Technical University of Denmark DTU

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Methodology and Testing of Waste Fishing Net as Fibre Reinforcement in Mortar

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Abstract

This Master Thesis examines the use of fibres from waste fishing nets as fibre reinforcement in cement mortar samples. The thesis is divided into two main part where the first part covers investigations of the waste fibres in terms of mechanical properties, alkali resistance and thermal properties. The second part investigates the waste fibres in cement mortar samples in terms of compressive strength, flexural strength and flexural toughness. To put the results from the polyamide waste fibre into perspective, the waste fibres are compared with two synthetic fibres used in the industry. The two fibres are both made of polypropylene and are called, Durus and Fibrin Fiberflex. The fibres were provided by PP Nordica, Denmark, and manufactured by ADFIL, England.

The waste fishing net was collected at Gilleleje Harbour and the net was identified to be made of polyamide 6 (nylon 6). The result of the mechanical properties showed a tensile strength of 838 MPa and a Young's Modulus of 961.5 MPa. The fibres showed good alkali resistance in terms of mass and volume perseverance, however the fibres had a strength reduction of 30% after exposure to high alkalinity. The thermal investigations yielded a melting point of 214.5°C and an ignition point >350°C.

When casting the fibre reinforced mortar samples, two length of fibres were used for the waste fibres; 2 cm and 4 cm. During and after casting the waste fibres showed good distribution qualities within the mortar mixture, which is crucial for fibre reinforcement.

The results for the strength tests conducted to the mortar samples showed a decrease in compressive strength for the samples with waste fibres, compared to the reference samples of plain cement mortar. The reduction in compressive strength was ranging between -5% to -15% for fibre content of 0.5%, 1.0% and 2.0% of weight fractions. The reduction in strength increased with the fibre content. Similar results where found for the mortar samples with Durus fibres, and a more severe strength reduction for the Fibrin Fiberflex fibres.

In terms of flexural strength, the waste fibres decreased the initial crack strength with -2% to -10% compared to the plain reference samples, but maintained a significantly flexural strength after the initial crack. The fibre reinforced mortar samples were able to maintain up to 50% strength of the initial flexural strength. For comparison, the Durus fibres resulted in a increase of +4% to +10% in initial strength compared to the reference sample and post-crack strength perserverence of up to 66%.

For the flexural toughness the waste fibres had a major positive effect and multiplied the amount of energy the cement mortar samples were able to absorb, compared to the unreinforced reference samples. However, the Durus fibres yielded higher toughness values than the waste fibres, but the waste fibres performed better than Fibrin Fiberflex.

In conclusion, the polyamide waste fibres yielded overall positive result as fibre reinforcement, but were not able to match the results from the Durus fibres. However, the waste fibres still outperformed the Fibrin Fiberflex fibres in terms of strength characteristics indicating a potential future for fibres made of waste fishing nets.

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Resume

Denne Kandidat Afhandling omhandler brugen af affaldsfiskenet til fiberarmering af cement mørtel prøver. Afhandlingen er opdelt i to hoveddele, hvor første del omhandler undersøgelse af fiskenetsfibrene i form af styrke parametre, alkaliresistens og termiske egenskaber. Anden del omhandler fiskenetsfibrene i cement mørtel prøver i form af trykstykre, bøjningsstyrke og bøjningssejhed. For at sætte resultaterne for fiskenetsfibrene i perspektiv, blev der foretaget tilsvarende tests med to syntetiske fibre der til daglig bruges i industrien. Begge fibre er lavet af polypropylene og går under navnene Durus og Fibrin Fiberflex. Fibrene blev leveret af PP Nordica, Danmark og fremstillet af ADFIL, England.

Affaldsfikenetne blev indsamlet ved Gilleleje Havn og polymer typen blev identificeret som polyamide 6 (nylon 6). Resultaterne for de styrkemæssige egenskaber af fiskenetsfibrene viste at de havde en gennemsnitlig trækstyrke på 838 MPa og et elasticitetsmodul på 961.5 MPa. Fibrene viste fine alkaliresistens egenskaber med henblik på masse og volumen bevarelse, men fibrene oplevede en styrke reduktion på 30% efter at have været udsat for høj alkalinitet. De termiske undersøgelser gav et smeltningspunkt på 214.5°C og antændingspunkt for temperaturer over 350°C.

Ved støbning af de fiberarmeret mørtel prøver, to længder af fiskenetsfibre blev benyttet af henholdsvis 2 cm og 4 cm. Under og efter støbningen viste affaldsfiskenetsfibrene gode blandings egenskaber, hvilket er en afgørende egenskab for fiberarmering.
Resultaterne af styrke forsøgene foretaget med mørtel prøverne viste en nedsættelse af trykstyrken for prøverne der indeholdt fibre, sammenlignet med reference prøverne af almindeligt cement mørtel. Reduktionen af trykstyrken lå imellem -5% til -15% for fiberindhold af 0.5%, 1.0% og 2.0% af vægt fraktionen, hvor styrkereduktionen blev forværret med et øget fiberindhold. Lignende resultater blev fundet for mørtel prøver med Durus fibre, mens prøver med Fibrin Fiberflex oplevede en større nedsættelse i trykstyrke.
I forhold til bøjningsstyrken viste brugen af affaldsfiskenetfibre en nedsættelse af brudstyrken med -2% til -10% sammenlignet med de rene reference prøver, men de fiberarmeret mørtel prøver var i stand til at bevare op til 50% i bøjningsstyrke efter brudstyrken var nået. Til sammenligning resulteret brugen af Durus fibre med en forøgelse af +4% til +10% af brudstyrken sammenlignet med reference prøverne og en bevarelse af bøjningsstyrke op til 66%.
I forhold til bøjningssejheden, viste brugen af affaldsfiskenetsfibre en betydelig positiv effekt of var i stand til at mangedoble mængden af energi som mørtel prøverne kunne optage, sammenlignet med de almindelige mørtel prøver. Dog viste brugen af Durus fibre en endnu højere forøgelse af bøjningssejheden end fiskenetsfibrene, men resultaterne fra fiskenetsfibrene viste dog bedre bøjningssejhed end Fibrin Fiberflex fibrene.
Afslutningsvis kan det konkluderes at affaldsfiskenetsfibrene af polyamide overordnet set viste gode egenskaber som fiberarmering, men var dog ikke i stand til at matche resultaterne fra de industrielle Durus fibre. Dog viste fiskenetsfibrene bedre styrkeegenskaber end Fibrin Fiberflex fibrene, hvilket kan indikere en potentiel fremtid for fibre lavet af affaldsfiskenet.

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Preface

This project represents the Master Thesis done by Simon Jacob Svensson, at the Department for Civil Engineering, Technical University of Denmark, DTU.

The thesis constitutes to the work of 32.5 ECTS Points and was conducted and written in the period from the 25th of January 2016 to the 16th of July 2016.

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signature

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List of Symbols

Latin Symbols

Symbol	Symbol explanation
A_{bundle}	Cross-sectional area of a PA6 fibre bundle
A_{fibre}	Cross-sectional area of a single PA6 fibre
b	Side length of square section of mortar sample
C_s	System compliance of PA6 fibre
d_{bundle}	Diameter of a PA fibre bundle
d_{fibre}	Diameter of a single PA fibre
E	Young modulus
f_{cr}	Crack strength
F_{cm}	Compressive load applied to mortar samples of area 40x40 mm
F_f	Load at middle of mortar sample at fracture
F_{ff}	Force at fracture of PA6 fibre bundle
I_2	Toughness index for 2 times initial crack deflection
I_5	Toughness index for 3 times initial crack deflection
l	Distance between supports for for testing flexural strength of mortar
l_0	Start length of PA6 fibre for tensile testing
MP	Melting Point
P	Load
P_{cr}	Critical load of mortar sample
P_{fcr}	Critical load of PA6 fibre bundle
P_{pb}	Maximum post-break load of mortar sample
R_c	Compression strength of mortar sample
R_f	Flexural strength of mortar sample
T	Toughness
$T_{\delta_{cr}}$	Toughness at initial crack deflection
$T_{2\delta_{cr}}$	Toughness at 2 times initial crack deflection
$T_{3\delta_{cr}}$	Toughness at 3 times initial crack deflection
w/c	Water/cement ratio

Greek Symbols

Symbol	Symbol explanation
α	Cement constant
δ	Midspan deflection
δ_{cr}	Midspan deflection at initial crack
δ_{fcr}	Critical deflection of PA6 bundle
Δl	Elongation of gage length of PA6 fibre bundle
Δl_{fcr}	Critical elongation of PA6 fibre bundle
ΔL	Critical elongation
ε	Strain of PA6 fibre bundle
σ_t	Tensile strength of PA6 fibre bundle

List of Abbreviations

Abbreviation	Elaboration
DSC	Differential Scanning Calorimetry
FRC	Fibre Reinforced Concrete
FRM	Fibre Reinforced Mortar
FTIR	Fourier Transform Infrared Spectroscopy
HDPE	High-density polyethylene
PA	Polyamide (Nylon)
PA6	Polyamide 6 (Nylon 6)
PE	Polyethylene
PET	Polyethylene terephthalate
PP	Polypropylene
Ref	Reference mortar sample
SD	Standard Deviation
SEM	Scanning Electromagnetic Microscope
TGA	Thermal Gravimetric Analysis

1 Introduction

Marine waste products and pollution of the sea is not a recent phenomenon, especially waste products made of plastic. Plastic waste products are very persistent and have a low degradability, so the accumulated effect is a growing problem. Therefore, it is of interest to minimize marine waste products and to find ways to recycle or reuse them, so they do not end up in the oceans. Marine waste products, such a waste fishing nets, are already being recycled by companies such as Plastix in Denmark, Omega Plastics in Italy and Nofir in Norway. These companies collect waste fishing nets and remelt them into plastic raw material. As these solutions all help reduce the amount of waste fishing nets, this thesis focus on yet another possible way to reuse waste fishing nets that is, to fibre reinforce cement-based composites. Fibre reinforce cement-based composites has a lot of advantages which will be elaborated later in this section and the next.

Recycling of plastics are becoming more and more normal and are being done at a higher level then ever before in the history. According to Plastics Europe, 26% of the worlds plastics are being recycled as of 2012 (Plastics Europe, 2016). This indicates that there is still room for improvement. This project aims at providing one solution to increase the recycling or reusing of plastic from waste fishing nets in cement-based composites. This makes for an appealing concept, as the recycled materials are waste products, which would otherwise end up at the local incineration plant. In addition, reusing waste products in the building sector is both beneficial from a economic and environmental point of view. This is due to the low cost of materials, as most waste products are free to acquire, plus the enhancement of the building material.

Looking closer at one of the industries that produces a lot of marine waste product is the fishing industry, mostly in the form of fishing nets. One particular problem with marine waste products is the dumping of fishing nets in the oceans. This is occasionally done by the fishermen in order to save space and weight when the fishing nets are well used and close to retirement. Sometimes this also happen by accident, if the nets gets stuck and cannot be retrieved. While the dumping of fishing nets may be beneficial for the fishermen from an economical point of view, it is not a sustainable solution. Currently 10 percent of all plastics in the ocean are from fishing nets (Macfadyen et al., 2009). If these used fishing nets could be reused in concrete production, this would be a beneficial situation for all involved. Usually, waste fishing nets are free to collect at the dumping site of any harbour with industrial fishing. If none are to collect them, the fishing nets is most likely sent off to combustion at the local incineration plant. Furthermore, it is not uncommon to find nearly new fishing nets at the dumping site, as it is cheaper to purchase a new net than repair a damaged net. Therefore, this thesis focuses on the aspect of using waste fishing nets to fibre reinforce cement mortar samples.

The use of plastic material in concrete have been tested many times, but using waste materials in this way has seldomly been investigated. The most used plastic fibres in concrete production is of polypropylene (PP), polyethylene terephthalate (PET) or high-density polyethylene (HDPE) (Yin et al., 2015b). Today, plastic fishing nets are mostly made of polyethylene or polyamide (nylon) (Euronete, 2016). This project focuses on the use of polyamide (nylon) fibres from waste fishing nets, or more specifically the polyamide known as Nylon 6. Nylon fibres from waste fishing nets in mortar samples has been done by Spadea et al. (2015) and shows promising results. Therefore this is the material that will be tested and used in the production to fibre reinforce mortar and potentially concrete.

Consequently, it is crucial to gain knowledge about the fibres and the characteristics and behavior alone, and in combination with the cement mortar. In order to gain knowledge about the fibres, a series of different tests will be done to the nylon fibres, such as strength testing and alkali resistance. These among others will provide the required data and knowledge about the material. After, the fibres will be mix into a mortar mixture to test the effect of the fibres as a reinforcement in cement-based composites. This is thought to enhance the properties of the material, so there is a use for waste fishing nets in the building sector.

1.1 Problem statement

This study was initially intended to cover the use of fibres, from waste fishing nets, to fibre reinforce *concrete*. However, the process of preparing the fibre material was very time consuming, hence the project was change to cover *mortar* samples and not full scale concrete beams. This heavily reduced the time spend to hand-cut fibres, as less fibres were needed for the mortar samples. Therefore, the problem statement became the use of fibres from waste fishing nets to fibre reinforce mortar samples.

1.2 Previous studies of fishing nets as fibre reinforcement

As mentioned, there are many studies that uses plastic fibres as fibre reinforcement, and there is a tendency that studies try to replicate the same properties from virgin materials using waste materials. Table 1.1 provides an overview of the most relevant studies using waste materials as fibre reinforcement, as well as studies using fishing nets as fibre reinforcement.

Studies using waste plastics as fibre reinforcement	
Reference	**Research**
Silva et al. (2005)	The study investigated the use of recycled PET fibres from bottles in Portland cement-based materials. The study showed that the PET fibres had no significant influence on mortars strengths and elasticity modulus, but had a high influence on the toughness. Further, it was found that the toughness decreased over time due to degradation of the PET fibres alkaline hydrolysis when embedded in the cement matrix.
Fraternali et al. (2013)	The study also investigated the use of recycled PET fibres from bottles as fibre reinforcement in cement mortars. The study found that the fibres showed remarkable alkali resistance and greatly improved the toughness of the mortar mixture.
(Ozger et al., 2013)	Effect of nylon fibres on mechanical and thermal properties of hardened concrete for energy storage systems. The study uses recycled nylon fibres from post-consumer textile carpet waste and found that the fibre-reinforced concrete was slightly more ductile and tougher than plain concrete.
Yin et al. (2015a)	The study investigated the mechanical properties of recycled PP fibres for reinforcing concrete. The study investigated the difference between recycled PP fibres and virgin PP fibres and a combination of both. The study showed that 100% recycled fibres had a tensile strength of 310 MPa and Young's modulus of 620 MPa, where fibres mad with 50% recycled and 50% virgin had a tensile strength of 360 MPa and Young's modulus of 800 MPa.
Studies using waste fishing nets as fibre reinforcement	
Reference	**Research**
Spadea et al. (2015)	Investigated the use of recycled nylon fibres as cement mortar reinforcement. The study investigated the effect of the fibres for flexural strength, compressive strength and toughness. The study showed a significantly increase in flexural strength of up to +35%, and increased toughness of the mortar samples, but also a reduction in compressive strength of up to -37%.

Table 1.1: Overview of previous studies using fishing nets as fibre reinforcement

Other studies that investigated fishing nets are (Al-Oufi et al., 2004) and (Thomas and Hridayanathan, 2006), who both investigated the effect of solar radiation upon the breaking strength of polyamide fishing nets. The two studies both found that solar radiation significantly decreases the breaking strength of the fibres. This is important when the quality of waste fishing net is assessed.

This study investigates many of the same aspects as (Spadea et al., 2015), but as stated before, this study was initially intended to cover fibres in concrete, not mortar. However, the two studies share a lot of common ground and investigates similar aspects. This makes

(Spadea et al., 2015) a good study for comparison. The new elements in this study that is different, is the fibres. (Spadea et al., 2015) uses fibrillated micro and macro fibres and this study uses polyfilament macro fibres. This study also includes a more in-depth analysis of the fibres and a comparison of the waste fishing net fibres with plastic fibres used in the industry.

1.3 Introduction to the report

The structure of the report is outlined below with a short description of each chapter.

Structure

The project has been divided into two main parts; The first part is a study of the waste polyamide fibres and the second is the performance of the waste polyamide fibres in mortar mixture. The true characteristics of the waste polyamide fibres are found and compared with the two polymer fibres from *PP Nordica* used in the industry. The waste polyamide fibres will be held against fibres from *PP Nordica*, as fibre reinforcement in cement-based composites. The second part investigates waste polyamide fibres in mortar samples, which includes the effect and interaction of different fibre lengths and fibre content in the mortar samples. The results are discussed and compared to similar studies in order to validate the use of fibres from waste fishing net in cement-based composites

Theory
The Theory, Chapter 2, includes description of cement-based materials in general and the different types of fibres that are used as reinforcement in cement-based materials, particular synthetic fibres.

Materials and Methods
The Materials and Methods chapters are divided into two chapters, Chapter 3 and 4, which each chapter describes each of the materials. Chapter 3 describes the waste polyamide fibres in detail, and the methods used to test the characteristics and quality of the material. Chapter 4 describes the mortar mixture in detail, as well as the fibres as reinforcement in cement-based material. The chapter also describes the methods used for the mortar samples, among the testing of the flexural and compressive strength of the fibre reinforce mortar samples as well as the plain mortar samples.

Results
Chapter 5 and 6 consist of the results from the fibre experiments and the mortar experiment, respectively. The results are briefly discussed internally, but not compared to other studies.

Discussion
Chapter 7 consist of the discussion and perspectivation of the results found in Chapter 5 and 6. This chapter compare the results with studies and research from the literature, in order

to validate the results in this study.

Conclusion
Chapter 8 includes the final conclusion for fibres from waste fishing nets as reinforcement in cement-based materials, as well as recommendation to future studies within the same field.

2 | Theory

This chapter focus on the theory behind cement-based composites, fibres, and fibres in combination with cement-based composites. This would provide an insight in all the elements present in this study.

2.1 Cement-based composites

Cement-based material includes every material in which cement is the main ingredient, such as mortar and concrete. The main ingredients in Mortar is:

- Cement
- Water
- Sand (aggregate size 0 - 4 mm)

Concrete consists of the same materials, but with the addition of stones (aggregate of size 4 - 32 mm). Cement-based building materials have been around for millennia due to its strength, workability and availability. All the components can be found almost all around the globe, and there are lots of them. Cement-based materials are known to perform good in compression, but not so in tension. Therefore cement-based materials are usually reinforced in order to improve the tensile and flexural strength or the material. Fibres as reinforcement have been used since Biblical times to strengthen brittle matrices; for example straw and horsehair was mixed with clay to form bricks and floors (Brandt, 2008). Later, steel became the number one material to reinforce cement-based materials. Steel is very much the most used reinforcement material today, but as steel are rather expensive other solutions are explored. One of these solutions is the use of various types of fibres, used to improve the properties of the cement-based material. In order for the fibres to improve the cement-based material there are three main criteria the fibres must fulfil:

- Must be easily dispersed in the mixture
- Must have suitable mechanical properties
- Must be durable in high alkaline environment

If these main issues is not fulfilled the fibres may not be suitable for fibre reinforcement. When it comes to material of fibres, there are mainly four types of fibres that can be used as reinforcement: Steel fibres, glass fibres, natural fibres, and synthetic fibres, (Danial et al., 2001). Natural fibres are materials such as wood fibres (Torkaman et al., 2014) or coconut rope fibre (Ali and Chouw, 2013). Table 2.1 provides information of the advantages and disadvantages of the different types of fibres, identified by Yin et al. (2015b) and (Danial et al., 2001).

Type of Fibre	**Advantages**	**Disadvantages**
Steel	High Tensile Strength High Flexural Strength Control Cracks	Expensive Corrodes
Glass	High Strength Effect	Low Alkali Resistance
Natural	Cheap Easy Availability	Low Durability
Synthetic	High Post-crack Behavior High Alkali Resistance	Not as strong as Steel

Table 2.1: Pros and cons for different type of fibres as reinforcement in cement-based materials

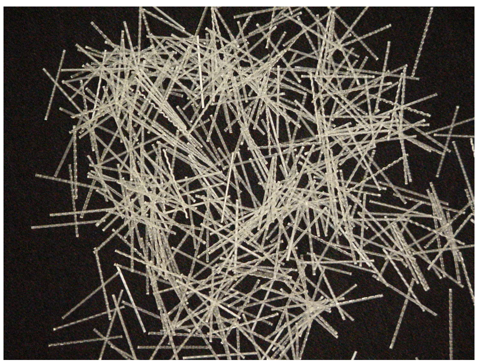
It should be noted that these are potential effects and are not for certain. The effect can vary, depending on the fibres, specific material and quality.

When adding fibres to a cement-based material is becomes a cement-based *composite*. Cement-based composite is traditionally without stones (aggregate size 4 - 32 mm), so it is a mortar-based composite reinforced with fibres, usually polymer fibres. If stones are included, the material is defined as Fibre Reinforced Concrete (FRC). The adding of fibres also gives the material a larger strain capacity, which makes the material more ductile. Another aspect where fibres have a positive effect is *Plastic Shrinkage*, which is cracks caused by moisture loss after casting (Banthia and Gupta, 2006). From the studies of Uno (1998) it was found that if the moisture evaporation exceeded 0.5 $kg/m^2/h$, it could cause negative capillary pressure inside the concrete, resulting in internal strain. Kim et al. (2008) found that although the macro plastic fibres did not affect the total moisture loss of the rate, the fibres could still effectively limit the plastic shrinkage cracking by improving integrity of the fresh concrete.

One of the most critical aspects of using fibres from recycled plastics is the quality. Recycled plastics have uncertain processing and service history and varying degrees of degradation, leading to processing difficulties and unstable mechanical properties, (Wang, 1997).

2.2 Fibres

When talking about fibres, there are primarily two kinds of fibres: Macro fibres and Micro fibres. Macro fibres is one coherent fibre, whereas Micro fibres are made up of many small fibres. Macro fibres are typically made of Monofilament fibres, and Micro fibres are typically made of Polyfilament fibres or Fibrillated fibres. Where monofilament is one fibre, polyfilament is one fibre made of multiply smaller fibres and fibrillated fibres are several small fibres huddled together but which acts individually. Macro fibres typically have a length of 30-60 mm and a diameter ranging from 0.6-1.0 mm^2, where micro fibres have a length of 5-30 mm and a diameter of 5-100 μm. The two kinds of fibres are shown in Figure 2.1, where these fibres are from *PP Nordica*. Figure 2.1a shows monofilament macro fibres called *Durus* and Figure 2.1b shows fibrillated micro fibres called *Fibrin Fiberflex*.



(a) Macro Fibre called *Durus*

(b) Micro Fibre called *Fibrin Fiberflex*

Figure 2.1: Macro and Micro fibres from PP Nordica

When fibres are used as reinforcement it is important to notify the different failure mechanisms. The most common failure mechanisms are *Fibre rupture*, where the fibre is ripped in two after the maximum tensile strength of the fibre have been reached. Second is *Fibre pull-out*, where the fibre is pulled out without contributing fully to the strength. Another is *Fibre Bridging* or *Fibre Debonding* where the cement-based material cracks around the fibre, but the material is held together. The most critical failure mechanism is the pull-out of the fibres as the fibres do not contribute to any work in this case. Therefore it is desired to eliminate this failure mechanism or reduce it to a minimum. This is done by producing the fibres in different shapes, with deformations or a combination of both. This secures a better attachment of the fibres into the cement-based material. Examples of the different shapes of fibres can be obtained in Figure 2.2, by (Sujivorakul and Naaman, 2003).

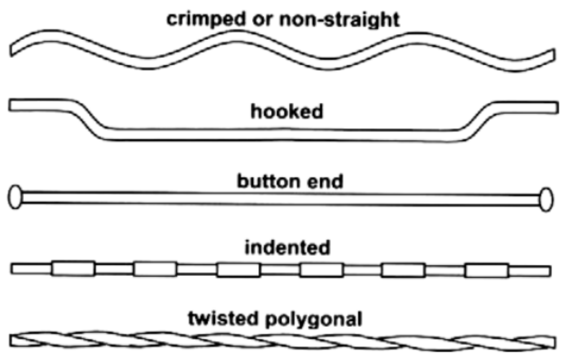


Figure 2.2: Examples of deformed steel fibres, (Sujivorakul and Naaman, 2003).

The fibres shown in Figure 2.2, all have deformed shapes or rough surfaces in common, which will secure a better grip in the cement and minimize failure by pull-out.

As the effects of macro and micro fibres differ from one another when used as reinforcement in cement-based materials, Table 2.2 provide and overview of the positive effects the two kinds of fibres can have.

Type of Fibre	**Effect**	**Comment**
Macro Fibre	Flexural Toughness	Improves the amount of energy the material can absorb.
	Post-crack performance	Increase the performance after the initial crack.
	Impact resistance	-
	Ductility	-
	Durability	Help improves crack behavior, which help maintain aggregates interlock and hence maintain load transfer.
Micro Fibre	Crack Resistance	Reduce the inducing of crack behavior, which reduce the maintenance in time.
	Impact resistance	-
	Shrinkage/expansion	Improves the plastic limit, which in time improves the serviceability.
	Fire Resistance	Reduction in explosive spalling and improved resistance to plastic shrinkage cracks.
	Durability	-

Table 2.2: Positive effects of fibre reinforcement in mortar and concrete

Many of these positive effects enhance the surface properties, making the cement-based composite more resistance to external elements. Long term, this means that the cement-based composite will need less maintenance and thereby are cheaper to maintain. Furthermore, fibres in concrete and mortar are easy to handle and cast, compared to traditional steel reinforcement. The most used applications for fibres in concrete according to ADFIL (2016) are the ones mention below:

- Internal floors
- External hardstandings (Truck and car parking areas)
- Precast concrete elements
- Agricultural waste tanks
- Tunnels

Naturally, fibre reinforcement have other uses as well, but these are the most common ones.

3 Methods and Materials - Fibres

This chapter includes description of the waste fishing net as an individual material and as a building material. The method section focus on the methods and standards used to analyse the characteristics of the waste polyamide fibres. Table 3.1 shows the experimental log for the fibre experiments. A more detailed experimental log can be obtained in *Appendix 1 - Experimental Log*.

Date	Experiment	Standard	Location
16-02-2016	Collecting of material	-	Gilleleje Harbour
18-02-2016	Washing of fishing nets	-	DTU Byg
25-02-2016	Tensile Strength of PA6 fibres	ASTM C1557	DTU Byg
04-03-2016	Density (Pycnometer)	DS/CEN ISO/TS 17892-3	DTU Byg
09-03-2016	FTIR	-	DTU Polymer Lab.
10-05-2016	SEM of PA6 fibres in 1M NaOH at 0 days	-	DTU Byg
18-05-2016	TGA of PA6 fibres	-	DTU Polymer Lab.
18-05-2016	DSC of PA6 fibres	-	DTU Polymer Lab.
27-05-2016	Tensile Strength of PA6 fibres emitted in 1M NaOH for 28 days	ASTM C1557	DTU Byg
31-05-2016	SEM of PA6 fibres in 1M NaOH at 28 days	-	DTU Byg

Table 3.1: Experimental log for fibre experiments

3.1 Materials

The fibres used as reinforcement for mortar samples are made of aliphatic polyamide 6, also known as nylon 6. Throughout the report the polyamide 6 fibres will be referred to as PA6 fibres or waste PA6 fibres. The fibres are polyfilament macro fibres, meaning the macro fibre is made up off many small fibres. The fibres in this project come from waste nylon fishing nets collected at Gilleleje Harbour, see Figure 3.1a. The waste fishing nets were collected the 16th of February 2016 at the dumping site of Gilleleje Harbour at Havnen 6, Gilleleje, Denmark, as seen on Figure 3.1.

(a) Map of Denmark, extracted from Google Maps.

(b) Dumping site for fishing nets at Gilleleje Harbour, 16th of February 2016.

Figure 3.1: Location of Gilleleje Harbour and the dumping site for fishing nets

The waste fishing nets were free to collect and from the locals at the harbour it was found that it was not uncommon to see nearly new fishing nets being discarded to the dump, due to breakage or shredding.
The fishing net collected in Gilleleje, which this study takes source from, is an outer net with a rather large mesh size. A section of the waste net has been cut out and can be seen on Figure 3.2.

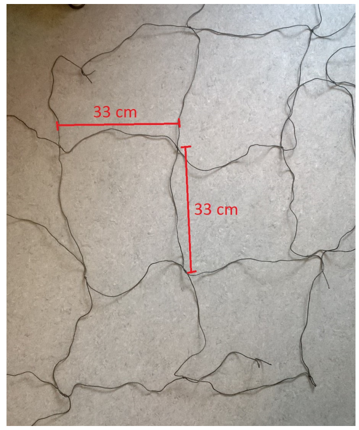


Figure 3.2: Section of waste nylon fishing net from Gilleleje Harbour

The visual properties of the waste fishing net are summarised in Table 3.2.

Material	Net type	Mesh size	Thickness	Color
Nylon 6	Twisted	$33x33$ cm	2 mm	Black

Table 3.2: Visual properties of waste fishing net

The fishing net was produced by twisting nylon fibres together where each string was made up of three twisted nylon bundles and it is these nylon bundles that are of interest for this study. The use of fibre bundles instead of fibre string was chosen to increase the surface area and the crimped or non-straight shape of the fibre bundles were thought to have a better attachment in the mortar mixture and less risk of pull-out of the fibres, as found by Brandt (2008). The strings and bundles of the fishing net are shown in Figure 3.3.

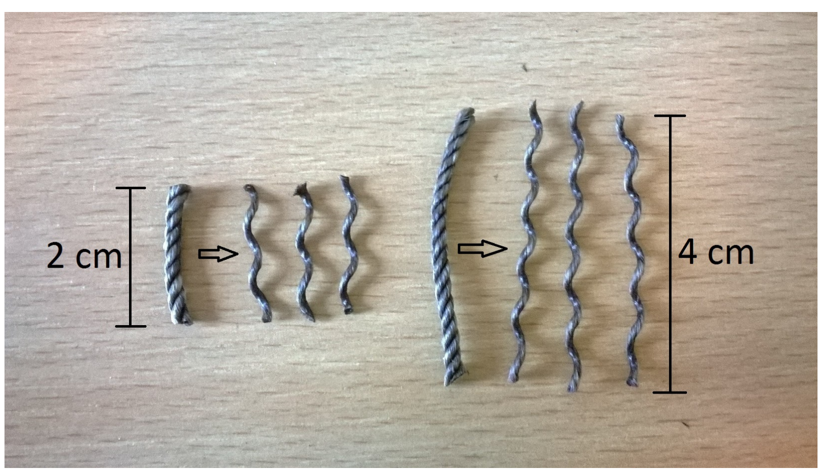


Figure 3.3: PA6 fibres from waste fishing net

The waste fishing net was deliberately choosing to be a well used net, so if the fibres from

this particular net were to yield positive results, it may suggest a future for the use of waste fishing nets in mortar and concrete production. The manufacturer of the net is unknown, but according to the local fishermen most net used in the harbour comes from the company *Euronete*, however this has not been possible to verify.
As this study focus on waste fishing nets, the quality of each net may vary significantly from fishing net to fishing net. One important aspect in this, is the weathering resistance - how well the fishing nets resist the weather conditions, both at sea and at land. It has been documented that fishing nets that spend a significantly amount of time exposed to sunlight becomes weaker. This phenomenon has been showed by (Thomas and Hridayanathan, 2006) and (Al-Oufi et al., 2004), who found that plastic fibres exposed to sunlight and UV-rays showed a reduction in breaking strength. In the past, fishing nets were made of biodegradable natural materials, such as cotton and linen, and these materials needed to be dried in order not to rot. However, as fishing nets today are made by plastic (polyethylene, polyamide etc.) these nets do not rot, meaning that there is no reason for the fishermen to let them dry in the sun. Fishing nets still spend a reasonable amount of time in the sun, however the fishermen in Gilleleje were aware of this and covered their nets when they were on land.

3.2 Methods

This section focus on finding the true characteristics of the waste fishing nets. As the polyamide fibres comes from used fishing nets the characteristics may differ from the ones of newly made fishing nets. Therefore the waste PA6 fibres were tested in order to find the strength and durability, which can give an indication of what can be expected from other waste fishing nets. The long-term durability of the fibres is of great interest, as the fibres are to be in the mortar for the entire lifespan of the material. To test the durability the fibres will be examined for alkali resistance. Information about the experiments is obtained in *Appendix 1 - Experimental Log*.

3.2.1 Density and Thickness

The density of the PA6 fibres was found by a pycnometer test done according to the standard of DS/EN-ISO/TS-17892-3 (2004), but with the modification that the sample is PA6 fibres and not soil material. This was done by putting 4 grams of PA6 fibres into a pycnometer flask, which then was filled with deaerated distilled water to secure zero air content. The filled pycnometer flask was then weighted and the density determined. This was done in triplets and the true density being the average of the three samples. The density of the fibres has an effect on how well the fibres are mixed into the mortar. Yin et al. (2015b) found that fibres with a density of 0.9 g/cm^3 or lower tends to float up to the surface of the mixture during the mixing process, and thereby distribute poorly in the mixture. Fibres with a density higher then 0.95 g/cm^3 showed significant better mixing characteristic.

