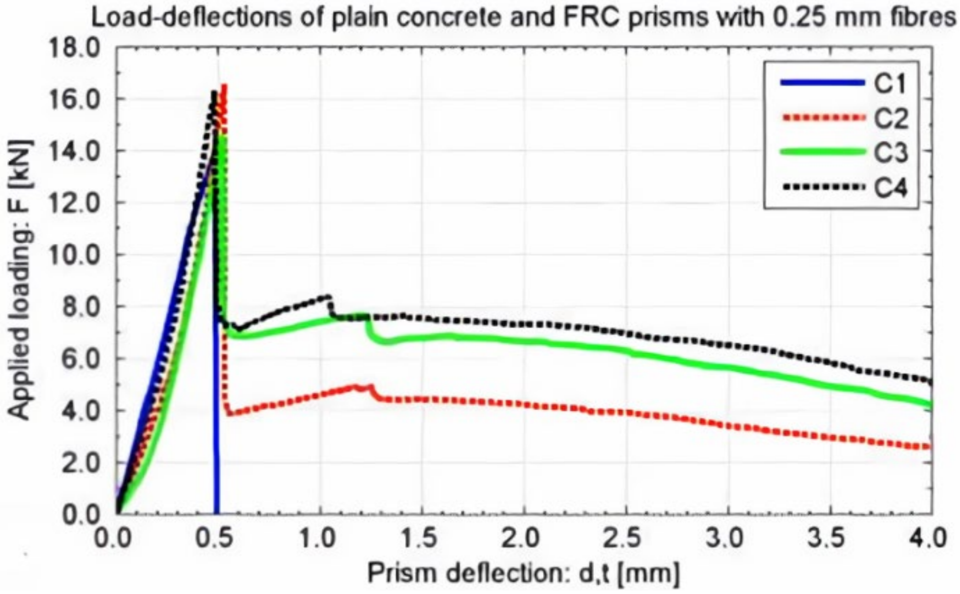


Figure 2-10: The flexural ductility of Polyethylene FRC. C1 – plain concrete, C2 – 0.4%, C3 – 0.75%, C4- 1.25%. (Zivanovic, 2016)

2.3.4.5. Carbon fibers

Carbon fibers were originally developed for use in the aerospace industry because of their desirable mechanical properties such as a high elastic modulus and high strength. In later years the use of carbon fibers has seen expanded use in broader structural engineering applications. The carbon fibers are made of tows, each of these tows consists of around 10,000 filaments. The filaments have a diameter ranging from 7 – 15 µm, the carbon atoms in the filaments are organized in a hexagonal array as shown in *Figure 2-11*. The carbon atoms withing these plains are held together by covalent bonds making them extremely difficult to break. To achieve a high modulus of elasticity and strength the planes must be layered and aligned parallel to the fiber axis. In practice this is rather difficult to achieve resulting in carbon fibers having varying properties depending on the degree of perfection. [25]

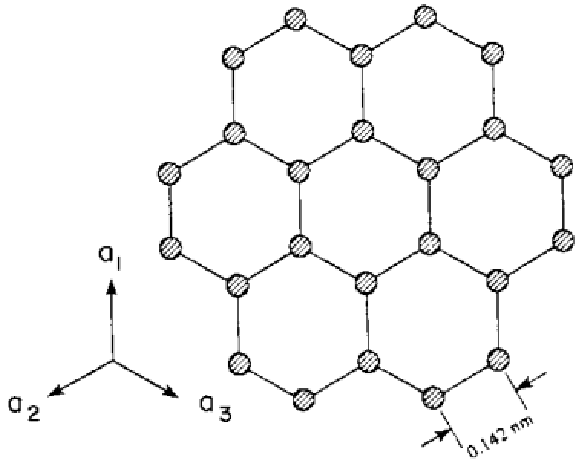


Figure 2-11: Carbon atoms arranged in a hexagonal array. [2]

There are two main ways of producing carbon fibers, each method is based on different starting materials. The first method is using polyacrylonitrile also known as PAN carbon fibers, the second method is using coal tar and petroleum pitch, these are known as pitch carbon fibers [26]. A better overview of each fiber type's properties can better be seen in *table 2-3*.

Table 2-3: Properties of PAN (type I and II) and pitch carbon fibers [27]

	PAN, Type I	**PAN, Type II**	**Pitch**
Diameter (µm)	7,0-9,7	7,6-8,6	18
Density ($\frac{Kg}{m^3}$)	1950	1750	1600
Modulus of elasticity (Gpa)	390	250	30-32
Tensile strength (Mpa)	2200	2700	600-750
Elongation at break (%)	0,5	1,0	2,0-2,4

Both types of fibers are manufactured in similar ways involving heat treatment. The grade of carbon fibers produced varies depending on the combination of oxidation, heat treatment and stretching. PAN fibers are regarded as superior when it comes to quality and subsequently have a higher production cost. The PAN fibers can be classified into two categories, type I and II. Type I fibers have a higher elastic modulus while type II fibers have a higher tensile strength. Pitch fibers on the other hand have a significantly lower elastic modulus and tensile strength, to compensate for this pitch fibers are much cheaper to produce. Even though the pitch carbon fibers have poorer mechanical qualities than PAN fibers they are still seen as more attractive for use in FRC due to their cost paired with their elastic modulus which matches that of cement matrices.

The use of both PAN and pitch fibers has shown to greatly increase the tensile strength of FRC. However, a significant increase in compressive strength cannot be seen, only with 3% fiber volume is there a slight increase and even a small decline when using fiber volumes of 4% or more [27]. Carbon fiber reinforced composites also exhibit a significant improvement of post-cracking behavior and flexural strength as can be seen in *figure 2-12*.

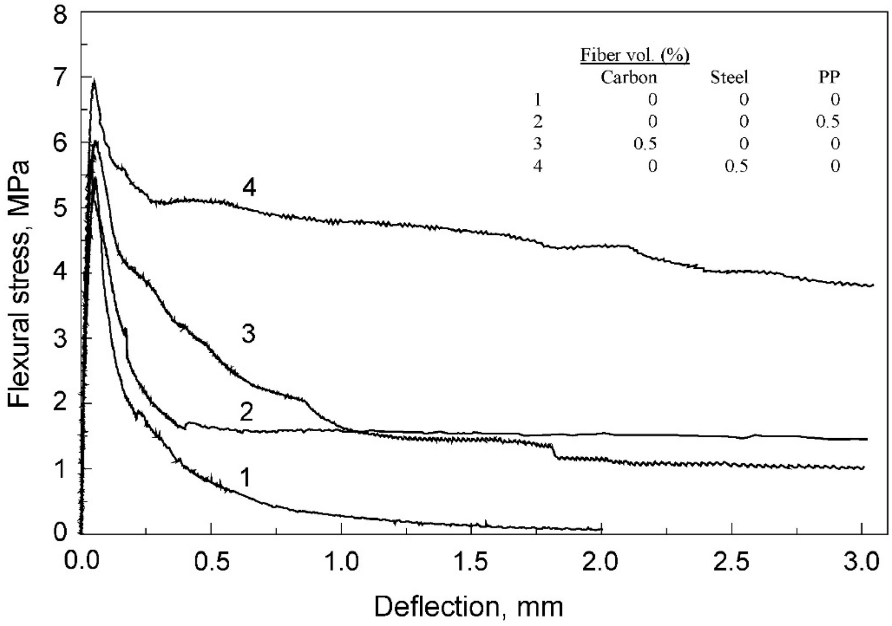


Figure 2-12: Comparison of different carbon fiber types (pitch and PAN) at different volumes. (Yao, 2003)

An interesting change in the load deflection curve after strengthening the matrix by altering the w/c ratio has been reported by Delvasto and co. Low toughness was observed in the lower (w/c = 0.298) w/c ratio. Although densifying the matrix has shown to have an adverse effect on the post cracking behavior without any increase in maximum sustained load the denser matrix has been observed to have a better bond with the fibers leading to a failure by fiber fracture rather than pullout. It is important to note that fiber lengths of 0.8-1.4mm carbon fibers were used but ended up breaking upon mixing resulting in a fiber length reduction of 3-4x of their original length. [28]

Both PAN and pitch fibers have shown to be effective at reducing strains in the concrete due to swelling and shrinkage concluding that carbon fibers are demntionaly stable. This reduction in strains seems to greatly increase with higher fiber contents, Briggs reported that the shirnkage was rudeced by a factor of 10 for 5,6% fiber content comapred to a reduction of 2-3 for 3% fiber. [29]

2.4. Mechanical properties of concrete and FRC

The properties of cement base matrices are improved in the curing and cured state through the addition of fibers. The fibers are able to bridge the cracks created in the concrete and counteract further crack growth. They also improver the durability and the fatigue behavior of the composite. The mechanical properties of FRC are affected by a multitude of factors such as:

- Fiber: geometry, volume, aspect ratio, orientation, distribution, type

- Specimen: size, casting method, curing method, loading speed of fibers, geometry
- Matrix: strength, max unit size

Fibers affect the cementitious composite in a variety of ways. In some cases, the fibers significantly improve the mechanical properties while in other cases have been observed to even hamper performance. The following subsections will describe the different mechanical properties of fiber reinforced composites

2.4.1. Strength in compression

Toughness is used to measure the ability of the FRC to absorb energy during deformation. Plain concrete is rather brittle and cannot carry any significant loads after cracking, FRC with low fiber volume performed better and FRC with high fiber volumes preformed significantly better. The FRC was able to carry loads past the cracking of the matrix resulting in increased ductility, toughness, and energy absorption. The addition of fibers can have varying effect on the compressive strength of the concrete, the fiber volume and fiber material are crucial. *Figure 2-13* shows how the compressive strength varies with different amounts of steel fiber volumes. When considering the use of FRC, compressive strength is usually not the main focus. This is because plain concrete is naturally strong in compression and can often handle the required loads on its own. [30]

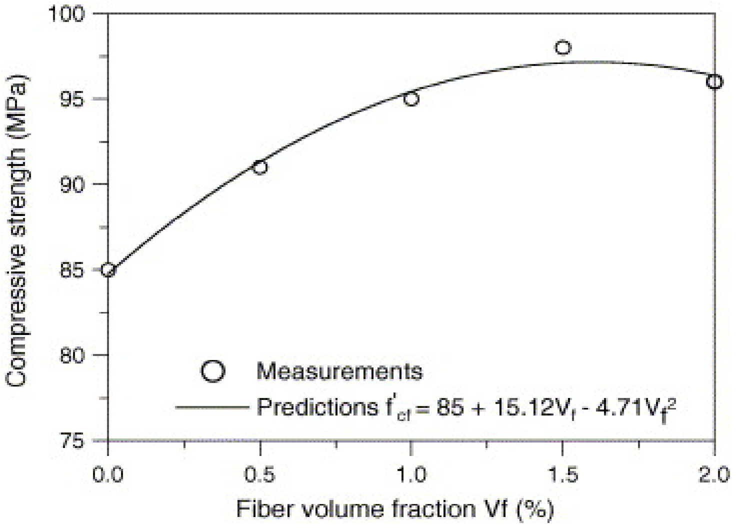


Figure 2-13: Effects of different SF volume fractions on compressive strength. (Song, 2004)

These same observations have been reported by Doo-Yeol and co. in a study regarding the effect of fibers on stress-strain of concrete in compression. Their results *figure 2-14* showed a significant increase in ductility but a rather small improvement in compressive strength [31]. Others such as Karihaloo and de Vriese observed an increase of 21% in compressive strength when comparing reactive powdered concrete with no fiber and reactive powdered concrete with a fiber volume of 4%. Similarly, Sun observed a 33% increase by recreating the same composite and test conditions. [32]

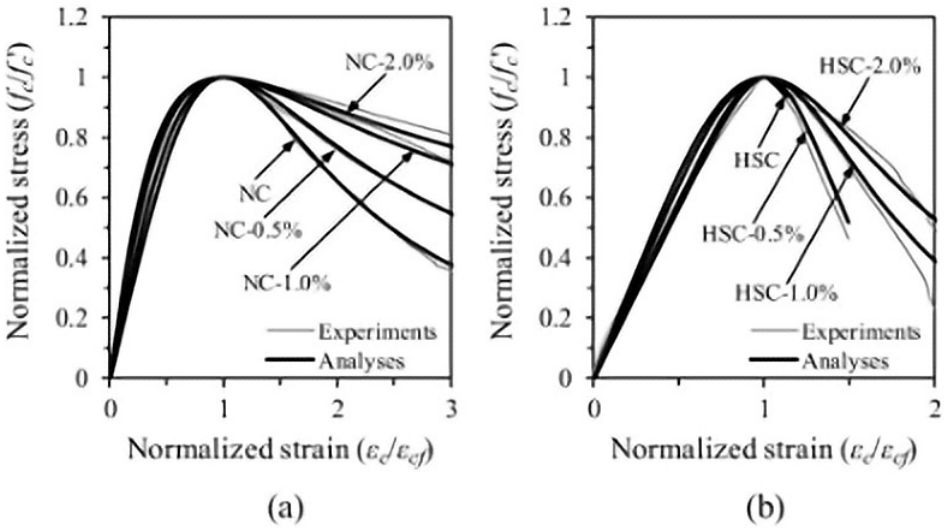


Figure 2-14: : Effects of different volume of steel fibers on stress-strain and compressive strength. NC – Normal strength concrete, HSC – High strength concrete. (Doo-Yeol, 2015)

2.4.2. Strength in tension

The behavior of concrete in tenson can be generalized into two different classes, either tensile softening or tensile hardening. Normal concrete is generally referred to as a tensile softening material. The same can be said for concrete with low to moderate volume fractions of fibers. There have been varying opinions among researches as to whether the addition of fibers leads to an increase of tensile strength. Zheng and co. compared the effects of fibers on the mechanical properties and found an increase of 36.99% in splitting tensile strength for fiber volumes up to 2% as shown in *figure 2-15* [33]. Shah and Rangan found that he orientation of the fibers was crucial when it comes to FRC, fibers that had been adjusted in the same direction as the tensile load gave a very large increase of direct tensile strength. The composite that was tested had a volume fraction of 5% smooth steel fibers and resulted in a 133% tensile strength increase. This is in contrast to the effect of randomly distributed fibers which can vary enormously. As with compression, steel fibers provide large increases in toughness and ductility of the composites. However fibrs apear to be more effectiv in tension than in compression [12]. Simmilar behaviour was obsevered by Krstulovic-Opara when testing the strength of SIMCON. The strength increased by aproximally 150% as a result of increasing the volume fraction of fibers from 2.16% to 5.25%. Tensile stregnth for SIMCON with 5.25% fibers was around 17 MPa. [34]. Shah and Rangan also tested the effect that different fiber shapes on the tenisle load bevaior. *Figure 2-15* shows the results of straigh, hooked and enlarged-end fibers, they concluded that deformed fibers perfomed best due to having a better anchroing effect and increasing the tenisle resitance beyond the first crack. [12]

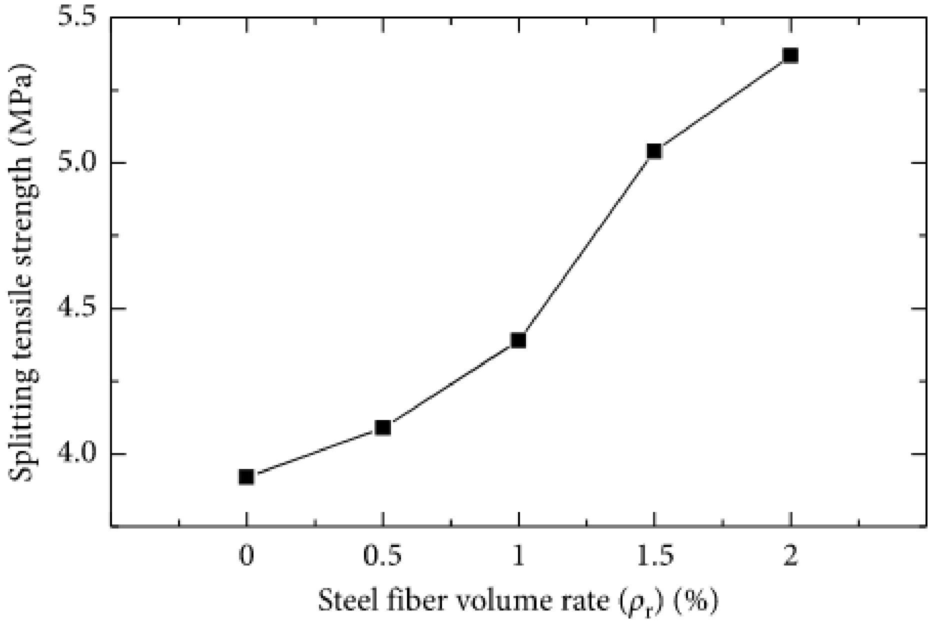


Figure 2-15: Effect of fiber concentration on splitting tensile strength in FRC. (Zheng, 2018)

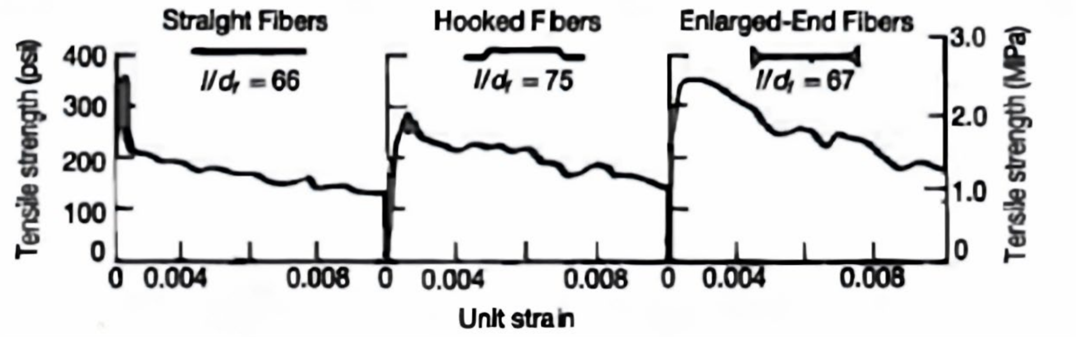


Figure 2-16: Effect of different shaped steel fibers on tensile strength in FRC. [12]

2.4.3. Shear strength

The combination of vertical stirrups and randomly distributed fibers within the matrix improves the shear capacity of beams and columns. Williamson conducted a study that reported an increase of 45% in shear capacity over beams without any stirrups, both beams contained a fiber volume of around 1.7% straight steel fibers. The same teste was preformed instead with a fiber volume of 1.1% deformed steel fibers, this resulted in a 45-67% increase in shear capacity. The fibers were again switched out with crimped fiber the shear capacity increase by around 100% [35]. Valle and Buyukoztyrk found a significant increase in the ductility and shear capacity of SFRC. The improved mechanical properties seemed to best in the case of high-strength concrete, this was due to the improved bonding between the fibers and the high-strength matrix [36]. Sun found and increase of 400% in shear strength, from 4 to 16.6 MPS, when comparing ordinary non reinforced concrete to SFRC with volume percent of 2.5%. [37] However, Barr concluded that shear strength was independent of fiber content but found a relation between increasing toughness of the composite and increasing fiber content. There seem to be varying results and conclusions regarding fibers effect on ultimate shear strength, but somewhat similar behavior can be seen as in compression and tension, that is an increase in toughness and ability to carry loads past cracking [38].

2.5. Material composition

2.5.1. General

The most important phase in a concrete mix is the proportioning. In general, making a concrete mixture comes down to following a recipe to get the desired chemical reaction and the proportions of the different ingredients that are used determine the quality and properties of the mixture. The ratios of ingredients that are chosen depends on the situation and the requirement of the specific project at hand. Through correct proportioning one can manipulate the strength, workability, machineability, durability and so on. Usually when making and proportioning FRC you have to find a good balance between cured state performance and workability, this may sometimes require a reduction in strength to be able to properly cast the concrete. For small amounts of fiber volumes (around 0.5%) regular concrete mix design can be used but for larger amounts of fiber the mix design should be adjusted based on usability and workability considerations. The addition of fibers has a negative effect on the concrete's workability with increasing fiber volumes and the margins for proportioning are rather narrow and making an optimized blend composition is difficult. *Figure 2-17* shows the difference of mix design between concrete with fibers and concrete without fibers. [39]

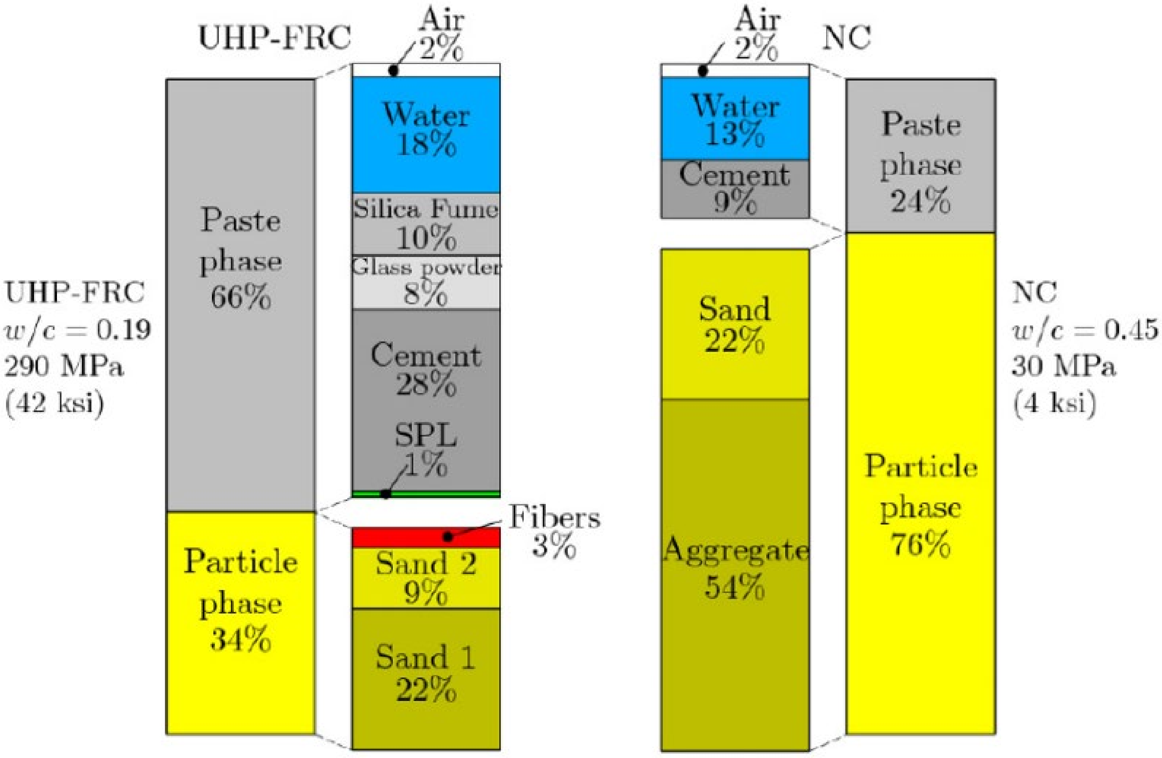


Figure 2-17: Comparison between the mix design of Ultra high-performance fiber reinforced concrete (UHP-FRC) and normal concrete. (Naaman, 2012)

The maximum fiber volume and workability of a concrete mixture are determined by factors such as:

- The type of fibers used
- Content of fibers
- The matrix in which the fibers are embedded
- Properties of the ingredients used in the matrix
- Technique used to add fibers into the mixture and blending process

As mentioned before the design of FRC is mostly based around usability, this chapter will therefore take a look at how the material composition affects flowability, workability and stability.

