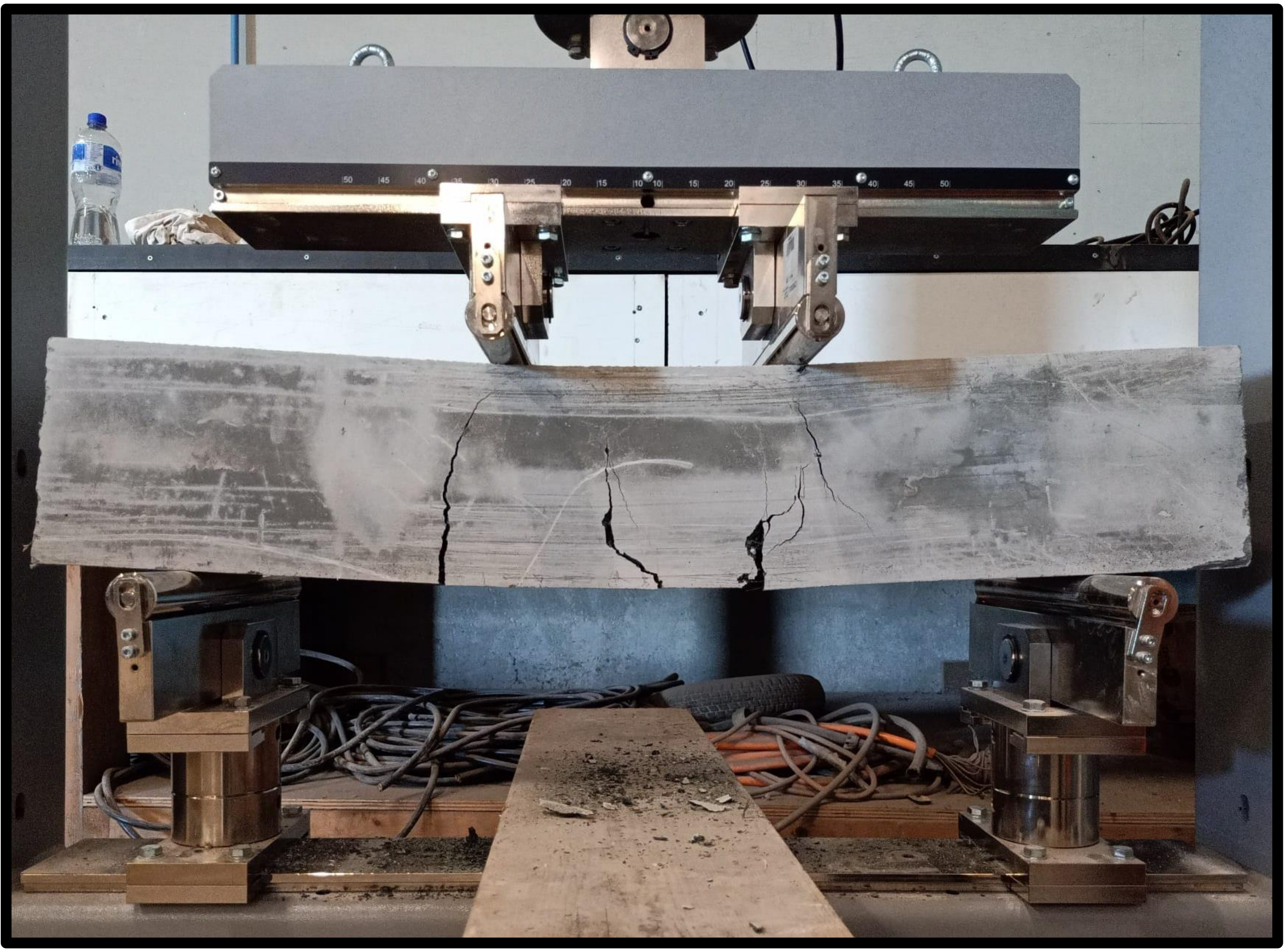


Basalt to replace steel in concrete quay wall aprons

Evaluation of basalt fibres and basalt reinforced polymer rebars to replace steel as reinforcement in quay wall aprons to reduce environmental impact.

Ron Slegers 4594908

Basalt to replace steel in concrete quay wall aprons

Evaluation of minibars and basalt reinforced polymer rebars to replace steel as reinforcement in quay wall aprons to reduce environmental impact.

In partial fulfilment of the requirements for the degree of

Master of Science
In Civil Engineering

At Delft University of Technology,
to be defended publicly on

Colophon

Master thesis report. Basalt to replace steel in constructions: Evaluation of minibars and basalt reinforced polymer rebars to replace steel as reinforcement in quay wall aprons to reduce environmental impact.

Author

Name	Ron Christian Slegers
Student number	4594908
University	Delft University of Technology
Faculty of	Civil Engineering and Geosciences
Department	Structural Engineering
Specialisation	Concrete Structures

Graduation committee

Prof. dr. H.M. Jonkers	TU Delft, Materials and Environment
Prof. dr. ir. M.A.N. Hendriks	TU Delft, Concrete Structures
dr. Ir. H.W.M. van der Ham	TU Delft, Concrete Structures
Laurenzo Victorie	Rutte Groep, Project Manager

Preface

This thesis report is the final product of the graduation research. It is written as part of the master Structural Engineering, specialization Concrete Structures, at Delft University of Technology, faculty of Civil Engineering and Geosciences in partnership with the company Rutte Groep, situated in Zaandam, Netherlands.

This research focusses environmental impact and design aspects of quay wall aprons with different types of reinforcement. The need for this environmental comparison follows from the environmental awareness within the company where sustainable concrete is already feasible to an extend where the reinforcement is the next step to optimize the environmental impact of the products that are delivered. This leads to the interest of the company in replacements for steel reinforcement. In this research steel rebars, steel fibres, basalt rebars and minibars are all compared to each other. This is done by performing strength tests and creating designs to account material usage per reinforcement type. With an environmental comparison the new designs can be checked to see how/if environmental impact can indeed be reduced with the new reinforcement types.

During my Bachelor I always had an interest in structural mechanics and especially in the concrete structures. Choosing a master track was therefore not a difficult choice. During the master my interest in sustainability and optimizing designs grew due to the course Materials and Ecological Engineering where for the first time environmental impact calculations where performed. When getting in contact with Rutte Groep their goal of optimizing a design of a concrete quay wall apron in terms of environmental impact was therefore extremely interesting to me, seeing as it brought together subjects of interest and provided me to also work with my hands in preparing and performing concrete tests.

Finally, I would like to thank my graduation committee who supported me during the research. Thank you Prof. dr. H.M. Jonkers, Prof. dr. ir. M.A.N. Hendriks and H.W.M. van der Ham for your insights and putting me on the right track to start the research and at the end when everything needed to come together. Additionally I would like to thank Rutte Groep, with special thanks to Laurenzo Victorie and René - and Rick Rutte for guiding me and providing me with a place to graduate. Within Rutte Groep I would also like to thank all workers present that were always willing to help with anything and teaching me how to prepare and perform all experiments. Besides Rutte Groep I would also like to thank Len Miller from ReforceTech who helped me figure out how to use the basalt reinforcement and was always ready to answer any question I had. I would also like to thank Anna Alberda van Ekenstein for her insights in graduating at the company of Rutte Groep. Finally, I would like to thank my family and friends for their support, encouragements and meaningful insights throughout the process.

R.C. Ron Slegers
Delft, December 2022

Abstract

Currently steel is the most used material to act as reinforcement in concrete. When moving towards a circular concrete building industry the reinforcement has to be taken into account. The production of steel reinforcement requires a lot of energy and accounts for a large portion of the environmental footprint of reinforced concrete. Another type of reinforcement producing a significantly lower impact on the environment is therefore interesting for innovative companies which already use recycled/reused concrete. The aim of this research is to gain insight in the possibilities of basalt as a replacement of steel as the material used for reinforcement in structures. This is achieved by comparing the designs for quay wall aprons on an environmental level by calculating the Environmental Cost Indicator (ECI) value i.e. shadow costs for a product that indicate the damages done to the environment caused by the life cycle of the product. When calculating this ECI value different impact categories are considered, the most well-known is the Global Warming Potential (GWP) which is indicated by kg CO_2 emission. Other impact categories are shown in chapter 8 of this research.

The aim of the research is to gain insight on the environmental costs by comparing different designs. The design criteria for each design contain the dimensions which are standardized for the four designs (figure A.1), the loads which are assumed to be equal for each design leading to equal strength requirements (see table A.1). The differences in the four designs are the types of reinforcements and the amounts of reinforcement that are used. Therefore the comparison in ECI value rests on the differences for the raw materials that are used. The entire life cycle of each material is considered taking into account the excavation of the raw material, the transport, production process (for fibres/rebars this means the production of the fibre from raw material) and the end of life stage (where a product/material is demolished/reused/recycled). More on this is explained in chapter 8 as well. The production process regardless of the type of reinforcement is similar for each design and is therefore not considered in this research.

