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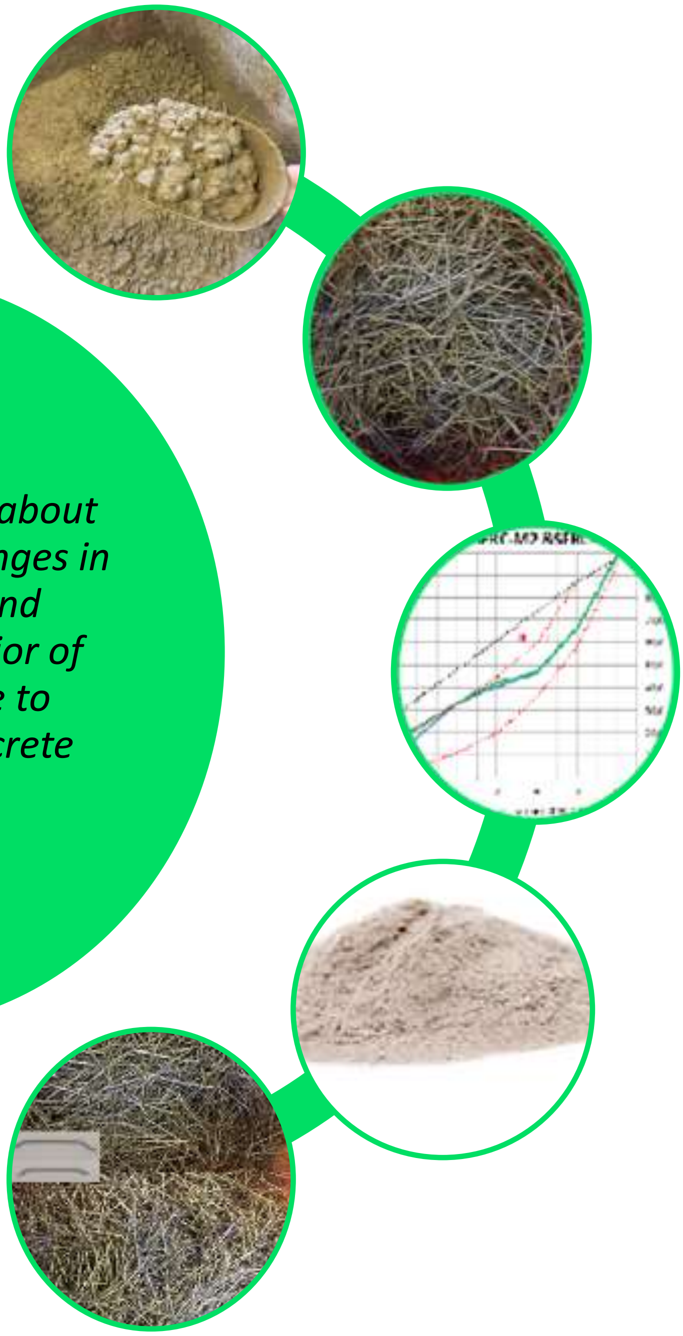

Thesis

The influence of concrete composition on the behavior of steel fibres reinforced concrete (SFRC) C30/37

Quantitative study about the subsequent changes in the mechanical properties of SFRC C30/37 due to adjusting the concrete composition.

By

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To obtain the degree of Master of Science at the Delft University of Technology.

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Preface

This thesis report contains the research results for the Master Building Engineering of the faculty Civil Engineering and Geosciences, Delft Technical University. The project has been performed at University and the Dutch contractor Dura Vermeer.

The content of this report reflects the problem and issues observed by the contractor by the application of steel fibre reinforced concrete in the practice. The problem has been analysed based on literature study and experimental program. Finally the results have been discussed and recommendations are given to the contractor.

I would like to thank my university committee: Prof. dr. ir. H.E.J.G. Schlangen, Dr. Ir. M. Lukovic, Dr. O. Copuroglu and company supervisor Ir. J. Meijdam for their academic support.
Also I would to thank Maiko van Leeuwen, who helped me with all the concrete preparations and experiments.

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BSc. A. Khazoum
Delft, August 15, 2018

Summary

Steel fibre reinforced concrete (SFRC) is gaining popularity as a composite material used in structural elements. The improved tensile and flexural strengths of SFRC made steel fibres an attractive addition to concrete. It enhances the permeability of structural elements by bridging cracks with the steel fibres.

SFRC can be obtained in different strengths and mechanical behavior. The concrete strength class and the steel fibres properties (fibres content, shapes, tensile strength, etc.) determine the identity and properties of SFRC. In the Netherlands, SFRC is mostly used for pavement and industrial floor with or without conventional reinforcement. The SFRC mixtures applied for these structural elements consist of concrete strength class C30/37 including circa 35 kg/m^3 of steel fibres.

Structural elements realised with these SFRC mixtures showed varieties in the mechanical strengths. The variation in the mechanical strengths of structural elements proposes a challenge to estimate the material behavior in future conditions and other constructions as it increases the complexity of the design procedures and calculations.

The reason behind the variation is related to the concrete or the steel fibres. In fact, the same steel fibres have been used in the realised structures and almost similar fibres content has been added. The possibility of deviation in the steel production is negligible. When it comes to the production of concrete the risk of variation increases, mainly due to concrete having strength class C30/37 can be designed in an infinite number of compositions.

Generally, the concrete composition depends on the strength class and environmental requirements. Economic factors play also a crucial role in the practice by choosing the concrete composition. Hence, the influence of the concrete composition on the mechanical behaviours of SFRC is ignored while the concrete composition has a decisive influence on the mechanical behaviours of SFRC.

Designing and ordering concrete mixtures, based on the price, concrete strength class (C30/37) and fibres content will not ensure standard SFRC mechanical behavior. Every concrete composition (of C30/37) may positively or negatively affect the properties of the SFRC mixture and the integrity of the steel fibres with the concrete matrix.

The aim of this research is to address the specific problem experienced by the contractor and provide in-depth explanation and future recommendations to limit the variation. In addition to this, the research aims to obtain an overview of the possible tools that can optimize and control the mechanical performance of SFRC in practice.

To get more insight about the impact of concrete composition on SFRC and to understand how each concrete parameter or ingredient can affect the mechanical performances and microstructure of SFRC the followed research question has been formulated:

''What are the consequences of adjusting the composition of concrete C30/37 on the properties and mechanical strengths of SFRC.''

This research question has been answered by the literature study and the experimental plan. Based on the problem statement and the literature review, the experimental program and microstructure analysis have been established. The experimental plan has been divided into four phases, the goal of every phase is given in Figure 1. In each phase, one or two SFRC mixtures have been designed according to the Dutch standard, manufactured with local material and tested.

In the first phase, the effects of adding 35 kg/m^3 of steel fibres to regular concrete C30/37 were specified. The comparison between the measured compressive, splitting tensile and flexural strengths of plain concrete M1 and reference steel fibres reinforced concrete mixture (SFRC-M2) showed an improvement of the strengths by the steel fibres addition.

Phase 2 and 3 analysed the consequences of adjusting the concrete composition of strength class C30/37 and its impact on the mechanical behavior of SFRC. In phase 2 the water/ cement ratio has been adapted and superplastizicer has been added to the reference SFRC mixture to obtain SFRC-SP-M3.The increase of air content in SFRC-SP-M3 results in a porous concrete matrix and decreases the mechanical strengths compared to the reference SFRC-M2.

In contrast to SFRC-SP-M3, the amount of fine material has been increased in the compositions of phase 3 to densify the concrete matrix and study the effect of modifying the concrete ingredients on the mechanical properties of SFRC.

In SFRC-F-M4, the amount of fine material has been increased by adjusting the aggregate grading, while in SFRC-LM-M5 a small amount of coarse aggregate (20 kg/m^3) has been replaced with limestone powder. The limestone powder had considerable effects and improved the mechanical strengths and the post-cracking behavior of SFRC.

In addition to the adjustment of concrete composition, the influence of combining two sizes of steel fibres, referred to as fibres hybridization in this thesis, has been studied. The mechanical strengths of this mixture SFRC-F3060-M6 were not enhance, only the ductility and post-cracking behavior were optimized compared to the reference SFRC-M2.

Concrete mixtures used for SFRC in the practice are selected based on the strength class. To ensure that the adjustments of the concrete composition did not affect the strength, the compressive strength of all mixtures has been measured by the compression test.

Further, by the addition of steel fibres, the splitting tensile strength and the maximum flexural strength are optimized. Both strengths have been investigated in the experimental program by the splitting tensile and 3-point bending tests, to find out if the mixture adjustments will affect these strengths as well. Because both strengths are relevant to the design process in the practice.

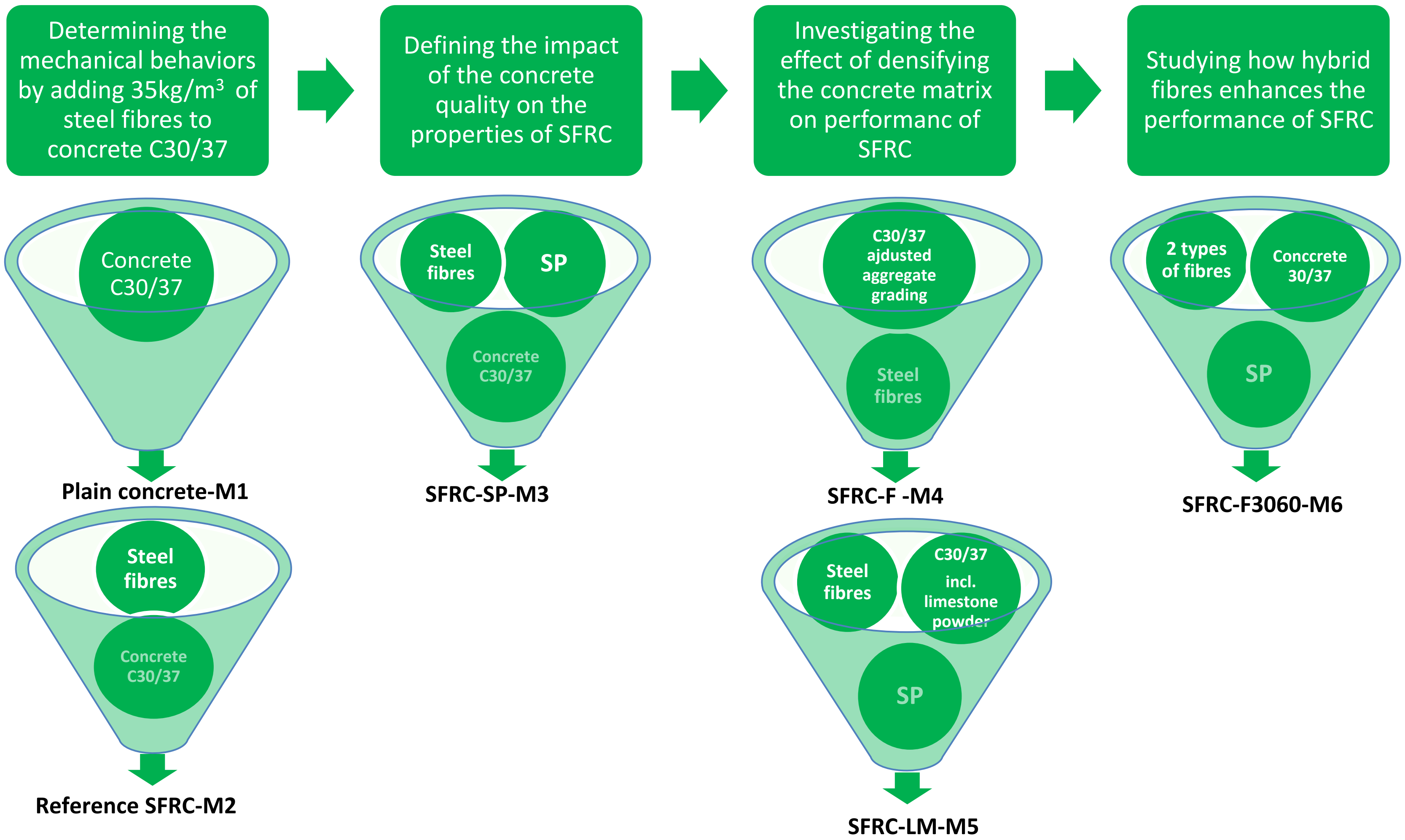

Figure 1: Infographic overview of the experimental plan accomplished in this research.

Despite the adjustments of the concrete compositions, the results of the compression test proved that all the designed SFRC mixtures belong to concrete strength class C30/37. But, the comparison of the mechanical strengths confirmed that the details of the concrete composition have relevant consequences on the mechanical strengths and post-cracking behavior of SFRC 30/37 (by constant steel fibres content).

Some of the adjusted SFRC mixtures optimized and improved the mechanical strengths (phase 3), while other modification decreased the strengths (Phase 2). Hence, the variation in the concrete composition of C30/37 will lead to variation in the mechanical strengths of SFRC C30/37. This is proved by the results of the mechanical tests accomplished in the experimental program of this thesis. It clarifies the cause of variation in the mechanical properties observed in the practice when constant fibre content is added to the different concrete composition of C30/37.

Adding 35 kg/m^3 of steel fibres to concrete mixture that has been chosen based on its strength class and price ignoring the details of the composition may not result in the required mechanical performances or standard properties. The concrete composition should be carefully designed when it will be mixed with steel fibre as it can be used to improve the mechanical properties of SFRC.

Tools and possibilities to optimize and control the mechanical behavior of SFRC are increasing the fine material content, limiting the maximum grain size, adding superplasticizer to obtain a workable mixture and most important is controlling the production and execution procedures.

Increasing the fine material content to densify the concrete matrix and improve the characterizes of the interface between the steel fibre and concrete matrix showed optimized strengths and post-cracking behavior in the experimental program.

Further, reducing the maximum aggregate grain size enhances the fibres distribution in the mixture (Phase 3). Using large grain size will hinder the steel fibres distribution in the mixture and lead to the stacking of fibres in one district. Therefore the maximum grain size should be limited by the addition of steel fibres to guarantee better fibre dispersion in the structure.

Another tool to optimize the post-cracking behavior of SFRC and limit the crack opening and propagation is combining two sizes of steel fibres. It will improve the ductility and post-cracking performance.

The six prims used for the 3-point bending test of each SFRC mixture showed differences in the post-cracking behavior. By comparing the cross-section of some specimens, it was concluded that the variation of fibres distribution and content in the cross section affected the post-cracking behavior.

Finally, for the application of SFRC in the future it is not recommended to choose the concrete mixture based on its strength class, the details of the concrete composition should be considered. Depending on the project requirements, fibre content and environmental classes the concrete composition of SFRC should be determined project as the SFRC mixture should be tested before applying it in practice.

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1. Introduction

Steel fibre reinforced concrete (SFRC) is increasingly used as a construction material for pavement, industrial floors and tunnels during the last years in the Netherlands. The optimized mechanical performances of SFRC made it a very popular and attractive material to apply for structural engineering purposes.

The most important and essential advantages of the fibres addition are the improvement of the tensile strength and controlling of the macro-cracks development in the concrete by bridging and delaying the cracks propagation [1]. Due to the development of the interfacial bond between the steel fibres and the concrete matrix, the strength and stiffness of the steel fibres are used to reinforce the brittle matrix. Once the concrete matrix cracks, the load is still transferred across the crack faces through the bridged steel fibres [2].

Fibres addition decreases the permeability of the concrete and improves its ductility after the cracks formation. This makes SFRC tough and ductile material, able to resist higher flexural strength and demonstrates post-cracking behaviour (Figure 2) either in the form of strain hardening or strain softening depending on the fibres content, fibres dispersions and concrete quality [3]. By strain hardening, the structural element will resist higher stress than its own capacity after the first crack development, while by strain softening the structural element will only resist lower stresses once it cracks.

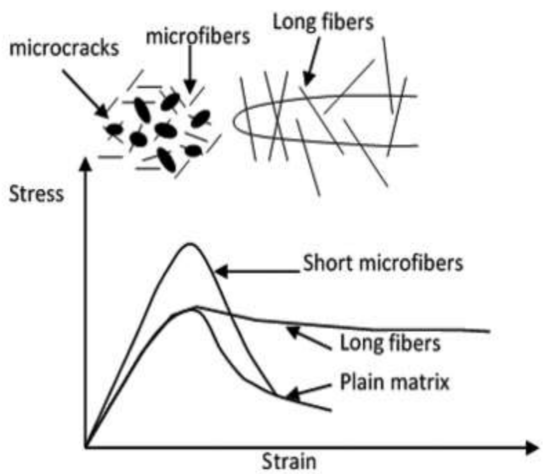


Figure 2: Illustration of fibres effect on crack bridging and post-cracking behaviour (After Betterman et Al. [4])

Steel fibres are available in different dimensions and properties. Depending on the function and purpose of the fibres addition, the steel fibres parameters can be chosen (shapes, length, dosages, etc.). In most of the structures where SFRC has been applied, one single type of steel fibre has been used. But in some cases, two types of steel fibres are combined, short fibres (6mm-13mm) and long fibres (30mm-60mm).

Combining two types of fibres is known as hybridization. Hybridization is the technique of maximizing the benefits of fibre addition in an effective way [5]. The two types of steel fibres will work on micro- and macro-level. At micro-level fibres arrest the development of micro-cracks, which will maintain the compressive strength [6], whereby a macro-level, fibres control cracks opening and increase the energy absorption capacity of the composite. Common examples of micro-cracks are the cracks appear due to shrinkage as water evaporates during hardening or cracks initiated when the construction is loaded. In both cases, the steel fibres will block the opening and provide higher tensile capacity [5].

However, it is not only the steel fibres parameters that determine the mechanical behaviours of SFRC. The response of SFRC is mainly governed by the tripartite interaction between the concrete matrix, steel fibres and bond strength [5]. Increasing the steel fibres content in the matrix will enhance the probability of intercepting micro-cracks by fibres. At the same time, large fibre content causes some perturbation of the concrete matrix, which can result in higher void content and porosity [7].

Another critical consequence of fibre addition is the decrease in the workability. A mixture with a low workability will be difficult to cast and will negatively affect the concrete quality in the hardened stage. It increases the risk of obtaining an inhomogeneous mixture where the fibres may be clustered at one district.

The mechanical benefits of steel fibres addition fascinated the Dutch contractor to use SFRC to fulfil the mechanical requirements (flexural and tensile strengths, controlling crack opening, etc.) of projects given by the government or clients. Based on the practical experiences of the contractor, the application of SFRC reduces labour costs and time, which make SFRC more interesting.

Structural elements realised with SFRC by the contractor showed differences in their properties and mechanical strengths when identical SFRC mixture has been used. The most used SFRC mixture by the contractor is concrete strength class C30/37 mixed with 35 kg/m^3 of steel fibres.

Dissimilarities and large variations in SFRC behaviours observed over the span of one structural element is a serious issue. The mechanical strengths, especially flexural and tensile strengths, may not be equal in the whole structure. Hence, the realised structure will not comply with assumptions done in the design and calculations.

This variation may be due to the differences in concrete composition of the SFRC mixture and the poor bond strength between concrete matrix and steel fibres. If the fibres are not properly mixed with and embedded in the concrete and good distributed, fibres will not be properly integrated with the concrete and may be stacked at some districts.

According to the literature review [5 & 8] and experiences with SFRC, the concrete composition and quality seem to have a considerable important effect on the mechanical behavior of SFRC. Starting with the concrete properties in fresh state (i.e. workability, flowability and stability) and ending up with the concrete microstructure and interface between the fibres and concrete matrix in the hardened state.

The main object of this research is to quantitatively analyse and establish the consequences of adjusting the concrete composition on the mechanical properties of SFRC, in particular the SFRC mixtures that is used by the contractor SFRC C30/37.

1.1 Problem Statement

The practical experiences with SFRC showed that using the same concrete strength class and fibre dosages do not guarantee a uniform performance of SFRC. In pavements and floor projects where SFRC has been applied, the composite material showed different behaviours in terms of crack opening and mechanical strengths.

Variation of SFRC behaviours observed in projects where identical SFRC mixtures were applied may be related to the differences in mixture composition, production technology, environmental and execution conditions. Because in these projects only the concrete compositions varied while similar fibres content and types have been used.

Same scenario when it comes to one particular structural element that shows variation of mechanical strengths over the whole span because it has been cast in multiple phases. It is supposed that in all phases exactly the same SFRC mixture has been applied. But the risk of some variation in the SFRC composition and quality delivered in every phase exists. If the SFRC mixture of each phase did not have the same integrity and workability then the behaviour of the SFRC will not be identical over the whole span of the structural element.

Designing and ordering concrete mixture, based on the concrete strength class (C30/37) did not seem to ensure the same SFRC performance, because there are infinite possibilities to design concrete strength class C30/37.

Each concrete composition may positively or negatively affect the properties of the SFRC mixture in the fresh state and the integrity of the steel fibres with the cement matrix. Concrete quality in the fresh state may be a key factor that influences the mechanical performance on structural as microstructure level, since it has an effect on the bond strength between concrete matrix and fibres.

To limit the deviation in SFRC behaviours, the design process and execution of SFRC mixtures need to be monitored. In order to do it in a controlled manner, it is important to understand how each concrete parameter or ingredient can affect the mechanical performances and microstructure of SFRC in the hardened state. This lead to the main research question:

''What are the consequences of adjusting the composition of concrete C30/37 on the properties and mechanical strengths of SFRC.''

1.2 Goal of the research

Literature studies give a rough indication only about the influence of fibres parameters (dosages, orientation, length, etc.) on the mechanical properties of SFRC. Researchers made graphs and diagrams presenting the increase as the decrease in strengths by the addition of certain fibre dosage.

On the other hand, there are some studies accomplished that provide a global information about the impact of some concrete ingredients and parameters (maximum aggregate grain size, w/c ratio, etc.) as concrete strength class on the behaviour of SFRC.

However, there are no specific guidelines and formula's available to determine the consequences of modifying the concrete composition of one concrete strength class. When there are various recipes to obtain concrete strength class C30/37.

The reason that more attention is given to the properties of the steel fibres than the concrete composition is due to the direct effect of fibres on the strengths and design process. The details of the mixture composition are not affecting the calculations and are ignored in the practice. Even more, in some projects, concrete mixtures used for SFRC are chosen based on the price.

Dura Vermeer is interested in obtaining a qualitative overview on the consequences of adjusting the concrete composition of SFRC. In particular, SFRC with strength class C30/37 mixed with 35kg/m3 of steel fibres.

The first goal of this research is to discover if the concrete composition has a considerable effect on the behaviour of SFRC by adjusting the concrete composition for strength class C30/37.

The second goal is to explain the reason behind the variation in SFRC behaviours observed in the practice by comparing all of the tested SFRC mixture having the same concrete strength class and fibres content but differ in their concrete composition.

Another point of discover is to gain insight if the adjustments enhanced the mechanical strengths and interface between the steel fibres and concrete matrix, in order to give advice and recommendations about the possibilities to optimize SFRC mixtures in the future.

1.3 Scope of the research

SFRC concrete compositions differ in each project due to environmental, durability requirements, production technology, material availability, economic and other aspects. In this research, a concrete mixture C30/37 will be designed to use it as a reference mixture. This mixture will be modified to study the effect of the adjustment on the behaviour of SFRC.

To obtain a mixture that proportionally reflects the practice it was decided to design a mixture for environmental class XC4, XD2 & XF3, and consistency class S4 (160mm-210mm). The main criteria's for all of the designed and tested mixtures are the concrete strength class C30/37 and the same fibres dosages 35kg/m^3. The compressive strength of every mixture will be measured to determine the influence of composition adjustment on the strength and if it is relevant to order concrete based on strength class.

Behaviours and performance of SFRC mixtures are based on the workability measured in the fresh state and the mechanical strengths (compressive, splitting tensile and flexural strength) that will be determined in the hardened state.

Fibre properties and parameters (like the fabrication, orientation, etc.) will not be handled in this research and fall outside the scope. Production and execution methods of SFRC in the practice are also not considered.

1.4 Relevance of the research

1.4.1 Knowledge gap

SFRC is becoming an interesting material to apply in the Dutch infrastructure world. By the application of SFRC, the heightened focus is being placed on the fibres content, fibres distribution in the structural element and how to obtain a very strong, ductile and high strength SFRC. Most of these aspects are studied and investigated in the literature. The concrete material aspects are discussed mostly from one perspective, namely using higher concrete strength class to improve the mechanical properties.

1.4.2 Scientific relevance

Adding steel fibres to different concrete strength classes and compare their behaviours is already studied in literature. In fact, every concrete strength class can be produced in infinite ways which may also affect the behaviours of SFRC.

In this research, experiments are accomplished by employing only one concrete strength class C30/37 and constant fibre content to find out if the concrete quality and composition have an influence on the behaviours of SFRC and its optimization possibilities.

1.4.3 Practical relevance

This research has been initiated by the Dutch Contractor Dura Vermeer with the aim to get insight on the reason of the observed variation in the practice. The comparison of the designed and tested SFRC mixtures gives an indication of the variation but also suggests tools to enhance the mechanical strengths of SFRC to achieve a worthy investment by adding steel fibres to concrete.

1.5 Outline of the thesis

This report consists of seven chapters. Starting with the Introduction (Chapter 1) where the problem statement, goals and scope of the research are illustrated.

In chapter 2, are the research questions presented and the research methodology. Chapter 3 provides a literature overview of SFRC ingredients and parameters. The literature review discusses the sub-questions of this research and based on the problem statement and information gathered from the literature, the experimental program has been set.

The experimental plan is step by step described in chapter 4. This chapter is divided into phases that are linked to the research sub-questions. Each phase starts with the aim and explanation of the experiment that will be conducted to answer the sub-question, followed by the results of the tests, discussion and conclusions. The experimental program will be followed by microstructure analysis in chapter 5.

In chapter 6 is the summary of all results and conclusions presented. Finally, in chapter 7, are the recommendations given to optimize SFRC in the future.

2. Research Approach

2.1 Research questions

The main research question presented in Chapter 1 is derived from the problem statement of this research. By answering the following question, the influence of the concrete composition on the behavior of SFRC will be identified:

''What are the consequences of adjusting the composition of concrete C30/37 on the properties and mechanical strengths of SFRC.''

This question will be answered in the form of sub-questions step by step in the experimental plan. Each sub-question will be generally discussed in the literature review and thereafter implemented in an experiment to get a specific answer. The sub-questions are divided into four phases:

Phase 1: How does the fibres addition of 35kg/m3 improve the mechanical behavior of concrete strength class C30/37?

First and foremost, the advantages and disadvantages of steel fibres addition should be determined by comparing plain concrete with SFRC based on the following points:

- Are the strengths and ductility of the mixture enhanced by the fibres addition?
- Will the air content increase by the fibre addition? How did it affect the compressive strength?
- What are the negative side's effects of adding fibres?
- In how far will the workability decrease? Does it hinder the casting procedure?

Phase 2: What are the benefits of increasing the mixture workability of SFRC?

It is well known that the workability will decrease when the fibres are mixed with the concrete and since the workability is a materials property, the workability will be adjusted to find out how it will affect SFRC behaviours.