2.5.2. Packing density

The addition of fibers into the matrix of the concrete results in a much denser matrix compared to that of conventional plain concrete. When considering a dense matrix, it is important to achieve sufficient packing density of all granular elements [40]. The packing density has been defined by Grünewald as the bulk density divided by the density of all the solids [41]:

$$PD = \frac{\frac{W_B}{Vol_c}}{\rho}$$

Where,

- PD is the packing density [-]
- W_B is the total weight of the solids [Kg]
- Vol_c is the total volume of the mold/container used $[dm^3]$
- ρ is the mean specific gravity of the solids $[\frac{Kg}{dm^3}]$

The packing density is regarded as a characteristic of the concrete's granular skeleton, the granular skeletons is defined as the aggregates and fibers withing the matrix. It takes into account the distribution and geometry of the grains, the packing process and the agglomeration degree of the powders used. Having a densely packed mixture requires less binder, it is therefore important to use particles of different sizes when proportioning FRC. The size difference of the particles causes the smaller ones to fill the voids between the larger particles, this in turn increases the packing density of the composite. *Figure 2-18* shows the difference between a loosely packed system and a densely packed system [42].

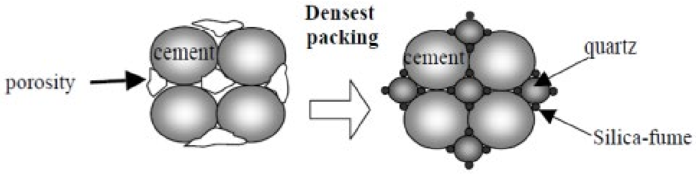


Figure 2-18: Effects of small particles on packing density.

The benefits of having a densely packed system can be seen in the interfacial transition zone (ITZ) around the aggregates. Having a highly porous ITZ results in a reduction of the concretes compressive and tensile strength and accelerates the rate of processes such as alkali-silica reaction and sulphate attacks. Therefore, having a densely packed system will aid in reducing the porosity of ITZ. Having a higher density also increases the number of contact points between the concrete and the fibers creating a better bond between the two [42].

2.5.3. Matrix volume

Concrete is considered as a two-component system made up of a matrix phase and a particle phase. The matrix phase is the flowable part of the concrete, this phase consists of free water, solid material that is smaller than 0,125mm such as cement, fly ash, filler, silica fumes and lastly additives. The matrix serves the purpose of filling the voids between the aggregates and incases the solid particle phase. The packing density plays a role as to how many voids are present in the mixture and thus a more densely packed granular skeleton will require less paste. Excess paste serves are a lubricant by surrounding the outer layer of the solids, shown in *figure 2-19*. As a result, this reduces the friction between fibers and particles and creates a more workable final product. Having a large amount of fine particles (silica fume, fly ash, filler) ensures that FRC will have optimal compactability and flow. Silica fume is especially useful due its very fine particles which are far smaller that of the cement and thus is effective at filling voids. Additionally, superplasticizers are often used to decrease the porosity of the granular skeleton through dispersing filler and flocculated cement particles and as a result substantially increasing the fluidity and workability. [41]

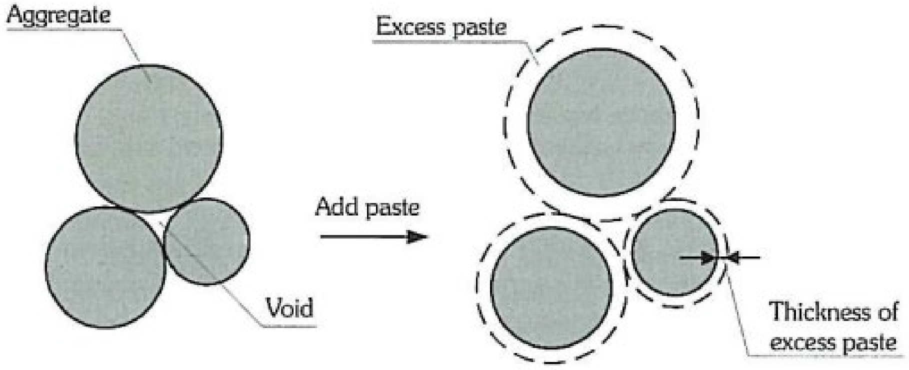


Figure 2-19: Effect of adding past to the existing aggregates. (Oh S. G., 1999)

Markovic and co. applied a model for self-compacting FRC, this model gave the required amount of cement paste if the packing density of the system is known. The model states that the amount of paste required for self-compacting FRC is divided into components [43]:

- V_p - The minimum paste content required to fill voids between aggregates and fibers

$(V_{pa}+V_{pf})$ – Additional paste content required to cover all fibers and aggregate. The composition of the final concrete mixture is then represented by volumes as:

$$V_a + V_f + V_p + V_{pa} + V_{pf} + V_{air} = 1$$

Where,

- V_a – volume of aggregates
- V_f – volume of fibers
- V_{air} – air content

Markovic and co. applied this model on concrete mixes with two different types of fibers, the first being 6 mm long straight steel fibers and the second being 60mm long hooked-end steel. They came to the conclusion that the model was applicable for short fibers and worked rather well for the longer fibers in volumes up to 1%. [43]

2.5.4. Fiber content

There are a multitude of reasons for why fibers effect the workability and flow of fresh concrete. Fibers have a much more elongated shape comparted to aggregates, this result in a much greater surface area at the same volume. Higher surface areas result in an increased water demand. The use of stiff fibers also causes the fibers to push the large aggregates particles away from each other causing an increase in porosity while smaller and flexible fibers fill in the spaces between the large particles. Flexible fibers also have a higher surface area than stiff fibers, Ando and co. preformed flow spread tests of FRC and found the flow spread to decrease linearly with increasing surface area of the carbon fibers, see *figure 2-20*. Fibers such as steel fibers are often deformed and as a result cause a much greater anchoring effect between the fiber and the matrix making the fresh concrete harder to handle [44]. Swamy and Mangat found a linear relation between the packing density and the aspect ratio for given fiber diameters and volume fractions [45]. The same conclusion was reach by Grünewald where tests were carried out to compare the packing density with steel fibers, a multitude of different aspect ratios and volume fractions were tested, the result can be seen in *figure 2-21*. [41]

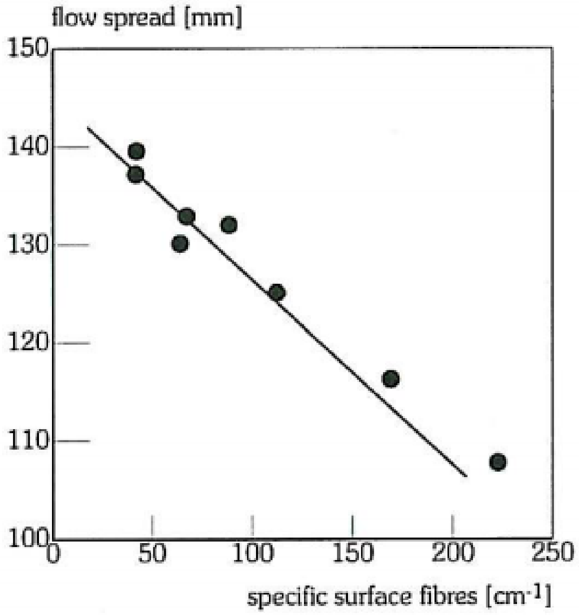


Figure 2-20: Relation between flow spread and specific surface area of carbon fibers (Ando T., 1990)

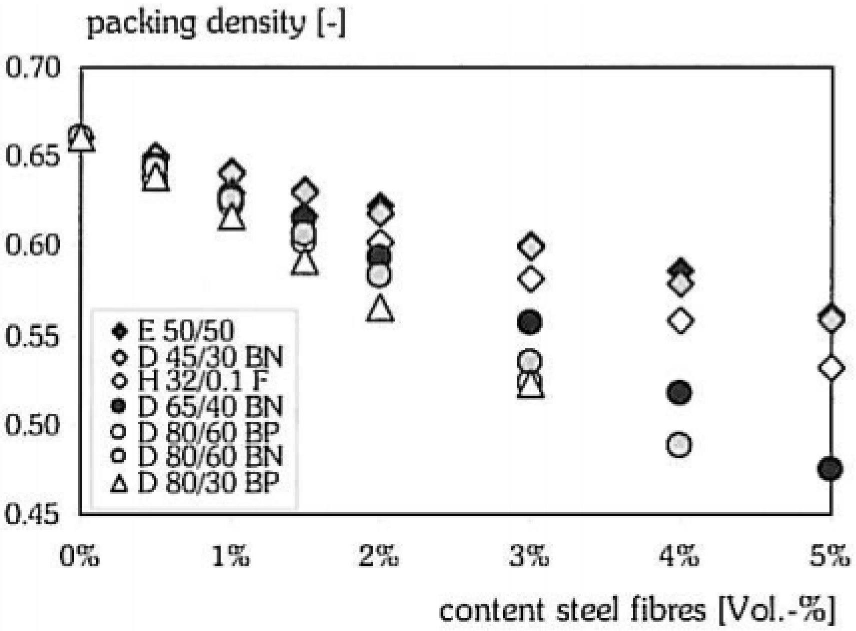


Figure 2-21: Packing density with steel fibers of varying volume fraction and aspect ratios. The first fiber index represents aspect ratio of the fiber and the second represents the length of the fiber (Grünewald, 2004)

Edgington and co. further back up that fiber content affect the workability and flow. They performed a study on the effect of fiber content and aspect ratio on the V-B time of concrete with a maximum aggregate size of 5mm. *figure2-22* shows the result of their studies. Through the work presented in this section it is safe to conclude that fiber type and content affects the flow and workability of concrete to varying degrees. [46] It is therefore important to choose a fiber volume that gives sufficient workability and at the same time gives the desired mechanical improvements to the composite.

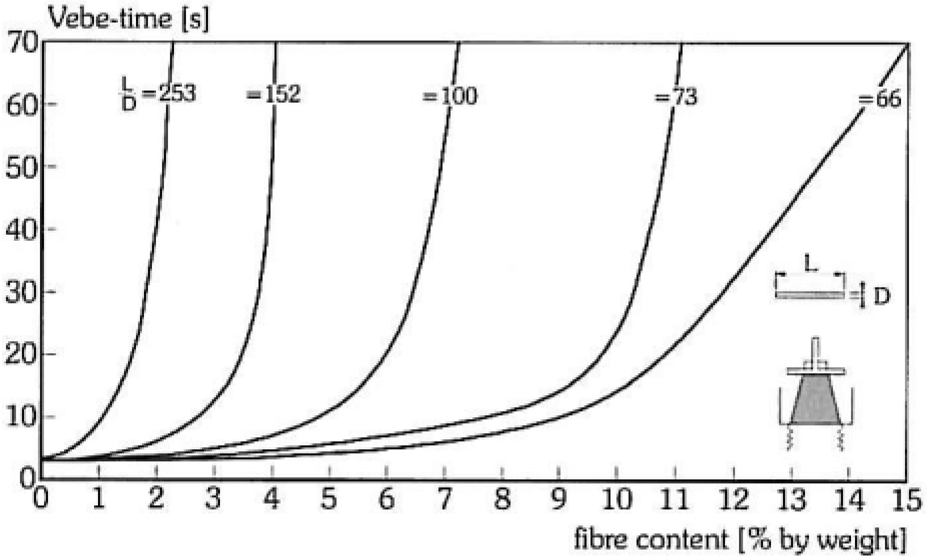


Figure 2-22: V-B time of concrete with 5 mm aggregates with different volumes of fibers and aspect ratios (Edgington J., 1978)

2.5.5. Aggregates

The workability of concrete is also influenced by the shape, size and content of coarse aggregate. As previously mention the introduction of fibers into the concrete mix reduces the workability, decreases the packing density, and increase the porosity of the granular skeleton. How much the porosity is increase depends on the size of the aggregates relative to the length of fibers used, as shown in *figure 2-23*. The general rule is that the fiber length should not be smaller than the maximum aggregate size used in the concrete, this is to maximize the fibers effectiveness in the hardened state [47]. Other more drastic suggestions have been made by Grünewald such as that the fiber length should be 2 to 4 times the length of the maximum aggregate size [41]. When the fiber content is increased it is suggested to add more fine aggregate content compared to coarse aggregate. Swamy and Mangat suggested a diagram (*figure 2-24)* that depicts how the maximum amount of fibers decreases when increasing the coarse aggregate content. The diagram was derived through testing 25mm long steel fibers and aggregates with a maximum size of 10 mm [45].

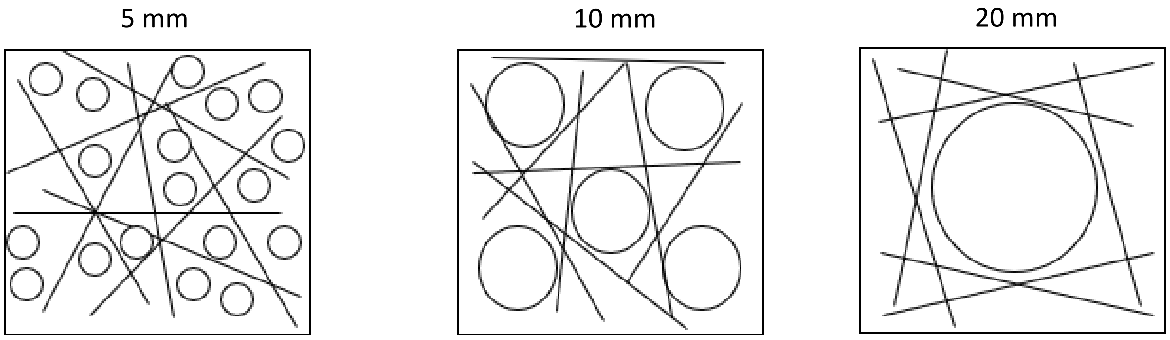

5 mm
10 mm
20 mm

Figure 2-23: The effect of aggregate size on fiber dispersement cubes are shown as 40x40 mm (Johnston, 1996)

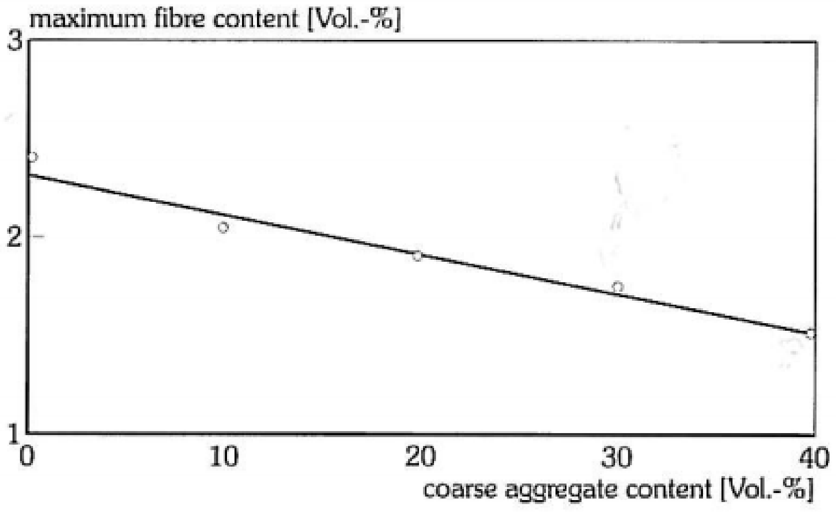


Figure 2-24: Relation between fiber content and coarse aggregate content (Swamy RN, 1974)

Similar conclusion was reached by narayanan and kreem-Palanjian. They found that the amount of fibers that was optimal increased when increasing the percentage of sand (3mm) and total aggregates in the concrete mixture. They used a variety of steel fiber types with lengths ranging between 25-43mm and a maximum coarse aggregate size of 14mm [48]. In an effort to optimize the granular skeleton of FRC Rossi and Harrouche proposed a deign method where they assumed that the optimal granular skeleton was independent of the cement paste. The composition and volume of the cementitious paste was kept constant. The design was based on testing different sand to gravel ratios and analyzing the flow time through the use of a LCL Workability meter, their goal was to find the optimum workability of FRC depending on the sand content [49].

An investigation was performed by Grünewald to see how the packing density was affected by the amount of sand in the aggretates with different conentes and types of steel fibers. The results can be seen in *figure 2-25*, the figure shows how different sand contents affected the packing denisty. The test was preformed with 1.5% fiber volume. The packing denisty was most affected at low sand contents. The figure also shows that the maximum packing density was achieved between 50% to 75%. The addition of more sand content to the mix seemed to be detrimental past 80%. To counteract the effect of adding fiber to the mix, a higher amount of fine aggregates needs to be incuded to compensete [41]. The same results were achived by Hoy, who prefmored a therotical study of the packing desity on SFRC's granular skeleton through the use of a particle packing program known as Solid Suspenion Model (SSM). As a result, the optimal sand content for a particulare volume of fibers was obtained and can be seen in *figure 2-26*. As previously theorized, the higher the fiber content the higher sand conent had to be. Sand conent also had to be increase with and increase of the fiber's aspect ratio. It is important to note that even though the figure applies for fiber volumes up to 17%, volumes greater than 2% create significant reduction in workabilty and handling [50].

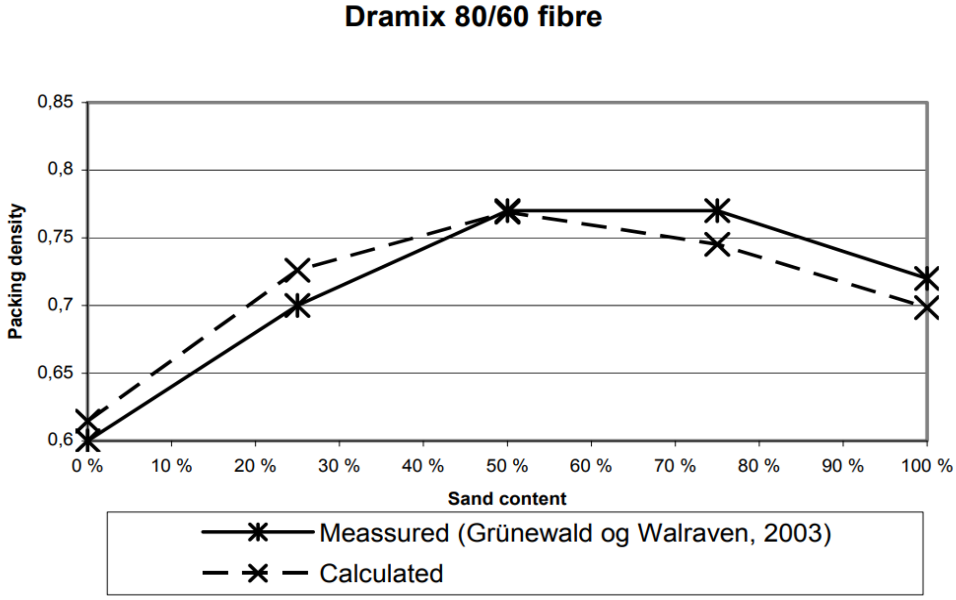


Figure 2-25: The effect of varying amounts of sand content on the packing density of FRC. (GRÜNEWALD, 2003)

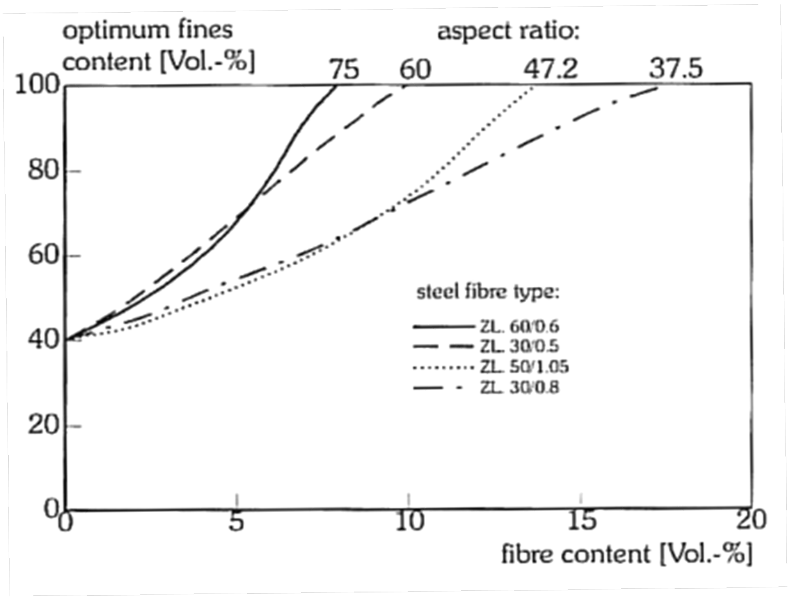


Figure 2-26: Theoretical (SSM) optimal amount of fine aggregates for varying amounts of fiber volume. (Hoy, 1998)

Edgington and co. researched the effect that fiber content and different maximum aggregate size had on the V-B time of concrete. All concrete mixes contained steel fibers with an aspect ratio of 100. They concluded that the V-B time of the concrete increased when using larger maximum aggregate sizes for specific steel fiber volumes, seen in *figure 2-27*, aggregates particle smaller than 5 mm were reported to not have little to no effect on the compaction behavior of the concrete mixture. Edgington and co. came up with an equation which can be used to estimate the critical percentage fibers. Beyond the critical percentage the SFRC would be unworkable. Where $PW_{C_{crit}}$ is the critical percent of fibers, it is recommended that the fiber volume in the concrete should not exceed 0.75*$PW_{C_{crit}}$ so that proper compaction can be achieved [46].

$$PW_{C_{crit}} = 75 * \frac{\pi * SG_f}{SG_c} * \frac{d}{l} * K$$

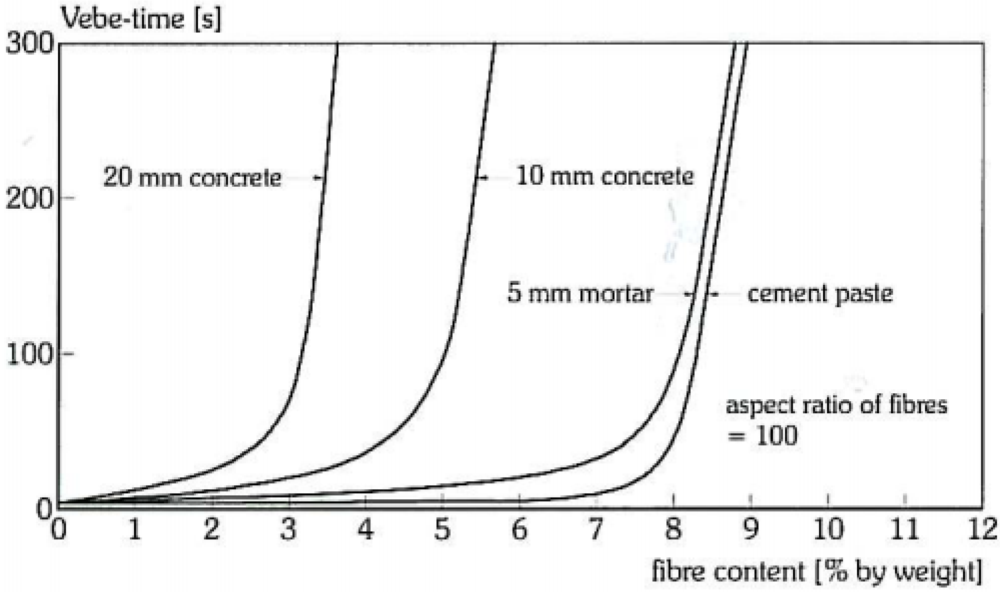


Figure 2-27: Effect of fiber content and different maximum aggregate sizes on V-B time (Edgington J., 1978)

2.6. Common types of cement in Norway

2.6.1. Standard FA cement

NORCEM Standard FA cement is a cement for ordinary concrete structures. The cement contains fly ash and therefore solves the problems for those users who have a reactive concrete aggregate. By using Norcem Standard cement FA, you can have greater flexibility in choosing an aggregates supplier. Norcem Standard cement FA is adapted to Norwegian conditions and can be used for concrete in all exposure, durability, and strength classes. Standard FA cement provides durable concrete in combination with alkali-reactive aggregates.