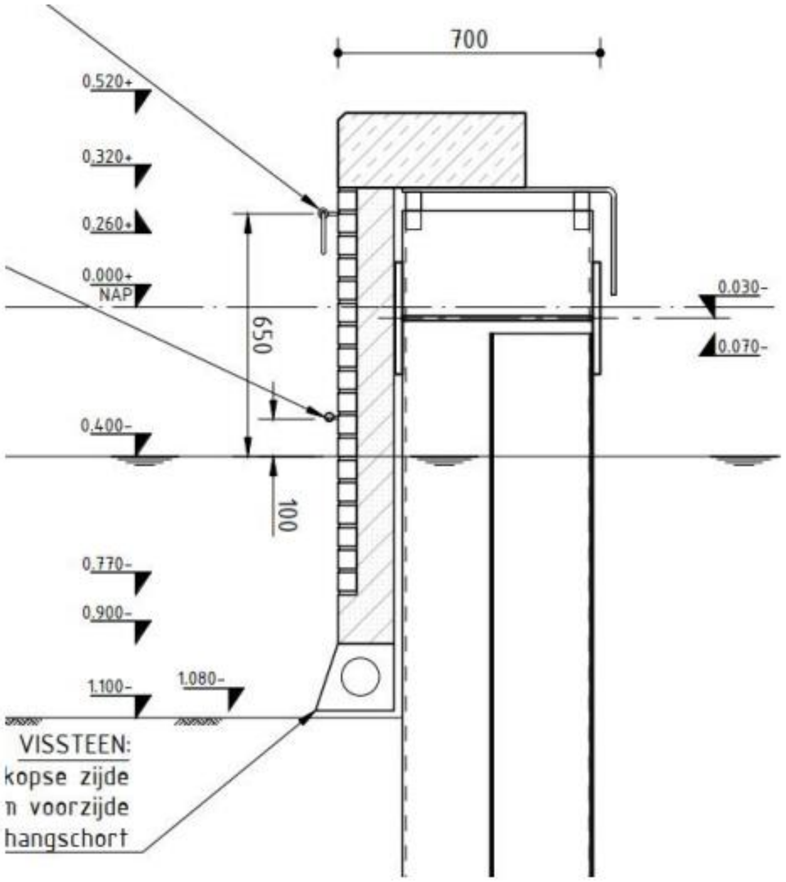


Figure A.1: Side view of quay wall apron design with steel fibres (Pouwels, 2021)

Table A.1: Strength requirements for different reinforcement types

Strength Requirements	Rebar designs	Fibre designs
$M_{Ed_{SLS}}$ & $M_{Ed_{ULS}}$ $[kNm/m]$	n/a	14.96
$M_{Ed_{y_+}}$ & $M_{Ed_{y_-}}$ $[kNm/m]$	14.96, 4.43	n/a
$M_{Ed_{x_+}}$ & $M_{Ed_{x_-}}$ $[kNm/m]$	8.00, 7.81	n/a
$V_{Ed_{ps}}$ $[kN]$	50	50

The types of reinforcement used in this research are B500 steel rebars (the most common type of reinforcement in concrete), Dramix 5D steel fibres, minibars and Basalt Fibre Reinforced Polymer bars (BFRP-bars later described as BasBars). The 4 types of reinforcement result in 4 designs that can be compared. Before this research started a design with steel rebars had already been produced for a different project (figure A.2). Therefore the dimensions and design loads are different to those used in this research. The visual result however is similar and gives a good view on what the end product of this research looks like. For the current project (Singelgracht Amsterdam) a design with the Dramix 5D steel fibres has been presented by the company ABT. This design forms the baseline for three new designs with the above mentioned reinforcement types resulting in a total of 4 designs. The dimensions and loads presented in figure A.1 and table A.1 follow from the design criteria from ABT..

Figure A.2: Prefab quay wall apron with steel rebars

The experiments performed in this research are presented in chapter 5 and provide the needed material/strength properties of the materials. For fibre reinforced concrete the two main tests that are performed are firstly a concrete compressive strength test to get the capacity of the concrete in compression and secondly a Crack Mouth Opening Displacement (CMOD) test to test the behaviour of the fibre reinforced concrete in tension. These tests have also been performed on steel fibre reinforced concrete to compare and to validate the steel fibre design. For the designs with rebars mainly three and four point bending tests are performed to obtain failure loads to compare to theoretical results and to check detailing such as anchorage lengths. These experiments together with the European norms are used to calculate and validate the four designs for structural performance and workability.

From the test results the designs have been validated in terms of strength and workability. As the aim of this research is to check the environmental impact in order to potentially reduce this, the results in table A.2 show the amounts of reinforcement for one apron for the different types of reinforcement note that these are not the values for a cubic metre of concrete. In the case of the fibre reinforced designs a value per cubic metre is known. For the Minibars the result is 30 kg/m^3 and for the Dramix 5D fibres this is 45 kg/m^3.

Table A.2: Design results for four reinforcement types (material usage + governing moment capacities)

Design	Reinforcement for one standardized apron (= 0.829 m^3) [kg]	Governing Unity checks for moment capacities [-]	Governing Unity checks for punching shear capacities [-]
Minibars	24.86 (= 30 kg/m^3)	$UC_{M_{Rd_{SLS}}} = 0.99$, $UC_{M_{Rd,ULS}} = 0.96$	$UC_{V_{Rd}} = 0.14$
BasBars	16.08 (= 19 kg/m^3)	$UC_{M_{Rd,y+}} = 0.94$, $UC_{M_{Rd,y-}} = 0.80$, $UC_{M_{Rd,x+}} = 0.92$, $UC_{M_{Rd,x-}} = 0.90$,	$UC_{V_{Rd,y}} = 0.55$, $UC_{V_{Rd,x}} = 0.55$
Dramix 5D steel fibres	37.29 (= 45 kg/m^3)	$UC_{M_{Rd_{SLS}}} = 0.99$, $UC_{M_{Rd,ULS}} = 0.92$	$UC_{V_{Rd}} = 0.12$
B500 steel rebars	69.62 (= 84 kg/m^3)	$UC_{M_{Rd,y+}} = 0.93$, $UC_{M_{Rd,y-}} = 0.36$, $UC_{M_{Rd,x+}} = 0.99$, $UC_{M_{Rd,x-}} = 0.89$,	$UC_{V_{Rd,y}} = 0.56$, $UC_{V_{Rd,x}} = 0.64$

With the designs validated an environmental costs indicator (ECI) value can be calculated. This is done with environmental product declarations (EPD's) obtained from the companies that produced/delivered the materials used in the concrete mixtures and the different reinforcement types. In these EPD's it is listed what impact the use/production of a building material has on the environment. This is distinguished in different impact categories. In the European norm NEN-EN 15804+A2, 19 impact categories are presented from which 11 are monetarized. These 11 impact categories are the ones used in this research. The most well-known is Global Warming Potential which is unitized in equivalent kg CO_2 emission which has a monetarized value of 0.05 euro/kg. This monetarization holds that for a certain amount of material (in this research a kilogram or one standardized apron) an amount of money is set to compensate for this environmental pollution. This research takes into account the life cycle of the end product, where production and end-of-life are taken into the calculation. In figure A.3 this coincides with modules A1-A3, C1-C4 and D, where modules A1-A3 represent product stage, C1-C4 represents the end of life stage and module D represents Benefits and loads beyond the system boundary (Reuse, recovery, recycling, potential).