Phase 3: What are the critical concrete ingredients and parameters that may enhance the behaviour of SFRC?

In every concrete composition, the content of cement, water, aggregate and additional are based on the design codes, requirements and costs. In this phase, interesting alternatives for adjustment that fit the scope will be studied. The mechanical strengths and properties of the adjusted SFRC mixtures will be compared with the reference SFRC mixture:

- Which concrete ingredients or parameters can be adjusted to optimise the strength, post-cracking behaviour, displacement or other SFRC properties?
- Is the interface between fibres and concrete affected by modifying the concrete composition?
- Is there a relationship between the mechanical performances and the SFRC microstructure?
- Are there variations observed in the results of the specimens of every SFRC mixture?

Phase 4: How can hybrid fibres improve the mechanical properties of SFRC?

- Is the crack propagation limited by combining two types of steel fibers?
- Are the mechanical strengths optimized by fiber hybridization?

2.2 Research methods

Research methodologies used are literature review and the experimental program, in addition to microstructure analysis (Figure 3). The information found in the literature has been used as background for the comparison and discussion of the experimental program and microstructure analysis.

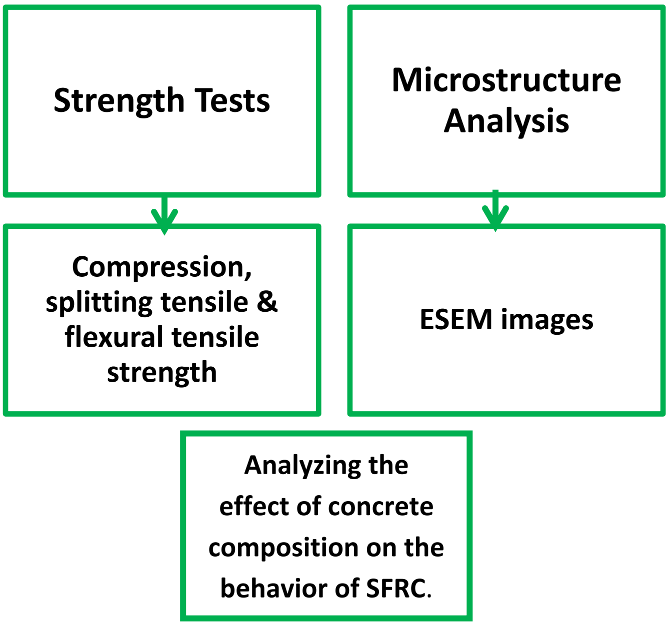


Figure 3: Research tools used in the experimental program and microstructure analysis.

2.2.1 Literature review

The literature provides plenty of information about SFRC and studies done by researchers from all over the world. Unfortunately, most of the studies focus on studying the behaviours of specific SFRC mixtures or parameters. Hence, the information and data obtained are related to special scenarios and may not be applicable to other cases.

However, the literature review gives useful information that has been considered in this research. The difficulties to completely reuse data from the literature were concretes strength class and fibers dosages used which did not comply with the scope.

2.2.2 Experimental program & microstructure analysis

In the experimental program, six mixtures have been designed, cast and tested. The same test procedure was followed in all phases to get comparable data and evaluate the performance of each mixture.

The behaviours of each mixture were defined by its properties in the fresh and hardened state. In the fresh state, the air content and slump were measured and in the hardened state the compressive, splitting tensile and flexural strength tests were conducted.

Microstructure analysis has been used as a tool to investigate the interface between the concrete matrix and steel fibre of SFRC mixtures designed in phase 3. By comparing the properties and mechanical strengths of the SFRC mixtures with the ESEM images, the relation between SFRC strengths and microstructure will be illustrated.

The results and conclusions of this research will give the contractor a better insight into the critical ingredients and parameters that should be monitored and considered in the practice. Due to the limited time of the research, it was not possible to study all the ingredients. The details of the experimental program are presented in chapter 5 of this thesis.

3. Literature review

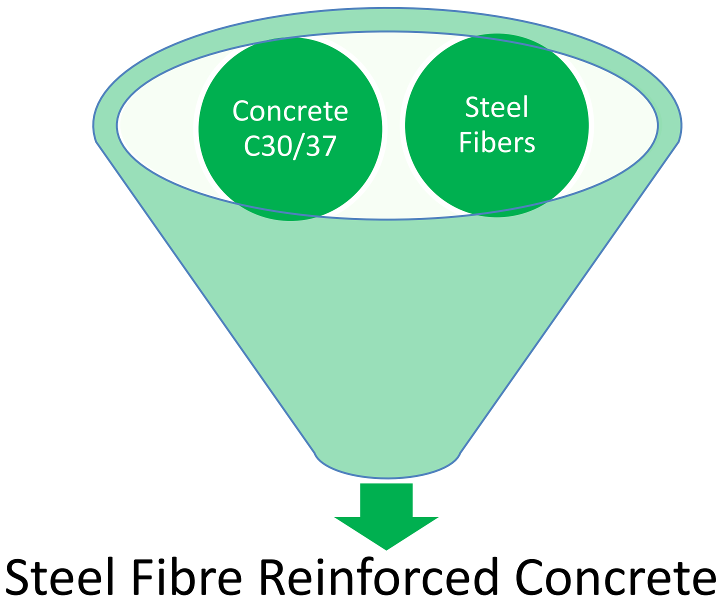
Fibers have been added to cementitious materials to improve the characteristics in the hardened state. Steel fibre is the most common fibre type in the building industry. Other fibres like plastic, glass and carbon fibres contribute to a smaller part of the market.

The fiber type, the mixture composition, the mixing process and the compaction technique determine the maximum fiber content. To optimize the performance of a single fiber, fibers need to be homogeneously distributed and fibers clustering have to be counteracted.

The mixture design of SFRC is often based upon the well-established rules of thumb. For example; by the addition of fibers, the cement paste content and the dosage of superplasticizer should be increased as extending the content of the fine aggregates by increasing the aspect ratio and fiber volume.

Rossi & Harrouche [1990] and Hoy [1998] [9], [10] approached the mixture design of fiber reinforced matrixes in a more systematic manner, namely by optimizing the granular skeleton. But considering the granular skeleton only is not enough, besides the granular skeleton the content and the characteristics of the paste have to be taken into account to link workability and the mixture composition. According to Grunewald [11], this link is not established yet for FRC and SCFRC.

The main ingredients of SFRC are similar to conventional concrete. The bond strength between concrete and steel fibres is like the bond strength between concrete and conventional concrete. In other words, the bond strength in SFRC is affected by the cement content, water/cement ratio and the aggregate as the steel fibres properties. In this chapter the role and effects of the steel fibers as the concrete mixture will be explored.



3.1 Steel fibers

Steel fibres are available in various shapes, dimensions and strengths (Figure 5 & Figure 4) like any other reinforcement. During the design process, the required fibres should be carefully selected depending on the required fibre length, diameter, shape and tensile strength. Currently, the steel fibres used for reinforcing concrete are manufactured from cold-drawn wire steel sheet and other forms of steel, mostly with a length up to about 60mm.

Figure 5: Examples of steel fibres [12].

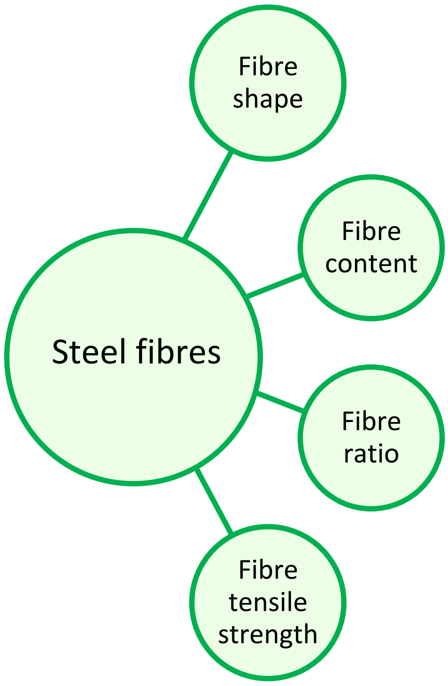


Figure 4: Steel fibres parameters.

The dosage of the steel fibres is also an important factor, as it influences the plastic viscosity and the yield stress of the concrete. From the experience in practice, for jointless slab construction, steel fibres at dosages in the order of 35-45 kg/m^3 are used to control the width and distribution of shrinkage-induced cracks. In floors with sawn joints, dosages in the range of 20-30 kg/m^3 are typical used [12].

Holschemacher, Mueller and Robakov [13] referred in their study on the dependence of the post-cracking load on the fibre content. As fibres play an important role in reaching a definite load-bearing capacity after the matrix-fracture. This depends on the allocation, orientation and embedded length of the fibre. These features are also influenced by the concrete composition (aggregate size and shape, cement content, w/c ratio and admixtures), fibre type, rheological properties, the casting method, consolidation and other [13].

The inclusion of steel fibre in the concrete mixture provides an improvement in the mechanical properties and a better resistance to high temperatures [14]. But still, it does not mean that steel fibres can completely replace conventional reinforcement. Conventional reinforcement is placed in the structures, in such a way to resist the applied tensile stress. Stroeven and Shad [15] approved with this stand since fibres are randomly distributed and oriented in the concrete matrix. Further, the fibre action can never be that effective as that of steel bars [8], because the steel bars are continuous and have a larger diameter compared to the fibres, hence the bond between the concrete and the steel fibres will be smaller [8]

3.1.1 Consequences of fiber addition on the mechanical properties

- Improving tensile and flexural strength paired with strength loss

The fibre addition (depending on the dosages) enhances the engineering properties of concrete, such as the tensile, flexural and fatigue strength. Also, it optimizes the deformation capability, load-bearing capacity after cracking and the toughness properties.

However, fibre addition may have negative sides' effects as well. According to the experimental study of Topcu and Canbaz [3], where they studied the mechanical properties of concrete with three different ratios of fly ash. It seems that the addition of fibres provides concrete with a better flexural performance. Where the fly ash in the mixture modifies the workability and strength losses caused by the fibre addition and improves strength gain [16].

Moreover the essential role of steel fibre added to plain concrete is the limitation of cracks propagation; in particular, the micro- and macro-crack developed during the hydration procedure. This aspect can be investigated when the SFRC specimens are loaded in a bending setup and the maximum tensile stress occurs on the bottom of specimens and the first crack starts developing [1]. At that moment concrete cracks, the fibre will be activated and starts to restrain early crack growth and transfers the load to the un-cracked parts of the concrete matrix. This will enhance its durability and enable it to withstand higher tensile loads at failure.

In Figure 6 is the load-deflection curve of plain concrete versus SFRC sketched; the beginning of the first crack is at the maximum stress in the load-deflection curve for the specimens that exposed to bending. The plain concrete will collapse after the first crack while the SFRC shows a post-cracking behavior.

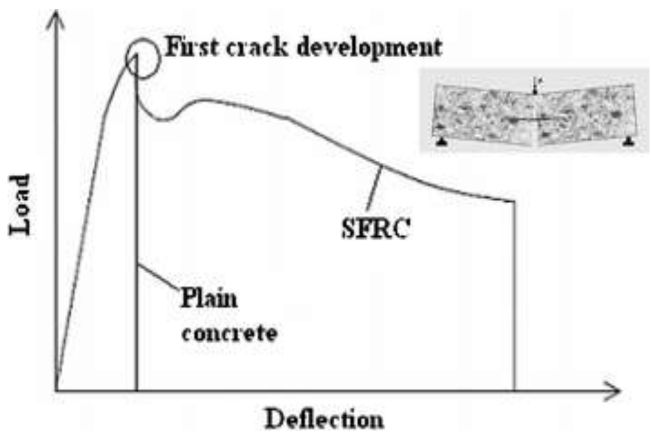


Figure 6: Comparison of load-deflection curve of plain concrete vs SFRC during bending [17].

- Decreasing the Young's modulus

The study of Holschemacher, Mueller and Robakov [13] concern the influence of matrix strength, fibre content and fibre diameter on the compressive behaviour of SFRC for two types of matrix and fibres, showed that the addition of fibres enhances the toughness and strain at peak stress but can slightly reduce Young's modulus.

This is confirmed by Fuat Koksal, Fatih Altun, Ilhami Yigitc and Yusa Sahina [18], by adding steel fibres to concrete, the compressive strength can increase but the modulus of elasticity tends to decrease. It also matches with the test results of Almeida et Al. [7], they emphasise on the relation between the compressive strength and Young's modulus. They showed that the presence of the fibres causes a slight decrease in Young's modules. The authors explained this decrease to the fact that fibres parallel to the load direction can act like voids.

Besides that, the addition of fibres causes perturbation of the concrete matrix, which leads to a higher quantity of voids. It is well known that voids are weak points where microcracking may start. Thus the influence of the fibres on the compressive strength may be considered as the balance between microcrack bridging and the addition of voids caused by fibre addition [7].

- *Decreasing of the workability*

The negative consequences of fibres addition on the workability are mainly due to four reasons which Grunewald summarized [11]:

- The *shape of the fibres* is more elongated than the shape of aggregates.
- *Stiff fibres* change the structure of the granular skeleton, while flexible fibres fill the space between them. Stiff fibres will push apart particles that are relatively large compared with the fibre length. This lead to increasing the porosity of the granular skeleton, which can have an impact on the strength.
- *The surface characteristics* of fibres differ from that of cement and aggregates, e.g. plastic fibres might be hydrophilic or hydrophobic.
- The steel fibres often are *deformed* (e.g. have hooked ends or are wave-shaped) to improve the anchorage between a fibre and the surrounding matrix. The friction between hooked-end steel fibres and aggregates is higher compared with straight steel fibres.

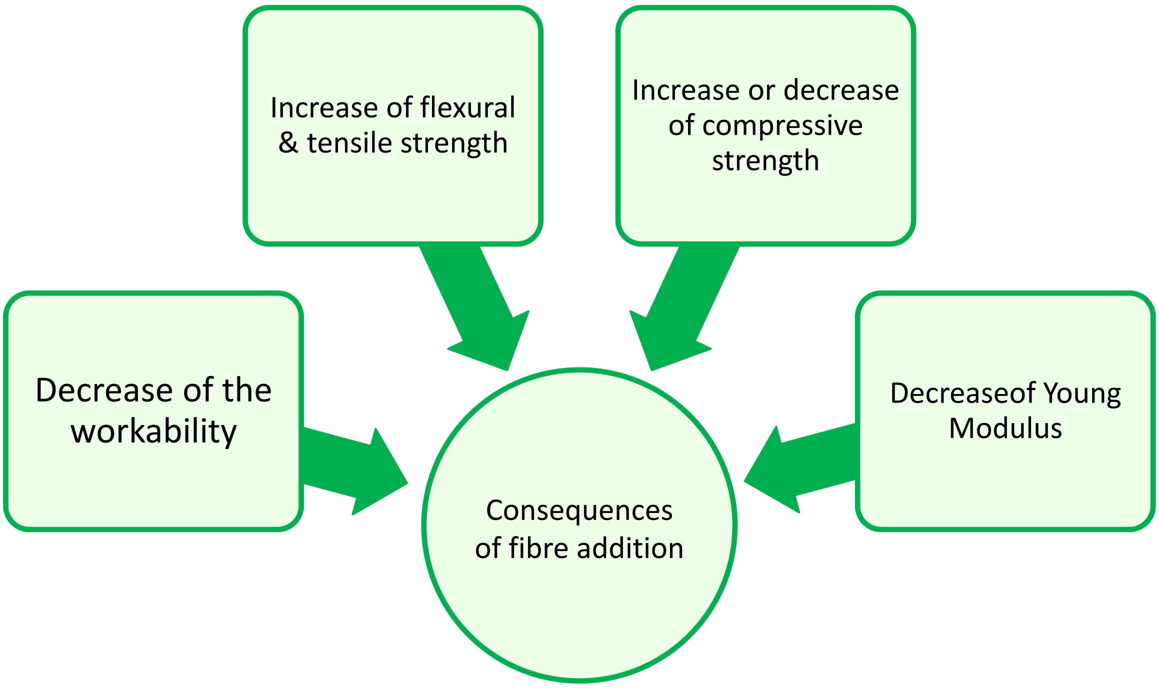


Figure 7: Summary of the consequences of fibre addition according to literature.

3.1.2 Hybrid Fibre Concrete

One of the latest developments in steel fibre concrete is the hybrid concrete. The term Hybrid refers to the hybridisation of fibres, for example, long and short fibres (Figure 8) or straight and hooked fibres combined in one concrete mixture. This is in contrast to the conventional SFRC where only one type of fibre is used.

The application of Hybrid Fibre Concrete rest on basic principles [10], namely the addition of short and long steel fibres together in one concrete will guarantee a homogeneous fibres distribution on the structural level and the fibres hybridization will ensure the efficiency of bridging the cracks on the material level.

Also, fibres hybridization enhances the fracture processes of concrete loaded in tension. Hybrid Fibre Concretes are characterised by high tensile and flexural strengths and high ductility as by a high compressive strength [8].

Fibre hybridization has positive advantages in the hardened state, but in the fresh state the addition of two types (or sizes) of fibres decreases the workability compared to conventional SFRC. Therefore it is recommended to combine it with self-compacting concrete [8].

The optimization of the mechanical properties in the hardened state is because the short fibres bridge the first micro-cracks appear. In this case, the concrete remains intact for a long time and maintain its compressive strength rather than decreasing by the appearance of the first cracks.

The mechanical properties of concrete are enhanced appreciably using short lengthened fibres. This increases the modulus of elasticity of the concrete and reduces the chances of brittleness and small crack formation. Hence short fibres will limit small cracks, known as the main factors behind the propagation and formation of large cracks.

After that, at the moment cracks propagate, longer fibres will be activated. The long fibres improve the post-cracking behaviour paired with increase of the ductility. Once the long fibres are activated and the cracks become larger, the short fibres will be pulled out of the concrete and no longer work [6].

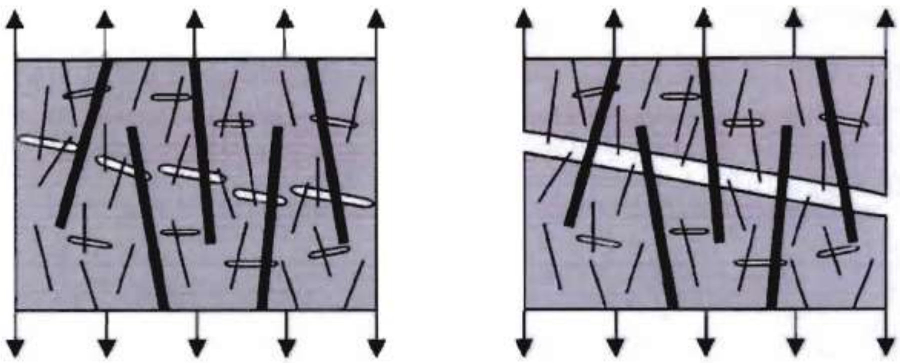


Figure 8: Left; micro cracks bridged by short fibres, Right: macro cracks bridged by long fibres and micro cracks by short fibres [6].

3.2 Concrete Composition

As earlier mentioned, the performance and the mechanical properties of SFRC are influenced by the fibre properties as the concrete composition. So basically the efficiency depends on the coherence between the applied type of fibre and the concrete quality surrounding the fibres.

The experiments of Neves and Almeida [7] with different fibre types showed higher strength by increasing concrete strength class. They emphasized that the compressive strength of the SFRC depends not only on the fibre type and content but mainly on the concrete mixture properties.

Markovic [8] affirmed in his research on the decisive role of concrete composition on the mechanical properties of SFRC, in particular by combining self-compacting concrete with fibres. The flowability and stability of the mixture in the fresh state have a major influence on the fibres distribution and orientation.

A good flowability can ensure that the fibres orientation follows the casting direction and optimizes its load-carrying capacity. The mixture stability can influence the dispersion of the fibres to obtain a constant number of fibres over the span of the structural element and to avoid segregation or fibres clustering. Also, the author enhances on the need to adapt and modify the concrete composition, especially by self-compacting concrete, to achieve the required flowability. This could be done by optimizing the cement type, grading of aggregate with respect to the fibres types and content.

Besides the mixture flowability and stability, is the workability a crucial mixture property that will negatively be affected by the fibres addition [3.1.1.]. Kooiman [1] indicates that the addition of fibre to a standard concrete mixture without any modification will lead to a decreased workability followed by negative consequences. The decrease of the workability will affect the homogeneity and compaction of the concrete structure around the fibres, thus the fibres may not be well bonded to the concrete [8]. Even, the tensile strength may remain similar to plain concrete, only the ductility will improve.

Figure 10 shows the differences between the two composites, where composite (b) is denser than composite (a). Clearly composite (a) has a weak fibre-matrix bond comparing to composite (b). Therefore the fibres are more efficient in composite (b) in when it comes to distribution of shear stress and smaller crack width. Hence, the concrete quality and composition affect the bond strength and the final SFRC behaviour. In order to understand how concrete composition can influence SFRC behaviour, the impact of all concrete ingredients and parameters will be discussed in this paragraph.

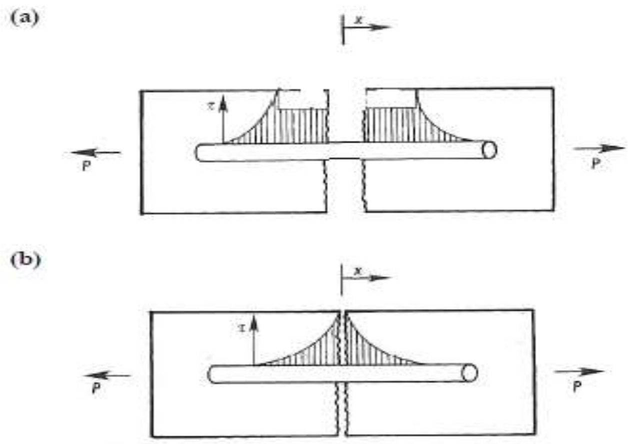


Figure 10: a) porous concrete mixture-weak bond (b) denser concrete mixture-strong bond [19].

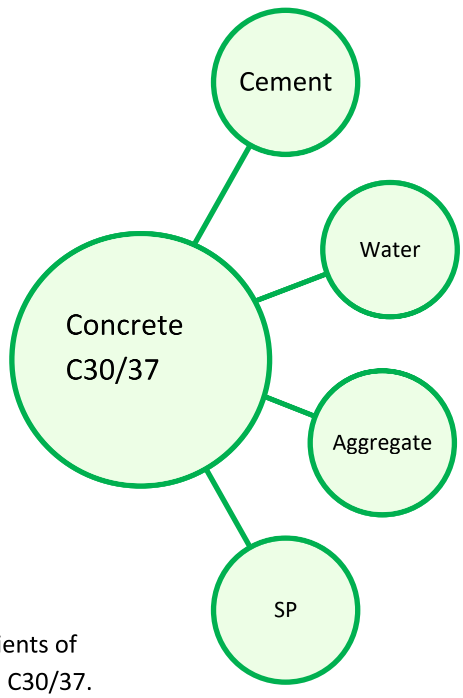


Figure 9: Basic ingredients of concrete composition C30/37.

3.2.1 Aggregate

The volume of concrete is by circa 75% occupied by aggregates. As one may expect, the aggregate properties have a great effect on the performance of concrete. Therefore all the parameters related to the aggregates, like the chemical and mineral compositions, shape, roughness, the degree of weathering, specific gravity, hardness, strength, physical and chemical stability and pore structure affect the features of concrete [20]

The size, shape and the content of the coarse aggregates as the geometry, together with the volume fraction of steel fibers determine the workability of concrete in the fresh state [19]. Therefore the relative fiber to coarse aggregate volume and the 'balling up' phenomenon govern the maximum possible content of steel fiber [19].

In Figure 11 is the relation between the coarse aggregate and fiber plotted, the maximum content of the steel fibers decreases by increasing the coarse aggregate content. The limitation of maximum fiber content is because of the decrease in the compactability [19].

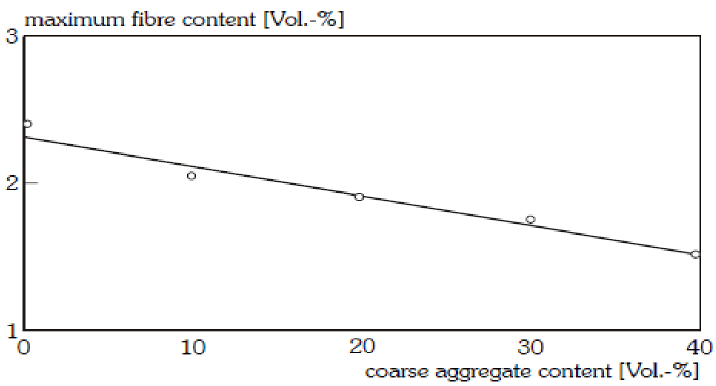


Figure 11: The effect of the coarse aggregate content on the maximum fibre content [19].

Aggregate grading

The grading describes the distribution of aggregate particles of various sizes. It gives for a specific mixture an indication about the properties of the aggregate composition if it is too coarse, too fine or lacing, as it reflects the amount of voids that must be filled by the cement paste [20]. Aggregate grading gives also an indication about the workability of the mixture during the execution and pumping.

M. Acikgens Ulas et al. (2017) [21] studied the impact of aggregate grading in SFRC. In their experiments, they considered a constant cement dosage and w/c ratio but two different maximum aggregate sizes D_{max} and four gradation curves (Figure 12). They showed that the compressive strength of the specimens with the finest grading was higher than specimens with the coarsest grain. Even it is possible to increase the compressive, tensile and flexural strength of SFRC by using finer grading. The best mechanical properties were achieved by finer grading and larger D_{max} paired with the decrease of the workability.

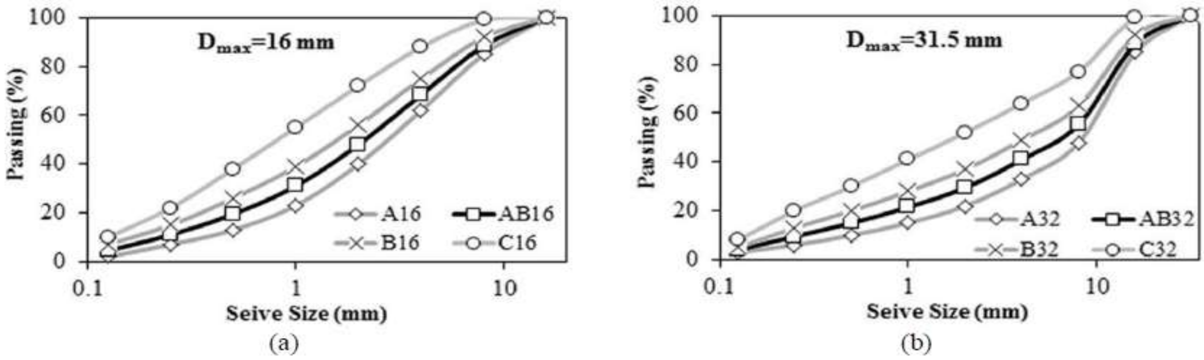


Figure 12: Examples of two different gradation curves of aggregate used in an experiment done by M. Acikgens Ulas et al. [21].

