CHALMERS
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Designed Experiment of Textile Reinforced Green Concrete

Master's Thesis in the Master's Programme Structural Engineering and Building Technology

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Concrete Structures
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Cover:
Different phases of the experiment are illustrated.

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ABSTRACT

One of the disadvantages of reinforced concrete is that Portland cement which is used in most concrete mixes requires large amounts of natural resources during production and it releases large amount of CO_2, hence having a direct negative impact on the environment. Another disadvantage is the risk of steel bar corrosion during the lifetime of the concrete structure. Despite these disadvantages the demand for this composite, versatile and relatively cheap material seems to be increasing globally. Textile reinforced green concrete (TRC) deals partially with both issues, since it replaces conventional reinforcing steel bars with high-strength, non-corroding textile reinforcement in the form of carbon or basalt fibres and it offers new cementitious matrices where some of the Portland cement is being replaced by some certain industrial waste products e.g. slag. Another advantage with TRC is that the extra concrete cover used for conventional reinforcement as a protection against corrosion can be omitted and hence allowing for a lighter structure. Although TRC is not a total new composite material and has been used as roof shells, façade, sandwich element and footbridges there is still little known about its mechanical behaviour. The primary aim of this master thesis is to study and evaluate combinations of different green concrete mixes with different textile reinforcement. The focus is on how the mechanical properties of the textile reinforcement like strength and deformation will be modified when using different concrete mixes. This aim is achieved be performing test of hypotheses. The secondary objective is to see how mechanical properties are affected when varying different factors and if there is any interaction between these factors. This is achieved by implementing the method of factorial design at two levels. For the case of basalt textile reinforcement the hypotheses testing results showed that replacing 50% of the cement amount with slag does not affect the maximum load per yarn however it does change the deformation response. The identical analyses for the case of carbon textile reinforcement showed unchanged response for both maximum load per yarn and deformation. The factorial experiment showed that yarn rupture did occur for a combination of long embedment length and low water-cement ratio.

Key words: Textile reinforced concrete, basalt, carbon, green concrete, slag, hypotheses testing, factorial experiment.

Contents

Preface

The work presented in thesis was performed between March and August 2016 at the division of Structural Engineering of the Department of Civil and Environmental Engineering at Chalmers University of Technology.

I would like to thank my supervisor Assistant Professor Filip Nilenius for outstanding competence, patience and support, from the first day to the last. I also want to thank Sebastian Almfeldt for assisting me in performing different test and last but not least I have to thank Marek Machowski for giving me practical advice on mixing concrete.

Göteborg, August 2016
Ihsan al khazaali

1 Introduction

1.1 Background

One does not have to look far to see how dominant reinforced concrete is as a building material in our society. It is used in housing, industrial and commercial buildings, and it is by far the most dominant building material when considering civil infrastructure systems e.g. roads, tunnels, drainage systems, bridges, offshore structures etc. The ability to be moulded or cast into almost any desired shape, cheapness of aggregates and its durability and low maintenance are some of the advantages that makes concrete such a suitable building material. Nearly two tons of concrete is produced annually for each living person [1] and this number is expected to increase in the near future, partly due to the growing demand from developing countries like China and India. Although concrete sometimes can be used as plain concrete if it is primary subjected to compression it is often occupied with steel bars as reinforcement in tension zones. This is done due to the low tensile strength of concrete. Reinforced concrete is a composite material consisting of two parts namely the concrete matrix and the steel reinforcement. These parts have different physical properties and different disadvantages. These issues are the underlying basis of this master thesis.

The major issue with conventional reinforcement is the risk of steel bar corrosion during the lifetime of the concrete structure. This could led to spalling of the concrete cover and loss in strength of the structural member. Another disadvantage with reinforced concrete is that Portland cement which is used in most concrete mixes requires large amount of natural resources during production and it releases large amount of CO_2, thus contributing in a negative way to the global warming issue.
An issue which is becoming more and more a hot topic in the west. The previously mentioned issues and disadvantages together with an increasing awareness of limitations in natural resources have paved the way for a new novel composite material called textile reinforced concrete (TRC).

Just like conventional reinforced concrete, TRC consist of two different parts. The differences are the replacement of steel bars with multiaxial non-corrosive textile fabrics which is usually made of carbon, basalt or glass fibre and the modification of the concrete matrix to a fine-grained matrix with the possibility to partly exchange some of the cement content with some certain industrial waste products e.g. slag, hence reducing the impact on the environment. Another benefit with TRC is that the extra concrete cover which is added to conventional reinforced concrete as a protective layer against corrosion is not required any more. This quality enables the construction of slender concrete structures which is appreciated by some architects.

Although TRC has been investigated for many years now both at TU Dresden and RWTH Aachen University in Germany insufficiently is known about the mechanical behaviour of this composite material [2]. Partially due to this reason the current Eurocode does not cover TRC. Hence more experiment is needed in order to provide more data.

1.2 Objectives

The primary aim of this master thesis is to study and evaluate combinations of different green concrete mixes with different textile reinforcement. The focus is on how the mechanical properties of the textile reinforcement like strength and deformation will be modified when using different concrete mixes. The secondary objective is to see how when varying different factors like e.g. water cement ratio, hydration age, and deformation rate affect the mechanical properties and if there is any interaction between these.

1.3 Methodology and structure of the thesis

The aforementioned objectives will be achieved by statistically analysing scientific data gathered from designed experiments. The experiments consists of preparing reinforced concrete specimens with different combinations of concrete mixes and textile reinforcement. These specimens will later be subjected to either tensile or bending testing depending on their size.

The structure of the experiments and the thesis can be divided in three distinct stages which are

1. Preparing
2. Performing
3. Presenting

Section three will cover both the preparing and performing part of the experiments whereas chapter four is entirely devoted to statistics. All the necessary theory will be explained here. The results of the experiments will be presented and analysed in section five and finally conclusions will be given in section six. The second section shortly introduce the used materials.

1.4 Limitations

- Only basalt and carbon fabrics has been used as reinforcement.
- Only slag has been used as substitute to cement.

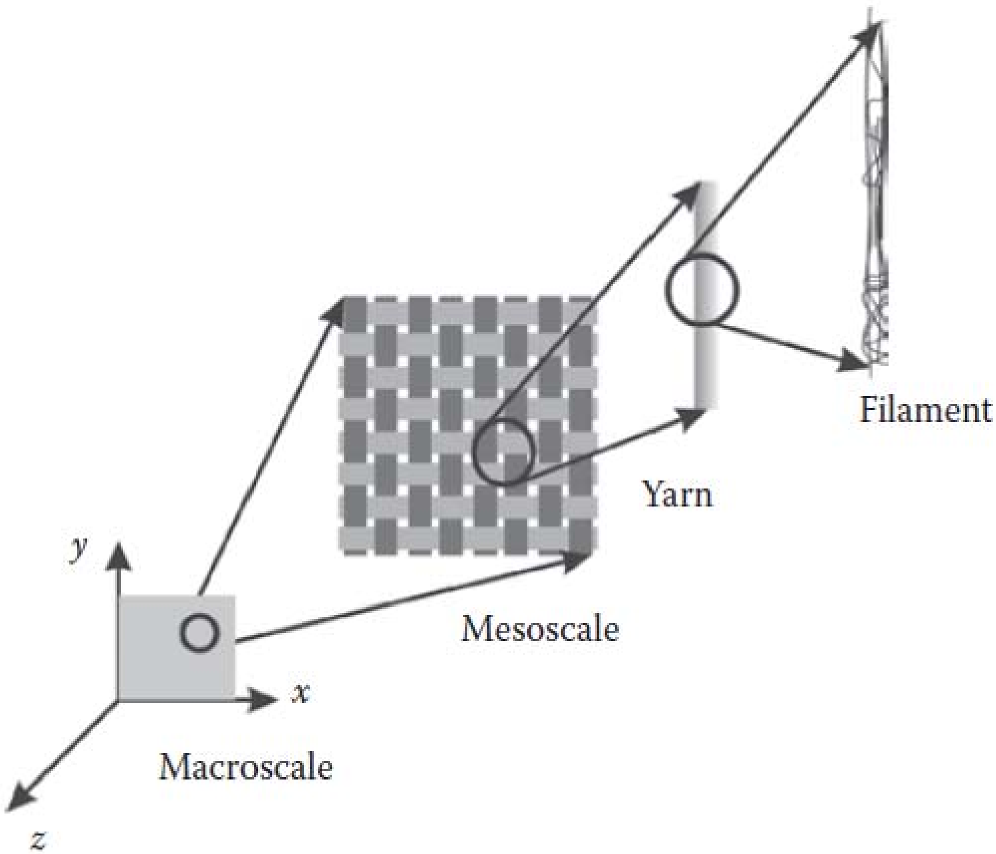
2 TRC a two-phase composite material

The aim of this chapter is to introduce and explain shortly the components and structure of TRC. This starts with filament which is the smallest unit in a textile fabric and ends with the surrounding mass which is the green concrete.

2.1 Textile reinforcement

2.1.1 Yarns

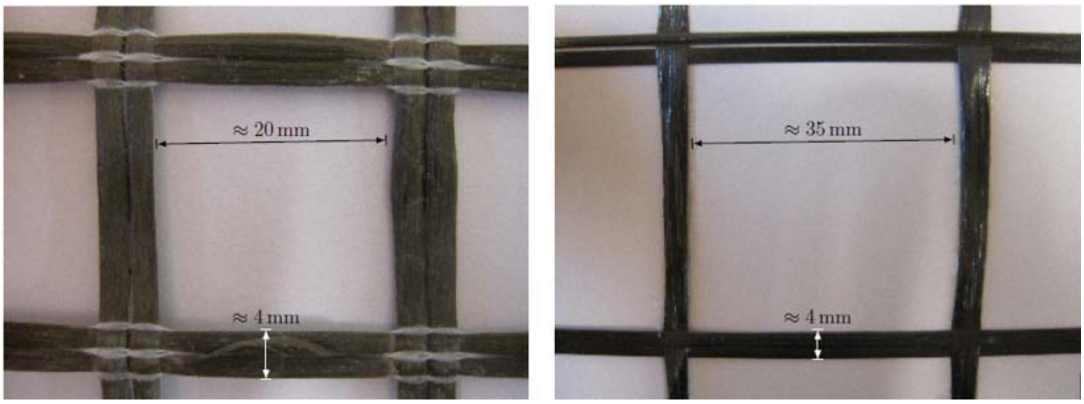
Although there are many different kind of fibres that are applicable as textile reinforcement both as bi- or multi-axial textile meshes, the focus in this thesis will be on 2D basalt and carbon fabrics which are shown in figure 2-2. The smallest unit in a textile fabric on a macrostructural level is the filament which is a single long and continuous fibre with a predominantly circular shape [6]. A schematic presentation of a textile mesh is shown in figure 2-1. These filaments are packed together to form a so called yarn. The number of filaments within a yarn varies for different textiles and even for the same fabric depending on the required strength e.g. for carbon yarn the number of filaments varies between 6000 and 24000 [5]. The fabric mesh in both of these materials consist of yarns arranged in a perpendicular system. The yarns that lie in the lengthwise direction are called warp whereas the one in the crosswise direction are called fills. Yarns can be constructed in three different forms: filament yarn, bundled or twisted yarns and foil fibrillated tape. Both basalt and carbon fabrics are made of filament yarn. Yarns can be arranged in several different ways, woven, glued together or held together using additional threads.



Figur 2-1 Discretization in textile composites representing scales of textile, yarn, and filament [6].

2.1.2 Basalt and carbon fabrics

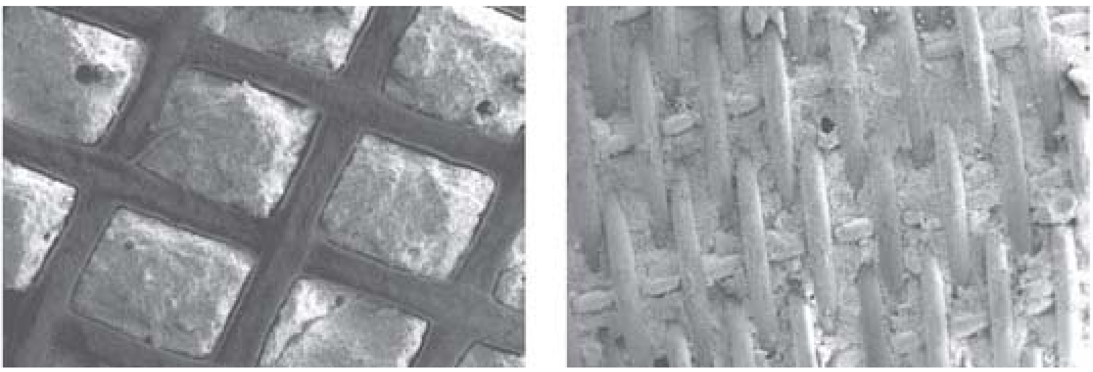
A closer look at figure 2-2 reveals some interesting differences between the two fabrics. In basalt mesh, threads are used to hold the yarns together at the junction point and in one direction two yarn passes over all the crosswise pairs of yarn. The yarns in the carbon fabric goes through each other and they are glued together. Another difference can be seen in the grid size. The basalt fabric has a more dense placed yarn with 20 mm squares. The tensile strength for basalt is 3038.38 N/5cm ±5% and 5500 N/fiber bundle. These values were provided by the companies that manufacture and develop these materials. It should be mentioned here that sine basalt fibre are mineral fibres extracted from volcanic rock it can show a variation both in chemical and mechanical properties if the source of extraction is different [3].



Figur 2-2 Left: Basalt reinforcement Right: Carbon reinforcement [4].

2.2 Green concrete

In this study only ground granulated blast furnace slag has been used as an environment friendly alternative to ordinary Portland cement. It is a by-product that is created from the 'scum' formed in iron smelting in a blast furnace, which is rapidly cooled in water and ground to a similar fineness to Portland cement [1]. It is essential for the concrete matrix to have fine aggregate and a highly flow able consistence so that the fresh concrete matrix can penetrate the opening of the fabric so that it can provide a satisfactory bond between the two parts [2]. The maximum aggregate size that has been used in all of the concrete matrices is less than 4 mm. Figure 2-3 shows the penetration of green concrete in two different types of textile fabric.



Figur 2-3 matrix embedment in two different types of textile fabrics [6].

3 Experimental studies

In this section the preparation and performing parts which are flexure and tension testing will be presented. This will start with the preparation stage which include the casting of the concrete.

3.1 Casting of green concrete

The first step in the preparation stage was to cut and place the textiles inside wooden concrete moulds. These were provided in two different sizes, 100x400 mm and 186x1000 mm. The small one is intended for tensile tests and a larger one for bending tests. The different wood moulds are in figure 3-1. Casting of three different concrete mixture was performed at Chalmers´ laboratory. The exact mix proportions are given in tables 3:1-3 below.

The casting for the two different tests was done separately. For bending test a total of six specimen were created. Before casting the fresh concrete into the wooden moulds, these were arranged in three groups. Each group consist of two moulds equipped with either basalt or carbon textile reinforcement. The moulds in each group were marked with numbers that corresponds to the number of the concrete matrix that they have been used for. Unfortunately when the bending specimen were tested in the lab some of them did not give reasonable results hence the casting for some of the specimens was repeated. For the tension test a total of sixteen specimens were prepared to be subjected for a factorial experiment. In contrast to bending specimens only concrete mixture one and carbon textile reinforcement was used. Figure 3-2 shows some finished specimens after replacement of textiles and casting of the concrete.

Table 3-1 Mixture 1: cement mortar matrix, 100% cement, C100.

cement	water	sand
500 g/L	250 g/L	1500 g/L
9 kg	4.5 kg	27 kg

Table 3-2 Mixture 2: slag supplementary-cement mortar, 50% cement, CS50.

cement	slag	water	sand
250 g/L	250 g/L	250 g/L	1500 g/L
4.46 kg	4.46 kg	4.46 kg	26.77 kg

Table 3-3 Mixture 3: alkali activatied slag, 100% slag, AS100.

slag	water	alkali solution	sand
493 g/L	122 g/L	219 g/L	1479 g/L
8.87 kg	2.20 kg	3.94 kg	26.62 kg

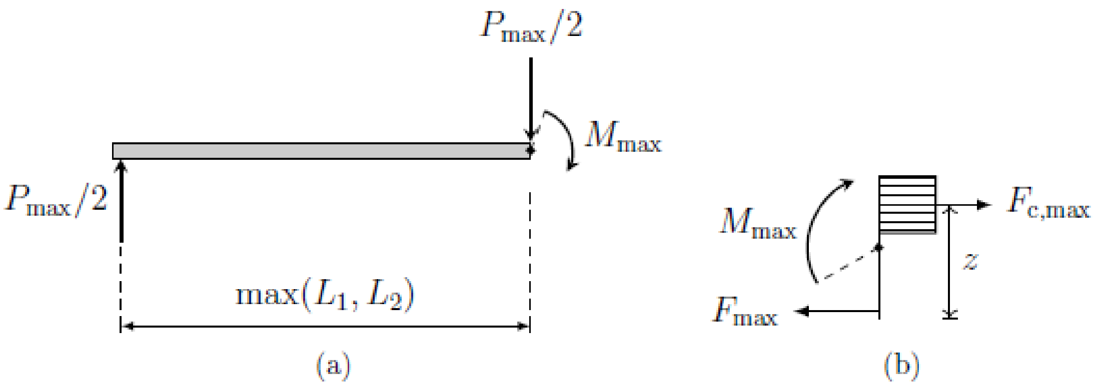
Figur 3-1 Different wood moulds (Photo: Ihsan Al-Khazaali).