Strength development is a key feature when it comes to planning, managing and construction of concrete structures. The strength development is dependent on the type of cement used, w/c ratio, aggregates, curing conditions (temperature, time, and humidity), use of additives and reinforcement. *Figure 2-28* shows the development of compressive strength as a function of mass ratio (effectively w/c) and age at 20 degrees Celsius water storage for concrete made with Norcem Standard FA cement.

Resistance to alkaline attacks is an important property to consider when looking at different types of cement. The Norwegian concrete association has set guidelines for the production of durable concrete with alkali-reactive aggregate. In the guidelines it is stated that for concrete with standard FA cement alkali-reactive aggregate may be used if the concrete alkali content does not exceed specific values.

The Norwegian standard, NS-EN 206: 2013 + NA: 2014 classifies the concrete's environmental impact in exposure classes. The exposure classes are grouped into different durability classes with different requirements regarding the concretes maximum mass ratio (w/c), these classifications can be seen in *figure 2-29*.
The Cement satisfies the requirements in accordance with: NS 3086: 1995 - Portland CEM II AV-42.5 R fly ash cement. The chromate content in Norcem cements is in accordance with the regulations of the Labor Inspection Authority of Norway [51].

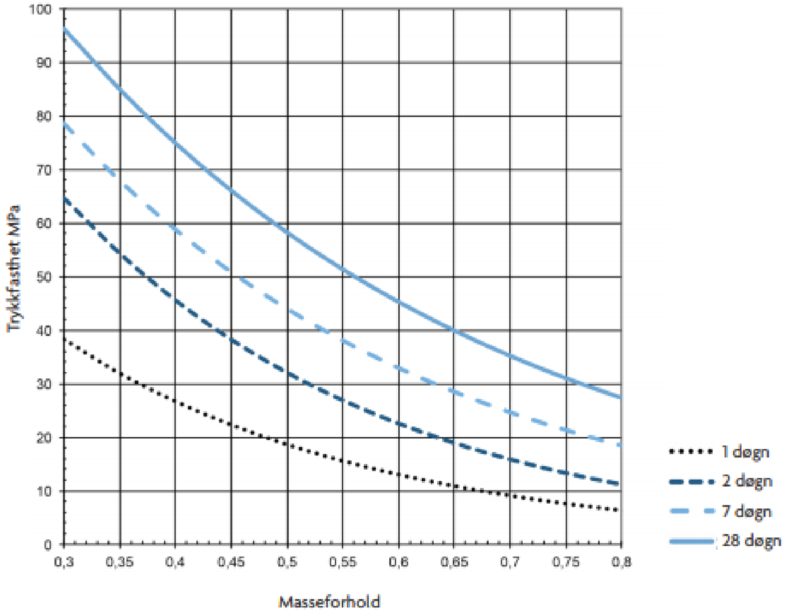
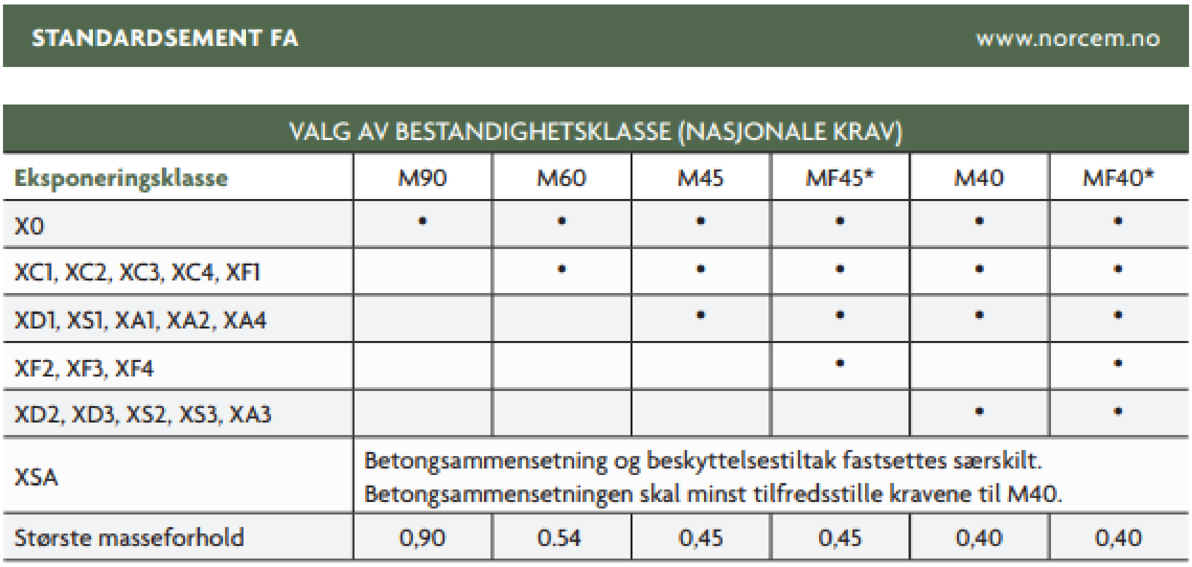


Figure 2-28:Compressive strength of concrete made using Standard FA cement after 1 day, 2 days, 7 days, and 28 days at varying mass ratios(w/c) (Norcem, 2021)



STANDARDSEMENT FA www.norcem.no

VALG AV BESTANDIGHETSKLASSE (NASJONALE KRAV)						
Eksponeringsklasse	M90	M60	M45	MF45*	M40	MF40*
X0	•	•	•	•	•	•
XC1, XC2, XC3, XC4, XF1		•	•	•	•	•
XD1, XS1, XA1, XA2, XA4			•	•	•	•
XF2, XF3, XF4				•		•
XD2, XD3, XS2, XS3, XA3					•	•
XSA	Betongsammensetning og beskyttelsestiltak fastsettes særskilt. Betongsammensetningen skal minst tilfredsstille kravene til M40.					
Største masseforhold	0,90	0.54	0,45	0,45	0,40	0,40

*Figure 2-29: Exposure classes, durability classes and maximum mass ratio(w/c) for Standard FA cement. *at least 4% air content (Norcem, 2021)*

2.6.2. Industrial cement

Norcem Industrial cement is a special cement with rapid strength development and is suitable for use in the production of concrete elements and concrete products. In addition, it suitable for casting work during the Norwegian winter. The compressive strength of Industrial cement at different mass ratios (w/c) can be seen in the figure bellow (*figure 2-30*).

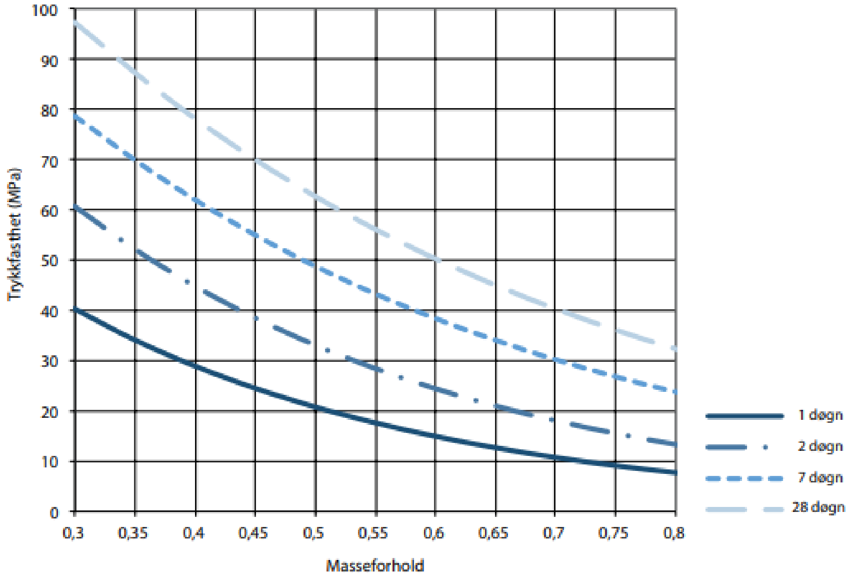
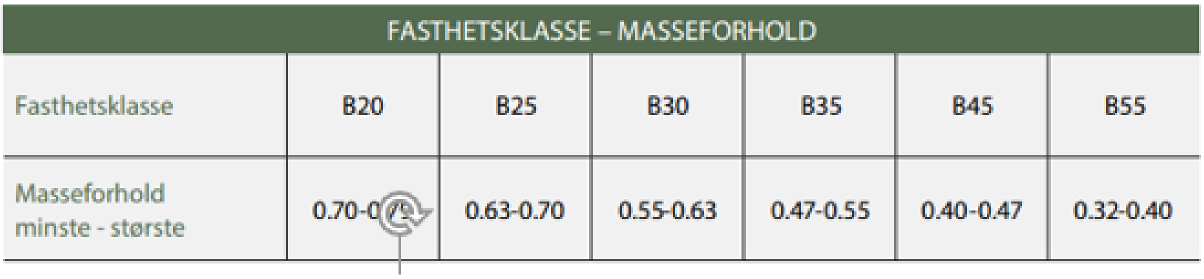


Figure 2-30: Compressive strength of Industrial cement at different mass ratios (w/c) after 1 day, 2 days, 7 days, and 28 days (NORCEM, 2021)

The cement is adapted for use in durability class M45 and MF45 or stricter, and in structures requiring high final strength. Resistance classes M45 and MF45 apply to structures in generally humid environments in combination with chlorides, moderate chemical load and / or frost load. To be classified in class M45, the concrete must have a mass ratio (w/c) of 0.45 or lower. MF45 concrete must additionally contain at least 4% oxygen and contain frost resistant aggregates. *Figure 2-31* provides the following guideline values for minimum and maximum mass ratios (w/c) in different strength classes of concrete without air entrainment and with Norcem Industry Cement [52].



FASTHETSKLASSE – MASSEFORHOLD						
Fasthetsklasse	B20	B25	B30	B35	B45	B55
Masseforhold minste - største	0.70-0.7[illegible]	0.63-0.70	0.55-0.63	0.47-0.55	0.40-0.47	0.32-0.40

Figure 2-31: Recommended mass ratios (w/c) for different strength classes [51]

3. Laboratory program

This task is based on work in the Department of Mechanical, Structural Engineering and Materials Science (Institutt for maskin, bygg og materialteknologi, IMBM) laboratory at UiS. It is important that the concrete recipes with the different amounts of fiber have approximately the same flow properties as the reference concrete. There are five different mixtures of 80 liters, the mixtures tested were as follows: plain concrete, 0.5% BF, 1% BF, 0.5% SF and 1% SF. The slump measurement of each batch was taken and compared; this measurement was taken to see the quality of the concrete. Measurements of air content and Density were also carried out.

3.1. Concrete proportioning

3.1.1. Materials used

We used two types of fiber in out laboratory work:

- Steel fibers 45/50BN by Rescon Mapei AS (*figure 3-1 a*). These steel fibers are cold drawn from a continuous steel wire, after which the fiber ends are deformed to have a hooked end. The fiber length is 50mm and the diameter is 1,05mm giving the fibers an aspect ratio of 48 and quality class of 45. The density of the fibers is given as 7800 $\frac{Kg}{m^3}$.

Figure 3-1: a) The steel fibers used, b) The basalt fibers used

- The Basalt fibers used are different type than the usual small microfibers, the fibers used are macro fibers known as $Minibars^{TM}$ and are produced by the Norwegian company Reforcetech (*figure 3-1 b*). The length of the fibers is 45mm and the diameter 0.65mm giving the fibers an aspect ratio of 69 and have a reported density of around 1900 $\frac{Kg}{m^3}$.

Cement

The cement used in the making of all the specimens is Standard Sement FA; CEM II/B-M 42,5 R produced by Norcem. Srandard FA cement is for ordinary concrete structures. The cement is made up of 78% klinker, 18% flyash and 4% limestone. The flyash solves the problem of using reactive aggregates thus providing greater flexibility when choosing an aggregate provider. The cement has a strength class of 42,5 and classified with the letter “R” meaning it has a high early age strength development.

Aggregates

Two types of aggregates were used in the making of all the specimens. The aggregates are produced by Norstone in Norway, the following aggregates were used:

- Årdal 0-8 mm
- Årdal 8-16 mm

The aggregate distribution used for the making of the concrete is shown in *figure 3-2,* where the proportioning of each aggregate size is included.

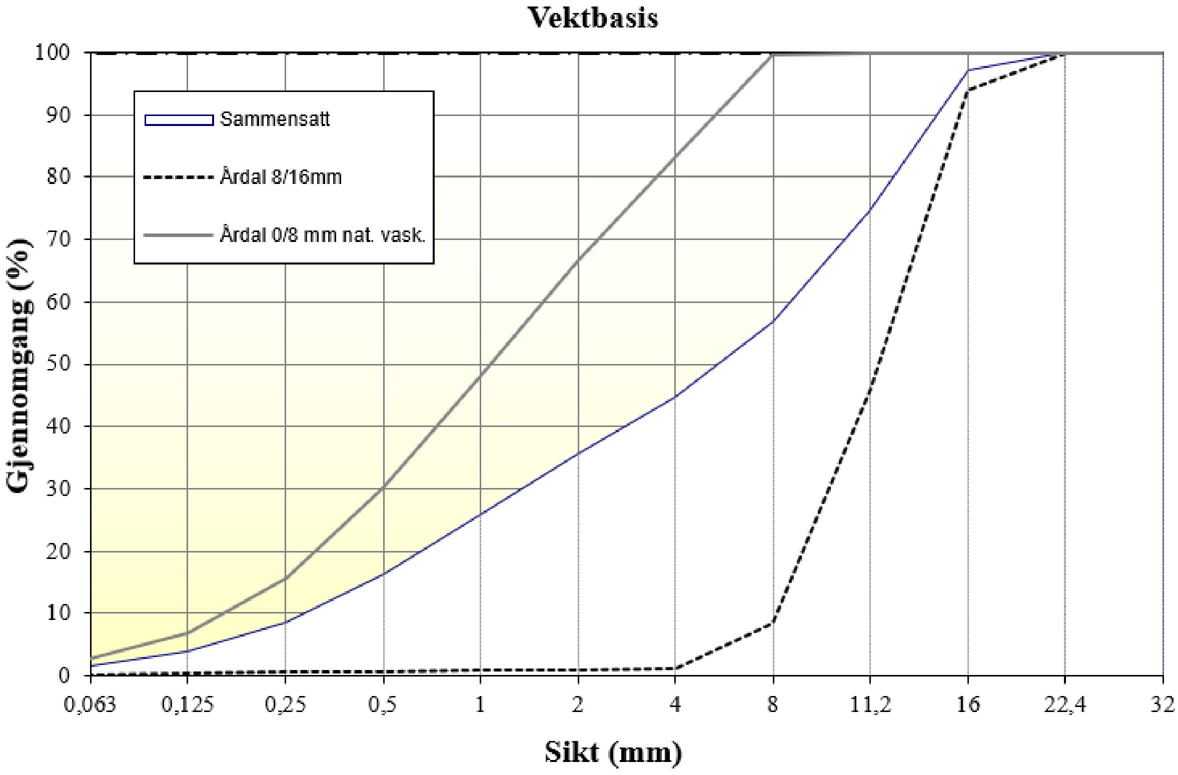


Figure 3-2: The aggregate distribution of the aggregates used to make the concrete

Superplasticizer

Water reducers or superplasticizers are an important component when mixing concrete as they act to improve the flow and workability of the concrete. The superplasticizer can be used to increase the concretes strength, by reducing the water amount needed in a concrete mixture. Superplasticizers work by dispersing the cement particles in the mix. The reason that cement particle flocculate in water is due to their surface charge, the result of this is that some of the water becomes entrapped and thus reducing the water availability in the concrete mix. The superplasticizers mange to disperse the cement particles by modifying their charge and releasing the entrapped water leading to an increase of flow and better constancy. The superplasticizer starts acting immediately after mixing with fresh concrete. [53] A superplasticizer by the name of Dynamon SX-N produced by Mapei was used in the making of the concrete batches. Dynamon SX-N is based on modified acrylic polymers and is a very efficient superplasticizer.

3.2. Mixing and handling process

A large 100 L concrete mixer was used to mix each of the batches, this mixer was inspected beforehand to check if there was any residual material from previous batches as to not contaminate the current batch. The same mixing procedure was followed for all mixtures to minimize errors, the process was as follows:

1. First the coarse aggregates (8-16mm) are added followed by the fine aggregates (0-8mm) and lastly the cement is added. The dry mixture is than allowed to mix for about a minute
2. Once the all the aggregates have been mixed properly, water is added in one go while the concrete mixier is still spinning. Wet mixing continues for around 2 minutes. Superplasticizer is added during this phase.
3. When the concrete has been sufficiently, fibers are added while the mixer is still spinning. The fibers are added by hand and in small amounts as to avoid balling and clumping. The fiber concrete mixture is then allowed to mix for a few minutes with periodic inspections to see if the fibers are homogenously dispersed throughout the concrete. Addition superplasticizer is added if the concrete mix is too tough to handle

Figure 3-3: The concrete mixer used

After the mixing process was complete, a small amount of concrete was taken out such that we could perform the slump test to determine if the batch has obtained the desired workability. The test was performed by having one person stand on the clamps of the slump cone so that the concrete does not leak from the bottom of the cone while the other person filled the cone in three equal layers and compacting the concrete after filling each layer to minimize the air bubbles in the fresh concrete. Once the cone is full, the top is leveled off using the compaction rod and excess cement surrounding the cone is removed. The cone was then lifted straight up with a constant speed taking around 2-5 seconds to complete the action. The concrete was left to settle for a few seconds and the cone was subsequently placed next to the concrete and the slump was measured (*figure 3-4*). The slump test was performed with accordance to NS-EN 12350-2, the slump was deemed acceptable as long as it was withing the range on 10-240mm as stated by the standard.

Figure 3-4: Technique used to measure the slump

After the slump of the concrete batch is measured the concrete is then moved to smaller containers so it is easier to fill the molds. The molds were then filled using trowels. We decided to cast both beams and cubes as to test the compressive strength of the concrete and the flexural strength. The casting technique used for the beams is in accordance to NS-EN 14651. The casting technique in the standard states that the center of the mold should be filled first and then the corners should be filled with smaller amounts of concrete. *Figure 3-5* show where the concrete should be placed. When the mold is completely full the concrete was then compacted using a compaction rod. Sufficient compaction is especially important when casting concrete with fibers as air has a tendency to become trapped between the fibers and aggregates. Over compaction should be avoided due to it causing separation in the concrete leading to the larger aggregates to sink to the bottom while the finer particles are pushed to the top resulting in a weaker final product.

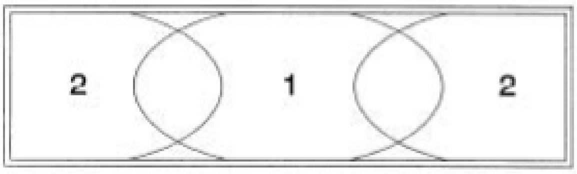


Figure 3-5: Technique used to cast the concrete beams

3.3. Curing methods

The curing of concrete plays a crucial role in the strength development and durability of the concrete. The curing process of concrete start immediately after casting and requires the maintenance of some crucial factors such as desired moisture and temperature over an extended period of time. Moisture is extremely important so that the concrete can stay continuously hydrated and have and adequate strength development, stability, abrasion and scaling resistance and resistance to thawing and freezing. When concrete is cast and the curing processes begins, a chemical reaction is initiated between the cement and the water, called hydration. This chemical reaction is accompanied by heat generation, this is known as curing heat. The generation of heat can prove to be beneficial specifically in Norway due to the cold climate, the heat can therefore be utilized during winter casting as to prevent the concrete from freezing and thawing thus preventing cracks. However the heat generated can also lead to problems for example in massive concrete structures where the developed heat from curing can't be conducted away in a controlled manner, this again can lead to large temperature differences in the concrete and as a result have the same damaging effect as freezing and thawing. Curing techniques are therefore extremely important and need to be considered according to the environment and size of the construction project at hand.