Aggregate maximum size

In order to achieve a better workability in SFRC mixtures, the D_{max} should be limited between 10 mm and 38 mm [21]. The size of fibres relative to that of the aggregates determines the fibres distribution (Figure 13) as well.

Generally, the fibre length should be 2-4 times that of the maximum aggregate size. In order to be effective in the hardened state, it is recommended to choose fibers not shorter than the maximum aggregate size [22 &23]. Furthermore; it is recommended to reduce the volume of coarse aggregates by 10% compared with plain concrete to facilitate pumping [10].

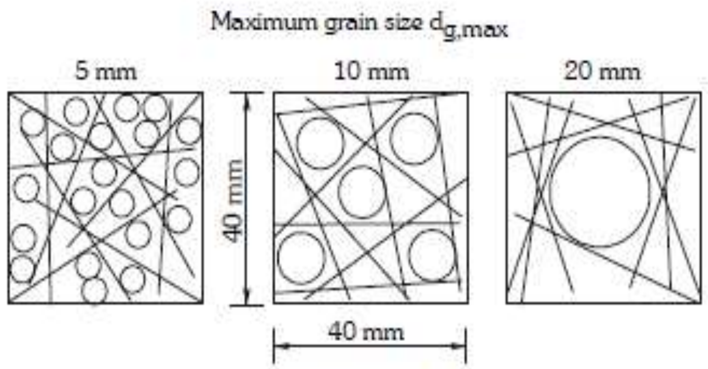


Figure 13: Effect of aggregate grain size on the fibers distribution [20].

3.2.2 Water and Cement Ratio

Experiments have shown that the lower the w/c ratio the higher the failure loads. In case of fibre de-bonding, the w/c ratio plays a minor role in the pull-out behaviour of the fibre. The length of the fibre and its orientation are major parameters, whereas the w/c ratio is a less signification parameter influencing the fibre matrix behaviour.

Offering a different point of view, Topcu and Canbaz [3] indicated in their study, that the impact (improvement) of the steel fibres is limited when it comes to a porous matrix. The results of the experiment indicate that changing the w/c ratio of the concrete mixture has a large effect on the compressive as the tensile strength of steel fibre concrete. Since the amount of the cement paste covering the fibres and the aggregate grains enhances the bond strength of the cement matrix and the steel fibres.

3.2.3 Cement

In most of the experimental studies found in literature, CEM I (Ordinary Portland cement) was used for SFRC, while in the Netherlands CEM III (Blast Furnace Slag) is mostly combined with CEM I. There is not a study found in the literature that describes the effect of cement type on the SFRC behaviour.

Further, there are some traditions in the Dutch market; one of them is adding a certain amount of fly ash to reduce cement content. The combination of two types of cement with fly ash is not discussed in the literature.

3.2.4 Admixtures

The addition of steel fibre to the fresh concrete negatively influences its workability. To maintain the workability without adding extra water, chemical admixtures and superplasticizers have been added in most of the experimental study.

3.3 Experimental studies

The literature provides plenty of studies and experiments done about SFRC. Each study has a specific aim and investigates the effect of an arbitrarily chosen concrete ingredient or mechanical behaviour. Due to the scope of the thesis, three studies have selected to discuss that fit with the goals to get a better overview of what the authors found about SFRC C30/37 including low fibre content.

In appendix A, the three studies are discussed and the results are summarized in Table 1.

Starting with the concrete composition, one of the authors did not take the fibres volume into account (Experimental study 1). The author tested the same concrete composition with 3 fibres dosages without adjusted the other ingredients by adding steel fibres. While the other 2 authors considered the fibres as aggregate by adding fibres and reduced the aggregate content.

The compressive strength clearly is affected by the fibre addition. The small number of specimen and the large standard deviation makes it complicated to precisely determine the influence. But it seems that for the short term, a small fibre addition can decrease the compressive strength compared to plain concrete.

By comparing the flexural tensile strength, the three mixtures had almost the same strength. There is not a sizable increase of the flexural tensile strength by a small fibre dosage. Even more, by comparing the SFRC mixture including small fibre dosage with plain concrete, there is not a noticeable improvement. Therefore adding a small amount of fibre to concrete may not improve the maximum flexural strength of the concrete, at the same time it may have negative effects, especially if the mixture is not properly cast.

	Study 1	Study 2	Study 3		
Fiber content	27.3 kg/m^3 (0.35%)	30 kg/m3 (0.38%)	0.250%	0.375%	0.500%
Fiber tensile capacity	1000 MPa	1100 MPa	1200 MPa		
Fiber length (ratio)	60mm (d=92mm)	50mm	60mm (d=0.90 mm)		
Concrete Strength Class	-	C30/37	C35 (Cylinder)		
Cement	347 kg/m^3	410 kg/m^3	400 kg/m^3		
Fine aggregate	796 kg/m^3	875 kg/m^3	663 kg/m^3		
Coarse aggregate	965 kg/m3	875 kg/m^3	1065 kg/m^3		
Maximum grain size	25mm	16mm	-		
w/c	0.49	0.524	0.495		
Superplasticizer	868 (ml/100 kg)	-	-		
Silica fume	-	-	-		
Air content	6%	-	-		
Slump SFRC/Slump plain concrete	110/200 mm	75/120 mm	Design criteria considered: a slump of more than 12cm		
Measured Compressive strength	34.2 MPa	41.3 MPa (σ=4.79)	34.6MPa (σ=2.90)	37.4 MPa (σ=4.20)	37.3 MPa (σ=3.11)
Measured Splitting Tensile strength	-	3.22 MPa (σ=0.14)	-		
Test method & specimen dimensions	Three point flexural test: 150mm*150mm*500mm	Three point flexural test: 150mm*150mm*500mm	Four point flexural test: 150mm*150mm*500mm		
Measured Flexural strength	4.68	4.95 MPa (σ=0.34)	4.74* 4.74**	4.07* 4.32**	4.16* 4.80**
$R_{e,3}$ (equivalent flexural strength ratio)	43 %***	-	1.161 **** (σ=0.315)	0.870**** (σ=0.094)	0.540 **** (σ=0.109)
E modulus	-	26771 MPa	-		

Table 1: Summary of the experimental measurements

*The first peak strength which initiates tensile cracking in the SFRC beams at which the elastic region finishes and the initial slope of the stress and deflection curve abruptly changes.

***The ultimate strength which is defined as the maximum stress observed from the flexural test.*

**** Calculated with the formula:* $\frac{f_{e,3}}{MOR} * 100$ *(where $f_{e,3}$=equivalent flexural strength and MOR=modulus of rupture)*

*****Calculated with the formula:* $\frac{energy\ absorption\ at\ 3mm}{first\ peak\ load * deflection\ at\ 3mm}$

3.4 Bond Strength of fiber-matrix

Concrete is a highly complex, heterogeneous and brittle composite material. As explained earlier, in order to increase its ductility and strength steel fibres are often used. The increase in ductility and strength is mainly achieved by fibre-bridging effect across matrix cracks and the stress transfer from the matrix to the fibre through the adhesive contact of cement paste surrounding the fibres [21]. This mechanism makes this type of composite materials very sensitive to the structure of the interface between the fibres inclusion and the cement paste [19]. Because the efficiency of fibre-bridging depends on the properties of fibre, cement paste and the transition zone. By larger cement paste the contact with the surface of fibres will increase, which will lead to an increase of strength and ductility [24].

In some instances, due to the wall effect and bleeding during the casting and compaction procedure (production technology), the matrix at the vicinity of aggregate and fibres becomes porously comparing to the bulk matrix. This area created between the steel fibre and the bulk matrix is known as the interfacial transition zone (ITZ).

The ITZ thickness in SFRC depends on the water and cement ratio, fillers and the diameter of fibre (or reinforcement). Generally, ITZ thickness has been reported to range from 20 to 50 µm [24]. Also, it is observed that when the fibre's diameter is bigger than the cement grains (typically <80 µm), an ITZ will form around the fibre. But if the fibre diameter is smaller than the cement grains, for example, carbon fibres with 7 µm, no ITZ will form around the fibre [24].

The properties of composite materials are very sensitive to the structure of the interface between the reinforcing inclusion and the matrix. It is now well established that in composites with Portland cement matrices (mortars, concretes, fibre-reinforced cement) the structure of the paste near the interface is significantly different from that of the bulk paste.

Akşaoğlu T, Tokyay M and Çelik [25] emphasized the impact of higher porosity in ITZ and its thickness on the mechanical properties of concrete. This problem can be controlled by increasing the particle packing to densify the ITZ.

Other researchers also pointed out that there is a link between the mechanical properties of SFRC, in particular, crack growth, flexural and tensile strength and the interfacial bond strength of fibre and hydrated cement paste [26]. These studies indicate that the interfacial bond was a deciding factor for the tensile as compressive strength [19].

The porous nature of the transition zone between fibres and matrix represents a weak zone where cracks may initiate. The densification of the transition zone may help to reduce the voids in the transition zone and optimize the fibre-matrix bond strength [27]. Other approaches to control the porosity of the ITZ may be improvement of the curing, addition of fillers (silica fume, limestone, polymeric additives, etc.) or reducing the w/c ratio [24].

Adding silica fume is tool used by a several researchers. The particle size of silica fume is less than 1µm and its high content of amorphous silica (SiO2) give silica fume two roles. Namely, physically as filler for the void in concrete and chemically in the pozzolanic reaction with CH to for C–S–H gel and reduces the paste porosity and permeability. This will improve the bond between the inclusion and the bulk matrix [24]. Despite these two characterises, replacing cement by more than 10% silica fume (by cement weight) may negatively influence the compressive strength of high-strength concrete.

From a different perspective, some studies demonstrated that the ITZ gives just a marginal effect on the performance of concrete [24]. The transition zone microstructure may not be the governing factor in interfacial bond strength. It may relate to the adhesion between the fibres and matrix [27].

Hild and Schwartz [28] indicated that fibres and matrix made up of materials with low surface energy (for example polymer), the adhesion between fibres and matrix may be the governing parameter for the de-bonding. For these composite materials, the densification of the ITZ will not strongly enhance the adhesion and bond strength between fibres and cement matrix.

Therefore, it is advisable to measure the mechanical strengths paired with quantitative microstructure analysis. Any improvement of the mechanical properties due to an adjustment of the cement matrix composition may involve adaption of the cement paste microstructure. Also, it is crucial to investigate both aspects from the same specimen to get a better insight into the relation between the mechanical properties and cement paste microstructure.

Microstructure of Transition zone

The transition zone has a special microstructure that strongly depends on the production technology and the nature of the matrix. During the hydration process, the cement particles ranging in diameter from 1µm to 100µm in the fresh state will react to form CSH particles and large crystals of CH. Therefore the nature of the fresh mixture has an important effect on the features of the transition zone.

The formation of air voids around the fibre may be due to bleeding and entrapped air or inefficient packing of the 10µm cement grains in the 20 to 40µm zone around the fibre surface. Consequently, the vicinity of the fibre becomes more porous and not filled with hydration products, where at the bulk paste a denser microstructure will develop rich with CH crystals.

Bentur et Al. [19] illustrate a schematic description of the transition zone in (Figure 14), showing the different layers of duplex film, CH layer, a porous layer consisting of CSH and ettringite crystals. The duplex layer is the CH layer that can be as thin as 1µm or much more. The rich CH layer around the fibre may be formed due to the precipitation from the solution in the area around the steel fibre, where the fibre surface acts as a nucleation site [19]. Another feature of the CH layer around the fibre is the discontinuity and it contains porous and needle-like material consisting of CSH and ettringite [19].

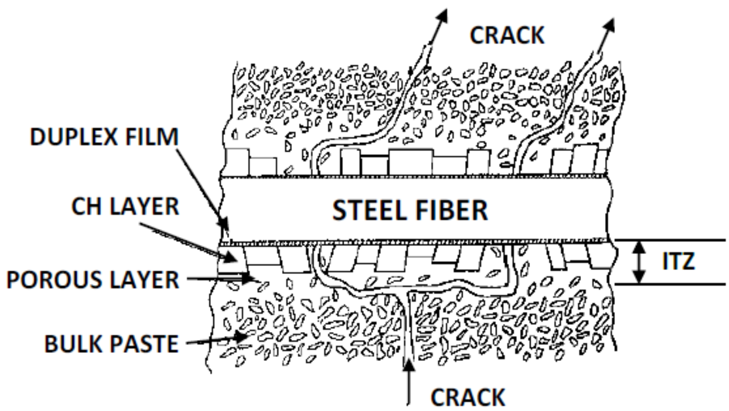


Figure 14: Schematic cracking and de-bonding of ITZ in SFRC [19].

Further, the thin duplex film may be observed in the vicinity of the porous zone not necessarily around the fiber & CH layer (Figure 14*)*. Hence, the weak link between the fiber and the matrix may not be related to the direct interface of fiber and massive CH layer, but to the porous layer between the massive CH layer and the dense bulk cement paste that extends to a distance of 10 to 40µm.

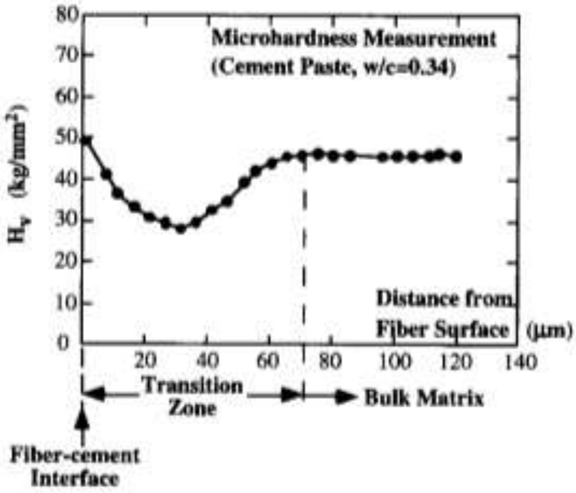


Figure 15: A schematic illustration of the relationship between the interfacial zone and microhardness after Wei et al. [29].

S. Wei, J.A. Mandel and S. Said [29] measured the mechanical properties of the transition zone by measuring the microhardness of the cement materials along radial lines in the annular region around the fibre. They ascertained that the matrix microhardness far from the fibre surface is stable and by getting closer to the fibre surface (a distance of 50µm), the microhardness tends to decrease leading to the formation of looser/porous material structure [29]. But by reaching the fibre interface the microhardness increases again (Figure 15). The microhardness increases nearby the interface may be related to the abundant deposit of Ch crystals around the fibre surface.

Commonly, the microhardness depends on the microstructure and material mechanical properties [27]. Studies and measurements observed high porosity and strength decrease by low microhardness. As Figure 15 shows, the decrease of the microhardness may occur in the transition zone, which makes the transition zone a weak point responsible for bond failure when de-bonding occurs in the transition zone.

Therefore the loose material structure, bleeding and wall effects strongly influence the transition zone microstructure, where the existence of a porous and weak transition zone may be a dominant factor for the bond failure [27]. Hence, the densification of the matrix microstructure can be a tool to strengthen the transition zone and optimize the interfacial bond strength.

Fibers-matrix adhesion bond

The adhesion bond is the united bond between the steel fibre and the concrete that surrounds it. The features of this bond depend on the quality of the interfacial transition zone as discussed above. Because when the fibre is under tensile stress, the bond will be affected and de-bonding will occur at the ITZ.

The reason is that very small cracks start initiating and spread at very small distance from the fibre and go through the ITZ and bulk matrix [19]. Therefore the structure and quality of this zone are very important. It is quite similar to the aggregate-cement paste interface. Non-efficient packing of the finest cement and sand particles in the fresh state will increase voids around fibres and hinder filling it with hydration products. This will lead to higher water entrapped as mentioned before [8].

Fibers failures at the interface

Slipping of fibres is a critical feature in SFRC; it is related to the bond strength between the fibres and the concrete matrix, degree of adhering to the concrete and the pulling out strength of a deformed fibre [6].
The fibres will be activated at the moment the concrete cracks. From a certain crack opening all the fibres slip and work together. As a result, the concrete exhibits tough behaviour. The adhesion of the fibres to the concrete should not be too great. If the bonding is too strong, the concrete will be brittle and breaks with a small crack width. If the bond strength is insufficient, the fibre only absorbs a slight tensile force because it will quickly pull out of the concrete matrix.

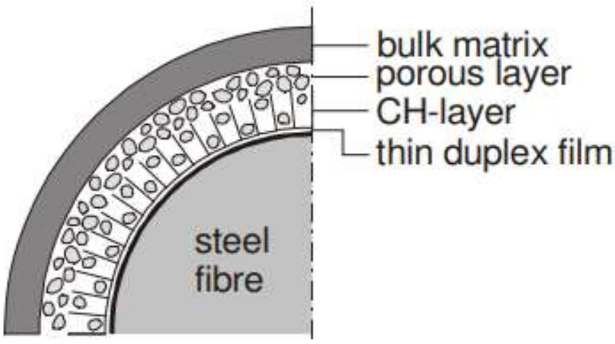


Figure 16: illustration of the steel fibre and bulk matrix interface after Markovic [8].

The pulling out of fibre from the concrete is one way of affecting negatively the bond strength. The other one when the fibre breaks. The collapse of the fibre gives brittle failure behaviour; the length of the fibre influences this. Therefore the fibre must not be longer or shorter than the critical length. This is the length at which the steel fibre and the matrix will collapse in theory [6].

Another point that should be considered in the design process is the development of the microstructure of the transition zone and the fibres types. By a discrete monofilament fibre (e.g. steel), the entire fibre surface may be in direct contact and embedded in the matrix. While for bundled filaments (e.g. glass) only the external filaments will have direct contact with the matrix [27].

ESEM analysis

In all studies, researchers used environmental scanning electron microscopy (ESEM) to study the morphology of the interfacial transition zone around the steel fibre. Generally, backscattered and secondary electron detectors are employed to generate images with various resolutions.

Mostly, images of 500µm are used to investigate the geometrical characteristics of steel fibres in the specimens. Lower resolutions are used to analyse the interface between the steel fibres and cement paste. In addition to the X-ray detector that can be used to specify chemical phases (CH, C-S-H, etc.) at the interface between the fibre and cement paste.

3.4.1 Measurements to optimize the bond strength

To improve the bond strength and to limit cracks width as obtaining higher tensile and flexural strength a summation of measurements proposed in the literature is given:

Measurements related to steel fibers

- **Fibre shape*:*** In order to gain pull out resistance and improve the bonding strength between the steel fibres and the concrete matrix, the steel industry is continuously developing new fibres that have enlarged, flattened or hooked ends, roughened surface textures or wavy profiles. Because friction is governing the pull-out mechanism of straight fibres (Figure 17).

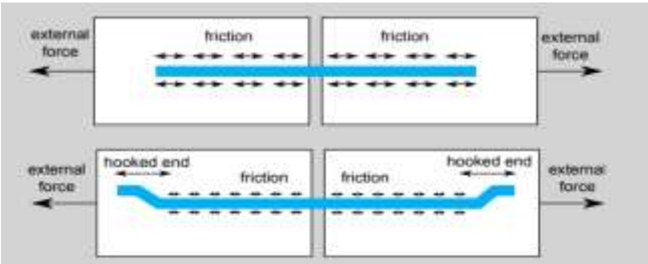


Figure 17: The influence of the fibre shape on the internal and external force [12]

- **Fibre orientation:** The effect of the fibre orientation can increase the pull-out resistance materials at particular angles.

- **Fibre tensile strength*:*** The tensile strength of the fibre contributes to the pull-out response of the fibres. By a fibre with hooked ends, rupture can occur when the fibre stiffness is too high or when the fibre tensile strength too low is (Figure 18).

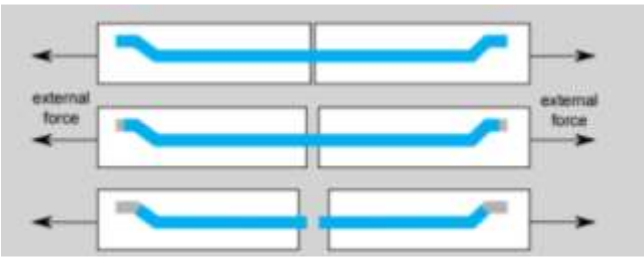


Figure 18: The influence of the steel fibre tensile strength on the fibre rupture [12].

- **Fibre content:** The compressive strength increases as the tensile splitting strength increases for all fibre types with raise in the fibres content [13] (Figure 19).According to Acikgens Ulas et al. [21], increasing fiber content as the Dmax will lead to increasing the clustering of the fibers but will improve the bond strength between steel fibers and concrete.

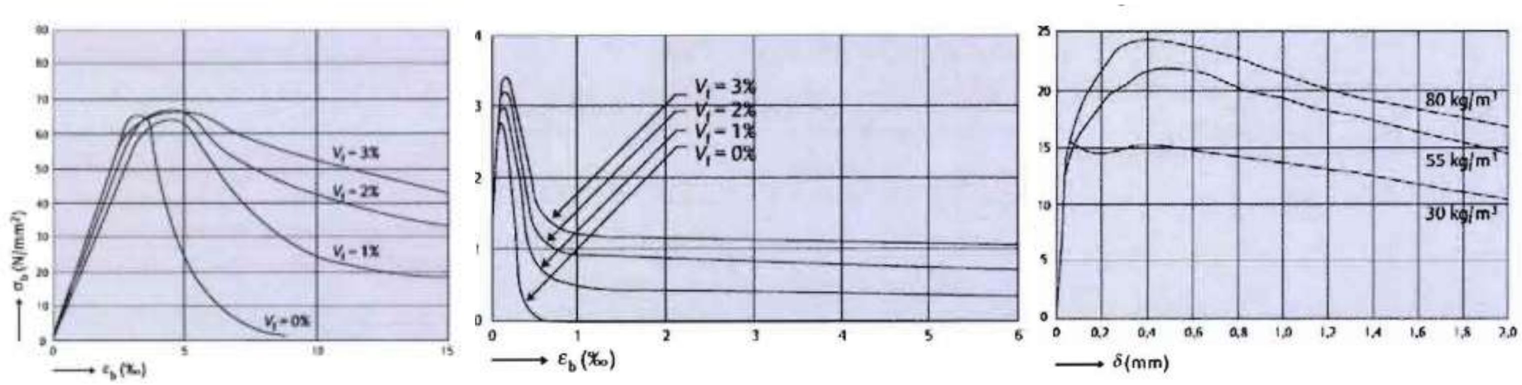


Figure 19: The effects of fibres addition on the mechanical strengths, graph (1): compression strength of SFRC, graph (2): tensile strength of SFRC and graph (3): flexural strength of SFRC [6].

- **Aspect ratio:** The performance of the hardened concrete is enhanced more by fibres with a higher aspect ratio since this improves the fibre-matrix bond [30].

Measurements related to concrete matrix

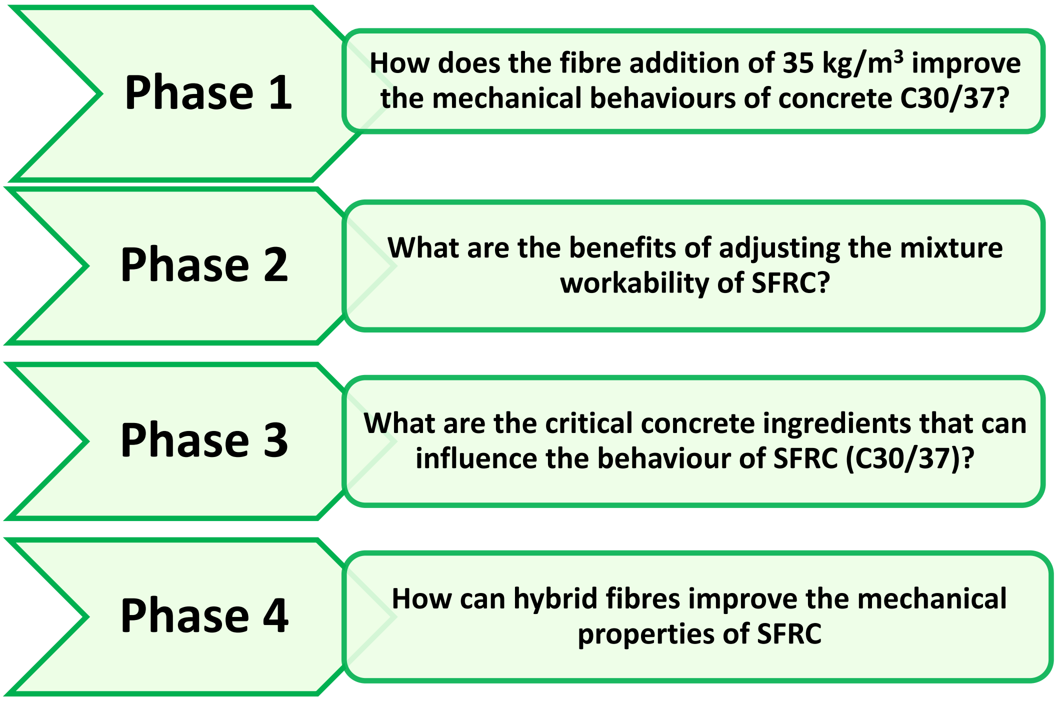
- Matrix densification to strength the ITZ [27], for example by combining steel fibres with self-compacting concrete or addition of fillers (limestone powder, silica fume, etc.)

- Optimizing the SFRC composition by determining the coarse and fine aggregate fractions with the best fresh properties [31].

4. Experimental plan

As described in Chapter 1, the main goal of this thesis is to analyse the consequences of the adjusting the concrete composition on the properties and mechanical strengths of SFRC and to find out the reason behind the variation in the behaviours of SFRC.

The literature review approximately provided insight into the research sub-questions. To obtain more specific answers concern the issues observed in the Dutch situation, six concrete mixtures were designed according to the Dutch Standards, prepared with local material and tested. This is accomplished in phases conform the sub-questions given in Chapter 2:



In the three studies, the performance of the SFRC was evaluated by measuring the compressive, splitting tensile and flexural strength. The results of the experiments showed a decrease in the compressive strength and a slight improvement of the splitting tensile and flexural strength by the fibres addition.

The concrete mixtures used in the literature experiments vary from the one used in the Netherlands. As mentioned earlier, the cement type used in the experiments is mainly Ordinary Portland Cement (CEM I). In the Netherlands, concrete mixtures should contain CEM III as well. Even the environmental as durability requirements differ in every country, which may also affect the concrete composition.

Further, the traditions and habits of the market play a role, for example in the Netherlands it is common to add a certain amount of fly ash to increase fine material content. Reusing the results and data of tests provided by the literature to analyse a problem in the Dutch context is risky and will not give a proper insight about the problem and the required solution.

Hence, the literature review has been used as guidelines to get an indication about the properties and mechanical strengths but also to learn from faults and mistakes of experiments to avoid them in this experimental plan.