The thickness of the fibres, both the thickness of a single fibre and the thickness of the fibres bundle, was determined using Scanning Electron Microscope (SEM). This was done by measuring the diameter of a the fibre in triplets to secure a true diameter. As the PA6 fibres are polyfilament it was of interest to find the diameter of a single fibre and the fibre bundle. This made it possible to estimate the number of single fibres in a fibre bundle. All SEM tests were done at DTU Byg.

3.2.2 FTIR - Identification of Polymer

To confirm that the polymer type of the fishing net is polyamide 6, a Fourier Transform Infrared Spectroscopy test was performed, abbreviated to FTIR. FTIR uses light waves to measure how well a material absorbs light at each wavelength, which is then obtained in a infrared spectrum of the material. This infrared spectrum is also known as the "fingerprint" of the polymer.

After finding the infrared spectrum, this was compared to a known library containing infrared spectrums of all known polymers in order to find a potential match and identification. The test was performed on a PerkinElmer Spectrum One model 2000 at the Polymer Laboratory at DTU, Denmark.

3.2.3 Washing of Fishing nets

The fishing net were washed in order to remove waste products and impurities within the fishing net. This would secure that salt from seawater and other by-products were not mixed into the mortar mixture, where they potentially could damage and weakening the mortar during and after curing.
The fishing net were handwashed in fresh water using a large vessel. The fishing net were left to soak for 30 minutes for each wash. The container used for washing was a big 250 L plastic barrel and the amount of water was 50 L per wash.

At the end of each wash, the water was stirred aggressively and about half a liter of water was extracted where 10 ml were filtrated into a sample. This samples was then tested for conductivity. The conductivity is strongly related to the number of ions in the water, where the main part of the ions comes from salts. Salts are known to damage and weakening cement-based materials. There are five main salts in seawater with the following percentages, as shown in Table 3.3 found by (Danmarksrejsen, 2016)

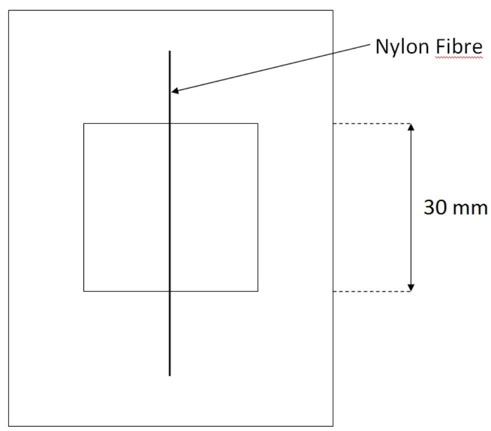
Salt:	NaCl	$MgCl_2$	$MgSO_4$	K_2SO_4	$CaCO_3$
Amount [%]:	77.7	10.8	4.7	3.6	2.5

Table 3.3: Salts in seawater

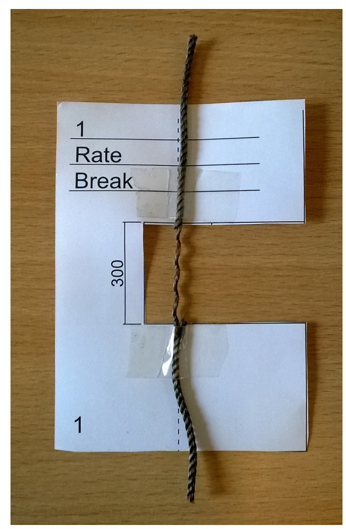
These five salts make up 99.3% of all the salts in seawater, the remaining 0.7% are ions from other salts which can be neglected in this matter. Therefore it was desired to have a minimum of salts in the mixture. Particular the sulphates (SO_4) are known to be very damaging to the cement-based materials. The fishing net were assumed clean when the curve for the conductivity was converging or had the same conductivity as fresh water. It was important that the same amount of water was used for each wash, so the mixing ratio was the same and the decreasing conductivity could be observed.

3.2.4 Tensile Strength

This subsection investigated both the tensile strength of the PA6 fibres as well as the Young's modulus. The testing of the tensile breaking strength of the fibres was done according to standard ASTM-C1557-14 (2014), where three gauge lengths of PA6 fibres were used to estimate the breaking strength and the modulus of elasticity. However, there was a modification to this standard, as ASTM-C1557-14 (2014) test the strength of a single fibre, where here a fibre bundle was tested. This was done due to the fact that PA6 fibre bundles were mixed into the mortar mixture and therefore the strength of the bundles was desired, not the strength of a single fibre. The three different gauge lengths of fibres was: 20 mm, 25 mm and 30 mm. This has been illustrated on Figure 3.4a, and actual sample on Figure 3.4b, both with the gauge length of 30 mm.



(a) Sketch of test specimen



(b) Actual test specimen

Figure 3.4: Tensile strength of fibre specimen

A total of 8 specimens were tested for the three lengths to determine the breaking strength. The tensile strength, σ_t, of the PA6 fibres were determined by equation (3.1).

$$\sigma_t = \frac{F_{ff}}{A_{bundle}} \tag{3.1}$$

Where F_{ff} is the force at fracture of a PA6 fibre [N] and A_{bundle} is the cross-sectional area of a PA6 fibre bundle [mm^2].

The strain, ε, was calculated by equation (3.2).

$$\varepsilon = \frac{\Delta l}{l_0} \tag{3.2}$$

Where Δl is the elongation of the gage length [mm] and l_0 is the start length of PA6 fibre [mm].

The critical elongation was found by equation (3.3).

$$\Delta L = \Delta l + C_s F \tag{3.3}$$

Where C_s is the system compliance [mm/N] and F is the force.

The Elasticity modulus, E, also known as the Young modulus, was determined using equation (3.4).

$$\frac{\Delta L}{F} = \frac{1}{E}\frac{L_0}{A} + C_s \tag{3.4}$$

The Young's modulus is a factor which measure the elasticity of the material, where a high E-modulus equals a stiff material, like steel, and a low E-modulus equals a more deformable material, like rubber.

3.2.5 Alkali resistance

The alkali resistance of the PA6 fibres is an important concern, as the environment in cement-based composites is very alkaline with a pH value of 13. The alkali resistance consists of two aspects: Strength and Volume. To investigate this, PA6 fibres were immersed into a 1M NaOH solution with a pH value of 14 for 28 days The immersed fibres in the NaOH solution was to stand in an oven at a temperature of 40°C. This was done in order to accelerate the alkali activity. This was the same procedure done by both (Sim et al., 2005) and yet unpublished study by (Bertelsen et al., 2016).

Volume

The fibres tested for mass reduction were immersed into the NaOH solution for 7, 14, 21, and 28 days respectively. After the immersing period, the volume reduction of the fibres was determined by SEM images before and after immersing. This was done both for PA6 fibre bundles and PA6 single fibres.

Strength

In order to investigate the strength perseverance, the immersed fibres was to be tested. This was done by immersing fibres at the appropriate length described by ASTM-C1557-14 (2014) and keep them in the 1M NaOH solution for 28 days. The strength test was then done the same way as described in section **3.2.4 Tensile Strength**. This would show if any strength reduction were present after exposure to a high alkali environment. This would give a good estimate of the durability of the PA6 fibres. This would also showed if any changes were for the elasticity of the fibres.

3.2.6 Thermal properties

The thermal properties of the PA6 fibres were of interest in respect to the fire resistance of the fibres in reinforced mortar samples.

Differential Scanning Calorimetry

Differential Scanning Calorimetry (DSC) was done in order to find the melting point of the polymer. This was performed on a TA Q1000 with the use of 10 mg PA6 fibre and where the temperatures ranged from 0 to 300 degrees Celsius. The TA Q1000 can be seen on Figure 3.5b.

To get the true melting point of the fibre, the sample was first warmed up to 300°C to remove impurities, so only pure polymer was remaining. Afterwards the sample was cooled down to 20°C and finally heated again in order to get the true thermal characteristics of the polymer. The process is described in Table 3.4.

Step	Start Temp. [°C]	Tempo [°C/min]	Final Temp. [°C]
1	20.00	+10.00	300.00
2	300.00	-10.00	20.00
3	20.00	+10.00	300.00

Table 3.4: Heating process for DSC

Thermal Gravimetric Analysis

Thermal Gravimetric Analysis (TGA) was performed to find the thermal degradation as a function of temperature. This makes it possible to determine the ignition point of the polymer. The ignition point was found when the curve for the mass started to decrease rapidly due to increase in temperature.

The test was performed on a TA Q500 with a sample of 10 mg PA6 fibre, where the temperatures ranged from room temperature at 20.00°C to 800.00°C with an increase in temperature of 10.00°C/min. The TA Q500 can be seen on Figure 3.5a.

(a) TGA test machine

(b) DSC test machine

Figure 3.5: Thermal testing machines

4 Methods and Materials - Mortar

This chapter includes description of the materials used in the mortar mixture, casting of the mortar samples and testing of the mortar specimens. The testing includes both bending and compression of the mortar specimens. Table 4.1 shows the experimental log for the mortar experiments. A more detailed experimental log can be obtained in *Appendix 1*.

Date	**Experiment**	**Standard**	**Location**
21-03-2016	Casting of 14 days samples	DS/EN-196-1	DTU Concrete Lab.
22-03-2016	Casting of 28 days samples	DS/EN-196-1	DTU Concrete Lab.
04-04-2016	Flexural testing of 14 days samples	DS/EN-196-1	DTU Byg
19-04-2016	Flexural testing of 28 days samples	DS/EN-196-1	DTU Byg
19-04-2016	Compression test of 28 days samples.	DS/EN-196-1	DTU Byg
03-05-2016	Casting of 7 days samples	DS/EN-196-1	DTU Concrete Lab.
10-05-2016	Flexural testing of 7 days samples	DS/EN-196-1	DTU Byg
01-06-2016	Casting of mortar samples with Durus fibres and Fibrin fibres	DS/EN-196-1	DTU Concrete Lab.
29-06-2016	Flexural test of 28 days samples with Durus and Fibrin fibres	DS/EN-196-1	DTU Byg
29-06-2016	Compression test of 28 days samples with Durus and Fibrin fibres	DS/EN-196-1	DTU Byg

Table 4.1: Experimental log for mortar experiments

4.1 Materials

This section describes the materials used in the mortar mixture, the preparation of the PA6 fibres and fibres from *PP Nordica*.

4.1.1 Preparation of fibres

The nylon fibres from the waste fishing net was cut into two different length at 2 cm and 4 cm, as shown on Figure 3.3. The tolerance length of the fibres were set to ±5% of the length, in accordance to ASTM-C1557-14 (2014) The fibres were added to the mortar mixture at weight percentage of 0.5%, 1.0% and 2.0% respectively. This enabled the determination of which percentage was the optimal for the mixture.

To compare the PA6 fibres with polymer fibres used in the industry, PP Nordica kindly provided two kinds of fibres, one being a macro fibre called *Durus* and a micro fibre called *Fibrin Fiberflex*, shortened to *Fibrin* in this study, as shown on Figure 2.1a and 2.1b. The fibres from PP Nordica needed no preparation and were ready to mix at arrival.

4.1.2 Mortar mixture

The mortar mixtures were made according to the standard DS/EN-196-1 (2005) and the materials were prepared according to standard DS/EN-197-1 (2012), with the following composition seen in Table 4.2. The mortar mixture has a water/cement ratio of $w/c = 0.5$. Reference samples were made with no fibre content in order to compare the results.

Material	**Amount [g]**
Cement	450 ± 2
Water	225 ± 1
Sand	1350 ± 5
Total	2025 ± 8

Table 4.2: Mortar mixture

The cement type was Aalborg Portland Basis cement with a strength class of CEM II/A-LL 52.5 N(IS/LA/$\leq$ 2), meaning the cement have a minimum compressive strength of 52.5 MPa after 28 days of curing (Aalborg Portland A/S, 2012). The specification for the cement can be obtained in *Appendix 3*. The sand used in the mixture was dried sand with zero water content and the water was regular fresh water. The PA6 fibres that were mixed into the Fibre Reinforced Mortar (FRM) was based on the weight percentage of 0.5%, 1.0% and 2.0% of the total weight of the mixture. This gave the following fibre content, shown in Table 4.3.

Fibre content [%]	**Amount [g]**
0.5	10.13
1.0	20.25
2.0	40.50

Table 4.3: Fibre content in mortar mixture

For each mixture, three mortar samples were produced with a prism shape of size 40 x 40 x 160 mm for each mortar sample. These mortar samples were then tested after 28 days of curing. Furthermore, in order to see the effect of the fibres over the curing period, samples were made for 7 days, 14 days and 28 days with fibre length of 2 cm. Table 4.4 below gives an overview of which samples were to be produced during the study period.

Fibre Type	**Fibre content [%]**	**Curing period [days]**
2 cm	0.5	7, 14 and 28
2 cm	1.0	7, 14 and 28
2 cm	2.0	7, 14 and 28
4 cm	0.5	28
4 cm	1.0	28
4 cm	2.0	28
Durus	0.5	28
Durus	1.0	28
Durus	2.0	28
Fibrin	0.5	28
Fibrin	1.0	28
Fibrin	2.0	28
Reference	-	7, 14 and 28

Table 4.4: Overview of mortar samples to be produced

The mixing of the mortar mixture was performed on a Hobart Mixer, as shown on Figure 4.1.

Figure 4.1: Hobart Mixer used to mix the mortar mixture.

The procedure for the mixing of the reference mortar samples was done according to DS/EN-196-1 (2005) and a step by step procedure for the reference samples can be obtained in Table 4.5. The mixing period was a total of 4 minutes. After the mixing, the mixture was cast into mortar molds. The Hobart Mixer have four settings of speed: Off, 1, 2 and 3, with 3 being the fastest. Only the three first settings were used during the mixing process.

Time	**Action**	**Period [s]**	**Mixing rate**
T0 - T30	Cement + Water	30	1
↓			
T30 - T60	Add Sand	30	1
↓			
T60 - T90	Fast mix	30	2
↓			
T90 - T120	Scrap down	30	-
↓			
T120 - T180	Rest	60	-
↓			
T180 - T240	Fast mix	60	2

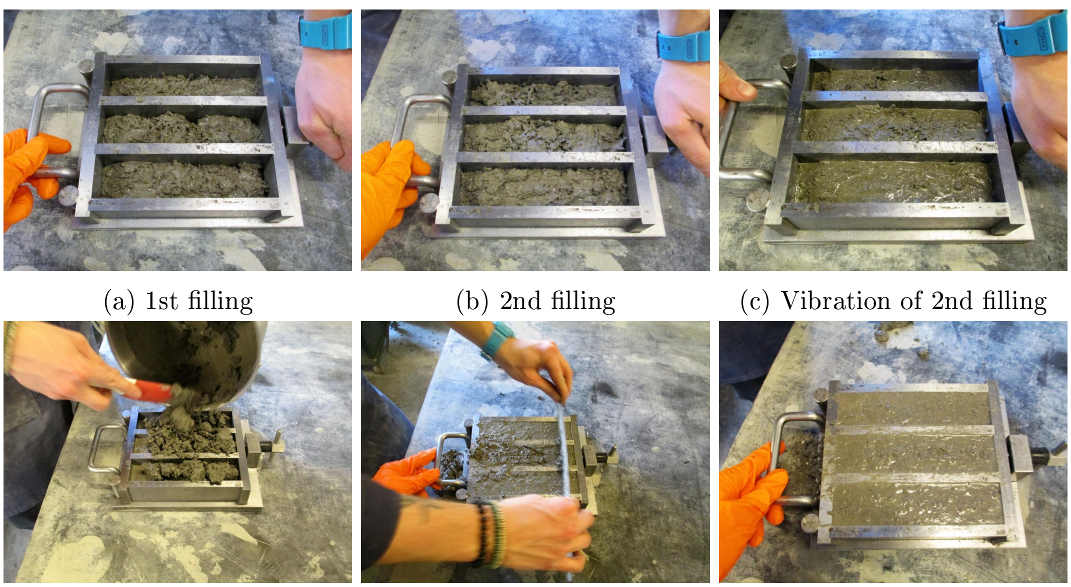
Table 4.5: Mortar mixing procedure for Reference samples

The step by step procedure for the mixing of the Fibre Reinforced Mortar (FRM) can be obtained in Table 4.6. The procedure was the same, but with the adding of fibres during the rest period.

Time	Action	Period [s]	Mixing rate
T0 - T30	Cement + Water	30	1
↓			
T30 - T60	Add Sand	30	1
↓			
T60 - T90	Fast mix	30	2
↓			
T90 - T120	Scrap down	30	-
↓			
T120 - T180	Rest	60	-
→	**Add Fibres**		
↓			
T180 - T240	Fast mix	60	2

Table 4.6: Mortar mixing procedure for FRM

After the 4 minutes mixing recipe, the mortar mixture were cast into molds using a vibrator table, where the molds were filled one third and vibrated for 30 seconds at 60 Hz. This was repeated until the molds were completely filled, and the excessive mortar was scraped off during the last vibration to get an even surface. This was done as seen on Figure 4.2. The samples were to cure in the molds for 24 hours, where the samples were then demolded and left to cure completely covered in water for the curing period of the respective samples.



(a) 1st filling (b) 2nd filling (c) Vibration of 2nd filling

(d) Last filling (e) Scrapping of excess mortar (f) Samples to cure in mold

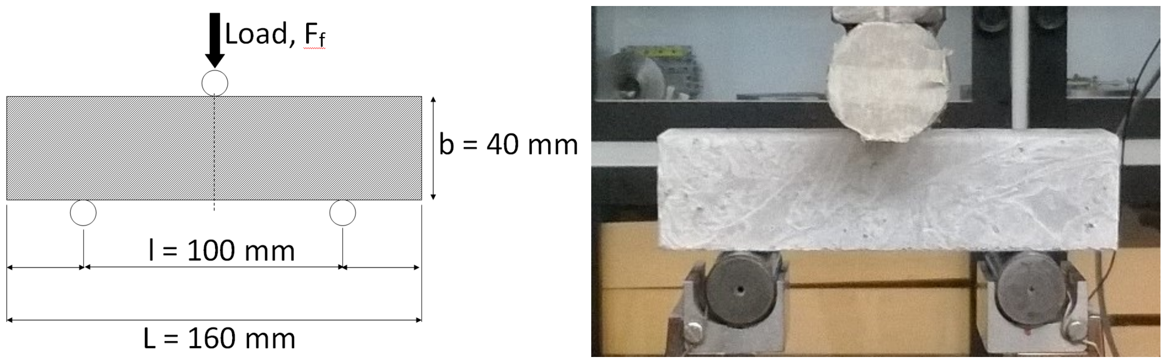
Figure 4.2: Selected steps in the casting procedure of mortar samples

4.2 Methods

In this section the mechanical properties of the mortar samples were investigated with the focus on flexural strength, toughness and compressive strength. For each mortar mixture there would be three results for the flexural strength and six results for the compressive strength. The final strength for flexural and compression would be an average of these results separately. However, if one of the six results for the compression strength deviated more than ±10% of the mean, that particular result was discarded and a new mean was calculated with the remaining results. This was repeated until all of the remaining results fulfilled the requirements.

4.2.1 Bending

To test the bending strength of the mortar samples a three point bending set-up was established. This was done on a hydraulic testing machine, Instron 6022, which recorded the working curve for each testing. The testing was done according to standard DS/EN-196-1 (2005), where load was applied at the middle of the mortar prism until fracture for the reference samples, or post-break strength starting to decrease significantly for the FRM samples. The load tempo was set to 2 mm/min downward deflection. The set-up has been illustrated on Figure 4.3a and actual experiment on Figure 4.3b.



(a) Sketch set-up (b) Actual set-up

Figure 4.3: Three point bending of mortar sample

To calculate the flexural strength of the mortar in MPa, R_f, was calculated by equation (4.1).

$$R_f = \frac{1.5 \cdot F_f \cdot l}{b^3} \tag{4.1}$$

Where F_f was the load applied to the middle of the prism at fracture [N], l was the distance between the supports [mm], and b was the side of the square section of the prism [mm].

The most interesting aspects of the working curve for FRM was the initial crack load, P_{cr}, the corresponding mid span deflection, δ_{cr}, and the post-break strength, P_{pb}, illustrated on Figure 4.4 as point A and B, respectively.

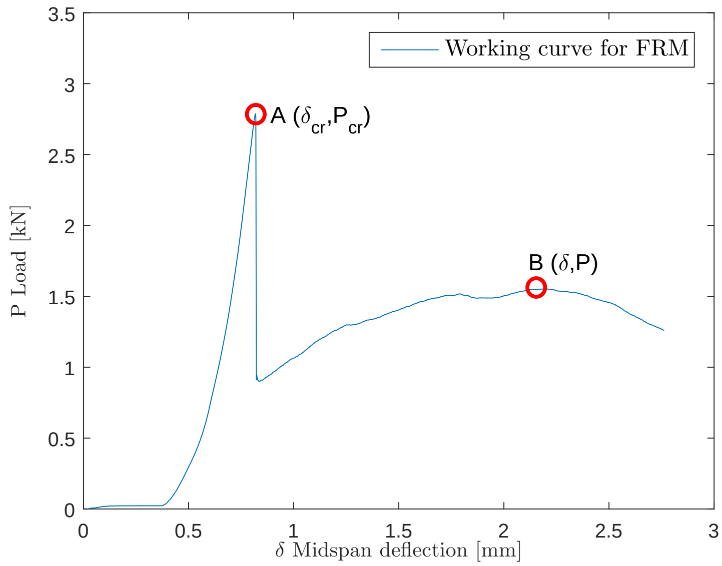


Figure 4.4: Working curve for FRM with maximum load (point A) and maximum post-break load (point B)

If the mortar was not reinforced with fibres, the load barring capacity would reach zero after the initial crack (point A), meaning the samples would break in two. Whereas the FRM would have a significantly load barring capacity after the initial crack. The area under the graph in Figure 4.4 has been defined as the flexural toughness, and so the FRM will have a significantly higher toughness then that of the reference samples.

4.2.2 Toughness

The flexural toughness can be calculated as the area under the load-deflection curve up to a target value of deflection, $\overline{\delta}$, by the following equation.

$$T_{\overline{\delta}} = \int_0^{\overline{\delta}} P\delta \, \mathrm{d}\delta \tag{4.2}$$

Using the standard of ASTM-C1018-97 (1993) to analyse the load-deflection curve for the mortar specimens. The following three toughness indexes are found to three specific values of deflection. First is the toughness value for the critical deflection $T_{\delta_{cr}}$.

$$T_{\delta_{cr}} = \int_0^{\delta_{cr}} P\delta \, \mathrm{d}\delta \tag{4.3}$$

This toughness value corresponds to the area shown on Figure 4.5

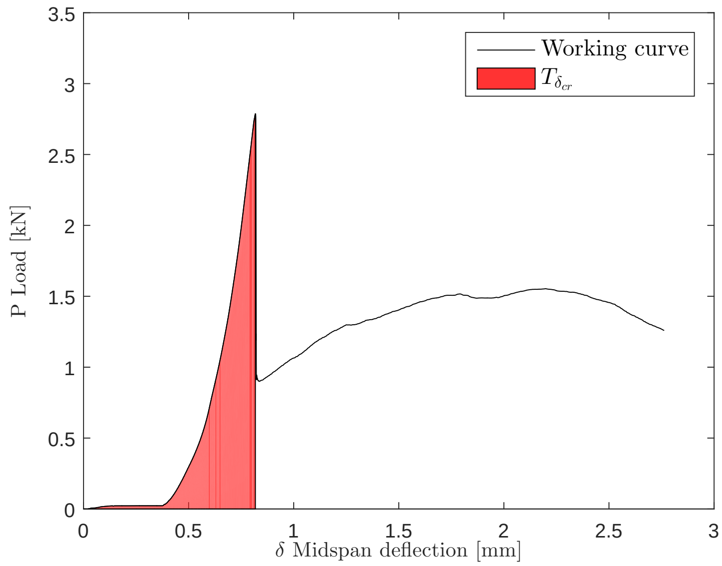


Figure 4.5: Toughness for value of δ_{cr}

The next toughness value is two times the critical deflection $T_{2\delta_2}$.

$$T_{2\delta_{cr}} = \int_0^{2\delta_{cr}} P\delta \, \mathrm{d}\delta \tag{4.4}$$

This toughness value corresponds to the area shown on Figure 4.6

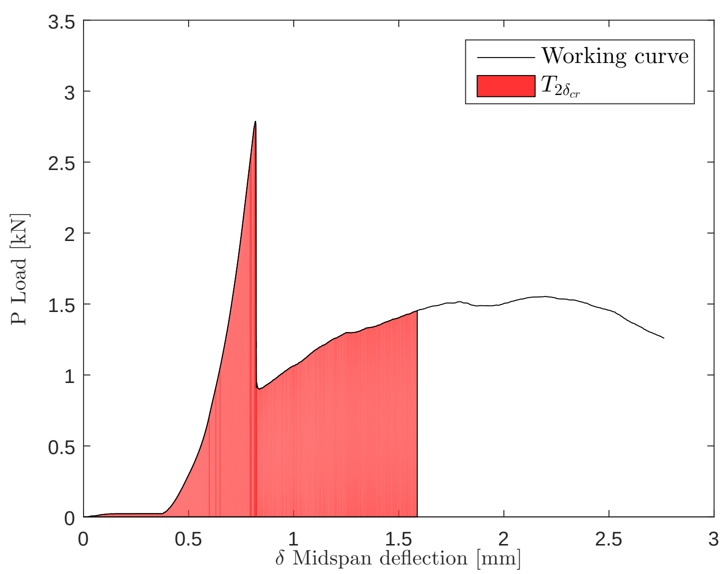


Figure 4.6: Toughness for value of $2\delta_{cr}$

The last toughness value is three times the critical deflection $T_{3\delta_{cr}}$.

$$T_{3\delta_{cr}} = \int_0^{3\delta_{cr}} P\delta \, \mathrm{d}\delta \tag{4.5}$$

This toughness value corresponds to the area for three times the critical deflection.

In line with the standard the following two toughness indices are introduced:

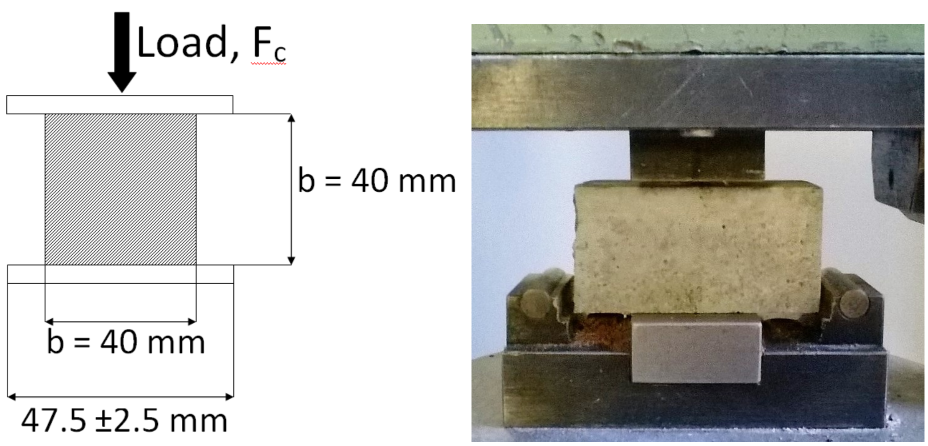
$$I_2 = \frac{T_{2\delta_{cr}}}{T_{\delta_{cr}}} \tag{4.6}$$

$$I_5 = \frac{T_{3\delta_{cr}}}{T_{\delta_{cr}}} \tag{4.7}$$

This provide an easy comparison between the toughness values before and after the initial crack.

4.2.3 Compression

The mortar samples were tested for compressive strength to see how the fibres affected this parameter. Polymer fibres in cement-based composites have a tendency to impair the compressive strength of the material. The potentially decrease in compressive strength is due to the highly deformable fibers assume the role of voids, which is known to impair the compressive strength. The mortar samples with fibres were compared to the reference samples without any fiber content. This was accomplished by following the standard of DS/EN 196-1 where load was applied on a $40x40$ mm surface of the prism until fracture. The sketch set-up has been illustrated on Figure 4.7a and the actual set-up on Figure 4.7b.



(a) Sketch set-up (b) Actual set-up

Figure 4.7: Compression of mortar sample.

Additionally the compression strength of the mortar in MPa, R_c, was calculated by equation (4.8).

$$R_c = \frac{F_{cm}}{b \cdot b} \tag{4.8}$$

Where F_{cm} was the load applied to a area of 40x40 mm of the prism at fracture [N] and b was the side of the square section of the prism [mm].

5 Results - Fibre

This chapter includes the the results from the experiments conducted to the PA6 fibres, as described in chapter 3. The raw data for the results can be obtained from *Appendix 4* to *Appendix 7*. In this Chapter the results are commented on, but the discussion and comparison of the results are presented in Chapter 7.

5.1 Preparation

The following sections contain the preparation of the fibres, which includes the washing, density, fibre size, and identification of the polymer (FTIR).

5.1.1 Washing

The washing of the fishing nets was done according to the description in **section 3.2.3**. A total of 4 washes was performed as the conductivity of the washed water reached the conductivity level of fresh water which was used to wash the fishing net. The results for the conductivity of the washed water and fresh tap water is presented in Figure 5.1. The conductivity of the fresh tap water was done in triplets to ensure the true conductivity of the water.

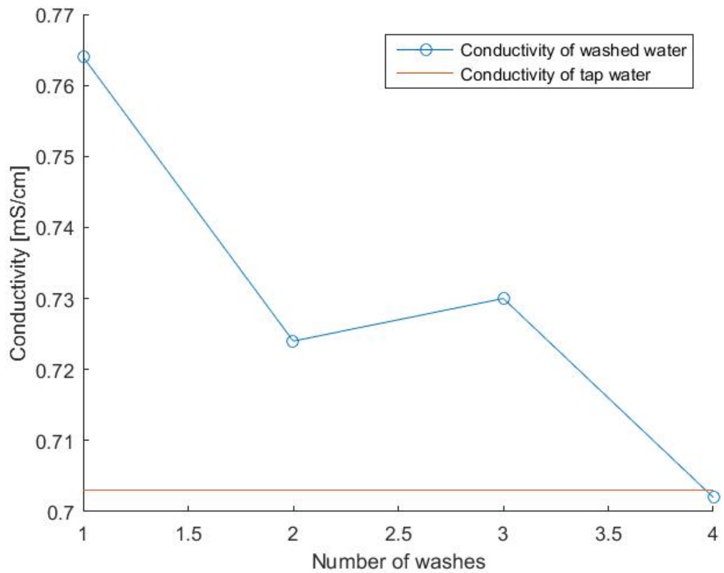


Figure 5.1: Conductivity of washed fishing net water

As the conductivity was reduced to the same level as the fresh tap water, it was assumed that all the impurities and salts are washed out of the fishing net and the fishing net were ready to be processed into fibres that can be mixed into the concrete mixture.

5.1.2 Density

The density was found by a pycnometer test and the density was made in triplets and the results are presented in Table 5.1 below and the detailed results is in *Appendix 4 - Pycnometer*.

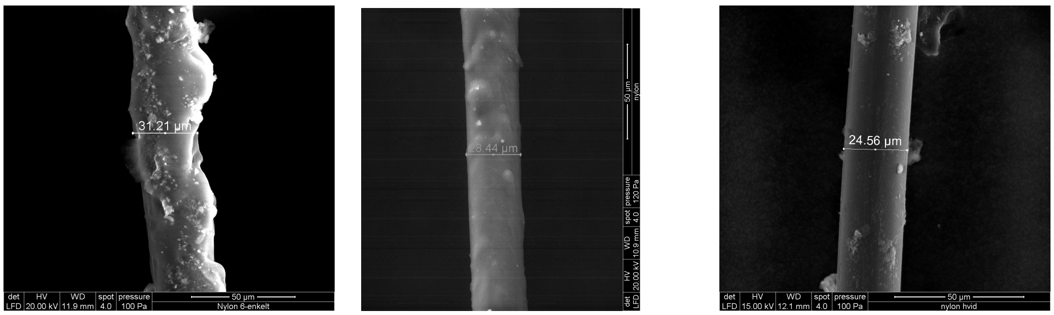
Sample	**Density** $[g/cm^3]$	**SD** $[g/cm^3]$
~~1~~	~~0.91~~	-
2	0.99	-
3	1.00	-
Mean	0.995	0.05

Table 5.1: Density of PA6 fibres

The first measuring, sample 1, of the density is outside the range of the mean minus the standard deviation. This is a considerable deviation and could be due to air trapped inside the polyfilament fibres. This would compromise the result and yield a lower density than the remaining samples, hence sample 1 has been discarded and the density is the mean of sample 2 and 3.