The curing processes is also as mentioned above dependent on the heat of the entire system. This means that it's a balance between the heat generated by the concrete's hydration process and heat loss to the surrounding environment. The concrete can reach temperatures up to 60 °C. The system's temperature also affects the speed of the chemical reactions between the cement and the water, *figure 3-6* shows how the reaction time scales with the temperature of the concrete system. [54]

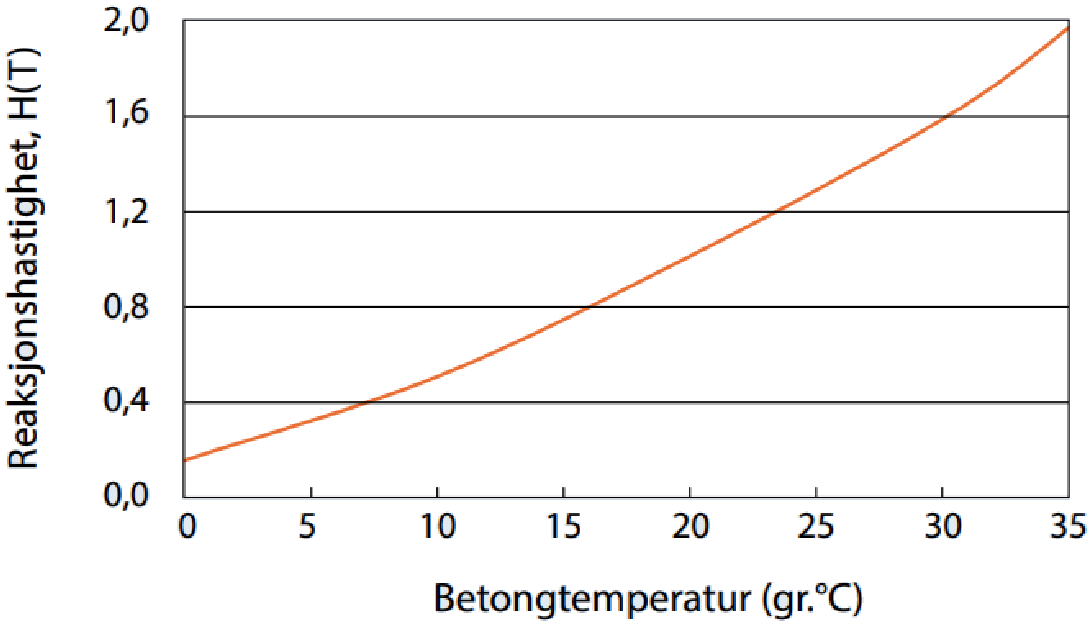


Figure 3-6: Relative reaction speed at different temperatures where reaction speed at 20 °C is set to 1. (NORCEM, 2021)

When there are temperature differences in a system, there will always be transfer of heat from high temperature areas to low temperature areas. Concrete is often cast in different types of formwork which act as isolation therefore the materials used also needs to be considered. The heat transfer takes place through three different ways:

- Head conduction
- Convection
- Radiation

The heat conduction resistance is constant for a given structure. The resistance is dependent on what material the construction is composed of and the thickness of the individual material layers. The heat conduction resistance is given through the following formula:

$$m = \frac{d}{k}$$

Where,

m – is the heat conduction resistance of the system
d – is the thickens of the layer
k – is the thermal conductivity of the material

The thermal conductivity of a material is largely dependent on the porosity of the material and the moisture content [54]. The thermal conductivity of some common materials is shown in *table 3-1*.

Table 3-1: Thermal conductivity of common materials (NORCEM., 2021)

Material	**Thermal conductivity, k in (KJ/mh°C)**
Steel	209
Fresh concrete	8,4
Hardened concrete	5,9
Light weight concrete	2,9
Wood (damp)	0,67
Common isolation materials	0,15

The formwork in which the concrete is cast acts as a type of insulation and is often composed of multiple layers. The layers depend on what the goal of the formwork is, if the structure is being constructed during the winter the formwork may be padded with extra insulation to preserve the heat of the concrete.

Heat loss due to convection occurs when the warmer air near the concrete or outside of the formwork is transported away and replaced with cold air. Heat loss due to convection is therefore largely dependent on the local wind conditions. The loss of heat due to convection increases with:

- Increasing temperature difference between the material and air
- Increases with increased surface area
- Decreases with increasing convection resistance

The convection resistance depends on how fast heat transfer can occur in the out most surface layer. The convection resistance is given though the following equation:

$$m_k = \frac{1}{a_k}$$

Where,
m_k - is the convection resistance
a_k – is the heat convection coefficient

The heat convection coefficient depends on what type of medium the transition takes place between. For example, the transition coefficient between a solid material and air is significantly lower than from a solid material to water. The coefficient is also impacted by the rate at which the water or air at the surface is replaced.

Heat radiation is a form of energy transfer from a hot object to a cold object through for example air. The energy that is radiated can either be reflected, absorbed, or let through (transmitted). A high absorption coefficient means that a material has great ability to absorb heat from radiation and also great ability to emit heat in the form of radiation.

As mentioned before, keeping as much moisture form evaporating from the concrete is crucial to the hydration process, strength development and the temperature of the concrete. When casting concrete elements where no form of cover is used, the drying and evaporation of water will significantly contribute to heat loss of the system. The heat loss occurs when the water evaporates and thereby the heat of vaporization is given off from the concrete to the air, therefore the more water that is lost to evaporation during the curing process the more heat is dissipated form the concrete. This effect can be drastically reduced by using a membrane hardener or alternatively a sheet of plastic can be placed over the fresh concrete to trap the water inside and regulate the temperature [54].

To prevent moisture loss after casting our specimens were placed on wooden pallets and subsequently covered with a sheet of plastic as to prevent significant moisture loss (*figure 3-7*). The specimens were left to cure for approximately 24 hours before being taken out of the molds. Some specimens were immediately tested after being taken out of the mold while the rest were placed in a curing tank filled with room temperature water as to again prevent water loss over the curing duration. The specimens were left in the curing tank for an addition 27 days before being taken out for testing. The temperature of the storage facility ranged from 18-20°C.

Figure 3-7: Specimens covered with plastic for the first 24 hours of curing and thereafter being placed in a curing tank for the remainder of the curing time.

3.4. Testing methods

It is of great importance to be able to test the properties of concrete whether it is normal, or fiber reinforced. Testing of concrete before use is critical to make sure that the specimens/batch has achieved the desired mechanical properties for the task. The most common test methods used to test the concretes properties are outlined in the European standards.

Compression test

Compressive strength is one of concretes most desired properties and is used to determine the strength classes of different concrete blends. Due to FRC practical limitations when it comes to fiber content due to its effects on workability, researchers have found that the addition of modest volumes of fiber have little to no effect on the compressive strength of FRC. However, it is still important to conduct compressive tests on FRC as the addition of certain types of fiber has been observed to reduce the compressive strength compared to normal plain concrete.

There are generally no compressive test methods that are specific to FRC. The same methods are used for FRC as conventional concrete. In Norway the most common method for testing the compressive strength of concrete is outlined in NS-EN 12390-2:2019. The code states that the testing machine needs to be in compliance with NS-EN 12390-4:

- Readable displays from the position of the operator
- System that records the maximum force applied before failure and allows the data to be read after the completion of the test
- Accurate sensors and displays that allow the force to be read to the desired accuracy

The method of testing the compressive strength is rather simple, the specimen is placed in the testing machine and the machine then loads the specimen with a constantly increasing compressive force until the specimen fails (*figure 3-9 b*). The peak compressive load is measured, and the compressive strength can subsequently be calculated by the following equation:

$$f_c = \frac{F}{A_c}$$

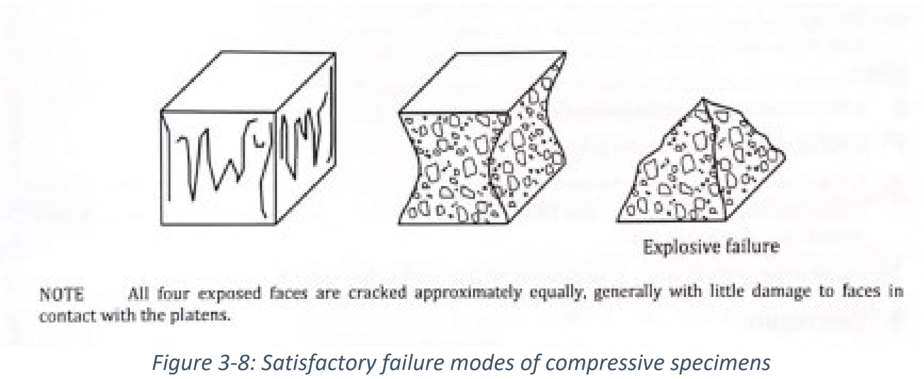
Where,

f_c – is the compressive strength, in Mpa

F – is the load at failure, in N

A_c – is the area of the specimen's cross section on which the compressive force acts, In mm

The specimens used for compression testing shall be in the shape of cubes or cylinders. The surface of the specimens is to be wiped dry before use and placed such that the load is applied perpendicularly to the casting direction. There are multiple modes of failure that have been outline in the European standard, some are deemed satisfactory while others aren't. The modes of failure can be seen in *figure 3-8, 3-9* below.



NOTE All four exposed faces are cracked approximately equally, generally with little damage to faces in contact with the platens.

Figure 3-8: Satisfactory failure modes of compressive specimens

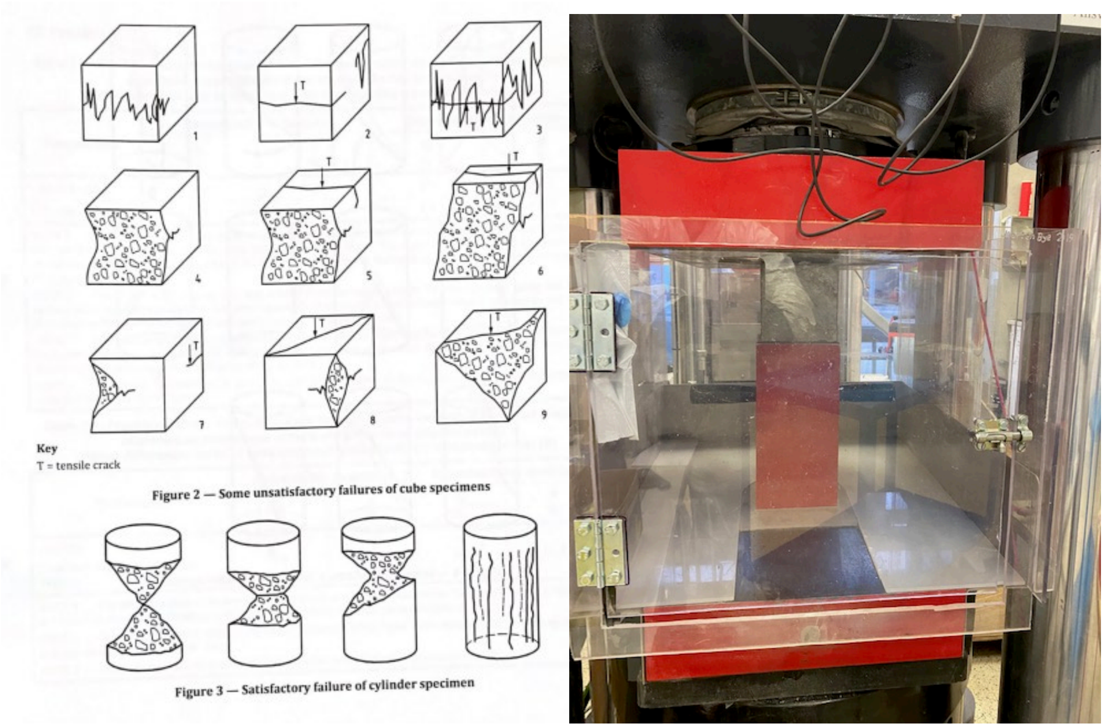


Figure 3-9: a) Examples of some satisfactory and unsatisfactory failure modes of concrete specimens in compression,

b) Compression test machine

Flexural bending test

The most important characteristic of FRC is its ability to perform well under flexural bending. The result from the flexural bending test is the stress-strain relation of the material tested, these can be used to find the ductility and toughness of a given material. There are two types of test that are used to gage the flexural strength of beam, these tests are the three point and four-point bending tests. The difference between the two is as the name suggest one is based to three points of contact on the beam while the four-point bending test has four points of contact. The three-point test produces peak stress directly at the mid-point of the beam while the four-point test distributes the peak stress along the material while being concentrated at the two loading points. The test setup is out lined in NS-EN12390-2:2019 and *figure 3-10* shows how the beams are supposed to be set up and loaded.

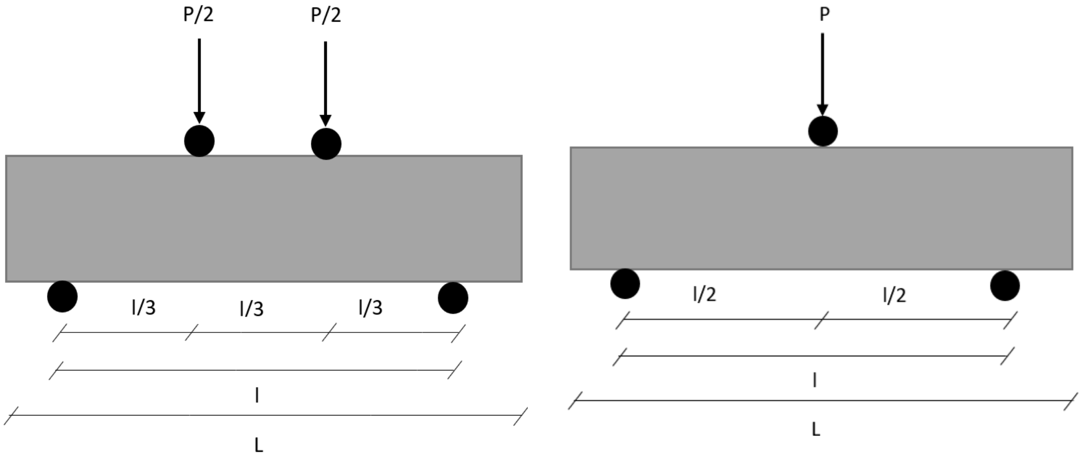


Figure 3-10: Test setup for four-point and three-point bending

For our testing we decided to use the three-point bending test because we wanted to test the strength and behavior of FRC under peak concentrated loads, research and comparisons conducted on both testing methods concluded that center point loading consistently gives higher values of flexural strength than two point loading, on average being 13% higher. The three-point bending test is therefore more appropriate due the nature of the loading. The equation given by NS-EN12390-2:2019 was used to calculate the flexural strength of the concrete and is as follows:

$$f_{ct.fl} = \frac{3 * F * l}{2 * d_1 * d_2^2}$$

Where,

$f_{ct.fl}$ – The flexural strength in MPa

F – The maximum load in N

l - The distance between the lower rollers in mm

$d_1 and\ d_2$ – The lateral dimensions of the cross-section in mm

Properties and test methods of fresh concrete

The addition of fibers into a concrete mix reduces its workability, therefore it is a challenge to achieve the desired mechanical properties while maintaining adequate workability that allows for proper compaction, mixing and casting. Proper concrete quality is crucial for the life of a structure. The quality is considered satisfactory when all requirements for the relevant concrete quality have been met. These concrete qualities can mostly be adjusted such as air content or consistency with different types of additives. If testing is not performed on the fresh concrete beforehand it can in the worst-case scenario require the structure to be demolished due to the structural integrity being compromised by insufficient mechanical properties of the concrete used. The main test methods which are used in this thesis will be outlined below.

Slump test

The most common method for testing the castability of concrete is to measure the slump of the concrete. The method is described in the Norwegian standard NS-EN 12350-2. The equipment used is a slump test cone (shown in *figure 3-11)* a compaction rod, measuring tool and enough concrete to fill the slump test cone. The cone is filled in three layers, compaction of each layer is required. Once the cone is filled up, round off the excess concrete from the top using the compaction rod and lift the cone straight up in a steady motion over 2-5 seconds. Place the cone next to the concrete and measure the distance from the top of the concrete to the top of the slump cone. According to the standard the method can be used when the slump of the concrete is between 10 and 210 mm but in practice the method used for slump measures of up to 240mm.

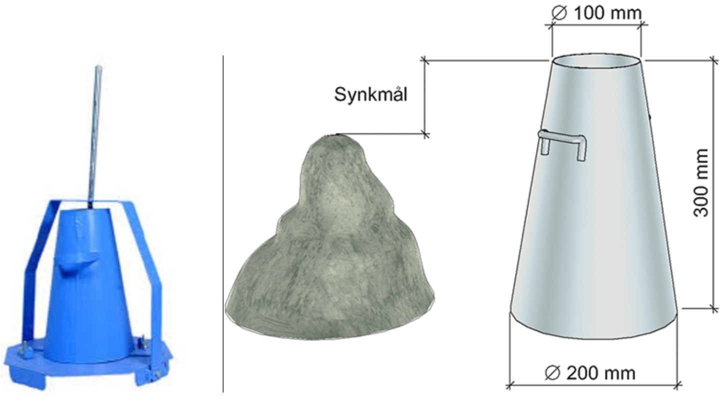


Figure 3-11: Example of how the slump is measured using the slump cone.

Alternative tests

There are multiple other types of tests that are used to test different properties of fresh concrete such as the concretes passing ability, segregation resistance and filling ability. Filling and passing ability are often considered when talking about self-compacting concrete, filling ability is the concretes ability to flow under its own weight and specifically its ability to fill in all gaps and spaces in the framework without compaction. The passing ability is the concretes ability to flow though openings around the size of the concrete's nominal max aggregate size. In proactive the passing ability refers to the concerts ability to no segregate when passing through steel rebar or similar reinforcement. Test to measure these properties are the J-ring test, V-funnel, filling vessel test, L-box, U-box and Orimet. These will not be further discussed as they are not used in our tests.

3.5. Casting of specimens

Casting of reference specimens

In order to be able to compare the effects and properties of FRC we needed to create a reference batch of plain concrete. The reference concrete was proportioned identically as the batches with fibers with the only exception being the matrix volume which was set to 320 L/m^3. The reference batch of concrete had a w/c ratio of 0.4 along with all the other batches. The proportioning of all the batches was done though an excel spreadsheet provided by the IMBM laboratory resources.

The materials needed for the concrete mix were proportioned the day before mixing and weighed to the right amounts and prepared in large buckets so that the mixing process could go as smooth as possible (*figure 3-12*). Before proportioning the amount of materials needed, the water content in the 0-8mm aggregates was measured using the speedy moisture test and the water content for the batch was subsequently adjusted. We also assumed a water absorption of 0.5% in both the fine aggregates and the coarse aggregates. The distribution of aggregates was set to 53% fine and 47% coarse aggregates.

Figure 3-12:How the materials were prepared the day before mixing

Data from day of casting

Table 3-2: data from the plain concrete batch

Total concrete:	80 L
Water used:	9.8L
Water added at time:	09:16
Cement used:	32.75 Kg
0/8mm aggregates:	80.9 Kg
8/16mm aggregates:	69.33 Kg
Superplasticizer used:	200 g
Air content measured:	2.8%
Weight of air content measurement:	19 Kg
Slump measured:	23 cm
Beams cast:	10
Cubes cast:	12
Density of concrete batch:	2309 $\frac{Kg}{m^3}$

When casting the reference batch, we cast both the day 1 test specimens and day 28 test specimens from the same batch to keep things consistent. This is because even though the portioning and materials used are the same there will always be slight variations from one batch to another, therefore all the specimens were done in one go. The amount of superplasticizer used was controlled by the lab supervisor, Jarle. The superplasticizer was added in small amounts and the consistence and workability of the concrete was observed after each time. The slump of the reference batch came out to approximately 23 cm, the concrete was rather fluid and perhaps slightly less superplasticizer could have been used but the slump was withing the acceptable range and had sufficient workability.

Casting of SF specimens

Steel fibers have been used in FRC for a long time and have had extensive research and development. The reason for casting steel fiber specimens is to have a benchmark that we can compare the basalt fibers to. Basalt fibers are a newer product and need to show desired properties equal or better than the preexisting solutions on the market. For the steel fiber batches only 28-day specimens were tested, this is due there being numerous research papers to compare to and the 28-day cured state to be a more accurate representation of the fibers effect on the concrete.

There was a total of 2 batches made with steel fibers, one with 0.5% fiber volume and one with 1% fiber volume. The proportioning of the batches was made using the aforementioned excel spreadsheet. The materials were weighed out and prepared in large buckets prior to the day of mixing such that the mixing process could go smoothly. The two batches were near identical, and the material used for both came from the same bags of cement and aggregates, the only difference being a slight adjustment of the water content by a few ml to compensate for the addition of the fibers, this was all in accordance to the proportioning sheet. The fresh concrete was mixed in 80 L batches and the fibers were added by hand in small amounts as to avoid any balling or clumping, after which addition super plasticizer was added to adjust the workability of the concrete. Note: The matrix volume of all the fiber batches was adjusted up to 340 L/m^3 as advised by the laboratory supervisor, Jarle who help us proportion the concrete mixes. This is to achieve better workability.

Data from day of casting

Table 3-3: Data from casting of 0.5% steel fiber batch

Total concrete:	80 L
Water used:	10.75L
Water added at	10:02
Cement used:	34 Kg
0/8mm aggregates used:	77.85 Kg
8/16mm aggregates used:	66.71 Kg
Steel fibers used	3.1 Kg (0.5% volume)
Slump:	21 cm
Air content:	1.5%
Density:	2340 $\frac{Kg}{m^3}$
Weight of concrete used in air content test:	19 Kg
Superplasticizer used:	200 g

The difference in the amount of water used compared to the reference concrete is due to increase of matrix volume. The slump test came out to approximately 21 cm which is slightly lower than the reference batch even though the same amount of superplasticizer was used. Even though the look and slump of the concrete was similar to the reference batch, there was a noticeable decrease in workability specifically the compaction process was tedious and difficult.

Table 3-4: Data from casting of 1% steel fiber batch

Total concrete:	80 L
Water used:	10.8L
Water added at:	09:20
Cement used:	34Kg
0/8mm aggregates used:	77.25 Kg
8/16mm aggregates used:	66.2 Kg

Steel fibers used:	6.24 Kg (1% volume)
Slump:	18cm
Air content:	1.4%
Density:	$2404 \frac{Kg}{m^3}$
Weight of concrete used in air content test:	19.5 Kg
Superplasticizer used:	240 g

The second batch with 1% steel fibers was mixed and proportioned the same way as the batch with 0.5%. For this mix we need to add extra superplasticizer to offset the higher amount of fiber content. The doubling of fiber content had a noticeable effect on the workability compared to the 0.5% mixture even with the addition of extra superplasticizer. The slump was approximately 18 cm, significantly lower than the reference concrete, this was expected as fibers in concrete are known to have an adverse effect on the flow and workability of the concrete. The casting and compaction of the 1% mixture was difficult and required a lot more time than the previous mixtures. Fiber volumes above 1% would probably need larger amounts of superplasticizer but might cause segregation of the fresh concrete. Another possibility is to use self-compacting concrete (SCC) when applying increasing doses of fiber.