4.1 Experiment of phase 1

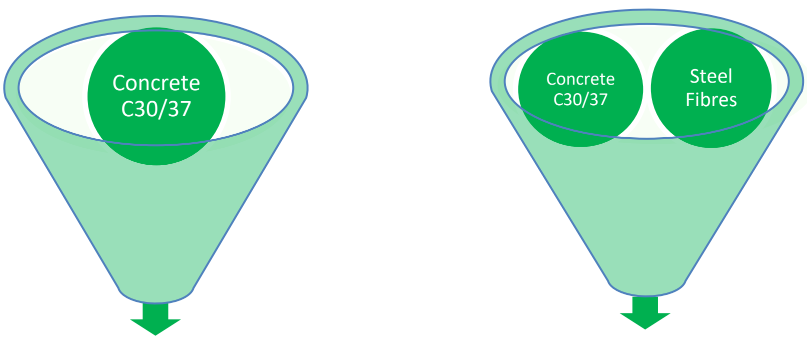
In the literature review (Chapter 3) are all the benefits and advantages of fibres addition mentioned based on the experiments and conclusions of other researchers. In most of the cases, larger fibre dosage (>35 kg/m^3) and higher concrete strength class have been combined. These results in a considerable strengths improvement compared to plain concrete.

For example by the addition of 1% (circa 60kg/m^3) of steel fibres to concrete the compressive, splitting tensile as the flexural strength will be enhanced (Figure 19). For smaller fibre content it is difficult to estimate the strengths based on graphs due to lack of information.

In order to determine the consequences of adjusting the concrete composition on the mechanical strengths of SFRC, it is essential to start from the beginning and determine what is happening with the concrete properties and mechanical strengths by the addition of 35 kg/m^3 of steel fibres.

Due to the privacy of the project realised with SFRC by the contractor, it was not an option to use existing data for this research. Therefore two mixtures, plain concrete C30/37 and SFRC (C30/37 including 35 kg/m^3) were designed. The basic design criteria's considered in both concrete mixtures were:

- Concrete strength class C30/37
- D_{max}=16 mm
- Cement types: CEM I & III
- Consistency class: S4
- Fly Ash: 20 kg/m^3
- Fibre content: 35 kg/m^3 (for SFRC)



Plain concrete-M1 **Reference SFRC-M2**

The comparison of the properties in the fresh state and the mechanical strengths in the hardened state between both mixtures gives an indication about the advantages as disadvantages of fibre addition. The comparison has been based on the followed measured parameters and strengths:

- Slump value
- Air content
- Compressive strength
- Splitting tensile strength
- Flexural strength
- Fracture energy

The concrete compositions are given in Table 2. The two mixtures are separately prepared, cast and tested after 28 days. Due to the limited capacity of the laboratory and available apertures at the university, it was not possible to cast and test both mixtures on the same days.

The cement types used for both mixtures are high strength Portland cement (CEM I 52.2) and Blast Furnace Slag cement (CEM III/B 42.5). Aggregates were all dried before use and the maximum aggregate size was 16mm. Steel fibres provided by Metal Products were hook-ended of 50mm length and 1.05mm diameter.

	w/c	**CEM I [kg]**	**CEM III [kg]**	**Fly ash [kg]**	**Fine aggregate [0-4mm]**	**Coarse aggregate [4-16mm]**	**Fiber [kg/m^3]**
Plain concrete-M1	0.5	98	280	20	843	905	0
SFRC-M2	0.5	98	280	20	828	905	35

Table 2: The mixture compositions of plain concrete-M1 and SFRC-M2 cast in phase 1.

The concrete was mixed using a laboratory concrete mixer. Starting with mixing the sand and aggregate particles, then cement, fly ash and water were added and mixed in times ranging from 3 to 6 minutes and compacted on a vibrating table.

Before casting the concrete in the molds, the workability of each mixture was measured by a slump test. The slump test was performed to check the consistency of the fresh concrete before it sets and the ease with which the concrete will flows. It gives also an insight by improper mixed concrete.

Slump test was carried out using Abrams cone that was filled in three stages and by each stage, the layer was tamped 25 times. After lifting the cone upwards, the concrete started to slump. The slump of concrete was measured from the distance at the top of the slumped concrete to the level of the top of the slump cone. The same sequences have been followed for the reference SFRC-M2, only the steel fibers have been added at the end.

Figure 20 shows the measured slump of the plain and reference SFRC-M2 mixtures. The slump of reference SFRC-M2 decreased by 5.5% compared to plain concrete M1 by the fibers addition. Despite this decrease, the workability of SFRC-M2 complies with the required consistency class of this research S4 (160mm-210mm).

Figure 20: The measured slump of plain concrete-M1 (left) & SFRC-M2 (right).

After measuring the workability and air content, the fresh concrete was cast in molds to test it after 28 days. Two shapes of molds (Figure 21) were used, cubes of 150*150*150mm for the compressive and splitting tensile tests and prims of 100mm*100mm*400mm for the 3-point bending test.

The specimens were de-moulded after 24 hours and saved in the curing room of the university, where the temperature is 20 degrees and relative humidity 96%.

Figure 21: The cubes and prims molds used to cast the concrete mixtures.

Results of the experiment phase 1

On the 28th day after the casting date of each mixture, the specimens were ready for the tests. All of the tests were accomplished on the same day. The test procedure started with the 3-point bending test to obtain a load-displacement curve and determine the maximum flexural strength (Figure 22).

This test has been applied to six specimens (prisms) to get more reliable results. The average value of the maximum flexural strength and standard deviation of both mixtures are given in Table 3. All the prisms had a notch of 15mm and the LVDT detectors were placed above the notch at both sides of the prism.

Figure 22: **Left**: Plain concrete and **Right:** SFRC prism during 3-point bending test

The 3-point bending test was followed by the compressive and splitting tensile. For both tests, the cube specimens were used. The speed of the compressive test was 13.5 kN/s while for the splitting tensile test 1.1kN/s. The tests stopped when the specimen failed. The strength appeared on the screen was noted. Again to have reliable results, six specimens have been used for every test and the average strength value as the standard deviation are given in Table 3.

	Plain concrete-M1	**Reference SFRC-M2**
Compressive strength	47.6 (1.5)	51.3 (2.4)
Splitting Tensile strength	3.7 (0.1)	4.6 (0.5)
Flexural strength	3.4 (0.2)	3.7(0.5)
Slump	180mm	170mm
Air content	2%	1.4%

Table 3: The measured properties and strengths (& standard deviation) of phase 1.

Figure 23 presents the crack pattern of plain concrete M1 and reference SFRC-M2 cubes after the compressive and splitting tensile strength. Obviously, the cube of the reference SFRC-M2 tested on splitting tensile showed a decrease of crack opening compared to the same tested cube prepared with plain concrete M1. Also, the reference SFRC-M2 cubes stayed intact after the compressive test.

Besides obtaining the maximum flexural strength, the test data of 3-point bending has been used to plot the strength versus displacement curve and to get an indication about the influence of the steel fibres on the post-cracking behavior of SFRC. As shown in Figure 24, by the addition of fibres, specimens demonstrated strain softening behavior in contrast to the specimens of plain concrete M1.

In Figure 25 and Figure 26 are the data of all tested specimen plotted of both mixtures. The specimens of the reference SFRC-M2 show more variation in their post-cracking behavior compared to the specimens of plain concrete M1. The increase in variation is related to the fibers distribution in every specimen.

Figure 23: **Top** Plain concrete-M1 specimens: 1) after the compression test 2&3) after the splitting tensile strength.
Below: SFRC-M2 specimens: 1&2) after the compression test 3&4) after the splitting tensile strength.

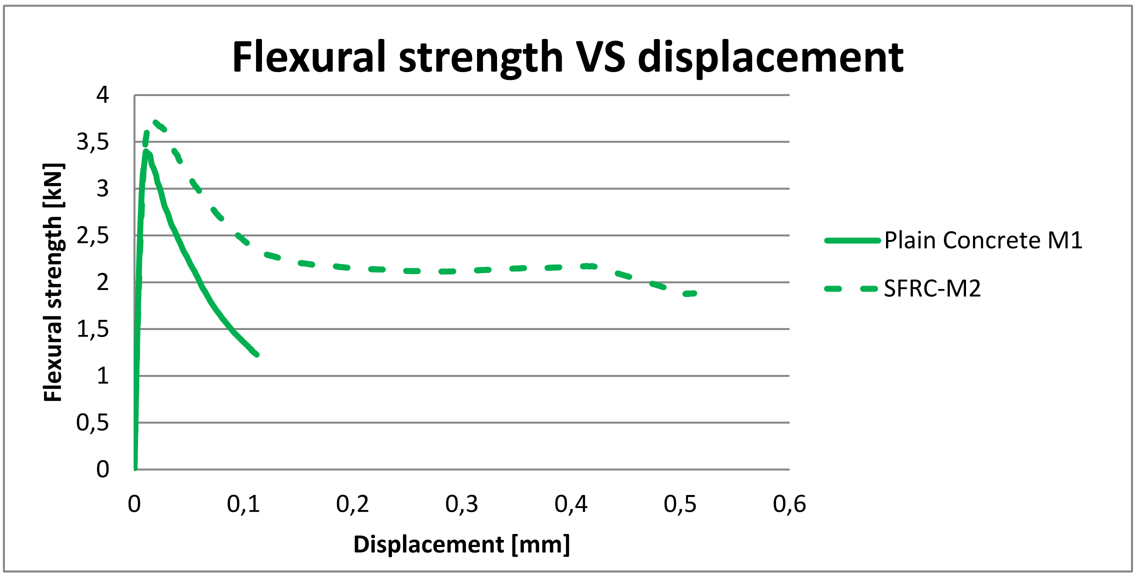


Figure 24: Average flexural strength vs. displacement curves obtained by the 3-point bending tests of plain concrete M1 and SFRC-M2.

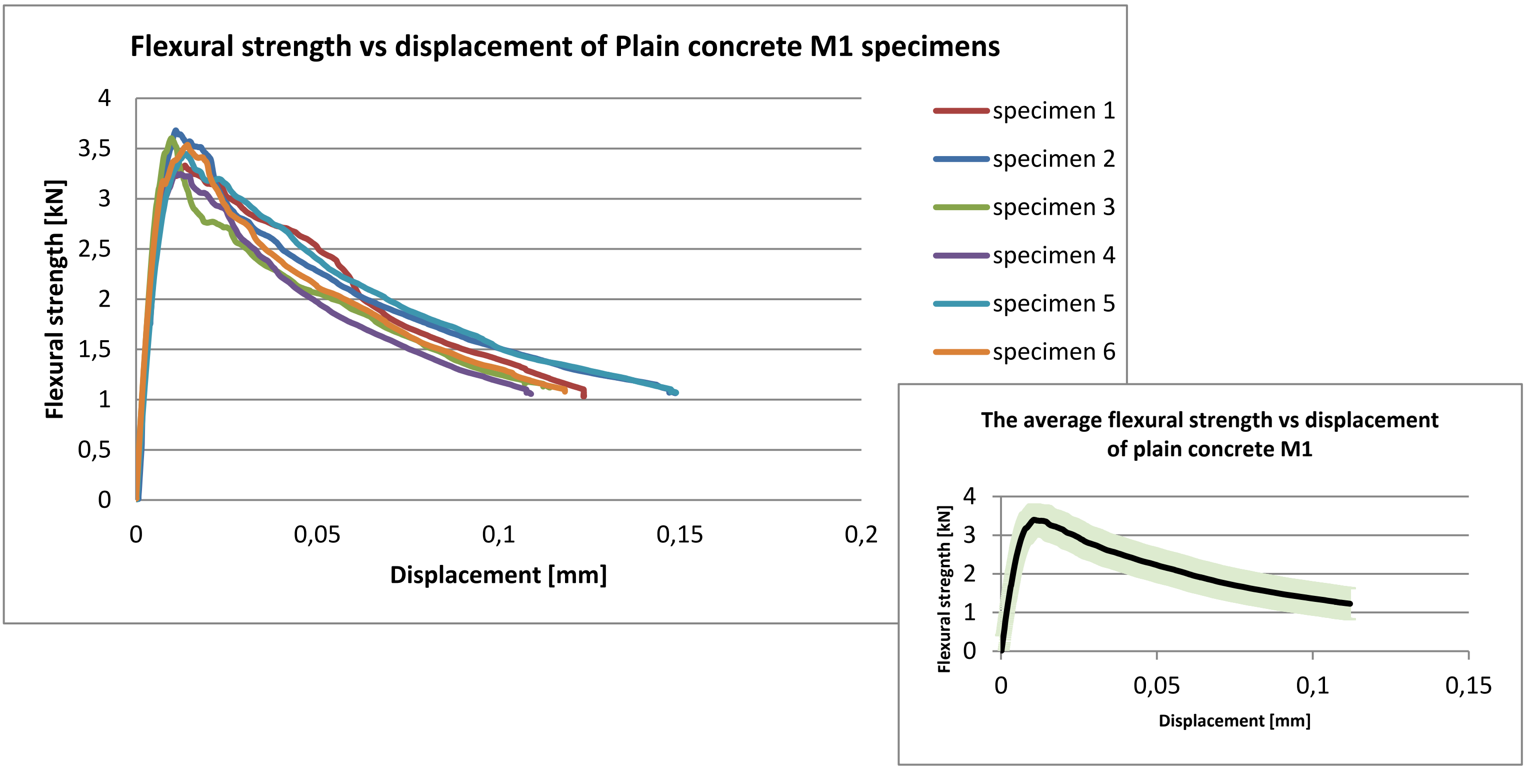
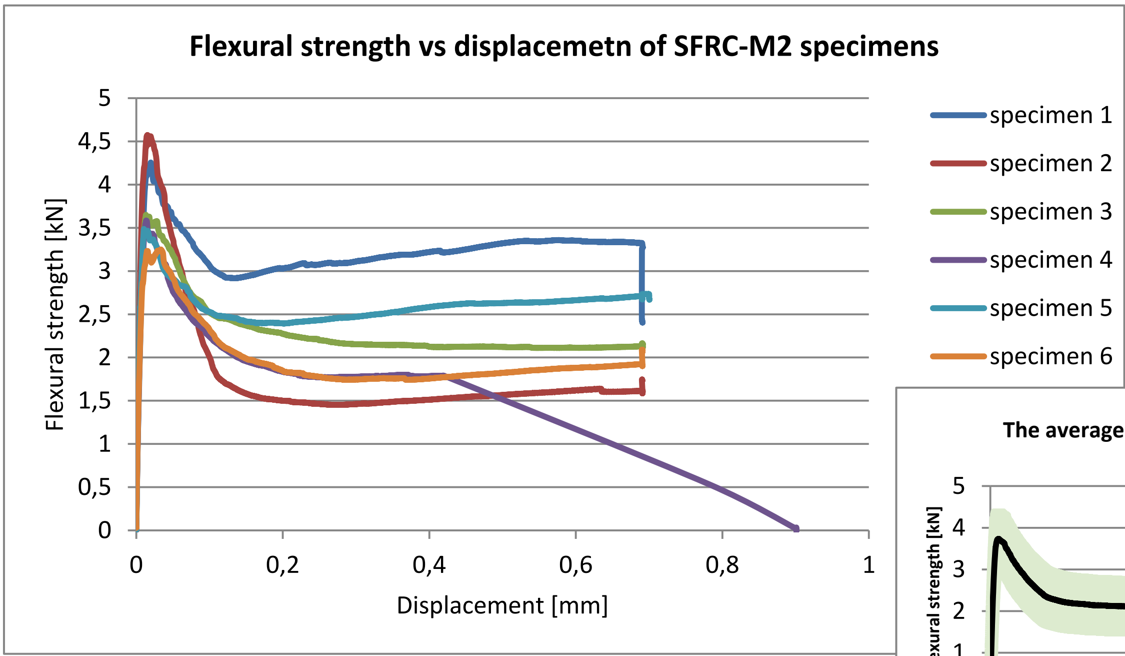


Figure 25: **Left:** Flexural vs. displacement curves obtained by the 3-point bending test of all plain concrete M1 specimens and **Right:** the average of the six tested specimens that will be used for the comparison.



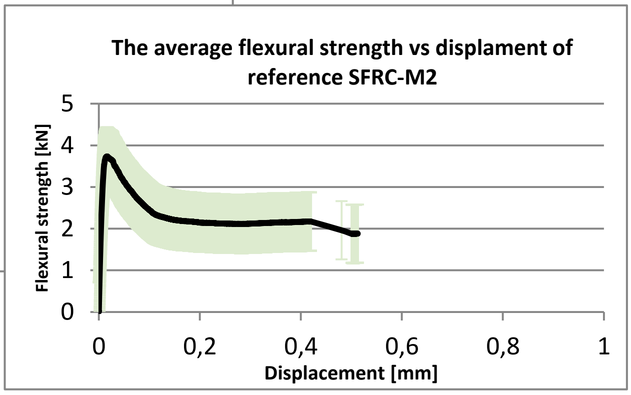


Figure 26: **Left:** Flexural vs. displacement curves obtained by the 3-point bending test all reference SFRC-M2 specimens and **Right:** the average of the six tested specimens that will be used for the comparison.

Discussion and conclusions of phase 1

The observed material properties during the experiment can be divided into two stages, the mixture preparation & casting (fresh state) and the test procedure (hardened state):

- ***Fresh state***

The measured slump of the reference SFRC-M2 showed a decrease of 5.5% (Figure 20) compared to the slump value of plain concrete M1 due to the fibres addition. This decrease was expected and complies with the literature review (Chapter 3). However, the measured slump still fulfils the required consistency class of this research but is at the lower side of the consistency class S4 (160-210mm).

Noticeably the workability (Figure 27) reduction did not bother the casting procedure; all the molds were filled before the SFRC started to harden. This may be related to the small number of molds and the short time between mixing and casting. Working conditions in the laboratory and using dried materials may also affect the mixture consistency.

Figure 27: Reference SFRC-M2 in the wheelbarrow before filling molds.

This is in contrast to the practice, where the mixing and casting of SFRC mixture will be on larger scale (i.e. industrial floors) and the decrease of the workability can be larger. In that case, the reduction of mixture consistency may hinder the casting process and the final SFRC quality.

Therefore, attention should be given to the consistency of the mixture delivered to the building site before starting with casting. By unworkable SFRC mixture, the employees may take measurement to adjust the workability of the SFRC mixture like using a wet pipe to cast SFRC, adding water, etc. These types of measurements may have negative side's effect on the performance of SFRC.

In the practice, the concrete mixture should maintain its workability for at least 90minutes until it is delivered to the building site. That means the measured slump of 170mm at the laboratory condition will decrease after a short time. Any decrease in the consistency will affect the SFRC quality in the hardened state. To preserve the required workability it is recommended to add superplasticizer.

Adjacent to the slump test, the air content was measured in the fresh state. The air content of the reference SFRC-M2 decreases compared to the air content of plain concrete M1. The decrease of the air content was against the expectations.

According to the literature review (Chapter 3), it is supposed that the air content will increase by the fibers addition. The increase of air content described in the literature may be related to the compaction and production technology of SFRC rather than the fibers addition. Reduced air content of the reference SFRC-M2 indicates that steel fibers addition does not have to be paired with an increase of air content.

Benefits of lower air content are the decrease of the capillary porosity, denser concrete microstructure and eventually smaller ITZ which results in a better bond strength between the steel fibers and concrete matrix (Table 3).

- ***Hardened state***

The fibre addition of 35 kg/m^3 increases the compressive and splitting tensile strength by respectively 7% and 23% (Table 3). Crack opening of the specimen after applying the splitting tensile test (Figure 23) decreases due to the fibres bridging and intercepting the cracks (Figure 28).

Figure 28: Comparison of cross-section specimens of plain concrete M1 (left) and reference SFRC-M2 (right)

The improvement of the maximum flexural strength is negligible, only the SFRC specimens showed a post-cracking behaviour and a better ductility compared to the plain concrete M1 specimens (Figure 25 & Figure 26). The mean flexural strength versus displacement curve showed a softening behaviour after the first crack development.

By taking a closer look at the individual performance of each specimen made of plain concrete M1 and reference SFRC-M2, the variation in the softening behavior increases in the SFRC specimens. One of the reference SFRC-M2 specimens, namely specimen 4 failed at the end of the test. In this specimen, the crack initiated above the notch and increased until it reached the top of the prism where the strength immediately dropped to zero. This did not occur in the rest of the SFRC-M2 specimens (Figure 26).

Also, the SFRC specimens took longer time during the tests compared to plain concrete specimens. Therefore the 3-point bending test was stopped after two runs of 700 microns (displacement). For specimen 4 the second run was not required, this specimen failed during the first run.

This specimen did not fail spontaneously or break in two parts but stayed intact (Figure 29). As reported in the literature, the steel fibres were activated by the first crack development, as they bridged the crack and contributed to transfer the stresses to the uncracked concrete.

However, specimen 4 was a scatter in the series of tested specimens, it was decided to break it to inspect the cross-section. The specimen was hit by a hammer at the middle point where the notch located, to break it in two parts.

As shown in Figure 30, only a few steel fibres were detected at the cross section. Still, this cross-section does not completely represent the fibres distribution in the whole prism. But obviously, the post-cracking performance of SFRC is governed by the fibres distribution and content in the prisms.

It can be concluded that the numbers and distribution of fibres vary per specimen, which explains the increase of variation in the post-cracking behaviour of SFRC specimens compared to the plain concrete specimens.

The difference in fibres content per specimen is related to the casting procedure, where the fibres and the concrete were mixed together in the mixer and the molds were filled by shovel. The fibres number differs per shovel, this may be the reason of variation in fibres content per specimen and resulted in variation in the post-cracking behavior.

It is already known that the steel fibres will be randomly distributed in the structural element, actually, this point falls outside the scope of this research. However, the six tested prisms confirm that casting specimens from the same batch of SFRC will not guarantee identical post-cracking behaviour, because the fibres orientation and dispersion stay dominant factors.

According to Kooiman [1], the specimen size has also an impact on the fibres distribution. For industrial floor or another large structural element, the effect of the fibres distribution and orientation may be larger than in the small tested prisms. To obtain more insight on the fibres distribution on larger scale, larger specimens should be tested in the future.

Figure 29: a) **Left:** partly cracked specimen of SFRC-M2 b) **Right**: completely cracked specimen (s4).

Figure 30: Specimen 4 of mixture SFRC-M2 after breaking it by hammer.

Conclusions of phase 1

"How does the fibers addition of 35kg/m3 improve the mechanical behavior of concrete strength class C30/37?"

- By the addition of 35 kg/m^3 of steel fibers the mixture workability decreases by 10mm compared to plain concrete. Despite the small decrease it still meets the prescribed consistency class S4.

- Adding 35 kg/m^3 of steel fibers to concrete strength class C30/37 increases its compression and splitting tensile strength as it decreases the crack width.

- Maximum flexural strength was not affected by the fibers additions, but the SFRC specimens improved the post-cracking behavior after the crack formation.

- The results of the 3-point bending test applied on six prisms showed variation in their strain softening behavior. The reason of variation relates to the fibers content and distribution in each specimen.

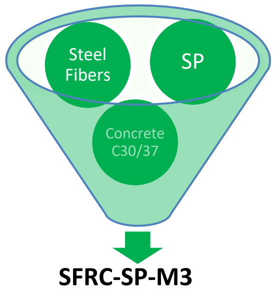
4.2 Experiment of phase 2

In phase 1, the experiment showed a workability decrease by the fiber addition. The small decrease did not hinder the casting procedure. However, the literature review emphasized on the relation between the mixture workability and the fibers distribution.

By an unworkable mixture, the steel fibers will not properly embed integrate with the mixture, whereby a more flowable and fluid mixture the fibers can be better mixed and flow in the casting direction which may ensure a better fibers dispersion.

The important role of fibers distribution was already noticed in experiment 1. The variation in the post-cracking behaviours of SFRC-M2 specimen's increases compared to the variation of the plain concrete specimens.

The mixture workability can be adapted by adding superplasticizer (SP) without modifying the mixture composition.To study the effect of workability on SFRC behaviours, SP was added to the same concrete composition as SFRC-M2.



The comparison of the properties and mechanical strengths between the new mixture SFRC-SP-M3 and the reference SFRC-M2 will display the influence of the workability on the fibers dispersion, variation in post-cracking behaviour and strengths.

During the mixing procedure of the third mixture, 0.3% SP (of cement content) was added to one of the water buckets. Water including SP was mixed with the other cement, sand, fly ash and the steel fibers. At a certain moment, the mixture becomes very flowable and laboratory supervisor advises to stop adding the water (contained SP). The measured slump of SFRC-SP-M3 was 220mm (Figure 31).

Figure 31: The slump test of SFRC-SP-M3 in phase 3.

Reducing the water content means a decrease of the w/c ratio to 0.49 and increase of the air voids (2.4%) compared to the reference SFRC-M2. The increase of entrapped air leads to a porous matrix and lower concrete quality than the reference SFRC-M2.

However, this experiment is a good example of mistakes which may happen in the practice as well. The test results demonstrate the consequences of deviating from the original concrete design and the effect of adjusting the w/c ratio on the behavior of SFRC.

Results of the experiment in phase 2

The specimens cast with SFRC-SP-M3 were cured in the temperature room and tested after 28 days, similar to the specimens in the previous phase. The same tests sequences have been followed as in phase 1. Starting with the 3-point bending test and continuing with the compressive and splitting tensile test.

The consequences of the adjustment done in the fresh state by decreasing the water content were clearly reflected in the mechanical strength. In Table 4 are the tests results of phase 1 & 2 given. There is a clear decrease of the mechanical strengths of SFRC-SP-M3.

	Plain concrete-M1	**SFRC-M2**	**SFRC-SP-M3**
Compressive strength	47.6 (1.5)	51.3 (2.4)	46.0 (2.6)
Splitting Tensile strength	3.7 (0.1)	4.6 (0.5)	3.9 (0.2)
Flexural strength	3.4 (0.2)	3.7(0.5)	3.5(0.3)
Slump	180mm [0% SP]	170 mm[0% SP]	220 mm [0.3%]
Air content	2%	1.4%	2.4%

Table 4: The measured properties and strengths (& standard deviation) in phase 1 & 2.

Figure 32 shows the state of the specimens after the compressive and splitting tensile strength. The specimen after the compressive test was more damaged than the specimens of reference SFRC-M2 in phase 1.

Despite the decrease of the strengths compared to the reference SFRC-M2, the specimens of SFRC-SP-M3 showed a post-cracking behavior during the 3-point bending test. Due to some technical issues, the test for this series of specimens has been stopped earlier than the previous phase. Therefore the maximum displacement is smaller than the reference SFRC-M2, this is not related to the material properties (Figure 33).

Again the results of 3-point bending of the specimens seem to be affected by the fibre content and distribution in each specimen. Figure 34 demonstrates the post-cracking behavior of all tested specimens. There is a clear difference between specimens 2&5 and the other specimens, but all of the specimens showed strain softening.

Figure 32: SFRCS-SP-M3 specimens: 1&2) after the compression test 3&4) after the splitting tensile strength.