5.1.3 Fibre size

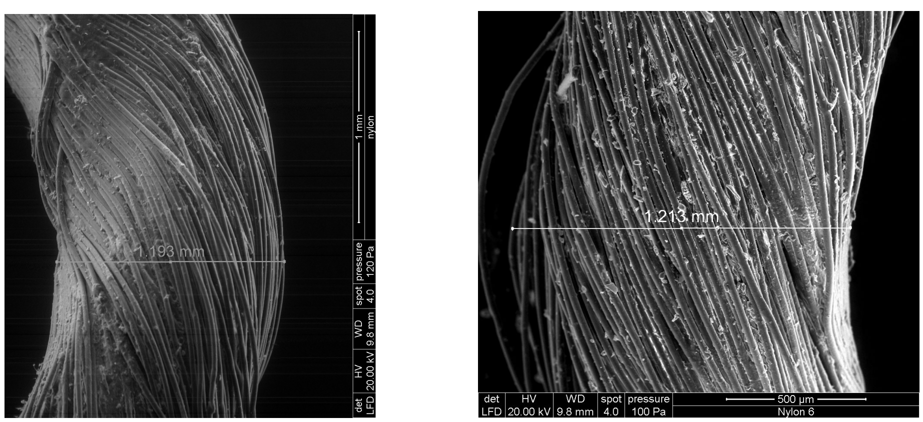
With the use of SEM images taking by a FEI - Quanta 200 machine, the diameter of a PA6 fibre bundle and a single PA6 fibre has been found to the following. The diameter of a single fibre was ranging between 25 μm to 31 μm, with the most appearing thickness of 28 μm. Therefore, the diameter of a single fibre was found to be approximately $d_{fibre} = 28\ \mu m = 2.8 \cdot 10^{-2}\ mm$. This is based on several SEM pictures of the waste PA6 fibres, as can be seen on Figure 5.2.



(a) Thickest (b) Average (c) Thinnest

Figure 5.2: SEM of single to show diameter differences, zoom x800

The diameter of a PA fibre bundle was found to be approximately $d_{bundle} = 1.2\ mm$, which is illustrated on Figure 5.3.



(a) PA6 fibre bundle x40 zoom (b) PA6 single fibre x65 zoom

Figure 5.3: SEM of waste PA6 fibre bundles

Assuming that the cross-section of all the single fibres are circular and that the cross-section of a fibre bundle is likewise circular, this gives a cross-section area of a PA6 fibre bundle of $A_{bundle} = 1.131\ \text{mm}^2$. This gives around 1800 single fibres per fibre bundle, meaning that the fibre bundles have a high degree of polyfilament.

5.1.4 FTIR

The FTIR analysis was performed at the Polymer Lab at the Department of Chemical and Biochemical Engineering on DTU. The spectra obtain for the collected waste PA6 fishing net is shown on Figure 5.4.

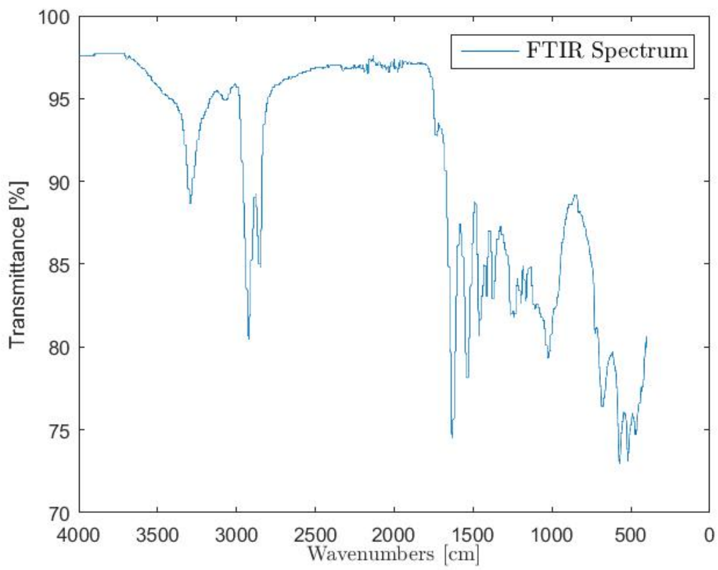


Figure 5.4: FTIR spectrum of collected nylon material.

Using the program OMNIC Specta it was found that the material was Nylon 6 with 83.2 % certainty. There were some noise on the spectrum at the low wavelengths, which can explain the lower certainty. This confirmed that the polymer was Nylon, as detected when the net was collected at the dumping site at Gilleleje Harbour. The FTIR data along with the library data can be seen in *Appendix 3 - FTIR*.

5.2 Mechanical Properties

This section covers the results from the mechanical tests of the PA6 fibres, which includes both tensile strength and elasticity modulus of the fibres.

5.2.1 Tensile Strength

The tensile strength was done accordingly to ASTM-C1557-14 (2014), but with the modification that the fibre bundle was tested and not the single fibre as it is the fibre bundle that is mixed into the mortar and therefore the strength of the bundle that is of interest. For all tensile strength testing a total of 8 specimens were tested.
When conducting the experiments it was noted that the fibres could break in two different ways. One where all the fibres broke simultaneously and one where they broke in steps.

This is due to the polyfilament of the fibres, which can results in varying working curves for the tensile strength. A working curve for a fibre bundle where all the single fibres break simultaneously has been illustrated on Figure 5.5. This is the desired working curve when the strength is to be considered.

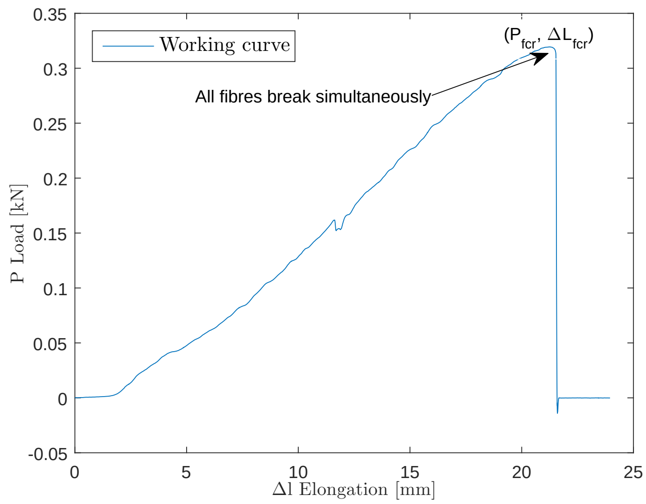


Figure 5.5: Correct working curve of PA6 fibre bundle

An example of a working curve for a fibre bundle where the single fibres do not break simultaneously can be seen on Figure 5.6. These results are left out when the breaking strength is calculated. However, this phenomenon can still occur when the fibres are working in the mortar samples, and as can be seen on Figure 5.6 these are not without any strength.

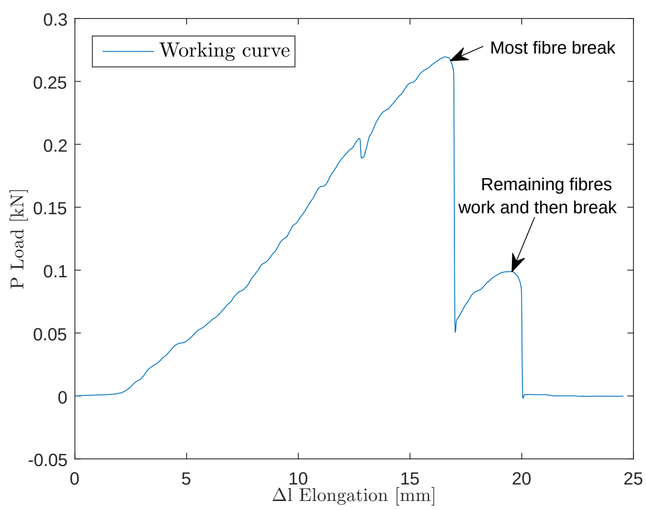


Figure 5.6: Incorrect working curve of PA6 fibre bundle

For the results of the the tensile Strength testing for fibres with gauge length of $l_0 = 20$ mm are presented in Figure 5.7, with a total of 8 test specimens.

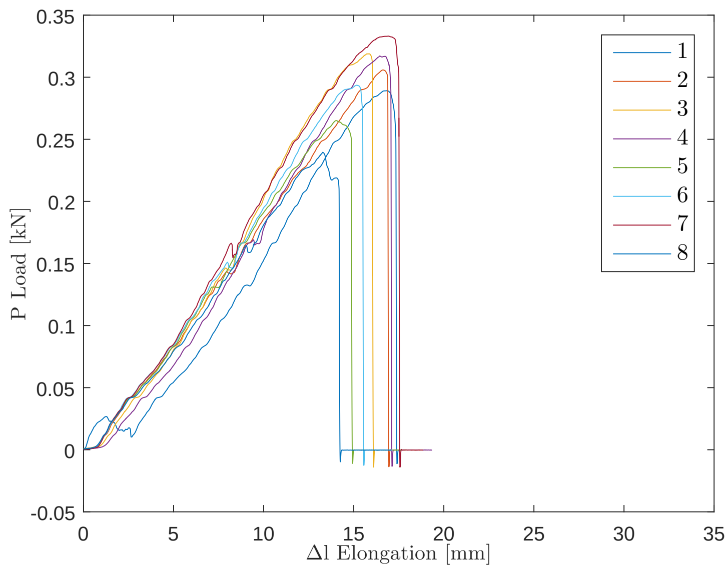


Figure 5.7: Working curves for PA6 fibres with 20 mm gauge length

From Figure 5.7 it can be seen that all the fibres break correctly as there are no fluctuations in the working curves.

Figure 5.8 presents the results for fibres with gauge length of $l_0 = 25$ mm.

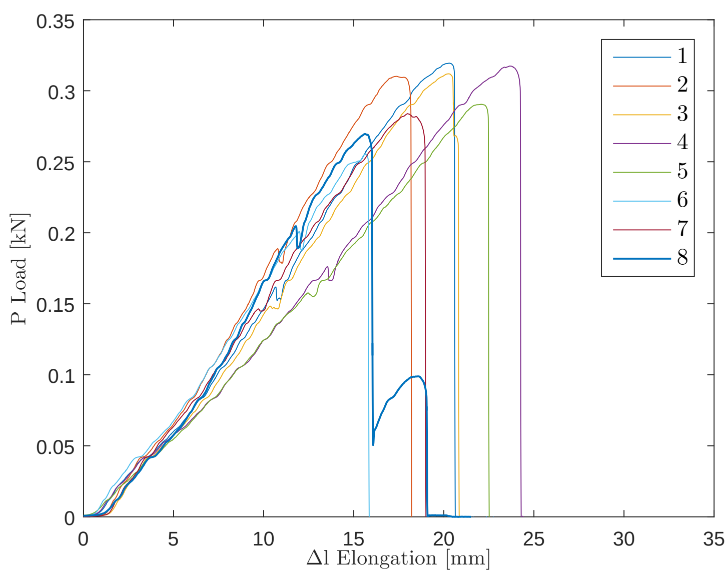


Figure 5.8: Working curves for PA6 fibres with 25 mm gauge length

From Figure 5.8 it can be seen that specimen "8" breaks incorrectly, and that particular result is left out when the mean strength is calculated.

Figure 5.9 presents the results for fibres with a gauge length of $l_0 = 30$ mm.

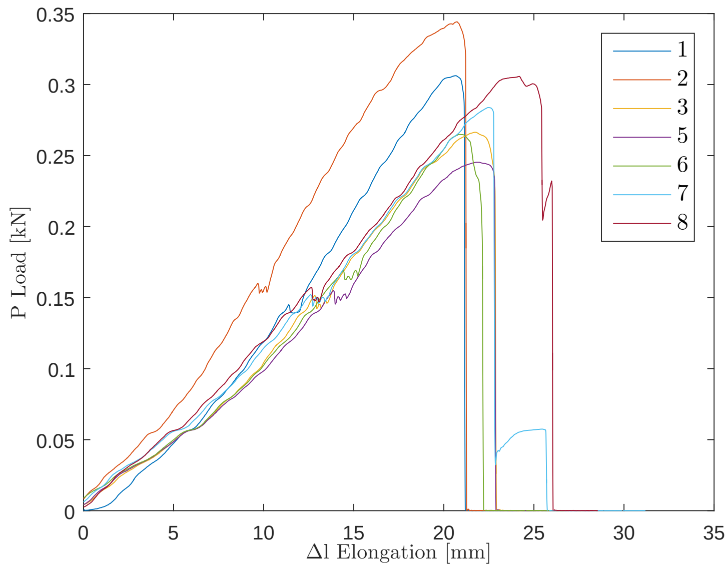


Figure 5.9: Working curves for PA6 fibres with 30 mm gauge length

From Figure 5.9 it can be seen that specimen "7" breaks incorrectly, and that particular result is left out when the mean strength is calculated. Specimen "4" was recorded incorrectly by the equipment and the sample were discarded.

Table 5.2 show the mean values for each gauge length of the waste PA6 fibre bundles. The strength, σ_t, was calculated using equation (3.1) with the area of being $A_{bundle} = 1.131$ mm. All the values for each test specimen can be obtained in Appendix 6.

l_0 **[mm]**	Δl_{cr} **[mm]**	F_{ff} **[kN]**	σ_t **[MPa]**	**SD [MPa]**
20	16.26	0.310	860	46.19
25	20.29	0.306	849	41.06
30	22.58	0.290	806	61.35
Mean	-	0.302	838	60.06

Table 5.2: Tensile strength test results for waste PA6 fibres

The standard deviation for the final result of 60.06, has been found by including all the correct results and not by an average of the standard deviations for "20", "25" and "30".

Based on the results for each of the test specimens the Young's modulus is found.

5.2.2 Young's Modulus

The Young's Modulus (E-modulus) is found by plotting the results from the tensile strength test, where the gauge length divided by the area is held against the critical elongation divided by the critical force. Figure 5.10 shows the result along with the linear regression between the data points and the corresponding equation for the linear regression.

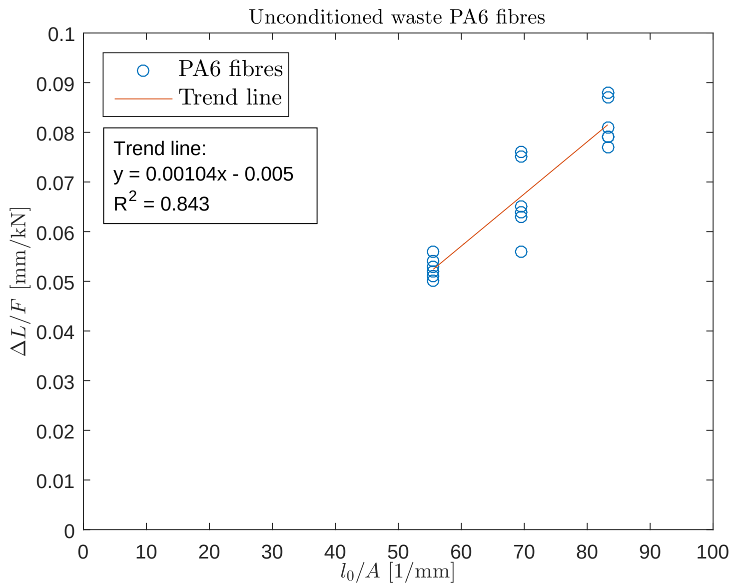


Figure 5.10: Young's Modulus for unconditioned waste PA6 fibres

From the equation of the trend line on Figure 5.10 it can be seen that the coefficient of determination, R^2, is 0.843. This means that 84 percent of the variance in the response variable is explainable, and the remaining 16 percent can be attributed to unknown, lurking variables or inherent variability. With large variation in recycled material, this is an acceptable result. Using equation (3.4) the linear regression of the data yields a straight line with the constant slope of $1/E$ (the inverse of the E-modulus). This gives an E-modulus of 961.5 MPa.

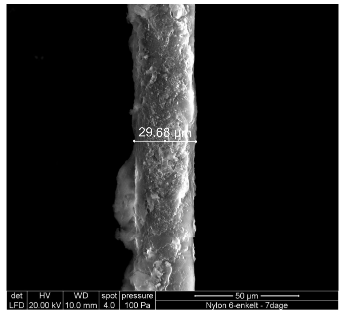
5.3 Alkali Resistance

This section includes the results for the alkali resistance of the waste PA6 fibres. The alkali resistance of the fibres is tested both for potentially volume and strength reduction.

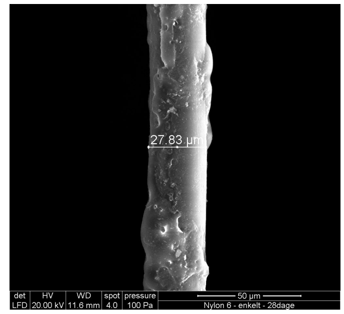
5.3.1 Volume

Waste PA6 fibres were immersed in a 1M NaOH solution for 0, 7, 14, 21, and 28 days at 40°C. This was done both for PA6 fibre bundles and single PA6 fibres. Figure 5.11 shows the SEM pictures for single fibres at 0 days, 7 days, and 28 days. The remaining SEM picture, and the ones below, can be obtained in larger size in *Appendix 6 - SEM of PA6 Fibres*.

(a) 0 days



(b) 7 days

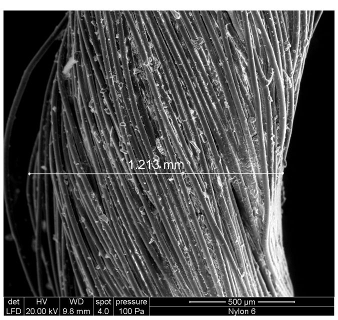


(c) 28 days

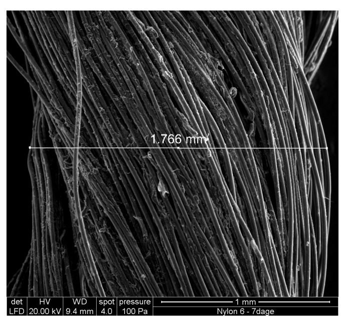
Figure 5.11: SEM of single waste PA6 fibre immersed in 1M NaOH solution, zoom x800

From Figure 5.11 it can be seen that the diameter of a single fibre have decreased from 31.21 μm at 0 days to 27.83 μm after 28 days, indicating a decrease in diameter of -10.8%. However, due to the small size of the fibres, it was somewhat impossible to find the same fibre and same section for each SEM image. In addition the fibres showed no, or very low, sign of disintegration during the 28 days exposure period. If any, the fibres became more streamlined as small impurities were removed. Therefore, the waste PA6 fibres showed good sign of alkali resistance when volume and mass reduction was considered.

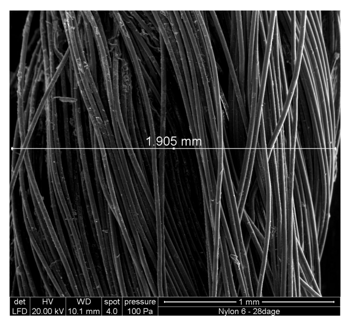
Looking at the waste PA6 fibre bundle, Figure 5.12 shows the SEM pictures for fibre bundle at 0 days, 7 days, and 28 days. The remaining SEM pictures, and the ones below, can be obtained in larger size in *Appendix 6*.



(a) 0 days, zoom x80



(b) 7 days, zoom x65



(c) 28 days, zoom x65

Figure 5.12: SEM of waste PA6 fibre bundle immersed in 1M NaOH solution, zoom x80 and x65

From Figure 5.12 it can be seen that the diameter of the fibre bundle increased from 1.213 mm to 1.905 mm. A smaller zoom value had to be used after immersing as the fibre bundle became less compact and the diameter increased, which were not expected. This is due to the fact that the PA6 fibre bundle are immersed into 1M NaOH in liquid form. When the highly polyfilament fibre bundle gets completely wet, the fibres spread out. The liquid is making the fibre bundle less compact, as can be seen clearly on Figure 5.12. This makes it difficult to estimate any volume or mass reduction for the PA6 fibre bundle. Judging from the SEM images, it is hard to see any disintegration of the fibres, which supports the theory

of high alkali resistance for nylon fibres.
It should be noted that the phenomenon with polyfilament fibres spreading out in liquid, is of no concern when they are mixed into the mortar mixture. The fibres are added to the mixture after the sand have been mixed in, making the mixture quite dense. Furthermore, the mixing process is only 4 minutes, which limit the chance of the polyfilament fibres to get separated.

5.3.2 Tensile Strength and Young's Modulus

To examine the strength perseverance of the waste PA6 fibres when exposed to a high alkali environment, tensile strength test was performed on waste PA6 fibre bundles immersed in a 1M NaOH solution for 28 days. The test was done according to section **3.2.5 - Alkali resistance** and ASTM-C1557-14 (2014)

The tensile strength testing for fibres with gauge length of $l_0 = 20$ mm are presented in Figure 5.13, with a total of 8 test specimens.

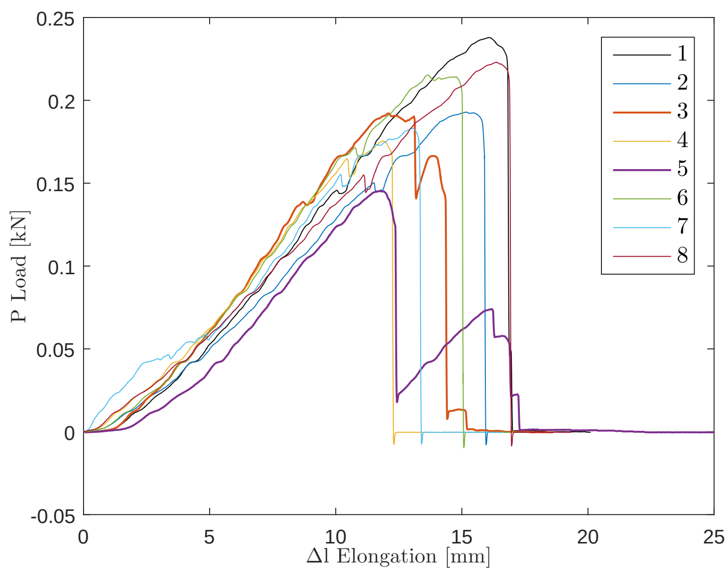


Figure 5.13: Working curves for PA6 fibres in 1M NaOH, with 20 mm gauge length

From Figure 5.13 it can be seen that most of the fibres break correctly, except specimen "3" and "5". These two results are left out when the tensile strength for alkali resistance fibres is calculated. In addition, it can be seen that the results are not as coinciding as the unconditioned samples on Figure 5.7.

Figure 5.14 presents the results for fibres with gauge length of $l_0 = 25$ mm.

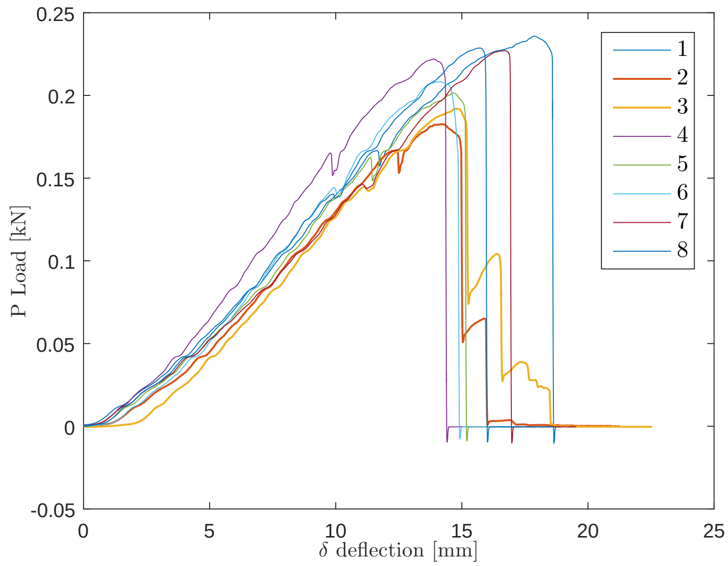


Figure 5.14: Working curves for PA6 fibres in 1M NaOH, with 25 mm gauge length

From Figure 5.14 it can be seen that specimen "2" and "3" break incorrectly, and these two results are left out when the mean strength is calculated.

Figure 5.9 presents the results for fibres with a gauge length of $l_0 = 30$ mm.

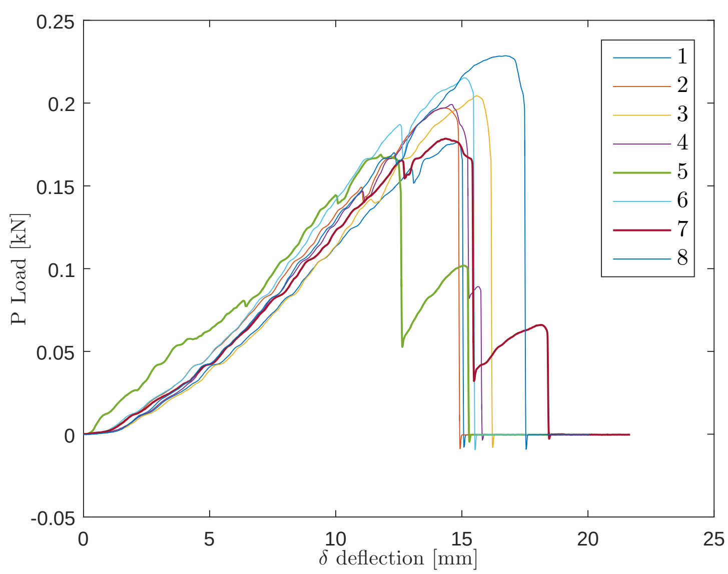


Figure 5.15: Working curves for PA6 fibres in 1M NaOH, with 30 mm gauge length

From Figure 5.15 it can be seen that specimen "5" and "7" break incorrectly, and the two results are left out when the mean strength is calculated. The results are more coinciding then on Figure 5.14.

Table 5.3 show the mean values for each gauge length of the waste PA6 fibre bundles immersed in 1M NaOH for 28 days. The strength, σ_t, was calculated using equation (3.1) with the area of being $A_{bundle} = 1.131$ mm. All the values for each test specimen can be obtained in *Appendix 6.*

ID	l_0 **[mm]**	Δl_{cr} **[mm]**	F_{ff} **[kN]**	σ_t **[MPa]**	**SD [MPa]**
1	20	15.14	0.210	585	61.9
2	25	15.98	0.221	613	36.3
3	30	14.96	0.203	565	49.1
Mean	-	-	0.211	587	50.51

Table 5.3: Tensile strength test results for waste PA6 fibres

From the results it can be obtained that for the fibres exposed to high alkalinity, there were considerably more fibres that broke incorrectly, then for the unconditioned fibres. Furthermore, the mean tensile strength was found to 587 MPa, which is a drop of 251 MPa or 30% for the fibres exposed to high alkalinity compared to the unconditioned fibres. The standard deviation for both tests are similar with 50.51 for the conditioned fibres and 60.06 for the unconditioned fibres. This indicates a lower alkali resistance for the waste PA6 fibres when it comes to strength preservation.

Young's Modulus

The Young's Modulus for the conditioned fibres is found the same way as for the unconditioned fibres. Figure 5.16 shows the result along with the linear regression between the data points and the corresponding equation for the linear regression.

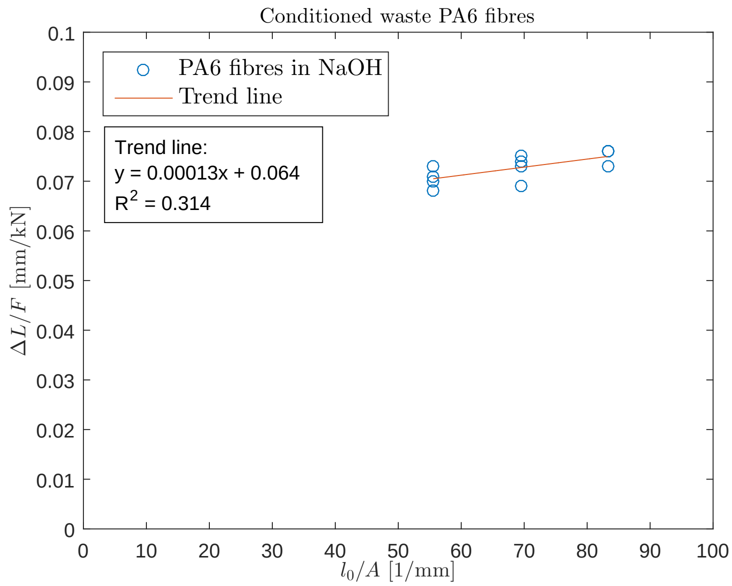


Figure 5.16: Young's Modulus for unconditioned waste PA6 fibres

From the equation on Figure 5.16 it can be seen that the coefficient of determination, R^2, is 0.314. This means that only 31 percent of the variance in the response variable is explainable. This is a considerable larger variation in the data. Using equation (3.4) the linear regression of the data gives an E-modulus of 7937 MPa. This is a very different result than for the unconditioned fibres with E-modulus of 961.5 MPa, and the result here of 7937 MPa is very questionable and corresponds with nothing similar from the literature. This could be a sign of lower alkali resistance or due to the immersion of the fibres in a liquid substance, which could have compromised the compactness of the polyfilament PA6 fibre bundles leading to this different result.

5.4 Thermal Properties

This section includes the results from the thermal properties of the PA6 fibres. The thermal properties of the waste PA6 fibres were of interest in respect to the fire resistance of cement-based composites.

5.4.1 Differential Scanning Calorimetry

To find the melting point of the waste PA6 fibre, Differential Scanning Calorimetry was performed. The result of the heating process of the PA6 fibre is illustrated on Figure 5.17.

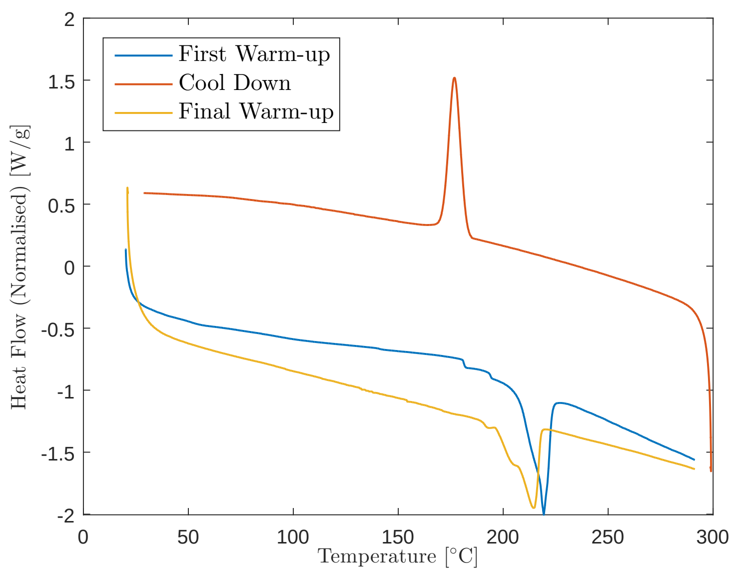


Figure 5.17: TGA of waste PA6 fibre

The graph of interest is the yellow line, Final Warm-up, which is the heating flow for the true polymer without impurities. The melting point is temperature corresponding to the lowest point of the Final Warm-up curve (yellow line on graph). From Figure 5.17 the melting point is $MP = 214.5°\text{C}$.

5.4.2 Thermal Gravimetric Analysis

Thermal Gravimetric Analysis was performed to find the ignition point of the PA6 fibre. The test was performed with start temperature of 20.00°C to 800.00°C with an increase of 10.00°C/min. The result for the TGA can be seen on Figure 5.18.

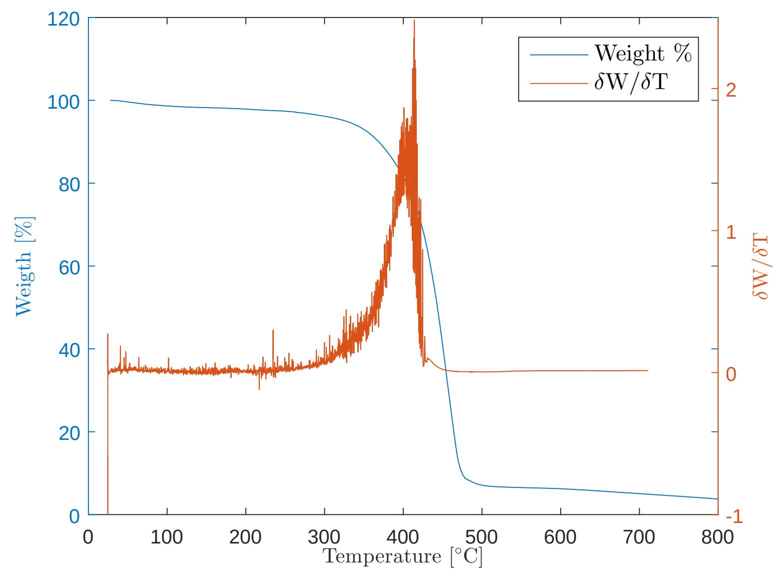


Figure 5.18: TGA of waste PA6 fibre

The loss of material starts to accelerate above 350°C, which is defined as the Ignition temperature. There are material loss at lower degrees, but this may be impurities that ignites at temperature lower than 350°C. After 480°C almost the whole material have been incinerated with only 8.68% of the starting mass left. The material is thermal stable at temperatures up to 350°C, but after the material starts to decompose quickly.

5.5 Summary of PA6 fibre results

This section summarize the results for the PA6 fibres and show the same characteristics for the macro (Durus) and micro (Fibrin Fiberflex) fibres from PP Nordica. The characteristics for the three different fibres are shown in Table 5.4. Full technical data sheets for the PP Nordica fibres, manufactured by ADFIL, can be obtained in *Appendix 2*.