Figur 3-2 Group one: cement mortar matrix, 100% cement, C100 (Photo: Ihsan Al-Khazaali).

3.2 Flexure test

The aim of these tests is to determine the load-displacement relation, ultimate load, failure mode, crack spacing and to determine the maximum load per yarn for both basalt and carbon. A displacement control was used to determine the mechanical behaviour from zero load until failure. In contrast to load control the failure is not brittle and the strain softening phenomenon will be captured. This characteristic response is attributed to the gradual decrease of load carrying capacity with an increase in the strain or widening of cracks in a tensile stress field [6]. A schematic section view of the plate is shown in figure 3-5 followed by table 3-4 which contains the span length and deformation rate for the different plates. The flexural test arrangement can be seen in figure 3-4.

In order to determine the maximum load per yarn an imaginary section is created in the plane were the force *P*/2 acts. The procedure is shown in figure 3-3. An external and an internal moment equilibrium equations around the cut are established. The external equilibrium equation gives:



Figur 3-3 cut in plate at failure, to determine maximal load per yarn [4].

$$M_{max} = -\frac{P_{max}L_{max}}{2} \tag{1}$$

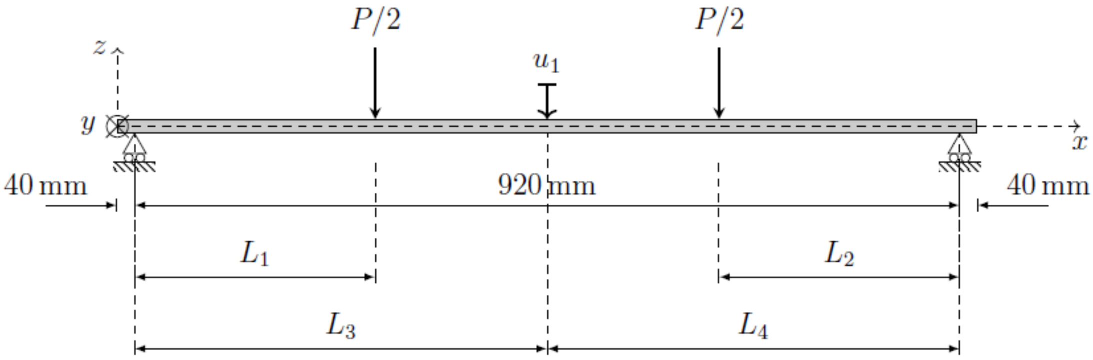
Which is then used in the second equation to determine the internal force F_{max}.

$$F_{max} = -\frac{M_{max}}{z} = \frac{P_{max}L_{max}}{2z} \tag{2}$$

This force is then divided by the number of yarns in the longitudinal direction of the plate to determine the maximum load per yarn.

$$F_{max,yarn} = -\frac{F_{max}}{n} = \frac{P_{max}L_{max}}{2zn} \tag{3}$$

Figur 3-4 Flexural test arrangement (Photo: Ihsan Al-Khazaali).



Figur 3-5 a schematic section view of the flexural test arrangement [4].

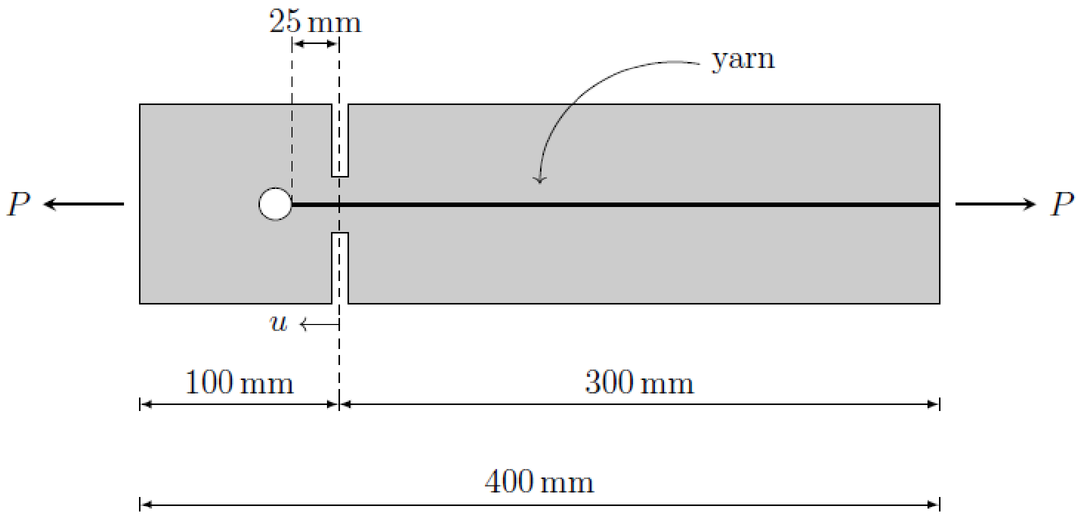
Table 3-4 Span length and deformation rate.

Plate	L_1 (cm)	L_2 (cm)	L_3 (cm)	L_4 (cm)	$\mathring{u}$ (cm/min)
Basalt-C	32.2	31.8	46.2	45.8	2.0
Carbon-C	32	32	46	46	2.0
Basalt-CS	32	32	46	46	2.0
Carbon-CS	31.8	32.2	45.8	46.2	2.0

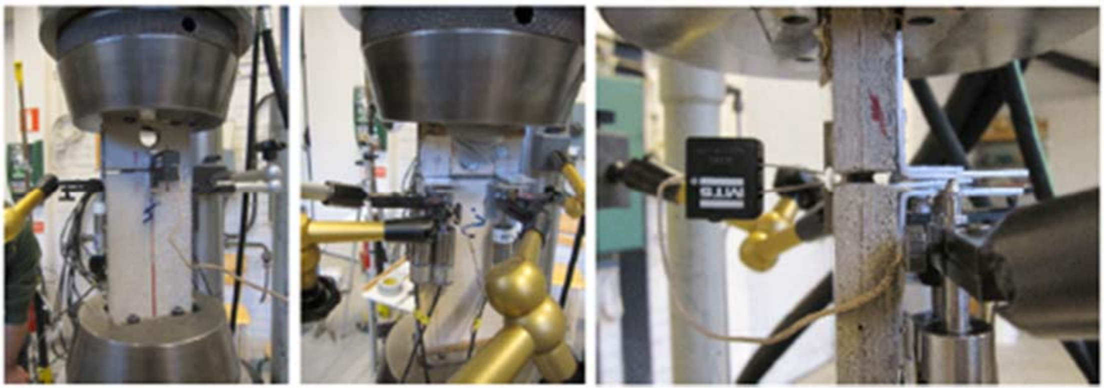
3.3 Tension test

The aim of these tests was to see how when varying different factors affect the mechanical properties such as strength and deformation and if there is any interaction between these factors.

First the tension specimen was both jacked and pierced before the actual testing. The area between the cuts will only contain the yarn that is in the middle of the specimen. The procedure is shown in figure 3-6 [4] and the final setup of the test can be seen in figure 3-7. After mounting the specimen in the tension equipment both ends of the specimen will be subjected to pressure transversal to the direction of the yarns. This will affect the normal bond behaviour. To get rid of this unwanted pressure one end is pierced in the middle and just like for bending test a displacement control will be applied.



Figur 3-3 Top view of textile reinforced tension specimen [4].



Figur 3-4 Mounting of test plates and measurement setup [4].

4 Statistics

This section is considered to be the core of this thesis since statistics is the only tool that is used to understand and to draw conclusions from the experiment results. To be more precise *hypothesis testing* will be applied to evaluate the effect of different combinations of green concrete and reinforcement textiles on parameters like strength and deformation.

Considering the fact that statistics is a quite extensive science only concepts and definitions which are relevant to this thesis will be explained. Nevertheless a brief introduction to statistics and its relation to structural engineering will be given. The aim of this is to illustrate the importance of statistical analysis in this field and to gradually present the concepts, equations and definitions that will be used later.

4.1 Strength variation in a composite material

Usually when mixing concrete the proportions of the different parts are chosen in a certain way to achieve a specific strength. This is followed by producing test specimens in the form of a cube or a cylinder which then are placed in water tanks for 28 days to gain proper strength. The placement under water will ensure constant environmental conditions, which in this case is 100% relative humidity. The specimens will be subjected to either compression or tension test. After performing the tests a mean value for strength is calculated. When comparing this value to the actual strength from each specimen one can observe a variation in strength. The primary source for this variation is due to the fact that a totally uniform distribution of the different materials after mixing is hard to achieve. This issue can be influenced through a better manufacturing process.

4.2 The concept of limit state

The concept of limit state is based on choosing strength and deformation values that are used in the design process to ensure that both safety and performance aspect of the structure are fulfilled during its intended lifetime. This is done in the ultimate limit state for safety and serviceability limit state for different performance aspects like deformation and vibration. In order to understand how these restricting values are chosen a closer look at strength variation is necessary. Figure 4-1 shows a normal distribution curve for strength variation in a material. The x axis represents strength while the y axis shows the number of specimens with the same strength (frequency) [8]. The equation for this normal distribution curve is

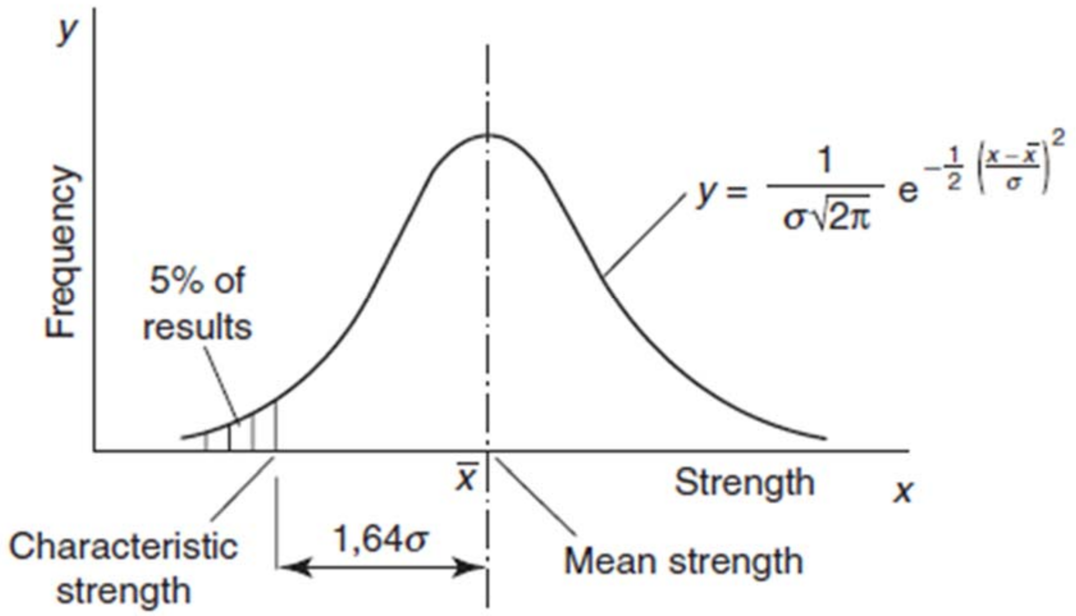
$$y(x) = 1/([\sigma(2\pi)^{0.5}]exp[-(x-\bar{x})^2/(2\sigma^2)] \qquad (4)$$

In order to plot the probability density function *y(x)* both the mean value $\bar{x}$ and the standard deviation σ has to be known. For a set of n values the equation for these parameters are

$$\bar{x} = (\sum x)/n \qquad (5)$$

$$\sigma = \left[\sum (x - \bar{x})^2 / n\right]^{0.5} \qquad (6)$$

It is assumed that the reader already has some basic knowledge about Probability and Statistics but nevertheless these parameters will be examined closer in the following sections.



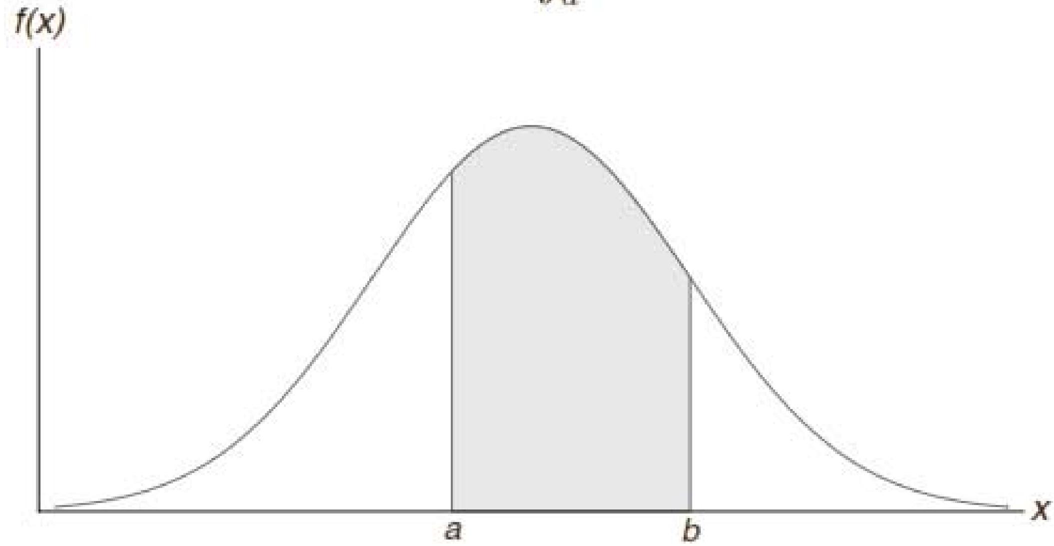
Figur 4-1 Strength variation in a material [8].

Two condition has to be fulfilled for a function *f(x)* to be a frequency function for the continuous random variable *X* [10]

1. $f(x) \geq 0$ for all *x* in its range
2. The total area under the curve *f(x)* and bounded by the *x* axis is equal to one i.e. $\int_{-\infty}^{\infty} f(x)dx = 1$

Calculating the probability for *X* to be between *a* and *b* is done via calculating the restricted area under the curve and the two ordinates at *x*=*a* and *x*=*b*. This is shown in figure 4-2.

$$P(a < X < b) = \int_a^b f(x)\, dx.$$



Figur 4-2 Calculating the probability for x to be between a and b.

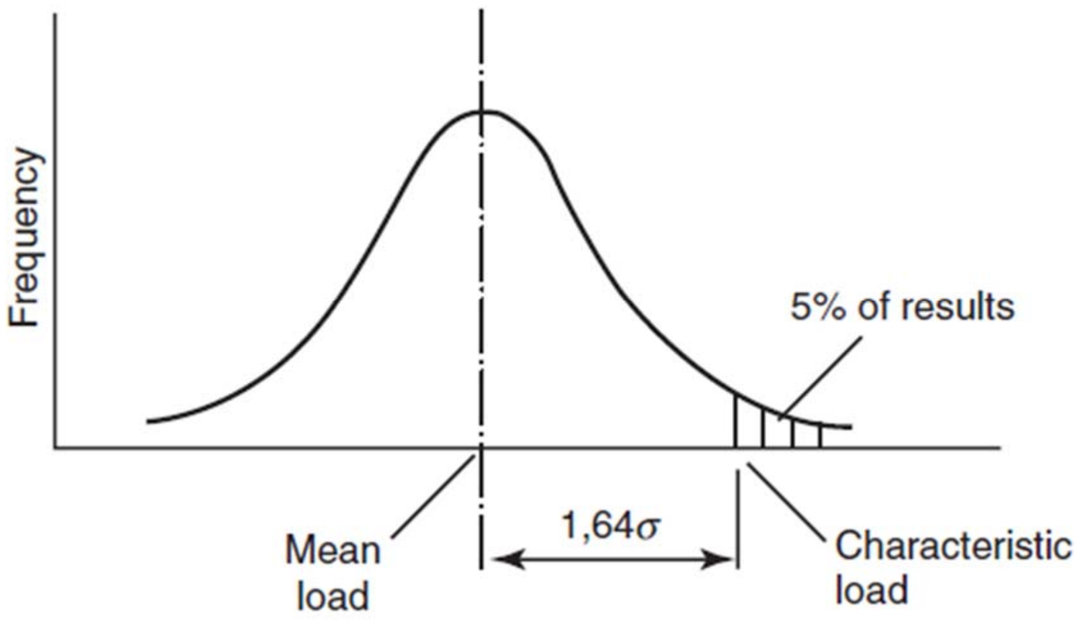
There is always a risk that some part of a structure contains material with lower strength than the one required by the design or that the load on some part becomes greater than the design load. Hence it is expected that 5% of the material in a structure will have lower strength than the design value and that occasionally 5% of the loads exceeds the design load. These risks are recognised and dealt with in the concept of limit state by introducing characteristic values. In the case of material strength the equation for the characteristic strength f_{ck} is

$$f_{ck} = f_{mean} - 1.64\sigma \quad (7)$$

Where σ is given by

$$\sigma = \left[\sum (f_{mean} - f\ )^2/(n-1)\right]^{0.5} \quad (8)$$

The characteristic value is chosen from the strength variation within the material. This is illustrated in figure 4-1. It is possible to choose a greater f_{ck} value but this also implies a bigger risk for failure since a greater percentage of the material will become under the new characteristic strength value. A similar procedure could be done for determining a characteristic load value. Here the variation in applied load during the whole life time of a structure is under focus. Figure 4-3 shows that only 5% of the applied load will some time under the structure´s life time exceed this characteristic load value.