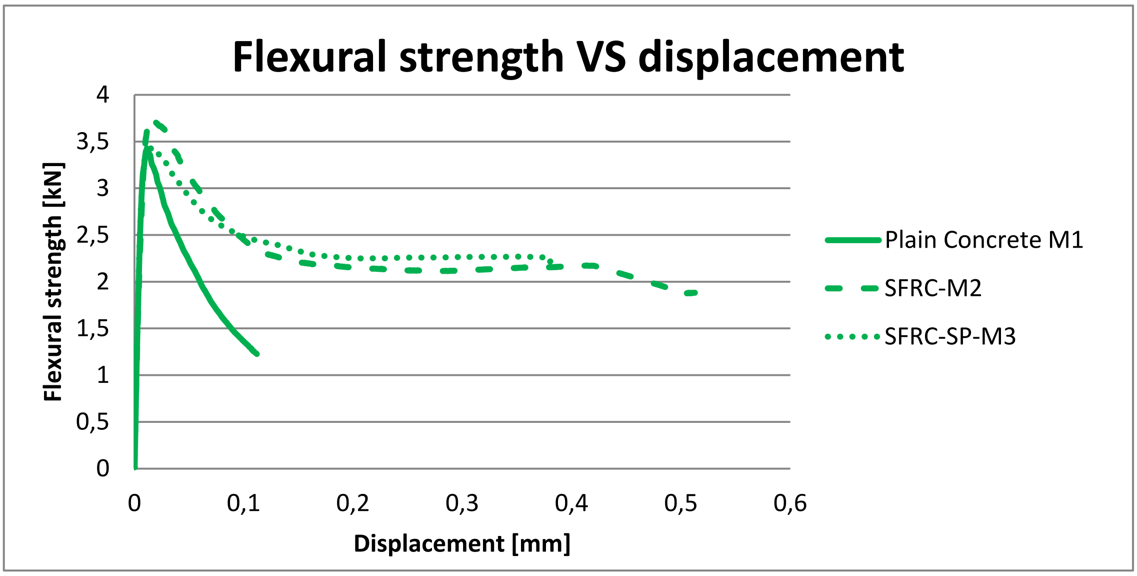


Figure 33: Flexural strength vs displacement curve obtained by the 3-point bending test of SFRC-SP-M3 compared with mixtures of phase 1.

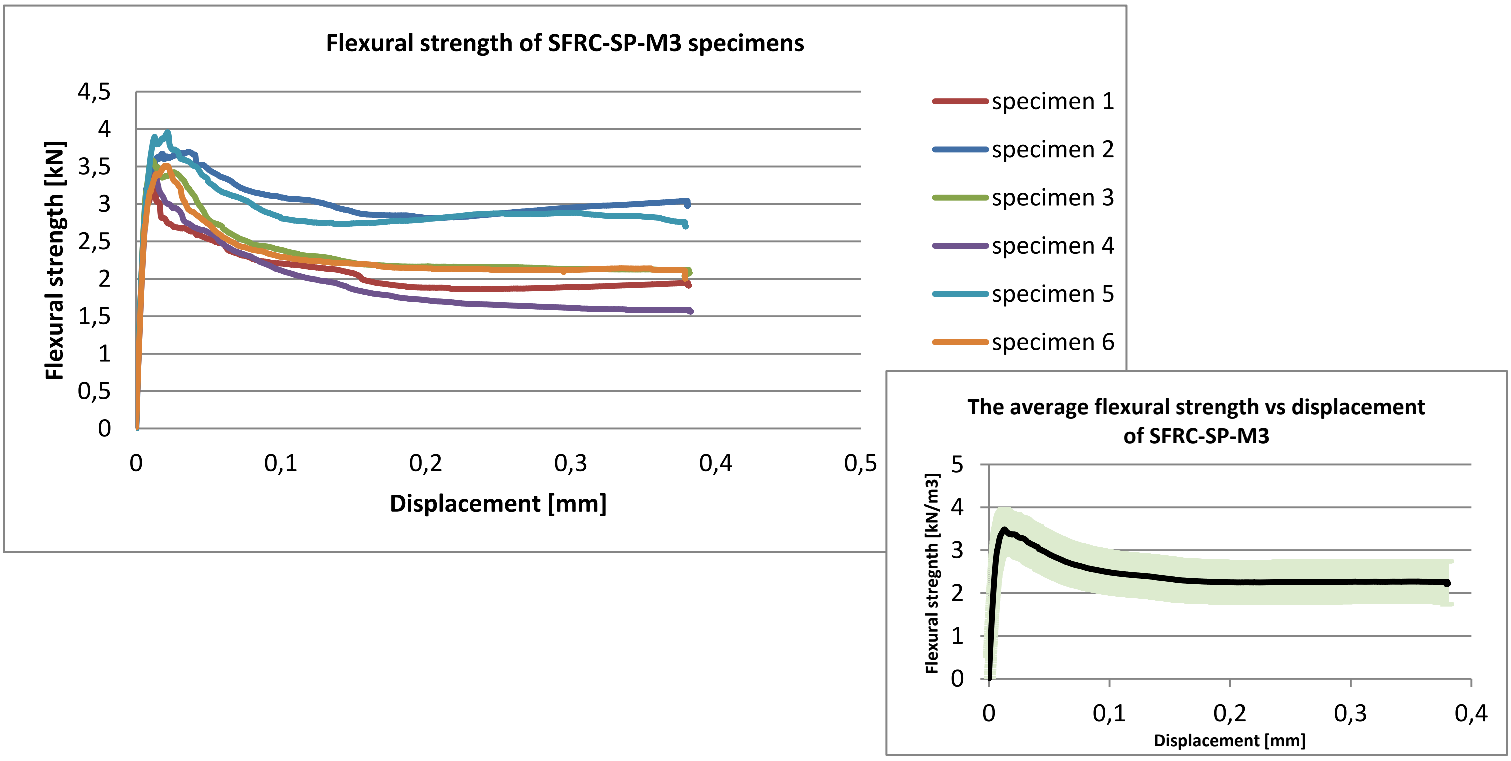


Figure 34: **Left***:* Flexural strength vs. displacement curves obtained by 3-point bending test of all SFRC-SP-M3 specimens and **Right:** the average of the six tested specimens that will be used for the comparison of all mixture.

Discussion and conclusions of phase 2

Reducing the water content and the addition of SP during the preparation phase increased the workability but had negative consequences on the mechanical strengths of SFRC in the hardened state. The results of the three tests given in Table 4 express the strong link between the concrete composition and strengths. It gives an indication of how adjusting the concrete composition can negatively or positively affect the final performance of SFRC.

- ***Fresh state***

By the addition of SP, the workability extremely increased and the consistency of this mixture passed the upper limit of the prescribed consistency class S4. It belongs to higher consistency class (S5), which was not the goal of the experiment.

The observed increase of the mixture workability was the main reason to decrease the water content, which led to deviating from the concrete recipe. The reduced water content was not replaced with other material rather than air, which results in higher air content and entrapped air in the concrete matrix. The air content of reference SFRC-M2 was 1.4% while the air content of SFRC-SP-M3 increased to 2.4%.

- ***Hardened state***

The higher porosity and air content of the concrete matrix undoubtedly led to the decrease of the mechanical strengths compared to reference SFRC-M2. The average compressive and splitting tensile strength decreased by respectively 11% and 18%. Even the average flexural strength showed a decrease as well.

Even by comparing the mechanical strengths of SFRC-SP-M3 with plain concrete M1, there is a decrease in the compressive strength. And the improvement of the splitting tensile and flexural strength is negligible. This means, the optimization of the compressive and splitting tensile strength of the reference SFRC-M2 in phase 1 may not completely relate to the fibre addition, but to the concrete quality and good cooperation between the steel fibres and the concrete matrix.

Reflecting on the literature review (Chapter 3), the microstructure and porosity of the concrete matrix should be affected by the steel fibres. Based on the results and observations of phase 1 and 2, it can be concluded that the increase of air content depends on the concrete composition, production and compaction procedure rather than the fibres addition.

The comparison of the experiment data's in phase 1 and 2, based on the small number of specimens, highlights the important role and contribution of the concrete composition and quality on the mechanical strengths of SFRC.

SFRC-SP-M3 represents a scenario of low concrete quality that has been mixed with the same fibres content as reference SFRC-M2, where the reference SFRC-M2 showed better properties and mechanical strengths than SFRC-SP-M3.

Despite the negative effects of composition adjustment on the mechanical behaviours, the higher workability of the mixture seems to affect the dispersion of fibres in the prism and its ductility. By using the average of the 3-point bending test, the fracture energy of the three mixtures has been calculated by the formula:

Gf= (W0+ m*g*δ0)/ Alig [1]

W0= area under the load displacement curve [kN/mm]
m= m1+m2
m= weight of the beam between the supports [kg]
g= acceleration due to gravity (9,81 kg/s^2)
δ0= deformation at the final failure of the beam [mm]
Alig= effective cross section of beam [(h-a)*b] [mm^2]

Formula 1: Fracture energy equation.

By filling in Formula 1, the fracture energy of the three mixtures has been calculated and given in Table 5. The fracture energy has been calculated by a displacement of 0.35mm. For the plain concrete M1, the curve has been extrapolated:

	Fracture Energy G [kN/mm]
Plain concrete M1	3.6
Reference SFRC-M2	3.8
SFRC-SP-M3	3.8

Table 5: Fracture energy of plain concrete M1, reference SFRC-M2 and SFRC-SP-M3.

Conclusions of phase 2

''What are the benefits of increasing the mixture workability of SFRC?''

- Adjusting the concrete composition in the fresh state strongly influences the mechanical behavior of SFRC in the hardened state.
- The fracture energy of SFRC calculated at a displacement of 0.35mm is not affected by adjusting the concrete composition.
- Adding steel fibers to improperly prepared concrete mixture may be an unworthy investment because the concrete quality affects the cooperation between steel fibers and concrete matrix.

4.3 Experiment of phase 3

Experiment accomplished in phase 2 demonstrated the first example of modifying the concrete composition and its effects on the performance of SFRC. The results showed how the concrete quality and high porosity negatively affected the strengths.

The literature review (Chapter 3) emphasizes on the densification of the concrete matrix to reduce the ITZ and enhance the bond strength between the steel fibres and concrete. This concept touches the goal of this research. By determining how the concrete composition can be adapted to optimize the behaviour of SFRC, this composite material will be used in an effective way, this will help designers of SFRC structural elements in the practice.

Hence, the focus of this phase will be on densifying the concrete matrix. According to the literature review, there are various possibilities for concrete densification. But due to the scope and the goals of this research to come up with an optimized mixture applicable alternative in the practice the options are limited.

Figure 35 demonstrates the main ingredients and parameters that can be adjusted to change the concrete composition by preserving its strength class. As mentioned earlier, the concrete mixture used for SFRC is in the practice selected based on the strength class and price. Therefore, the compressive test has been used as tool to control the concrete strength and the price of the adjustment has been considered by choosing the densification options.

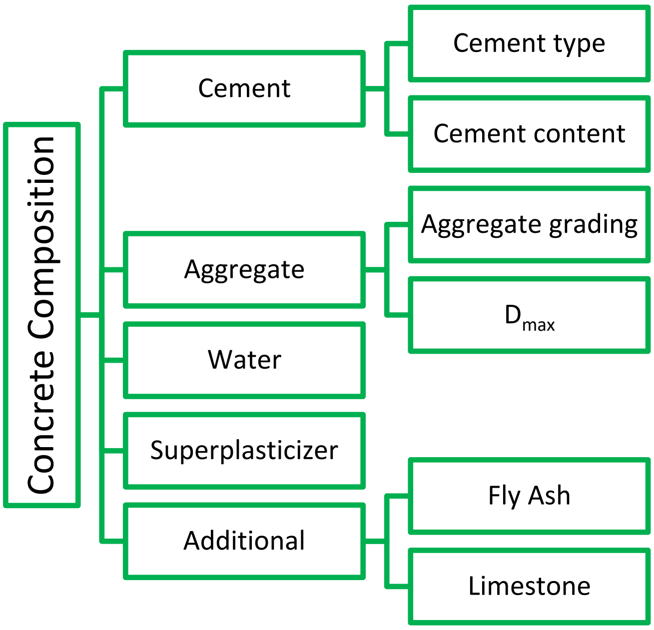


Figure 35: Ingredients and concrete parameters that can be modified in phase 3.

The most important concrete ingredient is cement, changing the cement type does not seem to have a considerable effect on the strengths of SFRC. In the literature studies, the authors used cement type CEM I while in phase 1 & 2 of this research a mix of CEM I & III was used. Using one type of cement or combing CEM I with CEM III did seem to have an impact on the results. The measured strengths in phase 1 and 2 were comparable with the literature strengths.

Increasing the cement content and decreasing w/c ratio are advisable options in the literature to densify the concrete matrix. But cement is an expensive material and increasing the cement content is not a desirable option for the practice. Further by increasing the cement content, attention should be given to w/c ratio. To preserve the strength class C30/37 the water content should be adapted, otherwise, the strength will increase.

Changing the cement type and increasing cement content were not the most interesting alternatives to achieve the goals of this research. Therefore they not considered as options for this phase.

Aggregate is another concrete ingredient that can be adjusted in different ways as discussed in the literature review (3.2.1). In the practice, it is preferable to use large grain size to reduce the price of the mixture. Decreasing the maximum grain size (Dmax) requires higher fine material content and more water which will be paired with an increase of the cement content.

The D_{max} used for SFRC mixtures in the practice can go up to 32mm. This is in contrast to the literature review (3.2.1), where it is recommended to use smaller D_{max} because large grains will hinder the fibres dispersions. Even the fibres will not be completely surrounded by the concrete matrix. This was also the case in the practice. During a visit to a project in Rotterdam, where SFRC was combined with conventional reinforcement, it was observed that large grain particles were not properly integrated and mixed with the steel fibres (Figure 36).

In this mixture the D_{max} was 32mm, the large grain particles were easy to spot during the execution. In fact, the figure does not show the final layer of SFRC. More layers will be poured and vibrated, which may redistribute the aggregate grains and steel fibres.

Still, using large grains is risky when it comes to the fibres distribution and integration of fibres with concrete. As shown in Figure 37, a spot of stacked steel fibres was detected underneath the conventional reinforcement. Definitely, the stacking of fibres will lead to variation in the mechanical strengths of SFRC over the whole span of the realised floor.

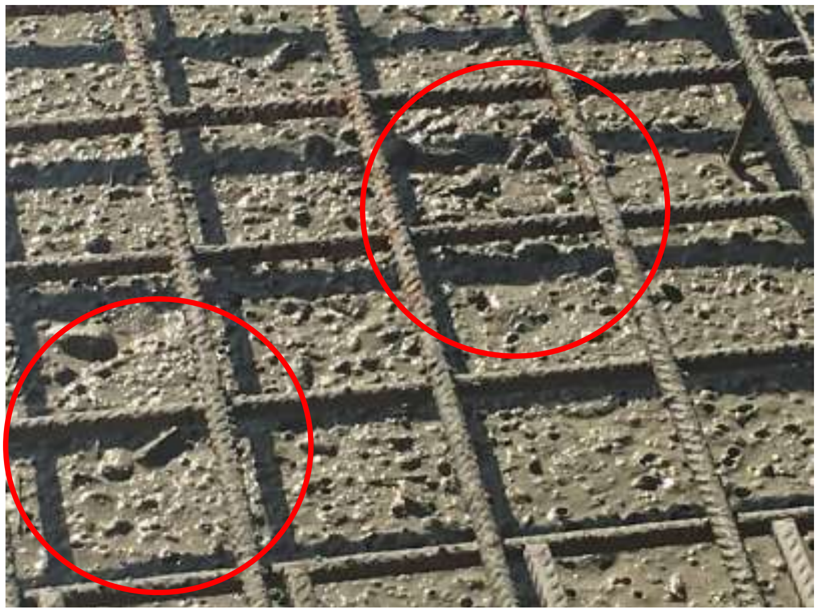


Figure 36: Examples of SFRC combined with conventional reinforcement in the practice.

Figure 37: Example of SFRC casted in the practice where the steel fibers are stacked at one zone.

The maximum aggregate grain size used in this research is 16mm. This is the maximum grain size available at the laboratory of the university. Therefore it was not possible to design SFRC mixture with D_{max} of 32mm to compare it with reference SFRC-M2 to confirm the side's effects of large grain particles.

Designing concrete mixture with D_{max} smaller than 16mm did not seem an applicable option for the practice. As mentioned earlier, reducing D_{max} will be paired with the increase of fine material (sand), water and cement content, hence the mixture price will increase.

Another parameter of aggregate that can affect the behaviour of SFRC, is the aggregate grading. As reported by other authors [3], modifying the aggregate grading and (slightly) increasing the fine sand proportion will change the concrete microstructure. ITZ becomes denser and the steel fibres will be surrounded by the concrete matrix which will optimize the stress transfer between steel fibres and concrete matrix.

In mixture SFRC-F-M4, the aggregate grading has been adjusted to study the influence of densifying the concrete matrix by enlarging the percentage of fine material on the final SFRC mechanical behaviours.

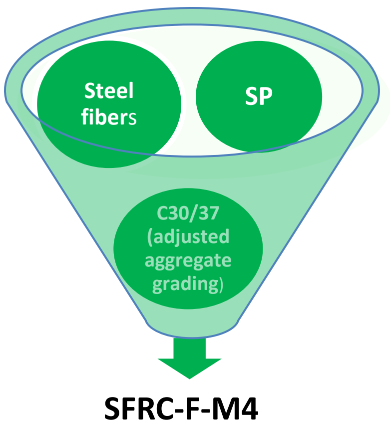


Figure 38 presents the aggregate grading curves of mixture SFRC-F-M4 versus the aggregate grading curve of SFRC-M2. At the beginning of the curve, the amount of fine aggregate is slightly increased compared to the reference SFRC-M2.

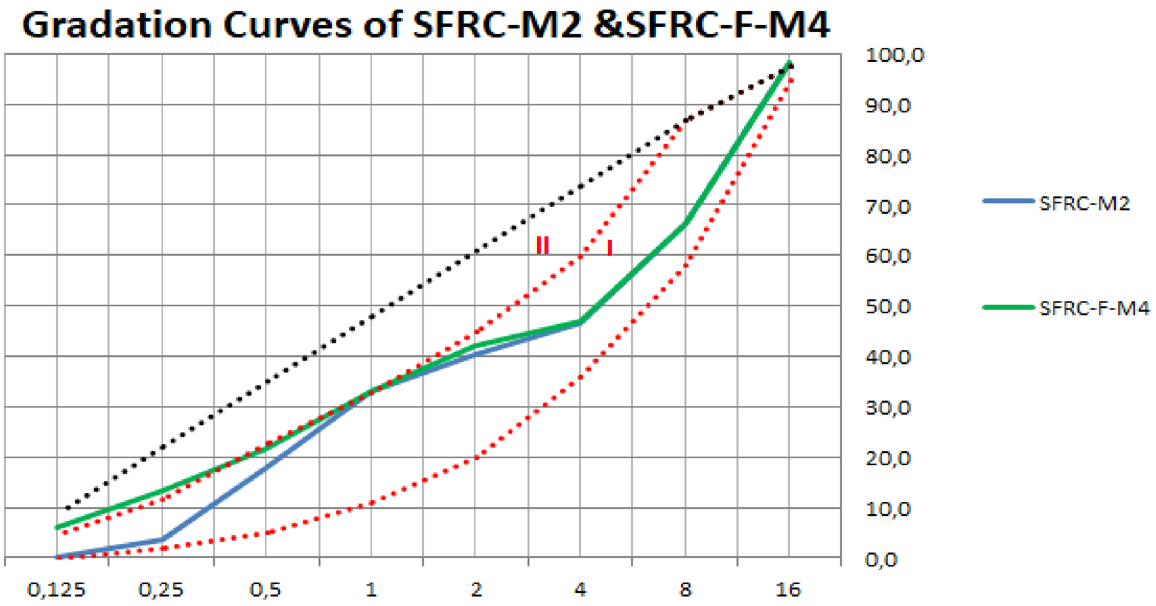


Figure 38: The gradation curves of SFRC-M2 (blue line) and SFRC-F-M4 (green line).

It is well known that by increasing the fine material content, the water content should be increased to maintain the consistency of the mixture. But again to preserve the w/c ratio and concrete strength class, the cement content was adjusted as well. Hence this mixture contained more cement and fine material than the previous mixtures.

One more alternative to increasing the fine material content in concrete is the addition of fillers. The most common fillers are limestone powder and silica fume. For mixture 5, it was decided to replace a small proportion of coarse aggregate with limestone powder to densify the concrete matrix. As the small replacement of limestone powder will not enormously increase the price of the mixture.

To determine the effect of increasing the fine material content, the same tests approaches have been followed as in phase 1 & 2 in, order to compare the properties and mechanical strengths of the new mixtures with the reference SFRC-M2.

Besides the mechanical tests, polished sections were prepared for the microscopic analysis. The comparison of the microscopic images of the reference SFRC-M2 with the images of SFRC-F-M4 and SFRC-LM-M5, will give an idea about the optimization of the interface by densification. It may also illustrate the link between the SFRC microstructure and the mechanical strengths.

Concrete compositions of SFRC-F-M4 and SFRC-LM-M5 are given in Table 6:

	w/c	CEM I [kg]	CEM III [kg]	Fly ash [kg]	fine aggregate [0-4mm]	Coarse aggregate [4-16mm]	Fiber [kg/m^3]	Additional
SFRC-M2	0.5	98	280	20	828	905	35	
SFRC-F-M4	0.5	110	311	20	766	869	35	
SFRC-LM-M5	0.5	98	280	20	828	885	35	20kg LM

Table 6: The mixtures compositions of SFRC-F-M4 and SFRC-LM-M5.

The measured slump of reference SFRC-M2 in phase 1, confirmed the decrease of workability by the fibre addition. While in phase 2, it was concluded that less than 0.3% SP was enough to achieve an acceptable workability for the used concrete composition C30/37 and fibres content.

Changing the concrete composition by increasing the amount of fine material is another reason leads to a decrease in the workability. To avoid the issue happened in phase 2 and adding more SP than required, a trial mixture of 10l was prepared to measure the workability of mixtures 4 & 5. Based on the measured slump of the trial mixture, a certain percentage of SP has been added to the larger batch.

The measured slump of the trial mixture (10l) prepared with SFRC-F-M4 was 170mm (Figure 39). This satisfies the required consistency class S4 given in the scope of this research. But it is again at the lower side of the consistency class. Actually, the trial mixture showed adequate workability to cast.

The next question was if mixing larger volume (85l) will result in the same workability. After preparing and mixing the larger volume of SFRC-F-M4, the workability was measured. Unexpectedly, the workability of the larger volume (85l) increases to 190mm without the addition of SP (Figure 39). This may be related to the concrete volume as the larger amount of cement paste compared to the previous mixtures.

Figure 39: Slump tests of SFRC-M4; trial mixture (left) and larger volume (right).

Replacing 20 kg/m^3 of coarse aggregate by limestone powder led to enormous workability decrease for SFRC-LM-M5, this in contrast to SFRC-F-M4. The measured slump of the trial mixture was 50mm (Figure 40). In steps of 0.1% of the cement volume, SP has been added to the mixture. This time SP was not mixed with water but added separately at the end. The obtained workability was 190mm (Figure 40) by adding 0.2% SP.

Figure 40: Slump tests of SFRC-LM-M5; trial mixture (left) and larger volume (right)).

Adjusting the aggregate grading and increasing the cement paste showed a decrease of air content in mixture SFRC-F-M4 (Table 7). On the other hand, the air content of SFRC-LM-M5 increased compared to the reference SFRC-M2 from 1.4% to 2.3%. Thus increasing the fine material content did not ensure decrease of air content because the air content depends on the production and compaction procedure as the composition.

Results of the experiment in phase 3

Similar to phases 1 & 2, the cubes and prims prepared with SFRC-F-M4 and SFRC-LM-M5 were tested after 28 days of the casting date. The tests results of both mixtures as plain concrete M1 and reference SFRC-M2 are given in Table 7:

	Plain concrete-M1	**SFRC-M2**	**SFRC-F-M4**	**SFRC-LM-M5**
Compressive strength	47.6 (1.5)	51.3 (2.4)	54.0 (3.1)	56.7(1.5)
Splitting Tensile strength	3.7 (0.1)	4.6 (0.5)	4.6 (0.3)	4.6(0.4)
Flexural strength	3.4 (0.2)	3.7(0.5)	3.7 (0.5)	4.3(0.3)
Slump	180mm[0% SP]	170mm[0% SP]	220mm [0% SP]	190mm[0.2% SP]
Air content	2%	1.4%	1.1%	2.3%

Table 7: The measured properties and strengths (& standard deviation) of phase 1 & 3.

There is almost no difference between the mechanical strengths of the reference SFRC-M2 and SFRC-F-M4. Splitting tensile and 3-points bending tests of SFRC-F-M4 showed the same strengths as reference SFRC-M2. Only the compressive strength of SFRC-F-M4 increases. The increase of the compressive strength, obviously this is related to the compacter concrete matrix and lower air voids. The failed specimens of SFRC-F-M4 after the compressive and splitting tensile tests demonstrated a similar crack pattern (Figure 41) as the specimens tested in phase 2.

In phase 1 & 2 the addition of steel fibers to specimens of reference SFRC-M2 and SFRC-SP-M3 enhanced the ductility and showed strain softening behaviour. Only the specimens differed in the maximum flexural strength achieved and the post-cracking curve.

In the specimen's of phase 3, the result of the 3-points bending test varied on another level. Specimen 3 of SFRC-F-M4 was a scatter and showed a strain hardening behaviour instead of strain softening. The rest of the tested specimens demonstrate softening behaviour, where 3 specimens failed at the end of the test.

Specimen 3 was a scatter and performed uniquely than the other specimens, it did not accurately represent the post-cracking behaviour of this mixture. Therefore it was not included in the average value of the flexural strength and curve given in Table 7 and Figure 42.

There was a variation in the post-cracking behaviours in the specimens of SFRC-LM-M5 as well. Specimen 1 failed in 10 seconds, on the other hand, specimen 3 was very strong and its strength passed the maximum load of the apparatus without cracking. The test stopped immediately and the LVDT were reset to try a second run. Again the strength reached the maximum load capacity without any crack formation.

Hence, the complete data and post-cracking curves of these specimens were missed as shown in Figure 44. Therefore specimen 1 and 3 are not included in the average flexural strength and flexural strength vs. displacement curve of SFRC-LM-M5.

Figure 41: **Top:** SFRCS-F-M4 specimens: 1&2) after the compression test 3&4) after the splitting tensile strength. **Below:** SFRCS-LM20-M5 specimens: 1&2) after the compression test 3&4) after the splitting tensile strength.