Characteristic	**Units**	**PA6**	**Durus**	**Fibrin**
Density	[g/cm^3]	0.995	0.905	0.905
Melting Point	[°C]	215	165	165
Ignition temperature	[°C]	>350	>360	>360
Diameter	[mm]	1.2	0.9	0.022
Length	[mm]	20/40	45	13 - 19
Tolerance	[mm]	±1.0/±2.0	±2.0	±1.5
Tensile Strength	[MPa]	838	465	380
Tolerance	[MPa]	-84	-35	-100
Young Modolus	[MPa]	961	3350	-
Tolerance	[MPa]	-	-335	-
Alkali Resistance	-	Medium/High	High	High
Tensile Strength	[MPa]	588	-	-

Table 5.4: Characteristics of waste PA6 fibres, Durus and Fibrin Fiberflex fibres

6 Results - Mortar

This Chapter includes the results from the all the tests performed on the mortar samples. The chapter is divided into four sections containing; casting of mortar samples, the flexural strength, toughness, and compressive strength, respectively. The raw data from the results can be obtained in *Appendix 8* to *Appendix 11*. In this Chapter the results are commented on, but the discussion and comparison are saved for Chapter 8, where the results are held against previous research and studies within the same field.

6.1 Casting

The following section includes the casting of the mortar and the distribution of the waste PA6 fibres in the mixture. The mixing of the mortar samples went smoothly, except for one instance. It was not possible to produce the mortar mixture containing weight percentage of 2.0% 4 cm fibres, equivalent to 40.5 g of 4 cm fibres. The combination of the longer fibres and the high amount, caused the Hobart Mixer to stop abruptly doing the mixing process several times. The fibres affected the workability of the mixture to a degree where the Hobart Mixer could not follow, and in order not to damage the equipment the test was terminated prematurely. As the mixture could not be mixed according to the standard of DS/EN-196-1 (2005), the mixing was discarded. The mix was not tried to cast again as it was clear that the Hobart Mixer struggled to perform this mixture.

This experience and knowledge about the mixing process, was extended when casting the samples including Durus and Fibrin fibres from *PP Nordica*. Here it was clear that both the macro fibres, Durus, and the microfibres, Fibrin, affected the workability even further than the waste PA6 fibres. Hence, the mortar samples containing these fibres were cast with a relatively lower amount of fibres. Table 6.1 provides information of the mortar samples that were cast throughout the project period.

Fibre Type	Fibre content [%]	Curing period [days]	Comment
2 cm	0.5	7, 14 and 28	√
2 cm	1.0	7, 14 and 28	√
2 cm	2.0	7, 14 and 28	√
4 cm	0.5	28	√
4 cm	1.0	28	√
~~4 cm~~	~~2.0~~	~~28~~	Failure at mixing
Durus	0.1	28	√
Durus	0.2	28	√
Durus	0.5	28	√
Durus	1.0	28	Could barely mix
~~Durus~~	~~2.0~~	~~28~~	Was no cast
Fibrin	0.1	28	√
Fibrin	0.2	28	√
Fibrin	0.5	28	Could barely mix
~~Fibrin~~	~~1.0~~	~~28~~	Was no cast
~~Fibrin~~	~~2.0~~	~~28~~	Was no cast
Reference	-	7, 14 and 28	√

Table 6.1: Overview of produced mortar samples

When casting the mortar samples it was clear that samples containing Fibrin fibres could not extend 0.5% (10.13 g) and 1.0% (20.25 g) for the ones containing Durus. As an illustration, Figure 6.1 gives a clear visual that 1.0% was the absolute maximum of fibres in mortar samples.

(a) Casting of samples

(b) Mortar samples

Figure 6.1: 1% Durus fibre in mortar samples

From Figure 6.1a it can be seen that the fibres are in abundance, especially at the top. It was difficult to get an even surface on the samples as can be seen on Figure 6.1b.

6.1.1 Distribution of PA6 fibres in mixture

This section focus on the distribution of the waste PA6 fibres in the mortar samples. This has been done by examine tested mortar samples for fibres, in both transverse cross-section and longitudinal cross-section, where mortar samples have been cut down the middle. Starting with the longitudinal cross-section, this has been done for reference sample, 2 cm 0.5%, 2cm 1.0% and 2 cm 2.0%, illustrated in Figure 6.2, 6.3, 6.4 and 6.5, respectively. The samples that were cut, all had a crack line at the center because the samples were tested for flexural strength before cutting. For the samples containing fibres, the fibres have been highlighted using a darkblue marker to increase the visibility.

Figure 6.2: Longitudinal cross-section of reference sample.

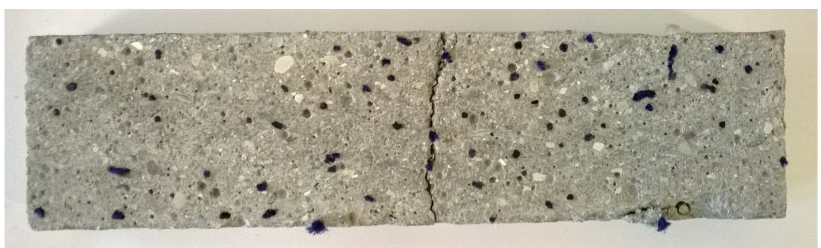


Figure 6.3: Longitudinal cross-section of sample containing 0.5% 2 cm fibres.

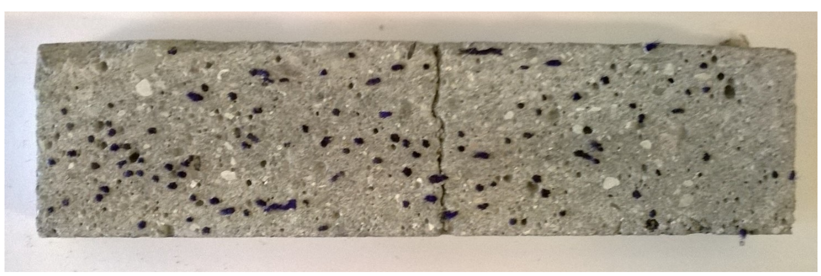


Figure 6.4: Longitudinal cross-section of sample containing 1.0% 2 cm fibres.

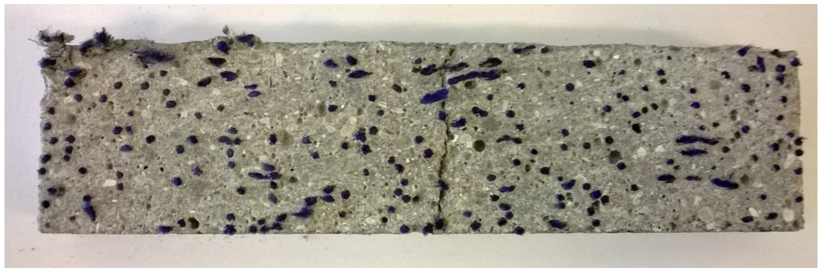
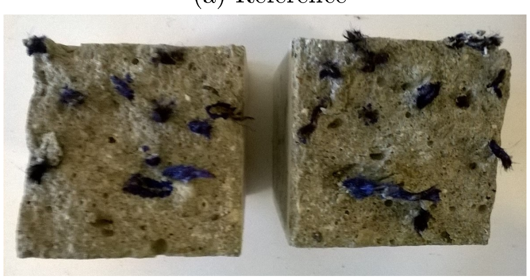


Figure 6.5: Longitudinal cross-section of sample containing 2.0% 2 cm fibres.

The mortar samples used to illustrate the fibres in the transverse cross-section, have all been tested for flexural strength where the samples were tested until breakage. This made it possible to separate the two halfs and look at the distribution of fibres along the cross-section. The transverse cross-section of reference sample, 2 cm 0.5%, 2cm 1.0% and 2 cm 2.0%, are all illustrated in Figure ??.

(a) Reference

(b) 2 cm 0.5%



(c) 2 cm 1.0%

(d) 2 cm 2.0%

Figure 6.6: Transverse cross-section of mortar samples with PA6 fibres

In order to get an overview of the waste PA6 fibres in the mortar samples, Table 6.2 shows the number of fibres in the different cross-sections.

Sample ID	Ref.	2 cm 0.5%	2 cm 1.0%	2 cm 2.0%
Longitudinal fibres	0	58	102	186
Transverse fibres	0	8	12	19

Table 6.2: Number of visible fibres in cross-section of mortar samples.

Table 6.2 shows that when the amount of fibres are doubled the number of visible fibres in each cross-section is likewise close to double as well. From the figures it can be seen that the waste PA6 fibres distributes evenly throughout the mortar samples for weight percentage of up to 2% with a length of 2 cm. Only Figure 6.4 showed a little sign of clumping of the fibres at the left side, but fibres are still present throughout the samples. As long as the mixing could be done according to DS/EN-196-1 (2005) the fibres were mixed properly into the mixture.

6.2 Flexural Strength

This section includes the results for the flexural strength of the mortar samples. The flexural strength was tested using three-point bending performed on an Instron 6022 hydraulic machine, which recorded the working curve for each sample. The test was done accordingly to the standard of DS/EN-196-1 (2005). The load tempo of the machine was set to 2 mm/min downward extension and terminated when the post break strength started to decrease significantly.

The first aspect was to see the effect of the PA6 fibres in the mortar mixture over the curing period. This was done by comparing the flexural strength of mortar samples with fibres for 7, 14 and 28 days of curing and compare with the reference samples. The average flexural strengths values for 7, 14 and 28 days samples are presented later in Table 6.3 along with the reference samples. These samples contain 2 cm PA6 fibres of weight percentage 0.5%, 1.0% and 2.0% respectively. The working curve for the 7 days samples are presented on Figure 6.7. All the working curves can be obtained in *Appendix 8* as individual working curves for a better overview.

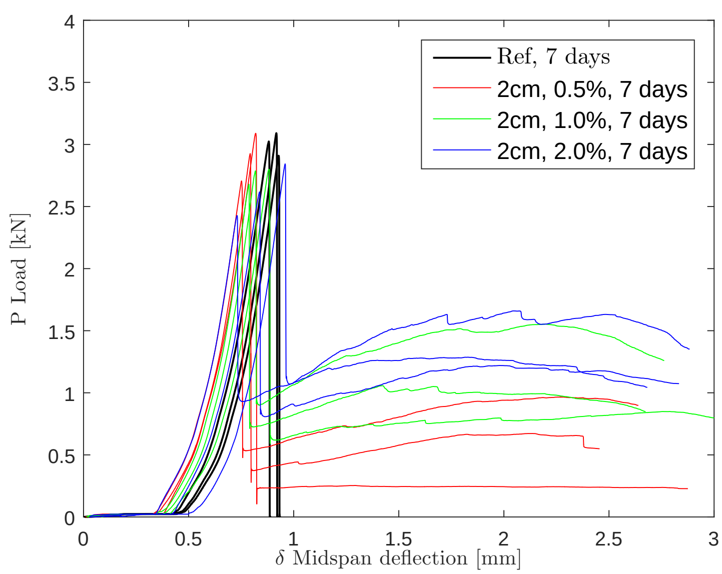


Figure 6.7: Working curve for all 7 days samples with 2 cm PA6 fibres.

From Figure 6.7 it can clearly be observed that there is an increase in energy that can be absorbed by the mortar samples containing fibres. The Reference samples (black lines) with no fibre content drops to zero immediately after the initial crack , whereas the FRM samples have significantæy load bearing capacity after the initial crack. It can further be observed that the post-crack strength increases with increased fibre content. The working curve for the 14 days samples are presented on Figure 6.8, and for the 28 days samples on Figure 6.9 and 6.10.

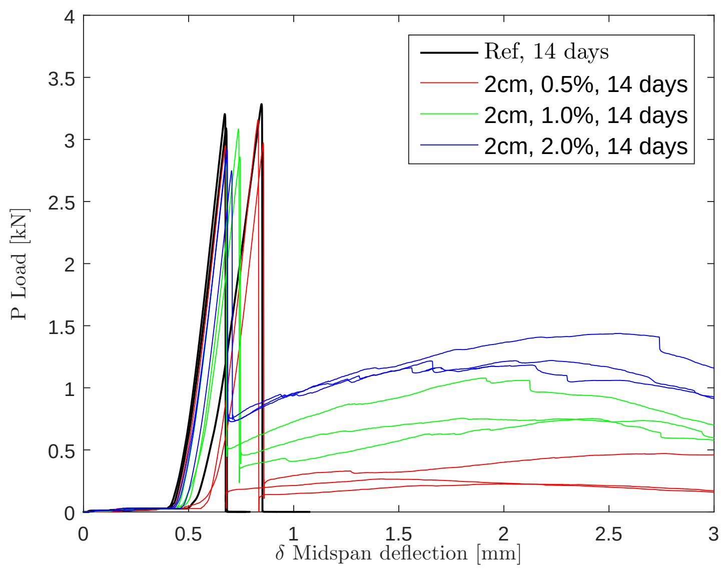


Figure 6.8: Working curve for all 14 days samples with 2 cm PA6 fibres.

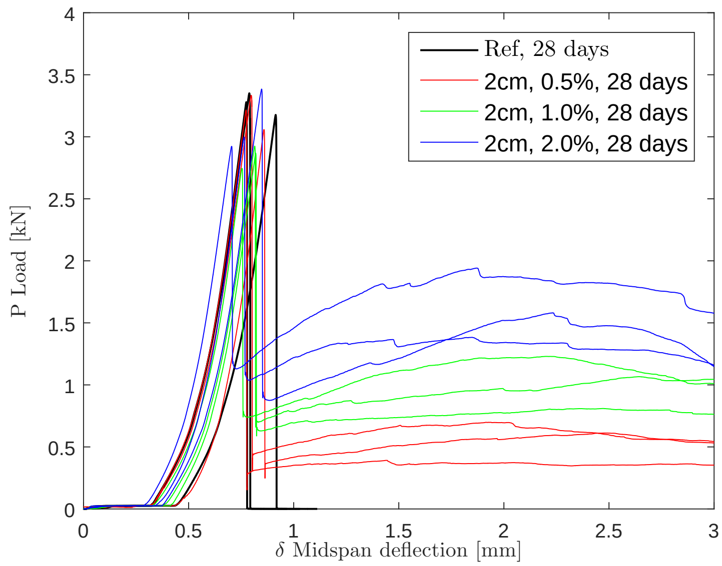


Figure 6.9: Working curve for all 28 days samples with 2 cm PA6 fibres.

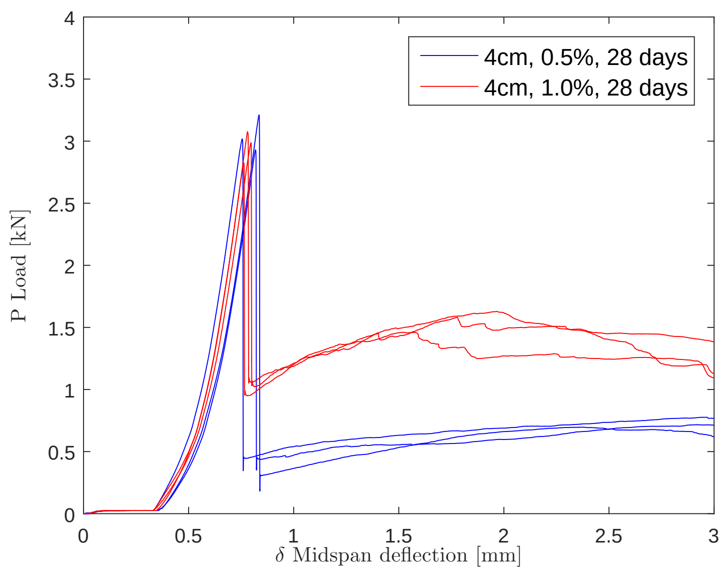


Figure 6.10: Working curve for all 28 days samples with 4 cm PA6 fibres.

Looking at the initial cracks, it can be seen that the strength increases over time, due to the curing of the cement in the mortar samples. However, to get a better overview of the initial crack strength of the mortar samples, a bar chart has been made to show the development of strength over time, and strength for the different fibre content. Each bar shows the mean initial crack strength along with the corresponding standard deviation. The bar chart is divided into groups showing the different fibre content with different colors for each curing period, with yellow being 7 days, orange being 14 days and red being 28 days of curing. The strength has been calculated using equation (4.1) and the full results for all the samples can be obtained in *Appendix 8* and *Appendix 9*.

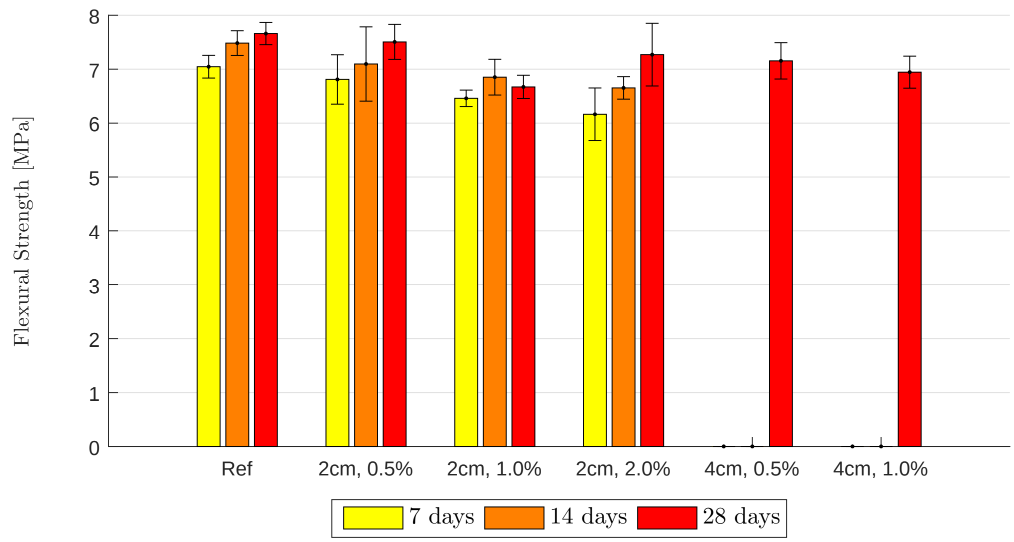


Figure 6.11: Bar chart showing the flexural strength of 7, 14 and 28 days mortar samples with variating fibre content.

The bar chart shows an increase in flexural strength over time for all the samples except "$2cm, 1.0\%$" where the 28 days samples are weaker than the 14 days samples. It can be seen that the waste PA6 fibres does not increase the flexural strength, as all the values are lower than the corresponding reference sample. It is noticeable that all the standard deviations are larger for the samples containing fibres than for the reference samples, as would be expected as the distribution of fibres can vary for each cross-section in each samples, which results in a larger uncertainty of the initial strength.

Tests were also done with fibres from *PP Nordica* to compared the waste PA6 fibres with industrial synthetic fibres. The working curve for the mortar samples with Durus and Fibrin fibres are presented in Figure 6.12 and 6.13.

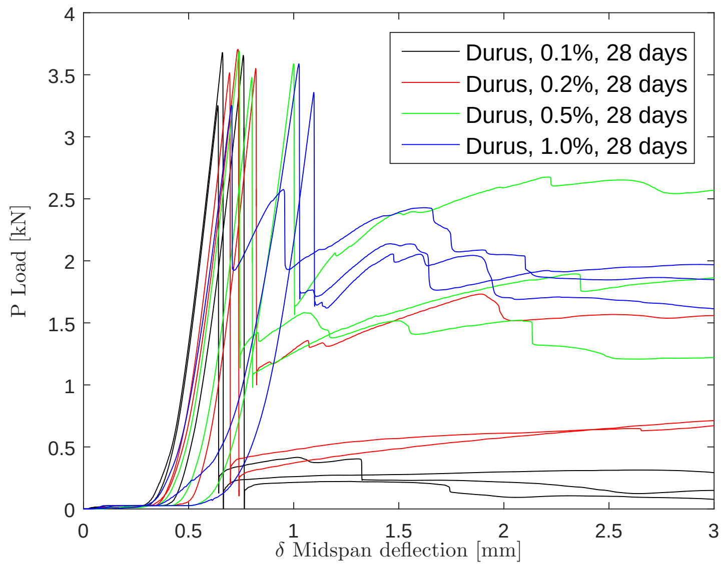


Figure 6.12: Working curve for all 28 days mortar samples with Durus fibres.

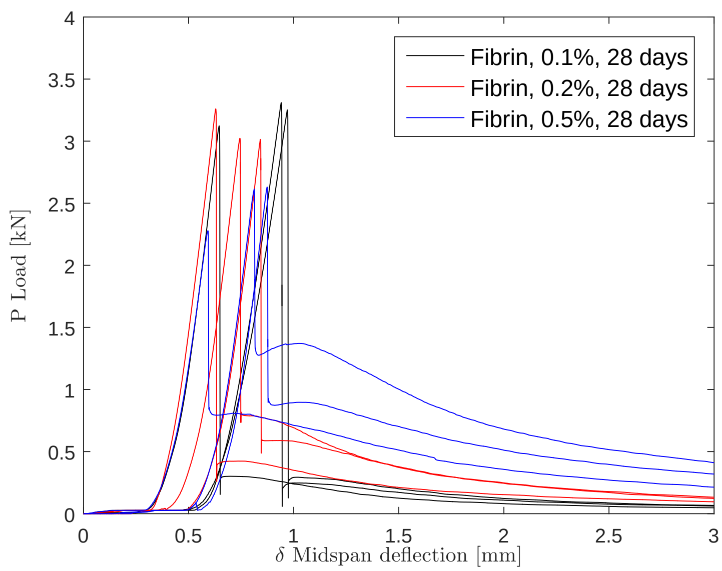


Figure 6.13: Working curve for all 28 days mortar samples with Fibrin fibres.

The working curves for the mortar samples with Durus fibres are similar to the ones of waste PA6 in some aspects, but it can clearly be seen that working curves with Durus fibres are more "bumpy", due to Durus being monofilament fibres which makes the breaking of the fibres more instant. The breaking of the Durus fibre is visible each time the working curves drops instantly in strength.

On Figure 6.13 it can be observed that the mortar samples containing Fibrin fibres behave differently, with a much faster decrease in post-strength behavior. From Figure 6.12 and 6.13 the initial flexural strengths have been extracted and presented in a Bar chart with corresponding standard deviation for each group. The initial flexural strengths are presented in Figure 6.14.

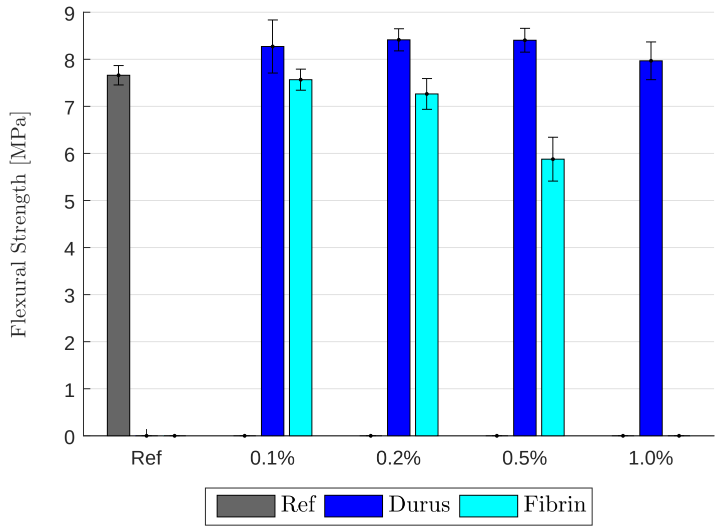


Figure 6.14: Bar chart showing the flexural strength of 28 days mortar samples with Durus and Fibrin fibres.

From Figure 6.14 it can be seen that the flexural strength is much higher for the samples containing Durus fibres than the ones with Fibrin fibres. Further, it can be observed that the mortar samples with Durus fibres have an increase in flexural strength when comparing with the reference samples, which is true for all the samples containing Durus fibres.

Table 6.3 provides an overview of the crucial data points from the working curves. The Table shows the results from all the mortar samples. The table shows the critical mid span deflection, δ_{cr}, the initial crack load, P_{cr}, the initial crack strength, R_F, with the standard deviation, as well as percentage of the strength compared to the corresponding reference samples. The Table further includes the maximum post-break load, P_{pb}, and the maximum post-break strength, R_{pb}. The strengths have been found using equation (4.1). The full results for all the samples can be seen in *Appendix 9*.

Curing	**ID**	δ_{cr} **[mm]**	P_{cr} **[kN]**	R_F **[MPa]**	SD **[MPa]**	% **of Ref**	P_{pb} **[kN]**	R_{pb} **[MPa]**
7 Days	Ref	0.91	2.97	7.05	0.21	100.0	-	-
	2 cm, 0.5%	0.79	2.91	6.81	0.46	96.7	0.63	1.47
	2 cm, 1.0%	0.86	2.76	6.46	0.15	91.7	1.15	2.70
	2 cm, 2.0%	0.84	2.63	6.16	0.49	87.5	1.39	3.26
14 Days	Ref	0.73	3.19	7.48	0.23	100.0	-	-
	2 cm, 0.5%	0.79	3.03	7.10	0.69	94.8	0.32	0.75
	2 cm, 1.0%	0.71	2.92	6.85	0.31	91.6	0.86	2.02
	2 cm, 2.0%	0.69	2.84	6.65	0.21	88.9	1.28	3.00
28 Days	Ref	0.83	3.27	7.66	0.21	100.0	-	-
	2 cm, 0.5%	0.81	3.20	7.51	0.33	98.0	0.57	1.33
	2 cm, 1.0%	0.80	2.85	6.67	0.22	87.1	1.04	2.43
	2 cm, 2.0%	0.77	3.10	7.27	0.58	94.9	1.64	3.83
	4 cm, 0.5%	0.79	3.05	7.16	0.34	93.4	0.75	1.75
	4 cm, 1.0%	0.78	2.96	6.95	0.30	90.7	1.56	3.65
	Durus, 0.1%	0.69	3.53	8.27	0.56	108.0	0.32	0.74
	Durus, 0.2%	0.75	3.59	8.41	0.24	109.8	1.09	2.56
	Durus, 0.5%	0.85	3.59	8.41	0.25	109.7	2.06	4.82
	Durus, 1.0%	0.94	3.40	7.97	0.40	104.0	2.26	5.29
	Fibrin, 0.1%	0.85	3.23	7.57	0.22	98.8	0.28	0.66
	Fibrin, 0.2%	0.88	3.10	7.26	0.33	94.8	0.61	1.44
	Fibrin, 0.5%	0.76	2.51	5.88	0.47	76.7	1.08	2.52

Table 6.3: Flexural strength for all mortar samples

From Table 6.3 it can be seen that the only fibres that increase the initial flexural strength of the mortar is the Durus fibres with an increase of +4 to +9 %. The waste PA6 fibres reduce the flexural strength with approximately -5 to -10%, and the Fibrin fibres reduced the flexural strength with -23.3% at fibre content of 0.5%. For the post-break strength it can be seen that R_{pb} increases with the increase of fibres, which is also illustrated in the working curves. It is notable that adding the waste PA6 fibres makes the mortar samples maintain up to 50% of the initial crack strength at 2.0% fibre content. This effect was larger for the Durus fibres, which were able to maintain up to 66% of crack strength at 1.0% fibre content.

Furthermore, it can be seen that there is no significant difference in the initial flexural strength for the different length of fibres. Although the working curves on Figure 6.10 indicates that the samples containing 4 cm fibres have a better grab in the mortar as the post-strength curve is more linear and the post-break strength is slightly higher for the 4 cm fibres compared to the 2 cm fibres.

6.3 Toughness

The flexural toughness are used to measure the flexural capacity of the FRM samples before and after the initial crack, and see which fibre content and length perform best in this regard. The mean toughness values extracted from the graphs on Figure 6.7, 6.8, and 6.9 for the 2 cm PA6, Figure 6.10 for 4 cm PA6, and Figure 6.12 and 6.13 for Durus and Fibrin. The toughness values have been found using equation (4.3), (4.4) and (4.5) for the critical value of δ_{cr}, $T_{\delta_{cr}}$, $T_{2\delta_{cr}}$ and $T_{3\delta_{cr}}$. Likewise have the toughness indexes I_2 and I_5 been found using equation (4.6) and (4.7). The results of the mean values are presented in Table 6.4 below. All toughness values for each individual sample can be obtained in *Appendix 10*.

Curing	**ID**	δ_{cr} **[mm]**	$T_{\delta_{cr}}$ **[Nmm]**	$T_{2\delta_{cr}}$ **[Nmm]**	$T_{3\delta_{cr}}$ **[Nmm]**	I_2 **[-]**	I_5 **[-]**
7 Days	Ref	0.908	483	-	-	-	-
	2 cm, 0.5%	0.788	431	834	1302	1.97	3.10
	2 cm, 1.0%	0.863	429	1276	2216	2.97	5.17
	2 cm, 2.0%	0.842	405	1421	2564	3.48	6.28
14 Days	Ref	0.732	396	-	-	-	-
	2 cm, 0.5%	0.788	342	538	774	1.57	2.26
	2 cm, 1.0%	0.719	317	746	1313	2.37	4.19
	2 cm, 2.0%	0.689	299	963	1790	3.23	6.02
28 Days	Ref	0.826	548	-	-	-	-
	2 cm, 0.5%	0.809	514	969	1466	1.91	2.91
	2 cm, 1.0%	0.795	430	1090	1864	2.54	4.35
	2 cm, 2.0%	0.772	493	1481	2681	3.04	5.50
	4 cm, 0.5%	0.787	499	897	1403	1.80	2.82
	4 cm, 1.0%	0.775	469	1467	2592	3.13	5.55
	Durus, 0.1%	0.687	470	692	819	1.49	1.76
	Durus, 0.2%	0.752	489	1086	1795	2.26	3.75
	Durus, 0.5%	0.847	524	2021	3727	3.80	7.00
	Durus, 1.0%	0.941	586	2439	4224	4.22	7.31
	Fibrin, 0.1%	0.852	487	705	760	1.50	1.57
	Fibrin, 0.2%	0.879	394	812	987	2.07	2.51
	Fibrin, 0.5%	0.759	288	991	1416	3.40	4.86

Table 6.4: Mean Toughness index for all mortar samples

There is a clear increase in toughness for the FRM samples compared to the reference samples, as the reference samples only have toughness until the initial crack. Further, it can be seen that the toughness increases with the amount of fibre in the mortar samples, with the highest values for the samples with the highest amount of fibres. For all samples the toughness index I_2 and I_5 are increasing with the increase of fibres. As with the flexural strength the best toughness values are for the mortar samples containing Durus fibres. The waste PA6 fibres perform better than Fibrin fibres, but not as well as Durus.

Comparing the fibre length of PA6, it can be derived that for 1.0% samples the 4 cm fibres perform better after the initial crack than the 2 cm fibres, due to the toughness values and indexes are higher then for any of the other samples with 1.0%. However, for the 0.5% samples the results are very similar for the 4 cm and 2 cm fibres. Toughness-wise there does not seem to be a significantly difference between the two lengths of fibres.

6.4 Compression

The compressive strength of the mortar samples was done in order to see the effect of the fibres. The FRM samples with PA6 fibres are held against reference samples with no fibre content and samples with Durus and Fibrin fibres.
For the 28 days sample compression was done on a Mohr & Federhaff AG mortar testing machine following the standard of DS/EN-196-1 (2005), which gave the following strength averages shown as a bar chart in Figure 6.15 with corresponding standard deviation. The strength was calculated using equation (4.8). The compressive strength results for all the 28 days mortar samples can be seen in *Appendix 11*.

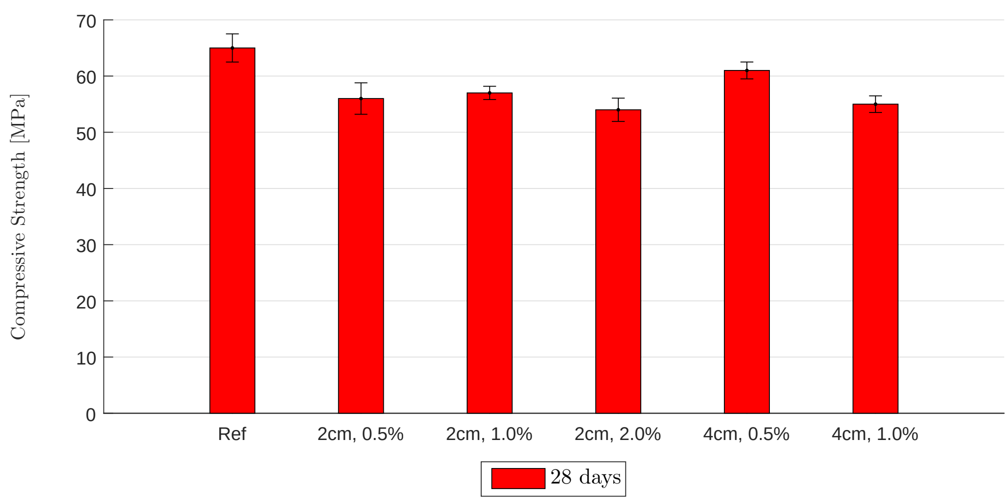


Figure 6.15: Bar chart showing the compressive strength of 28 days mortar samples.