Figur 4-3 Characteritic load value [8].

The concept of limit state design is based on establishing limits gained from processing scientific data from experiment via statistical methods, hence statistic is the foundation of this concept. This section has hopefully illustrated the role and of statistic in the field of structural engineering and how it can contribute to a deeper understanding of scientific phenomena. It is hard to think of any engineering or industrial fields were this powerful tool does not play an important role hence there is a lot to gain by learning and applying statistics.

4.3 Designed experiment

The statistical analysis used in this thesis is based on results from designed experiments, hence a short presentation about this type of statistical studies and others will be given below.

Statistical studies can be divided in three different categories. Designed experiment, observational study and retrospective study. In a designed experiment the experimenter has the possibility to choose both *factors* and *factor levels*. The factors that are of interest in this thesis and the corresponding factor levels are

- The distance between the piercing and the jack in the specimen subjected to tension with factor levels d_1=25mm and d_2=50mm
- The deformation rate with factor levels $\dot{u}_1 = 1\text{mm/min}$ and $\dot{u}_2 = 3\text{mm/min}$
- The water cement ratio with factor levels $(w/c)_1$=0.4 and $(w/c)_2$=0.5
- The hydration age with factor levels t_1=2 weeks and t_2=4 weeks
- Slag proportion of the binder material with factor levels $s_1=0\%$ and $s_1=50\%$

This ability of choosing and controlling experimental conditions is the main difference between a designed experiment and an observational study where the experimenter most of the time cannot affect any factors. Instead he or she gathers data from what already exist. Another difference between the two is that in the case of designed experiment a proper planning is necessary and the quality of the experiment results will depend on the quality of planning. The last type which is retrospective study relay only on historical data gathered in an earlier study. Although this type of study might be helpful sometimes especially due to the fact that it is a cheaper way of gathering data it has many disadvantages. These will not be discussed since they have no relevant for this thesis work.

4.4 Test of hypothesis

Among the things that will be done in the following chapter is the calculation of the mean strength value for maximum load per yarn for all the mentioned cases of combinations. These mean values will be later compared in pairs. For instance the mean value from basalt with mixture one will be compared with the one obtained from basalt with mixture two. The aim of this is to see if any change to this mean value has occurred as a result of changing the concrete mixture to number two. This is just a different and a clearer way of expressing the primary objective of this thesis.

It will be assumed for now that no considerable change to the mean value has occurred. This is only a hypothesis that need to be tested. This type of hypothesis is called *null hypothesis* and it is denoted by H_0. If it turns out that the assumption of unchanged mean value is invalid then an *alternative hypothesis* denoted by H_1 has to be adopted. This is simply the concept of test of hypothesis. However the alternative hypothesis can be either *one-sided* or *two-sided*. A one-sided alternative hypothesis implies one of the following

$$H_0: \mu = \mu_0$$
$$H_1: \mu > \mu_1$$

Or

$$H_0: \mu = \mu_0$$
$$H_1: \mu < \mu_1$$

Whereas a two-sided alternative hypothesis is defined by

$$H_0: \mu = \mu_0$$
$$H_1: \mu \neq \mu_1$$

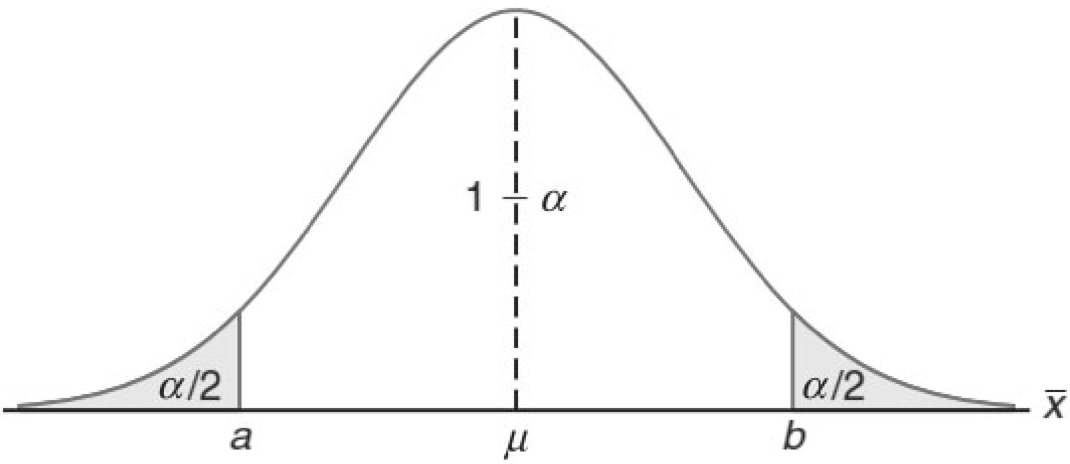
A two-sided test simply means that any deviation from the null hypothesis is of interest. Changing the concrete mixture might enhance, deteriorate or have insignificant effect on the mechanical parameters of the textile reinforcement. Therefore only the two-sided test will be further explained and used later. Based on this concept together with the data from experiments one can draw conclusions that have scientific support.

Testing a statistical hypothesis can be divided into five different stages [10]. These will be shortly introduced under the assumptions that the tested parameter is represented by a *standard normal distribution* which implies that both the *expected value μ* and *standard deviation σ* are known, namely N(0,1).

Step 1: First the hypothesis will be formulated here. The known value of the tested parameter will be placed in H_0. All discrepancies from this value will be placed in H_1. This is expressed mathematically as follows

$$H_0: \mu = \mu_0$$
$$H_1: \mu \neq \mu_0$$

Step 2: In order to be totally certain of the accuracy of a statistical hypothesis it is required to examine the entire population. Most of the time this is impractical if not impossible. Instead a random sample is taken from the population and examined.
The aim of this is to either support or reject the null hypothesis based on the data from the sample. Although it's a quite forward procedure it might sometime lead to an incorrect decision about the statistical hypothesis if the samples mean value by chance happen to differ a lot from the tested parameter. Hence there is always a risk for misconception involved when only examining a specific sample and therefore one has to decide the size of this risk. The size of this risk is called the *level of significance* and it is denoted by α. a general convention is to choose α as 0.05 (5%) [10]. For a two-sided test the level of significance is represented by the shaded areas in figure 4-4. The shaded area is called the critical region whereas the rest of the distribution is referred to as the acceptance region. The limits between these two regions are the critical values a and b. In the case of a standard normal distribution the critical values are denoted as $\pm Z^C$ and these can be obtained from the standard normal distribution table.



Figur 4-4 A two-sided hypothesis test

Step 3: Choosing the mathematical formula that will be used to decide if the tested parameter has changed or not. The standard normal random variable Z is usually used if the tested parameter is represented by a normal distribution. This Z is usually called the test statistic and formulated as

$$Z = \frac{\bar{x} - \mu}{\sigma/\sqrt{n}}$$

Step 4: A random sample from the population will be taken followed be calculation of its mean value in order to determine the test variable Z. The test variable will be now compared to the critical values $\pm Z^C$.

Step 5: If the test variable Z happens to be in the critical region then a change might has occurred to the test parameter and hence H_0 can be rejected.

As mentioned earlier these five steps has been presented under the assumption that the standard deviation σ is known. If σ is unknown and the number of elements in the randomly chosen sample is $n \geq 30$ [10] then the *Central Limit Theory* can be used. However if σ is unknown and $n < 30$ then a *t-statistic* or a (t-test) based on the *student t-distribution* will be used instead. The same five steps mentioned earlier applies for a t-test with two exceptions. The standard normal distribution table used in step 2 will be replaced with a t-distribution table and the standard deviation σ in the test statistic presented in step 3 will be replaced by an estimation denoted by *s* and defined in equation (9). Additional modification to these five steps will be done in section 5.1.2 before using them for the analysis.

4.5 Factorial experiment

The aim of this experiment is to study the effect of four factors on two responses namely maximum load and yarn rupture and to determine if there is any interaction between these factors. The smaller concrete specimen were prepared for this purpose.

The factors or variables are presented in table 4-1 together with two fixed levels that has been defined for each factor and coded be either a minus or plus sign depending on their size. Since there is four factors involved and each one of them can be given on to different level there is totally $2^4=16$ different ways of combining these factors. These sixteen unique combinations are shown in table 4-2 and this is a typical example of a so called two-level factorial design. All the factors in this experiment are quantitative, however one of the responses namely the yarn rupture is qualitative and even factors can be qualitative e.g. if two different equipment are involved in the experiment and considered as one factor.

Table 4-1 Factors and their levels

Factor	Level		Factor name
	-	+	
$\dot{u}$	1 mm/min	3 mm/min	X_1= deformation rate
d	25 mm	75 mm	X_2= distance between piercing and jack
W/C	0.4	0.5	X_3= water cement ratio
t	2 weeks	4 weeks	X_4= hydration age

Table 4-2 Experimental design

Specimen	X_1	X_2	X_3	X_4	Maximum load	Yarn rupture
1	-	-	-	-		
2	-	-	-	+		
3	-	-	+	-		
4	-	-	+	+		
5	-	+	-	-		
6	-	+	-	+		
7	-	+	+	-		
8	-	+	+	+		
9	+	-	-	-		
10	+	-	-	+		
11	+	-	+	-		
12	+	-	+	+		
13	+	+	-	-		
14	+	+	-	+		
15	+	+	+	-		
16	+	+	+	+		

The testing was performed in four rounds with four specimens in each one. The way this was organised can be seen in tables 4:3-6. One can also see the actual date of the testing for each round in the name of the tables.

Table 4-3 Tension test number one performed 2016/06/27

Specimen	X_1	X_2	X_3	X_4
1 (- - - -)	1 mm/min	25 mm	0.4	2 weeks
5 (- + - -)	1 mm/min	50 mm	0.4	2 weeks
9 (+ - - -)	3 mm/min	25 mm	0.4	2 weeks
13 (+ + - -)	3 mm/min	50 mm	0.4	2 weeks

Table 4-4 Tension test number two performed 2016/06/30

Specimen	X_1	X_2	X_3	X_4
3 (- - + -)	1 mm/min	25 mm	0.5	2 weeks
7 (- + + -)	1 mm/min	50 mm	0.5	2 weeks
11 (+ - + -)	3 mm/min	25 mm	0.5	2 weeks
15 (+ + + -)	3 mm/min	50 mm	0.5	2 weeks

Table 4-5 Tension test number three performed 2016/07/11

Specimen	X_1	X_2	X_3	X_4
2 (- - - +)	1 mm/min	25 mm	0.4	4 weeks
6 (- + - +)	1 mm/min	50 mm	0.4	4 weeks
10 (+ - - +)	3 mm/min	25 mm	0.4	4 weeks
14 (+ + - +)	3 mm/min	50 mm	0.4	4 weeks

Table 4-6 Tension test number four performed 2016/07/14

Specimen	X_1	X_2	X_3	X_4
4 (- - + +)	1 mm/min	25 mm	0.5	4 weeks
8 (- + + +)	1 mm/min	50 mm	0.5	4 weeks
12 (+ - + +)	3 mm/min	25 mm	0.5	4 weeks
16 (+ + + +)	3 mm/min	50 mm	0.5	4 weeks

An alternative method to factorial design is the One-Factor-at-a-Time method in which each factor are varied one at time with the remaining factors held constant [9]. A disadvantages with this method is that any possible interaction between factors will not be detectable. However in order to solve problems and make discoveries in science and engineering, it is required to determine which factors do what to which responses [9]. This is the power of factorial design since it provide a method to see the effect of different factors on different responses but it also enable the researcher to detect any possible interaction. This will be clearer in section 5.2 were the results from the factorial design will be presented.

5 Experimental results

This chapter consists of the final stage of the thesis. The data from the experiment will be presented here both as graphs and pictures and some chosen parameters like e.g. the maximum load per yarn will be calculated. The final step in this chapter is to apply the concepts, definitions and equations from chapter 4 in order to draw some conclusions in chapter 6.

5.1 Flexure test results

The initially behaviour for all the bending specimens is linearly elastic with different stiffness but with increasing load crack will start to develop and propagate in the stress field. The first crack load is defined as the load at which the deformation response deviates from linearity [6] and the mechanical behaviour after the first crack is expected to be different for the different plates. Each crack will reduce the overall stiffness of the plate and entail a moment redistribution to stiffer regions. This mechanical response will continue until failure i.e. until the load carrying capacity of the plate is zero.

5.1.1 Basalt with different concrete mixtures

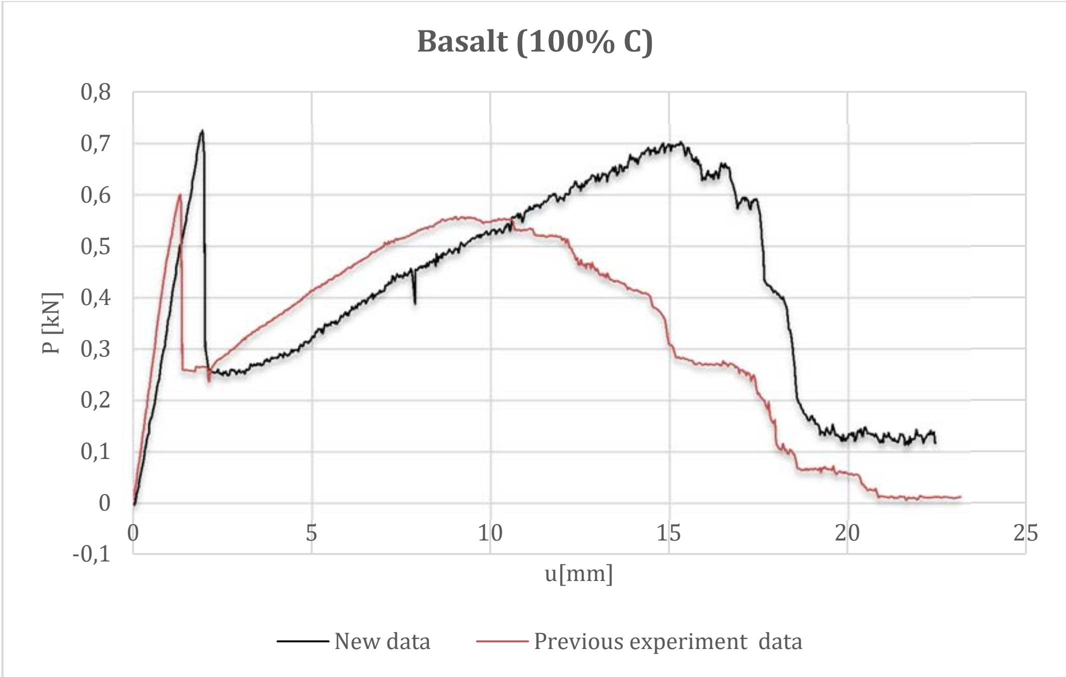
The mechanical behaviour for basalt with mixture 1 is shown in figure 5-1. The first part of the graph shows a linear elastic relation as expected with a maximum load of 0.72 kN. The plate cracks after this load and it is the only one developed. After the crack the plate restart to take increased load until rupture of yarns occurs which has been the observed failure mode for all the plates in this experiment. Figure 5-2 shows the crack and the condition of the basalt yarns after failure.

Figures 5:3-5 shows the load deformation relation from basalt with mixture 2 taken from three identical specimens and figure 5-7 shows these specimens after testing. This might seems a little bit odd since in the previous case only one specimen was tested and it was presented together with test result from a previous experiment done at Chalmers. For some reason the experiment result for basalt with mixture 2 turned out to be incorrect. This was obvious both from the graph shape and load magnitude when this result was plotted in the software excel. Hence it was decided to repeat the test with some reserve specimens just in case something goes wrong before, during or after the testing. Therefore three plate were prepared and tested for basalt with mixture 2. Even here the result from previous experiment is added and shown in figure 5-6. Increasing the number of specimen will increase the quality of the result since it will enhance the mean value which will be calculated later in this chapter. However this could also create some misconceptions. If one of the tested specimen shows values that differs a lot in relation to the rest and if it is included in the calculation of the mean value then the later will be distorted and hence it will not reflect the real behaviour of the tested group. However since the number of tested specimens in these experiments are small there is no risk for this issue in this case.