Casting of BF specimens

The basalt fiber Minibar (BFMB) specimens were prepared in two batches just like with the SFRC, one 0.5% fiber volume batch and one with 1% fiber volume. A total of 20 beams and 28 cubes were cast. Due to the basalt fiber Minibar technology being rather new compared to steel fibers both early strength after 1 day and final cured strength after 28 days was tested in compression and tension. As expected with fiber concrete, both the 0.5% and 1% mixtures had significantly reduced workability compared to plain concrete, but the mixtures were still easer to work with as opposed to the steel fiber batches. This is an important factor to consider as FRC is designed and proportioned after workability rather than maximum strength as the strength of FRC is irrelevant if the fibers make it impossible to cast and work with. The BFMB were added in small batches and dispersed throughout the concrete while the mixer was still spinning as to avoid clumping and balling of the fibers. Even though correct techniques were applied when adding the fibers to the concrete, balling and clumping was still present compared to the steel fibers where this was present to a much smaller degree. The amount of super plasticizer used was once again controlled by Jarle and added throughout the mixing. Both mixes were rather stiff with the 1% batch having the lowest slump, as can be seen in *table 3-6*.

Table 3-5: Data from casting 0.5% basalt fiber specimens

Total concrete:	80L
Water:	10.8L
Water added at time:	11:00
Cement used:	34 Kg
0/8 aggregates used:	77.85 Kg
8/16mm aggregates used:	66.71 Kg
Basalt fibers (Minibars) used:	0.78 Kg (0.5% volume)
Slump:	15 cm
Air content:	1.5%

Weight of concrete used to test air content:	19kg
Density:	2340 $\frac{Kg}{m^3}$
Superplasticizer used:	200g

Table 3-6: Data from casting 1% basalt fiber specimens

Total concrete:	80 L
Water:	10.8L
Water added at time:	11:00
Cement used:	34 Kg
0/8 aggregates used:	77.25 Kg
8/16mm aggregates used:	66.2 Kg
Basalt fibers (Minibars) used:	1.56 Kg (1% volume)
Slump:	20cm
Air content:	1.4%
Weight of concrete used to test air content:	19.6 Kg
Density:	2416$\frac{Kg}{m^3}$
Superplasticizer used:	200g

4. Results

4.1.1. Compressive strength

Even though the compressive strength is not the main focus when adding fibers to concrete it is still important to test and benchmark to see how it performs specifically for different types of fibers, such as steel fibers and basalt Minibars. This is because Different types of fibers can either positively of adversely affect the compressive strength, in some cases significantly lowering it when using high doses of fibers.

While it can take up to one or two years for concrete to fully cure the percentage gain in strength is rather small after a certain time. The design strength of concrete is said to be achieved after 28 days of curing; however, the testing of its early strength development can also be of interest. In our case the reason for testing after 1 day is due to the use of Standard FA cement which is classified as a high early strength development cement. By testing after 1 day we can see to which degree the addition of fibers effects the early strength and mechanical behavior of the concrete. Other practical reasons for testing the early strength of concrete is to see if the curing process and strength development is going as expected without having to wait out the full 28 day curing period.

The compressive strength of the specimens can be seen in *figure 3-13*, three specimens from each batch are compared as the rest of the specimens were made as a precaution in case there were any defects or errors. The full overview of the day 1 compression tests can be seen in *table 3-7*. As previously mentioned, the cement used is a high early strength cement and this can clearly be observed across all the specimens. The plain concrete specimens exhibited higher than the anticipated strength when compared to the data sheet provided by Norcem (*figure 2-28*). The plain concrete had on average a compressive strength of 33 MPa meanwhile the predicted day 1 strength was 27 MPa. This difference could be due to differences in the mix design as the full details of the concrete used in the Norcem datasheet are not disclosed.

The early strength of both the 0.5% and 1% BF specimens seem to be nearly identical with an average compressive strength of 29.9 and 30 MPa respectively. The compressive strength of the specimens is above the advertised number of 27 MPa, however a slight but clear decrease can be seen when compared to the plain concrete specimens. This reduction of compressive strength may be due to the increased matrix volume as this in turn means less aggregates to support the matrix under compression. The difference could also be down to the variation of the different specimens as no two specimens are identical even if they are produced from the same batch.

When comparing the early strength of the 0.5% SFRC we can see a clear increase in the compressive strength. The 0.5% SFRC specimens exhibited an average compressive strength of 42.63 MPa which is an improvement of 42% over both BFRF batches and a 29% improvement over the plain concrete batch.

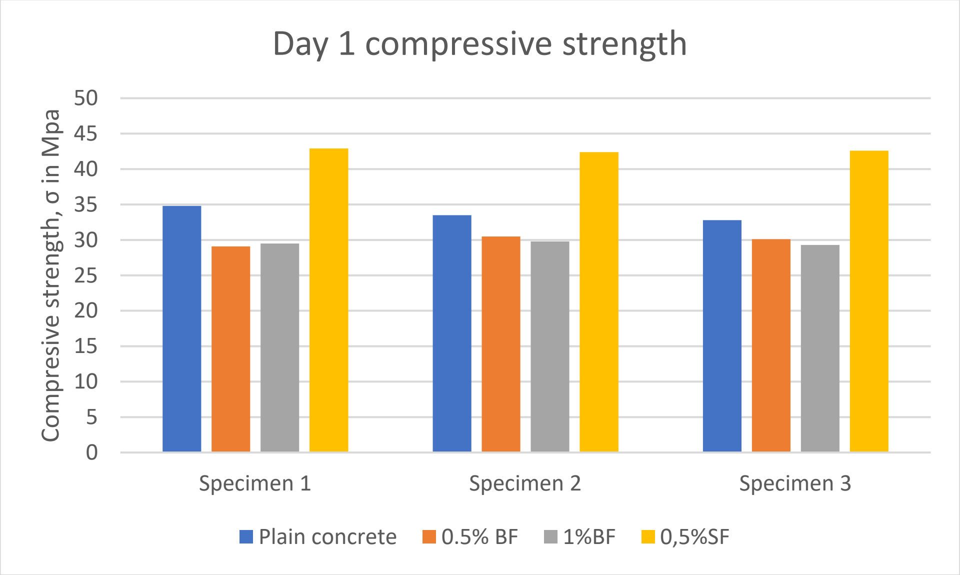


Figure 3-13:Comparisson of day 1 compressive strength

Table 3-7: Raw data from day 1 compression tests

Specimen number	**Compressive strength (MPa)**	**Average compressive strength (MPa)**
Reference 1	34.8	33
Reference 2	33.5	
Reference 3	32.8	
Reference 4	33.8	
Reference 5	33.1	
Reference 6	32.8	
0.5% BF 1	29.1	29.9
0.5% BF 2	30.5	
0.5% BF 3	30.1	
1% BF 1	29.5	30
1% BF 2	29.8	
1% BF 3	29.3	
1% BF 4	29.2	

1% BF 5	30	
1% BF 6	29.8	
0.5% SF 1	42.9	42.63
0.5% SF 2	42.4	
0.5% SF 3	42.6	

The 28-day compressive strength is of greater interest because the concrete has had time to cure and a proper bond has been formed between the matrix and fibers/aggregates. The strength development of the plain concrete specimens was satisfactory as they reach an average compressive strength of 72.65 MPa which when compared to the Norcem datasheet is in line with the expected value of approximately 73 to 74 MPa. The compressive strength of 72.65 MPa places the concrete within the B55 strength class, in accordance with the classification guidelines given in NS-EN13791 and NS-EN 206-1.

The hypothesis bases on previous literature and research indicated that the addition of basalt fibers would not significantly increase the compressive strength in any meaningful way. The results seen in *figure 3-14* highlight that the basalt fibers can have an adverse effect on the compressive strength. The 0.5% BFRC and 1% BFRC reached an average strength of 70 and 65.4 MPa respectively which is 4% and 30% less than that of plain concrete. Research conducted by Branston and co. [55] stated that longer fibers of length up to 50mm such as the ones we used lead to greater variation in the compressive strength. This is due to the increased difficulty to achieve proper consolidation when using long fibers or Minibars. The apparent difference of compressive strength between the 0.5% and 1% batches could be caused by the increase clumping and balling of the fibers at higher doses. This was observed even in the fresh state where the Minibars had a tendency to separate into balls or clumps. The balling of the fibers can lead to workability issues and compactions issues as the entrained air becomes more difficult to expel. When the fibers clump in excessively large balls it reduces the structural integrity of the concrete by affects the homogeneous dispersion of the aggregates throughout the concrete mix. BFMB should therefore be avoided if the circumstances require a high compressive strength. However, the BFRC had a significant increase in toughness and post cracking behavior. Branston and co. noted that the cube specimens could be loaded significantly more past failure compared to the plain concrete specimens, but these values were not recorded and not discussed further.

The effects of the steel fibers seemed to be minor but still present, *figure 3-14* shows the comparison between the reference plain concrete and the 0.5% volume SFRC. On average the compressive strength of the concrete specimens increased by about 15 MPa, which translates to roughly a 21% strength increase. However, the increase of fibers from 0.5% to 1% didn’t seem to have any further effect on the compressive strength of the cubes as seen in comparison of the two volume fractions. There even seemed to be a slight drop of 2 MPa in compressive strength but this can be neglected due to margin of error and slight uncontrollable differences between the concrete batches. Compared to previous literature and testing, these results were expected and fit right in with predicted values. We expected the fibers to do little to enhance the compressive strength of the concrete considering we used small to average amounts of fibers (<2%). Karihaloo and de Vriese came to the same conclusion when testing compressive strength of SFRC, they tested different volumes of steel fibers ranging from 0 to 4% and found increase of 120 MPa to 145 MPa a total of 21% increase in compressive strength [32]. Sun and co. similarly found an increase from 150 MPa to 200 MPa using the same volume fractions as Karihaloo and de Vriese, a total increase of 33% was observed. Additional tests have been performed on even higher amounts of fibers, all the way up to 10%, but didn't seem to increase the compressive strength by as much as might be expected. Sun and co. observed that SIFCON with fiber contents of 10% only had a 25-50% increase in compressive strength. It is to be noted that when approaching such high fiber volumes, proper compaction of the matrix might prove difficult and thus leading to an increase in porosity and decrease in strength. [56]

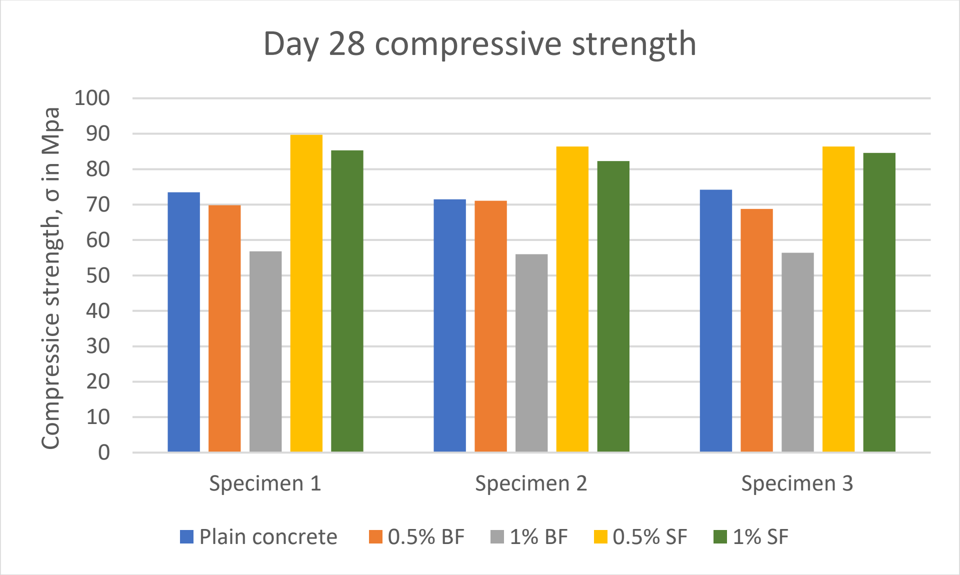


Figure 3-14: Comparison of day 28 compressive strength

Table 3-8: Raw data from day 28 compression tests

Specimen number	**Compressive strength (MPa)**	**Average compressive strength (MPa)**
Reference 1	73.5	72.65
Reference 2	71.5	
Reference 3	74.2	
Reference 4	73.5	
Reference 5	71.2	
Reference 6	72.3	
0.5% BF 1	69.8	70
0.5% BF 2	71.1	
0.5% BF 3	72.3	
0.5% BF 4	68.7	
1% BF 1	56.8	56.4
1% BF 2	56	
1% BF 3	56.4	
1% BF 4	56.4	
1% BF 5	56.2	
1% BF 6	56.5	
0.5% SF 1	89.7	87.4
0.5% SF 2	86.4	
0.5% SF 3	86.4	
0.5% SF 4	89.1	

0.5% SF 5	89.1	
0.5% SF 6	83.8	
1% SF 1	85.3	85
1% SF 2	82.3	
1% SF 3	84.6	
1% SF 4	86.8	
1% SF 5	85	
1% SF 6	86.3	

4.1.2. Failure mode in compression

The compressive strength of the basalt fiber Minibar specimens did not see any improvement, even a decrease in strength was observed in the case of the 1% BF mixture. However, a significant improvement was observed in the failure mode of the cubes. The mechanism of failure for concrete in compression typically consists of four stages. The first stage is the formation of micro cracks, these micro cracks occur in the interfacial transition zone (ITZ) around the aggregates. This happens under no load and is caused by the hydration process. The second stage is the expansion of the micro cracks which happens when load is applied to the specimen and eventually these micro cracks take over the entire ITZ. The third stage is the appearance of mortar cracks, meaning the micro cracks start to extend from the ITZ into the matrix of the concrete. The last stage is the connection of the mortar cracks between aggregates, at this stage the concrete can no longer carry loads and has reached compressive failure. Typical compressive failure was present among all of the specimens in the form of approximately even zigzag cracking along all exposed faces as outlined by NS-EN 12390-2:2019. *Figure 3-15* compares the degree of compressive failure of the plain concrete, BFRC and SFRC respectively. Both SF and BF were effective at reducing the post peak deformation and cracking, when compared to the plain concrete a more explosive and brittle failure can be observed. The fibers effectively held together the cracked faces of the cubes and limited further crack propagation as well as increasing the post failure structural integrity and toughness. The plain concrete specimen could easily be picked apart by hand while both the SFRC and BFRC only allowed small flakes to be picked off from the surface.

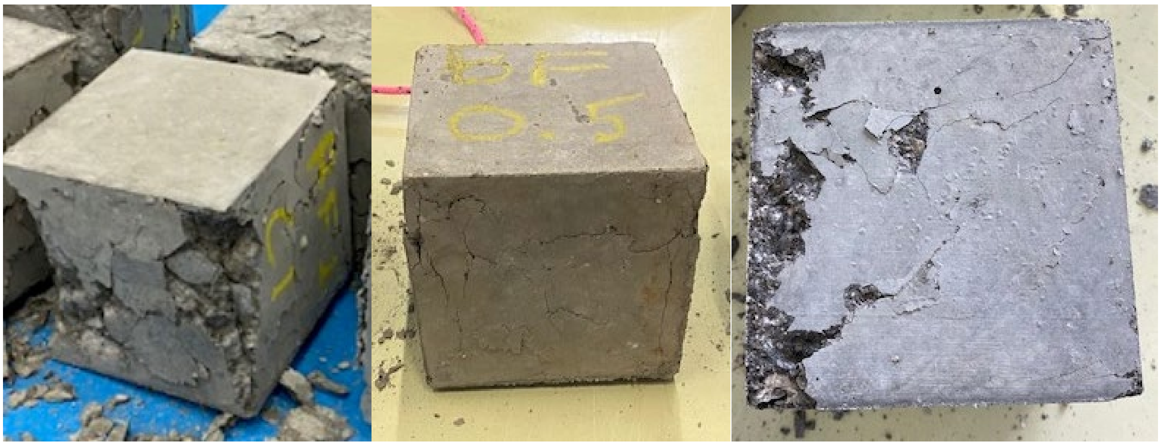


Figure 3-15: Failure mode of a) plain concrete b) BFRC c) SFRC

4.1.3. Flexural strength

The goal of adding fibers or other types of reinforcement is to increase the concrete's flexural performance whether it be an increase of ultimate flexural strength or an increase of toughness and ductility compared to plain concrete. The flexural strength is of greater importance when considering FRC, this is because plain concrete already has great performance under compressive loads. Due to concrete's brittle nature it struggles with carrying significant flexural/tensile loads compared to its compressive strength capacity.

There were some problems and errors encountered when using the three-point tensile test machine, the original plan for testing the beams flexural strength and behavior involved comparing the stress- strain curves of all of the composites and comparing the load-deflection curves to determine the ductility factor and post cracking load behavior. Unfortunately, due to calibration errors with the machine we were unable to obtain proper strain and deflection readings. The comparison of the composites will therefore be discussed using the peak stresses at failure, failure modes and post cracking behavior through the use of pictures taken during the testing, visual observations, and comparison to previous literature regarding the topic

Figure 3-16 shows the flexural strength of the concrete beams after 1 day of curing, all the plain concrete specimens seem to be within the same strength range with the only exception being reference beam 4 which exhibited slightly lower flexural strength. There were no obvious defects when visually inspecting the beams and the difference in strength can therefore be broken down to inconstancies when casting or handling the fresh concrete. An obvious decrease in flexural strength was observed when comparing the day 1 plain concrete beams to both the 0.5% and 1% BFRC batches. The plain concrete beams had a reasonable early average flexural strength of 5.26 MPa which is 75% greater than the 0.5% BFRC batch with an average of 3.02 MPa and 65% greater than the 1% BFRC batch with an average of 3.2 MPa. This is and inserting observation as the very early flexural strength of BFRC (specifically Minibar reinforced) hasn't been studied as in depth as other common fibers such as SF or PP fibers. The lack of early flexural strength is suspected to be due to the short curing time of the FRC. During the early stages of curing the matrix is unable to create a strong enough bond with the fibers thus making the fibers potentially act as addition failure points of the ITZ.

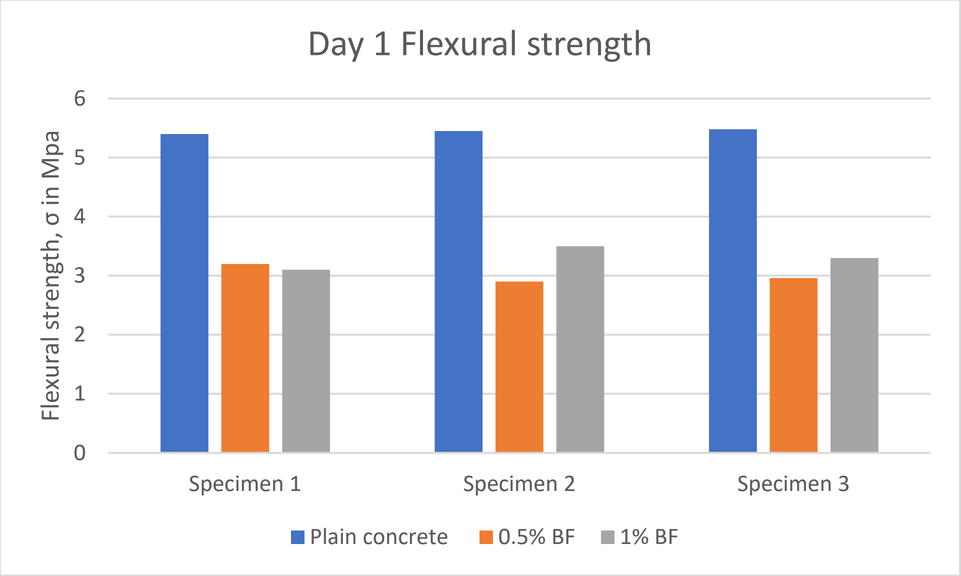


Figure 3-16: Comparison of day 1 flexural strength

Table 3-9: Raw data from day 1 flexural tests

Specimen number	Flexural strength (MPa)	Average flexural strength (MPa)
Reference 1	5.41	5.26
Reference 2	5.45	
Reference 3	5.29	
Reference 4	4.65	
Reference 5	5.48	
0.5% BF 1	3.2	3.02
0.5% BF 2	2.9	
0.5% BF 3	2.96	
1% BF 1	3.1	3.2
1% BF 2	3.3	
1% BF 3	3.5	
1% BF 4	2.8	

The 28-day flexural test results are of particular interest as they show how the FRC performs in its final cured state. This assumes that the matrix of the concrete has had enough time to form a proper bond with the fibers allowing for full utilization of the fibers during flexural loads. When comparing the plain concrete to both of the BFRC batches we can see a similar phenomenon as in the early strength test however the difference of flexural strength between them isn’t as drastic. The plain concrete beams achieve an average flexural strength of 9.65 MPa which is 9% greater than the 0.5% BFRC which had an average strength of 8.8 MPa and 22% greater the 1% BFRC which had am average strength of 7.98 MPa. This result is rather peculiar as the fibers in the concrete are expected to increase the ultimate flexural strength or at least remain within the same range as plain concrete and not reduce it by such a large factor. It is interesting to note that the flexural strength of the 1% mixture is on average lower than the 0.5%, this is not the case for the day 1 test where the 1% mixture proved to be on average slightly stronger.

The SFRC performed better than the BFRC when it came to ultimate flexural strength but still fell short compared to the expected results. This result was also strange, SFRC is one of the most researched fiber composites and it is generally accepted that the addition of steel fibers in concrete especially at significant doses increases the ultimate flexural strength. This increase is also proportional with the increase of fiber volume until a certain point. The 0.5% SFRC was on average 4% weaker than the plain concrete with an average flexural strength of 9.3 MPa. The 1% SFRC saw a slight increase of 2.8% with an average flexural strength of 9.9 MPa.