Figure 6.15 shows that for all the sample groups the Reference samples have the highest compressive strength. There is a decrease in compressive strength when the fibre content is increased, although $2cm1.0\%$ is a little higher than $2c, 0.5\%$. The decrease in strength is lower for $4cm0.5\%$ compared to $2cm0.5\%$, but the trend is not repeated at 1.0% fibre content where the two fibre lengths are very similar.

For comparison with the industrial fibres, the same compression tests were performed on the mortar samples containing Durus and Fibrin fibres. A bar chart has been made of the compressive results with mean compressive strength for the different fibre content and the corresponding standard deviation. The bar chart can be seen on Figure 6.16 and all the results for the individual samples can be obtained in *Appendix 11*.

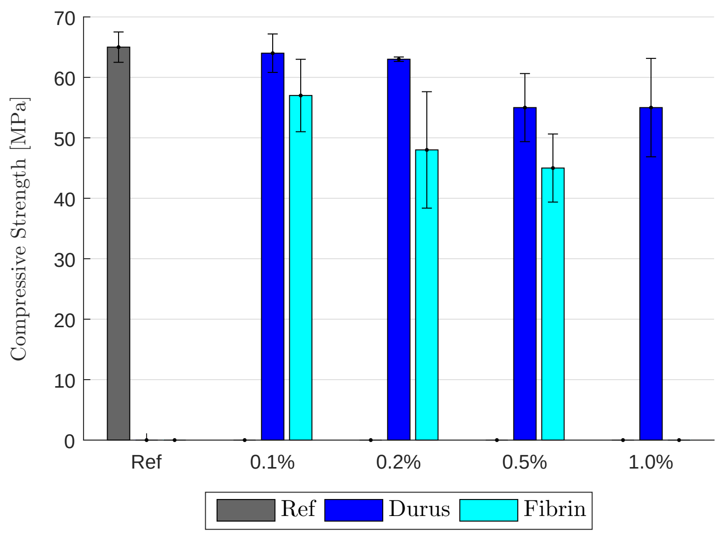


Figure 6.16: Bar chart showing the compressive strength of 28 days mortar samples with Durus and Fibrin fibres.

From the bar chart it can be seen that the Durus fibre only have a very small reduction at the low fibre amounts of 0.1%, 0.2%, but at 0.5%, 1.0% the results are similar to that of the waste PA6 fibres. Further it can be seen that the Fibrin fibres impair the compressive strength even at relative low fibre contents of 0.1%, 0.2% and further at 0.5%.

The values from the compressive tests can be seen in Table 6.5, which shows the exact values from Figure 6.15 and 6.16 along with the compressive strength as percentages of the strength of the reference samples.

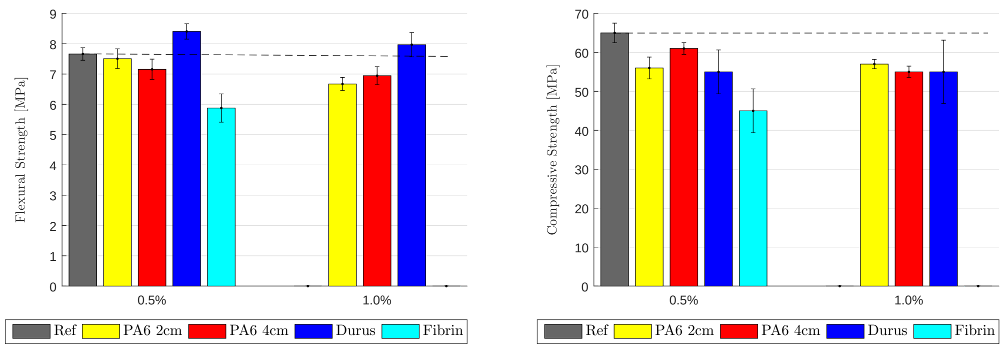
Sample ID	F_c **[kN]**	R_c **[MPa]**	**SD [MPa]**	**% of Ref**
Ref	103.3	65	2.51	100.0
2 cm, 0.5%	90.2	56	2.80	87.4
2 cm, 1.0%	91.8	57	1.18	88.9
2 cm, 2.0%	85.6	54	2.07	82.9
4 cm, 0.5%	96.8	61	1.50	93.8
4 cm, 1.0%	88.7	55	1.48	85.9
Durus, 0.1%	102.6	64	3.18	99.3
Durus, 0.2%	101.4	63	0.37	98.2
Durus, 0.5%	88.4	55	5.63	85.6
Durus, 1.0%	88.5	55	8.14	85.7
Fibrin, 0.1%	91.8	57	5.99	88.9
Fibrin, 0.2%	77.5	48	9.63	75.0
Fibrin, 0.5%	72.3	45	5.63	70.0

Table 6.5: Compression strengths of 28 days mortar samples

Each group have an decrease in compressive strength when fibres are added to the mixture. This is true for all the mixtures with fibres. Here the waste PA6 fibres perform equally to the Durus fibres, when looking at the 0.5% and 1.0% samples. The largest reduction is for the samples containing 2.0% weight percentage of fibres with a reduction of -17.1% and the Fibrin fibres with -11.1% to -30% reduction, compared to the reference samples.

6.5 PA6 vs Durus vs Fibrin

This section is a comparison of the different strength values from the mortar samples with the same amount of fibres for waste PA6 fibre, Durus and Fibrin fibres. The reference sample have been included as well as the grey bar, where the dashed line represents the value of the reference sample. Figure **??** presents the data for both flexural and compressive strength at fibre content 0.5% and 1.0%.



(a) Flexural Strength

(b) Compressive Strength

Figure 6.17: Mortar samples with 0.5 and 1.0% fibre content of PA6, Durus and Fibrin, plus Reference sample.

In regard to the flexural strength, only the Durus fibres increase the initial strength, where both the waste PA6 and Fibrin decreases the initial strength. This could be due to the higher E-modulus of the Durus fibres, which makes the fibres perform better together with the cement matrix, in the sense that the more flexible fibres such as PA6 and Fibrin may assume the role of voids in the cement matrix. This, in combination with Durus being a monofilament fibres and PA6 and Fibrin being polyfilament and fibrillated fibres could have an impact as well, due to the compactness of the fibres. However, all samples show a decrease in compressive strength when compared to the reference sample.

Looking at the toughness, adding fibres have an positive effect. This is true for all the fibres tested here, but there is a clear indication of which fibre perform the best. The values are presented in Table 6.6.

Fibre	Length [mm]	Content [%]	$T_{\delta_{cr}}$ [Nmm]	$T_{3\delta_{cr}}$ [Nmm]	I_5 [-]
Ref	-	-	-	548	-
PA6	2.0	0.5	514	1466	2.91
	4.0	0.5	499	1403	2.82
Durus	4.5	0.5	524	3727	7.00
Fibrin	1.3-1.9	0.5	288	1416	4.86
PA6	2.0	1.0	430	1864	4.35
	4.0	1.0	469	2681	5.55
Durus	4.5	1.0	586	4224	7.31

Table 6.6: Toughness values for mortar samples with 0.5 and 1.0% of waste PA6, Durus and Fibrin fibres, plus reference sample

Looking at Table 6.6 it can be seen that the Durus fibres perform the best, both in regard to initial toughness, $T_{\delta_{cr}}$, and especially for $T_{3\delta_{cr}}$ with values much higher than waste PA6 and Fibrin. The reason the toughness index, I_5 is so relatively high for the Fibrin sample is due to the low initial toughness of 288 Nmm, which is approximately only at 60% of the other samples initial toughness. However, the toughness value $T_{3\delta_{cr}}$ is close to identical for the PA6 fibres and the Fibrin fibres at 0.5%.

For the results with waste PA6 fibres with length of 2.0 or 4.0 cm, the length does not seem to have an significantly impact on the strength and toughness results. There is an slight improvement for the 4.0 cm fibres than the 2.0 cm fibres regarding the toughness, which may indicate a better grip for the longer fibres. The short Fibrin fibres perform very badly in terms of strength values, however these fibres have other positive effects such as stated by (ADFIL, 2016). However, if the Fibrin fibres are used alone there will be a severe reduction in strength.

6.6 Summary of FRM results

This section summarize the results for the mortar samples with waste PA6 fibres, Durus fibres and Fibrin fibres as well as the reference samples. The characteristics for the mortar samples are shown in Table 6.7.

Fibre	**Polymer**	**Type**	**Length [mm]**	**Content [%]**	R_c **[MPa]**	R_f **[MPa]**	$T_{\delta_{cr}}$ **[Nmm]**	$T_{3\delta_{cr}}$ **[Nmm]**	I_5 **[-]**
Ref	-	-	-	-	65	7.66	548	-	-
PA6	PA	Macro	20	0.5	56	7.51	514	1466	2.91
				1.0	57	6.67	430	1864	4.35
				2.0	54	7.27	493	2681	5.50
			40	0.5	61	7.16	499	1403	2.82
				1.0	65	6.95	469	2681	5.55
Durus	PP	Macro	45	0.1	64	8.27	470	819	1.76
				0.2	63	8.41	489	1795	3.75
				0.5	55	8.41	524	3727	7.00
				1.0	55	7.97	586	4224	7.31
Fibrin	PP	Micro	13-19	0.1	57	7.57	487	760	1.57
				0.2	48	7.26	394	987	2.51
				0.5	45	5.88	288	1416	4.86

Table 6.7: Characteristics of FRM samples and reference samples

7 | Discussion

This chapter includes the discussion of the results from Chapter 6 and Chapter 7. The chapter includes more in-depth discussion of the results internally, as well as perspectivation and comparison to previous related studies and research. As there are very few studies using fibres from waste fishing nets, other waste materials used as fibre reinforcement will be considered and used for comparison. This will show if the waste PA6 fibres have a future as fibre reinforcement in cement-based composites.

7.1 Fibres

This section discus the results from Chapter 6 and compare the results to other studies of synthetic fibres. Table 7.1 gives an overview of the fibre characteristics of previous relevant studies of synthetic fibres. The studies in Table 7.1 will be used to validate the strength, durability and quality of the PA6 fibres. The letter "R" in the polymer type section means that the polymer is recycled. Under the type banner, "M" means that the type is monofilament, "P" means the type is polyfilament and "F" mean the fibres are fibrillated. So, "Macro-M" means a macro monofilament fibre.

Study	**Polymer**	**Type**	**Length [mm]**	**Density [g/cm^3]**	**Tensile Strength [MPa]**	**Young's modulus [MPa]**
PA6	PA6-R	Macro-P	20/40	0.995	838	961.5
Durus	PP	Macro-M	45	0.905	465	3350
Fibrin	PP	Micro-F	13 - 19	0.905	380	-
Silva et al. (2005)	PET-R	Macro-M	20	-	324	41.8
Won et al. (2010)	PET-R	Macro-M	50	1.38	421	10175.4
(Song et al., 2005)	PA	Micro-F	19	1.14	896	5170
Yin et al. (2015a)	PP-R	Macro-M	45	0.92	313	619
	PP Virgin	Macro-M	45	0.90	437	868
	PP Mix	Macro-M	45	0.91	364	804
Spadea et al. (2015)	Nylon-R	Macro-F	25	-	338	728
	Nylon-R	Macro-F	32	-	348	728

Table 7.1: Overview of fibre characteristics from previous studies used as fibre reinforcement

As mentioned earlier, it is only fibres from (Spadea et al., 2015) that comes from waste fishing nets, which makes that study highly relevant for this thesis. In terms of classifying the fibres from (Spadea et al., 2015), the fibres have a thickness that classify them as micro fibres, but a length that classify them as macro fibres according to (Brandt, 2008). However, due to their performance in the cement mortar the fibres of length 25 mm or higher are classified as macro fibres and lower is classified as micro.

7.1.1 Mechanical Properties

The tensile strength of the waste PA6 fibres are rather high, with 838 MPa, compared to the other synthetic fibres as seen in Table 7.1. All the studies using recycled fibres have tensile strengths ranging between low 300 to mid 400 MPa, with varying types of polymer. Spadea et al. (2015) which also uses nylon fibres from waste fishing nets have under half the tensile strength as the waste PA6 fibres, with average strength of 343 MPa against 838 MPa for the waste PA6 fibre bundles. Compared to new nylon fibres, (Song et al., 2005) used nylon fibres with a tensile strength of 896 MPa, this is just 6.5% higher than the waste PA6 fibres. The reason for the high tensile strength of the waste PA6 fibre bundles could be due to the alignment of the material, similar to that a steel wire of a certain diameter has a stronger tensile strength than a steel rod of the same diameter.
In regard of strength of fibres from recycled materials, there can be large deviation due to the varying process history of the material. The study of (Yin et al., 2015a) showed that the recycled PP fibres had a tensile strength of 313 MPa compared to 437 MPa for virgin fibres, which is a reduction in strength of 28.5%. As a solution to boots the properties of

the recycled fibres, (Yin et al., 2015a) found that by remelting the recycled material with new virgin material of the same plastic, the strength was increased with 51 MPa, equivalent to 16.3% of that of the pure recycled PP fibres. This could well be a solution to secure the quality of recycled fibres.

The elasticity modulus is much more difficult to determine with absolute certainty, as has been shown with this study. This is also shown in the literature with (Silva et al., 2005) and (Won et al., 2010) whom both uses PET fibres from recycled bottles which have an E-modulus of 41.8 MPa and 10175.4 MPa, respectively. This is a major difference given that their tensile strength is within 100 MPa difference, and the materials come from similar sources. This underline that the elasticity modulus is a more complex property.
The result for the waste PA6 fibre is similar to that of (Spadea et al., 2015) which has a value 20,6% lower than the waste PA6. However, the uncertainty for the waste PA6 was much higher than that of (Spadea et al., 2015) with a coefficient of determination of $R^2 = 0.843$ for the waste PA6 and $R^2 = 0.95$ for (Spadea et al., 2015).

7.1.2 Alkali Resistance

the alkali resistance of the waste PA6 fibres corresponds well with previous studies of polyamide fibres such as (Guo et al., 2014) and (Spadea et al., 2015) in regard of mass and volume perseverance. Polyamide is known to have high alkali resistance and the PA6 fibres showed little, or no sign of mass reduction when exposed to high alkalinity, and in addition there were no sign of disintegration of the fibres. This is crucial for the waste PA6 fibres that there are no sign of disintegration as this will lead to reduction of the strength of the FRM over time. For instance, recycled PET fibres tested for alkali resistance by Silva et al. (2005) showed a more rough surface indicating that the fibres suffered from alkaline attack from the cement paste. This ultimately led to decrease of toughness after 35 days in the mixture.
However, when it comes to strength perseverance in a alkaline environment, the PA6 fibres experienced a reduction in tensile strength of 30%. This is not similar to studies of (Spadea et al., 2015). Where there were a high strength perseverance of the polyamide fibres. which makes them suitable for fibre reinforcement in cement-based composites.

Some of the strength reduction for the PA6 fibres could be explained by the high degree of polyfilament and immersion into liquid which have compromised the compactness of the fibres leading to a lower tensile strength. However, in total the the alkali resistance was lower for the PA6 fibres than (Spadea et al., 2015).

7.1.3 Thermal Properties

The thermal investigation for the waste PA6 fibres showed that the fibres had a melting point of 214.5°C and a ignition point of 350°C and above. This was a higher melting point compared to the polypropylene fibres of Durus and Fibrin with a melting point of 165°C. The difference lies within the different polymer type. Looking at thermal properties for other polyamide fibres, (Song et al., 2005) found a melting point of 225°C for new nylon fibres. This is similar results, given that the PA6 fibres in this study has a process history, whereas the fibres from (Song et al., 2005) were new virgin fibres. This could result in a slightly lower melting point.

The ignition point of 350°C is equal to that of the Durus and Fibrin at 360°C. This could indicate similar fire resistance properties, but it could be interesting to investigate how the waste PA6 fibres performed in terms of fire resistance and if the waste PA6 fibres had equal fire resistance properties as the Fibrin fibres.

7.2 Mortar

This section includes the discussion of the mortar results in relation to previous studies in the literature. The most relevant results from the studies and researches are presented in Table 7.2. The studies all revolves around synthetic fibres in cement-based composites, which means no concrete samples. The strength for all the studies are after 28 days of curing. The Table shows the polymer type of the study, the amount of fibre in the samples, the flexural strength, the compressive strength and the toughness values for the critical deflection and three times the critical deflection along with the toughness index I_5.

When it comes to fibre content many studies use volume percentage to determine the amount of fibres and not weight percentage, as have been done in this study and by (Kragh-Poulsen, 2009) and (Spadea et al., 2015). It is important to notice which percentage is being used, as the volume percentage equals a slightly lower amount of fibres in grams, compared to the weight percentage. Studies using weight percentage is denoted a "W" and studies using volume percentage is denoted "V" in the "Content" banner in Table 7.2.

Study	**Polymer**	**Type**	**Length [mm]**	**Content [%]**	**Compressive Strength [MPa]**	**Flexural Strength [MPa]**	**Toughness**		
							$T_{\delta_{cr}}$ [Nmm]	$T_{3\delta_{cr}}$ [Nmm]	I_5 [-]
Ref	-	-	-	-	65	7.66	-	-	-
PA6	PA-R	Macro-P	20	0.5 W	56	7.51	514	1466	2.91
			20	1.0 W	57	6.67	430	1864	4.35
			40	0.5 W	61	7.16	499	1403	2.82
			40	1.0 W	65	6.95	469	2681	5.55
Durus	PP	Macro-M	45	0.1 W	64	8.27	470	819	1.76
				0.2 W	63	8.41	489	1795	3.75
				0.5 W	55	8.41	524	3727	7.00
				1.0 W	55	7.97	586	4224	7.31
Fibrin	PP	Micro-F	13-19	0.5 W	45	5.88	288	1416	4.86
Silva et al. (2005)	PP	Macro	45	0.8 V	-	-	-		
Won et al. (2010)	PET-R	Macro-M	50	1.0 V	-	-	-		
Fraternali et al. (2013)	Ref	-	-	-	-	2.88	-	-	-
	PET-R	Macro-M	11.3	1.0 V	-	2.31	-	-	2.25
	PET-R	Macro-M	22.6	1.0 V	-	2.83	-	-	3.13
	PET-R	Macro-M	35.0	1.0 V	-	2.86	-	-	5.29
Spadea et al. (2015)	Ref	-	-	-	49.4	4.46	339	-	-
	PA-R	Micro-F	12.7	1.0 W	32.7	5.18	412	952	2.40
	PA-R	Macro-F	25.4	1.0 W	38.9	5.87	665	1772	2.70
	PA-R	Macro-F	38.1	1.0 W	41.5	5.86	409	1199	2.90

Table 7.2: Overview of results from previous studies concerning FRM samples

7.2.1 Mixing

From the casting process it was found that the adding of fibres affected the workability, by making the mortar mixture more firm. The loss of fluency increased with the increase of fibres added to the mixture. This ultimately led to a failed mixture containing 2.0% 4 cm PA6 fibres. When casting with the fibres from *PP Nordica*, this happened much sooner. For the Durus fibres it was notified that 1.0% was the absolute maximum, and for the Fibrin fibres the maximum was at 0.5%. Micro fibres affect the workability more than macro fibres, which is also confirmed by (ADFIL, 2016). According to (ADFIL, 2016), when mixing with Durus and Fibrin fibres, additional water should be added to bring ud the workability to the desired level. However, adding more water to the mixture changes the water/cement ratio leading to a different strength characteristics. Therefore, this was not used in this study, as it would lead to too many changing variables.
Another aspect which affect the mixing properties of the cement mortar is the density of the fibres. The density of the PA6 fibres were found to be 0.995 g/cm^3. Studies by (Yin et al., 2015b) showed that fibres with a density of 0.9 g/cm^3 or lower, have a tendency to float to the surface during the mixing, which gives an uneven distribution. Fibres with a density of 0.95 or higher had a much better mixing properties, which secured a better distribution of the fibres. Comparing this to the Durus and Fibrin fibres, the fibres from *PP Nordica* mixed well with a density of 0.905 g/cm^3, although there were complications at the higher amount of fibre content. The reason for the possibility of mixing PA6 fibres at higher degrees is a combination of the higher density and the compactness of the fibres. This enable the possibility of mixing at higher degrees of fibre content as with the other fibres. For mixing with PA fibres and PP fibres, (Song et al., 2005), found similar results which were that the more dens nylon fibres mixed better than the lighter polypropylene fibres.
When fibres in concrete are considered, a study by (Kragh-Poulsen, 2009) showed that 0.5% was the maximum amount of fibres in concrete without complication during the mixing process. At higher amount of fibres, the fibres started to huddled together into fibre-balls. When mixing fibres in concrete this is a legitimate concern, and the amount should be chosen to avoid fiber-balling.

7.2.2 Flexural

Plastic fibres as reinforcement in bending is in the literature often said to have an positive effect on the flexural strength compared with no reinforcement. However, some studies also report a decrease in initial flexural strength when using plastic fibres.

Studies which report an increase in flexural strength is (Nili and Afroughsabet, 2010), (Fraternali et al., 2011) and (Spadea et al., 2015) which all found a positive effect in flexural strength when fibres where added to the mixture. Other studies show no effect like (Silva et al., 2005) who found that fibre content of 0.4 and 0.8% volume fraction had no effect on the flexural strength of mortar samples, using recycled PET fibres, but a significant increase in toughness.
In terms of fibre length and strength, (Fraternali et al., 2013) found interesting results, which is in cohesion with the results found in this thesis with PA6 fibres and Fibrin. (Fraternali

et al., 2013) found that for a fibre content of 1.0% volume fraction using short fibres of length 11.3 mm had a negative effect on the flexural strength with a decrease of -19.8%, but with increased fibre length the decrease was only -1.7% and -0.7% for length 22.6 mm and 35.0 mm, respectively, compared to the reference sample. This showed a decrease for short fibres and more or less no effect for fibres with length over 2.26 mm. This is similar to this study as the short Fibrin fibres had a more negative effect than the longer fibres such as the waste PA6.

The effect of the waste PA6 fibres showed a decrease in initial flexural strength, whereas the Durus fibres increased the flexural strength. The Fibrin fibres likewise showed a decrease in flexural strength, which was much severe. Again it should be notated that the Fibrin fibres have other positive effects and that PP Nordica and ADFIL suggest a mixture of both fibres in other to gain all the benefits from the two fibres. The reduction could be due to the short length of fibres (13-19 mm), as with the results from (Fraternali et al., 2013).
At 0.5% fibre content, the PA6 fibres reduced the flexural strength with -2.0% for 2 cm fibres and -6.6% for 4 cm fibres compared to the reference samples. At the same fibre content the Durus fibre increased the strength with +9.7%. This is a difference between 11.7% - 16.3%, which is noticeable difference, given that the fibres is the only difference in the FRM samples. This was also shown at 1.0% fibre content with -12.9% for PA6 2 cm, -9.3% for PA6 4 cm fibres and +4.0% for Durus.
Comparing with (Spadea et al., 2015), who also uses fibres from waste fishing nets, found that adding of recycled polyamide fibres increased the flexural strength with up to 35% of the reference samples. This is significantly difference than the results from this study. One aspect where the two studies deviates is the cement, the cement used in (Spadea et al., 2015) was a weaker cement type which could result in more positive results when adding the fibres. The cement used in (Spadea et al., 2015) was strength class R4 with compressive strength of 45 MPa compared to 52.5 MPa in this study.

7.2.3 Toughness

It has been well documented that synthetic fibres have a great positive influence on the toughness of fibre reinforced cement mortar and concrete samples. From the literature and (ADFIL, 2016) it has been established that macro fibres have a more positive effect than micro fibres in this aspect. This is in cohesion with the results found in this thesis.

For the waste PA6 fibres at 0.5% fibre content, there were no difference in toughness index I_5 for the two lengths, however at 1.0% the 4 cm fibres performed better with I_5 of 5.55 compared to 4.35 for 2 cm fibres. This is similar to (Fraternali et al., 2013), which also found an increase in toughness with I_5 of 2.25 for 1.13 cm fibres, 3.13 for 2.26 cm fibres and 5.29 for 3.5 cm fibres. This indicates that the longer fibres have a better grip in the cement mixture and failures such as pull-out is limited, which ultimately leads to a more optimal use of the fibres in regard of flexural toughness.

When comparing the two macro fibres in this thesis, the mortar samples with Durus fibres was superior to the samples with fibres from waste fishing net, PA6, as seen in Table 7.2. The toughness value until the initial crack, $T_{\delta_{cr}}$, for the two FRM samples at 0.5% fibre content were very similar with 514, 499 and 524 Nmm for 2 cm PA6, 4 cm PA6 and Durus, respectively. However at three times the critical deflection the toughness value $T_{3\delta_{cr}}$ was

1466, 1403 and 3727 Nmm for the same samples. This is a substantial increase for the Durus fibres as can further be seen with the toughness index I_5 at which were 2.91, 2.82 and 7.00 respectively for the three different FRM samples. The FRM samples with Fibrin fibres had a much lower value for $T_{\delta_{cr}}$ at 288 Nmm, but still maintained a $T_{3\delta_{cr}}$ value of 1416 Nmm, which is similar to that of the two length of waste PA6 fibres.
At 1.0% fibre content the longer PA6 fibres at 4 cm performed better than the shorter fibres at 2 cm at three times the critical deflection with $T_{3\delta_{cr}}$ values of 2681 Nmm for 4 cm and 1864 Nmm for 2 cm, but they were both inferior to the Durus fibres with $T_{3\delta_{cr}}$ of 4224 Nmm.

Comparison between the study of (Spadea et al., 2015) the samples containing waste PA6 from this study was superior with higher toughness values. At fibre content 1.0% (Spadea et al., 2015) had similar results for the initial toughness values, $T_{\delta_{cr}}$, but for $T_{3\delta_{cr}}$ the values were substantial lower than the waste PA6 FRM samples. With toughness indexes I_5 from (Spadea et al., 2015) of 2.40, 2.70 and 2.90 for 1.27 cm, 2.54 cm and 38.1 cm length of fibres respectively, contra I_5 values of 4.35 and 5.55 for 2 cm and 4 cm for the PA6 fibres. This clearly showed a good performance for the waste PA6 fibres regarding to toughness, whereas (Spadea et al., 2015) performed significantly better in the flexural strength.

7.2.4 Compression

The effect of plastic fibres as reinforcement in compression is often debated, and the literature is divided as some studies report an increase in compressive strength, some a decrease, and others no effect.
Selected studies which report an increase in compressive strength when synthetic fibres are used are; (Banthia et al., 2014), (Nili and Afroughsabet, 2010) and (Fraternali et al., 2011). It should be noted that (Nili and Afroughsabet, 2010) used much less fibre content, with 0.2%, 0.3% and 0.5% of volume, additionally silica fume was also added to the mixture. Silica fume is particularly known to increase the compressive strength of concrete. (Banthia et al., 2014) also uses low amount of fibres at 0.1%, 0.3% and 0.5% volume fractions and the increase in compressive strength was moderate with an increase of 1.7% to 8.8%.
Studies which report a decrease in compressive strength after adding of polymer fibres are; (Meddah and Bencheikh, 2009), (Karahan and Atis, 2011), (Kim et al., 2010) and (Fraternali et al., 2014). It is notable that Fraternali has performed studies where one study showed an increase and another study which showed a decrease in compressive strength when both studies used recycled PET fibres. Other studies report no effect, which are the likes of (Silva et al., 2005), (Spadea et al., 2014) and (Ozger et al., 2013).

In regard of compressive strength there are many parameters that affect the strength, such as the cement, the water/cement ratio and other additional filler materials. Therefore it is easy to compare the fibres in this study, as the only difference between the FRM samples in this study is the fibres; PA6, Durus or Fibrin. All samples use the same cement, same water/cement ratio, same sand and same casting procedure. This enables a much more precise comparison between these three fibres.
The above mentioned studies show that plastic fibres as reinforcement in compression can lead to very different results. However, the tests done in this thesis all showed a decrease in compressive strength when fibres were added. This was true for both waste PA6, Durus and

Fibrin fibres. At the lower amount of fibres of 0.1% and 0.2%, the Durus fibres showed only little sign of decrease in compressive strength with -0.7% and 1.8%, compared to the reference samples. The most severe impair in compressive strength came from the Fibrin fibres, with a decrease of 30.0% at 0.5% fibre content, and the strength reduction was in general significantly larger for the samples containing Fibrin fibres. The waste PA6 performed equally to that of the Durus fibres when 0.5% fibres were added. Both FRM samples impaired the compressive strength with -12.6% for 2 cm, -6.2% for 4 cm and -14.4% for Durus. The similarity was again confirmed at 1.0% fibre content with decrease of -11.1% for 2 cm, -14.1% for 4 cm and -14.3% for Durus. In this aspect the two macro fibres performed equally, which indicates that fibres from waste fishing nets can compete with the fibres used in the industry.

7.3 Challenges

One of the major issues with fibres from waste materials is the quality of the material. Recycled plastics have uncertain processing and service history and varying degrees of degradation, leading to processing difficulties and unstable mechanical properties, (Wang, 1997). For fishing nets, especially the exposure to solar radiation has a significant reduction on the breaking strength as found by both (Al-Oufi et al., 2004) and (Thomas and Hridayanathan, 2006). This can make it difficult to implement fibres from waste materials in the industry, as there are many regulations and quality standards that have to be met. Further, there is also the aspect that the industry tend to be quite conservative.
One solution could be as examined by (Yin et al., 2015a), who remelts recycled plastic with virgin plastics in order to improve and secure quality of the fibres. This still reuses 50% of the waste material and would secure more consistent mechanical properties of the fibres.

Another challenge with further studies of waste plastic fibres is the preparation of the fibres. For a study within this field to be scientifically correct, the fibres need to have same dimensions for thickness and length. The thickness is typically not an issue and the length is not problematic to achieve either, but it is time consuming. As waste plastic materials all have different shape and sizes, the most applied way to cut the fibres is by hand. This has been done in this study and by (Fraternali et al., 2013) and (Spadea et al., 2015). This takes a lot of time which means that most studies investigates mortar samples instead of concrete samples, due to the smaller size, which minimize the fibre-cutting process. As the weight of each fibre is so light, the hand-cutting process have to be repeated in, for what seems like eternity, in order to achieve a decent amount of usable fibres. It is the labor of Sisyphos reincarnated in modern form.
A machine could be developed to do this job, but it would be very expensive and the combination of the varying shapes and sizes for the waste plastic materials and the precision for the dimensions of the fibres, would complicate the process. For now, manually hand-cutting the fibres is the best possible solution, although it is time consuming and quite boring.

8 Conclusion

This thesis investigated the use of fibres from waste fishing nets as fibre reinforcement in cement mortar samples. The fishing net investigated was collected at Gilleleje Harbour and made of polyamide 6. The waste fibres were held against two industrial polypropylene fibres, Durus and Fibrin Fiberflex, from PP Nordica.

From the experimental work the following conclusions were derived:

- The fibre from waste fishing nets made of polyamide 6, showed good mechanical properties with a high mean tensile strength compared to other synthetic fibres and a decent elasticity modulus. The fibres showed good alkali resistance in terms of mass and volume perseverance, with little sign of volume reduction and no sign of degradation. However, the fibres suffered a decrease in tensile strength of 30% after exposure to high alkalinity.

- As fibre reinforcement the waste fibres showed good distribution qualities, with equal distribution throughout the cement mortar samples. The maximum amount of fibres was found to 2.0% of weight fraction, when mixing according to (DS/EN-196-1, 2005).

- It was found that the FRM samples with waste fibres had a reduction in compressive strength, compared to the reference samples of plain cement mortar. The reduction was ranging between -5% to -15% for fibre content of 0.5%, 1.0% and 2.0% of weight fractions, where the reduction in strength increased with the fibre content. Similar results where found for the mortar samples with Durus fibres, and a more severe strength reduction for the Fibrin Fiberflex fibres. For compressive strength the waste fibres performed equally to the industrial Durus fibres.

- In terms of flexural strength, the waste fibres decreased the initial strength with -2% to -10% compared to the plain reference samples, but maintained a significantly flexural strength after the initial crack. The FRM samples were able to maintain up to 50% strength of the initial flexural strength. Whereas, the Durus fibres resulted in a increase of +4% to +10% in initial strength and post-crack strength perseverance of up to 66%.

- For the flexural toughness the waste fibres had a major positive effect and multiplied the amount of energy the cement mortar samples were able to absorb compared to the unreinforced reference samples. However, the Durus fibres yielded higher toughness values than the waste fibres, but the waste fibres performed better than Fibrin Fiberflex.

Based on the results in this thesis it has been concluded that fibres from waste fishing nets made of polyamide showed overall promising features as fibre reinforcement in cement mortar samples, even though the waste fibres did not match the industrial Durus fibres in all aspects.

8.1 Future Studies

The recommendation for future studies can be divided into two fields, one regarding the waste fishing nets and the other being fibres from waste fishing nets in cement-based composites. For future studies the author recommends the following suggestions.

A better understanding of the the raw material, that is the waste fishing nets. A classification of the quality of waste fishing nets. How the overall quality of waste fishing nets are when collected at the dumping sites and what the tolerance is for which nets are usable as fibre reinforcement and which are not.