A first glimpse at the graphs from the three specimens reveals some interesting changes in relation to the previous case. The load capacity has been somewhat reduced while the deformation before ultimate failure has been increased. The general mechanical behaviour is also different between the two combinations. Several minor cracks appear now and the highest load is found between these and before failure and this has been the same for all three specimens. On the other hand the combination of basalt with mixture 1 shows exactly the opposed behaviour as has been discussed previously. There is also some slight differences when comparing with the result obtained from previous experiment. Figure 5-6 shows fewer cracks and a smaller total deformation. It should be mentioned here that the testing of the three specimens were performed with a newer software which controls the testing equipment. This has been the only difference in relation to the result from the previous experiment and it might have some effect on the results. However in order to eliminate this uncertainty the previous experiment result will not be used in any of the following calculations for this specific case.

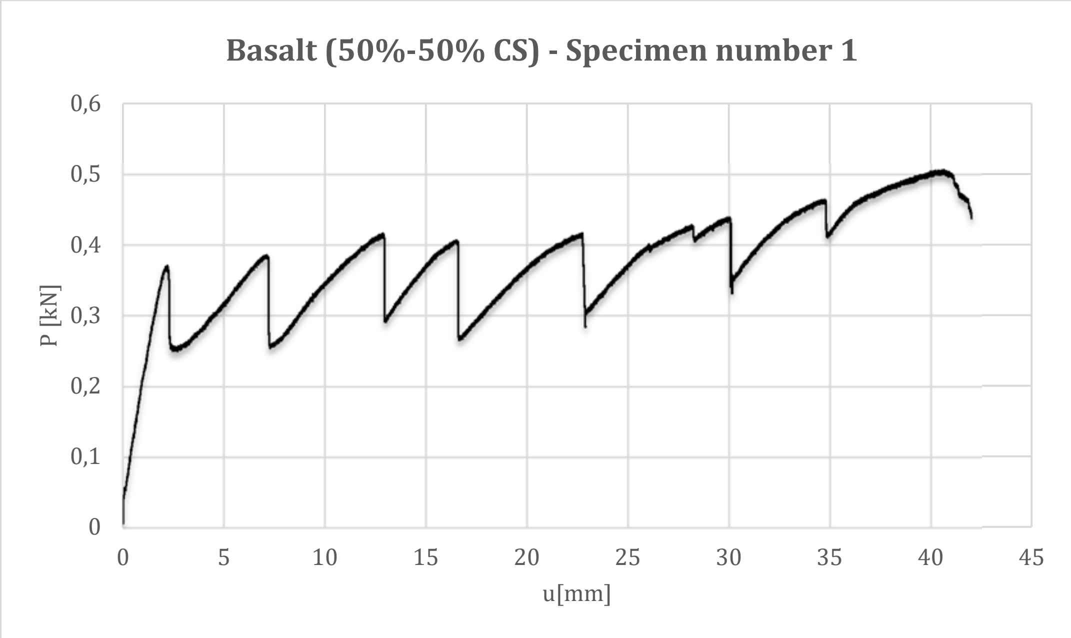
In mixture three all the cement was replaced with slag. When the wooden moulds were taken of several cracks were observed. It turned out that the shrinkage rate in slag is higher than the corresponding in Portland cement. The behaviour of this shrinkage rate as a function of time is unknown. Cracking is an unwanted phenomena and a major challenge in concrete structures especially if it occurs at an early stage of the intended structures life time. Early cracking negatively effects the performance of the structure both in the ultimate and serviceability limit state. Although it has not been mentioned previously but it is assumed that the specimens prepared for the experiments are uncracked before loading at least in the case for flexure tests. A cracked specimen will not reflect the true combined mechanical behaviour of TRC. Hence the plates with mixture three are not suitable for these experiments. Figure 5-8 shows the early shrinkage cracks prior to loading for a plate with mixture three reinforced with carbon textile.

There has been some research both at Chalmers University and other universities that suggest the replacement of 15% of the used slag with calcium hydroxide and calcium carbonate [11]. It is believed that this action will reduce the early shrinkage of slag. However this has not been examined in this master thesis since it is not included in the objective of it. Nevertheless it could be an ideal subject for future master thesis especially for student with good knowledge and interest in chemistry. Considering what has been said so far about slag and mixture three it will be excluded from all experiments and any discussion in the upcoming chapters.

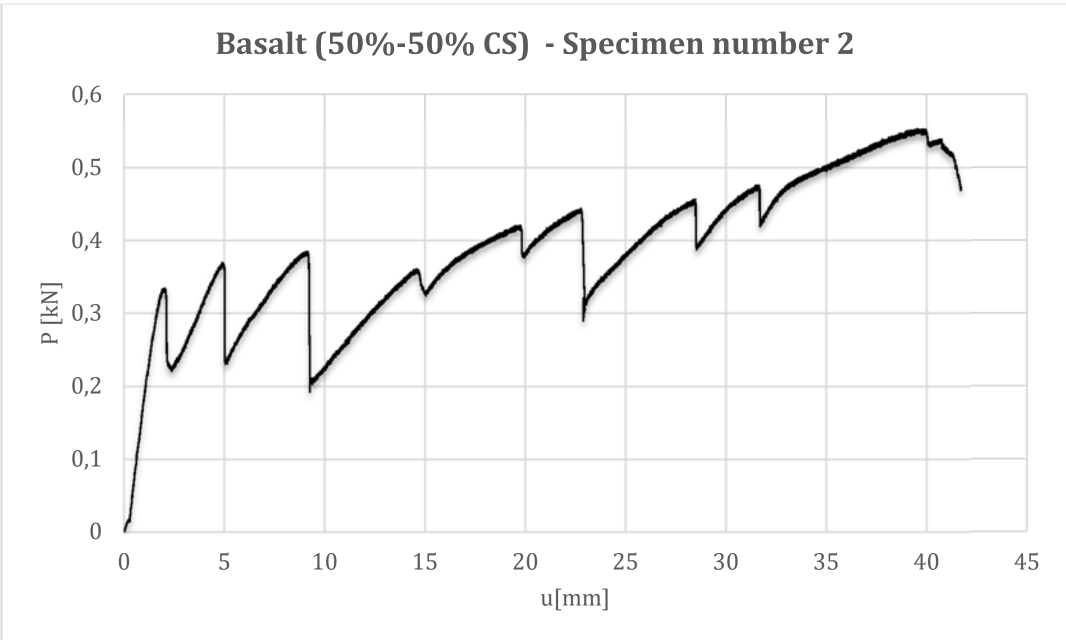


Figur 5-1 Results for basalt textile with concrete mixture 1.

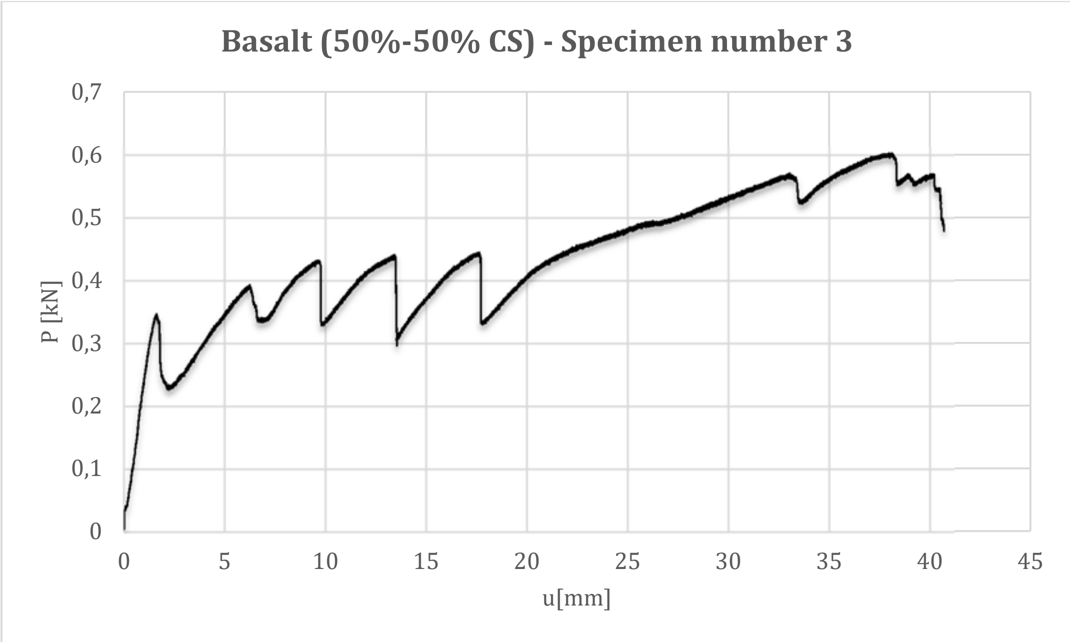
Figur 5-2 The condition of a plate with basalt textile and concrete mixture 1 after failure.



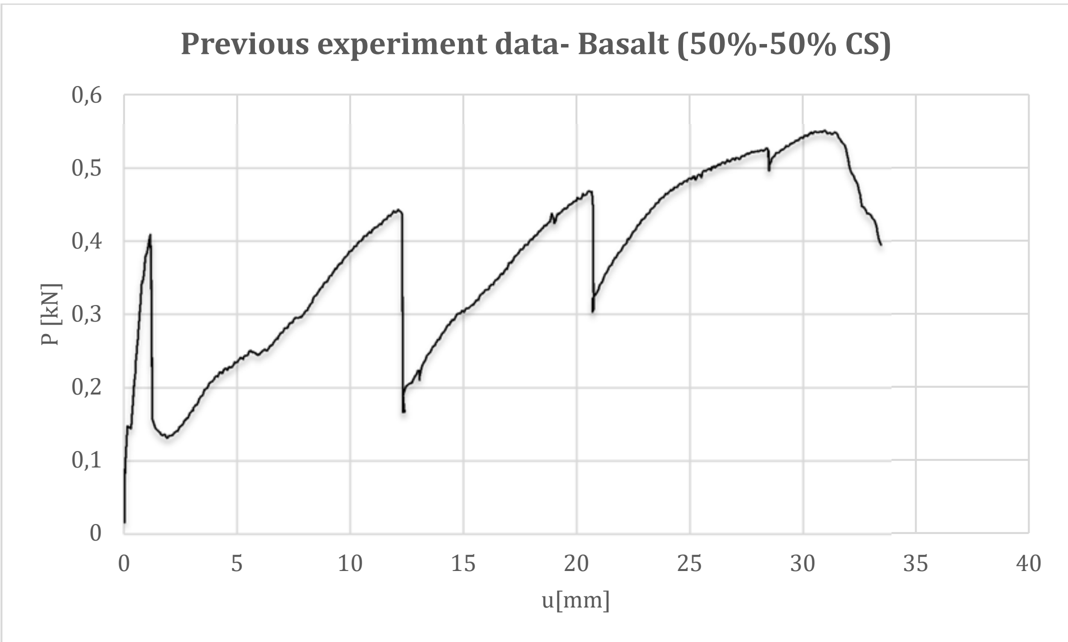
Figur 5-3 Results from specimen number 1 basalt textile with concrete mixture 2.



Figur 5-4 Results from specimen number 2 basalt textile with concrete mixture 2.

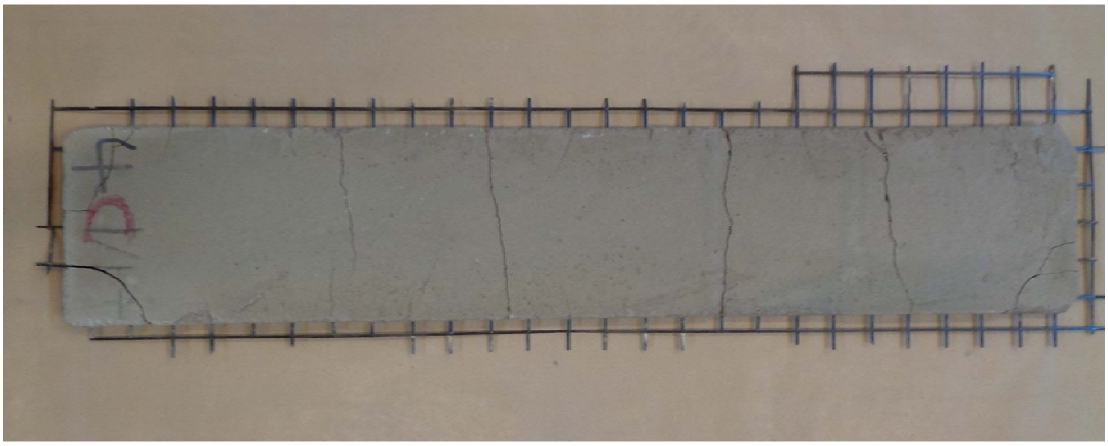


Figur 5-5 Results from specimen number 3 basalt textile with concrete mixture 2.



Figur 5-6 Results from supervisor for basalt textile with concrete mixture 2.

Figur 5-7 The condition of three plates with basalt textile and concrete mixture 2 after failure.


Figur 5-8 Development of cracks due to early shrinkage of slag for a plate reinforced with carbon textile.

5.1.2 Data analysis for basalt

The aim of this section is to compare the mean values from two populations using the five steps described at section 4.4 in order to see if changing the concrete mixture have affected the mechanical properties of basalt. This will be done both for the maximum load per yarn and the total deformation, however as mentioned earlier some modification to the five step procedure has to be done first.

The sample size from any population in these experiments is small, hence the standard deviation σ is unknown and will by estimated by the sample standard deviation *s* using equation (9). Therefore s_1 will represent the standard deviation for sample one and s_2 for sample two. However it is recommended to use a common standard deviation where both s_1 and s_2 are used if the sample size is small provided that the samples are independent, represent a normal distribution and that s_1 and s_2 are not that different in size. This is done in order to get a more accurate estimation. The pooled standard deviation is presented in equation (10) followed by a slightly modified t statistic and degree of freedom.

$$\mathrm{s} = \sqrt{\frac{\sum_{\mathrm{i}=1}^{\mathrm{n}}(\mathrm{x_i} - \bar{\mathrm{x}})^2}{\mathrm{n} - 1}} \tag{9}$$

$$s_p = \sqrt{\frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2 - 2}} \tag{10}$$

$$t = \frac{(\bar{x}_1 - \bar{x}_2) - d_0}{s_p\sqrt{\frac{1}{n_1} + \frac{1}{n_2}}} \tag{11}$$

$$H_0\colon d_0 = \mu_1 - \mu_2 \tag{12}$$

$$df = n_1 + n_2 - 2 \tag{13}$$

The analysis will start with maximum load per yarn in focus. This parameter is calculated for all the described specimens by using equation (3) and presented together with the corresponding results from the previous experiment followed be calculation of the mean values and standard deviations.

$$F_{b,mix1} = \frac{P_{\max}L_{\max}}{2zn} = \frac{0.72 \text{ x } 10^3\text{N x } 32.2 \text{ x } 10^{-2}\text{m}}{2 \text{ x } 15 \text{ x } 10^{-3}\text{m x } 7} = 1104 \text{ N}$$

$$F_{b,mix1,previous\ experiment} = 825 \text{ N}$$

$$F_{b,mix2,nr1} = \frac{P_{\max}L_{\max}}{2zn} = \frac{0.5 \text{ x } 10^3\text{N x } 31 \text{ x } 10^{-2}\text{m}}{2 \text{ x } 15 \text{ x } 10^{-3}\text{m x } 7} = 738 \text{ N}$$

$$F_{b,mix2,nr2} = \frac{P_{\max}L_{\max}}{2zn} = \frac{0.55 \text{ x } 10^3\text{N x } 31 \text{ x } 10^{-2}\text{m}}{2 \text{ x } 15 \text{ x } 10^{-3}\text{m x } 7} = 812 \text{ N}$$

$$F_{b,mix2,nr3} = \frac{P_{\max}L_{\max}}{2zn} = \frac{0.6 \text{ x } 10^3\text{N x } 31 \text{ x } 10^{-2}\text{m}}{2 \text{ x } 15 \text{ x } 10^{-3}\text{m x } 7} = 886 \text{ N}$$

$$F_{b,mix2,supervisor} = 812 \text{ N}$$

$$\bar{x}_1 = \frac{(1104 \text{ N } + 825 \text{ N})}{2} = 965 \text{ N}$$

$$\bar{x}_2 = \frac{(738 \text{ N } + 812 \text{ N } + 886 \text{ N})}{3} = 812 \text{ N}$$

$$s_1 = \sqrt{\frac{(1104 \text{ N} - 965 \text{ N})^2 + (825 \text{ N} - 965 \text{ N})^2}{2-1}} = 197 \text{ N}$$

$$s_2 = \sqrt{\frac{(738 \text{ N} - 812 \text{ N})^2 + (812 \text{ N} - 812 \text{ N})^2 + (886 \text{ N} - 812 \text{ N})^2}{3-1}} = 74 \text{ N}$$

$$s_p = \sqrt{\frac{(2-1)(197 \text{ N})^2 + (3-1)(74 \text{ N})^2}{2+3-2}} = 129 \text{ N}$$

Step 1: Defining the hypotheses sort:

H_0: $\mu_1 = \mu_2$
H_1: $\mu_1 \neq \mu_2$

Step 2: Choosing the significance level:

$\alpha = 0.05$

Step 3: Computing the t-statistic from equation (11):

$$t = \frac{965 - 812 - 0}{129\sqrt{\frac{1}{2} + \frac{1}{3}}} = 1.3$$

Step 4: Determining degree of freedom and critical values:

Since it is a two sided test the significance level will be divide equally on both tails hence when using the t distribution table the value 0.025 will be used together with the degree of freedom to get the critical values.

$$\alpha/2 = 0.025$$
$$df = 2 + 3 - 2$$
$$\pm t^C = \pm 3.182$$

Step 5: Conclusion:

The t statistic is in the acceptance region since -3.18 < t=1.3 < 3.18 and therefore H_0 cannot be rejected at $\alpha = 0.05$

These five steps will be now repeated to see the effect on the total deformation for the case with basalt textile reinforcement. The observed total deformations are presented in table 5-1.