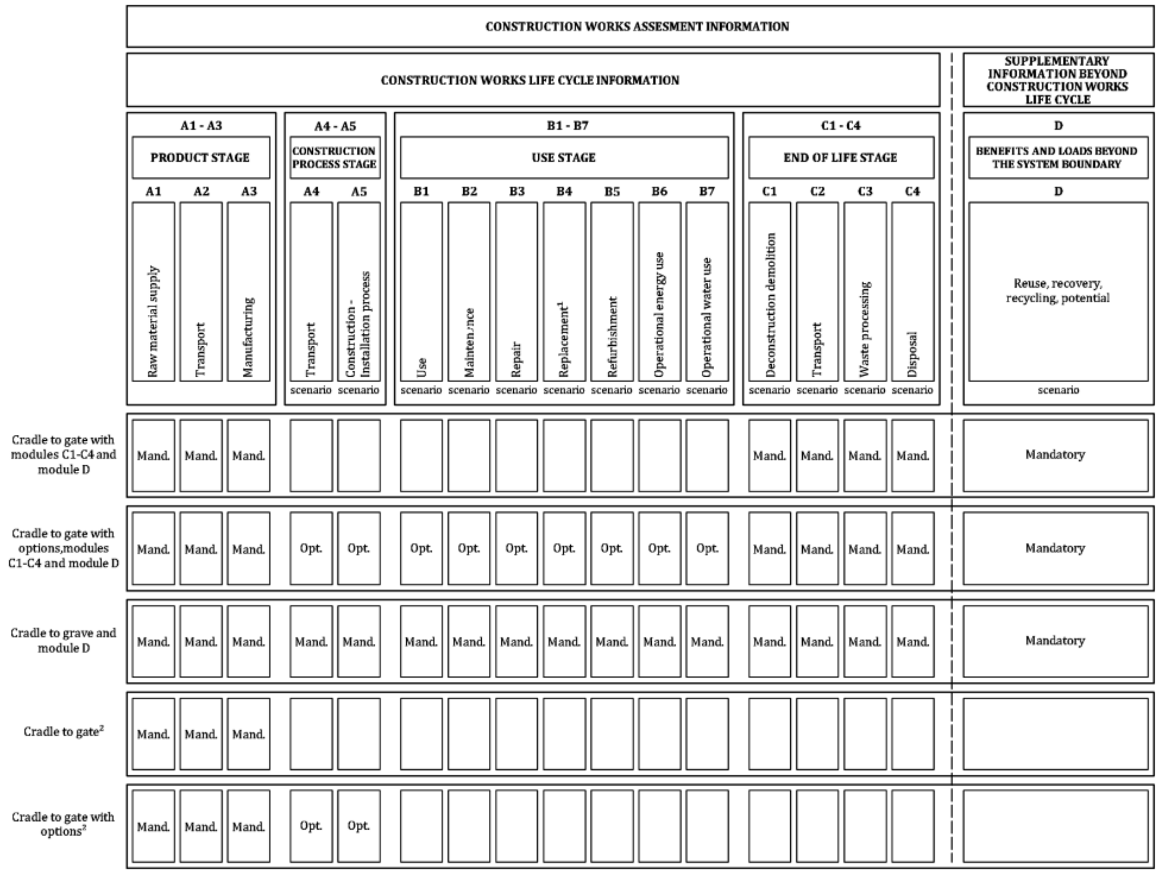


Figure A.3: Types of EPD with respect to life cycle stages covered and life cycle stages and modules for the construction works assessment (NENd, 2019)

For this research the values used for the different reinforcement types can be summarized in table … In this table values in euro/kg material used are given for each module separately and a total value for all modules together.

Table A.3: ECI values for a kilogram of reinforcement material

Module	Basalt reinforcement (Minibars & BasBars)	Dramix 5D steel fibres	B500 steel rebars
A1-A3	0.3659	0.1978	0.1628
C1-C4	0.0033	0.0008	0.0008
D	-0.0005	-0.0187	-0.0187
Total (A-D)	0.3687	0.1798	0.1445

When looking at these values it is clear that the basalt reinforcement has double the environmental impact compared to the steel fibres and an even higher ratio compared to the steel rebars. When looking at the total picture the materials are more in balance. When taking the results for the designs and the amounts of material used there, it can be seen that for the designs with basalt reinforcement a lower mass of reinforcement is required which compensates for the higher impact. Next to that, the product discussed in this research (the quay wall apron) is placed in a water environment. This has consequences for the design life span of the designs presented. For the designs with steel reinforcement the design lifespan is 50 years. The life-span is limited due to risk of corrosion. For the designs with basalt reinforcement corrosion is not a risk and therefore the design life-span of these designs can be set to 100 years. When looking at the environmental impact over the entire life-span the results of the ECI calculation can be divided over the years, leading to another advantage for the basalt reinforced designs. Table A.4 shows the different outcomes for all designs. For the comparison also values are presented in case the designs with basalt reinforcement would have a life-span of 50 years.

Table A.4: ECI values for different designs

1 apron ECI / yr	**Traditional mixture (no fibres) 50 yrs**	**BasBars 50 yrs**	**BasBars 100 yrs**	**B500 Steel 50 yrs**	**30 (Minibars) 50 yrs**	**30 (Minibars) 100 yrs**	**45 (Dramix 5D) 50 yrs**
A1-A3	0.36	0.48	0.24	0.59	0.54	0.27	0.51
C1-C4	0.02	0.04	0.02	0.02	0.02	0.01	0.02
D	-0.08	-0.09	-0.05	-0.10	-0.08	-0.04	-0.09
Total	0.30	0.43	0.21	0.51	0.48	0.24	0.44

From this table it can be seen that the design with the BasBars provides the outcome with the lowest ECI-value with the design with the Minibars coming second. In terms of recyclability of the basalt material at the moment not a lot is sure yet. It is known that the thermal process to produce the products is one way and from used basalt reinforcement it is therefore not possible to make new reinforcement. With experiments it can be tested whether there is still some residual strength if directly reused as fibre reinforcement. This might prove to be a slight advantage over the BasBars as they cannot be reused if concrete is crushed and the bars are broken into smaller parts. With more research the basalt material might therefore even perform better than it does right now and might have better values in module D of the ECI calculation and it can therefore be concluded that both Basalt reinforced designs perform better and to answer the research question, the design of the prefab quay wall apron can indeed be optimized in terms of environmental impact (ECI value) when Basalt Fibre Polymer (BFRP) bars and/or minibars are used instead of steel rebars and steel fibres whilst the structural performance remains guaranteed.

Table of contents

List of Figures

List of Tables

List of Abbreviations

BCF	Basalt Continues Fibre
BFRP	Basalt Fibre Reinforced Polymer
CMOD	Crack Mouth Opening Displacement
ECI	Environmental Cost Indicator
EPD	Environmental Product Declaration
IPK	Innovatief Partnerschap Kademuren
LCA	Life Cycle Assessment
LOP	Limit of Proportionality
SLS	Serviceability Limit State
ULS	Ultimate Limit State
ADnf	Abiotic Depletion Potential non-fuel
ADf	Abiotic Depletion Potential fossil-fuel
GWP	Global Warming Potential
ODP	Ozone Layer Depletion Potential
POCP	Photochemical Oxidation Potential
AP	Acidification Potential
EP	Eutrophication Potential
HT	Human Toxicity
FAETP	Ecotoxicity Potential, Fresh water
MAETP	Ecotoxicity Potential, Marine water
TETP	Ecotoxicity Potential, Terrestrial environment
WDP	Water Depletion Potential

1 Introduction

This chapter contains the description of the research project. First through some background information more insight is given in the current problem and to have a better understanding of the research significance. Next the research scope states the content which is covered during the research. Then the aim of the research contains the formulations of main research question as well as the sub-questions to answer this main research question. The methodology elaborates on the structure of the thesis. Finally the content of each chapter is described in the outline of the report.

1.1 Background

One of the most important challenges of our current generation is to reduce the emission of CO_2. Within the construction industry this is a trending topic. With an increase in demand of buildings or other constructions, the demand of building materials keeps increasing as well. Besides these depletion of the natural resources, the use of raw materials also has a big impact on the environment as it considerably contributes to the CO_2 emission and the energy consumption. To overcome material depletion and reduce the impact on the environment it is key for our generation to move to a more sustainable and preferably circular building industry.

1.1.1 The need for reinforcement in concrete

Concrete is the most used building material in the current building industry. The company Rutte Groep is currently developing concrete consisting of purely recycled aggregates and additives, which have been cleaned and separated to an extend to where they can be considered the same as new material. This separation process is done with a so called Smart Liberator. This process provides a huge step towards making the concrete industry circular and have less polluting impact on the environment. The research on this topic is currently at a microscopic level where CO_2 can even be captured in quantities leading to a product that has a negative CO_2 value. The resulting product is essentially not different to normal concrete and thus holds the same material properties. The main benefits of concrete lie in the compressive strength of the material. The tensile capacity however is significantly lower and to fully benefit from the compressive capacity of the material reinforcement is often used to increase the tensile strength of the resulting composite material used in an element of a building like a beam or column.

Currently steel is the most used material to act as reinforcement in concrete. When moving towards a circular concrete building industry the reinforcement has to be taken into account. The use of steel requires lots of energy to transform the raw material into reinforcement. Another type of reinforcement producing a significantly lower impact on the environment is therefore interesting for innovative companies which already use recycled/reused concrete.