Future studies regarding fibres from waste fishing nets as fibre reinforcement in cement-based composites:

- Test of other parameters such as; Plastic Shrinkage, Crack Resistance, Impact Resistance and Fire Resistance.
- Long-term durability of waste fibres from fishing nets. See if the positive enhancement of the fibre reinforced mortar samples is consistent, or experience a decrease over time due to eventual degradation of the fibres.
- Waste fibres from fishing nets in combination with silica fume in order to eliminate the decrease in flexural and compressive strength. Evaluate if the two materials can perform in combination.
- Larger concrete samples with fibres from waste fishing nets. To see if the enhancement is also applicable for full size concrete samples. Problem here is the preparation process of the fibres.

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9 | Appendix

This is the Appendix for Master Thesis *Methodology and Testing of Waste Fishing Net as Fibre Reinforcement in Mortar* by Simon Jacob Svensson, s102950 at Technical Univeristy of Denmark. July 16, 2016.

The Appendix consists of the following appendixes:

- Appendix 1 - Experimental Log
- Appendix 2 - PP Nordica Fibres
- Appendix 3 - Aalborg Portland Basis Cement
- Appendix 4 - Pychnometer
- Appendix 5 - FTIR
- Appendix 6 - PA6 Fibre Results
- Appendix 7 - SEM of PA6 Fibres
- Appendix 8 - Working Curves of Mortar Samples
- Appendix 9 - Flexural Strength of Mortar Samples
- Appendix 10 - Toughness of Mortar Samples
- Appendix 11 - Compression Strength of Mortar Samples

9.1 Appendix 1 - Experimental Log

This Experimental Log shows when and where the experiments took place and further notices if anything did not occur according to the plan or standard.

Date	Experiment	Standard	Location	Comments
16-02-2016	Collecting of fishing nets	-	Gilleleje Harbour	Free to collect at the harbour's dumping site. Collected nets estimated to be of polyamide.
18-02-2016	Washing of fishing nets	-	DTU Byg	Washing of fishing nets until conductivity of washed water was the same as tap water.
25-02-2016	Tensile Strength of fibres	ASTM C1557	DTU Byg	Performed on an Instron 6022 hydraulic testing machine.
04-03-2016	Pychnometer - Density of fibres	DS/CEN ISO/TS 17892-3	DTU Byg	Performed with the help of laboratory technician Malene Grønvold.
09-03-2016	FTIR analysis of fibres	XX	DTU Polymer Lab.	Performed at Polymer Lab at the Department of Chemical and Biochemical Engineering at DTU with help from Qian Huang and Kim Chi Szabo.
21-03-2016	Casting of 14 days Mortar samples	DS/EN-196-1	DTU Concrete Lab.	-
22-03-2016	Casting of 28 days Mortar samples	DS/EN-196-1	DTU Concrete Lab.	Unable to mix sample containing 2.0% 4 cm fibres.

Date	Experiment	Standard	Location	Comments
04-04-2016	Testing of 14 days Mortar samples	DS/EN-196-1	DTU Byg	Performed on an Instron 6022 hydraulic testing machine with the help of Christian Peter Rasmussen.
15-04-2016	SEM of PA fibres	-	DTU Byg	Done at The Department of Civil Engineering with the help of Laboratory Coordinator Ebba Schnell.
19-04-2016	Testing of 28 days Mortar samples	DS/EN-196-1	DTU Byg	Performed on an Instron 6022 hydraulic testing machine.
19-04-2016	Compression strength of 28 days mortar samples.	DS/EN-196-1	DTU	Done on a Mohr and Federhaff AG mortar testing machine.
03-05-2016	Casting of 7 days Mortar samples	DS/EN-196-1	DTU Concrete Lab.	-
03-05-2016	Volume reduction of fibres in 1M NaOH at 0 days	-	DTU Byg	Done using SEM with help from Ebba Schnell.
10-05-2016	Testing of 7 days Mortar samples	DS/EN-196-1	DTU Byg	Performed on an Instron 6022 hydraulic testing machine.
10-05-2016	Volume reduction of fibres in 1M NaOH at 7 days	-	DTU Byg	Done using SEM with help from Ebba Schnell.
17-05-2016	Volume reduction of fibres in 1M NaOH at 14 days	-	DTU Byg	Done using SEM with help from Ebba Schnell.
24-05-2016	Volume reduction of fibres in 1M NaOH at 21 days	-	DTU Byg	Done using SEM with help from Ebba Schnell.

Date	Experiment	Standard	Location	Comments
18-05-2016	Thermal Gravimetric Analysis	-	DTU Polymer Lab.	Performed with the help of Associate Professor Anders Egede Daugaard and Liyun Yu
18-05-2016	Differential Scanning Calorimetry	-	DTU Polymer Lab.	Performed with the help of Anders Egede Daugaard and Liyun Yu
26-05-2016	Tensile strength of fibres emitted in 1M NaOH for 28 days.	ASTM C1557	DTU Byg	Performed on an Instron 6022 hydraulic testing machine.
31-05-2016	Volume reduction of fibres in 1M NaOH at 28 days	-	DTU Byg	Done using SEM with help from Ebba Schnell.
01-06-2016	Casting of mortar samples with Durus fibres and Fibrin fibres	DS/EN-196-1	DTU Concrete Lab.	-
29-06-2016	Flexural testing of 28 days samples with Durus and Fibrin fibres	DS/EN-196-1	DTU Byg	-
29-06-2016	Compression strength of 28 days samples with Durus and Fibrin fibres	DS/EN-196-1	DTU Byg	-

9.2 Appendix 2 - PP Nordica Fibres

Performance Declarations for fibres from PP Nordica, manufactured by ADFIL.

First the macro fibre Durus and second the micro fibre Fibrin.

Durus S400 45mm

Macro / Embossed Monofilament

Technical data sheet

Product description

Polymer	Density	Melting Point	Ignition temperature
PP	0,905 kg/dm³	165 °C	> 360°C

Properties

Physical Properties	Standard	Performance	Tolerance
Equivalent Diameter	EN 14889-2	0,9 mm	+/-0,05 mm
Length	EN 14889-2	45 mm	+/-2 mm
Aspect ratio	EN 14889-2	50	+/- 5
Number of fibres per kg		38600	

Mechanical Properties	Standard	Performance	Tolerance
Elastic Modulus	EN 14889-2	3350 MPa	-335 MPa
Tensile strength	EN 14889-2	465 MPa	-35 MPa

Effect on consistency of concrete	Standard	Performance	Dosage
Vebe Time	EN 14889-2	2 s	5 kg
Control concrete	EN 14889-2	1 s	

Effect on strength of concrete	Standard	Performance	Dosage
Strength @CMOD - 0,5mm	EN 14889-2	1,5 N/mm²	5 kg
Strength @CMOD - 3,5mm	EN 14889-2	1,7 N/mm²	

CE regulation	Standard	Performance	
Class	EN 14889-2	II	

Version n° 1

Version date : 1/07/2013

Advantages

The product will enhance the toughness of the concrete and alleviate the need for steel mesh or steel fibres when used with the appropriate design and at the recommended dosage.

Mixing instructions

When adding fibres into a cementitious product careful attention must be taken in the batching and mixing procedure in order to achieve optimum results. If you need further details on the recommended mixing instructions, please consult a member of the ADFIL team.

Storage

Fibres must be stored on a clean surface in dry conditions, undercover and away from the possibility of damage.

Bonar N.V.
Industriestraat 39, 9240 Zele, Belgium
T: +32 (0) 52 457 487 / F: +32 (0) 52 457 495
info@bonar.com / www.bonar.com

ADFIL
Construction Fibres

Fibrin XT

Monofilament Fibre

Technical data sheet

Product description

Polymer	Density	Melting Point	Ignition temperature
PP	0,905 kg/dm³	165 °C	> 360°C

Properties

Physical Properties	Standard	Performance	Tolerance
Equivalent Diameter	EN 14889-2	22 µm	-0,9/+1,3 µm
Length	EN 14889-2	13,0/19,0 mm	+/-1,5 mm
Aspect ratio	EN 14889-2	545 / 864	-
Spinfinish content	EN 14889-2	0,7 %	-0,5/+0,3 %
Moisture content	EN 14889-2	1 %	-0,7/+1,0 %

Mechanical Properties	Standard	Performance	Tolerance
Tensile strength	EN 14889-2	380 MPa	-100 MPa

Effect on consistency of concrete	Standard	Performance	
Vebe time - 0,6kg	EN 14889-2	-	
Vebe time - 0,75kg	EN 14889-2	-	
Vebe time - 0,9kg	EN 14889-2	-	
Vebe time - 0,91kg	EN 14889-2	8 s	
Vebe time - 1,2kg	EN 14889-2	-	

CE regulation	Standard	Performance	
Class	EN 14889-2	Ia	

Version date : 1/07/2013

Version n° : 1

Advantages

Special surfactant coatings enable excellent dispersion of individual filaments, allowing the formation of homogeneous three-dimensional matrix within the concrete mix. The inclusion of ADFIL Construction fibres provides significant technical benefits in both the plastic and hardened state of concrete.

Mixing instructions

When adding fibres into a cementitious product careful attention must be taken in the batching and mixing procedure in order to achieve optimum results. If you need further details on the recommended mixing instructions, please consult a member of the ADFIL team.

Storage

Fibres must be stored on a clean surface in dry conditions, undercover and away from the possibility of damage.

9.3 Appendix 3 - Aalborg Portland Basis Cement

Performance Declarations for Aalborg Portland Basis Cement as of 2015.

YDEEVNEDEKLARATION

Nr. 08 / August 2015

1. Byggevaretype:

Portlandkalkstenscement EN 197-1

2. Byggevareidentifikation:

BASIS® AALBORG CEMENT®

Portlandkalkstenscement CEM II/A-LL 52,5 N (LA)

3. Byggevarens tilsigtede anvendelse(r):

Anvendes til fremstilling af beton, mørtel mv.

4. Fabrikantens navn og adresse:

Aalborg Portland A/S, Rørdalsvej 44, 9100 Aalborg

5. Navn og adresse på den bemyndigede repræsentant:

Ikke relevant

6. Systemerne for vurdering og kontrol af konstansen af byggevarens ydeevne (AVCP):

System 1+

7. Notificeret Organ's opgave:

Notificeret produktcertificeringsorgan Bureau Veritas Certification,
Identifikationsnummer 0615 - har udført

bestemmelse af produkttyperne på grundlag af prøvning, prøveudtagning og den indledende inspektion af fabriksanlæggets produktionskontrol, den løbende overvågning, overensstemmelse og evaluering af fabrikkens produktionskontrol og har udstedt overensstemmelsescertifikat/ydeevneerklæring.

Senest opdateret: 2015-08-20

8. Deklareret ydeevne

Alle egenskaber for Portlandkalkstenscement CEM II/A-LL 52,5 N (LA) iht. standarden er opfyldt.

Egenskaber	**Deklarerede værdier**	**Krav i DS/EN 197-1**
2-døgnsstyrke	28 - 36 MPa	≥ 20 MPa
28-døgnsstyrke	55 - 63 MPa	≥ 52,5 MPa
Begyndende afbinding	100 - 190 min	≥ 45 min
Chlorid	≤ 0,10 %	≤ 0,10 %
Vandopløseligt chromat	≤ 2 mg/kg	≤ 2 mg/kg *(Krav i EU Direktiv 2003/53/EC)*
Absolut densitet	3020 - 3120 kg/m^3	Ingen

For hver egenskab er angivet et variationsområde, som er fastlagt således, at sandsynligheden for, at en værdi falder udenfor, er mindre end 5 %.

9. Ydeevnen for den byggevare, der er anført i punkt 1 og 2, er i overensstemmelse med den deklarerede ydeevne i punkt 8.

Denne ydeevnedeklaration udstedes på eneansvar af den fabrikant, der er anført i punkt 4.

Aalborg, den 20. august 2015

Underskrevet for og på vegne af producenten af:

B. Jensen
……………………………………………………………………
Birgit Jensen, Kvalitets- og Arbejdsmiljøchef, Aalborg Portland A/S

Væsentlig egenskab iht. DS/INF 135	**Deklareret værdi**	**Krav**
Alkaliindhold	≤ 0,6 %	≤ 0,6 %

Senest opdateret: 2015-08-20

9.4 Appendix 4 - Pychnometer

Dato	04.03.2016
Navn	Simon Svensson
Projekt	Speciale F16 v. Lisbeth Ottosen
Prøvemateriale	Black Nylon waste fibres

Metode:
Efter Laboratoriehåndbogen, dgf-bulletin 15 (dgf15)
Efter DS/CEN ISO/TS 17892-3

Resultat
Beregning
Input

Bestemmelse af kornrumvægt
Sand

				1	**2**	**3**
Fra kalibrering af pyknometer						
Pyknometer nummer				2	1	1
Pykn. + prop (tomt)		m_0	g	43,4429	47,5231	47,5231
Pykn. + prop (vandfyldt)	W_2	m_1	g	142,5256	149,2449	149,2449
Temperatur ved kalibrering	T_k	T_1	°C	22	22	22
Densitet af vand ved T_k *	$\rho_{w,k}$	$\rho_{w;1}$	g/cm^3	0,9978	0,9978	0,9978
Måling						
Pykn.+ prop + jord		m_2	g	47,4464	51,5374	51,7916
Pykn.+ prop + jord + vand	W_1	m_3	g	142,0942	149,1924	149,2151
Temperatur	T	T_3	°C	24	24	24
Densitet af vand ved T *	$\rho_{w,t}$	$\rho_{w;3}$	g/cm^3	0,99733	0,99733	0,99733
Jord - masse	W_s	m_4	g	4,0035	4,0143	4,2685
Jord - volumen	V_s		cm^3	4,39997639	4,02964449	4,26176425
Korndensitet	ρ_s	ρ_s	g/cm^3	0,90989125	0,9961921	1,00158051
Resultat - middel	ρ_s	ρ_s	g/cm^3	**0,9692**		
Betegnelser fra	dgf15	DS				

* Se faneblad med vands densitet

Dgf-bulletin 15:

$$\rho_s = \frac{W_s}{V_s} = \frac{W_3 - W_0}{\frac{W_2 - W_0}{\rho_{w,k}} - \frac{W_1 - W_3}{\rho_{w,t}}}$$

DS/CEN ISO/TS 17892-3:

$$\rho_s = \frac{m_4}{\frac{m_1 - m_0}{\rho_{w;1}} - \frac{m_3 - m_2}{\rho_{w;3}}}$$

Der bør ikke være stor forskel på temperaturen ved kalibrering og måling.
Der kan evt. foretages kalibrering ved flere temperaturer, eller udføres en teoretisk korrektion af volumen af pyknometer:

$$V_{pyk;test} = \frac{W_2 - W_0}{\rho_{w,k}} \alpha$$

$$\alpha = 1 + 3 \cdot 0.000003 (T - T_k)$$

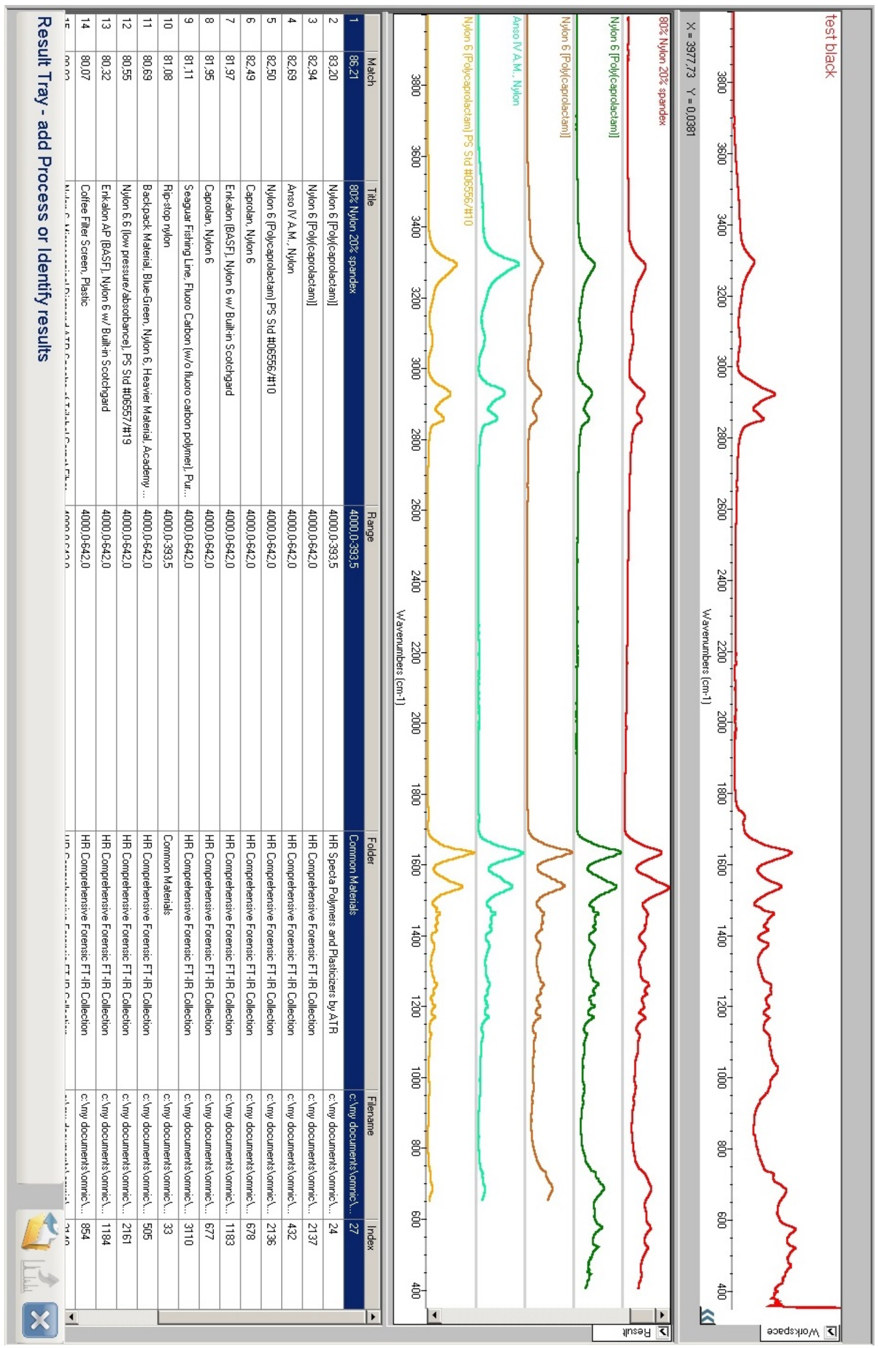
$$V_{pyk;3} = \frac{m_1 - m_0}{\rho_{w;1}} \alpha$$

$$\alpha = 1 + 3 \cdot 0.000003 \ (T_1 - T_3)$$

C:\Users\Simon\Documents\DTU\Speciale\Resultater\Density PA waste fibre_black

9.5 Appendix 5 - FTIR

FTIR data of collected Nylon material with the spectra from the library in OMNIC Specta the corresponding certainties.



9.6 Appendix 6 - PA6 Fibre Results

Area of PA6 Fi	0,36	mm^2
Pink = out of ±10% of mean		
Orange = Failure in breaking/working curve		

Fibre, 20 mm

ID:	Elongation [mm]	Tension [kN]	Strength [MPa]	SD [MPa]	l/A [1/mm]	ΔL/F [mm/N]
20.0 mm, 1	16,20	0,289	803	-	55,56	0,056
20.0 mm, 2	16,63	0,306	850	-	55,56	0,054
20.0 mm, 3	15,86	0,319	886	-	55,56	0,050
20.0 mm, 4	16,44	0,317	881	-	55,56	0,052
20.0 mm, 5	14,02	0,265	737	-	55,56	0,053
20.0 mm, 6	15,49	0,294	816	-	55,56	0,053
20.0 mm, 7	16,93	0,333	925	-	55,56	0,051
20.0 mm, 8	13,27	0,240	665	-	55,56	0,055
Mean	**16,26**	**0,310**	**860**	**46,19**		

Fibre, 25 mm

ID:	Elongation [mm]	Tension [kN]	Strength [MPa]	SD [MPa]	l/A [1/mm]	ΔL/F [mm/N]
25.0 mm, 1	20,31	0,319	887	-	69,44	0,064
25.0 mm, 2	17,40	0,310	861	-	69,44	0,056
25.0 mm, 3	20,25	0,312	866	-	69,44	0,065
25.0 mm, 4	23,69	0,317	882	-	69,44	0,075
25.0 mm, 5	22,09	0,290	807	-	69,44	0,076
25.0 mm, 6	18,27	0,255	709	-	69,44	0,072
25.0 mm, 7	17,99	0,284	789	-	69,44	0,063
25.0 mm, 8	15,63	0,270	749	-	69,44	0,058
Mean	**20,29**	**0,306**	**849**	**41,06**		

Fibre, 30 mm

ID:	Elongation [mm]	Tension [kN]	Strength [MPa]	SD [MPa]	l/A [1/mm]	ΔL/F [mm/N]
30.0 mm, 1	23,59	0,306	851	-	83,33	0,077
30.0 mm, 2	20,74	0,349	969	-	83,33	0,059
30.0 mm, 3	21,16	0,266	740	-	83,33	0,079
30.0 mm, 4	-	-	-	-	-	-
30.0 mm, 5	22,43	0,254	707	-	83,33	0,088
30.0 mm, 6	23,05	0,265	736	-	83,33	0,087
30.0 mm, 7	22,88	0,284	788	-	83,33	0,081
30.0 mm, 8	24,19	0,306	849	-	83,33	0,079
Mean	**22,58**	**0,290**	**806**	**61,35**		

Fibres emitted in 1M NaOH for 28 days.

Fibre, 20 mm

ID:	Elongation [mm]	Tension [kN]	Strength [MPa]	SD [MPa]	)/A [1/mm]	ΔL/F [mm/N]
20.0 mm, 1	16,07	0,238	661	-	55,56	0,068
20.0 mm, 2	15,17	0,193	536	-	55,56	0,079
20.0 mm, 3	12,10	0,192	534	-	55,56	0,063
20.0 mm, 4	11,86	0,175	487	-	55,56	0,068
20.0 mm, 5	11,70	0,145	403	-	55,56	0,081
20.0 mm, 6	15,04	0,215	598	-	55,56	0,070
20.0 mm, 7	13,08	0,183	509	-	55,56	0,071
20.0 mm, 8	16,36	0,223	619	-	55,56	0,073
Mean	**15,14**	**0,210**	**585**	**61,94**		

Fibre, 25 mm

ID:	Elongation [mm]	Tension [kN]	Strength [MPa]	SD [MPa]	)/A [1/mm]	ΔL/F [mm/N]
25.0 mm, 1	18,84	0,236	655	-	69,44	0,080
25.0 mm, 2	14,23	0,183	507	-	69,44	0,078
25.0 mm, 3	14,72	0,192	533	-	69,44	0,077
25.0 mm, 4	13,85	0,222	617	-	69,44	0,062
25.0 mm, 5	14,69	0,202	560	-	69,44	0,073
25.0 mm, 6	15,53	0,208	578	-	69,44	0,075
25.0 mm, 7	16,69	0,227	631	-	69,44	0,074
25.0 mm, 8	15,74	0,229	635	-	69,44	0,069
Mean	**15,89**	**0,221**	**613**	**36,34**		

Fibre, 30 mm

ID:	Elongation [mm]	Tension [kN]	Strength [MPa]	SD [MPa]	)/A [1/mm]	ΔL/F [mm/N]
30.0 mm, 1	14,86	0,176	490	-	83,33	0,084
30.0 mm, 2	14,29	0,197	547	-	83,33	0,073
30.0 mm, 3	15,61	0,204	568	-	83,33	0,076
30.0 mm, 4	14,57	0,199	553	-	83,33	0,073
30.0 mm, 5	11,79	0,169	469	-	83,33	0,070
30.0 mm, 6	13,72	0,215	598	-	83,33	0,064
30.0 mm, 7	14,38	0,178	496	-	83,33	0,081
30.0 mm, 8	16,73	0,229	635	-	83,33	0,073
Mean	**14,96**	**0,203**	**565**	**49,10**		

9.7 Appendix 7 - SEM of PA6 Fibres

Appendix 7 contains the SEM pictures of waste PA6 fibres immersed in 1M NaOH solution for 0, 7, 14, 21, and 28 days, both for single fibres and fibre bundles.

PA6 Single Fibre

This include the SEM of waste PA6 single fibre.

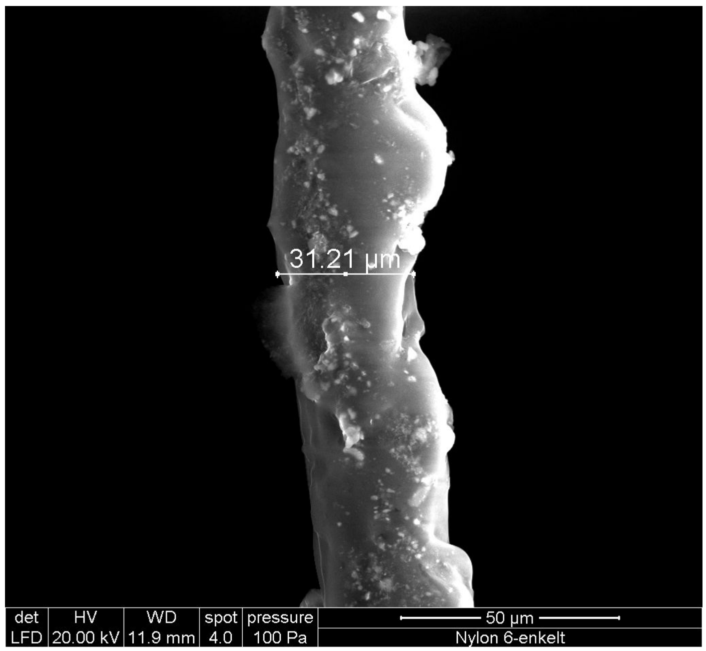


Figure 9.1: 0 days, zoom x800

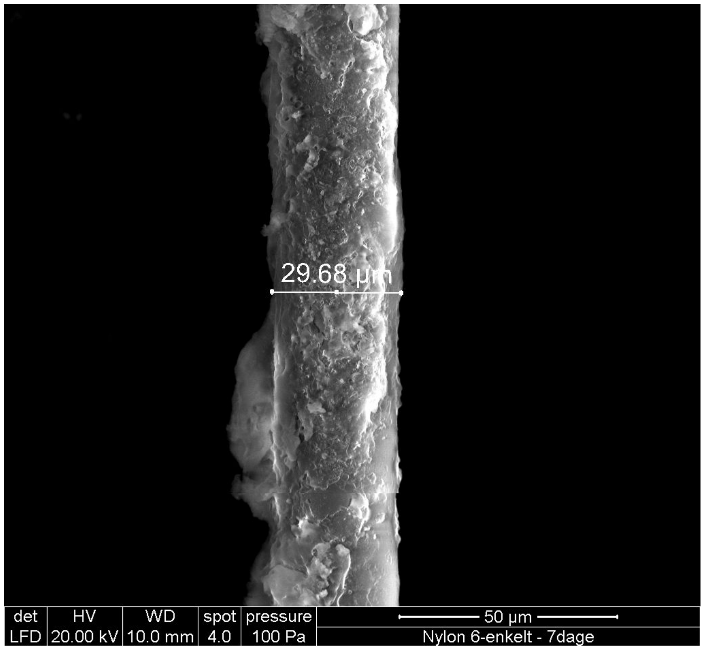


Figure 9.2: 7 days, zoom x800

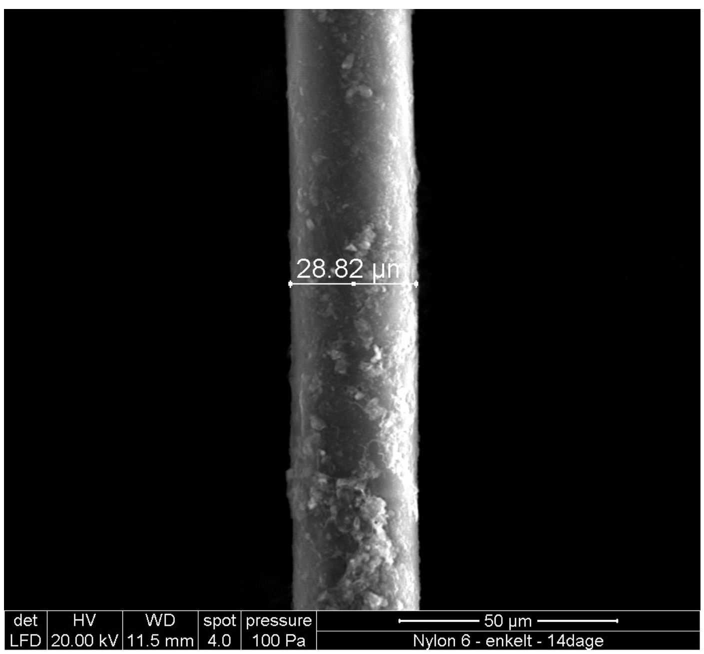


Figure 9.3: 14 days, zoom x800

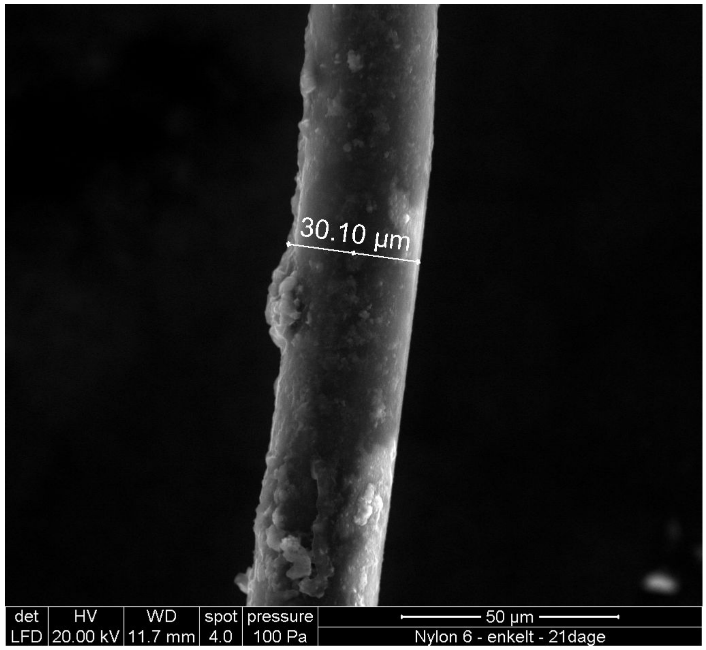


Figure 9.4: 21 days, zoom x800

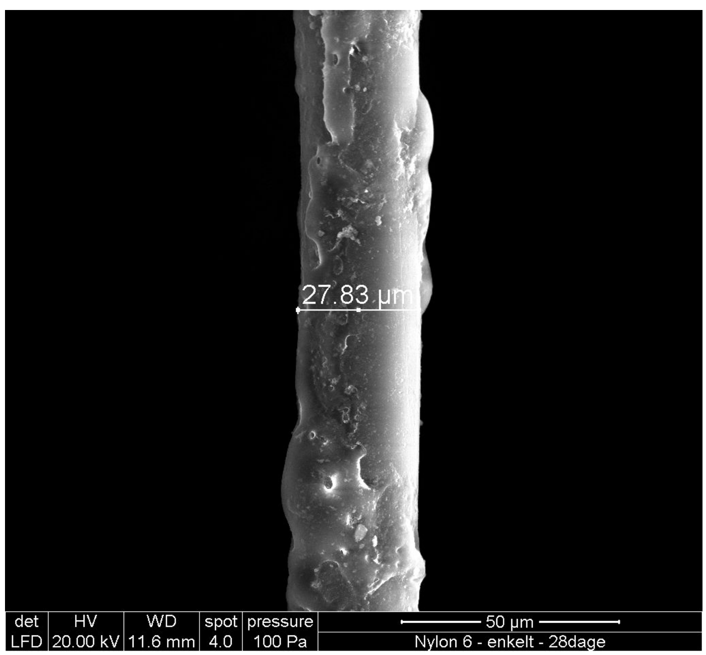


Figure 9.5: 28 days, zoom x800

PA6 Fibre Bundle

This includes the SEM of waste PA6 fibre bundle.