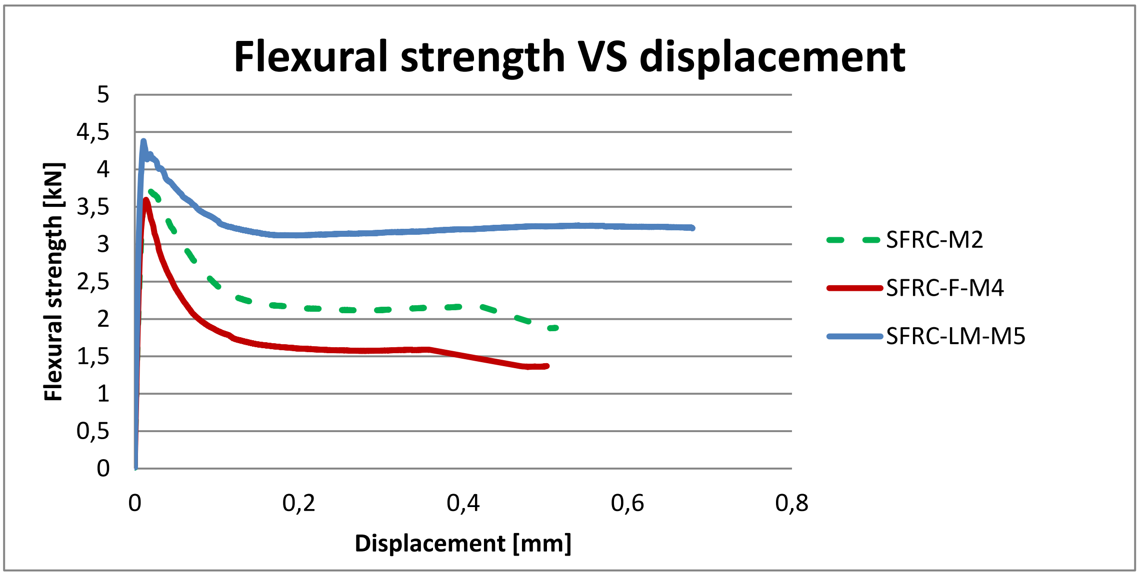


Figure 42: Flexural strength vs. displacement curves obtained by the 3-point bending test of reference SFRC-M2, SFRC-F-M4 and SFRC-LM-M5

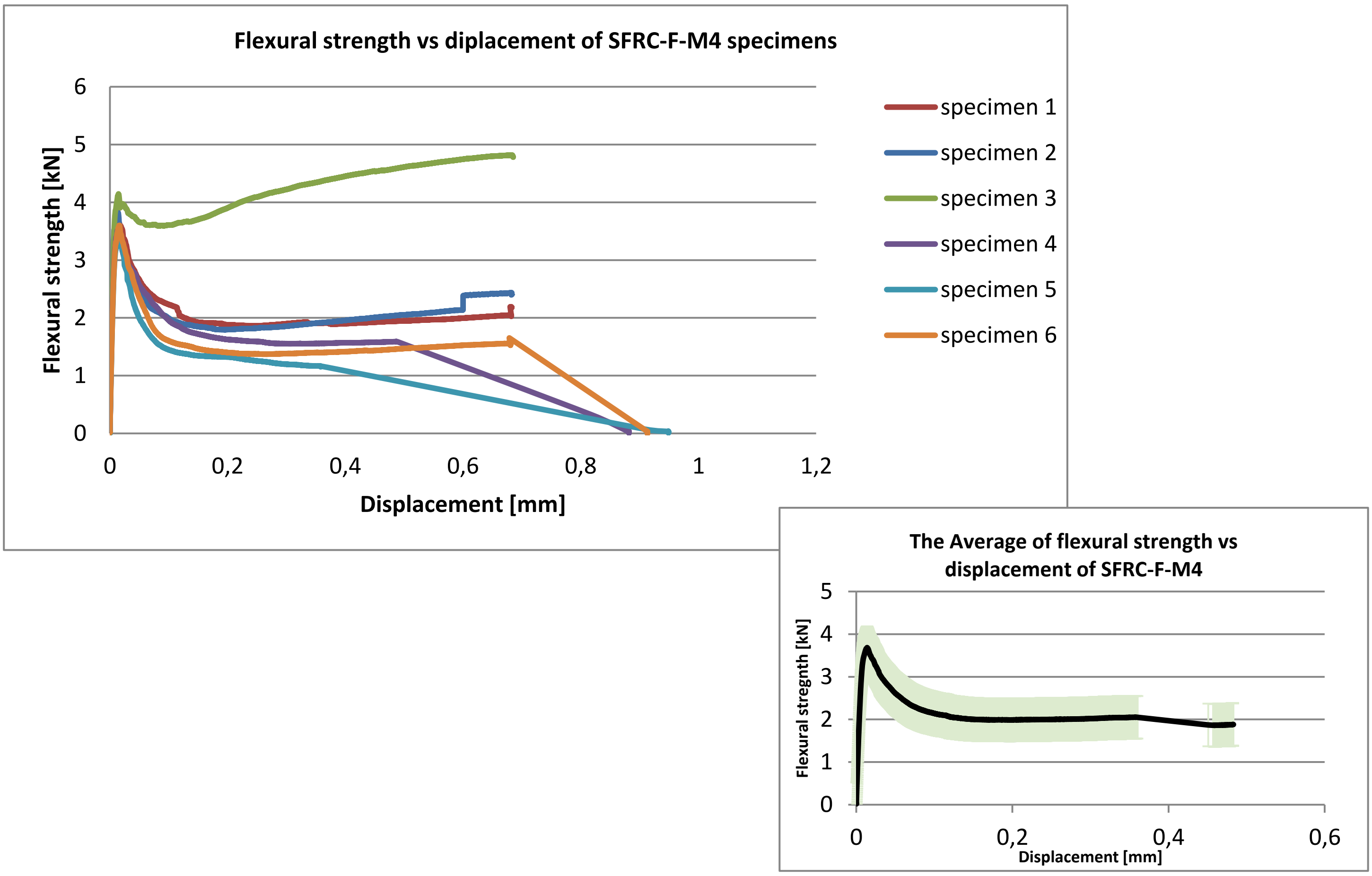


Figure 43: **Left**: Flexural strength vs. displacement curves obtained by 3-point bending test of all SFRC-F-M4 specimens and **Right:** the average of the five specimens excluding the scatter specimen 3.

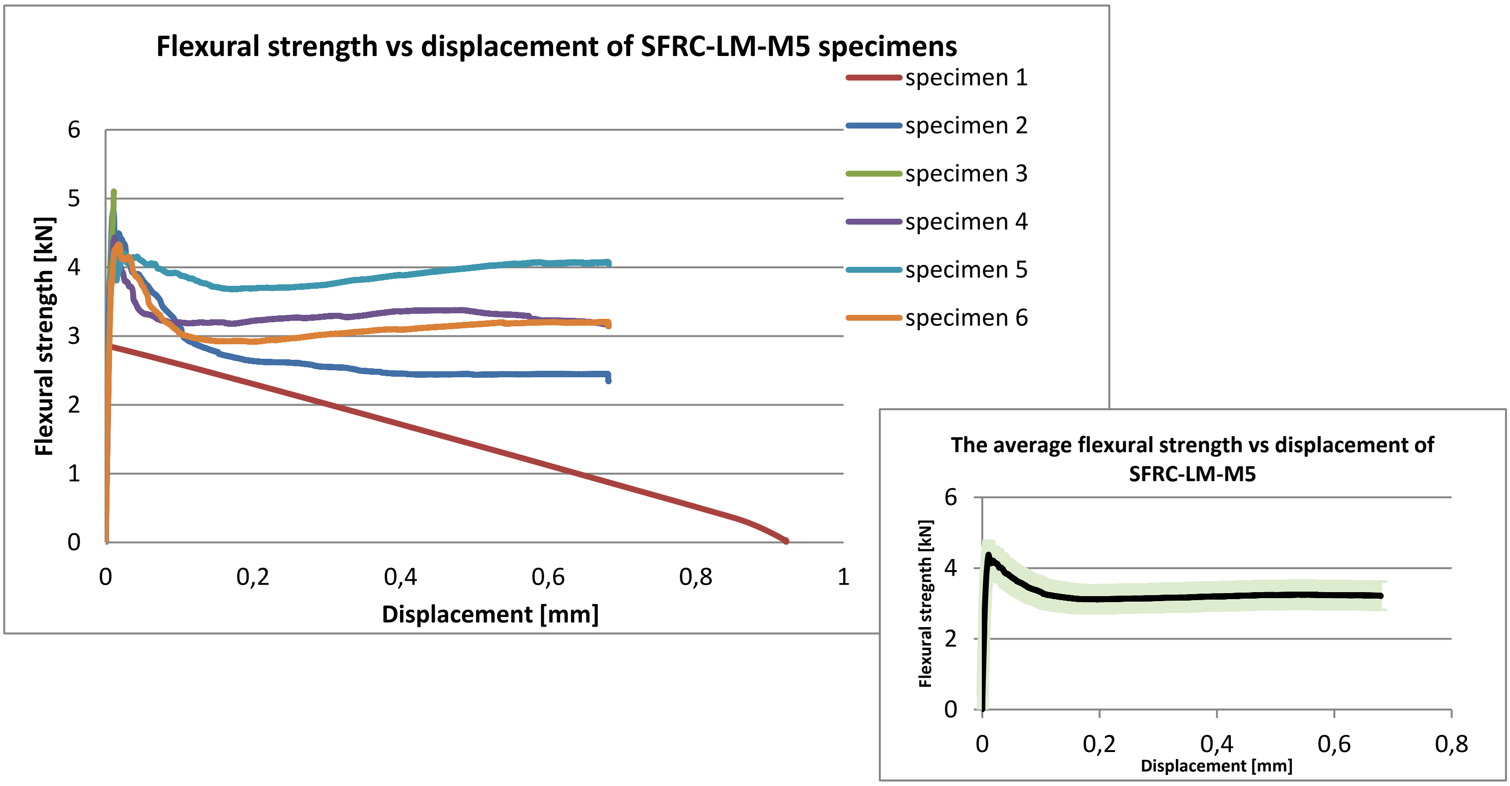


Figure 44: **Left:** Flexural strength vs. displacement curves obtained by 3-point bending test of all SFRC-LM-M5 and **Right:** the average of the four specimens that passed the test excluding specimen 1 & 3.

Discussion and conclusions of phase 3

- ***Fresh state***

The adjustment of the concrete composition showed two different slump results. In the first situation, the modification of the aggregate grading and increase of material content in SFRC-F-M4 did not alter the workability. The measured slump of the trial mixture as the large volume satisfied the workability requirement of the research (Figure 45).

The second situation is the addition of filler to SFRC-LM-M5, which shows a fast decrease in workability. Addition of SP was a must for this mixture, it was stiff and difficult to cast with its original workability.

Figure 45: SFRC-F-M4 (left) and trial mixture of SFRC-LM-M5 (right) in fresh state.

As shown in Figure 45, the mixture was not homogenous at all and the fibers were not properly integrated into the concrete matrix. And in contrary to the expectations, the air content increases to 2.3% due to the lower consistency which affected the compaction.

- ***Hardened state***

The modification of the concrete composition in SFRC-F-M4 had a positive effect on the mixture properties in the fresh state and the workability increases. In the hardened state, the adjustment of the aggregate grading showed an increase of the compressive strength by 5%. The splitting tensile and flexural strength did not show any improvement compared to the reference SFRC-M2. Only the specimens which passed the two runs of the 3-point bending test reached a larger displacement than the reference SFRC-M2. This is an improvement is not recognizable in the average flexural strength vs displacement curve of this mixture (Figure 43) because of the other three specimens failed at the end of the test as specimen 3 was not included.

Specimens of SFRC-F-M4 showed three post-cracking behaviour at the 3-point bending test (Figure 43). Specimen 3 demonstrated the ideal performance and a strain hardening behaviour. The flexural strength slightly decreased when the concrete matrix cracked but then increased again. Specimen 1 & 2 showed a strain softening behaviour and the last 3 specimens failed at the end of the test.

The variation in the post-cracking behaviour is similar to the case in phase 2. Strain hardening of specimen 3 may be related to the fibres content, dispersion and orientation in this specimen. To check this assumption, specimen 1& 3 were hit by a hammer to get insight about the difference of the fibres distribution and content at both cross sections.

Before breaking the specimens, the crack pattern and crack width of the first three specimens were compared. In Figure 46, are the three specimens given where specimen 1 and 2 have almost a straight crack pattern and comparable crack width. In specimen 3, the crack initiated above the notch but did not follow the same path as the other specimens this may be due to steel fibres located at that point which blocked the crack. Even the crack opening is smaller in this specimen.

Figure 47 shows the broken parts of specimens 1 and 3. Obviously, the fibres were all horizontally situated at the cross-section and located very close to each other at the upper part of specimen 3, the massive fibres content made this specimen stronger and increased its ductility. This may be the reason of thinner crack opening and strain hardening behaviour.

Figure 46: The crack pattern of SFRC-F-M4 specimen after the 3-point bending test.

Figure 47*:* **Left:** the cross-section of specimen 1, **Right*:*** cross-section of specimen 3 of SFRC-F-M4.

Moreover, the comparison of the failed cross-sections of specimens 4 & 5 (Figure 48) at the end of the test indicated that the fibres content was smaller than specimen 3. Although the fibre parameters (dispersion, orientation, etc.) fall outside the scope of this research, it is clear that the fibres content and distribution in the prisms control the post-cracking behaviour.

Figure 48: **Left:** The cross-section of specimen 4, **Right*:*** cross-section of specimen 5 of SFRC-F-M4.

The higher slump obtained in this mixture did not seem to affect the flowability and fibres distribution during casting. However, more experiments and specimens are needed to confirm the relationship between the higher workability and fibres dispersions.

Based on the mechanical tests results of SFRC-F-M4, the chosen aggregate grading did not highly optimise the mechanical behaviours. But, there are infinite possibilities to design aggregate grading curve which may optimise the mechanical strengths. Hence the results of this experiment don’t clarify to exclude this tool to densify the concrete and improve SFRC behaviour.

The small replacement of coarse aggregate by limestone powder optimised the SFRC behaviours as given in Table 7. The average compressive strength increased by 10% and flexural strength by 16% in respect to the reference SFRC-M2. The splitting tensile strength is not affected but maintained the same strength as the reference SFRC-M2.

Mechanical strengths of SFRC-LM-M5 were optimized with respect to SFRC-SP-M3, while in both mixtures the air content increased compared to reference SFRC-M2. The higher fine material content in SFRC-LM-M5 compensated the air voids during hardening state as it can be related to the synergetic effect and chemical reaction of all concrete ingredients (cement, fly ash, limestone powder and aggregate). To specifically define the contribution of limestone powder more experiments are needed.

The 3-point bending test results showed softening behaviour after the crack development. With the exception of two specimens, specimen 1 that immediately failed and specimen 3 which passed the maximum load capacity of the apparatus. The explanation of the test results is according to phase 2 and mixture SFRC-F-M4 the difference in fibres content and distribution at the cross section where the notch is situated.

To confirm this explanation, both specimens were hit by hammer until they were completely opened. The cross-sections of both specimens are presented in Figure 49. At cross-section of the failed specimen there are almost no fibres, while the other specimen contains more fibres.

Figure 49: **Left**: the cross-section of the failed specimen of SFRC-LM-M5, **Right:** the cross-section of the strong specimen SFRC-LM-M5.

However the displacement at the end of the 3-point bending test increases which is related to the ductility of the mixtures. The fracture energy of both mixtures has been calculated at the same displacement as in phase 3 to make a comparison with reference SFRC-M2 (Table 8).

	Fracture Energy G [kN/mm]
Reference SFRC-M2	3.8
SFRC-F-M4	3.6
SFRC-LM-M5	3.9

Table 8: Fracture energy of reference SFRC-M2, SFRC-F-M4 and SFRC-LM-M5.

Conclusions of phase 3

"What are the critical concrete ingredients and parameters that may enhance the behavior of SFRC?"

- Adjusting the gradation curve optimized the compression strength, while the splitting tensile and maximum flexural strengths remain similar to strengths of reference SFRC-M2.

- Increasing the cement paste content positively affects the workability.

- Densification of the concrete matrix by adjusting aggregate grading and increasing the fine material content may be a useful measure but require more experiment to test different grading curves in order to find out the most optimal one.

- The differences in post-cracking behavior showed by the six specimens of SFRC-F-M4 indicated that the fibers content varies in each specimen. There is a strong relationship between the fibers numbers and distribution at the cross section above the notch and the post-cracking behavior.

- The small replacement of coarse aggregate with limestone powder positively influenced the mechanical behavior of SFRC. Compression and flexural strength increased by respectively 10% and 16% as it optimized the displacement and fracture energy.

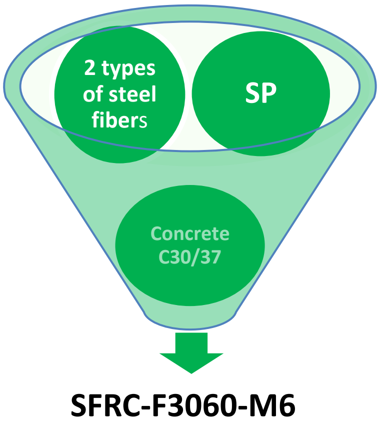
- Despite the dominant effect of the fibers distribution in the specimen, it can be concluded that the adjustment of the concrete composition affects the SFRC behavior. By a low-quality concrete matrix (SFRC-SP-M3) the mechanical strengths decreased whereby another adjustment (limestone powder) optimized the mechanical behavior of SFRC.

- Synergetic effect and chemical reactions of the concrete ingredients should be considered as well, the optimization by the limestone powder may be related to the cooperation of all mixture ingredients.

4.4 Experiment phase 4

The concrete matrix is brittle and by the appearance of the first micro-cracks, the concrete matrix starts losing its strength. The advantage of steel fibres addition is the decrease of crack propagation and limitation of crack openings.

The concept hybrid fibres by combining two sizes of steel fibres discussed in the literature review will be implemented in this phase. The extra added short fibres of 30 mm will hinder the micro-cracks that develop in an early stage of the hardening process. By limiting the micro-cracks propagation, the matrix will maintain its stiffness for a longer time and delay the de-bonding between the concrete matrix and the longer fibres (50mm). The effect of short fibres on the behaviour of SFRC will be studied in this phase.



The long fibres used for this mixture SFRC-F3060-M6 are exactly the same fibres used in the previous experiments. The shorter fibres added in this experiment are also hooked fibres and provided by Metal Products (Figure 50).

Figure 50: Steel fibers provided by Metal Products used for the experiment.

The composition of this mixture is similar to the reference SFRC-M2, only the aggregate content was adjusted due to the short fibers addition. The composition of SFRC-F3060-M6 is given in the Table 9:

	w/c	CEM I [kg]	CEM III [kg]	Flyash [kg]	fine aggregate [0-4mm]	Coarse aggregate [4-16mm]	Fibre [kg/m3]	Additional *(micro fibres 30mm)*
Reference SFRC-M2	0.5	98	280	20	828	905	35	
SFRC-F3060-M6	0.5	98	280	20	804	907	32	17.5

Table 9: The mixture compositions of SFRC-F3060-M6.

The hybrid fibres and increasing the total fibers content in SFRC-F3060-M6 led to a tremendous decrease in the workability. The measured slump of the trial mixture was 10mm. Figure 51 shows the stiff and inhomogeneous cone, such mixture is very difficult to cast and will result in a terrible SFRC quality in the hardened state. The steel fibers will be stacked at one zone and will not spread in the structure.

To obtain a workable mixture, SP was required to bring the mixture consistency to an acceptable level. SP was not mixed with the water but added at the end in steps of 0.1% SP, the measured slump by 0.2% SP was 210mm (Figure 51). Additionally, the air content decreases with respect to the air content of the reference SFRC-M2.

Figure 51: **Left**: Slump test of SFRC-LM-M6 trial mixture and a close-up on the gaps in the slump, **Right:** the slump of the larger volume after adding SP.

Results of the experiment in phase 4

The mechanical tests results of SFRC-F3060-M6 were compared with the reference SFRC- M2. The average strengths of the three tests are given in Table 10. Hybrid fibres did not optimize the mechanical strength relative to the reference SFRC-M2. All the measured strengths remain more or less constant while the post-cracking behavior improved.

	Plain concrete-M1	SFRC-M2	SFRC-F3060-M6
Compressive strength	47.6 (1.5)	51.3 (2.4)	50.3(1.6)
Splitting Tensile strength	3.7 (0.1)	4.6 (0.5)	4.7 (0.7)
Flexural strength	3.4 (0.2)	3.7(0.5)	3.9 (0.2)
Slump	180mm	170mm[0% SP]	210 mm [0.2% SP]
Air content	2%	1.4%	1.2%

Table 10: The measured properties and strengths (& standard deviation) of phase 1 & 4.

The cubes specimens were relatively more damaged and cracked after the compressive and splitting tensile strength as shown in Figure 52. While the mean flexural strength did not giant increases by combining two types of stee fibres, the crack pattern and displacement were enhanced (Figure 53). Post-cracking behaviour and ductility were optimized compared to the reference SFRC-M2 (Figure 54). All of the prisms passed the 3-point bending test and there was no failed specimen, as one of the specimens showed a strain hardening behavior (Figure 55).

Figure 52: Failed pattern of SFRC-F3060-M specimens after compression en splitting tensile test.

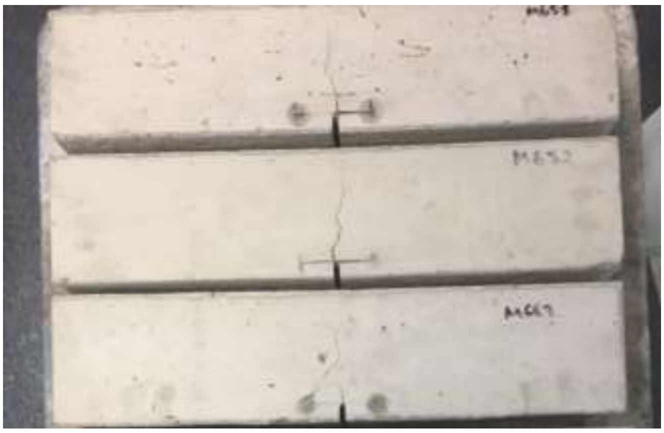


Figure 53: The crack pattern of SFRC-F3060-M6 prisms after the 3-point bending test.

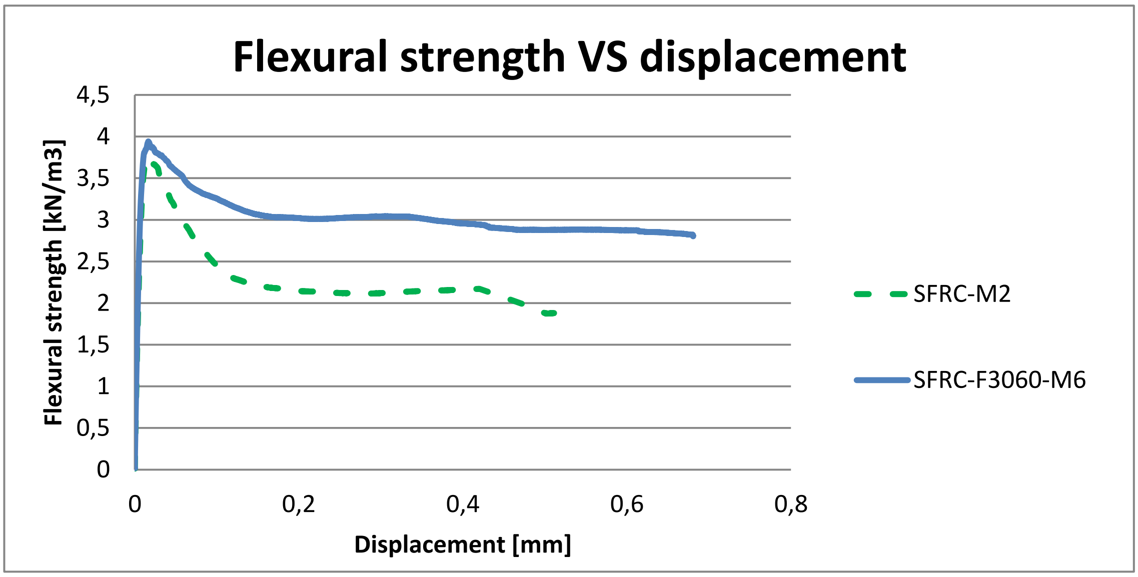


Figure 54: Flexural strength vs. displacement curves obtained by the 3-point bending tests of reference SFRC-M2 and SFRC-F3060-M6.

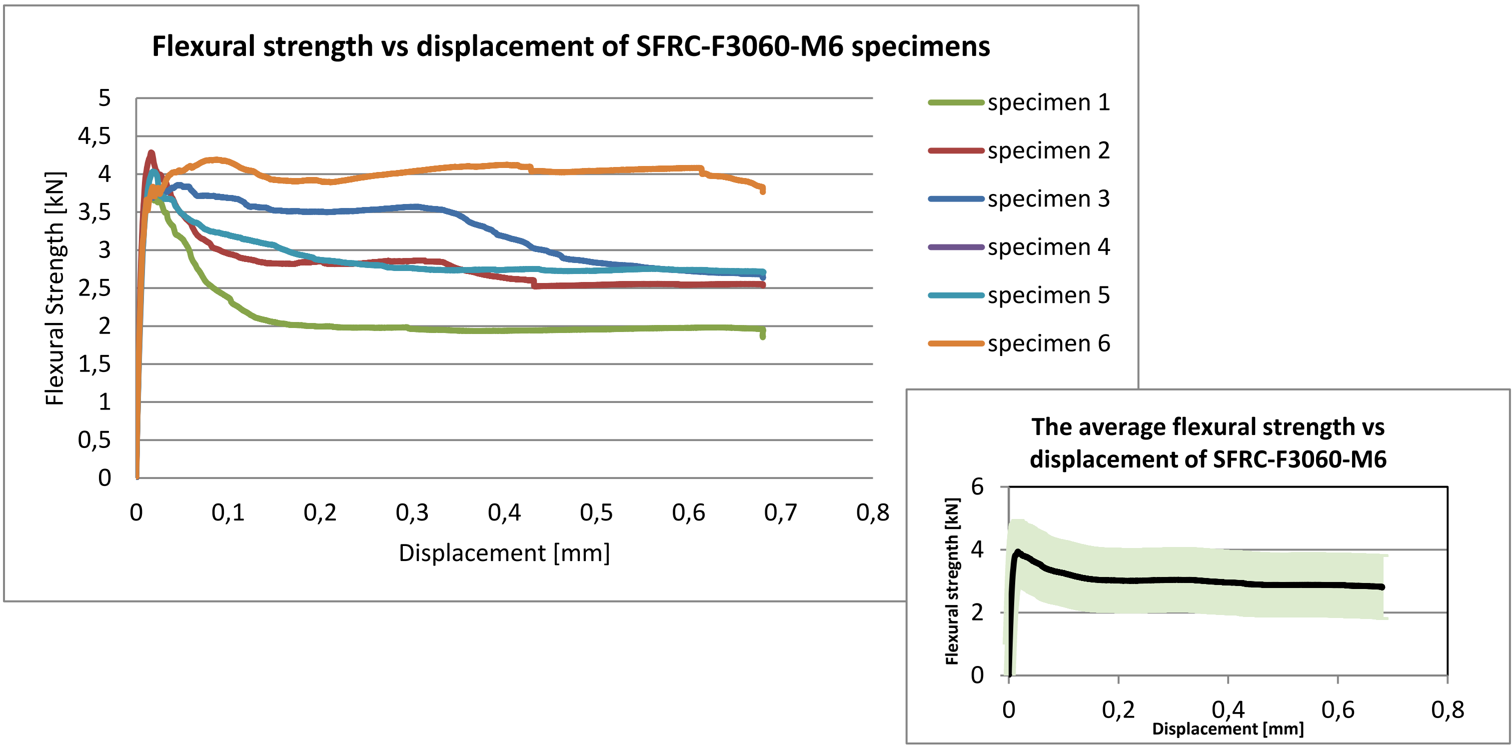


Figure 55 **Left:** Flexural strength vs. displacement curves obtained by 3-point bending test of all SFRC-F3060-M6 and **Right:** the average of the six tested specimens.