1.2 Research scope

In this project a research will be conducted for the company Rutte Groep under the guidance of Rene Rutte. The company is currently developing concrete consisting of purely recycled aggregates and additives, which have been cleaned and separated to an extend to where they can be considered the same as new material. This separation process is done with a so called Smart Liberator/Crusher. This process provides a huge step towards making the concrete industry circular and have less polluting impact on the environment. The research on this topic is currently at a microscopic level where CO2 can even be captured in quantities leading to a product that has a negative CO2 value. However the use of steel as reinforcement bars takes of a little from the “environmentally friendly” concrete. Therefore the company is interested in research into Basalt Fibre Reinforced Polymer (BFRP) bars and regular minibars as reinforcement. From already conducted researches it is said that BFRP bars yield a lower environmental impact compared to steel rebars. From research it is also shown that “basalt fibre reinforced polymer bars exhibit suitable resistance in aggressive environments, a density of about only one-third of that of steel, a tensile strength of about two to three times of that of steel, and a thermal expansion coefficient close to that of concrete” (Wang, Wang, Li, Liu, & Li, 2021). These positive points also hold for the minibars in comparison with steel fibres. Yet next to these properties there is also research done concerning lower bond slip and ultimate bond strengths of BFRP bars compared to steel rebars (Wang, Wang, Li, Liu, & Li, 2021). This research however does concern other types of BFRP bars which are coated with a sand layer to provide the bond strength. The experiments that are conducted for this thesis project are done with materials from the supplier ReforceTech from Norway. The BFRP bars which this company produces have a bond strength which is slightly higher compared to steel rebars. In general for these BFRP bars the same design rules with respect to anchorage length can be used. The research of (Mohamed, Hawat, & Keshawarz, 2021) also shares concerns about the variation in properties for batches from manufacturers. Compared to steel the properties tend to be inhomogeneous. Research of (Banibayat & Patnaik, 2014) refutes the stated concerns, but researching the properties is still important therefore experiments to be performed for this thesis are done in sufficient quantity.

At the moment Rutte Groep is involved in a project concerning the replacement and reinforcement of quay walls in the canals of Amsterdam. The designs that they have available at the moment are made with steel reinforcement. For a project at the Boomsloot there are two designs, one for both sides of the canal. The reinforcement of the first variant consists of a double reinforcement mesh. The second variant is optimized and only has a single reinforcement mesh. The third variant is applied at the Singel in Amsterdam and the reinforcement of this variant purely consists of steel fibres. The thickness of this last variant has also been brought back from 150 mm to 100 mm and instead of an L shaped quay it is a straight wall attached on the sides instead of at the top. All of these variants are produced as prefab quay wall aprons as shown in figures 1 and 2.

Figure 1.1: Prefab quay wall apron with steel rebars

1.3 Aim of the research

As mentioned before, BFRP-bars and minibars have the potential to replace steel reinforcement. On the topic of the design of basalt reinforced structures few studies are available. Most studies focus on the testing of the materials. These studies however cannot directly be compared to the current research as minibars and bars from other suppliers/manufacturers are used. In this research the aim is to evaluate the fibres and bars from one supplier to see if they can offer a potential type of reinforcement to replace steel in structural design projects. This is done throughout a design project as mentioned before where a design of a quay wall apron is acting as a test project to see if the basalt reinforcement does indeed provide a possible replacement for steel reinforcement.

This study therefore aims to answer the following research question.

"Can the design of the prefab quay wall aprons be optimised in terms of environmental impact (ECI value) when Basalt Fibre Reinforced Polymer (BFRP) bars and/or minibars are used instead of steel rebars and steel fibres whilst the structural performance remains guaranteed?"

The ideal outcome is be a prefab element that meets all strength and dimension criteria and provides a better environmental performance compared to the old designs. This research leads to two new designs for the quay wall aprons. The first is a design with only minibars as reinforcement and the second design has a single reinforcement mesh consisting of BFRP bars. In a potential follow-up research a combination of bars and fibres can be investigated to see if this could lead to a further optimization. For now the design is not part of the study, however a setup has been made and a few experiments have been conducted on samples with a combination of minibars and BFRP bars.

1.3.1 Sub-questions

To answer the research question and come to the new designs the following sub-questions will be answered throughout the report for each question some known background information and assumptions are already presented in this chapter. Together these 5 sub-questions lead to answering the main research question presented above.

1) What material properties from the new reinforcement types are needed for the design of the quay wall aprons and which experiments have to be performed to obtain these properties?

With the right properties concerning the minibars and BFRP bars obtained, a new design can be made. In the case of the design with the minibars it is important to obtain an optimal amount of fibres in terms of kg fibres /m^3 which represents a comparable capacity to the amount of steel fibres in the design by ABT. An important note here is that due to the lower self-weight of the minibars the relation to the steel fibres will not be 1:1. This means that for a similar mass of fibres 5 times more fibres are present in case of minibars. The expectation is that due to the increased strength a lower mass of minibars is required with a slightly higher volume to the otherwise used steel fibres.

2) In the case of the design with minibars, what is the optimal amount of fibres to be added in the concrete mixture to obtain comparable strength results to the current steel fibre design?

The design with steel fibres is made by Niek Pouwels from ABT. In this design an optimization is found in the amount of fibres to ensure sufficient strength and workability. This process can be repeated with minibars. To obtain this new design the results from the experiments are needed to provide the correct material properties for concrete with minibars. Strength properties that have to be found are the tensile strength of the concrete with fibres, the compressive strength and the flexural tensile strength. These properties are tested on both cubes and small beams.

3) In the case of the design with the reinforcement mesh, what is the optimal distribution and size of BFRP bars to obtain a design that satisfies the strength and durability requirements.

The design with steel rebars is made by Frank Loeffen from the company Van Der Werf en Lankhorst. The report (Ingenieursburo Van Der Werf En Lankhorst, 2021) shows calculations for the steel variant. In this design an optimization is found in the distribution and size of the rebars based on the prestation characteristics of the steel. This process can be repeated with the basalt rebars. Concerning the durability requirements the allowable crack width has to be re-examined as the situations is more favourable since the steel is replaced with a non-corroding material (basalt). It has to be examined to which extend the allowable crack width can be increased without causing additional problems, this is not part of this research. Only simple designs are produced. In this research it is assumed that with the basalt reinforcement bigger crack-widths are allowed and that these are not exceeded.

4) What methods are applied to verify the new designs?

Which experiments have been performed to test the steel reinforced quay wall designs and how can these experiments be performed on the basalt reinforced designs in order to verify functional performance requirements of the designs?

By performing the same experiments on the new designs with basalt reinforcement a direct comparison can be made with the results from previously performed experiments on the designs with steel reinforcement. However the design with steel fibres has not been produced yet and therefore no experiments have been conducted on a small/full scale mock-up. With a small scale mock-up both the steel fibre mixture is tested as well as the minibar mixture. The main focus here lies with the workability of the mixtures and how they flow through the gaps between the bricks.

5) After obtaining new designs which are verified and comparable to the steel reinforced designs in terms of strength, what is the difference in Environmental Cost Indicator (ECI) value?

By performing a Life Cycle Assessment (LCA) calculation on the designs with steel reinforcement and on the new designs, a comparison can be made between the two types of reinforcement to see whether the basalt reinforced aprons are indeed performing better in terms of environmental impact. In this part of the research it is important that not only the production of the reinforcement is taken into account, but the entire mixture is analysed for differences. Expected lifetime and reuse potential are important as well in this section.

1.4 Methodology

This research is divided into three parts, a literature review, experimental research and a conclusion. Together these parts provide the necessary information to answer the research question.

Part I: Literature Review

In part I, the relevant topics for the thesis are explained. Insight in the basalt products are presented by a literature study and additionally the existing designs with steel reinforcement are elaborated. Important in preparation for the experimental research, are the relevant material properties that are required for the calculations in the design phase. In this part also the design criteria are presented. These are taken from the ABT design with the Dramix 5D steel fibres.

Part II: Experimental Research

In part II, the material properties of the basalt and steel reinforcement are studied experimentally. This experimental research consists of multiple parts. For the first part assumptions are made for the materials amounts that are used, these are based on previously obtained information. The next part of the experimental research consists of performing tests and analysing the results. In an iterative process with different test sessions, the end results lead to the properties used for the two designs. Between each test session theories and expectations of the results are compared with observations. This process can be described as the “Wheel of Science” (Palys & Atchison, 2014).

The last part of the experimental research compares the resulting designs in terms of Environmental Costs Indicator (ECI). This part combines the literature study with experimental results to form one of the most important factors to determine whether the basalt material would be a right replacement for steel reinforcement. The assumptions and hypothesis this research is based on, are tested in this part of the research.

Part III: Conclusions

In this last part of the research. The results of the experimental study and the ECI calculation are used to answer the research question. With a final conclusion leading to the answer of the main research question, recommendations are given with respect to the future of basalt reinforcement and possible follow-up research.

1.5 Outline

Part I: Literature Review

Chapter 2 presents an overview of all the information about the basalt reinforcement delivered by ReforceTech. It describes the production process of the different products that are used in this research and it shows the data that is known concerning environmental impact. The current steel reinforced designs are fully elaborated in chapter 3. Here the complete design is given including the loads acting on the quay wall aprons. This chapter gives an insight in how the basalt reinforced designs are taking shape. As for the basalt, in chapter 3 the data about environmental impact are presented at the end. Chapter 4 uses the information about the designs in chapter 3 to present the different material properties that are needed for the minibars and the BasBars. This chapter also indicates the different experiments that are conducted to obtain these properties that are requested for later calculations.