Table 5-1 Observed total deformations for the case with basalt textile reinforcement.

$\mu_{b,mix1}$	$\mu_{b,mix1,previous\ experiment}$	$\mu_{b,mix2,nr1}$	$\mu_{b,mix2,nr2}$	$\mu_{b,mix2,nr3}$
23 mm	25 mm	42 mm	40 mm	40 mm

$$\bar{x}_1 = \frac{(23\text{ mm} + 25\text{ mm})}{2} = 24\text{ mm}$$

$$\bar{x}_2 = \frac{(42\text{ mm} + 40\text{ mm} + 40\text{ mm})}{3} = 41\text{ mm}$$

$$s_1 = \sqrt{\frac{(23\text{ mm} - 24\text{ mm})^2 + (25\text{ mm} - 24\text{ mm})^2}{2-1}} = \sqrt{2}\text{ mm}$$

$$s_2 = \sqrt{\frac{(42\text{ mm} - 41\text{ mm})^2 + (40\text{ mm} - 41\text{ mm})^2 + (40\text{ mm} - 41\text{ mm})^2}{3-1}}$$
$$= \sqrt{\frac{3}{2}}\text{mm}$$

$$s_p = \sqrt{\frac{(2-1)(\sqrt{2}\text{ mm})^2 + (3-1)(\sqrt{\frac{3}{2}}\text{ mm})^2}{2+3-2}} = \sqrt{\frac{5}{3}}\text{ mm}$$

Step 1: Defining the hypotheses sort:

$$H_0: \mu_1 = \mu_2$$
$$H_1: \mu_1 \neq \mu_2$$

Step 2: Choosing the significance level:

$$\alpha = 0.05$$

Step 3: Computing the t-statistic from equation (11):

$$t = \frac{24 - 41 - 0}{\sqrt{\frac{5}{3}}\sqrt{\frac{1}{2} + \frac{1}{3}}} = -14.4$$

Step 4: Determining degree of freedom and critical values:

$$\alpha/2 = 0.025$$
$$df = 2 + 3 - 2$$
$$\pm t^C = \pm 3.182$$

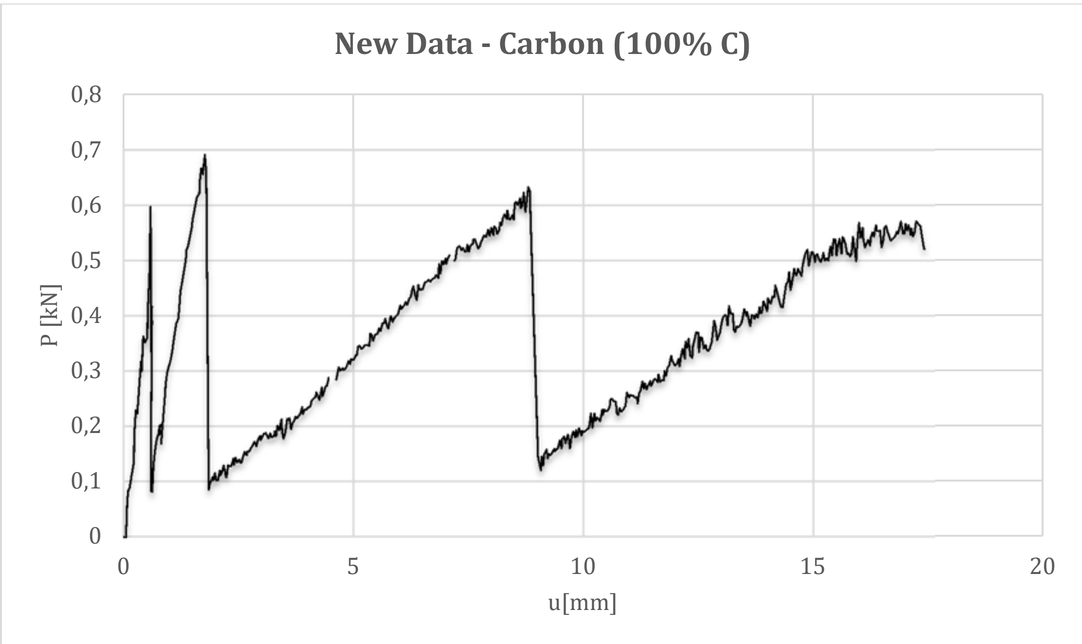
Step 5: Conclusion:

The t statistic is in the critical region and therefore H_1 should be adopted.

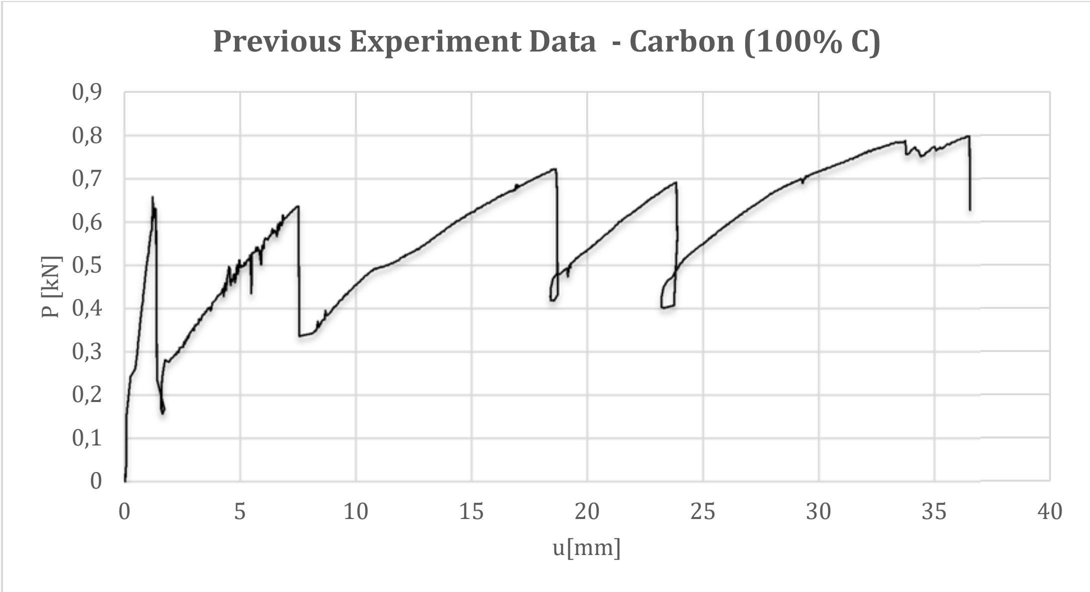
5.1.3 Carbon with the different concrete mixtures

For the plate with carbon and mixture 1 the initial cracking start at a load of approximately 0.60 kN. More than one crack have been observed for this plate. The distance between the first and second crack has been measured to 19 cm. This can be seen in figure 5-11. The mechanical behaviour is shown in figure 5-9. Here one can see the reduction of stiffness due to cracking through the change of the graphs inclination after each crack. The maximum load is approximately 0.70 kN. The corresponding result from the previous experiment is shown in figure 5-10.

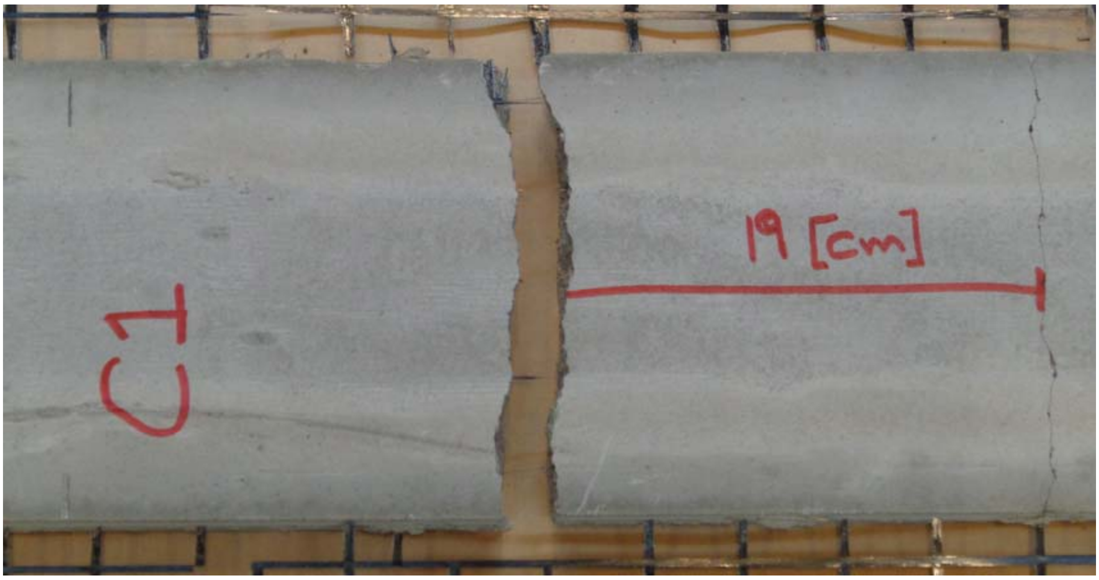
Two specimens with carbon and mixture 2 has been tested. The first one shows three distinct cracks whereas the second specimen shows significantly more minor cracks. This comparison is based on figure 5-12 and 5-13. The distance between these cracks has been measured to 9 cm and 11.5 cm for specimen number one and can be seen in figure 5-15. Each of these cracks occur around a load of approximately 0.55 kN. After the third crack the plate start to take an increased load up to 0.75 kN before raptures of the yarns occurs leading to ultimate failure of the plate. This behaviour differs for specimen number two where the load capacity is reduced to 0.65 kN while the total deformation is increased from 27 mm to 88 mm. In general the mechanical behaviour of specimen number two complies more with the corresponding one provided by the previous experiment which is shown in figure 5-14.



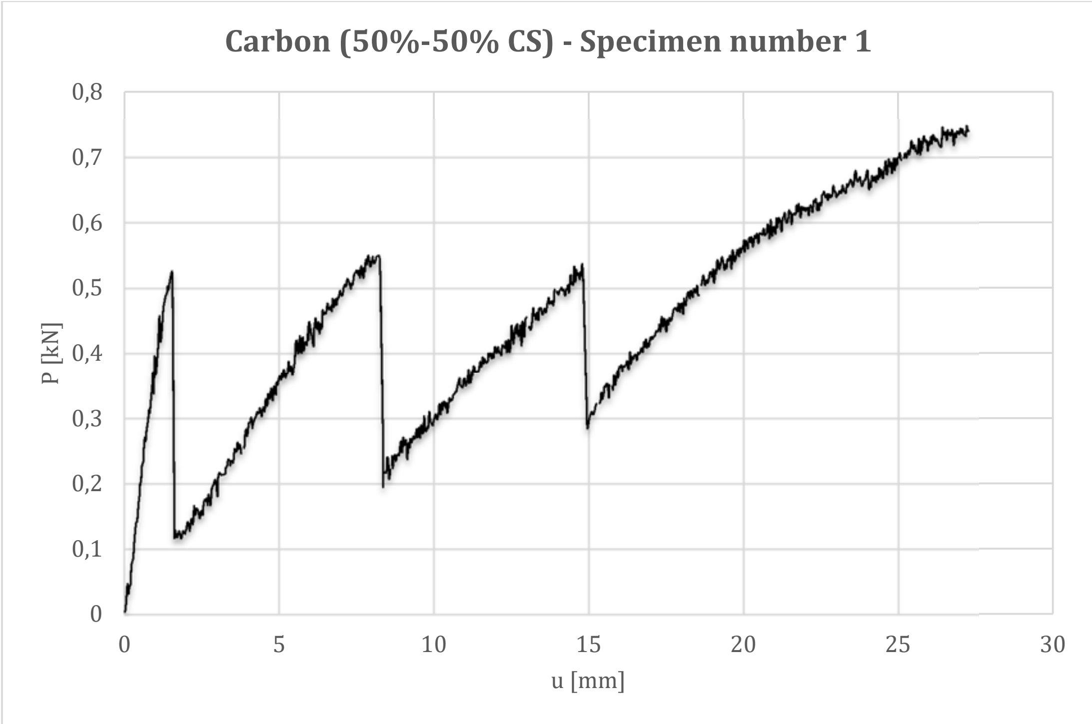
Figur 5-9 Results for carbon textile with concrete mixture 1.



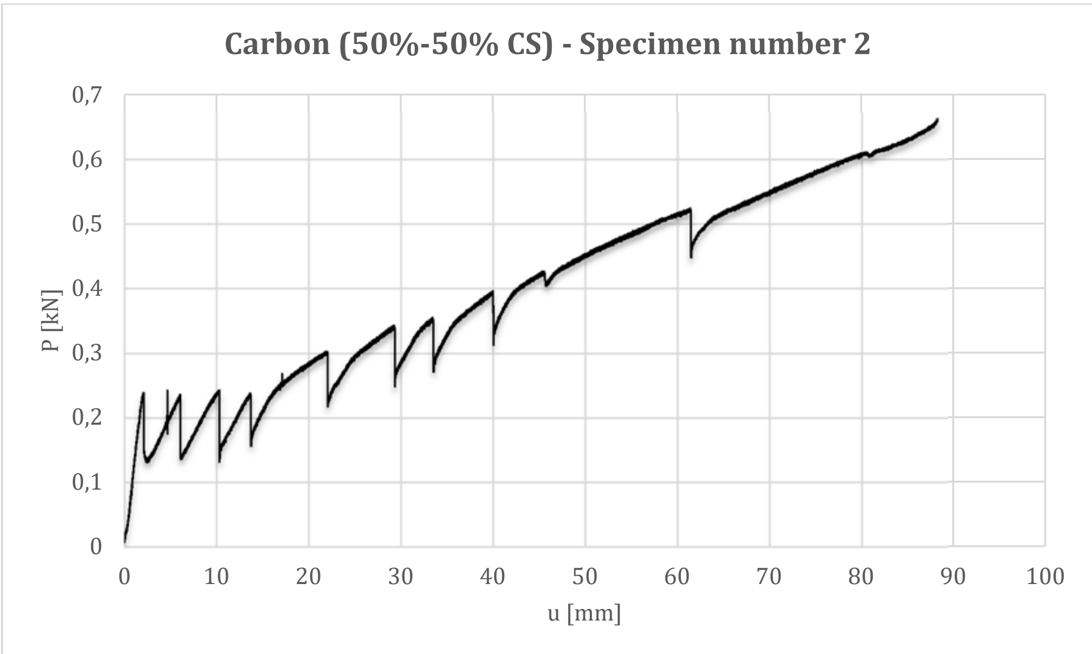
Figur 5-10 Results from supervisor for carbon textile with concrete mixture 1.