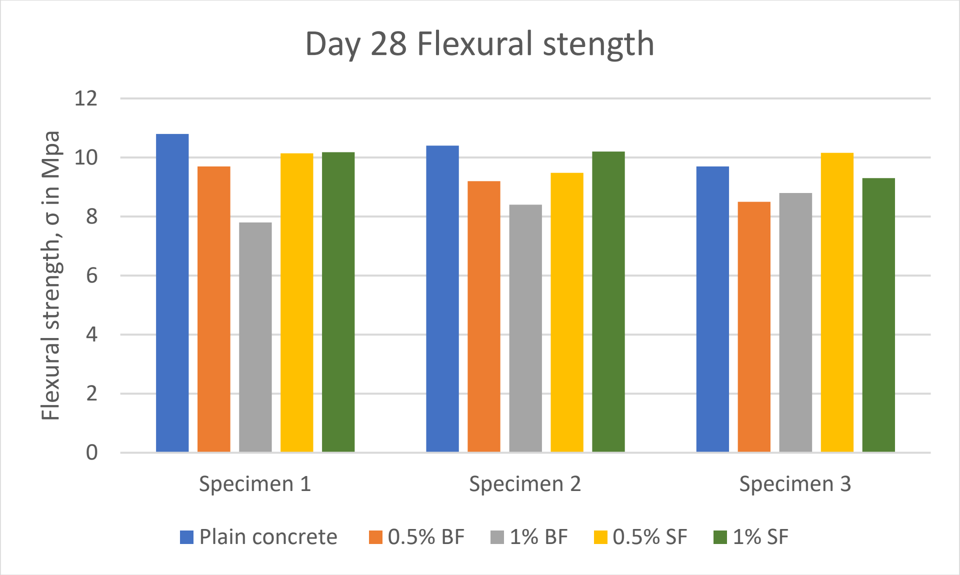


Figure 3-17: Comparison of day 28 flexural strength

Table 3-10: Raw data from day 28 flexural tests

Specimen number	Flexural strength (MPa)	Average flexural strength (MPa)
Reference 1	10.8	9.65
Reference 2	10.4	
Reference 3	9.7	
Reference 4	7.7	
0.5% BF 1	9.7	8.8
0.5% BF 2	9.2	
0.5% BF 3	8.5	
0.5% BF 4	8.3	
0.5% BF 5	8.2	
1% BF 1	8.8	7.98
1% BF 2	8.4	
1% BF 3	7.8	
1% BF 4	7.8	
1% BF 5	7.1	
0.5% SF 1	10.14	9.27
0.5% SF 2	10.16	
0.5% SF 3	9.48	
0.5% SF 4	7.32	
1% SF 1	10.18	9.9
1% SF 2	10.2	
1% SF 3	9.3	

4.1.4. Failure mode in tension

Even though the SF and BF didn't provide the desired increase in flexural strength they did significantly alter the failure mode and post peak behavior of the beams. Plain concrete is known to be strong but brittle material that can't withstand a lot of flexural stress. As expected, this was observed in the failure of the plain concrete specimens. The day 1 plain concrete beams developed a crack at the mid span as can be seen in the in *figure 3-18 a* , this was in contrast to the day 28 plain concrete specimens which experienced a total collapse once failure load was reached as can be seen in *figure 3-18 b.* The 28-day plain concrete had no visual crack development and reached catastrophic failure (complete separation of the beam into two parts) without warning. This was observed across all plain concrete specimens. The suspected reason for the crack development and slightly more ductile failure of the day 1 concrete is due to the internal matrix not being full hydrated and still being wet at the time of testing allowing for a slightly more elastic failure. The initiation of one or multiple macrocracks at the midspan of the beam is characteristic of flexural failure and is the desired failure method of the beams in this situation. Flexural failure within the concrete occurs in similar fashion as compression failure. There are micro cracks present within the concrete in the ITZ, as the beam is loaded, and tension increases the micro cracks are elongated and as a result expand until the failure of the beam occurs.

Figure 3-18: Flexural failure of plain concrete a) day 1 specimen b) day 28 specimen

Although the steel fibers didn't seem to improve the ultimate flexural strength of the concrete, they did provide significant improvements when it came to post cracking behavior by holding the beam together past failure as opposed to the total collapse of the plain concrete. In contrast to the failure of the plain concrete the crack development in the SFRC was gradual and ductile demonstrating the effect of the tension bridge created by the steel fibers. The reason for the negligible increase in flexural strength might have to do with the type of fiber failure present in the beams. There were two main failure modes present, pull out and fiber fracture. Failure by pullout comes as a result of the bond between the matrix and the fibers outer surface failing, demonstrated in *figure3-19.* This does not allow the fibers full tensile carrying potential to be utilized thus negating the purpose for including the fibers in the concrete. The second more desirable type of failure is fracture of the fiber before debonding occurs, this means the fiber has acted as tension bridge and has been loaded to its maximum capacity. When inspecting the fibers in the cracked beams (*figure 3-20)*, we can see that almost all the fibers have failed by pullout or by fracture of the matrix around the fiber ends meaning the bond between the fibers and the matrix was poor. This could have been the cause for the lack of flexural strength increase.

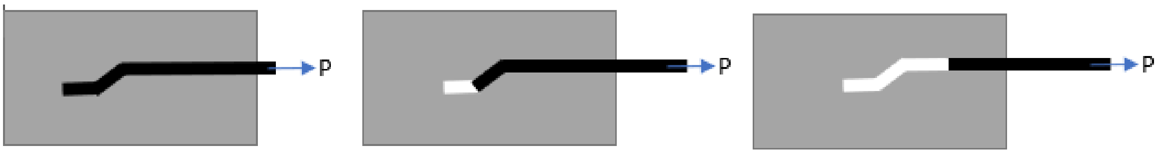


Figure 3-19: How failure by pullout occurs

Figure 3-20: Flexural failure of day 28 SFRC specimen

Another fact to consider when discusing the potential effect of fibers on the concrete is the orientation and dispersment throughout the beam. In theory the dispermsent of the steel fibers through out the beam is random, however for two of the beams we observed few to no fibers at the top og the beam (*figure 3-21)*, the fibers also apear to clumped togeather due to balling while mixing and casting the fresh concrete. The clumping and balling of the fibers can cause insuffiecnt compaction in the beam and results in increased amount of voids. This is charectaristic of fibers with heavier desitys as they tend to sink to the bottom of the fresh concrete under compaction. Orientetion of the fibers is significant because the fibes are only able to contribute to the tensile strength through bridging crack if they are oriented in the same direction as the tensile force.

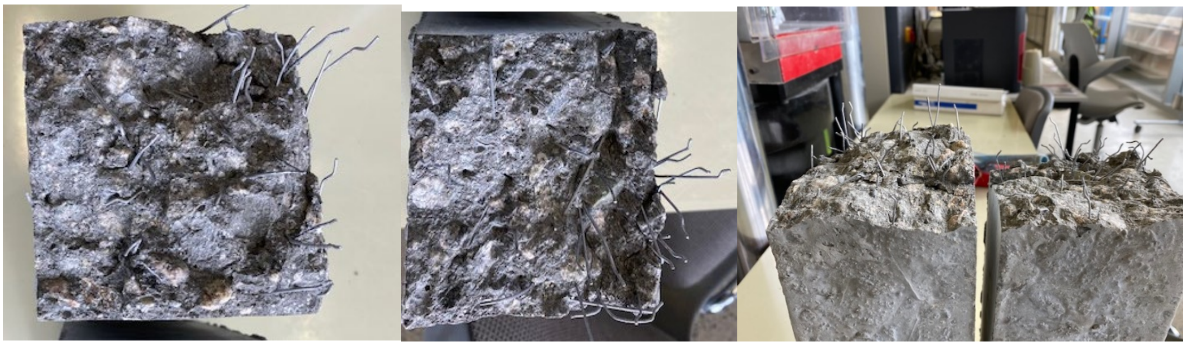


Figure 3-21: Cracked cross section of SFRC specimen

The failure mode of the BFRC was similar to that of the SFRC, however a few key differences were observed. All BFRC mixtures exhibited significant increase in ductility over the plain concrete and managed to avoid complete separation of the two pieces of the beam. This was in all likelihood due to the basalt fibers action as tension bridges and transferring the load and thus bridging the crack past failure. The failure of the day 1 specimens can be seen in *figure 3-22,* after failure the specimens were cracked open to inspect the failure mode of the fibers within. The day 1 specimens had a large presence of fibers that failed by pullout, likely due to the aforementioned lack of bond development between the matrix and the fibers. Through counting of the fibers in the cracked section it was established a ratio of approximately 80% pullout failure and 20% fiber fracture. This ratio improved for the day 28 specimens to approximately 60% pullout failure and 40% fiber fracture signifying and improvement in the fiber-matrix bond, the failure of the fibers can be seen in *figure 3-23*. The basalt fibers seem to generally form a better bond with the matrix compared to the steel fibers which are of similar tensile strength. This could be due to the steel fibers being smooth with only a hooked end while the basalt fibers have rough helix like surface creating a larger surface area for the matrix to bond with. Both of the 28-day BFRC mixes saw a decreased crack width compared day 1 specimens and the day 28 SFRC mixes, the crack widths of the specimens are outlined in *table 3-11* and *table 3-12*

Figure 3-22: Failure mode of a) day 1 0.5% BFRC b) day 28 0.5% BFRC c) day 28 1% BFRC

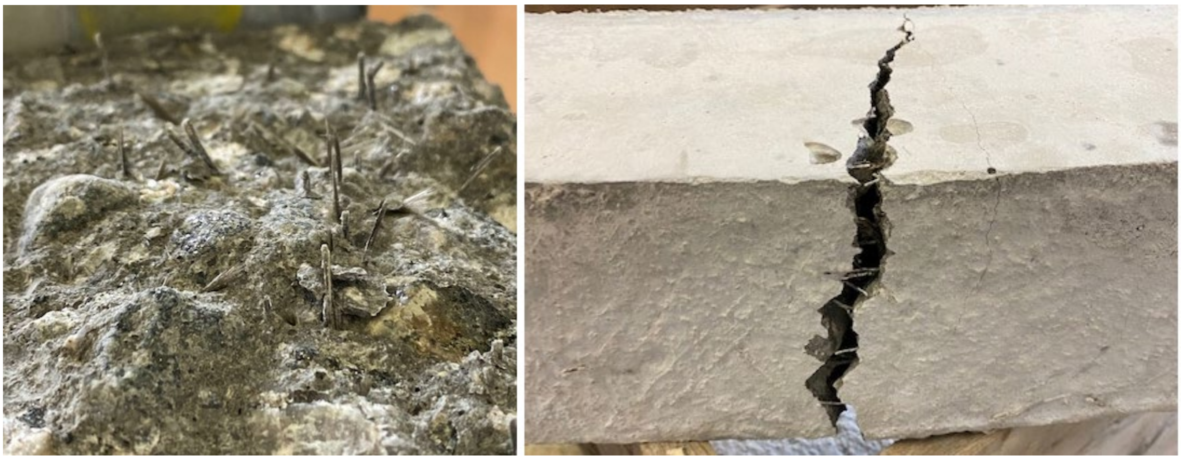


Figure 3-23: Cracked cross section of day 28 BFRC

4.1.5. Crack width

The crack width of the early strength specimens was very varried and inconsistenent, this was likley due to the aforemetinoned issues with the matrix – fiber bond. The results still show a clear advantage when using BFRC. Due to the varriance and inconstancy of the crack development of the day 1 testing the main focouse will be on the day 28 results.

Table 3-11: Crack width of day 1 specimens

Specimen number (days)	Crack width (mm)	Average crack width(mm)
Plain concrete 1 (1)	0,15	0,16
Plain concrete 1 (1)	0,15	
Plain concrete 1 (1)	0,1	
Plain concrete 1 (1)	0,2	
Plain concrete 1 (1)	0,2	
0.5% BF 1 (1)	11	12
0.5% BF 2 (1)	2	
0.5% BF 3 (1)	21	
1% BF 1 (1)	10	12,75
1% BF 2 (1)	6	
1% BF 3 (1)	12	
1% BF 4 (1)	23	

To properly understand the what the crack width tells us it is important to note that the loading mechanism of the machine is load controlled and was set to 0.05 N/mm^2*s and was calibrated to end the test once a 10% decline was noticed in the load carrying capacity. The instant complete failure at peak load of the plain concrete beams tells us that after cracking they had no addition post peak carrying capacity which was expected due to the plain concrete's brittle nature. The 0.5% BFRC had an average crack width of 4,4 mm while the 1% BFRC had an average crack width of 7,4 mm, this is a 70% increase. However, the 0.5% SFRC saw a 370% increase in crack width compared to the 0.5% BFRC and the 1% SFRC similarly saw a 372% increase compared to the 1% BFRC. Due to the 10% failure condition imposed on the testing machine the increase in crack width depicts a larger post peak carrying capacity and increased ductility. While the BF is effective at acting as a tension bridge and carrying loads across the crack to increase the toughness and post peak behavior the SF appear to be on average 4x more effective. The BF and SF are reported to have very similar tensile strengths, but the SF are a lot more rigid than the BF. This can explain the relatively similar ultimate strength but difference in post peak behavior. The larger crack width also tells us that the subsequent deflection before failure is also greater for the SFRC. The increased rigidity and structural integrity of the SFRC beams compared to the BFRC beams was also observed after removing the beams from the testing machine and attempting to completely sever the two pieces of the beam. All of the BFRC beams didn’t require much additional force and could be separated in two at the crack by hand meanwhile all the SFRC required addition strikes with a hammer to be able to separate the two pieces proving more effective at bridging the crack past failure.

Table 3-12:Crack width of day 28 specimens

Specimen number (days)	**Crack width (mm)**	**Average crack width(mm)**
Plain concrete 1 (28)	Complete failure	N/A
Plain concrete 2 (28)	Complete failure	
Plain concrete 3 (28)	Complete failure	
Plain concrete 4 (28)	Complete failure	
0.5% BF 1 (28)	4	4.4
0.5% BF 2 (28)	4	
0.5% BF 3 (28)	5	
0.5% BF 4 (28)	4	
0.5% BF 5 (28)	5	
1% BF 1 (28)	7	7.4
1% BF 2 (28)	7	
1% BF 3 (28)	8	
1% BF 4 (28)	7	
1% BF 5 (28)	8	
0.5% SF 1 (28)	15	16.25
0.5% SF 2 (28)	17	
0.5% SF 3 (28)	18	
0.5% SF 4 (28)	15	
1% SF 1 (28)	28	27.6
1% SF 2 (28)	30	
1% SF 3 (28)	25	

4.2. Discussion

Our findings when testing the flexural strength of SFRC beams was surprising as there was no noticeable increase in strength when adding volumes of 0.5% and 1% steel fibers. Even though we observed no increase in flexural strength, the toughness and ductility of the concrete beams improved significantly with the addition of fibers. SFRC beams have previously shown to have improved flexural strength especially at higher fiber volumes. Jhatial and co. performed similar tests to ours but instead tested fiber volumes all the way up to 5%. They tested using M20 grade concrete with a w/c ratio of 0.5 and used beams of the same dimensions (500x100x100). Their studies found a 17% increase in flexural strength when going from no fibers to 1% fibers, the strength was further increased by 51% for the 3% fiber volume beams and decline for higher fiber volumes due to compaction difficulties and balling of the fibers. Similar increase in ductility was also observed and resistance to cracking and crack propagation compared to plain concrete. The disparity of our results when it comes to ultimate flexural strength may be due to the previously outlined factors, yet comparable increase in ductility and post cracking behavior was present. [57].

The BFRC exhibited a reduction in ultimate flexural and compressive strength when compared to SFRC and plain concrete. This result was also rather strange as the theory and previous research supports the claim that fibers in moderate doses have a positive impact on the flexural strength of concrete. The 1% BFRC mix seemed to have a greater detrimental effect on the flexural strength compared to the 0.5% mix. As previously mentioned Branston and co. found a 50% increase in flexural strength with the addition of 1% Minibars [55]. The reason for this decrease in strength could have come down to the compaction as compaction of the 1% mixture was cumbersome and some pockets of entrained air were observed when inspecting the cracked sections. Another factor could have been the increase of matrix volume for the fiber mixtures. The matrix volume was increased from 320 L/m^3 for the plain concrete mixture to 340 L/m^3 for the fiber mixtures. This increase of water and cement was proportional with the set 0.4 w/c ratio that was set for this experiment. The reduction in compressive strength was expected as similar results were achieved by previous literature.

5. Conclusion and Future studies

Conclusion

When comparing the fresh state of the SFRC and BFRC we saw a reduction of workability and flow as was expected due to the fiber addition, but this can be improved though the use of admixtures such as superplasticizers. The compaction process was significantly hindered at 1% fiber volumes for both types of fibers with the steel fibers being slightly harder to work with due to their rigidity. The basalt fibers did however have a higher tendency to ball and clump and had to be picked apart by hand in some cases. All mixtures had roughly the same air content and density.

The addition of BF and SF purely for increased compressive strength is sub optimal as the increase observed in the case of SFRC is not enough to warrant the reduction in workability, flow, and compaction difficulties. For the BFRC the compressive strength was reduced compared to plain concrete and it is therefore not feasible to use BF as compressive reinforcements. The addition of SF and BF solely for an increase in ultimate flexural strength also seems sub optimal due to the previously outlined downsides of working with FRC. For situations that require a large ultimate flexural strength traditional steel rebar should be used. Even though both SF and BF mixtures failed to increase the ultimate flexural strength compared to the plain concrete they did significantly increase the post cracking behavior of the beams. An increase of ductility and post cracking carrying capacity was observed. The SF performed better than the BF in the 28-day hardened state by having better flexural strength, ductility, post failure carrying capacity and improvement of the concretes compressive strength as opposed to the reduction caused by the basalt fibers. The obvious advantages of the BF are however their light weight and improved capability to resist pullout. It can therefore be concluded that the steel fibers resulted in greater overall performance in these experiments and should be used in cases where significant improvement of the concretes ductile behavior and toughness are required.

Future studies

Future research should be conducted on the comparison of plain concrete with the same matrix volume as that of the fiber mixture to ensure that the results are more in line with each other. Additional test at higher or lower w/c ratios should also be conducted to investigate the behavior of the fibers across varying water contents and compare the strength and workability of the mixes. Additionally, different volumes and dimensions can be used to get a better overview of the effects of the fibers. The observed pullout/slippage of the steel fibers warrant for testing of fibers with different geometrical properties to see how much of an impact it has on the mechanical properties. The use of a scanning electron microscope can also be employed to investigate the bond quality between the fibers and the matrix at different stages of the curing process. Due to some calibration errors and recording errors we were unable to record the specific deformation and ductility of the FRC, therefore it is necessary to repeat the tests to compare the specific numbers of the different concrete mixes.

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Appendix

ReforceTech™
Basalt Fiber Reinforcement Technology

MiniBars™

Patent Pending

ENABLING INNOVATION IN CONCRETE STRUCTURES

ReforceTech Basalt Fiber Reinforced Polymer (BFRP) MiniBars™ are an engineered macrofiber designed to increase the structural tensile strength of concrete by uniform distribution of MiniBars™ throughout the matrix.

Concrete reinforced with RFT MiniBars™ demonstrates excellent flexural toughness and energy absorption capability after cracking when tested according to ASTM C78 and C1399 and EN16451.

Testing demonstrates that MiniBars™ satisfy the relevant residual strength requirements based on ASTM C1609 tests (as specified in ACI 318) using MiniBars™ as shear reinforcement in reinforced concrete slabs and beams.

ReforceTech BFRP MiniBars™ are engineered to deliver high flexural tensile strength and average residual strength in concrete in conjunction with proven alkali resistance and engineered bond strength.

Det Norske Veritas (DNV) testing has demonstrated that the unique ReforceTech process delivers a strong bond between the concrete and the BFRP bars. Further testing with the University of Akron demonstrated results of Flexural Tensile Strength (ASTM C78) enabling the increase from 4.5 MPa (653 psi) for normal concrete up to 17 MPA (2465 psi) depending on volume fraction of MiniBars™. Testing Average Residual Strength (ASTM C1399) has developed ARS from zero in normal concrete to over 17 MPa (2465 psi). The Norwegian technical university NTNU has demonstrated the bond strength of MiniBars™ in single fiber testing.

From volcanic basalt stone, thin basalt fibers are assembled in ReforceTech's patented process to create unique macro fiber called MiniBars™ cut to the prescribed length 20 to 60 mm (0.79" to 2.36") to achieve the desired concrete performance.

UNIQUE ENABLING FEATURES TO REDUCE PROJECT COSTS

- Corrosion Free allows thinner lighter structures
- Zero Conductivity, eliminates galvanic corrosion
- Improved Flexural and Average Residual Strength of Concrete allowing design freedom, elimination or reduction of normal reinforcement
- Compatible Specific Gravity of 1.9 g/cm3 means uniform distribution, MiniBars™ do not settle or float and are easily mixed
- Suitable for site work, precast or dry mix concrete
- No MiniBars protrude from Concrete; no MiniBars™ are visible on the surface
- Improved freeze thaw resistance
- Savings of labor costs and faster construction
- Improved abrasion resistance
- Improves safety on site by eliminating handling of traditional steel reinforcement
- Excellent bond related to engineered helix, rough fiber surface, bond length and diameter

MiniBars Properties

Diameter	0.65mm	0.026 inches
Length	20 to 60mm	0.8 to 2.40 inches
Specific Gravity	1.9g/cc	0.069 oz/inch3
Water Absorption	None	None
E modulus	60GPa	8700 KSI
Tensile Strength	1100MPa	159 KSI
Alkaline Resistance	Excellent	Excellent

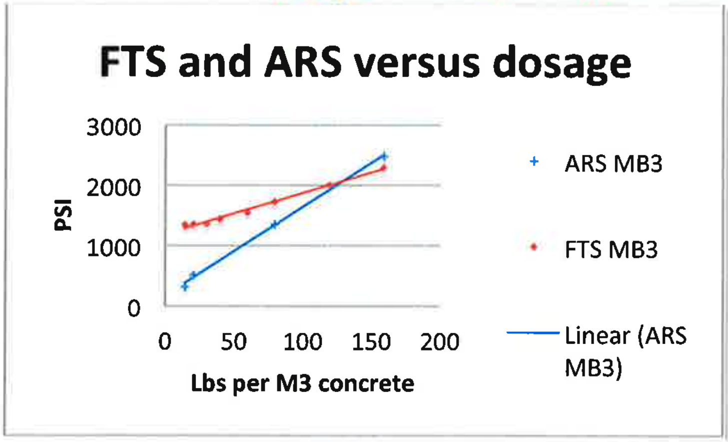
MiniBars ™

ADVANTAGES

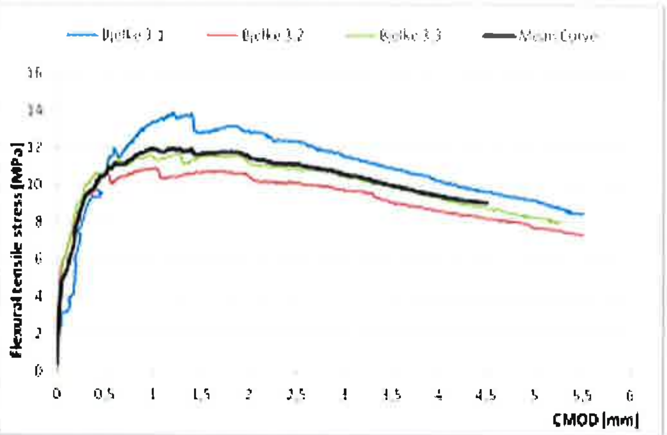
- ***Greatly increases toughness and strength of concrete at low dosage***
- ***Enables thinner sections, lighter weight products for easier installation and transportation***
- ***Suitable for aggressive chloride environments***
- ***Acts as minimum reinforcement to lower cost***
- ***Transforms concrete from a brittle material requiring steel reinforcement to ductile with tensile strength capacity***

REFORCETECH IS 9001 CERTIFIED

Improved Concrete Tensile Properties



ASTM C78 and 1399



EN 14651 at 2% VF

Typical Applications

- ***Submersed Concrete Products***
- ***Structural Slab on Grade***
- ***Thinner Precast and Cast-In-Place Facades***
- ***Highway Slabs & Bridge Decks***
- ***Floating Infrastructure***
- ***Agricultural Products***
- ***Drainage Systems***
- ***Grout Systems***
- ***Blast & Impact Resistance***
- ***Inner Walls***
- ***Bridge Beams***
- ***Sound Walls***
- ***Barrier Walls***
- ***Block Walls***
- ***Power Poles***
- ***Barrier Poles***
- ***High Performance Concrete***
- ***Balconies***

Specification for MiniBars™ - MasterFormat® Section 03 24 00

Generic: Use macrofibers made from Basalt FRP rods with helix winding geometry and diameters in the range of 0.65mm to 0.70mm. BFRP macrofibers should be fabricated with CBF (continuous basalt fiber) and vinyl ester resin with a minimum Heat Distortion Temperature of 235F (115C) and Modulus of Elasticity of 8700 ksi (60 GPa). The length of the fibers will be from 0.80" to 2.40" (20mm to 60mm) with exact length to be determined by trial batch with guidance from the manufacturer. Dosage will be determined by trial batch up to130 lbs/cu.yd based on the minimum ARS (average residual strength per ASTM C1399) and FTS (flexural tensile strength per ASTM C1609) established by the engineer-of-record. The BFRP macrofiber reinforced concrete shall be capable of achieving an ARS of 2400 psi (17.2 MPa) and FTS of 2300 psi (15.8 MPa) at maximum dosage.