Part II: Experimental Research

In chapter 5 first the concrete mixture that is used for the research is given. An elaboration is given on how the mixture changes when fibres are added and fibre amounts are changed. Then the different test procedures conducted in the research are presented. Chapter 6 gives the results of these tests per test session and gives comments on the process after testing to determine the contents of the next test session. This process is done per test for the relevant tests. The end results are then used in chapter 7 where all previous information is put together to make two designs. First the design with the minibars is presented and secondly the design with the BasBars. Finally in chapter 8 the steel reinforced designs from chapter 3 are compared with the designs from chapter 7 in terms of material use and environmental impact. This is done via a Life Cycle Assessment presented in the form of a Environmental Cost Indicator (ECI) calculation.

Part III: Conclusions

Chapter 9 is a summary of the conclusions obtained from the research. In this chapter the research question is answered. To arrive to this answer the sub-questions from chapter 1.3 are answered. Finally in the recommendations section potential follow-up research is discussed.

Part I
Literature Review

2 Basalt

The basalt minibars and basalt fibre reinforced polymer rebars (BasBars) are both made from the same material, namely so called basalt continuous fibre (BCF) (Jamshaid & Mishra, 2016). Minibars can be divided into two groups: Discrete fibres known as basalt fine fibres (examples are mineral insulting wool and staple fibre) and the above mentioned continuous fibres. Even though the production process of the short length minibars is cheap and simple as it can directly be produced from the crushed basalt stones, the resulting mechanical properties are poor and uneven. Therefore the continues minibars are used for the production of the reinforcement used in this research. The basalt itself is a raw material that can be found in volcanic rocks that are originated from frozen lava. ReforceTech obtains the basalt rocks from Russia, China and the USA. and in the factory it is crushed before the production process starts (Mohamed, Hawat, & Keshawarz, 2021). This chapter gives an insight in the production process and in the benefits of the material. At the end the information about the environmental impact is presented to later be used in chapter 8, where an ECI value is calculated for the end products (quay wall aprons with different reinforcement designs).

2.1 Production process

The production process of the minibars is similar to that of glass. It does not require additives and also less energy is consumed in the process, therefore it is cheaper than glass or carbon fibres. The production process of the fibres consists of 3 steps:

1) Melting the raw material in a furnace at 1450-1500 degrees
2) Forcing the material through platinum/rhodium crucible bushings to obtain fibres
3) Spinning the material into basalt fiber coils named bobbins

The resulting coils with thin minibars can then be used to obtain either the minibars or the BFRP bars.

The minibars are obtained by combining the fibres until the required thickness of 0.7 mm is achieved. After this the minibars (which are still long) are given a tough venylester resin in ReforceTech's patented process to create the resulting minibars. The last step is to cut the minibars to the required length (43 mm in this case) (ReforceTecha, 2021) (ReforceTechb, 2021).

The process for the BFRP bars is similar but with different bar thicknesses. The so called BasBars can be supplied in coils and cut on sight with regular tools. Bends are also possible, but the bars must be formed to shape in the ReforceTech factory. Some shape codes are standard and others can be made available on request. This makes is possible to get stirrup reinforcement as well in case of designing a beam with required shear reinforcement. It is also possible to obtain angles for anchorage.

2.2 Benefits of basalt reinforcement from ReforceTech

Some of the benefits listed by ReforceTech are presented here. Some are important to check in combination with the steel designs as they might indeed proof more beneficial or not.

- The BasBars and the Minibars have zero corrosion/ are non-conductive and make way for a non-magnetic manufacturing plant or construction site.
- A reduced concrete cover layer enables less concrete weight and lighter structures
- As for steel it can be used as pre- and post-tensioning material
- It has a longer lifetime expectancy and thus lower life cycle costs
- The material does not result in additional water demands (same holds for steel)
- The material is significantly lighter compared to steel resulting in easy handling

When looking at these benefits the most important pro is the non-corrosive nature. This makes for easy applications in wet conditions (constructions near or in water for example).

The given benefit of a non-magnetic manufacturing plant/construction site does also bring a negative. As the material is non-magnetic, removing it from concrete waste is more difficult.

2.3 Environmental impact

To obtain an insight in the environmental impact of the materials that are used in this research so called Environmental Product Declarations (EPDs) are. The values obtained can be used to put a monetary value to this environmental impact (Environmental Cost Indicator ECI). In this chapter the values for the basalt reinforcement are presented. In chapter 8 these values are used to make a comparison with the other designs. In chapter 8 also the whole process is explained as to how the values are used and which lifecycle parts of the material are taken into account.

Table 2.1 shows the different life cycle stages of the material that are taken into account in this research according to the European standard NEN-EN 15804 + A2 (NENd, 2019) and the corresponding ECI value for a kilogram of basalt material (BasBars/Minibars) as provided by ReforceTech and Ecochain (Baltussen, 2022).

Table 2.1: ECI values for basalt reinforcement

Life stage	ECI Basalt $[€/kg]$
A1 (Raw material supply)	0.3301
A2 (Transport)	0.0237
A3 (Manufacturing)	0.0121
A1-A3 (Product stage)	0.3659
C1 (Deconstruction demolition)	0.0032
C2 (Transport)	0.0000
C3 (Waste processing)	0.0001
C4 (Disposal)	0.0000
C1-C4 (End of life stage)	0.0033
D (Benefits and loads beyond the system boundary) (Reuse, recovery, recycling, potential)	-0.0005
Total (A-D) (Cradle to gate with modules C1-C4 and D)	0.3687

As can be seen the total ECI value (also known as shadow costs) for a kilogram of basalt product is equal to 0.37 euros. In chapter 3.5 the ECI values for steel reinforcements are given. In chapter 8 these are used together with the values for the concrete mixtures. It can also be seen that there is little to no rest value in Module D, whereas steel can be remelted and used to make new reinforcement.

2.4 Other research with interesting findings

To recall some earlier presented concerns and findings from other researches about basalt reinforcement the following was said:

From already conducted researches it is said that BFRP bars yield a lower environmental impact compared to steel rebars. From research it is also shown that “basalt fibre reinforced polymer bars exhibit suitable resistance in aggressive environments, a density of about only one-third of that of steel, a tensile strength of about two to three times of that of steel, and a thermal expansion coefficient close to that of concrete” (Wang, Wang, Li, Liu, & Li, 2021). These positive points also hold for the minibars in comparison with steel fibres. Yet next to these properties there is also research done concerning lower bond slip and ultimate bond strengths of BFRP bars compared to steel rebars (Wang, Wang, Li, Liu, & Li, 2021). This research however does concern other types of BFRP bars which are coated with a sand layer to provide the bond strength. The experiments that are conducted for this thesis project are done with materials from the supplier ReforceTech from Norway. The BFRP bars which this company produces have a bond strength which is slightly higher compared to steel rebars. In general for these BFRP bars the same design rules with respect to anchorage length can be used. The research of (Mohamed, Hawat, & Keshawarz, 2021) also shares concerns about the variation in properties for batches from manufacturers. Compared to steel the properties tend to be inhomogeneous. Research of (Banibayat & Patnaik, 2014) refutes the stated concerns, but researching the properties is still important therefore experiments to be performed for this thesis are going to be done in sufficient quantity.

The main things to take from these notes for the current research are the parts about the bonding properties, the environmental impact, the corrosion resistance and the lower density. The most important thing to note is that due to different production processes of the basalt reinforcement no clear conclusions can be drawn from those works and therefore as mentioned experiments and calculations need to be performed for the different points mentioned. The bonding properties cannot be directly measured from tests as the right type of equipment is not available for this research. Calculations in this area therefore rest on the given properties as presented by ReforceTech stating that the bond strength is slightly stronger compared to regular steel rebars. This increased bond strength comes from removing sand from the production process and the product itself. Before the bond strength was provided by vinyl ester holding the sand particles. Regarding the inhomogeneous properties the expectations are that with the current batches of reinforcement from ReforceTech this is not a concern as they provided the right certificates to confirm the properties of the reinforcement. The lower density is confirmed and does have an effect on the results in this research. As later shown the lower density results in both pros and cons as the reduced mass gives better environmental performance but also makes for more difficult production as the rebars have a lower density compared to concrete.

3 Design for steel fibre reinforced quay wall aprons

The design criteria follow from ABT. The design report from ABT (Pouwels, 2021) contains the design for the steel fibre reinforced aprons. It provides the design dimensions and location and the given loads and corresponding load factors. These design criteria are the same for the design with the basalt reinforcement.

3.1 Dimensions and design criteria

This information is directly copied from (Pouwels, 2021) chapter 2 ("Dimensies en locatie") seeing as the same design will be used but now the minibars are replacing the steel fibres in the concrete.

In this research the focus lies on the general straight quay wall aprons with a height of 1.22 m. Closer to bridges, the height goes up to 2.55 m. In figure 2 a side view of the general design is shown including the water level and the different elements. This general straight design (the other parts will vary in height from one side of the panel to the other) is applied over 130 m of the total 208 m.