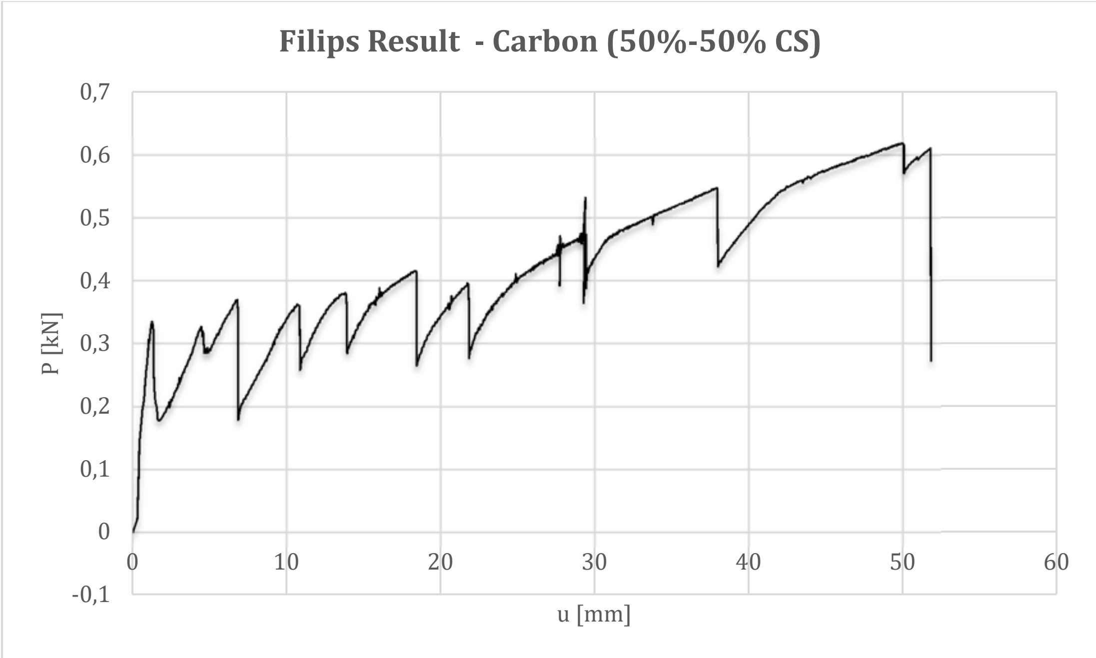
Figur 5-11 The condition of a plate with carbon textile and concrete mixture 1 after failure.



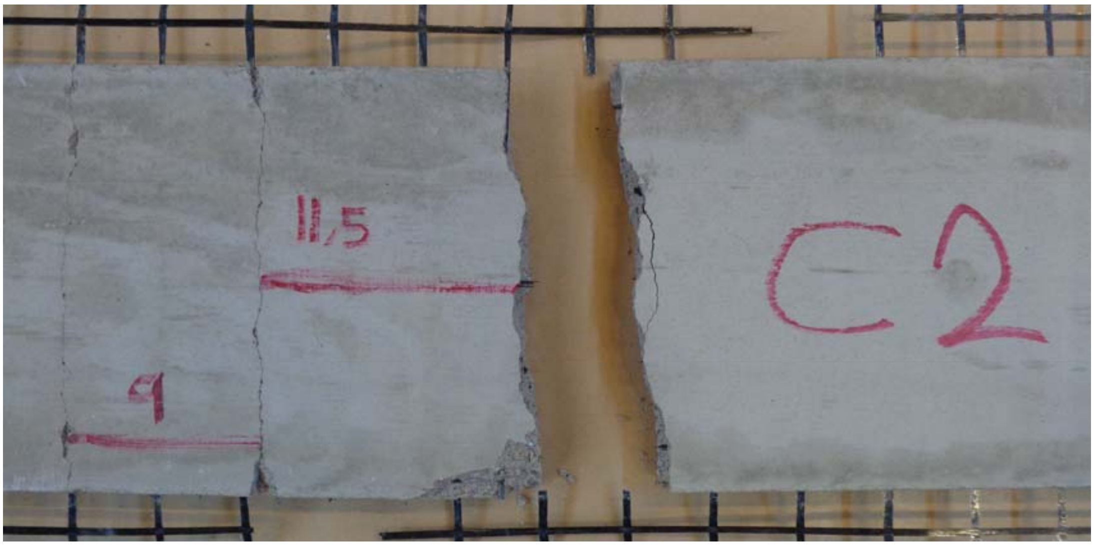
Figur 5-12 Results from specimen number 1 for carbon textile with concrete mixture 2.



Figur 5-13 Results from specimen number 2 for carbon textile with concrete mixture 2.



Figur 5-14 Results from supervisor for carbon textile with concrete mixture 2.



Figur 5-15 The condition of specimen number one with carbon textile and concrete mixture 2 after failure.

5.1.4 Data analysis for carbon

Everything that has been done in section 5.1.2 will be repeated here for the case of carbon textile reinforcement.

$$F_{\text{c,mix1}} = \frac{P_{\text{max}}L_{\text{max}}}{2zn} = \frac{0.58 \text{ x } 10^{3}\text{N x } 32 \text{ x } 10^{-2}\text{m}}{2 \text{ x } 15 \text{ x } 10^{-3}\text{m x } 5} = 1237 \text{ N}$$

$$F_{c,mix1,supervisor} = 1612 \text{ N}$$

$$F_{\text{c,mix2,nr1}} = \frac{P_{\text{max}}L_{\text{max}}}{2zn} = \frac{0.75 \text{ x } 10^{3}\text{N x } 32 \text{ x } 10^{-2}\text{m}}{2 \text{ x } 15 \text{ x } 10^{-3}\text{m x } 5} = 1600 \text{ N}$$

$$F_{\text{c,mix2,nr2}} = \frac{P_{\text{max}}L_{\text{max}}}{2zn} = \frac{0.65 \text{ x } 10^{3}\text{N x } 31 \text{ x } 10^{-2}\text{m}}{2 \text{ x } 15 \text{ x } 10^{-3}\text{m x } 5} = 1343 \text{ N}$$

$$F_{c,mix2,supervisor} = 1318 \text{ N}$$

$$\bar{x}_1 = \frac{(1237 \text{ N} + 1612 \text{ N})}{2} = 1425 \text{ N}$$

$$\bar{x}_2 = \frac{(1600 \text{ N} + 1343 \text{ N} + 1318 \text{ N})}{3} = 1420 \text{ N}$$

$$s_1 = \sqrt{\frac{(1237 - 1425)^2 + (1612 - 1425)^2}{2 - 1}} = 265$$

$$s_2 = \sqrt{\frac{(1600 - 1420)^2 + (1343 - 1420)^2 + (1318 - 1420)^2}{3 - 1}} = 156$$

$$s_p = \sqrt{\frac{(2 - 1)265^2 + (3 - 1)156^2}{2 + 3 - 2}} = 199$$

Step 1: Defining the hypotheses sort:

$$H_0: \mu_1 = \mu_2$$
$$H_1: \mu_1 \neq \mu_2$$

Step 2: Choosing the significance level:

$$\alpha = 0.05$$

Step 3: Computing the t-statistic from equation (11):

$$t = \frac{1425 - 1420 - 0}{199\sqrt{\frac{1}{2} + \frac{1}{3}}} = 0.028$$

Step 4: Determining degree of freedom and critical values:

$$\alpha/2 = 0.025$$
$$df = 2 + 3 - 2$$
$$\pm t^C = \pm 3.182$$

Step 5: Conclusion:

The t statistic is in the acceptance region since -3.18 < t=0.028 < 3.18 and therefore H_0 cannot be rejected at $\alpha = 0.05$

Next the effect on the total deformation for the case with carbon textile reinforcement will be analysed. The observed total deformations are presented in table 5-2.

Table 5-2 Observed total deformations for the case with carbon textile reinforcement.

$\mu_{c,mix1}$	$\mu_{c,mix1,supervisor}$	$\mu_{c,mix2,nr1}$	$\mu_{c,mix2,nr2}$	$\mu_{c,mix2,supervisor}$
18 mm	37 mm	27 mm	88 mm	52 mm

$$\bar{x}_1 = \frac{(18\text{mm} + 37\text{mm})}{2} = 28\text{mm}$$

$$\bar{x}_2 = \frac{(27\text{mm} + 88\text{mm} + 52\text{mm})}{3} = 56\text{ mm}$$

$$s_1 = \sqrt{\frac{(18\text{mm} - 28\text{mm})^2 + (37\text{mm} - 28\text{mm})^2}{2-1}} = 13\text{mm}$$

$$s_2 = \sqrt{\frac{(27\text{mm} - 56\text{mm})^2 + (88\text{mm} - 56\text{mm})^2 + (52\text{mm} - 56\text{mm})^2}{3-1}} = 31$$

$$s_p = \sqrt{\frac{(2-1)(13\text{mm})^2 + (3-1)(31\text{mm})^2}{2+3-2}} = 26\text{mm}$$

Step 1: Defining the hypotheses sort:

$$H_0: \mu_1 = \mu_2$$
$$H_1: \mu_1 \neq \mu_2$$

Step 2: Choosing the significance level:

$$\alpha = 0.05$$

Step 3: Computing the t-statistic from equation (11):

$$t = \frac{28\text{mm} - 56\text{mm} - 0}{26\text{mm}\sqrt{\frac{1}{2} + \frac{1}{3}}} = -1.2$$

Step 4: Determining degree of freedom and critical values:

$$\alpha/2 = 0.025$$
$$df = 2 + 3 - 2$$
$$\pm t^C = \pm 3.182$$

Step 5: Conclusion:

The t statistic is in the acceptance region since -3.18 < t= -1.2 < 3.18 and therefore H_0 cannot be rejected at $\alpha = 0.05$

5.2 Results from Factorial design at two levels

The results from the factorial experiment is presented in table 5-3. Yarn rapture has occurred in specimen number 5, 6, 13 and 14. Figure 5-1 shows this yarn rapture response in specimen number five whereas figure 5-2 shows a specimen where the yarn was pulled out. All of these four specimens have one thing in common namely that while factor X_2 is on its highest level the factor X_3 is on its lowest level. This indicate that there is an interaction between these factors.

Table 5-3 Results from the factorial experiment

Specimen	**X_1**	**X_2**	**X_3**	**X_4**	**Maximum load (kN)**	**Yarn rupture**
1	-	-	-	-	1.30	No
2	-	-	-	+	1.20	No
3	-	-	+	-	0.35	No
4	-	-	+	+	0.70	No
5	-	+	-	-	1.80	Yes
6	-	+	-	+	1.84	Yes
7	-	+	+	-	0.93	No
8	-	+	+	+	1.40	No
9	+	-	-	-	1.40	No
10	+	-	-	+	1.10	No
11	+	-	+	-	0.82	No
12	+	-	+	+	0.90	No
13	+	+	-	-	2.00	Yes
14	+	+	-	+	1.81	Yes
15	+	+	+	-	1.22	No
16	+	+	+	+	1.33	No

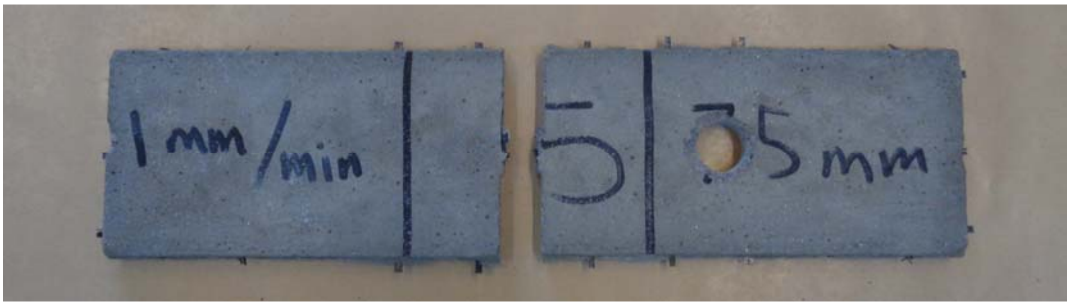


Figure 5-1 A specimen where yarn rapture did occur.

Figure 5-2 A specimen where the yarn was pulled out.

5.2.1 Main effects

The difference in maximum load between the first and second run from table 5-3 is 1.20-1.30=-0.10 kN. This value shows one measure of the effect of factor four while all the other factors are held constant. By looking at pairs of signs from the first and second run in table 5-3 it is obvious that any change in the maximum load between these two runs is only due to a change in factor four. It is also obvious from the same table that there are in total eight such measures and these are shown in table 5-4.

Table 5-4 Effect of changing the hydration age from two weeks to four weeks.

Run 1 and 2	1.20 - 1.30 =-0.10 kN
Run 3 and 4	0.70 - 0.35 = 0.35 kN
Run 5 and 6	1.84 - 1.80 = 0.04 kN
Run 7 and 8	1.40 - 0.93 = 0.47 kN
Run 9 and 10	1.10 - 1.40 =-0.30 kN
Run 11 and 12	0.90 - 0.82 = 0.08 kN
Run 13 and 14	1.81 - 2.00 =-0.19 kN
Run 15 and 16	1.33 - 1.22 = 0.11 kN

The *main effect* of the hydration age on the response is defined as the average of these measures which in this case is determined as (-0.1+0.35+0.04+0.47-0.3+0.08-0.19+0.11)/8=0.06. This main effect value can also be expressed as the difference between two averages where all the results are included.

$$main\ effect = \bar{y}_{+} - \bar{y}_{-} \tag{14}$$

$$\frac{1.20 + 0.70 + 1.84 + 1.40 + 1.10 + 0.90 + 1.81 + 1.33}{8} - \frac{1.30 + 0.35 + 1.80 + 0.93 + 1.40 + 0.82 + 2.00 + 1.22}{8} = 0.06$$

Everything that has been said about the main effect of hydration on the maximum load response also applies for the other remaining factors. Hence there is totally four main effects for this specific experiment one for each factor.

5.2.2 Interaction between factors

It was stated in section 5.2 that an interaction does exist between factor X_2 and X_3 regarding the yarn rupture response however it is not possible to give that interaction any estimated numerical value since the response is qualitative. This is not the case for the maximum load response. In this section a simple and effective method for calculating main effects and interactions for quantitative responses will be presented and used. Before starting with method it should be mentioned here that an interaction effect is a difference between to averages where all the results are included just like a main effect but with a slightly different geometrical interpretation.
The method will be explained through table 5-5. In contrast to table 5-3 all the factors are exchanged with their subscriptions e.g. factor X_1 is replaced with 1 in the first column hence the first four columns represent the four factors X_1, X_2, X_3, and X_4. The number 12 in the fifth column stands for X_1 by X_2 interaction. The first four columns together with their signs are the design matrix taken from table 5-3. However the signs for the interactions is determined by multiplying the signs of their respective factors. For example the signs under the interaction 12 is obtained by multiplying the signs of factor 1 and 2 from each row. The estimated value of interaction 12 is then calculated as

$$\frac{1.3 + 1.2 + 0.35 + 0.7 - 1.8 - 1.84 - 0.93 - 1.4 - 1.4 - 1.1 - 0.82 - 0.9 + 2 + 1.81 + 1.22 + 1.33}{8} = 0.14 \text{ kN}$$

This concept also applies for the remaining ten interactions. The estimated effect of both factors and interactions are calculated and presented in table 5-6.

Table 5-5 Table of signs for 2^4 Factorial Design.

1	2	3	4	12	13	14	23	24	34	123	124	134	234	1234	Maximum load (kN)
-	-	-	-	+	+	+	+	+	+	-	-	-	-	+	1.30
-	-	-	+	+	+	-	+	-	-	-	+	+	+	-	1.20
-	-	+	-	+	-	+	-	+	-	+	-	+	+	-	0.35
-	-	+	+	+	-	-	-	-	+	+	+	-	-	+	0.70
-	+	-	-	-	+	+	-	-	+	+	+	-	+	-	1.80
-	+	-	+	-	+	-	-	+	-	+	-	+	-	+	1.84
-	+	+	-	-	-	+	+	-	-	-	+	+	-	+	0.93
-	+	+	+	-	-	-	+	+	+	-	-	-	+	-	1.40
+	-	-	-	-	-	-	+	+	+	+	+	+	-	-	1.40
+	-	-	+	-	-	+	+	-	-	+	-	-	+	+	1.10
+	-	+	-	-	+	-	-	+	-	-	+	-	+	+	0.82
+	-	+	+	-	+	+	-	-	+	-	-	+	-	-	0.90
+	+	-	-	+	-	-	-	-	+	-	-	+	+	+	2.00
+	+	-	+	+	-	+	-	+	-	-	+	-	-	-	1.81
+	+	+	-	+	+	-	+	-	-	+	-	-	-	-	1.22
+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	1.33
8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	

Table 5-6 Estimated effects from 2^4 factorial design.

Factors and interactions	Effect [kN]
1	0.13
2	0.57
3	- 0.6
4	0.06
12	-0.04
13	0.09
14	-0.13
23	-0.04
24	0.05
34	0.20
123	-0.08
124	-0.02
134	-0.03
234	-0.01
1234	-0.05

It is obvious from table 5-6 that the main effect of factor three (water cement ratio) is the largest and it shows that the effect by changing this factor from 0.4 to 0.5 is to reduce the maximum load with 0.6 kN. The size of the estimated effects is important since it gives guidelines on which factor can be individually interpreted and which factors that has to be considered jointly e.g. although factor three has the largest effect it has to be considered together with factor four due to the relatively large three by four interaction.