Discussion and conclusions of phase 4

- ***Fresh state***

The trial mixture containing two types of fibres was very hard to cast without SP. This was expected because phase 1 already confirmed the decrease in workability by small fibres concrete. Hence by increasing the total fibres content by adding short fibres, the workability will decrease much more. Fibres hybridization leads to workability decrease of 30% compared to reference SFRC-M2. Further, the mixture was not homogeneous.

To obtain a workable mixture SP was added to adjust the mixture workability. The 0.2% of SP improved the mixture integration and cohesiveness and the aggregate particles, cement paste and fibres were better mixed (Figure 56).

Figure 56: SFRC-F3060-M6 in the wheelbarrow before filling the molds.

- ***Hardened state***

According to the literature review, the expectations by fiber hybridization are optimization of the mechanical behavior of SFRC. Especially, the stiffness and ductility because the short fibers will bridge the micro-cracks to limit the crack propagation and maintain the concrete strength. This was not the case for mixture SFRC-LM20-M6 where the compressive strength did not increase and the short fibers did not have an effect on the strengths.

Splitting tensile and flexural strengths remain similar to the reference SFRC-M2. The variation in the results of the 3-point bending test was smaller than the previous phases and all the specimens passed the two runs (according to the test procedures followed in this program) and end up at larger displacement, due to the better ductility of this mixture.

However, the performance of specimen 6 complies with the theory and showed strain softening (Figure 57). This specimen took longer time till reaching the maximum flexural strength as it did not show a sharp peak like the other curves. This could be related to the effect of the short fibres that hindered the crack propagation and retarded the crack development.

Figure 57: Comparison between the cross-section of specimen 4 and specimen 6.

The fibres distribution in this specimen was different than the other specimens, when the test was stopped after two runs (according to the test procedures followed in this program) the softening curve was much higher than the softening curves of the other specimens.

Another interesting issue observed in this series of specimens was the crack pattern. In the previous phases, the crack started initiating above the notch when the load was build up and the crack reached the top of the prims by the load increase. In this phase, the cracks started above the notch, afterwards, it was obviously hindered by the fibres and appeared somewhere else (Figure 58).

Further, in none of the specimen the crack reaches the top of the prims or the specimen failed like the previous phases (Figure 53). Here is also a matter of synergetic effect. Markovic explained synergetic effect as two subjects acting together and achieve a better result than each of them acting independently from each other. Hybrid fibers had a better ductility and post-cracking behavior with respect to the reference SFRC-M2 where only one type of fibers has been used.

Figure 58: Crack pattern of SFRC-F3060-M6 specimen during 3-point bending test, where the first crack initiates above the notch that was hinder by fibres, hence another crack appeared above and went through the fibre.

The short as long fibres were visible on the outer surface of the hardened specimens (Figure 59). This did not appear in other phases and may be related to the concrete composition of the mixture or it may be due to the segregation of the aggregate particles that pushed the fibres to the sides of the molds. Or the cement paste that should cover and surround the fibres was not enough. For this mixture the same concrete recipe as the reference has been used with some modification because of the addition of short fibres.


Figure 59: Examples of SFRC-F3060-M6 where short as long fibres were visible at the outer surface of the specimens.

Conclusions experiment 4

''How can hybrid fibre improve the mechanical properties of SFRC?''

- Addition of short fibres improved the post-cracking behavior and displacement of SFRC in the hardened state.
- Fibres hybridization did not affect the compression and splitting tensile strengths.
- The larger fibres dosages (comparing to previous phases) does not increase the measured strength, but it decreases the standard deviation. The increase of the (total) fibres content in the whole batch improved the fibres distribution over all specimens, all specimens passed the 3-point bending test.
- Concrete composition (cement and water content) should be adjusted by increasing the fibres dosage.
- When it comes to the test results, the compression strength slightly decreased compared to the reference SFRC-M2, while the splitting tensile strength and the maximum flexural strength showed a negligible increase.

5. Microstructure Analysis

Concrete is a highly complex and heterogeneous composite material. The properties of the concrete depend on the aggregate, matrix, steel reinforcement and/or fibre, as well as the interfacial transition zone (ITZ) between the aggregate and matrix, and the steel and/or fibre and matrix. Those transition zones determine many of the important properties of concrete, such as strength, cracking and fracture behaviour.

In the literature review, it was found that the interfacial bond was the deciding factor for the tensile strength and played a little role on the compressive strength. Hence it was concluded that the properties of the ITZ may have a moderate influence on mechanical properties of concrete and have a drastic effect on the mechanical properties of SFRC.

ITZ properties have a particular importance on the cracking mechanism and fracture behaviour of concrete. The strength of the interface affected the fracture energy in different ways depending on the shape of the particles; the critical crack opening decreased when the interface was strong, and it increased when the crack was rough. And whenever the w/c ratio increased, the porosity in ITZ was also increased, resulting in the initiation and development of cracks in this zone. The above-mentioned properties and behaviours of cementitious materials at the macroscale are all significantly affected, if not dominated, by their structural features and properties at the microscale where the deterioration and failure process starts—properties at ITZ.

At the same time, the ITZ is the weakest and most porous layer connecting the constituents of the composite and which is important for the tensile capacity of the concrete reinforced with steel fibre.
As discussed earlier, the goal of phase 3 was designing two mixtures to obtain a denser concrete matrix and decrease the porosity of the ITZ to improve the bond between steel fibres and cement paste.

The experimental program of phase 3 showed that replacing a small content of aggregate with limestone powder had affirmative effects on the mechanical performance of the specimens compared to the reference SFRC-M2. SFRC-F-M4 did not show a considerable optimization. Still, it does not exclude designing aggregate gradation curve contains a larger proportion of fine sand is not a useful tool to densify the ITZ. There are multiple options to design it but it requires more experiments and trial mixture. In phase 3, is only one mixture tested, obviously it was not the most optimal one. To determine the effect of the adjustment done on the mixture in phase 3, the morphological characteristic of the microstructure of ITZ need to be characterized.

Throughout the studies accomplished in the literature, Scanning Electron Microscopy (SEM), Environmental Scanning Electron Microscopy (ESEM) and Transmission Electron Microscopy (TEM) have been used. In order to investigate and quantify microstructural gradients across the ITZ, backscattered electron imaging has been also used.
In this research, ESEM has been used to produce BSE images to study the morphology of the interfacial transition zone, (ITZ), present at steel fibre and cement-paste interface.
The two different cement-paste recipes will be examined and compared with the reference mixture.

The specimens were investigated by using the environmental scanning electron microscope (ESEM) and energy dispersive X-ray analysis. The backscattered and secondary electron detectors were employed. The images with the resolution of 100 µm were made to study the geometrical characteristics of steel fibres and the cement paste around. The resolution of 400 µm was used to zoom in on the ITZ and identify the stiction between the steel fibre and cement-paste. The chemical consistency within the ITZ layer was specified by X-ray detector, by which calcium hydroxide, (CH), and calcium-silicate-hydrate crystals, (C-S-H), and limestone powder were detected.

By comparing the ESEM images of the reference SFRC-M2 with SFRC-F-M4 and SFRC-LM-M5 the features of the ITZ, the relationship between the bond strength and mechanical strengths will be illustrated.

The ESEM analysis requires polished sections to generate the images. These polished sections were prepared from the prisms used for the 3-point bending test. After sawing and drying the sections, they were ground and impregnated with epoxy for 24 hours. Again the sections were ground to remove the epoxy layer with grid plates of 500 and 1200 to obtain a flat surface (Figure 60). Thereafter Stellapol machine was used for polishing that has been done in four steps (6µm, 3µm, 1µm and 0.25 µm). At every step, a microscope was used to check the effectiveness of the grinding and polishing and ultrasonic bath cleaning was performed to remove all dust and diamond particles

The properties of the interfacial transition zone (ITZ) of steel fibre and the bulk matrix were quantified using the backscattered electron imaging analysis (BSE-IA) and the scanning electron microscopy with energy dispersive X-ray analysis (SEM-EDX).

Figure 60: The apparatus used to prepare the polishes sections of reference SFRC-M2, SFRC-F-M4 and SFRC-LM-M5.

Discussion of the ESEM images

In the polished section of the reference SFRC-M2 (Figure 61) two fibres were spotted. In the images produced at a magnification of 100x, it was observed that the fibres cross section varies.

The features of the interface zone between the fibres and cement paste are comparable. Around the fibres there are voids detected which were filled with the epoxy. Similar voids are visible around the sand particle situated nearby the fibre. The appearance of these voids may be related to the compaction and bleeding during casting procedure.

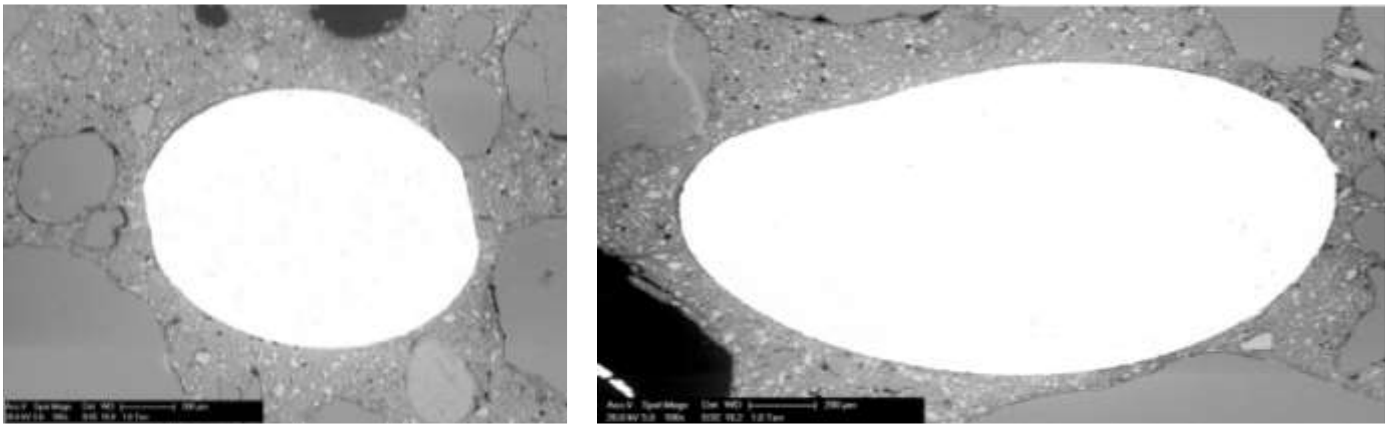


Figure 61: BSE images of the reference SFRC-M2 polished section obtained by ESEM.

Similar gaps filled with epoxy were detected in the polished section of SFRC-LM-M5 (Figure 62). In this polished section two fibres were found. One of the fibres was perfectly surrounded with the cement paste, while the other one had some weak interfaces spots filled with the epoxy. Based on the images, it seems that the zone filled with epoxy around the fibre in SFRC-LM-M5 is larger than the reference SFRC-M2. However, the pores around the fibre and the ITZ properties depend on the concrete quality. The air content of the reference SFRC-M2 was smaller than the air content of SFR-LM20-M5, where it increases from 1.4% to 2.3%. Despite the large increase of air content in SFRC-LM-M5 the mechanical properties and post-cracking behaviour were enhanced. Even the microstructure of both fibres does not indicate that there was a matter of porous structure. Since the only difference between both mixtures is the replacement of some aggregate by limestone powder, the higher air content was compensated by the filler.

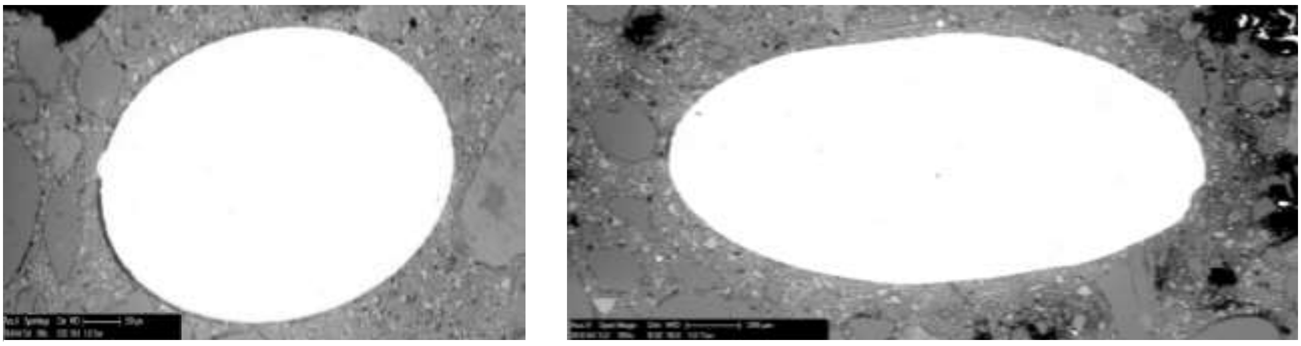


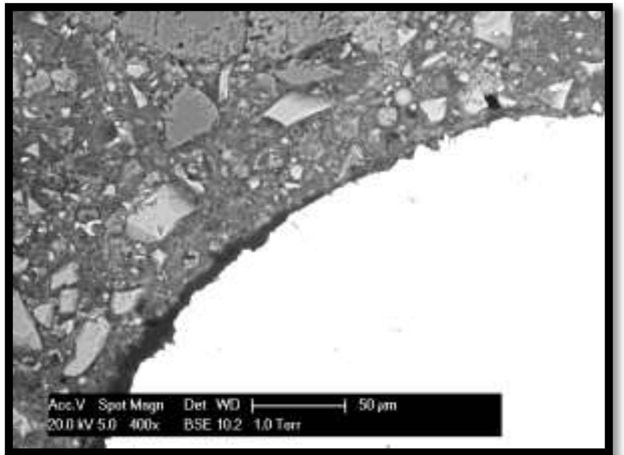
Figure 62: BSE images of SFRC-LM-M5 polished section obtained by ESEM.

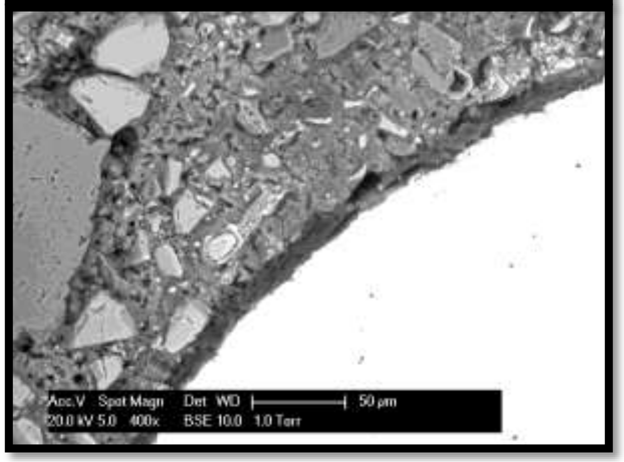
To analyse and compare the ITZ properties of the three mixtures, six spots were selected to make images at 400x magnifications. The images are given in Table 11. The images of the reference SFRC-M2, indicate that the thickness and nature of the ITZ changeover around the fibres. The second image shows a very porous ITZ, where the slag particles are larger and closer to the interface. When in the first image, the ITZ is smaller and the distance is larger between the slag particles and the fibre surface. Also, fly ash particles are observed at the denser zone of ITZ along the fibre.

The two images of SFRC-F-M4 given in the Table 11 are of different sides of the same fibres. The polished section contained only one fibre. The first image shows a better distribution of the slag particles and more fly ash particles around the fibre. Even the ITZ is slightly smaller than the reference SFRC-M2 and the fibre edge is smoother and less deteriorated due to the chemical reactions. However, there is on spot filled with epoxy at the middle of the fibre. While the features of the ITZ in the second image which is also of the same fibre are different. The fly ash particles are stacked to the fibre surface, even the slag particles are sharper and larger.

Finally, images of SFRC-LM-M5 zoomed in on the difference in the ITZ observed in Figure x. The first image shows a denser hydration product adjacent to the fibre surface.
Somewhere at the midpoint of the fibre, the bulk matrix becomes lighter; this may be related to the limestone powder. By moving down, the slag particles become larger and shapers. Again, here is a micro crack initiated from the fibre interface going through the slag particles.

The ITZ and cement paste are denser comparing to the other 2 mixtures. This may indicate that there is no matter of segregation and the formation of cement hydrates in the ITZ of steel fibre was mainly influenced by the wall effect and the degree of hydration. A better chemical bond between the fibre and the concrete matrix delays the de-bonding. The fly ash particles are a bit far from the ITZ (near the dark spot). The ITZ (void filled with epoxy) is thicker than image 1, hence the ITZ is at this spot is porous and acts as a weak point where de-bonding of the fibre and matrix paste occurs.
However, the difference of the ITZ properties in the three mixtures is small, which is similar to the mechanical properties measured in chapter 4.

<table>
<tr><th>Reference SFRC-M2</th><th>SFRC-F-M4</th><th>SFRC-LM-M5</th></tr>
<tr>
<td>




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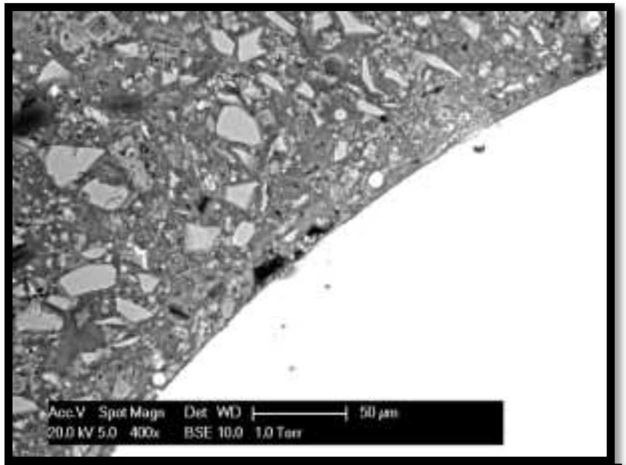

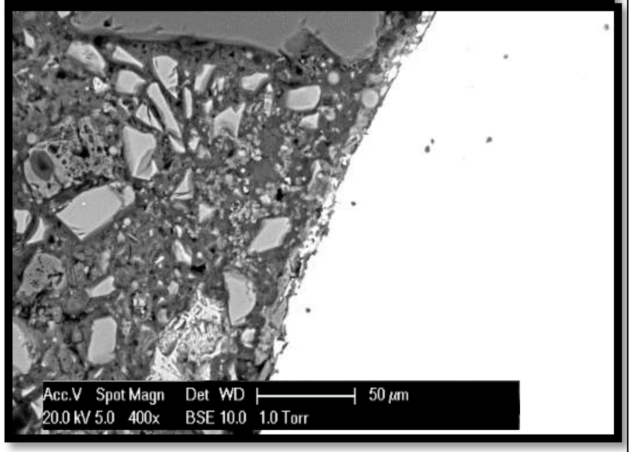

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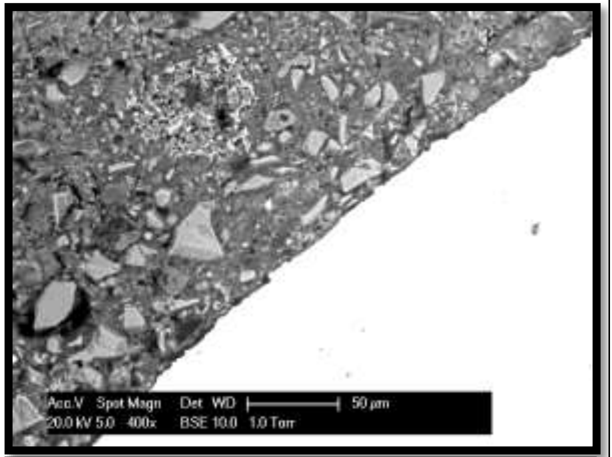

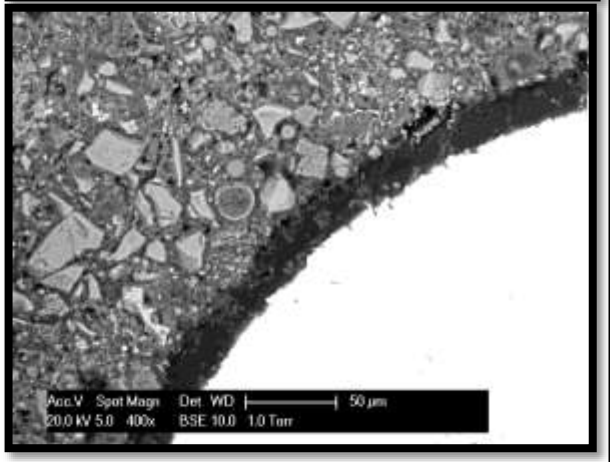

</td>
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Table 11: Comparison of BSE images of reference SFRC-M2, SFRC-F-M4 and SFRC-LM-5 at magnification of 400x. .

6. Conclusions

In the experimental program the problem statement has been analyzed and discussed in phases. Based on the results of the mechanical tests and sub conclusions, the main conclusion and answer of the research questions is:

The details of the concrete composition have a decisive role on the mechanical properties of SFRC. Different concrete compositions of strength class C30/37 mixed with 35 kg/m^3 of steel fibre showed variation in the mechanical strengths. Therefore choosing SFRC mixtures based on strength class and constant fibre content do not ensure standard mechanical properties but it will lead to variation. Hence this clarifies the variation of mechanical properties observed in the practice.

Thus leading to the following detailed conclusions:

- The fibre addition of 35 kg/m^3 to concrete strength class C30/37 has positive effects and enhances the mechanical strengths in the hardened state. The results of the experiment conducted in phase 1 showed an increase of the compressive and splitting tensile strengths by respectively 7% and 23% compared to plain concrete M1 while the maximum flexural strength slightly increased. Most important was the optimized post-cracking behavior. As the air content decreased from 2% to 1.4%. Only the workability was negatively affected by the (small) fibre addition, which can be compensated by adding SP (Table 12).

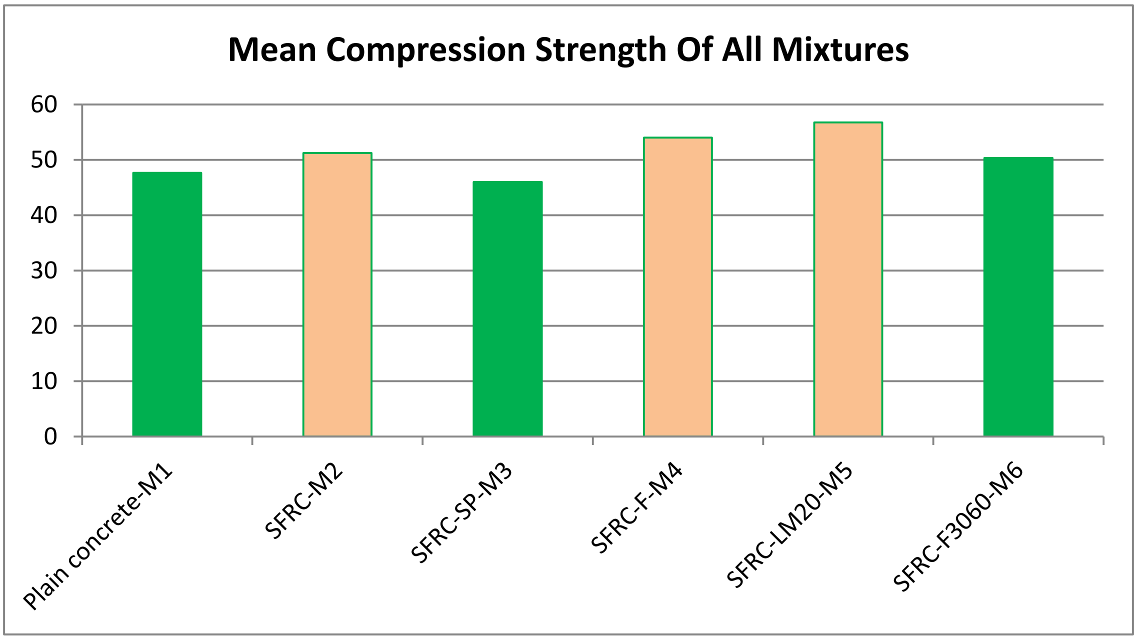
- Adjusting the concrete composition had direct effects on the behavior of SFRC. Phase 2 presented a scenario which may occur in the practice as well, where the mixed concrete deviates from the original design. The adjustment of the water content results in a porous and low concrete quality which had negative consequences on the mechanical strengths. Even more, the measured strengths of SFRC-SP-M3 were very close to the strengths of plain concrete M1 the only difference was the improved post-cracking behavior.

- In phase 3, the concrete compositions have been adjusted to obtain a denser concrete matrix and decrease the ITZ between the steel fibres and concrete matrix. The modification of the aggregate grading in SFRC-F-M4 did not lead to a considerable optimization with respect to the reference SFRC-M2 (Table 12). While the replacement of some coarse aggregate with limestone powder enhanced the mechanical strengths and post-cracking behaviour.

- The compressive and splitting tensile tests results of SFRC-SP-M3, SFRC-F-M4 and SFRC-LM-M5 showed that adjusting the concrete composition has adequate effects on the strengths. Meanwhile results of the 3-point bending test, in particular the post-cracking curve, proved that the fibres distribution and content at the (failed) cross-section are dominant factors.

	Plain concrete M1	Reference SFRC M2	SFRC-SP-M3	SFRC-F-M4	SFRC-LM-M5	SFRC-F3060-M6
Concrete composition details	**Reference C30/37 mixture**	**Reference C30/37 mixture+ steel fibres**	**Reference C30/37 mixture+ steel fibres+ SP:** *w/c ratio adjusted*	**Reference c30/37 mixture+ steel fibres:** *aggregate grading adjusted*	**Reference C30/37 mixture+ steel fibres+ SP:** *incl. limestone powder*	**Reference C30/37 mixture+ steel fibres+ SP:** *incl. 2 sizes of steel fibres*
Compressive strength	47.6 (1.5)	51.3 (2.4)	46.0 (2.6)	54.0 (3.1)	56.8 (1.5)	50.3(1.57)
Splitting Tensile strength	3.7 (0.1)	4.6 (0.5)	3.9 (0.2)	4.45(0.3)	4.6(0.4)	4.7 (0.7)
Flexural strength	3.4 (0.2)	3.7 (0.5)	3.48(0.3)	3.68 (0.5)	4.3(0.3)	3.9(0.2)
Slump	180mm	170mm	220mm	220mm	190mm	210 mm
SP	-	-	0.3%	-	0.2%	0.2%
Air content	2%	1.4%	2.4%	1.1%	2.3%	1.2%

Table 12: Overview of all mixtures properties measured in fresh and hardened state.