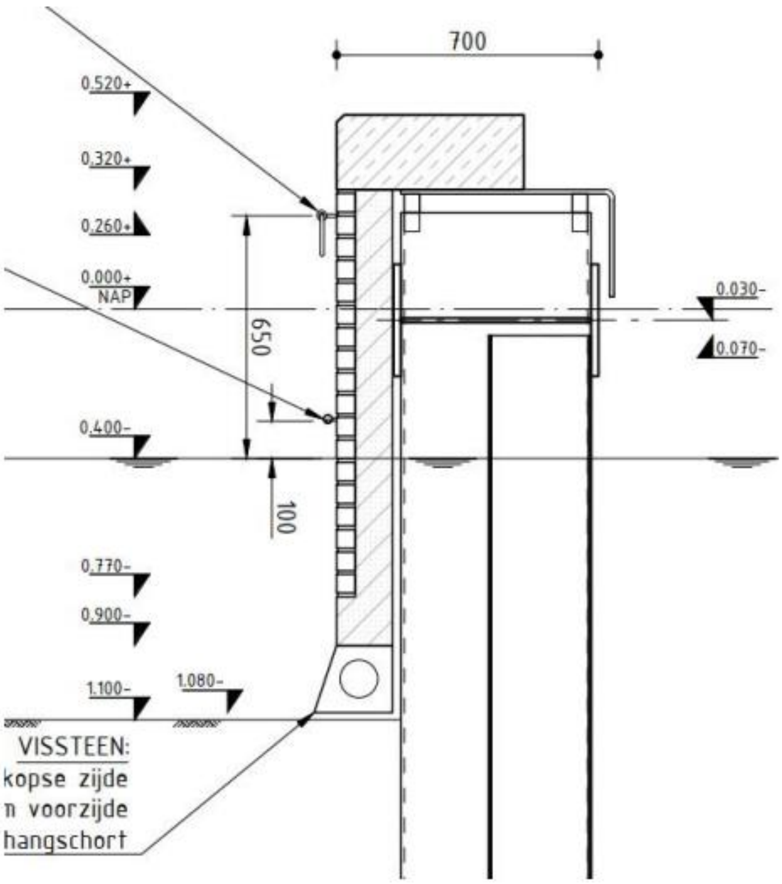


Figure 3.1: Side view of quay wall apron design with steel fibres (Pouwels, 2021)

Dimensions that are not present in figure 2 are the width of the aprons which is 3.25 m, the thickness of the concrete layer behind the bricks which is 100 mm and the thickness of the bricks which is 50 mm.

Figure 3.1 also shows a so called Fish-stone (vissteen) which is placed on the bottom of the apron to provide shelter for small fish.

3.2 Loads

Again the design loads are directly copied from (Pouwels, 2021) chapter 3 ("Belastingen") and chapter 4 ("Belastingfactoren").

3.2.1 Self-weight

According to NEN-EN 1991-1-1 Annex A the following volumetric weights are used.

Steel fibre reinforced concrete: 25,0 kN/m^3

Masonry: 18,0 kN/m^3

Steel: 78,5 kN/m^3

Note that minibar reinforced concrete is lighter compared to steel fibre reinforced concrete. Exact values have to be determined.

The self-weight of the fish-stones is: 0,75 kN/m

3.2.2 Wind-load

Due to the location of the quay wall (In Amsterdam wind-zone II according to NEN-EN 1991-1-4. The extreme water pressure on the aprons follows from NEN-EN 1991-1-4 table NB.5:

q_p = 0.58 kN/m^2

3.2.3 Mooring forces/loads

Following from the functional requirements, every 5 m a mooring ring should be placed able to carry 40,0 kN both perpendicular as parallel to the quay wall.

3.2.4 Collision loads

A collision load of 50 kN can be assumed spread over an area of b = 0,5 m and h = 1,0 m. This force is applied on an arbitrary location above the waterline. Figure 3.2 shows the governing locations for this collision load.

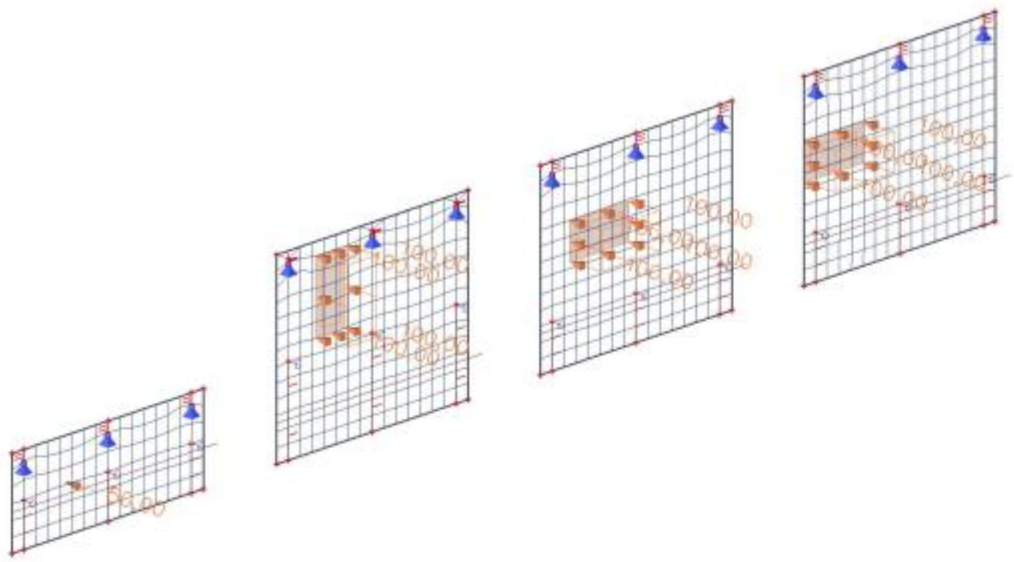


Figure 3.2: Governing locations of collision load

3.2.5 Load factors

The consequence class according to NEN-EN 1990 Table B1 is CC1. The corresponding design lifespan is 50 years. The following partial load factors are adhered to:

Permanent loads (unfavourable): $\gamma_{G,sup}$ = 1,1

Permanent loads (favourable): $\gamma_{G,inf}$ = 0,9

Variable loads: γ_Q = 1,35

3.2.6 Criteria and loads for BFRP bars

In a design with BFRP bars the variable loads will not change, the self-weight of the construction might change slightly so those changes must be determined to see whether that would change the design criteria. The dimensions and general design layout will not change either.

3.3 Design Moments and Forces

The design moments and forces follow the model from Niek Pouwels from ABT (Pouwels, 2021) and van der Werf en Lankhorst (Ingenieursburo Van Der Werf En Lankhorst, 2021).

3.3.1 Design Moments

The resulting design moments can be found from the SCIA-Engineer model. For the x direction (M_{xD_+}) this moment is found in the design for a low apron (height of 1220 mm). The critical moment distribution in x direction is shown in figure 3.3, however the dimensions that are used in the designs in this thesis are different. In this thesis the high aprons are used resulting in a different (lower) moment in x direction as can be seen in figure 3.4. For the y direction (M_{yD_+}) the maximum moment occurs in the high apron (height of 2550 mm) this is shown in figure 3.5. As can be seen from this figure 3 possible locations for the collision load are presented. The situation where the impact is applied on the left side, in the middle of the apron, is governing. The resulting moments are given:

$$M_{xD_+} = M_{Ed,x_+} = 8.00\ kNm/m$$

$$M_{yD_+} = M_{Ed,y_+} = 14.96\ kNm/m$$

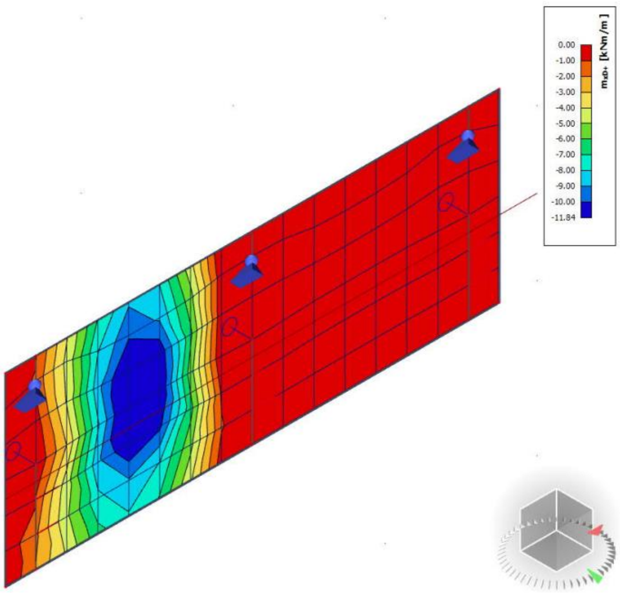


Figure 3.3: Moment distribution in x direction for apron with height = 1220 mm (Pouwels, 2021)