6 Conclusions and discussion

The aim of this Master's thesis project was to study and evaluate combinations of different green concrete mixes with different textile reinforcement. The research has been limited to basalt and carbon reinforcement and slag as a substitute to cement in the green concrete. The study particularly focused on how the mechanical properties like strength and deformation of a test specimen with a particular reinforcement changed when changing the concrete mix. This aim was achieved by conducting designed experiment and using statistics as a tool to understand and drawing conclusions from the scientific data gathered from the experiment.
Three types of concrete mixes were prepared for the experiment with different amount of slag in them.

The first observation after the concrete casting and prior to the flexural testing was that the concrete mix with 100% slag had several cracks due to early shrinkage. One of the test specimens with this mix showed four major cracks with almost constant distance between them. Obviously the shrinkage rate in slag is higher than the corresponding one in Portland cement. The nature of slags shrinkage rate as a function of time is unknown and it has not been examined in this research. Instead it was decided to exclude this mix from the study.

The data gathered from the flexural tests was used in the software excel to plot load-displacement relation graphs. The graphs revealed some interesting differences in the mechanical response between different test specimens. For example in the case of basalt textile reinforcement embedded in concrete mixture one the plate cracked after reaching a maximum load of approximately 0.72 kN and it was the only crack developed during the testing. After this crack the plate restarted to take increased load until rupture of yarns occurred. However in the case of basalt textile reinforcement embedded in concrete mixture two several minor cracks appeared and the highest load was found between these and before failure. Also the load capacity was somewhat reduced while the deformation before ultimate failure was increased. The maximum load and deformation for each tested specimen was gained from its corresponding graph. The maximum load was used to calculate the maximum load per yarn. These values was later used in different test of hypotheses to see if any significant change to the tested parameter had occurred as a result of changing the concrete mix.

The result from the test of hypotheses showed that the effect of replacing 50% of the cement amount with slag on the maximum load per yarn in test specimens with basalt textile reinforcement had no significant effect, since the t-statistic was in the acceptance region. This means that if this test was repeated hundred times the t-statistic would be in the acceptance region in 95 cases. However a similar test of hypotheses but with deformation response in focus showed that the replacement of cement with slag changes the deformation response significantly since the t-statistic was in the critical region. These two tests of hypotheses were repeated for the case of carbon textile reinforcement and in contrast to basalt reinforcement it was shown that the slag replacement had no significant effect on either the maximum load per yarn or the deformation response. The result for the carbon case could be used to promote the use of slag.

A secondary objective was to see how when varying different factors like e.g. water cement ratio, hydration age, and deformation rate affect the mechanical properties and if there is any interaction between these. The focus was on the maximum load and when the failure yarn rapture occurred. This was achieved by conducting a factorial experiment with four factors where each was given on two levels. The results showed that yarn rupture did occur for a combination of long embedment length and low water-cement ratio. The estimated main effects and interactions on the maximum load from table 5-6 showed that factor two and three are much more dominant then factor one and four. Another interesting point is that although the main effect of factor four is the lowest the largest interaction is the three by four interaction. It is not clear at the moment how the results from the factorial experiment can be used in practise but nevertheless they can provide a good reference for further studies with more specific objective and the methodology of factorial deign has been introduced.

Finally as a suggestion for further research an investigation in the chemistry of the different materials is needed to better understand the mechanical differences between the different test specimens.

7 References

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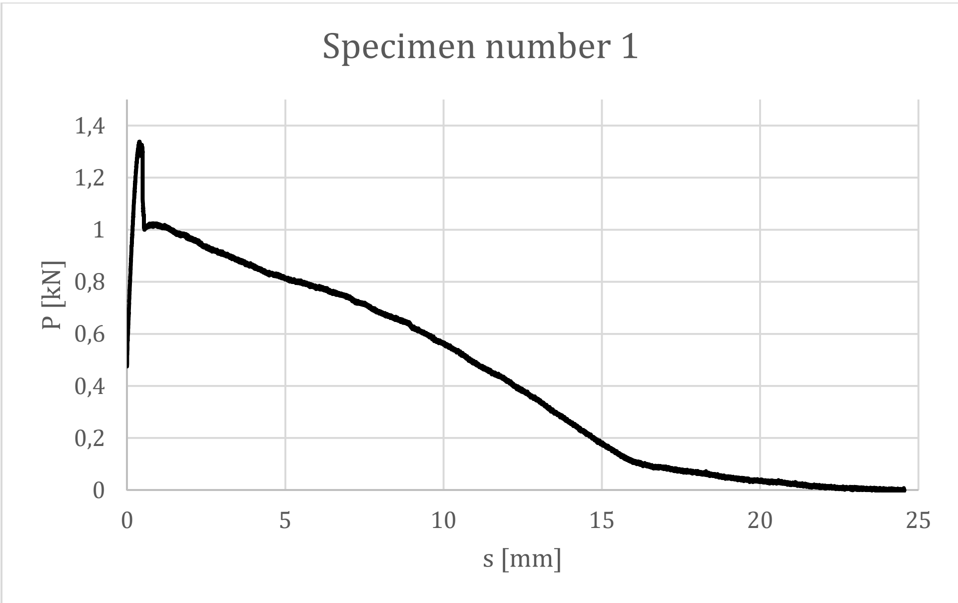
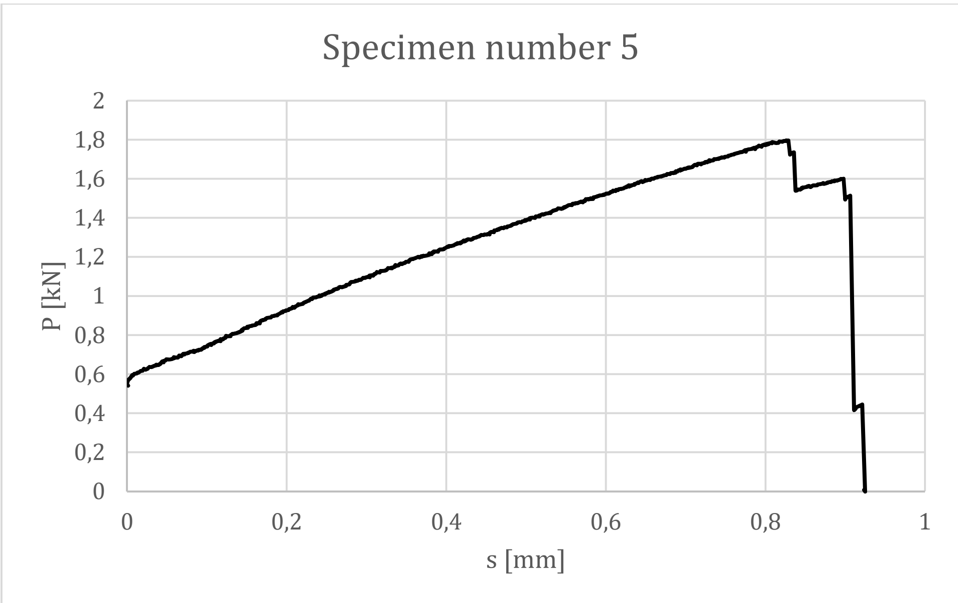
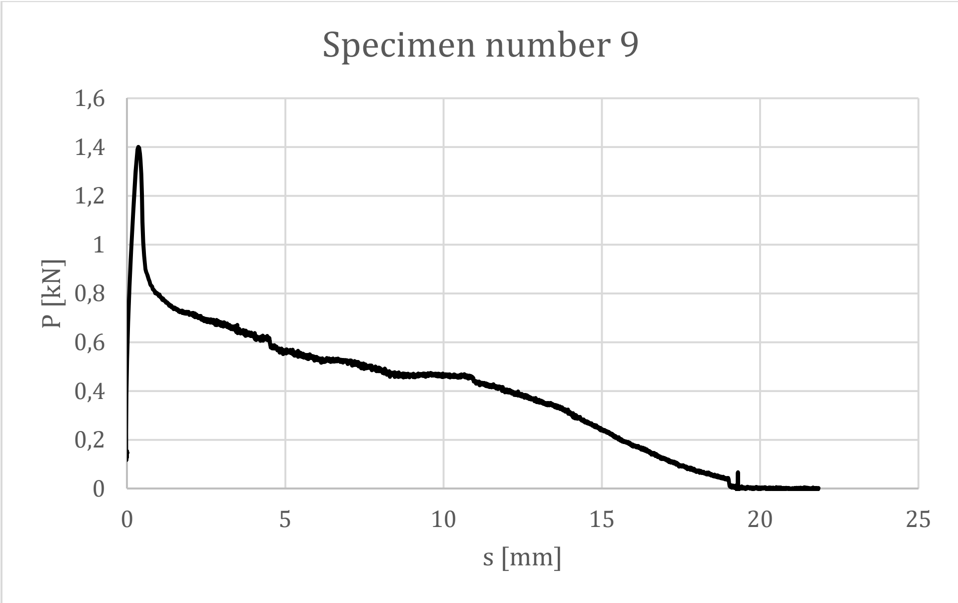
Appendix A

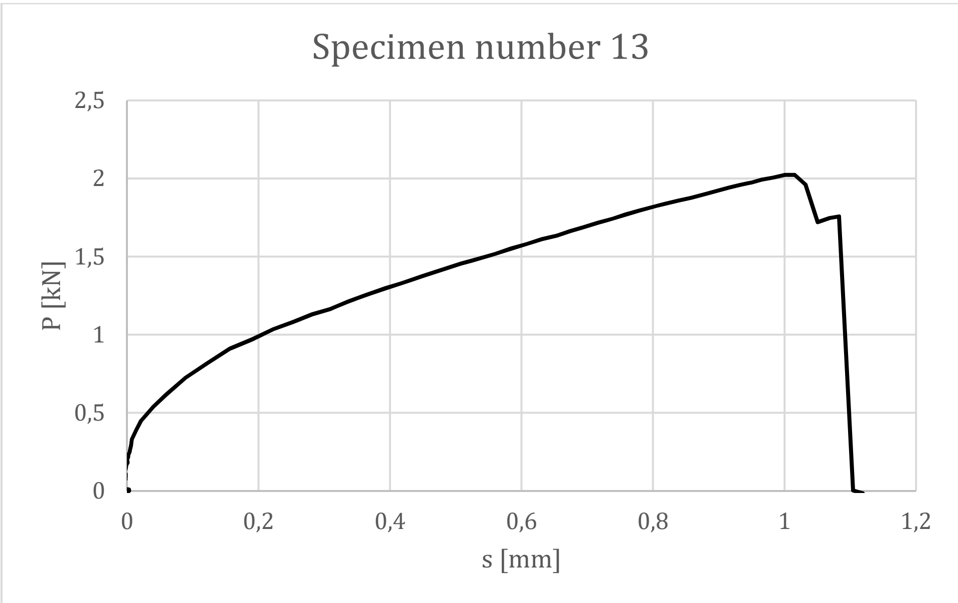
Tension test results

Tension test number one performed 2016/06/27

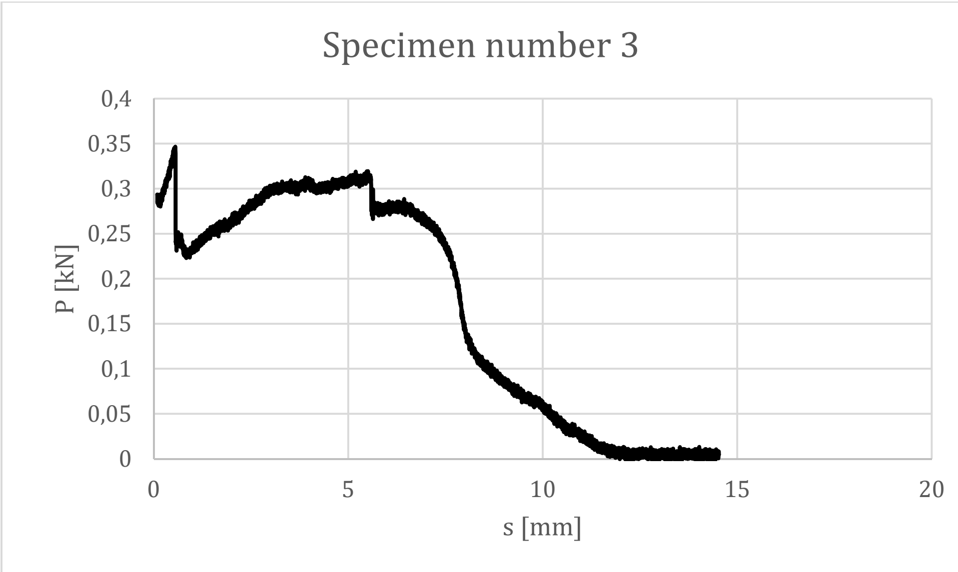


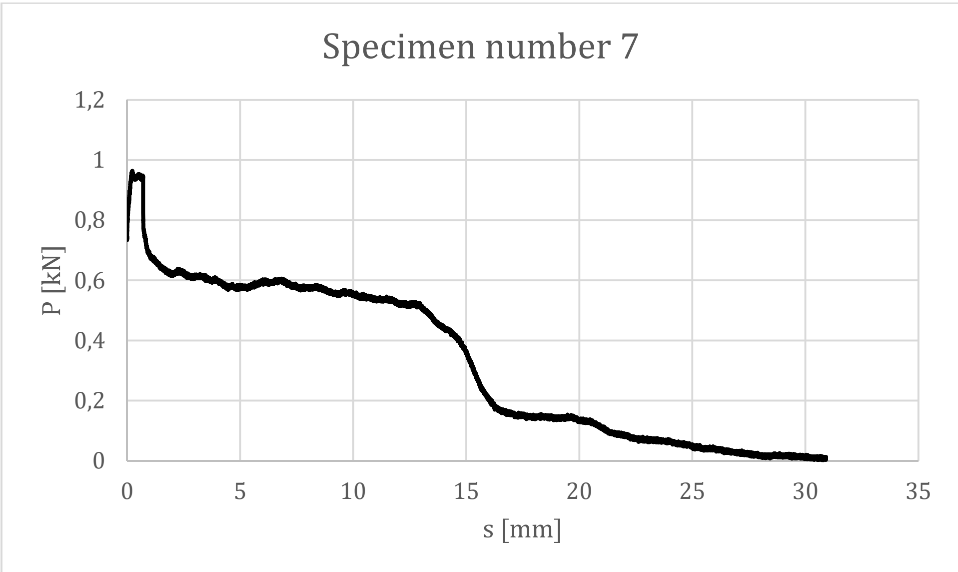


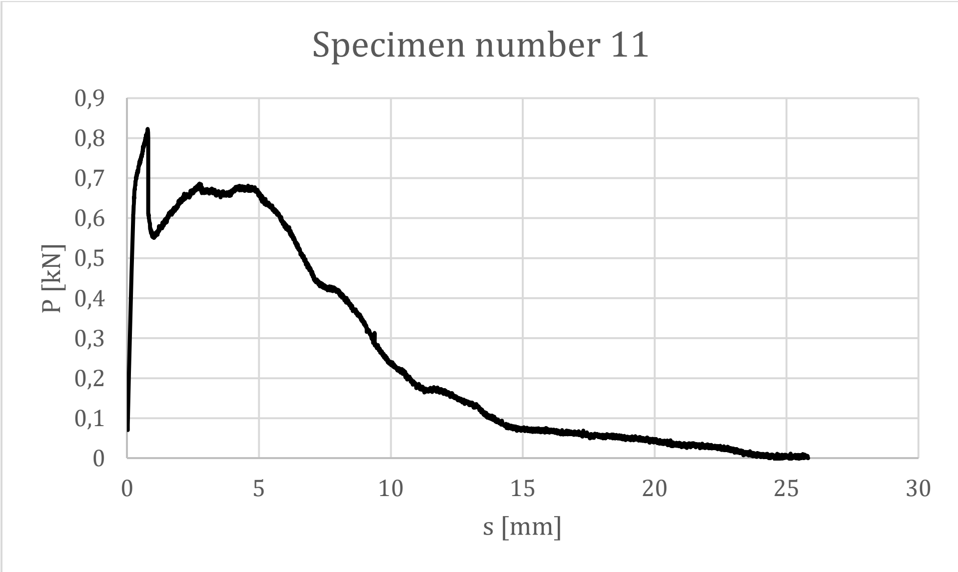

Specimen number 9
1,6
1,4
1,2
1
0,8
0,6
0,4
0,2
0
P [kN]
0
5
10
15
20
25
s [mm]