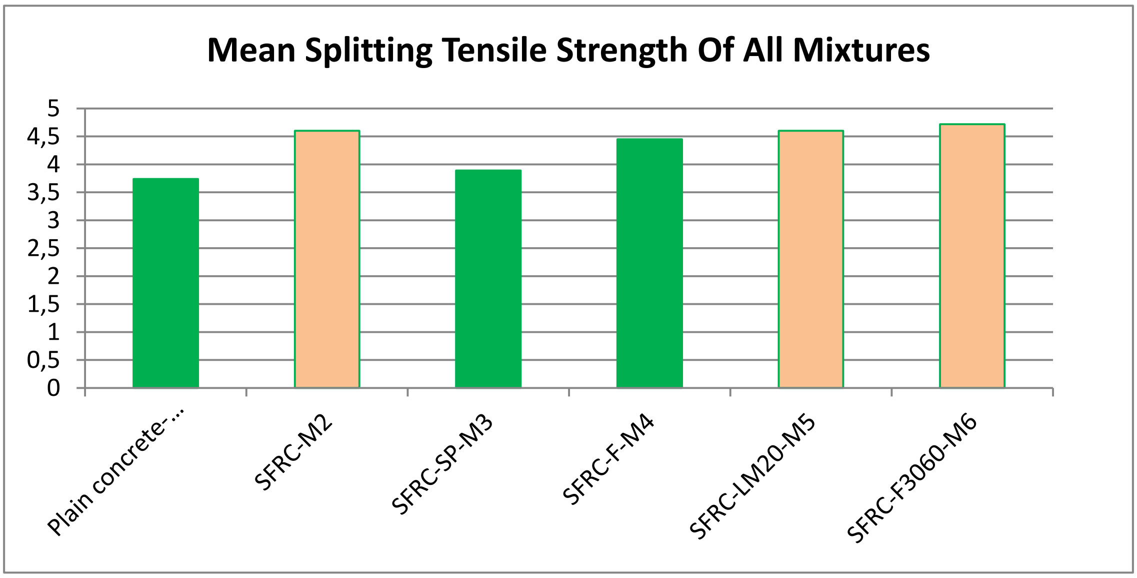


Figure 63: Average compressive and splitting tensile strengths of all mixtures studied in the experimental program.

- Figure 63 shows that the mixtures containing a larger proportion of fine materials (cement, fine sand or limestone powder) have higher compressive strength. As combining two types of fibres did not affect the compressive strength, this in contrast to the literature. It is supposed that the compressive strength should increase by the fibre hybridization. The hindrance of micro-cracks and limitation of crack propagation should maintain the strength of the concrete matrix intact for longer time.

- The splitting tensile strength seems to be affected by a dense microstructure and mixture as the fibres hybridization (Figure 63). Noticeably the rate of increase in the splitting strength of the adjusted mixtures compared to the reference SFRC-M2 is negligible.

- The results of the 3-point bending test indicate that the maximum flexural strength and post-cracking behaviour depend on the concrete composition and the fibres distribution at the cross-section of the prism (above the notch). In Figure 64 is the average post-cracking curve of all mixtures plotted. The five SFRC mixtures show softening behaviour after the crack formation. The mixtures containing limestone powder and short fibres performed better than the other mixtures. The small content of limestone powder had almost the same effect and even better than the addition of 17.5 kg/m^3 of short fibres.

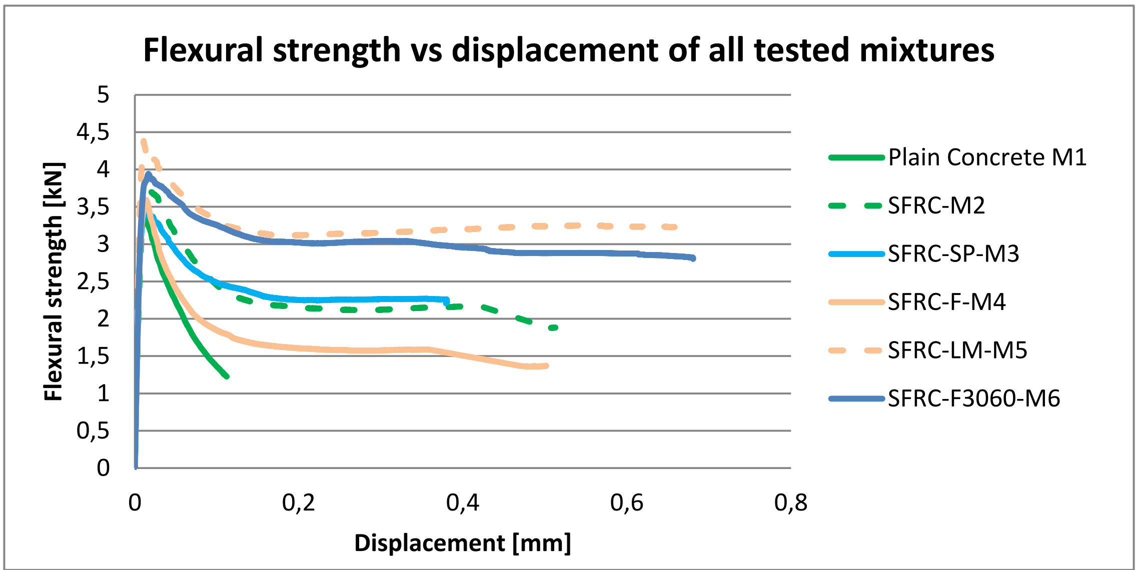


Figure 64: Average flexural strength vs. displacement curves obtained by 3-point bending tests results of all mixtures studied in the experimental program.

- The synergistic effect of the concrete ingredients should be considered as well. The optimization of the strengths in SFRC-LM-M5 may not completely relate to the limestone powder but to the cooperation of all concrete ingredients.

- The small differences in the mechanical properties of the reference SFRC-M2, SFRC-F-M4 and SFRC-LM-M5 are expressed in the ESEM images as well. However, slightly it was possible to detect the modification done in the concrete composition in the images of the polished section. In the polished section of SFRC-F-M4 it was obvious that this mixture contains more slag particles. Same for the polished section of SFRC-LM-M5, which showed a dense interface that, reflect the increase in strengths, but at the same time it showed a porous interface that may be relating to higher air content compared to reference SFRC-M2.

- In Table 12 are all the measured properties and mechanical strengths of the SFRC mixtures given. The consequences of adjusting the concrete composition are clearly reflected in the variation of the mechanical behavior of each SFRC mixture. Hence, the variation of SFRC performance observed in the practice where more or less the same SFRC mixture has been applied relate to the variation in the concrete composition. Other reasons for the variation, especially in the post-cracking behavior, are the fibers distribution and content in every specimen.

- Addition of steel fibres increases the total price of the mixture for the contractor, therefore the investment should be worthy and the fibres addition should optimize the performance of the structural element. To use the steel fibres in the most efficient way, the concrete mixture should be carefully designed, manufactured and cast. In case of any adjustment or application of new execution technology, this should be tested beforehand on a trial mixture. Once the concrete composition is adjusted on the building site, it is almost impossible to expect, limit and handles the side's effects on the performance of SFRC. And according to the CUR 111 it is already obligated to test SFRC mixtures before using it as construction material in the practice.

7. Reflections & Recommendations

The tests results of this research indicated that the concrete composition and quality affect the performance of SFRC. Concrete that will be mixed with the steel fibres should be carefully designed for every structural element and tested beforehand to ensure the achievement of the required mechanical behaviours. Using a standard C30/37 mixture based on the price and strength class will not guarantee standard properties and strengths of SFRC.

Based on this research, the following recommendations can be given for application of SFRC in the future:

- Increasing the fine material content and limiting the maximum grain size are key parameters that should be considered in the design process of the concrete composition in the future. To determine the optimum concrete composition and behavior, trial mixtures should be tested.

- The mixture workability and flowability should be measured during the design procedure of the concrete composition. The experiments accomplished in this research showed a decrease in the workability by adjusting the concrete composition (for example: by adding limestone powder) paired with increase in the variation of the result of the tests.

- According to the CUR 111, it is already obligated to test the SFRC mixture before applying it in the practice. The CUR 111 referred to testing small specimens of 150mm*150mm*500mm comparable to the specimens used in this research. But to obtain more representative data it is recommended to test specimens with larger spans especially when the mixture will be used for floors.

- The fibres distribution in the specimen is related to the casting procedure. The molds were filled by a shovel, the risk that some shovels included more fibres than the other one exists. But also it depends on the workability and flowability of the mixture in the fresh state. By a workable and flowable mixture, the fibres will flow in the casting direction and may be better distributed while by a stiff mixture the fibres will improperly spread and stacked at one zone. The mixture workability and consistency in the fresh state may be used to monitor the fibres distribution in the specimens, this aspect need be further investigated.

- Quality control: SFRC mixtures require a high level of quality control during the production, transport and casting. The produced SFRC and delivered to the building site should not deviate from the designed mixture (and eventually the tested trial mixture). Because SFRC mixture seems to be very sensitive to any adjustment, especially adjustment in the fresh state that can affect the quality and performances in the hardened state.

- Combining steel fibres with conventional reinforcement is not investigated in this research. The expectations are that the concrete composition will also affect the mechanical behavior, in particular, the maximum grain size.

- The small replacement of coarse aggregate by limestone powder showed an optimization of the mechanical strengths and post-cracking behavior. More experiment can be done to confirm if the optimization is only related to the limestone powder or to the synergetic effect of all materials (cement, fly ash, etc.).

- The concrete composition can be used as a tool to enhance and monitor the mechanical strengths of SFRC without increasing the steel fibres content. By comparing the mechanical strengths of SFRC-LM-M5 and SFRC-F3060-M6 given in Table 12, it is interesting how the small content of limestone powder results in better strength than increasing the total fibres content (by the addition of short fibres). This means that the performance of SFRC is not only related to the fibres content, but also to the concrete composition, quality, production and execution.

- Hybrid fibres can be a useful technique for structural elements where the cracks formations are very critical. The results of the experiment conducted in phase 4 showed a decrease of crack opening and crack propagation in the tested specimens.

What does it mean for the practice?

The main goal of this research is to reflect the Dutch situation and the problem detected in the practice by the application of SFRC. As a common SFRC is obtained by adding 35 kg/m^3 of steel fibres to regular concrete strength class C30/37.Therefore all the experiments were set and handled from the perspective of the practice and with the goal to give an indication about the possible composition adjustments to control the SFRC behavior.

One thing should be considered, the results of this research are based on small specimens size. According to the literature, size factor may affect the fibres distribution; therefore additional research is required to study the size effect the mechanical strengths.

However, the recommendations of this research relevant for the practice are:

- Small fibers addition of 35 kg/m^3 optimizes the concrete ductility, crack opening and improved the post-cracking behavior. The addition of steel fibers did not strongly influence the maximum flexure strength. To increase the maximum flexural strength and improve the post-cracking behavior, concrete composition and/or fibres content should be adjusted.

- The concrete quality and composition can positively as negatively affect the final behavior of SFRC in the fresh and hardened state. Therefore it is absolutely not recommended to choose concrete for SFRC based only the concrete strength class and price. The details of the concrete composition (fine material content, maximum grain size, etc.) should be considered.

- Fibers content and dispersions in the structural elements are critical and dominant factors. The mixture workability and flowability may enhance the fibres distribution. However, this hypothesis needs to be investigated.

- Limestone powder and short fibers were tools that optimized the mechanical behavior with respect to the reference SFRC-M2. But there may be more tools to adjust the concrete composition of SFRC and optimize the mechanical behavior, this can be done in further studies.

- For the practice, the prices and costs are important factors. In order to evaluate if the improvement is worth the price invested in the adjustment of concrete composition, a multi-criteria analysis is given in the Table 13. The test results of plain concrete M1 and the reference SFRC-M2 are given, while for the other four mixtures where the concrete composition has been adjusted a sign of -,+ or -/+ is given. The (–) sign refers to decrease of strength compared the reference SFRC-M2, while by increase of strength or improvement a (+) sign is used. When there is neither decrease nor increase (-/+) sign is given. Based on the multi-criteria analysis the mixture containing limestone powder optimized the mechanical strengths without increasing the prices of the mixture.
  In fact, the prices of SFRC mixtures depends on the ordered amount of concrete, type of vibrating, transportation, distance from the concrete plant to the building site, fibers, etc. But to get a rough indication of the prices as given in Table 13, the price unit of each ingredient has been used excluding the other aspects.

	Plain concrete M1	**Reference SFRC M2**	**SFRC-SP-M3**	**SFRC-F-M4**	**SFRC-LM-M5**	**SFRC-F3060- M6**
Compressive strength	47.6	**51.25**	**-**	**+**	**+**	**-**
Splitting tensile strength	3.7	**4.6**	**-**	**-/+**	**-/+**	**-/+**
Flexural strength	3.4	**3.7**	**-**	**-/+**	**+**	**+**
Post-cracking behaviour & displacement	0.12	**0.5**	**-/+**	**-/+**	**++**	**+**
Price for 1m^3	€275	**€344**	**€346**	**€351**	**€344**	**€373**

Table 13: Multi-criteria analysis based on the mechanical properties and price of all mixtures.

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Appendix A-Experimental studies from the literature

Experimental study 1

S. Altoubat et al. [32] investigated the impact of small fibre dosage on the performance of FRC. In their research, they designed mixtures with steel fibres as synthetic fibres. They used the equivalent flexural strength ratio ($R_{e,3}$) to quantify the increase of the flexural capacity in the specimens.

The most interesting results of this study are the ones of the SFRC mixtures (including hooked & crimped steel fibres) as the results of the plain concrete. By comparing the SFRC mixtures with the plain concrete, the consequences of the fibre addition are defined. The mixture compositions are given in the Table below:

	Plain Concrete	SFRC (Hooked fibers)	SFRC (Crimped fibers)
Fiber content (kg/m^3)	0	27.3	39
Coarse aggregate (kg/m^3)	995	965	983
Fine aggregate (kg/m^3)	823	796	813
Cement (kg/m^3)	363	347	363
Water	178	163	172
Superplasticizer (ml/100kg)	925	868	1328
w/c ratio	0.49	0.49	0.47
Air content (%)	1.8	6.0	3.2
Slump (mm)	200	110	190

Table 14: The concrete properties of the three mixtures used in the experimental study 1.

Obviously, the mixtures compositions including fibres are adjusted while almost the same w/c is maintained. The reason for the small variation of the w/c ratio is that three separate mix trucks were used to cast the test specimens. This could happen in the practice and comply with the problem statement of this research (1.3).

The adjusting of the mixture composition corresponds to the theoretical design process where the volume of the fibre content should be considered since the fibre acts like aggregate in the matrix. Even the maximum aggregate size (D_{max}) is limited to 25mm in all mixtures.

Table 15 shows the negative consequences of the fibre addition, the air content increases and the slump decreases. At the same time, the increase of the air content could be related to the preparation procedure and compatibility, which is not discussed in the research.
The workability is affected by the fibre addition and the slump decreased in the SFRC mixtures.

In Table 15, the measurements of the compressive and flexural strength of the small scale test are given. The plain concrete had a higher compressive strength compared to the SFRC variants.
The compressive strength decreases with the fibre addition because of the higher air content (Table 1). The effect of the fibre on the flexural strength is small, in SFRC (crimped fibres) mixture the flexural strength slightly increases while it decreases in the SFRC (Hooked fibres).

Small scaling test	Plain Concrete	SFRC (Hooked fibers)	SFRC (Crimped fibers)
Fiber dosage (%)	0	0.35	0.5
Loading location	center	center	center
Compressive strength (MPa)	41.1	34.2	37.2
Flexural strength (MPa)	4.73	4.68	5.28
$R_{e,3}$ (%)	3	43	35

Table 15: The experiment results of the tests.

Experimental study 2

In the experimental and analytical analysis of creep on SFRC carried out by D. Nakov et al. [33], the influences of different fibre volume fractions on the mechanical properties of SFRC were studied.

Table 16 shows the mixtures compositions used for the specimens. All the ingredients are constant only the fibre volume fraction differs (0.38% & 0.76%). That means, in this experimental program, the matrix is not adjusted by the fibre addition like the previous experimental study. The maximum aggregate size is limited to 16mm.

Mixture proportions	(kg/m^3)		
Cement CEM II/A-M 42.5 N	410		
Water	215		
w/c ratio	0.524		
0-4 mm river sand (50%)	875		
4-8mm limestone (20%)	350		
8-16mm limestone (30%)	525		
Fibers dosage	Plain concrete (0)	C30/37 FL 1.5/1.5 (30kg/m^3)	C30/37 FL 2.5/2.0 (60kg/m^3)
Slump	120 mm	75mm	50

Table 16: Mixture proportions of the specimens used in experimental program 2.

The mechanical properties of the specimens were measured after 40 & 400 days. The measurements results are given in the Table 17. Noticeably that the compressive and splitting tensile strength by lower fibre content is better in the long term when the flexural strength by higher fibre content showed better and more Table results in the long term.

Mechanical properties	Age at test. t(days)	C30/37	σ (st.dev)	C30/37FL 1.5/1.5	σ (st.dev)	C30/37 FL 2.5/2.0	σ (st.dev)
Compressive strength (MPa) (cubes 15/15/15cm)	40	42.89	0.18	41.63	4.79	44.59	1.83
	400	45.70	5.742	47.41	1.07	46.15	1.69
Increase (%)		6.55		13.88		3.50	
Splitting tensile strength (MPa) (cubes 15/15/15cm)	40	3.51	0.10	3.22	0.14	4.00	0.31
	400	4.17	0.02	4.58	0.13	4.24	0.13
Increase (%)		18.80		42.23		6.00	
Flexural tensile strength (MPa) (beams 15/15/70cm)							
-σ_1(stress at δ_L=0.05mm)	40	5.18	0.56	4.95	0.34	5.30	0.66
-σ_2(stress at $\delta_{R,1}$=0.46mm)				1.80	0.44	2.83	0.67
-σ_3(stress at $\delta_{R,4}$=3.00mm)				1.53	0.40	2.33	0.73
-σ_1(stress at δ_L=0.05mm)	400	5.00	0.66	4.40	1.32	5.95	0.13
-σ_2(stress at $\delta_{R,1}$=0.46mm)				1.38	0.28	2.90	0.44
-σ_3(stress at $\delta_{R,4}$=3.00mm)				1.15	0.47	2.38	0.32
Increase σ_1 (%)		-3.5		-11.11		12.26	
Modulus of Elasticity (MPa) (cylinders 15/30cm)	40	26956	127.2	26771	93.2	26120	423.2
	400	27041	811.4	30809	618.2	28224	674.2
Increase (%)		0.32		15.08		8.06	

Table 17: The experimental results of the tests.

Still, it is complicated to declare the improvement of small fibre addition to C30/37. By comparing these results with the previous study, it is clear that by short-term test, the compressive strength decreased comparing to plain concrete by the addition of steel fibres.

The contribution of the fibre to the splitting tensile strength is almost negligible by a small fibre addition, the strength may even decrease compared to plain concrete. There is also a negligible improvement of flexural strength. The only difference between the plain concrete and the two SFRC mixtures is the post-cracking behavior.

Experimental study 3

The third and last experimental study selected is the research about the flexural capacity of SFRC accomplished by J. Lee et Al [34]. The authors designed specimens of three different concrete strength classes (C25, C35 and C45) with three fibre volume fractions of 0.25%, 0.35% and 0.50%.

In this research, the equivalent flexural strength ratio Re, 3 has been used to evaluate the flexural tensile strength. For the determination of this ratio, the first peak strength and energy absorption capacity are needed. The two parameters of this study, concrete strength and fibre volume, showed a strong relationship with the first peak strength and absorption energy.

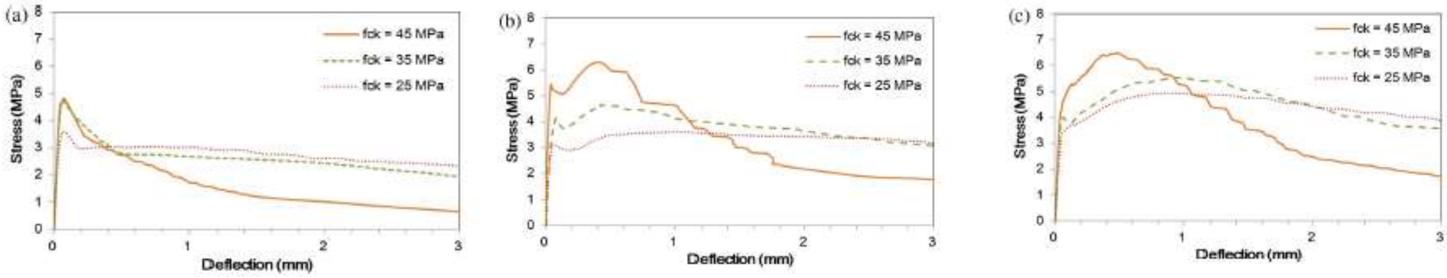

Figure 65: The measurements results of the stress and deflection from the SFRC beams that differ in strength for three fibre volume fractions a) 0.25% b) 0.375 and c) 0.50%.

Starting with the stress and deflections measurements, Figure 65 presents the test results of all specimens. Clearly, the concrete strength has a prominent influence on the maximum flexural strength.

The mixture compositions of the three concrete strength classes are the same (Table 18), despite the water content. Superplasticizer is only added to concrete strength class 45. Again in this study, the concrete matrix is not adjusted and the fibres volume is not considered in the mixture composition.

Mix proportion of the concrete (Units: kg/m^3).

Name of Specimens	Strength (MPa)	Steel fiber	Cement	Water	Gravel	Sand	Silica fume	Super-plasticizer
C25-250	25	20	400	242	1065	663	40	0
C25-375		30						
C25-500		40						
C35-250	35	20	400	198	1065	663	40	0
C35-375		30						
C35-500		40						
C45-250	45	20	400	165	1065	663	40	4.4
C45-375		30						
C45-500		40						

Table 18: Mixture compositions of specimens used in experiment study 3.

Figure 66 shows the relationship between the concrete strength and the absorption energy. The first peak strength is strongly dependent on the concrete strength. While Figure 67 shows the correlation between the fibre volume and the absorption energy.

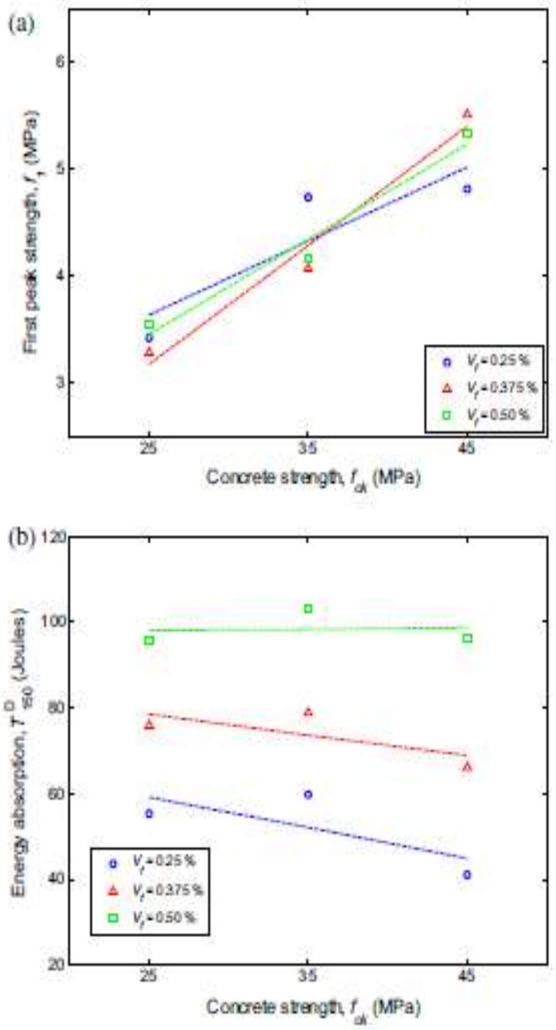

Figure 66: The relationship between the concrete strength and the first peak strength & energy absorption.

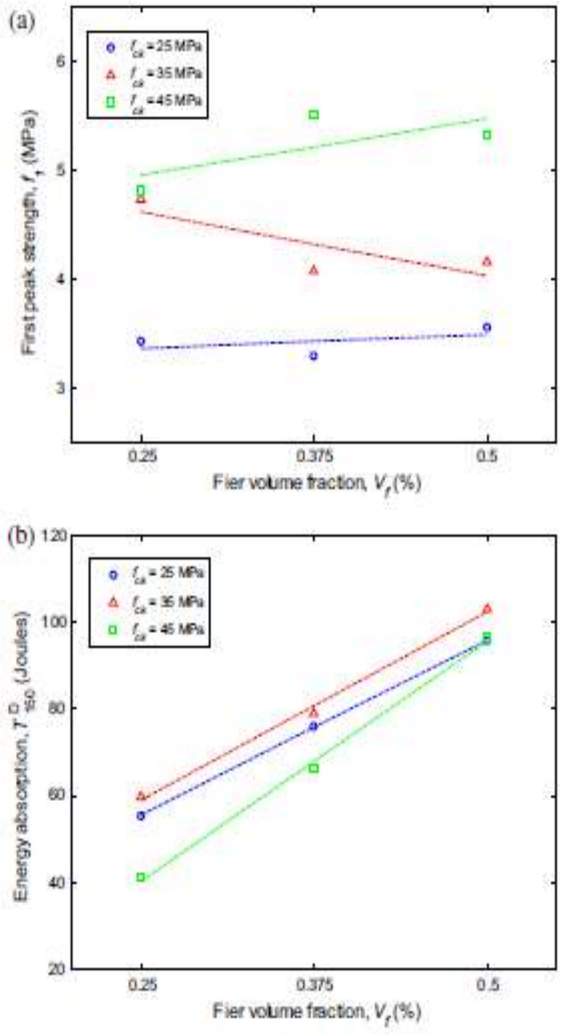

Figure 67: The relationship between the fibre volume fraction and the first peak strength & energy absorption.

The equivalent flexural strength ratio depends on the concrete strength and fibre volume. The results showed an increase of strength by larger fibre volume fraction and decrease by higher the concrete strength.

The compressive strength of the specimens is also measured; the results are given in the Table 19 below. Adding steel fibres to concrete strength class C25 & C35 led decrease as an increase of the compressive strength:

Design strength	**0.25%**	**0.35%**	**0.50%**	**Mean**
C25 (MPa)	26.1 (0.80)	26.2 (0.70)	27.0 (0.48)	26.4
C35 (MPa)	34.6 (2.90)	37.4 (4.20)	37.3 (3.11)	36.4
C45 (MPa)	46.7 (3.45)	48.7 (3.45)	48.2 (3.45)	47.9

Table 19: Compressive strength of the specimens designed in experimental study 3