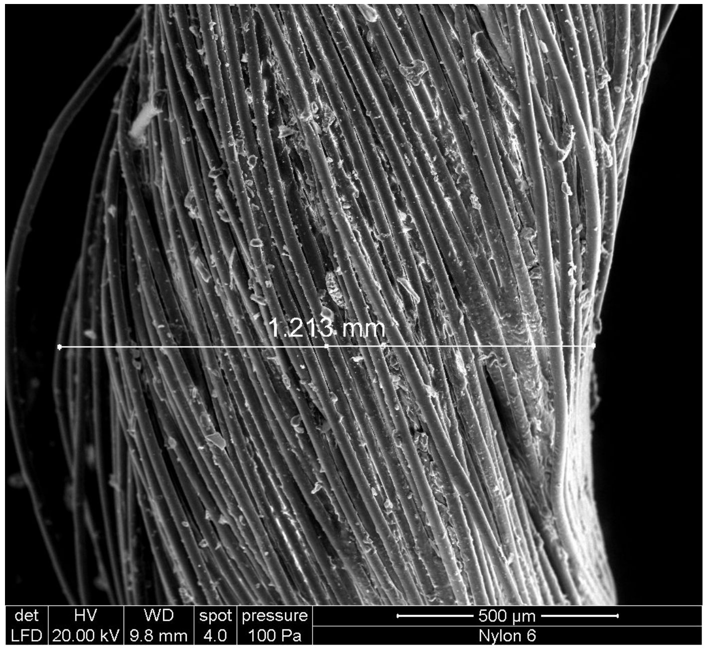


Figure 9.6: 0 days, zoom x80

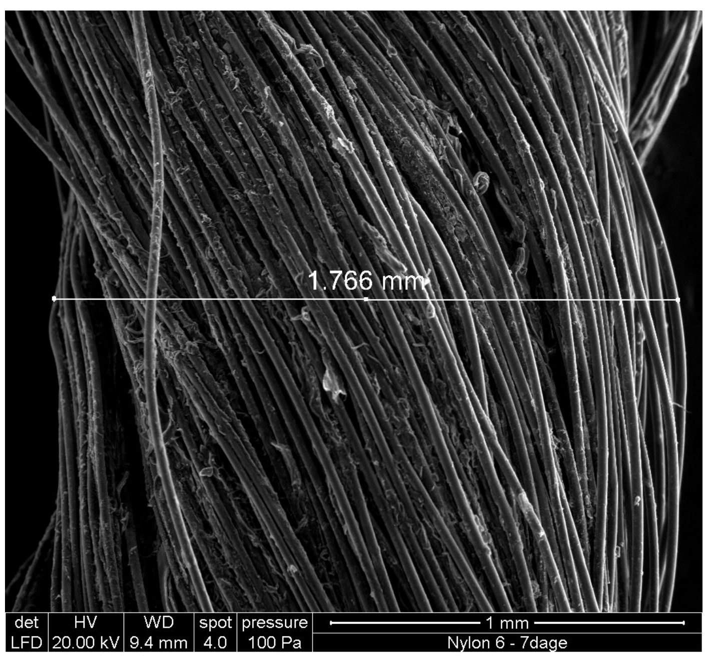


Figure 9.7: 7 days, zoom x65

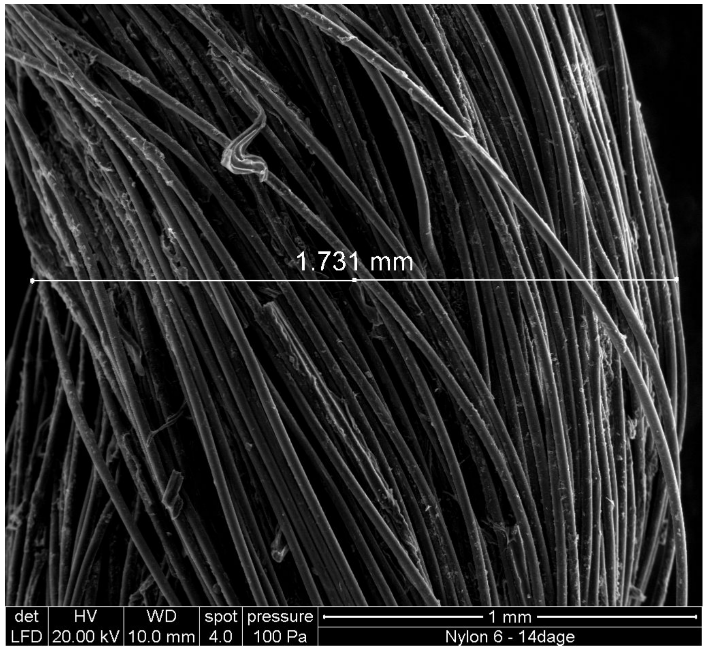


Figure 9.8: 14 days, zoom x65

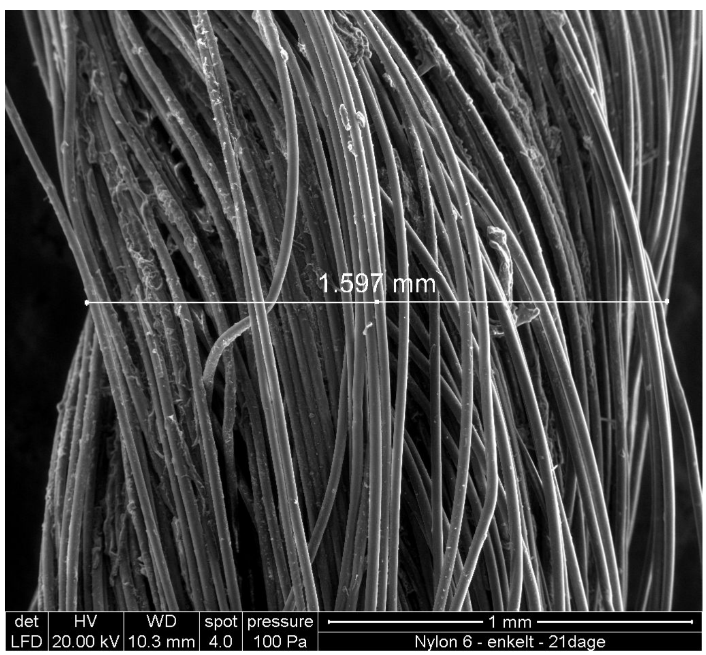


Figure 9.9: 21 days, zoom x65

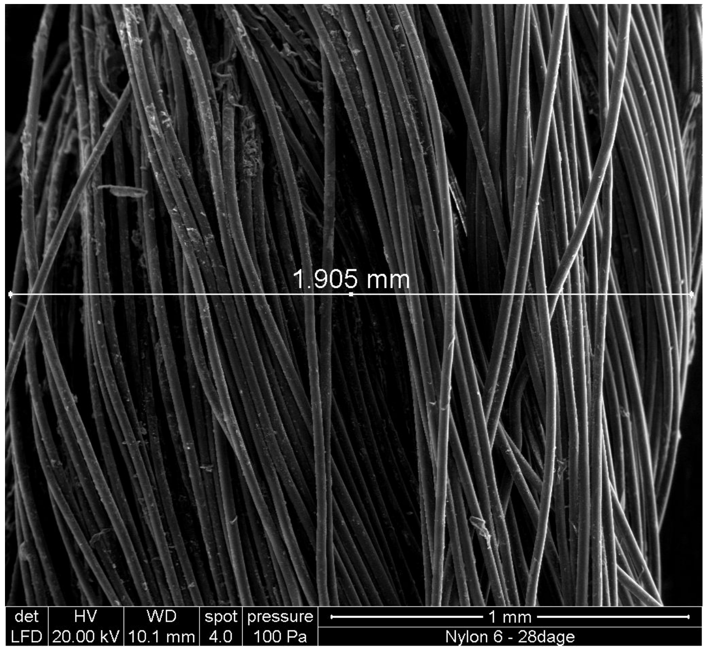


Figure 9.10: 28 days, zoom x65

9.8 Appendix 8 - Working Curves of Mortar Samples

Appendix 8 contains the working curve for all the three-point bending test performed on mortar samples. After the working curves the key values has been extracted to the tables below in this Appendix.

7 Days Samples

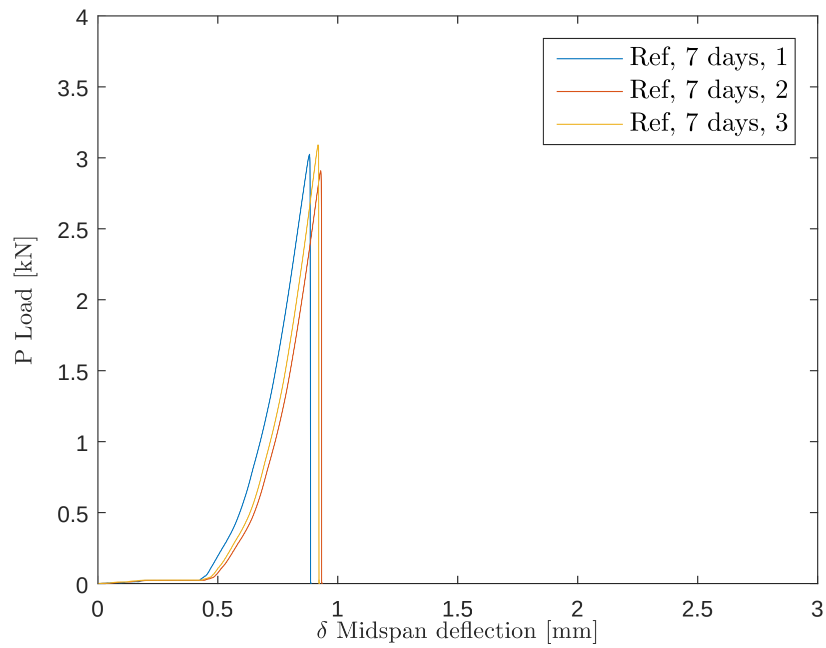


Figure 9.11: Working curve for reference mortar sample.

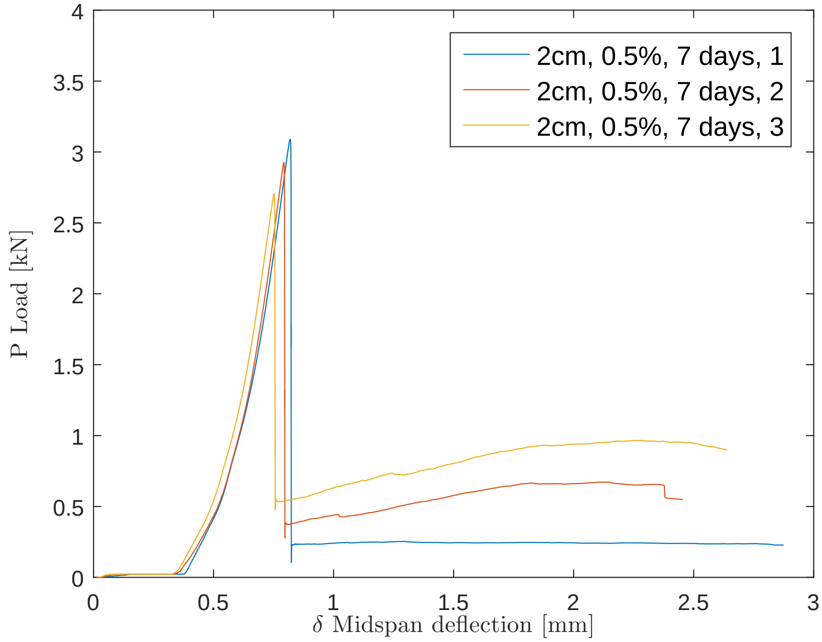


Figure 9.12: Working curve for mortar sample with 0.5 % 2 cm fibres.

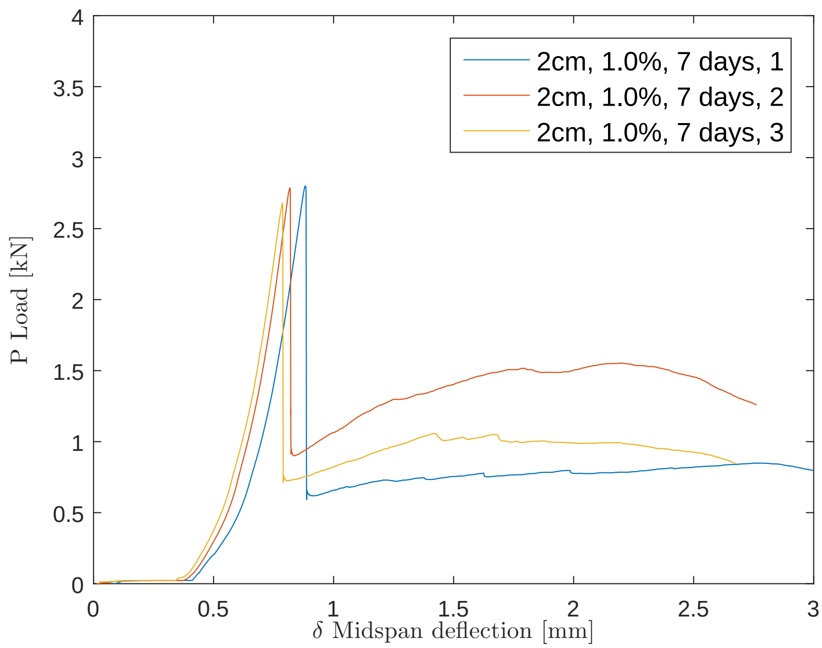


Figure 9.13: Working curve for mortar sample with 1.0 % 2 cm fibres.

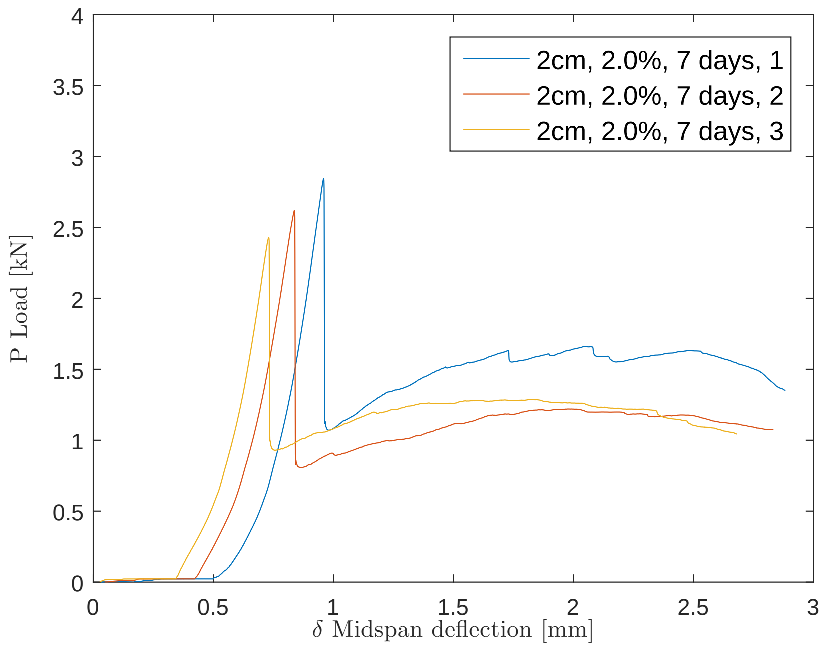


Figure 9.14: Working curve for mortar sample with 2.0 % 2 cm fibres.

14 Days Samples

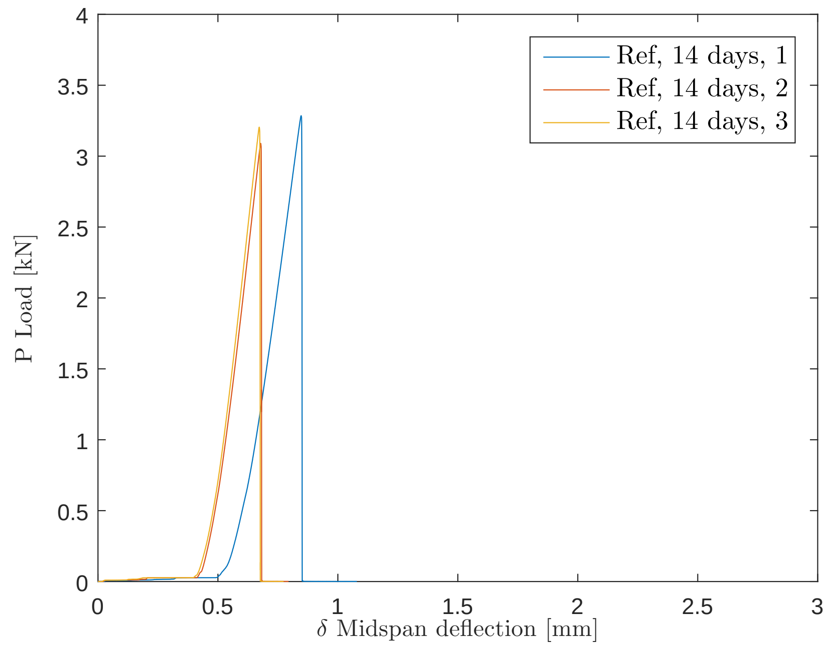


Figure 9.15: Working curve for reference mortar sample.

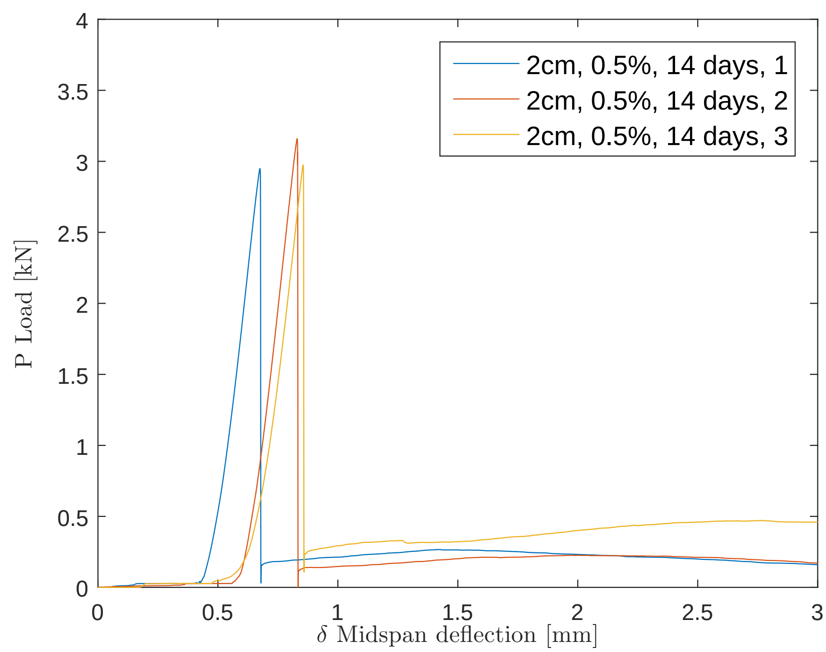


Figure 9.16: Working curve for mortar sample with 0.5 % 2 cm fibres.

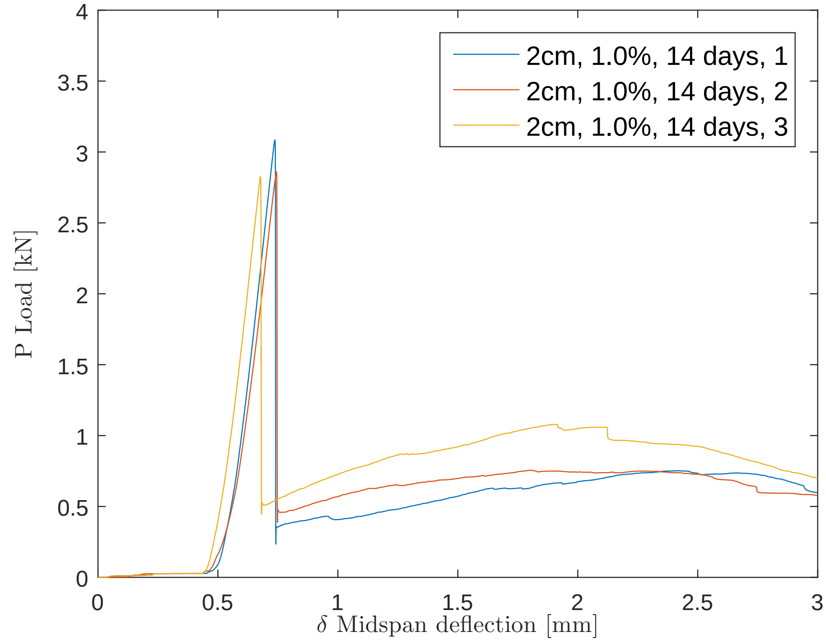


Figure 9.17: Working curve for mortar sample with 1.0 % 2 cm fibres.

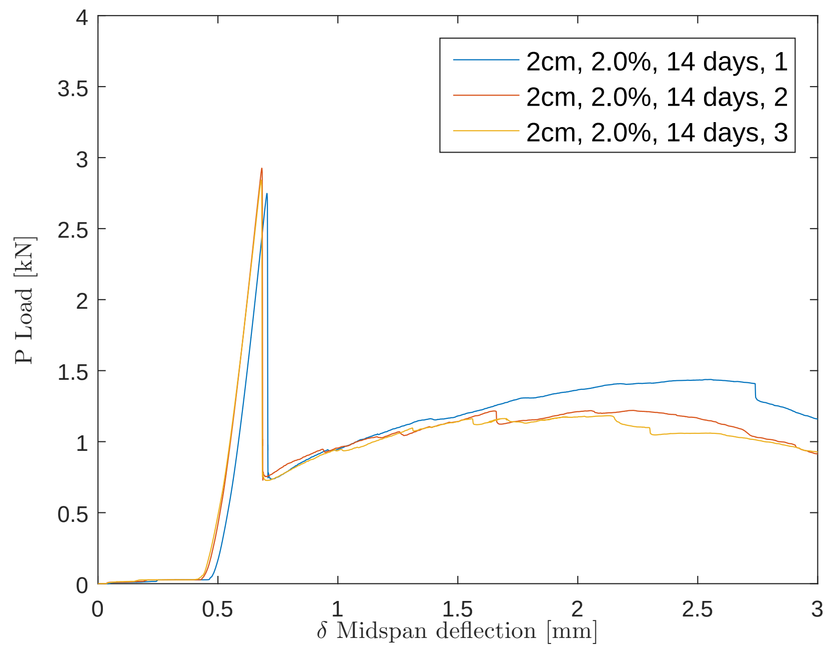


Figure 9.18: Working curve for mortar sample with 2.0 % 2 cm fibers.

28 Days Samples

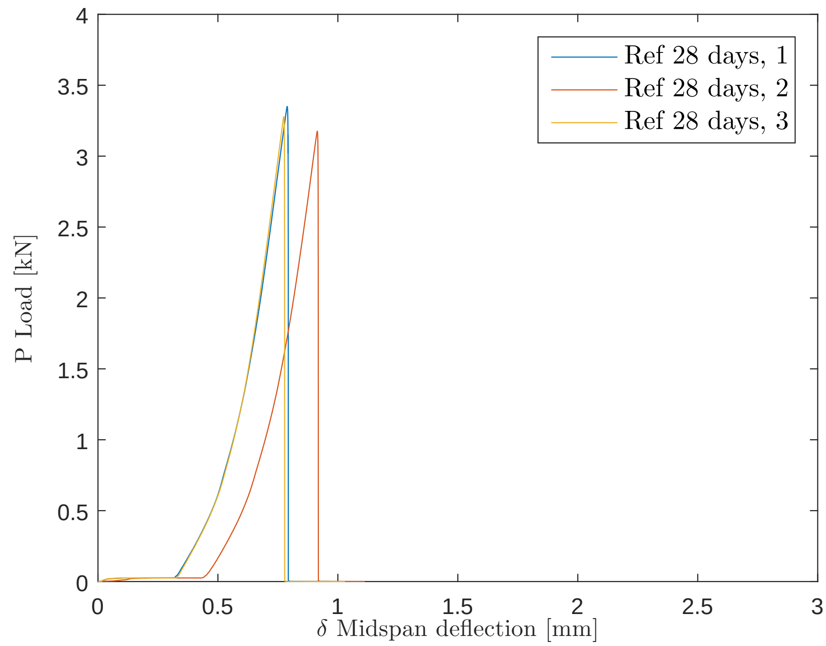


Figure 9.19: Working curve for reference mortar sample.

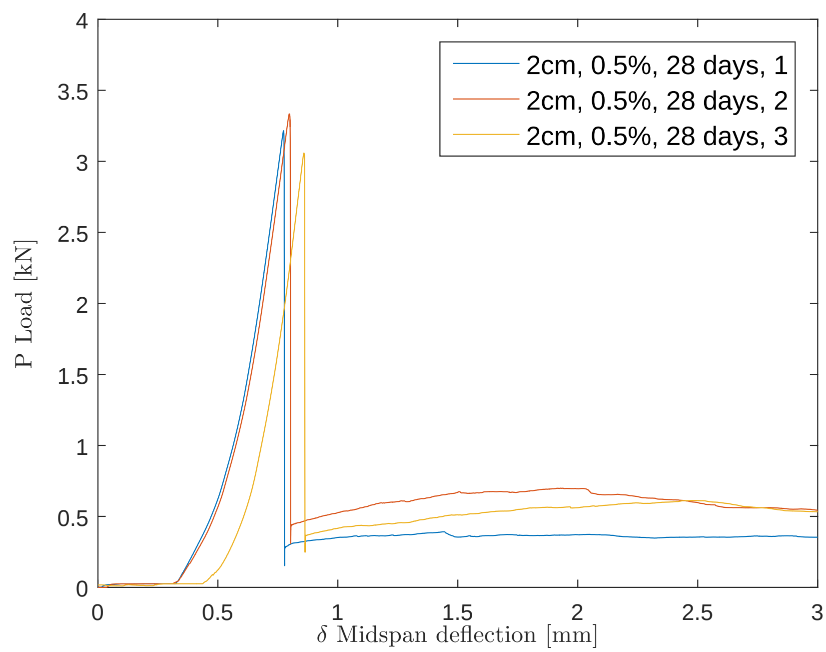


Figure 9.20: Working curve for mortar sample with 0.5 % 2 cm fibres.

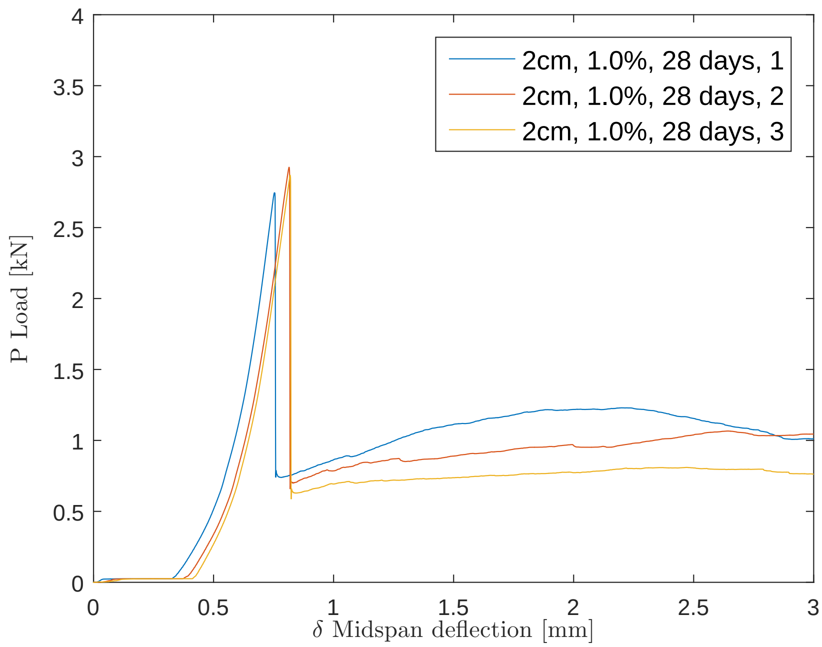


Figure 9.21: Working curve for mortar sample with 1.0 % 2 cm fibres.

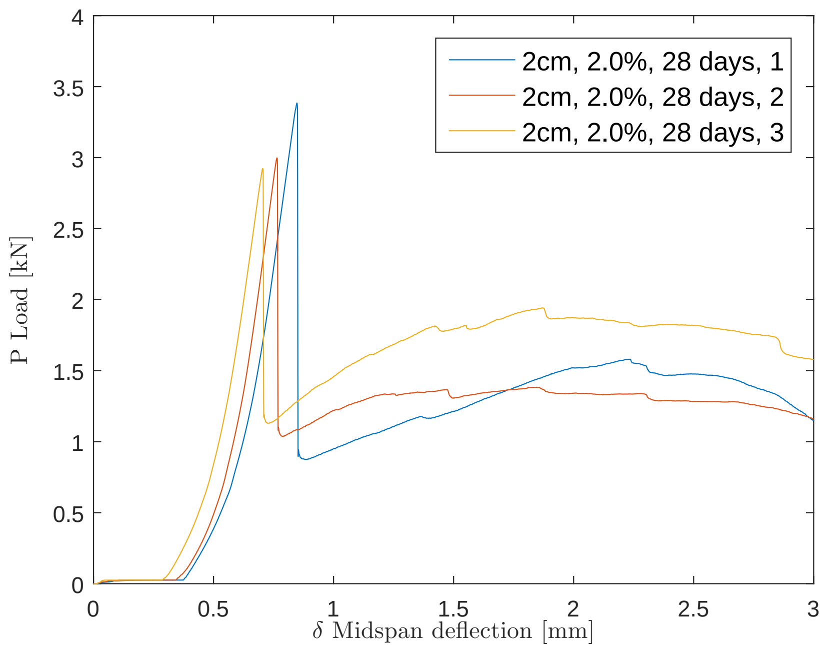


Figure 9.22: Working curve for mortar sample with 2.0 % 2 cm fibers.

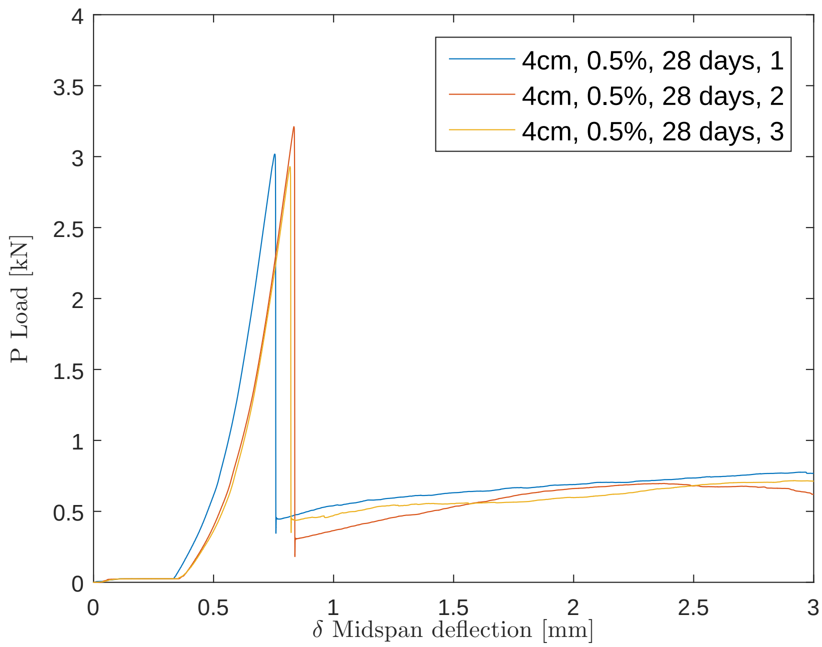


Figure 9.23: Working curve for mortar sample with 0.5 % 4 cm fibres.

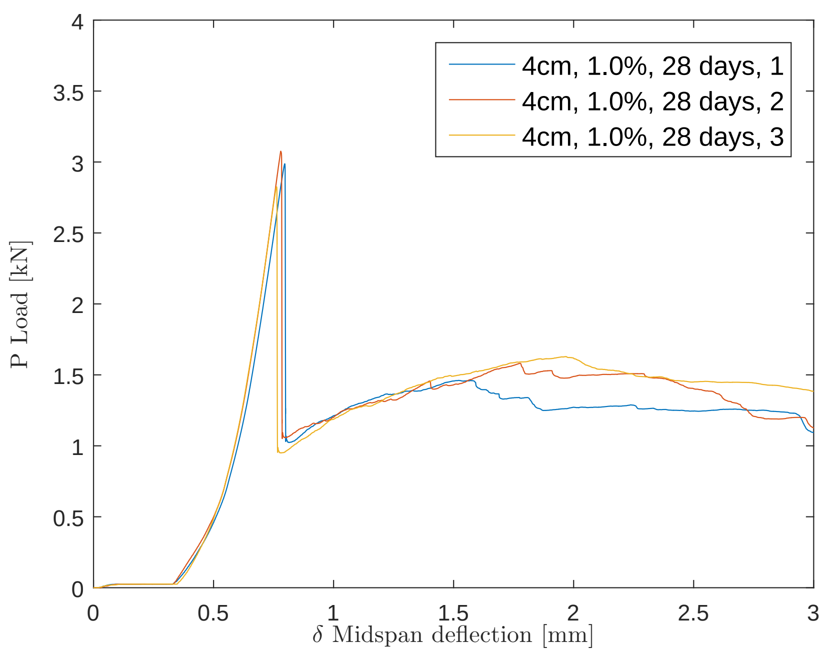


Figure 9.24: Working curve for mortar sample with 1.0 % 4 cm fibres.

Durus Mortar samples with Durus fibres from PP Nordica.