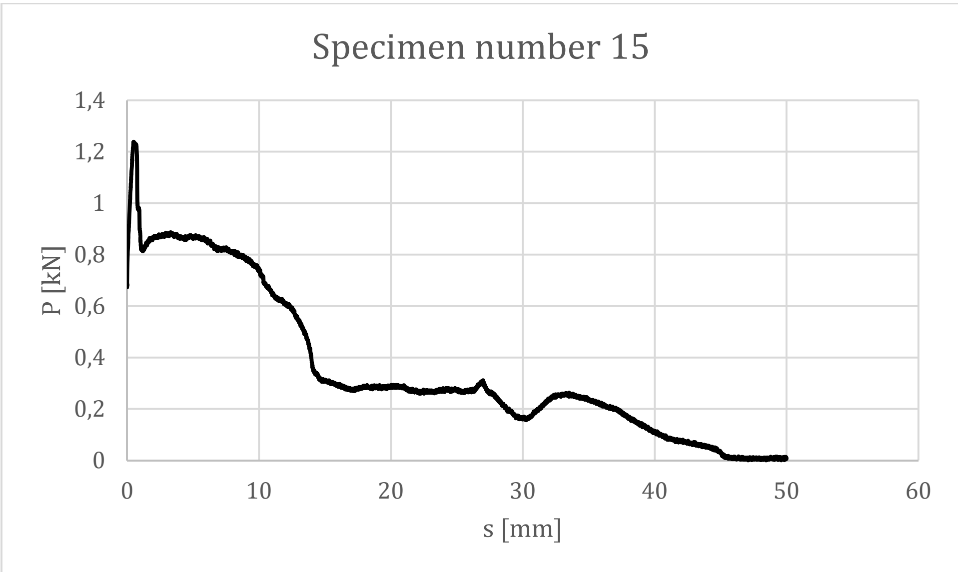

Specimen number 13
2,5
2
1,5
1
0,5
0
P [kN]
0
0,2
0,4
0,6
0,8
1
1,2
s [mm]

Tension test number two performed 2016/06/30

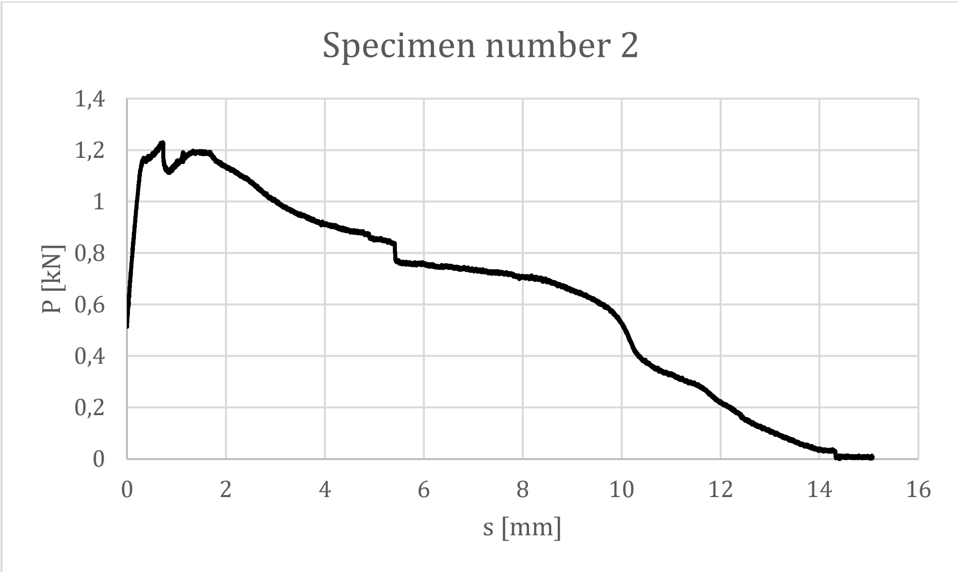


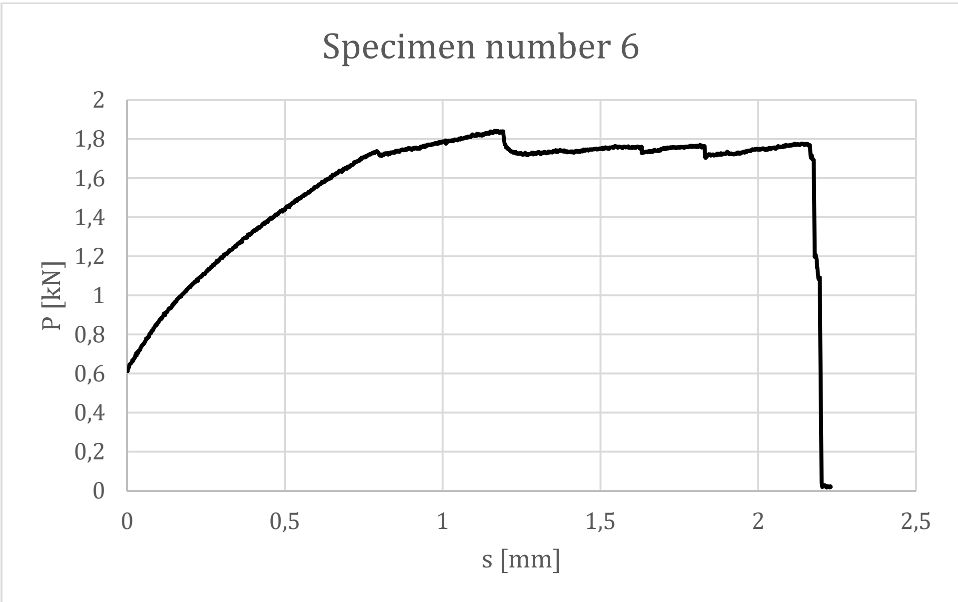


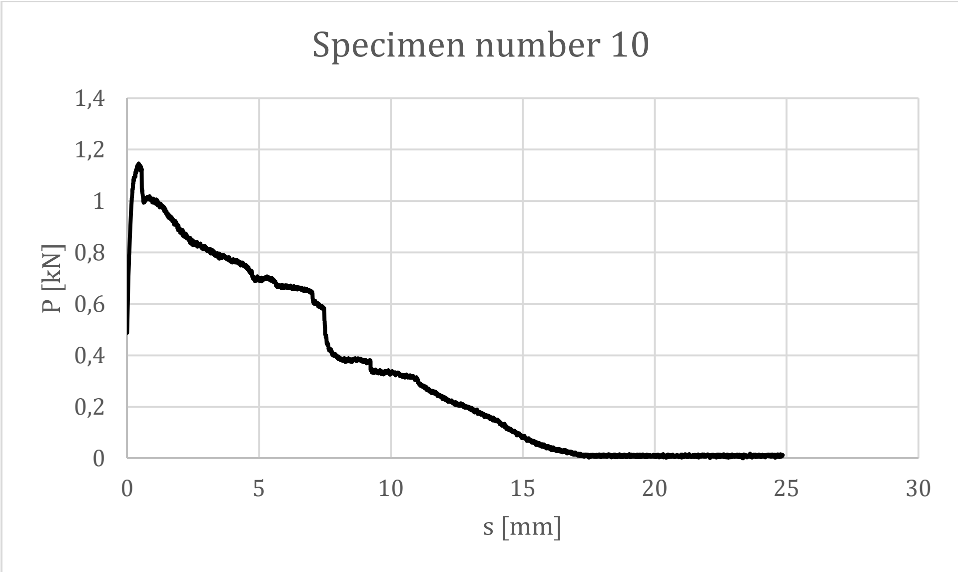

Specimen number 11
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
P [kN]
0
5
10
15
20
25
30
s [mm]


Specimen number 15
1,4
1,2
1
0,8
0,6
0,4
0,2
0
P [kN]
0
10
20
30
40
50
60
s [mm]

Tension test number three performed 2016/07/11



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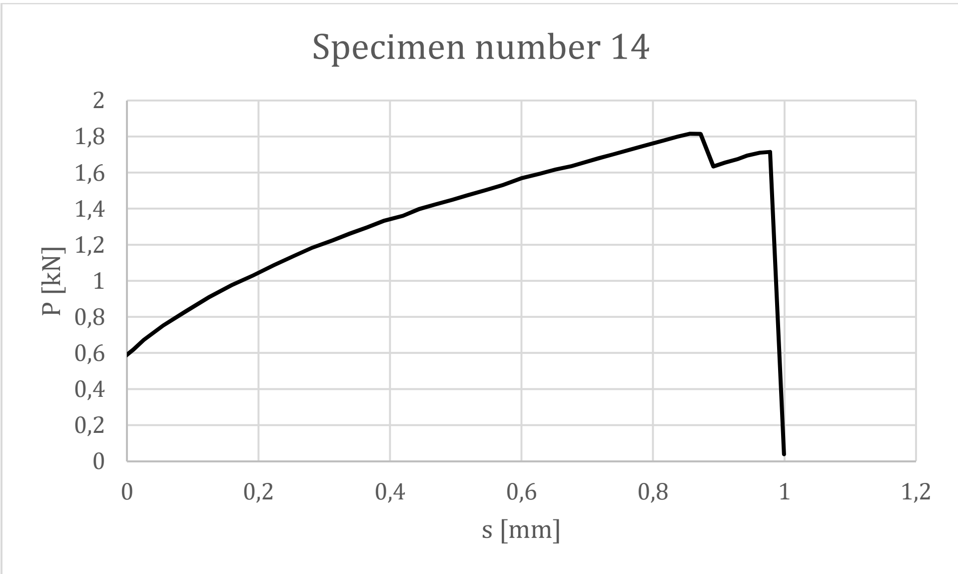
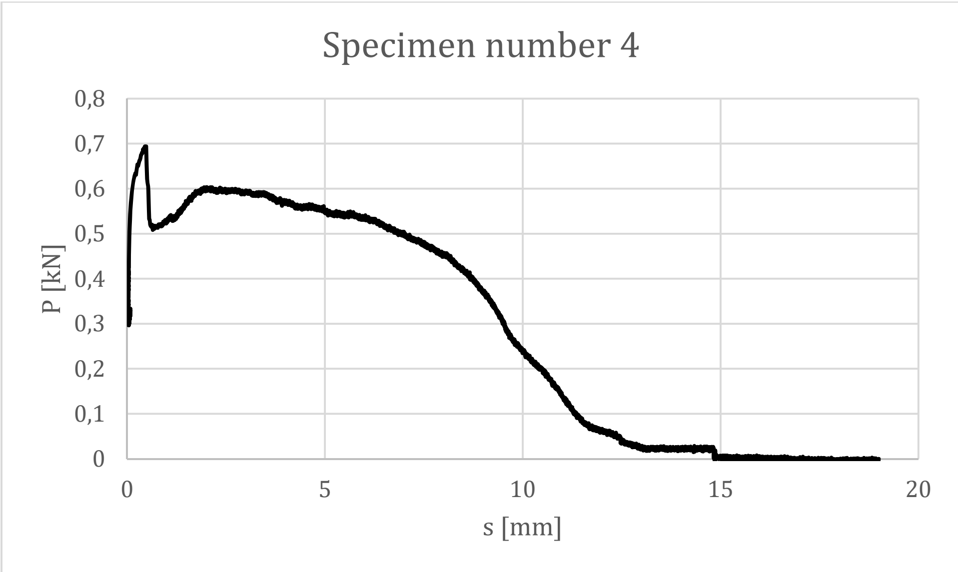
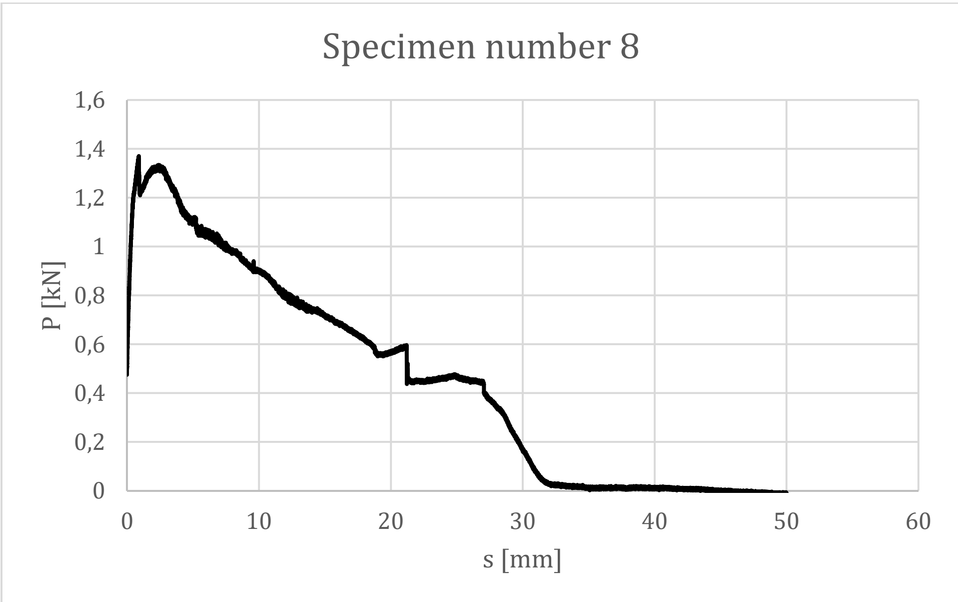
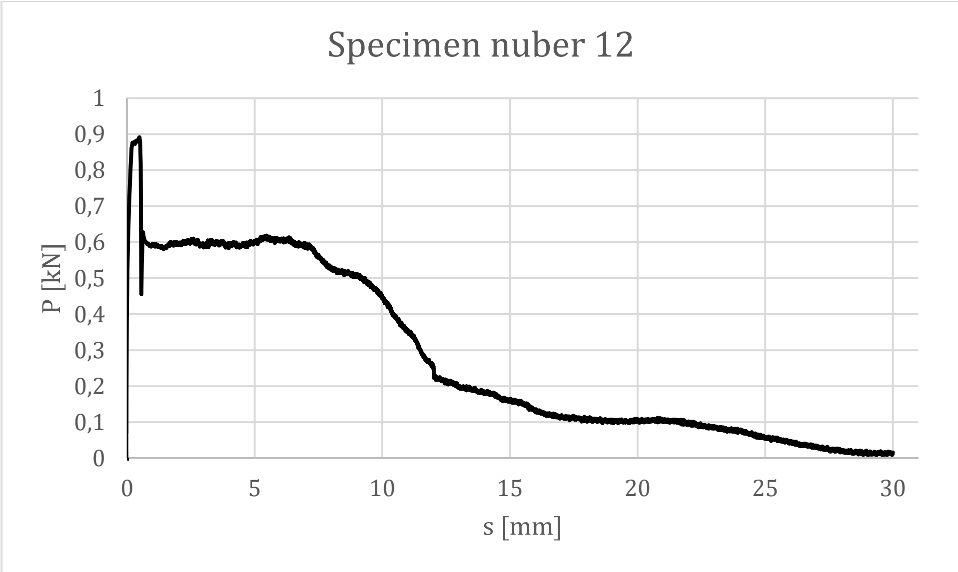
1,4
1,2
1
0,8
0,6
0,4
0,2
0
P [kN]
0
5
10
15
20
25
30
s [mm]

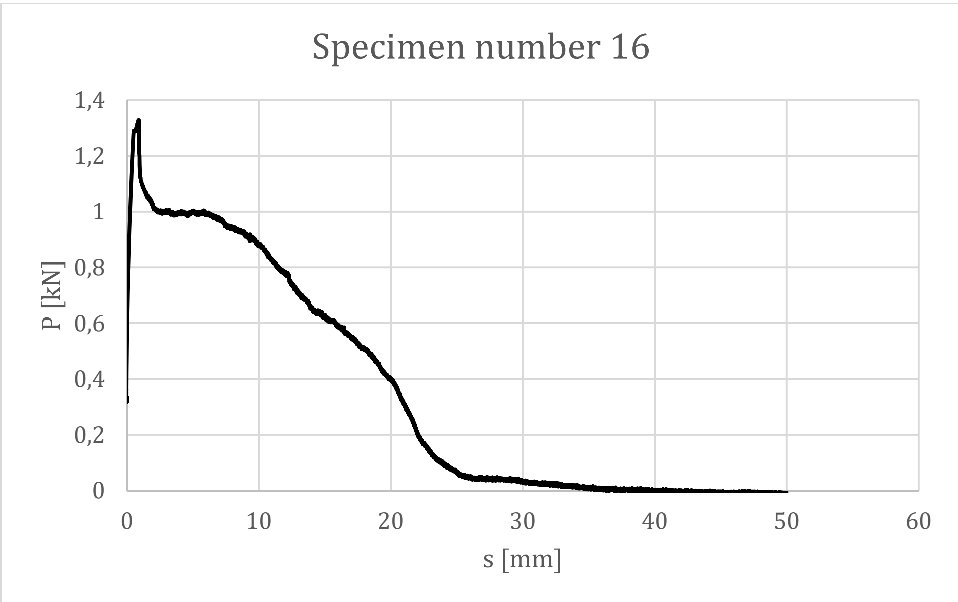

Specimen number 14
2
1,8
1,6
1,4
1,2
1
0,8
0,6
0,4
0,2
0
P [kN]
0
0,2
0,4
0,6
0,8
1
1,2
s [mm]

Tension test number three performed 2016/07/14






Specimen nuber 12
1
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
P [kN]
0
5
10
15
20
25
30
s [mm]


Specimen number 16
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1,2
1
0,8
0,6
0,4
0,2
0
P [kN]
0
10
20
30
40
50
60
s [mm]

Appendix B

Flexure test results for specimens with an excess of sikament 56