Specific: Use MiniBars™ by ReforceTech AS. Length of fibers and dosage to be determined by trial batch with guidance from the manufacturer per the requirements for ARS (ASTM C1399) and FTS (ASTM C1609) established by the engineer-of-record for the project.

Mixing Instructions

- **Due to the MiniBars™ unique density and geometry they are very simple to mix. They do not float, ball or sink.**
- **MiniBars are added in either the batching plant or in the truck and follow normal practices by adding after water and add mixtures. Mix for 5 to 10 minutes.**
- **Higher volume fraction dosage's are possible with minor mix design adjustments**
- **Contact your representative for specific instructions for your mix design, application or concrete**

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RESCON MAPEI

Stålfiber 45/50BN

03.06

PRODUKTBESKRIVELSE

Stålfiber 45/50 BN er ståltråd, formet og klippet i lengder, til armering av betong, mørtler og andre komposittmaterialer.
Stålfiber 45/50 BN er en kaldtrukket ståltrådfiber med endekroker.

BRUKSOMRÅDE

Industrigulv.
Stålfiber 45/50 BN brukes i betong og mørtel hvor tradisjonell armering er helt eller delvis tatt ut.

GEOMETRI

Lengde (l): 50mm
Diameter (d): 1,05 mm
Kvalitetsklasse 45
Slankhetstall (=l/d): 48
Antall: 2800 fibre/kg

STREKKFASTHET

- Ståltrådens strekkfasthet: 1000 N/mm^2
- Oppfyller EN 10016-2 - C9D

OVERFLATEBEHANDLING

Ingen.

ANBEFALINGER - BLANDING

Generelt

- Tilsetting av fibre på betongfabrikk anbefales
- Anbefalt maksimal dosering *⁾:

Maks. korn-størrelse (mm)	Dosering (kg/m^3)	
	Støpt	Pumpet
8	160	120
16	100	75
32	80	60

* *se nærmere informasjon på våre nettsider www.resconmapei.no, ved databladet*

- En jevn siktekurve anbefales

Tilsetting av fibre

Sekkene er ikke vannløselige og kan derfor ikke kastes inn i betongen.

I betongfabrikkens blander

- Tilsett aldri fibre som første komponent i blanderen
- Fibrene kan tilsettes sammen med tilslaget eller i den nyblandede betongen

I trommelbil

- Anvend maksimal omdreiningshastighet 12-18 o.p.m.
- Betongens synkmål skal være minst 12 cm
- Tilsett fibrene med en maks. hastighet på 60 kg/min.
- Fibrene tilsettes f.eks. via et transport bånd
- Etter tilsetting av fibrene: fortsett å blande på full hastighet i 4-5 min. (± 70 omdr.)

LAGRING

Beskytt paller mot regn og fukt.
Unngå å stable pallene.
Leveres i 20 kg ikke vannløselige sekker på pall (1200 kg). Big bags (900 kg).

VERNETILTAK

For helse-, miljø- og sikkerhetsinformasjon - se eget HMS-datablad. HMS-databladene finnes på **www.resconmapei.com**.

MERK

De tekniske anbefalinger og detaljer som fremkommer i denne produktbeskrivelse representerer vår nåværende kunnskap og erfaring om produktene.
All ovenstående informasjon må likevel betraktes som retningsgivende og gjenstand for vurdering.
Enhver som benytter produktet må på forhånd forsikre seg om at produktet er egnet for tilsiktet anvendelse.
Brukeren står selv ansvarlig dersom produktet blir benyttet til andre formål enn anbefalt eller ved feilaktig utførelse.

Alle leveranser fra Rescon Mapei AS skjer i henhold til de til enhver tid gjeldende salgs- og leveringsbetingelser, som anses akseptert ved bestilling.

TEKNISKE SPESIFIKASJONER

Strekkfasthet (N/mm^2):	*> 1000*
Lengde (mm):	*50*
Diameter (mm):	*1,05*
Slankhetstall (l/d):	*48*
Antall fiber pr. kg:	*2800*
Densitet (kg/m^3):	*7800*
Emballasje:	*20 kg sekk, 1200 kg pr. pall*

Produsent:
Rescon Mapei AS
Vallsetvegen 6, 2120 Sagstua, Norway
Tlf: +47 62 97 20 00 Fax: +47 62 97 20 99
post@resconmapei.no
www. resconmapei.com

Rescon Mapei AS
et selskap i
MAPEI

NORCEM
HEIDELBERGCEMENT Group

Norcem AS
Postboks 142, Lilleaker, 0216 Oslo
Tlf. 22 87 84 00
firmapost@norcem.no
www.norcem.no

PRODUKTINFORMASJON

STANDARDSEMENT FA

CEM II/B-M 42,5 R

Norcem Standardsement FA er tilpasset norske forhold og kan benyttes til betong i alle eksponerings-, bestandighets- og fasthetsklasser. Standardsement FA gir bestandig betong også i kombinasjon med alkalireaktivt tilslag. Produktet er tilpasset for bygningskonstruksjoner i bestandighetsklasse M60 og M90, men er også godt egnet for strengere bestandighetsklasser.

Standardsement FA tilfredsstiller kravene i NS-EN 197-1:2011 til Portlandblandingssement CEM II/B-M 42,5 R.
Ytelsesdeklarasjon nr.: 1111-DoP-NO11-0573 (Brevik) og 1111-DoP-NO12-0575 (Kjøpsvik).
Sertifikat-Konstant ytelse nr.: 1111-CPR-0573 (Brevik) og 1111-CPR-0575 (Kjøpsvik).
Sist revidert: 2015

DISTRUBISJON OG LAGRING

Sementen leveres i sekk, big bag og bulk. Sementen skal lagres i tørr og tett silo da fukt skader sementen. Lagringstiden bør begrenses til 6 måneder. Effekten av kromatreduseringen av sementen er effektiv i 6 måneder etter produksjonsdato, dersom sementen lagres tørt og tett.

SIKKERHET VED BRUK

All sement skal oppbevares utilgjengelig for barn og er farlig å spise. Sement i øynene kan gi alvorlige øyeskader. Fuktig sement danner kalsiumhydroksid som virker irriterende på hud og åndedrettsorgan. Sikkerhetsdatablad med fullstendig informasjon finnes på Norcems hjemmeside www.norcem.no under «Våre produkter».

PRODUKTDATA

Produktdata med deklarerte verdier finnes på Norcems hjemmeside www.norcem.no under «Våre produkter».

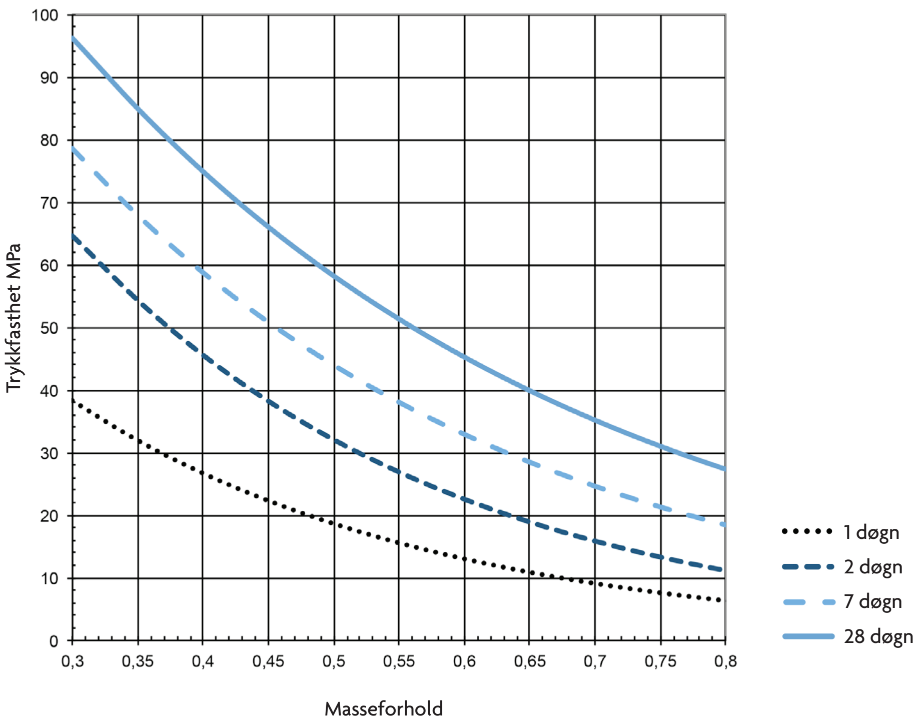
FASTHETSUTVIKLING

Fasthetsutvikling er en sentral egenskap for planlegging, styring og utførelse av alle betongarbeider. Fasthetsutvikling er avhengig av sementtype, tilslag, masseforhold, innhold av luft, herdeforhold (temperatur, tid og fuktighet) og eventuell bruk av tilsetningsmaterialer eller –stoffer. I figur 1 er vist eksempel på trykkfasthetsutviklingen som funksjon av masseforhold og alder ved 20°C vannlagring for betong uten tilsetningsstoff og med Norcem Standardsement FA.

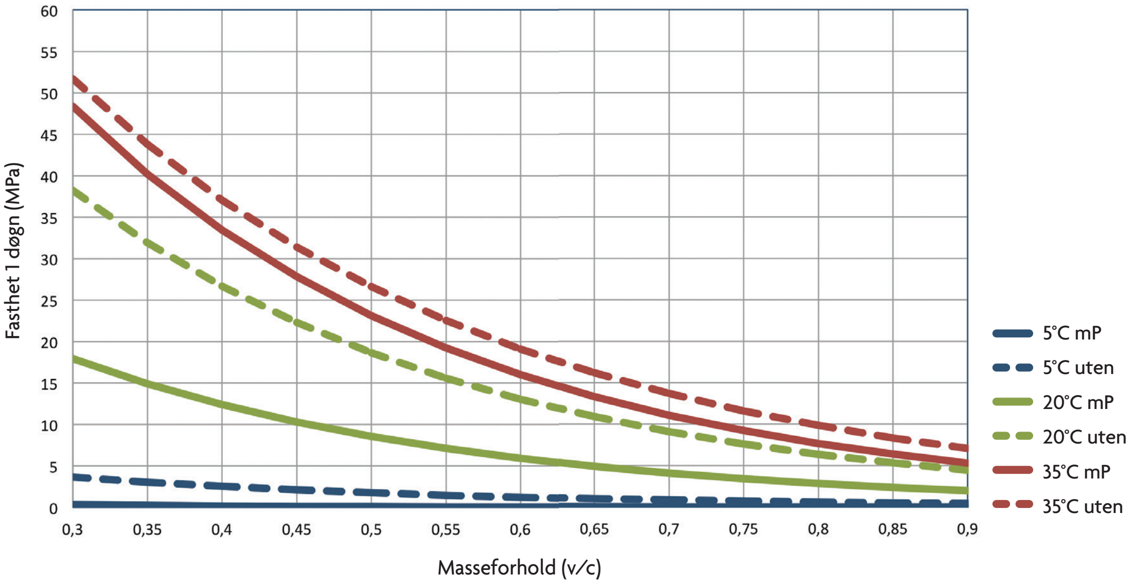
TIDLIGFASTHET

Tidligfastheten i betong er meget avhengig av temperatur og eventuell dosering av tilsetningsstoff med retarderende effekt. I figur 2 er vist trykkfasthet etter 1 døgn med forskjellige masseforhold med og uten plastiserende tilsetningsstoff (P-stoff) med Standardsement FA. Prøvene er vannlagret ved varierende temperatur.

FASTHETSUTVIKLING - fig. 1



TIDLIGFASTHET - fig. 2



MOTSTAND MOT ALKALIREAKSONER

Norsk Betongforenings Publikasjon nr. 21 fastsetter retningslinjer for produksjon av bestandig betong med alkalireaktivt tilslag. Publikasjonen fastlegger at for betong med Standardsement FA kan det benyttes alkalireaktivt tilslag dersom betongens totale alkali-innhold ikke overstiger visse verdier. For betong der Standardsement FA blandes med andre sementer, gjelder andre grenser. For grenseverdier – se www.betong.net under «Publikasjoner» og «Vedlegg C til Publikasjon 21».

FASTHETSKLASSE – MASSEFORHOLD

Med normal god styring av betongproduksjonen er det behov for en overhøyde på ca 7 MPa ved de ulike fasthetsklassene for å produsere med tilstrekkelig sikkerhet mot undermålere. Tabell 1 gir følgende retningsgivende verdier for minste og største masseforhold i ulike fasthetsklasser for betong med Standardsement FA og uten luftinnføring.

FASTHETSKLASSE – MASSEFORHOLD

Fasthetsklasse	B20	B25	B30	B35	B45	B55
Masseforhold minste - største	0.65-0.73	0.60-0.65	0.53-0.60	0.46-0.53	0.40-0.46	0.35-0.40

Tabell 1

BESTANDIGHETSKLASSE

NS-EN 206:2013+NA:2014 klassifiserer betongens miljøpåvirkninger i eksponeringsklasser. I nasjonalt tillegg til denne standarden er de ulike eksponeringsklassene gruppert i bestandighetsklasser med krav til betongens største masseforhold (tabell 2). Tabell 3 viser anbefalte kombinasjoner av bestandighets- og fasthetsklasser. I figur 3 er vist sammenhengen mellom bestadighetsklasse og fasthetsklasse, i et variasjonsbelte forårsaket av ulike produksjonsforutsetninger (bl.a tilslag). Figur 3 gjelder for betong uten luftinnføring med Norcem Stanardsement FA og vannlagring i 20°C i 28 døgn.

VALG AV BESTANDIGHETSKLASSE (NASJONALE KRAV)

Eksponeringsklasse	M90	M60	M45	MF45*	M40	MF40*
X0	•	•	•	•	•	•
XC1, XC2, XC3, XC4, XF1		•	•	•	•	•
XD1, XS1, XA1, XA2, XA4			•	•	•	•
XF2, XF3, XF4				•		•
XD2, XD3, XS2, XS3, XA3					•	•
XSA	Betongsammensetning og beskyttelsestiltak fastsettes særskilt. Betongsammensetningen skal minst tilfredsstille kravene til M40.					
Største masseforhold	0,90	0.54	0,45	0,45	0,40	0,40

*Minst 4% luft

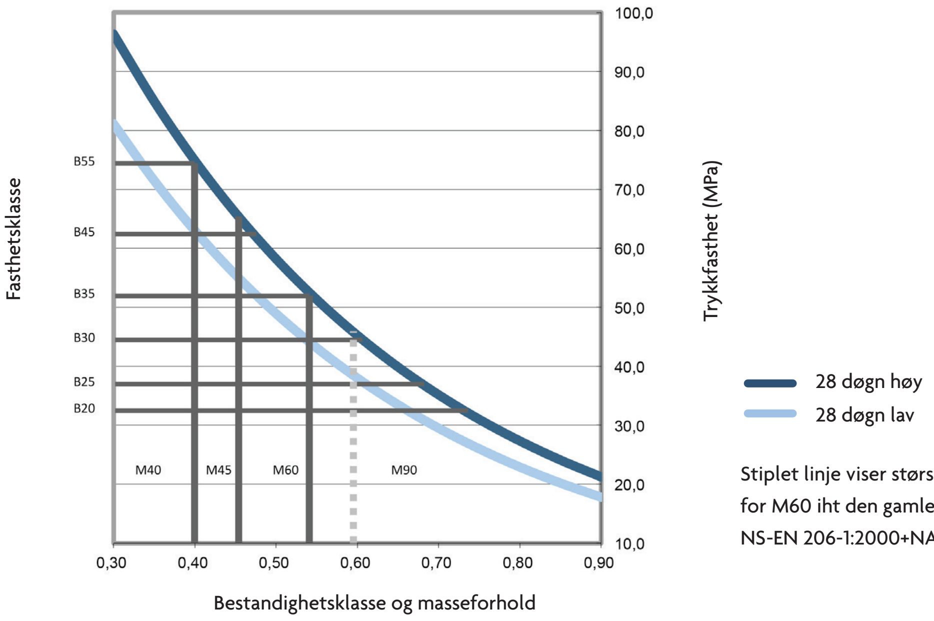
Tabell 2

ANBEFALTE KOMBINASJONER

Bestandighetsklasse	**Fasthetsklasse**
M90	B20 eller høyere
M60	B30 eller høyere
M45	B35 eller høyere
M40	B45 eller høyere

Tabell 3

BESTANDIGHETSKLASSE - FASTHETSKLASSE - fig. 3



Stiplet linje viser største masseforhold
for M60 iht den gamle standarden
NS-EN 206-1:2000+NA:2007

Dynamon SX-N

EN 934-2
T 3.1/3.2

Superplasticising admixture

PRODUCT DESCRIPTION

Dynamon SX-N is a very efficient liquid superplasticising admixture, based on modified acrylic polymers.
The product belongs to the **Dynamon System** based on the DPP (Design Performance Polymers) technology, a new chemical process that can model the admixture's properties in relation to specific performances required for concrete. The process is developed by means of a complete design and production of monomers (an exclusive Mapei know-how).

AREAS OF APPLICATION

Dynamon SX-N is an all-round product to be used in nearly all types of concrete to improve the workability and/or reduce the amount of water needed.

Some specific applications are:

- Concrete with reduced permeability with specifications as to very high mechanical strength and to long durability in aggressive environments.

- Concrete with high levels of workability (consistency classes S4 or S5 - according to EN 206)

- Self-compacting concrete where high slump retention is required. If extra stabilisation is needed, a viscosity enhancing agent, **Viscofluid** or **Viscostar** can be used.

- Production of frost resistant concrete - in combination with air entraining agents (AEA), **Mapeair**. The correct type and amount of AEA is dependent on the properties of the other available ingredients.

- Concrete for flooring where a smooth concrete with high workability is aimed for. Larger dosages and lower tempe ratures may increase the retardation.

TECHNICAL PROPERTIES

Dynamon SX-N is an aqueous solution of active acrylic polymers that very efficiently disperses clusters of cement grains.

This effect can in principle be used in the following three ways:

1. To reduce the amount of added water, yet retain the same workability. Lower water to cement ratio means higher mechanical strength, reduced permeability and increased durability.

2. To increase workability compared to concrete with equal water to cement ratio. With the same mechanical strength the casting is facilitated.

3. To reduce both the amount of water and the amount of cement without changing the concrete's mechanical strength. In this way it is possible to

reduce the total cost of the concrete (less cement), reduce the concrete's shrinkage potential for (less water) and reduce the possibility of cracks due to temperature gradients (less hydration heat). Especially with concretes that normally have high amounts of cement, this effect is very important.

COMPATIBILITY WITH OTHER PRODUCTS

Dynamon SX-N can be combined with other admixtures from Mapei; such as a set-accelerating admixture, **Mapefast** or a set-retarding admixture, **Mapetard**. The product is also compatible with air entraining admixtures to produce frost resistant concrete, **Mapeair**.

The choice of admixture is done after an evaluation of the properties of the other ingredients in the mix.

DOSAGE

To obtain the prescribed properties (i.e. strength, durability, workability, cement reduction), **Dynamon SX-N** is added in dosages between 0.4 and 2.0% of the amount of cement + fly ash + microsilica. Increased dosages will also increase the slump retention, i.e. the time to be able to work with the concrete.

Higher dosages and lower temperatures will delay the setting of the concrete. To obtain correct knowledge, tests with actual parameters are advisable, especially before larger pours.

As opposed to traditional superplasticisers based on melamines or naphtalenes, the maximum effect of **Dynamon SX-N** is obtained regardless of when it isaddes during the mixing procedure it is added, but the time of addition can influence the mixing time. If at least 80 % of the mixing water is added before **Dynamon SX-N** the required mixing time will generally be shortest. It is nevertheless important to perform using the actual mixing equipment.

Dynamon SX-N can also be added directly into the truck on site. The concrete should then be mixed at full speed at least for one minute pr m^3 of concrete, and never shorter than 5 minutes.

PACKAGING

Dynamon SX-N is available in 25 liter cans, 200 liter drums, 1000 liter IBC tanks and in tank.

STORAGE

The product must be stored at temperatures between +8 and +35°C, and will retain its properties for at least one year if stored unopened in its original packaging. If the product is exposed to direct sunlight, colour variation may occur, but this will not affect the technical properties of the product.

SAFETY INSTRUCTIONS FOR PREPARATION AND INSTALLATION

Instructions for the safe use of our products can be found on the latest version of the SDS available from our website www.mapei.no

PRODUCT FOR PROFESSIONAL USE.

WARNING

Although the technical details and recommendations contained in this product data sheet correspond to the best of our knowledge and experience, all the above **-** *information must, in every case, be taken as merely indicative and subject to confirmation after long-term practical application: for this reason, anyone who intends to use the product must ensure beforehand that it is suitable for the envisaged application: in every case, the user alone is fully responsible for any consequences deriving from the use of the product.*

Please refer to the current version of the technical data sheet, available from our web site www.mapei.no

LEGAL NOTICE

The contents of this Technical Data Sheet ("TDS") may be copied into another project-related document, but the resulting document shall not supplement or replace requirements per the TDS in force at the time of the MAPEI product installation.
The most up-to-date TDS can be downloaded from our website www.mapei.no
ANY ALTERATION TO THE WORDING OR REQUIREMENTS CONTAINED OR DERIVED FROM THIS TDS EXCLUDES THE RESPONSIBILITY OF MAPEI.