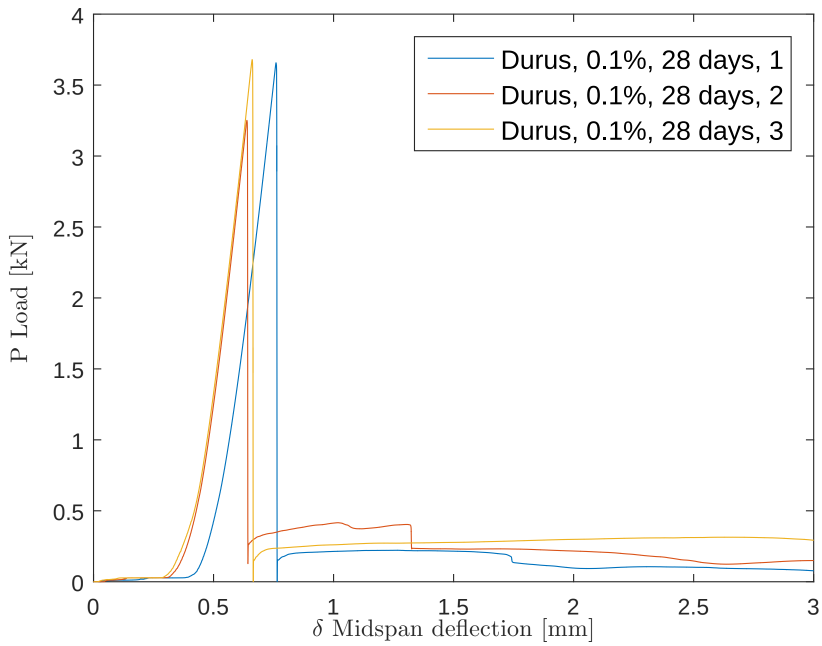


Figure 9.25: Working curve for mortar sample with 0.1 % Durus fibres.

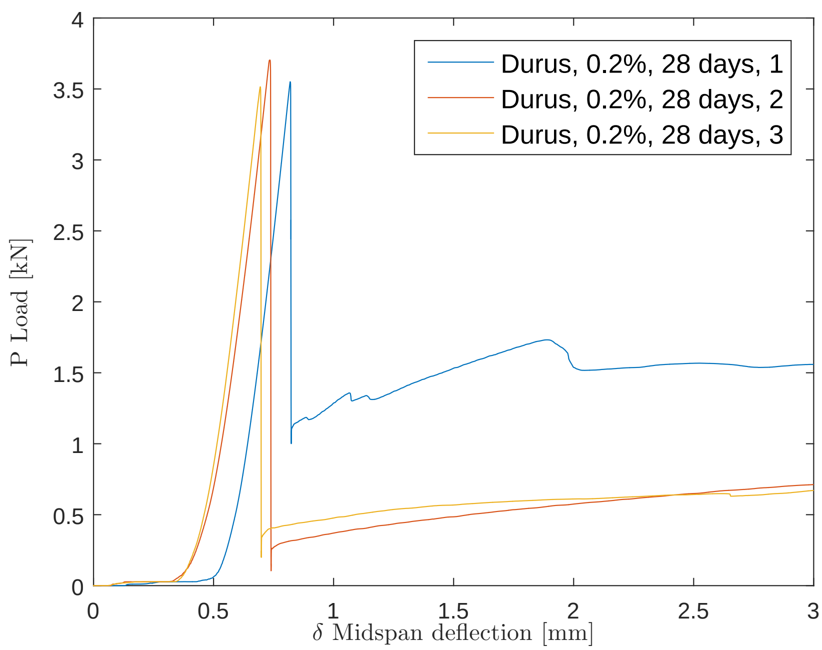


Figure 9.26: Working curve for mortar sample with 0.2 % Durus fibres.

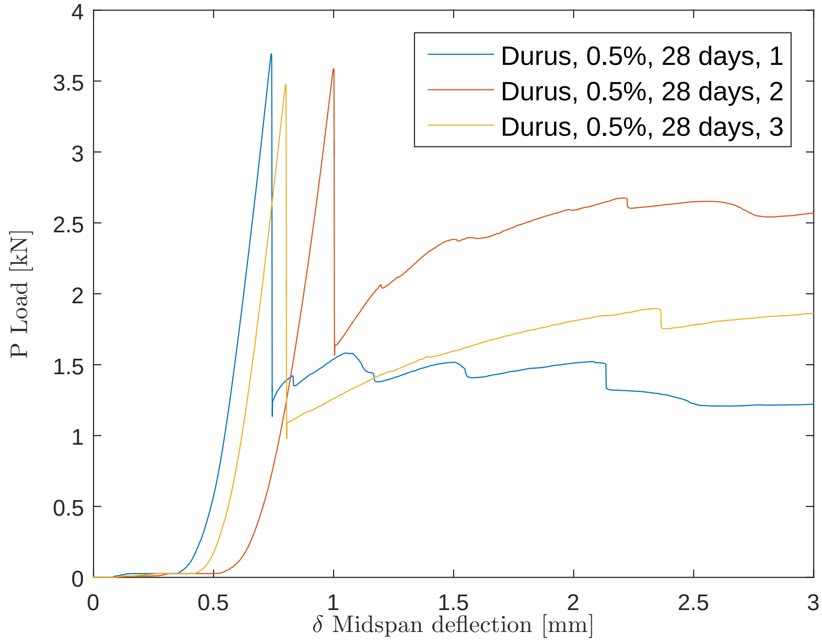


Figure 9.27: Working curve for mortar sample with 0.5 % Durus fibres.

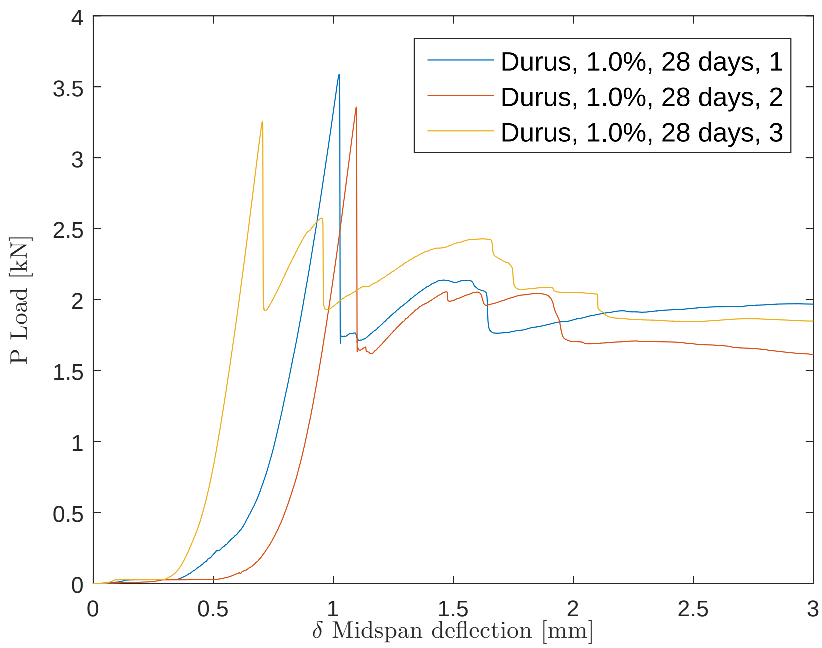


Figure 9.28: Working curve for mortar sample with 1.0 % Durus fibres.

Fibrin Mortar samples with Fibrin Fiberflex fibres from PP Nordica.

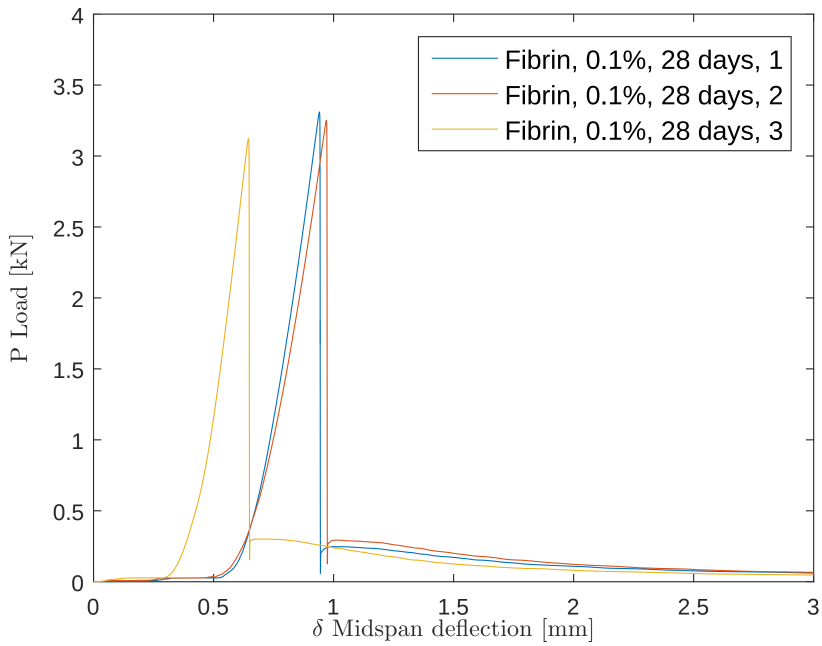


Figure 9.29: Working curve for mortar sample with 0.1 % Fibrin fibres.

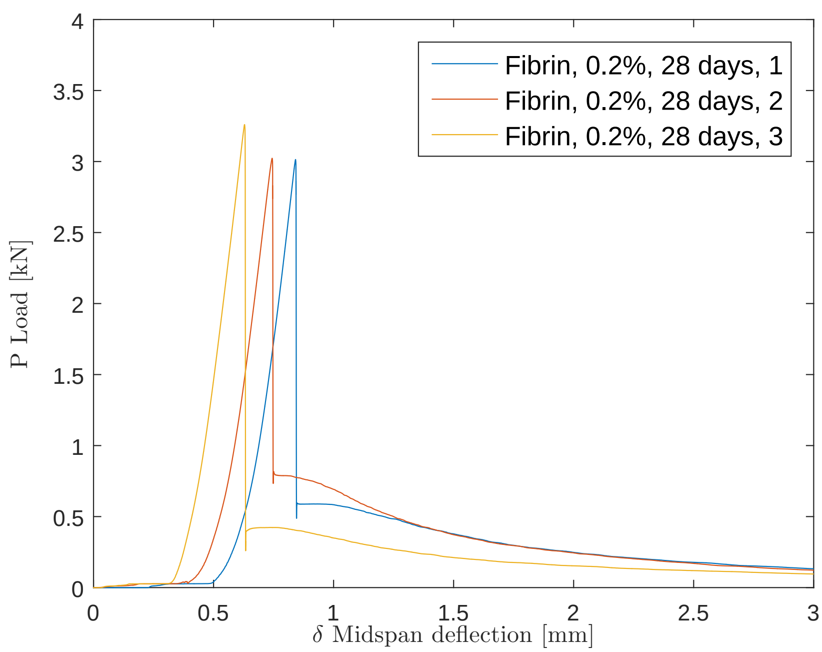


Figure 9.30: Working curve for mortar sample with 0.2 % Fibrin fibres.

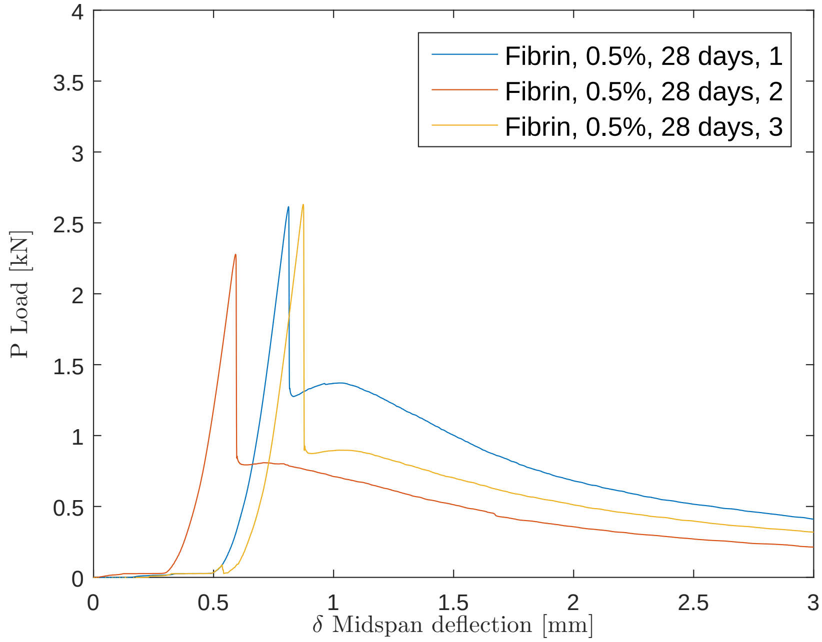


Figure 9.31: Working curve for mortar sample with 0.5 % Fibrin fibres.

9.9 Appendix 9 - Flexural Strength of Mortar Samples

7 days Mortar Samples

PB Str. = Post-Break Strength

ID:	Break Load [kN]	Crack Def. [mm]	Strength [MPa]	Std. [MPa]	PB Str. [kN]	PB Str. [MPa]
Ref 1	3,086	0,916	7,233	-	0	0
Ref 2	3,024	0,881	7,088	-	0	0
Ref 3	2,909	0,928	6,818	-	0	0
Ref Average	**3,006**	**0,908**	**7,046**	**0,210**	**0**	**0**
2 cm 0.5% 1	3,090	0,819	7,242	-	0,247	0,579
2 cm 0.5% 2	2,926	0,793	6,858	-	0,672	1,575
2 cm 0.5% 3	2,701	0,751	6,330	-	0,966	2,264
0.5% Average	**2,906**	**0,788**	**6,810**	**0,458**	**0,628**	**1,473**
2 cm 1.0% 1	2,800	0,985	6,563	-	0,849	1,990
2 cm 1.0% 2	2,787	0,818	6,532	-	1,554	3,642
2 cm 1.0% 3	2,680	0,787	6,281	-	1,057	2,477
1.0% Average	**2,756**	**0,863**	**6,459**	**0,154**	**1,153**	**2,703**
2 cm 2.0% 1	2,844	0,959	6,666	-	1,660	3,891
2 cm 2.0% 2	2,618	0,837	6,136	-	1,220	2,859
2 cm 2.0% 3	2,427	0,730	5,688	-	1,287	3,016
2.0% Average	**2,630**	**0,842**	**6,163**	**0,489**	**1,389**	**3,255**

14 days Mortar Samples

PB Str. = Post-Break Strength

ID:	Break Load [kN]	Crack Def. [mm]	Strength [MPa]	Std. [MPa]	PB Str. [kN]	PB Str. [MPa]
Ref 1	3,285	0,847	7,700	-	0	0
Ref 2	3,090	0,678	7,243		0	0
Ref 3	3,205	0,672	7,511	-	0	0
Ref Average	**3,193**	**0,732**	**7,484**	**0,230**	**0**	**0**
2 cm 0.5% 1	2,950	0,675	6,914	-	0,267	0,625
2 cm 0.5% 2	3,160	0,830	7,405	-	0,226	0,530
2 cm 0.5% 3	2,974	0,859	6,971	-	0,471	1,103
0.5% Average	**3,028**	**0,788**	**7,097**	**0,269**	**0,321**	**0,753**
2 cm 1.0% 1	3,085	0,737	7,231	-	0,752	1,764
2 cm 1.0% 2	2,860	0,744	6,704	-	0,756	1,771
2 cm 1.0% 3	2,826	0,677	6,622	-	1,078	2,527
1.0% Average	**2,924**	**0,719**	**6,852**	**0,331**	**0,862**	**2,021**
2 cm 2.0% 1	2,748	0,704	6,441	-	1,438	3,370
2 cm 2.0% 2	2,926	0,683	6,857	-	1,220	2,860
2 cm 2.0% 3	2,842	0,680	6,660	-	1,183	2,772
2.0% Average	**2,839**	**0,689**	**6,653**	**0,208**	**1,280**	**3,001**

28 days Mortar Samples

PB Str. = Post-Break Strength

ID:	Break Load [kN]	Crack Def. [mm]	Strength [MPa]	Std. [MPa]	PB Str. [kN]	PB Str. [MPa]
Ref 1	3,351	0,789	7,854	-	0	0
Ref 2	3,176	0,914	7,444	-	0	0
Ref 3	3,279	0,774	7,685	-	0	0
Ref Average	**3,269**	**0,826**	**7,661**	**0,206**	**0**	**0**
2 cm 0.5% 1	3,216	0,773	7,538	-	0,391	0,916
2 cm 0.5% 2	3,334	0,797	7,814	-	0,699	1,638
2 cm 0.5% 3	3,058	0,858	7,167	-	0,612	1,434
0.5% Average	**3,203**	**0,809**	**7,506**	**0,325**	**0,567**	**1,330**
2 cm 1.0% 1	2,745	0,753	6,434	-	1,230	2,883
2 cm 1.0% 2	2,925	0,814	6,855	-	1,066	2,498
2 cm 1.0% 3	2,869	0,819	6,724	-	0,810	1,898
1.0% Average	**2,846**	**0,795**	**6,671**	**0,216**	**1,035**	**2,427**
2 cm 2.0% 1	3,385	0,847	7,934	-	1,580	3,703
2 cm 2.0% 2	2,998	0,764	7,027	-	1,383	3,241
2 cm 2.0% 3	2,923	0,705	6,851	-	1,941	4,549
2.0% Average	**3,102**	**0,772**	**7,270**	**0,581**	**1,635**	**3,831**

ID:	Break Load [kN]	Crack Def. [mm]	Strength [MPa]	Std. [MPa]	PB Str. [kN]	PB Str. [MPa]
4 cm 0.5% 1	3,018	0,741	7,073	-	0,785	1,840
4 cm 0.5% 2	3,211	0,801	7,526	-	0,697	1,634
4 cm 0.5% 3	2,930	0,818	6,867	-	0,758	1,777
4 cm 0.5% Aver	**3,053**	**0,787**	**7,155**	**0,337**	**0,747**	**1,750**
4 cm 1.0% 1	2,988	0,797	7,003	-	1,461	3,424
4 cm 1.0% 2	3,076	0,766	7,209	-	1,581	3,705
4 cm 1.0% 3	2,826	0,762	6,623	-	1,629	3,818
4 cm 1.0% Aver	**2,963**	**0,775**	**6,945**	**0,297**	**1,557**	**3,649**

DURUS - 28 days Mortar Samples

PB Str. = Post-Break Strength

ID:	Break Load [kN]	Crack Def. [mm]	Strength [MPa]	Std. [MPa]	PB Str. [kN]	PB Str. [MPa]
0.1% 1	3,657	0,760	8,571	-	0,222	0,520
0.1% 2	3,252	0,639	7,622	-	0,416	0,975
0.1% 3	3,680	0,661	8,624	-	0,314	0,736
0.1% Average	**3,530**	**0,687**	**8,272**	**0,564**	**0,317**	**0,744**
0.2% 1	3,551	0,819	8,322	-	1,732	4,059
0.2% 2	3,704	0,735	8,681	-	0,771	1,807
0.2% 3	3,515	0,703	8,239	-	0,774	1,814
0.2% Average	**3,590**	**0,752**	**8,414**	**0,235**	**1,092**	**2,560**
0.5% 1	3,693	0,740	8,655	-	1,582	3,708
0.5% 2	3,588	0,999	8,409	-	2,676	6,272
0.5% 3	3,477	0,801	8,150	-	1,909	4,474
0.5% Average	**3,586**	**0,847**	**8,405**	**0,253**	**2,056**	**4,818**
1.0% 1	3,588	1,024	8,410	-	2,138	5,011
1.0% 2	3,358	1,095	7,869	-	2,055	4,816
1.0% 3	3,254	0,704	7,626	-	2,575	6,035
1.0% Average	**3,400**	**0,941**	**7,968**	**0,401**	**2,256**	**5,288**

FIBRIN - 28 days Mortar Samples

PB Str. = Post-Break Strength

ID:	Break Load [kN]	Crack Def. [mm]	Strength [MPa]	Std. [MPa]	PB Str. [kN]	PB Str. [MPa]
0.1% 1	3,311	0,941	7,759	-	0,247	0,579
0.1% 2	3,252	0,970	7,622	-	0,294	0,688
0.1% 3	3,123	0,645	7,320	-	0,301	0,706
0.1% Average	**3,229**	**0,852**	**7,567**	**0,224**	**0,281**	**0,658**
0.2% 1	3,014	0,842	7,065	-	0,597	1,398
0.2% 2	3,023	0,744	7,086	-	0,818	1,916
0.2% 3	3,260	1,051	7,641	-	0,423	0,992
0.2% Average	**3,099**	**0,879**	**7,264**	**0,327**	**0,613**	**1,436**
0.5% 1	2,615	0,812	6,128	-	1,371	3,213
0.5% 2	2,279	0,591	5,340	-	0,926	2,171
0.5% 3	2,630	0,873	6,165	-	0,927	2,173
0.5% Average	**2,508**	**0,759**	**5,878**	**0,466**	**1,075**	**2,519**

9.10 Appendix 10 - Toughness of Mortar Samples

7 days Mortar Samples

ID:	Crack Def. [mm]	T_δ_cr [Nmm]	T_2δ_cr [Nmm]	T_3δ_cr [Nmm]	I_2	I_3
Ref 1	0,916	504	0	0	0	0
Ref 2	0,881	468	0	0	0	0
Ref 3	0,928	478	0	0	0	0
Ref Average	**0,908**	**483**	**0**	**0**	0	0
2 cm 0.5% 1	0,819	476	725	924	1,52	1,94
2 cm 0.5% 2	0,793	435	850	1369	1,96	3,15
2 cm 0.5% 3	0,751	383	927	1611	2,42	4,21
0.5% Average	**0,788**	**431**	**834**	**1302**	**1,97**	**3,10**
2 cm 1.0% 1	0,985	458	1263	2064	2,76	4,51
2 cm 1.0% 2	0,818	426	1441	2675	3,38	6,28
2 cm 1.0% 3	0,787	404	1125	1908	2,78	4,72
1.0% Average	**0,863**	**429**	**1276**	**2216**	**2,97**	**5,17**
2 cm 2.0% 1	0,959	442	1816	3325	4,11	7,51
2 cm 2.0% 2	0,837	415	1258	2258	3,04	5,45
2 cm 2.0% 3	0,730	359	1187	2111	3,31	5,89
2.0% Average	**0,842**	**405**	**1421**	**2564**	**3,48**	**6,28**

14 days Mortar Samples

ID:	Crack Def. [mm]	T_δ_cr [Nmm]	T_2δ_cr [Nmm]	T_3δ_cr [Nmm]	I_2	I_3
Ref 1	0,847	471	0	0	0	0
Ref 2	0,678	352	0	0	0	0
Ref 3	0,672	366	0	0	0	0
Ref Average	**0,732**	**396**	**0**	**0**	0	0
2 cm 0.5% 1	0,675	321	476	646	1,48	2,01
2 cm 0.5% 2	0,830	358	510	692	1,43	1,93
2 cm 0.5% 3	0,859	347	627	985	1,80	2,84
0.5% Average	**0,788**	**342**	**538**	**774**	**1,57**	**2,26**
2 cm 1.0% 1	0,737	339	680	1160	2,01	3,42
2 cm 1.0% 2	0,744	324	775	1323	2,39	4,08
2 cm 1.0% 3	0,677	288	784	1457	2,72	5,05
1.0% Average	**0,719**	**317**	**746**	**1313**	**2,37**	**4,19**
2 cm 2.0% 1	0,704	278	971	1874	3,50	6,75
2 cm 2.0% 2	0,683	310	969	1762	3,12	5,68
2 cm 2.0% 3	0,680	308	949	1735	3,08	5,63
2.0% Average	**0,689**	**299**	**963**	**1790**	**3,23**	**6,02**

28 days Mortar Samples

ID:	Crack Def. [mm]	T_δ_cr [Nmm]	T_2δ_cr [Nmm]	T_3δ_cr [Nmm]	I_2	I_3
Ref 1	0,789	571	0	0	0	0
Ref 2	0,914	542	0	0	0	0
Ref 3	0,774	532	0	0	0	0
Ref Average	**0,826**	**548**	**0**	**0**	0	0
2 cm 0.5% 1	0,773	530	815	1097	1,54	2,07
2 cm 0.5% 2	0,797	568	1044	1575	1,84	2,77
2 cm 0.5% 3	0,858	443	1047	1728	2,36	3,90
0.5% Average	**0,809**	**514**	**969**	**1466**	**1,91**	**2,91**
2 cm 1.0% 1	0,753	408	1115	2012	2,73	4,93
2 cm 1.0% 2	0,814	455	1142	1926	2,51	4,24
2 cm 1.0% 3	0,819	427	1014	1655	2,38	3,88
1.0% Average	**0,795**	**430**	**1090**	**1864**	**2,54**	**4,35**
2 cm 2.0% 1	0,847	583	1526	2788	2,62	4,78
2 cm 2.0% 2	0,764	449	1413	2442	3,15	5,44
2 cm 2.0% 3	0,705	448	1505	2815	3,36	6,29
2.0% Average	**0,772**	**493**	**1481**	**2681**	**3,04**	**5,50**

ID:	Crack Def. [mm]	T_δ_cr [Nmm]	T_2δ_cr [Nmm]	T_3δ_cr [Nmm]	I_2	I_3
4 cm 0.5% 1	0,741	479	895	1393	1,87	2,91
4 cm 0.5% 2	0,801	545	890	1412	1,63	2,59
4 cm 0.5% 3	0,818	474	907	1404	1,91	2,96
4 cm 0.5% Aver	**0,787**	**499**	**897**	**1403**	**1,80**	**2,82**
4 cm 1.0% 1	0,797	492	1536	2568	3,12	5,22
4 cm 1.0% 2	0,766	487	1463	2617	3,00	5,37
4 cm 1.0% 3	0,762	429	1402	2591	3,27	6,05
4 cm 1.0% Aver	**0,775**	**469**	**1467**	**2592**	**3,13**	**5,55**

DURUS - 28 days Mortar Samples

ID:	Crack Def. [mm]	T_δ_cr [Nmm]	T_2δ_cr [Nmm]	T_3δ_cr [Nmm]	I_2	I_3
0.1% 1	0,760	509	683	786	1,34	1,54
0.1% 2	0,639	399	712	803	1,78	2,01
0.1% 3	0,661	501	680	868	1,36	1,73
0.1% Average	**0,687**	**470**	**692**	**819**	**1,49**	**1,76**
0.2% 1	0,819	460	1595	2905	3,47	6,31
0.2% 2	0,735	539	840	1242	1,56	2,30
0.2% 3	0,703	468	822	1239	1,76	2,65
0.2% Average	**0,752**	**489**	**1086**	**1795**	**2,26**	**3,75**
0.5% 1	0,740	518	1603	2679	3,09	5,17
0.5% 2	0,999	581	2857	5467	4,92	9,41
0.5% 3	0,801	472	1603	3035	3,39	6,43
0.5% Average	**0,847**	**524**	**2021**	**3727**	**3,80**	**7,00**
1.0% 1	1,024	730	2688	4676	3,68	6,40
1.0% 2	1,095	559	2621	4428	4,69	7,92
1.0% 3	0,704	468	2009	3568	4,29	7,62
1.0% Average	**0,941**	**586**	**2439**	**4224**	**4,22**	**7,31**

FIBRIN - 28 days Mortar Samples

ID:	Crack Def. [mm]	T_δ_cr [Nmm]	T_2δ_cr [Nmm]	T_3δ_cr [Nmm]	I_2	I_3
0.1% 1	0,941	512	698	780	1,36	1,52
0.1% 2	0,970	550	609	857	1,11	1,56
0.1% 3	0,645	398	809	642	2,03	1,61
0.1% Average	**0,852**	**487**	**705**	**760**	**1,50**	**1,57**
0.2% 1	0,842	379	783	980	2,07	2,59
0.2% 2	0,744	388	840	1047	2,16	2,69
0.2% 3	1,051	413	813	933	1,97	2,26
0.2% Average	**0,879**	**394**	**812**	**987**	**2,07**	**2,51**
0.5% 1	0,812	307	1284	1841	4,18	5,99
0.5% 2	0,591	254	701	1009	2,76	3,97
0.5% 3	0,873	303	988	1399	3,26	4,62
0.5% Average	**0,759**	**288**	**991**	**1416**	**3,40**	**4,86**

9.11 Appendix 11 - Compression Strength of Mortar Samples

28 days Mortar samples

Pink = out of ±10% of mean

ID:	Compression [kN]	Strength [MPa]	SD [MPa]	Pct. of Ref [%]
Ref 1	1133	71	-	-
Ref 1	1056	66	-	-
Ref 2	1061	66	-	-
Ref 2	1041	65	-	-
Ref 3	917	57	-	-
Ref 3	974	61	-	-
Ref Average	**1033**	**65**	**2,51**	**100**

ID:	Compression [kN]	Strength [MPa]	SD [MPa]	Pct. of Ref [%]
2 cm 0.5% 1	957	60	-	-
2 cm 0.5% 1	927	58	-	-
2 cm 0.5% 2	903	56	-	-
2 cm 0.5% 2	930	58	-	-
2 cm 0.5% 3	848	53	-	-
2 cm 0.5% 3	850	53	-	-
0.5% Average	**902**	**56**	**2,80**	**87,36**

ID:	Compression [kN]	Strength [MPa]	SD [MPa]	Pct. of Ref [%]
2 cm 1.0% 1	913	57	-	-
2 cm 1.0% 1	926	58	-	-
2 cm 1.0% 2	889	56	-	-
2 cm 1.0% 2	937	59	-	-
2 cm 1.0% 3	936	59	-	-
2 cm 1.0% 3	905	57	-	-
1.0% Average	**918**	**57**	**1,18**	**88,85**

ID:	Compression [kN]	Strength [MPa]	SD [MPa]	Pct. of Ref [%]
2 cm 2.0% 1	858	54	-	-
2 cm 2.0% 1	793	50	-	-
2 cm 2.0% 2	885	55	-	-
2 cm 2.0% 2	871	54	-	-
2 cm 2.0% 3	857	54	-	-
2 cm 2.0% 3	875	55	-	-
2.0% Average	**856**	**54**	**2,07**	**82,91**

ID:	Compression [kN]	Strength [MPa]	SD [MPa]	Pct. of Ref [%]
4 cm 0.5% 1	975	61	-	-
4 cm 0.5% 1	953	60	-	-
4 cm 0.5% 2	970	61	-	-
4 cm 0.5% 2	1004	63	-	-
4 cm 0.5% 3	933	58	-	-
4 cm 0.5% 3	976	61	-	-
4 cm 0.5% Ave	**968**	**61**	**1,50**	**93,75**

ID:	Compression [kN]	Strength [MPa]	SD [MPa]	Pct. of Ref [%]
4 cm 1.0% 1	876	55	-	-
4 cm 1.0% 1	859	54	-	-
4 cm 1.0% 2	900	56	-	-
4 cm 1.0% 2	923	58	-	-
4 cm 1.0% 3	870	54	-	-
4 cm 1.0% 3	897	56	-	-
4 cm 1.0% Ave	**887**	**55**	**1,48**	**85,91**

DURUS - 28 days Mortar Samples

Pink = out of ±10% of mean

ID:	Compression [kN]	Strength [MPa]	SD [MPa]	Pct. of Ref [%]
0.1% 1	803	50	-	-
0.1% 1	1062	66	-	-
0.1% 2	990	62	-	-
0.1% 2	691	43	-	-
0.1% 3	825	52	-	-
0.1% 3	725	45	-	-
0.1% Average	**1026**	**64**	**3,18**	**99,32**

ID:	Compression [kN]	Strength [MPa]	SD [MPa]	Pct. of Ref [%]
0.2% 1	1015	63	-	-
0.2% 1	1009	63	-	-
0.2% 2	698	44	-	-
0.2% 2	1010	63	-	-
0.2% 3	718	45	-	-
0.2% 3	1022	64	-	-
0.2% Average	**1014**	**63**	**0,37**	**98,16**

ID:	Compression [kN]	Strength [MPa]	SD [MPa]	Pct. of Ref [%]
0.5% 1	921	58	-	-
0.5% 1	1053	66	-	-
0.5% 2	1024	64	-	-
0.5% 2	812	51	-	-
0.5% 3	810	51	-	-
0.5% 3	855	53	-	-
0.5% Average	**884**	**55**	**5,63**	**85,61**

ID:	Compression [kN]	Strength [MPa]	SD [MPa]	Pct. of Ref [%]
1.0% 1	1038	65	-	-
1.0% 1	1096	69	-	-
1.0% 2	948	59	-	-
1.0% 2	769	48	-	-
1.0% 3	1082	68	-	-
1.0% 3	785	49	-	-
1.0% Average	**885**	**55**	**8,14**	**85,67**

FIBRIN - 28 days Mortar Samples

Pink = out of ±10% of mean

ID:	Compression [kN]	Strength [MPa]	SD [MPa]	Pct. of Ref [%]
0.1% 1	687	43	-	-
0.1% 1	1000	63	-	-
0.1% 2	948	59	-	-
0.1% 2	945	59	-	-
0.1% 3	658	41	-	-
0.1% 3	779	49	-	-
0.1% Average	**918**	**57**	**5,99**	**88,87**

ID:	Compression [kN]	Strength [MPa]	SD [MPa]	Pct. of Ref [%]
0.2% 1	660	41	-	-
0.2% 1	681	43	-	-
0.2% 2	964	60	-	-
0.2% 2	921	58	-	-
0.2% 3	613	38	-	-
0.2% 3	649	41	-	-
0.2% Average	**775**	**48**	**9,63**	**75,02**

ID:	Compression [kN]	Strength [MPa]	SD [MPa]	Pct. of Ref [%]
0.5% 1	832	52	-	-
0.5% 1	643	40	-	-
0.5% 2	528	33	-	-
0.5% 2	713	45	-	-
0.5% 3	796	50	-	-
0.5% 3	629	39	-	-
0.5% Average	**723**	**45**	**5,63**	**69,95**