All relevant references for the product are available upon request and from www.mapei.no

TECHNICAL DATA (typical values)

PRODUCT IDENTITY

Appearance:	liquid
Colour:	yellowish brown
Viscosity:	easy flowing; < 30 mPa·s
Solids content (%:)	18.5 ± 1.0
Density (g/cm^3):	1.06 ± 0.02
pH:	6.5 ± 1
Chloride content (%):	< 0.05
Alkali content (Na_2O-equivalents) (%):	< 2.0

MAPEI®

BUILDING THE FUTURE

MAPEI

Mapeform Eco 31

Form release-agent based on vegetable oils in water emulsion with chemical action

WHERE TO USE

Anti-adhesive treatment of iron, aluminum and plastic forms (epoxy, phenolic, polyester and polyurethane resins). It is particularly suitable for vertical applications.

Some application examples

- To facilitate form release of precast concrete. Its particular viscosity makes it suitable for vertical applications on formworks where it is important to limit product pouring when sprayed.
- To facilitate form release of steam-cured concrete.
- To form release concrete cast in plastic forms.
- To form release concrete cast in metal forms.

TECHNICAL CHARACTERISTICS

Mapeform Eco 31 consists of a stable emulsion of vegetable oils, corrosion inhibitors and special admixtures developed in the MAPEI Research Laboratories.

The efficiency of **Mapeform Eco 31** is given by its action of chemical concrete stripping from formwork.

Mapeform Eco 31 features the following advantages:

- improved surface quality thanks to the drastic reduction of large and micro surface air bubbles;
- no surface dusting;
- no grease stains, even with white cements;
- less cleaning of forms;
- simple low-cost application;
- **easily and rapidly biodegradable**; non toxic, does not irritate and does not cause sensitization;
- not subject to the Italian law for the use of form release-agents based on mineral oils.

RECOMMENDATIONS

- Do not dilute **Mapeform Eco 31** with water.
- Do not dilute **Mapeform Eco 31** with solvents or other oils.
- Preferably use **Form Release Agent DMA 1000** with raw wood forms.
- Do not use **Mapeform Eco 31** with concrete, gypsum and polystyrene forms.
- When using with rubber forms make sample tests or contact the MAPEI Technical Services Department.

HOW TO USE

Mapeform Eco 31 is ready-to-use.

Application

Apply **Mapeform Eco 31** on the clean, dry formwork, preferably in a single coat, using pumps or atomisers at a pressure of 6 bar. To get the best finish, we recommend wiping over the formwork with a cotton wool rag, although this step is not absolutely necessary.

For effective stripping of forms, do not exceed the recommended dosage. This can cause the formation of a fine dust on the surface which can alter the final finish.

Cleaning

Tools used for applying **Mapeform Eco 31** can be cleaned with water.

Mapeform Eco 31

TECHNICAL DATA (typical values)

PRODUCT IDENTITY	
Consistency:	fluid liquid
Colour:	white
Density (g/cm^3):	0.96 ± 0.02 at +23°C
Brookfield viscosity at +23°C (cPs):	< 50 (1 shaft - 20 revs)
Release action:	chemical
APPLICATION DATA	
Preparation:	ready-to-use
Application:	suitable pressure pump > 6 bar

CONSUMPTION

Metal forms: 15-25 g/m^2.
Plastic forms: 15-25 g/m^2.

STORAGE

Mapeform Eco 31 can be stored for 12 months in sealed containers away from prolonged, direct exposure to sunlight and at a temperature between +5°C and +35°C.

PACKAGING

The product is supplied in 1000 l IBC, 200 l drums and 23 kg tanks.

SAFETY INSTRUCTIONS FOR PREPARATION AND APPLICATION

Mapeform Eco 31 is not considered hazardous according to current standards and regulations regarding the classification of mixtures. It is however recommended to use gloves, eyes protection and to take the usual precaution for the handling of chemicals.

For further and complete information about the safe use of our product please refer to our latest version of the Material Safety Data Sheet.

PRODUCT FOR PROFESSIONAL USE.

WARNING

Although the technical details and recommendations contained in this product data sheet correspond to the best of our knowledge and experience, all the above information must, in every case, be taken as merely indicative and subject to confirmation after long-term practical application; for this reason, anyone who intends to use the product must ensure beforehand that it is suitable for the envisaged application. In every case, the user alone is fully responsible for any consequences deriving from the use of the product.

Please refer to the current version of the Technical Data Sheet, available from our website www.mapei.com

All relevant references for the product are available upon request and from www.mapei.com

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BUILDING THE FUTURE

Parameter table:

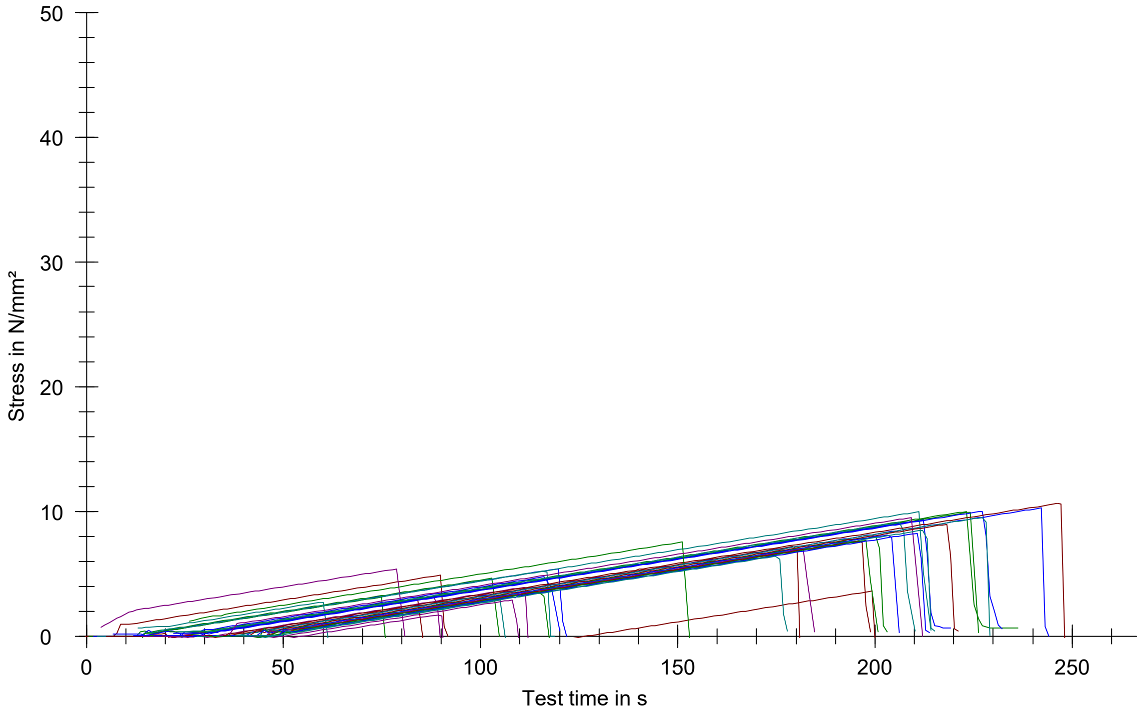
Test protocol : Bachelor oppgave
Tester : Nikolay og Omed
Customer :
Test standard :
Strength grade :
Creation date :
Age : 0 T
Other :

Type strain extensometer :
Machine data : Controller TT1412
PistonStroke
LoadCell 250 kN

Results:

Nr	Date	ID	a mm	b mm	A mm²	h mm	F_m kN
1	10.03.2021	100x500 RF dag 1 A1	100,0	500,0	50000,0	100,0	7,21
2	10.03.2021	100x500 RF dag 1 B1	100,0	500,0	50000,0	100,0	6,21
3	10.03.2021	100x500 RF dag 1 C1	100,0	500,0	50000,0	100,0	7,26
4	10.03.2021	100x500 RF dag 1 A2	100,0	500,0	50000,0	100,0	7,06
5	10.03.2021	100x500 RF dag 1 B2	100,0	500,0	50000,0	100,0	7,31
6	11.03.2021	100x500 BF0.5% dag 1 A1	100,0	500,0	50000,0	100,0	0,25
7	11.03.2021	100x500 BF0.5% dag 1 B1	100,0	500,0	50000,0	100,0	4,26
8	11.03.2021	100x500 BF0.5% dag 1 C1	100,0	500,0	50000,0	100,0	0,52
9	11.03.2021	100x500 BF0.5% dag 1 A2	100,0	500,0	50000,0	100,0	3,89
10	11.03.2021	100x500 BF0.5% dag 1 B2	100,0	500,0	50000,0	100,0	3,94
11	12.03.2021	100x500 BF1% dag 1 A1	100,0	500,0	50000,0	100,0	4,02
12	12.03.2021	100x500 BF1% dag 1 B1	100,0	500,0	50000,0	100,0	4,69
13	12.03.2021	100x500 BF1% dag 1 C1	100,0	500,0	50000,0	100,0	-
14	12.03.2021	100x500 BF1% dag 1 A2	100,0	500,0	50000,0	100,0	3,71
15	12.03.2021	100x500 BF1% dag 1 B2	100,0	500,0	50000,0	100,0	4,37
16	23.03.2021	100x500 SF0.5% dag 28 A1	100,0	500,0	50000,0	100,0	9,76
17	23.03.2021	100x500 SF0.5% dag 28 B1	100,0	500,0	50000,0	100,0	13,52
18	23.03.2021	100x500 SF0.5% dag 28 C1	100,0	500,0	50000,0	100,0	12,65
19	23.03.2021	100x500 SF0.5% dag 28 A2	100,0	500,0	50000,0	100,0	13,55
20	23.03.2021	100x500 SF0.5% dag 28 B2	100,0	500,0	50000,0	100,0	5,33
21	23.03.2021	100x500 SF1% dag 28 A1	100,0	500,0	50000,0	100,0	4,89
22	23.03.2021	100x500 SF1% dag 28 B1	100,0	500,0	50000,0	100,0	13,58
23	23.03.2021	100x500 SF1% dag 28 C1	100,0	500,0	50000,0	100,0	13,60
24	23.03.2021	100x500 SF1% dag 28 A2	100,0	500,0	50000,0	100,0	12,40
25	23.03.2021	100x500 SF1% dag 28 B2	100,0	500,0	50000,0	100,0	2,27
26	06.04.2021	100x500 RF dag 28 A1	100,0	500,0	50000,0	100,0	14,44
28	06.04.2021	100x500 RF dag 28 B1	100,0	500,0	50000,0	100,0	10,23
29	06.04.2021	100x500 RF dag 28 C1	100,0	500,0	50000,0	100,0	13,96
30	06.04.2021	100x500 RF dag 28 A2	100,0	500,0	50000,0	100,0	12,93
31	07.04.2021	100x500 BF0.5% dag 28 A1	100,0	500,0	50000,0	100,0	12,91
32	07.04.2021	100x500 BF0.5% dag 28 B1	100,0	500,0	50000,0	100,0	12,18
33	07.04.2021	100x500 BF0.5% dag 28 C1	100,0	500,0	50000,0	100,0	10,85
34	07.04.2021	100x500 BF0.5% dag 28 A2	100,0	500,0	50000,0	100,0	11,02
35	07.04.2021	100x500 BF0.5% dag 28 B2	100,0	500,0	50000,0	100,0	11,54
36	08.04.2021	100x500 BF1% dag 28 A1	100,0	500,0	50000,0	100,0	9,45
37	08.04.2021	100x500 BF1% dag 28 B1	100,0	500,0	50000,0	100,0	10,36
38	08.04.2021	100x500 BF1% dag 28 C1	100,0	500,0	50000,0	100,0	10,42
39	08.04.2021	100x500 BF1% dag 28 A2	100,0	500,0	50000,0	100,0	11,21
40	08.04.2021	100x500 BF1% dag 28 B2	100,0	500,0	50000,0	100,0	8,69

Series graphics:



Statistics:

Series n = 39	a mm	b mm	A mm²	h mm	F_m kN
$\bar{x}$	100,0	500,0	50000,0	100,0	8,59
s	0,0	0,0	0,0	0,0	4,14
ν	0,00	0,00	0,00	0,00	48,17

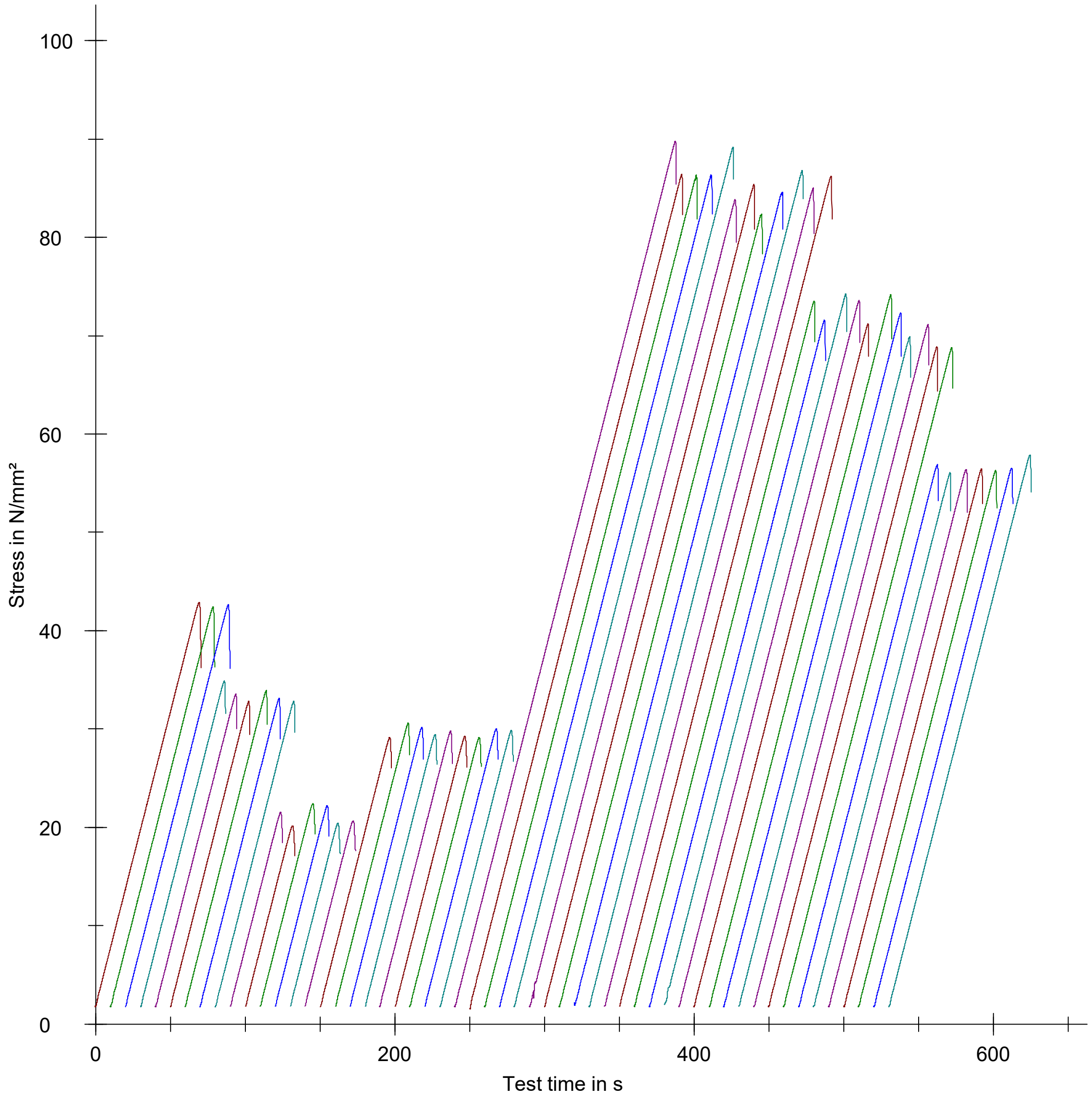
Parameter table:

Test protocol	: Test Bachelor	Type strain extensometer	:
Tester	: Nikolay og Omid	Machine data	: Controller TT1412 PistonStroke LoadCell 3 MN
Customer	:		
Test standard	:		
Strength grade	:		
Other	:		

Results:

Nr	Date	ID	a mm	b mm	F_m kN	Clock time	σ_m N/mm²
1	23.02.2021	100x100 SF0,5% dag 1 A1	100,0	100,0	428,98	09.41.11	42,90
2	23.02.2021	100x100 SF0.5% dag 1 B1	100,0	100,0	424,14	09.45.38	42,41
3	23.02.2021	100x100 SF0.5% dag 1 C1	100,0	100,0	426,68	09.48.44	42,67
4	10.03.2021	100x100 RF dag 1 A1	100,0	100,0	348,82	08.27.39	34,88
5	10.03.2021	100x100 RF dag 1 B1	100,0	100,0	335,42	08.29.47	33,54
6	10.03.2021	100x100 RF dag 1 C1	100,0	100,0	328,38	08.31.39	32,84
7	10.03.2021	100x100 RF dag 1 A2	100,0	100,0	338,96	08.33.47	33,90
8	10.03.2021	100x100 RF dag 1 B2	100,0	100,0	331,01	08.35.39	33,10
9	10.03.2021	100x100 RF dag 1 C2	100,0	100,0	328,16	08.37.31	32,82
10	11.03.2021	100x100 BF 0.5% dag 1 A1	100,0	100,0	215,23	08.39.29	21,52
11	11.03.2021	100x100 BF 0.5% dag 1 B1	100,0	100,0	201,22	08.41.38	20,12
12	11.03.2021	100x100 BF 0.5% dag 1 C1	100,0	100,0	223,94	08.43.47	22,39
13	11.03.2021	100x100 BF 0.5% dag 1 A2	100,0	100,0	221,93	08.49.23	22,19
14	11.03.2021	100x100 BF 0.5% dag 1 B2	100,0	100,0	204,31	08.51.52	20,43
15	11.03.2021	100x100 BF 0.5% dag 1 C2	100,0	100,0	206,69	08.54.10	20,67
16	11.03.2021	100x100 BF 0.5% dag 1 A3	100,0	100,0	291,41	13.07.58	29,14
17	11.03.2021	100x100 BF 0.5% dag 1 B3	100,0	100,0	305,74	13.09.53	30,57
18	11.03.2021	100x100 BF 0.5% dag 1 C3	100,0	100,0	301,55	13.11.37	30,16
19	12.03.2021	100x100 BF 1% dag 1 A1	100,0	100,0	294,46	12.12.37	29,45
20	12.03.2021	100x100 BF 1% dag 1 B1	100,0	100,0	297,68	12.14.22	29,77
21	12.03.2021	100x100 BF 1% dag 1 C1	100,0	100,0	292,65	12.16.05	29,26
22	12.03.2021	100x100 BF 1% dag 1 A2	100,0	100,0	291,41	12.17.54	29,14
23	12.03.2021	100x100 BF 1% dag 1 B2	100,0	100,0	300,52	12.19.42	30,05
24	12.03.2021	100x100 BF 1% dag 1 C2	100,0	100,0	298,35	12.21.27	29,83
25	23.03.2021	100x100 SF 0.5% dag 28 A1	100,0	100,0	897,67	09.55.37	89,77
26	23.03.2021	100x100 SF 0.5% dag 28 B1	100,0	100,0	864,33	09.59.47	86,43
27	23.03.2021	100x100 SF 0.5% dag 28 C1	100,0	100,0	863,69	10.03.24	86,37
28	23.03.2021	100x100 SF 0.5% dag 28 A2	100,0	100,0	863,42	10.06.52	86,34
29	23.03.2021	100x100 SF 0.5% dag 28 B2	100,0	100,0	891,61	10.11.02	89,16
30	23.03.2021	100x100 SF 0.5% dag 28 C2	100,0	100,0	838,76	10.14.24	83,88
31	23.03.2021	100x100 SF 1% dag 28 A1	100,0	100,0	853,89	10.18.03	85,39
32	23.03.2021	100x100 SF 1% dag 28 B1	100,0	100,0	823,53	10.21.40	82,35
33	23.03.2021	100x100 SF 1% dag 28 C1	100,0	100,0	846,22	10.25.04	84,62
34	23.03.2021	100x100 SF 1% dag 28 A2	100,0	100,0	868,12	10.28.48	86,81
35	23.03.2021	100x100 SF 1% dag 28 B2	100,0	100,0	850,44	10.33.10	85,04
36	23.03.2021	100x100 SF 1% dag 28 C2	100,0	100,0	862,50	10.36.38	86,25
37	06.04.2021	100x100 RF dag 28 A1	100,0	100,0	735,42	09.39.06	73,54
38	06.04.2021	100x100 RF dag 28 B1	100,0	100,0	715,79	09.44.23	71,58
39	06.04.2021	100x100 RF dag 28 C1	100,0	100,0	742,88	09.47.47	74,29
40	06.04.2021	100x100 RF dag 28 A2	100,0	100,0	735,64	09.51.06	73,56
41	06.04.2021	100x100 RF dag 28 B2	100,0	100,0	712,37	09.54.08	71,24
42	06.04.2021	100x100 RF dag 28 C2	100,0	100,0	741,78	09.57.23	74,18
43	06.04.2021	100x100 RF dag 28 A3	100,0	100,0	723,40	10.00.50	72,34
44	07.04.2021	100x100 BF0.5% dag 28 A1	100,0	100,0	698,80	09.31.49	69,88
45	07.04.2021	100x100 BF0.5% dag 28 B1	100,0	100,0	711,14	09.34.54	71,11
46	07.04.2021	100x100 BF0.5% dag 28 C1	100,0	100,0	688,56	09.37.46	68,86
47	07.04.2021	100x100 BF0.5% dag 28 A2	100,0	100,0	687,87	09.40.51	68,79
48	08.04.2021	100x100 BF1% dag 28 A1	100,0	100,0	568,66	09.22.10	56,87
49	08.04.2021	100x100 BF1% dag 28 B1	100,0	100,0	560,59	09.25.21	56,06
50	08.04.2021	100x100 BF1% dag 28 C1	100,0	100,0	564,15	09.27.55	56,41
51	08.04.2021	100x100 BF1% dag 28 A2	100,0	100,0	564,45	09.30.27	56,44
52	08.04.2021	100x100 BF1% dag 28 B2	100,0	100,0	562,80	09.33.08	56,28
53	08.04.2021	100x100 BF1% dag 28 C2	100,0	100,0	565,21	09.35.47	56,52
54	08.04.2021	100x100 BF1% dag 28 A3	100,0	100,0	578,93	09.38.36	57,89

Series graphics:



Statistics:

Series n = 54	a mm	b mm	F_m kN	σ_m N/mm²
n	54	54	54	54
$\overline{x}$	100,0	100,0	544,82	54,48
s	0,0	0,0	240,21	24,02
max.	100,0	100,0	897,67	89,77
min	100,0	100,0	201,22	20,12
med	100,0	100,0	564,30	56,43
ν	0,00	0,00	44,09	44,09