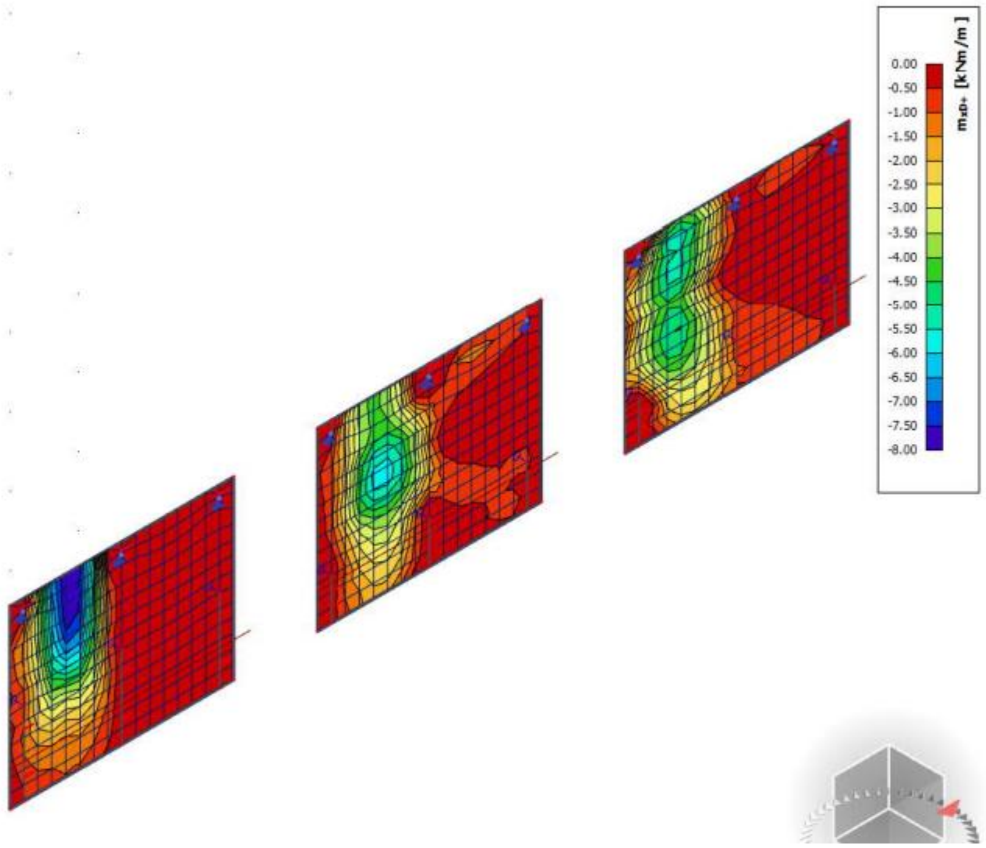


Figure 3.4: Moment distribution in x direction for apron with height = 2550 mm (Pouwels, 2021)

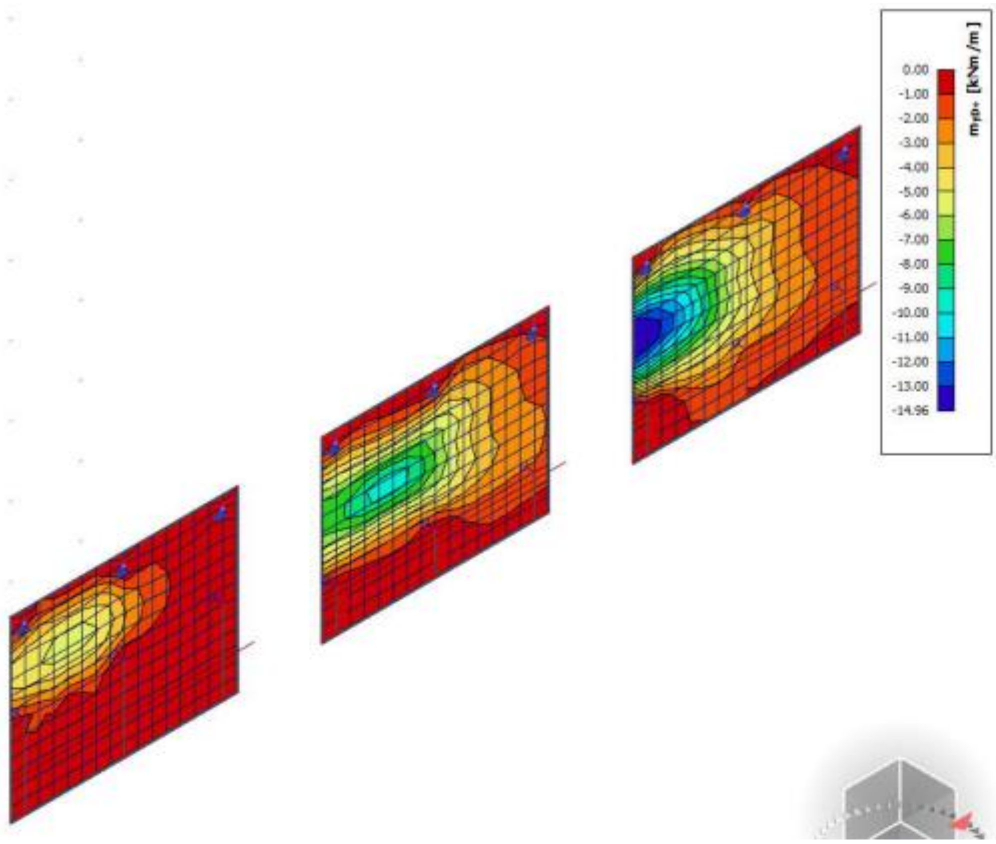


Figure 3.5: Moment distribution in y direction for apron with height = 2550 mm (Pouwels, 2021)

Applying this collision load also leads to an $M_{yD\_}$ & $M_{xD\_}$. These values are:

$$M_{xD\_} = M_{Ed,x\_} = 7.81\ kNm/m$$

$$M_{yD\_} = M_{Ed,y\_} = 4.73\ kNm/m$$

Combination of moment and normal force

Due to the self-weight the plate is subject to a tensile force in plane of loading. This tensile force interacts with the design moments and causes a shift in stresses. With the self-weight of the structure as described above, the tensile force at the location of the maximum moment is calculated by multiplying the self-weight of the different parts of the structure with the thickness of that layer and multiplying the total with the distance to the location of the maximum moment. Resulting in $N_{Ed} = (25 \cdot 0.1 + 18 \cdot 0.05) \cdot 1.505 + 0.75 = 5.867\ kN/m$ which is equal to a tensile stress of $\sigma_{tensile} = \frac{N}{A} = \frac{5.876}{1000 \cdot 100} = 0.05876\ MPa$. This is an insignificant stress which does not influence the design calculations.

3.3.2 Design Forces

The design shear forces follow from the calculations for the connections from van der Werf en Lankhorst (Ingenieursburo Van Der Werf En Lankhorst, 2021). At the location of the upper connections the governing shear force is found. The added value of the force in the bolts in the connections is taken as the design shear force. This is done in equation 3.1 and 3.2. The connection is shown in figure 3.6.

$$V_{Ed,SLS} = n_b F_{Ed,b} = 6 \cdot 2.767 = 16.60\ kN \qquad \text{(eq. 3.1)}$$

Where:

$n_b = 6 = number\ of\ bolts$

$F_{Ed,b} = 2.767\ kN = maximum\ force\ in\ one\ bolt$

This derived value of 16.60 kN is a value for the SLS situation. No values are given for ULS, therefore it is assumed that this SLS load is 70% of the ULS load as 70% is usually taken in the Eurocodes when determining SLS deflections. This results in the following $V_{Ed,ULS}$:

$$V_{Ed,ULS} = \frac{V_{Ed,SLS}}{0.70} = 23.72\ kN \qquad \text{(eq. 3.2)}$$

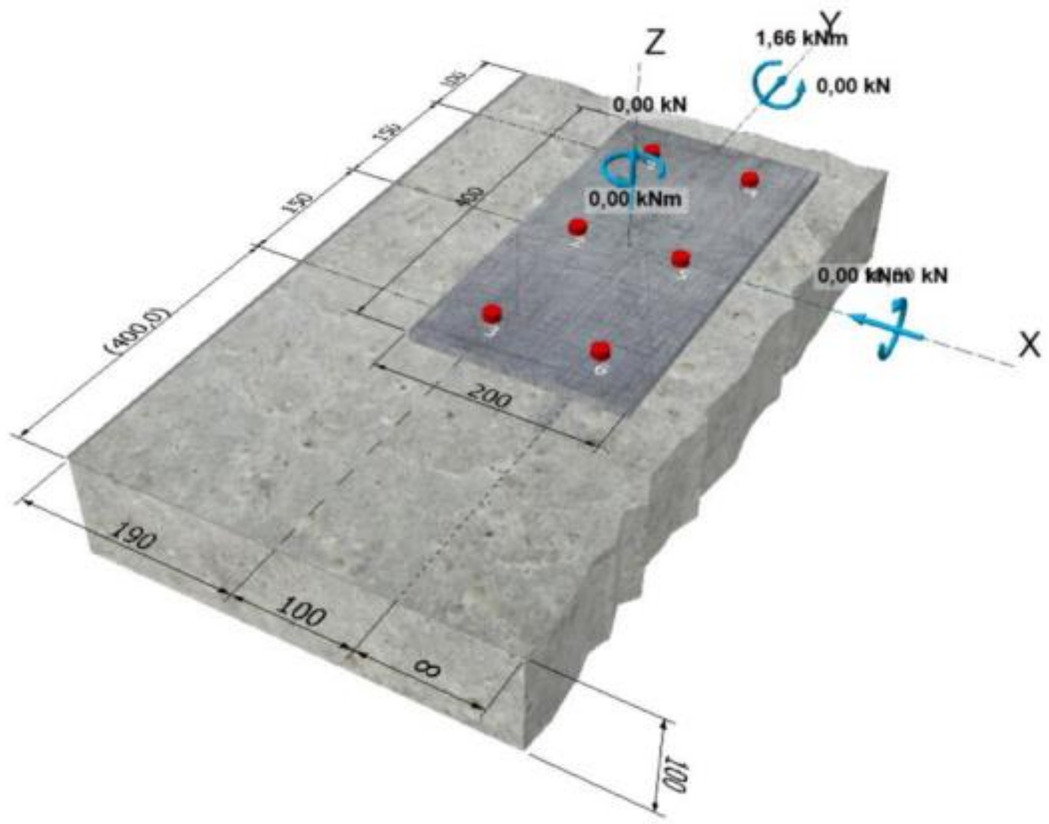


Figure 3.6: Visualisation of support plate at upper supports with circumference of 1200 mm (Ingenieursburo Van Der Werf En Lankhorst, 2021)

Note that this design shear force is located at the supports and the calculations for the supports are beyond the scope of this research and are provided by Van Der Werf En Lankhorst.

The collision load that is present is however taken into account and a punching shear check is performed with this load. The load is equal to 50 kN and is spread over an area of 500x1000 mm^2 as presented by (Pouwels, 2021).

3.4 Current Reinforcement Design

There are two designs for the steel reinforced aprons. The first design contains the Dramix 5D steel fibres and the second contains B500 steel rebars. Both designs are elaborated in terms of material use and in the design with the rebars the design layout is presented as well.

3.4.1 Steel fibre reinforced design (Dramix 5D steel fibres)

At the moment the steel fibre reinforced design is still theoretical meaning that awaiting the results from the experiments in this research the design can be completed. From the design obtained from Niek Pouwels from ABT (Pouwels, 2021) it can be derived that for the project different sizes of the aprons are requested. The width is constant but the height may vary dependant on the location. In this research the dimensions presented in figure 3.7 are used for all calculations and designs. To make sure the design is sufficient for all different dimensions the maximum obtained moments as mentioned in chapter 3.3.1 are taken, this also holds for the design with the rebars.

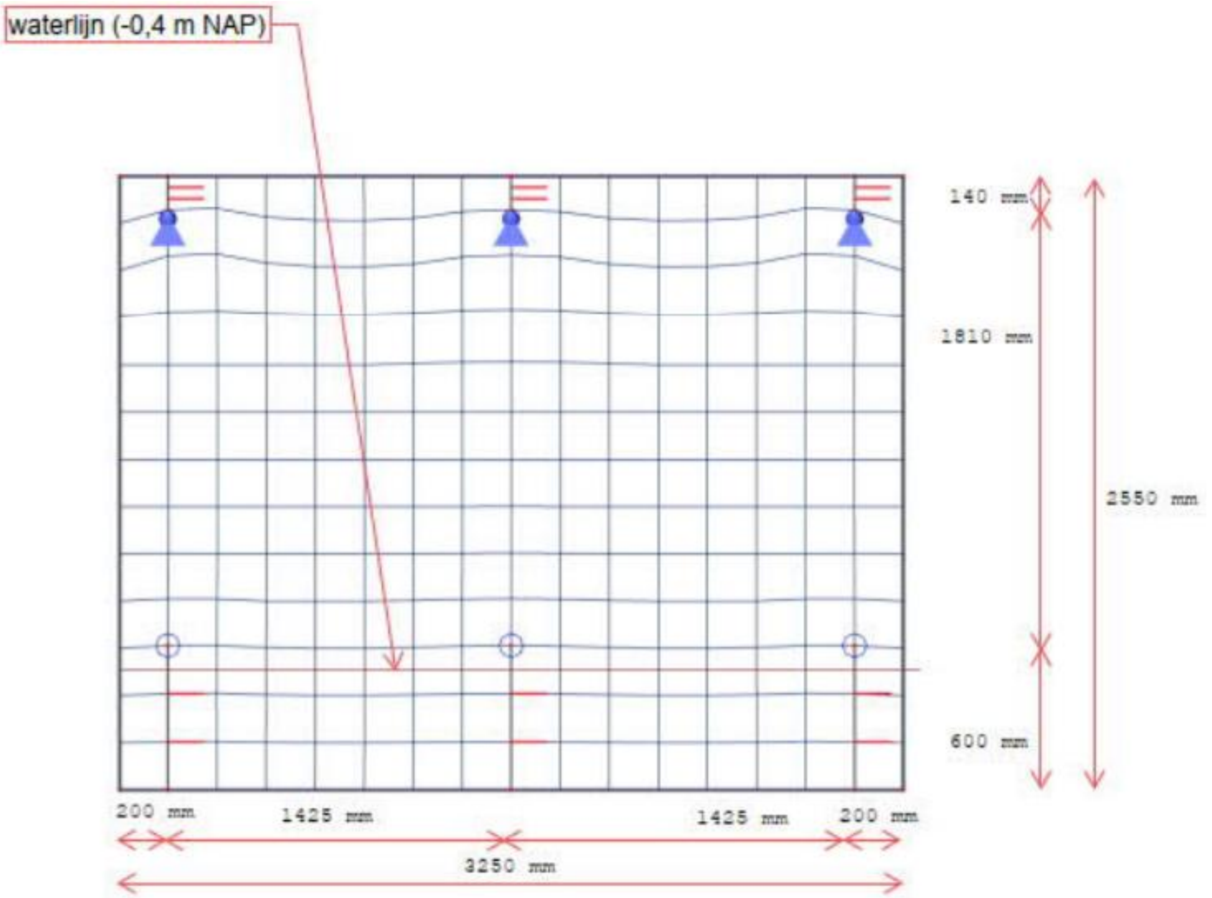


Figure 3.7: Dimensions and layout standard apron with height = 2550 mm and Dramix 5D fibres (Pouwels, 2021)

The dimensions of the plate are summarized in table 3.1. There are two thicknesses given. One for the thickness of the end product. This is 150 mm and includes the bricks that are poured with the concrete. The other thickness is that of the concrete layer on top of the bricks, which is 100 mm. The fibre amount that is mentioned in the design is the expected value which is 30-45 kg/m^3. For this research in first instance 45 kg/m3 is assumed.

Table 3.1: Dimensions and layout standard apron with height = 2550 mm and Dramix 5D fibres

Design	Width $[m]$	Height $[m]$	Thickness concrete $[m]$	Thickness total $[m]$	Volume concrete $[m^3]$	Fibre amount $[kg/m^3]$	Fibre amount apron $[kg]$
Dramix 5D steel fibres	3.25	2.55	0.10	0.15	0.83	45	37.3

3.4.2 Steel reinforced design (B500 steel rebars)

The design with steel rebars differs significantly from the design with the fibres. This is an old design which has been produced as seen in figure 1.1. The design had different locations for the supports. The aprons have a L shape where the bottom of the L is placed at the top acting as the support. Due to design restrictions (minimum concrete cover with regards to the steel rebars the thickness of the concrete layer is 150 mm compared to the 100 mm for the steel fibre design. The width and height also differ as the apron with a straight top edge has a height of 1.43 mm compared to the 2.55 m from the steel fibre design. This is due to the project being located elsewhere requiring less height. The dimensions and volumes are displayed in table 3.2. The different rebars that are used are presented in table 3.3. To give a better comparison the mass of steel per cube of concrete is also presented. As can already be seen this amount is more than three times as high compared to the 45 kg/m3 fibre design.

Table 3.2: Dimensions and layout standard apron with height = 2550 mm and steel rebars

Design	Width $[m]$	Height $[m]$	Thickness concrete $[m]$	Thickness total $[m]$	Volume concrete $[m^3]$	Volume steel $[m^3]$	Mass steel $[kg]$	Mass steel per cube $[kg/m^3]$
Steel Rebars (B500)	3.25	1.43	0.15	0.20	0.92	0.016	126.9	138.44

Table 3.3: Steel mass per bar diameter for one apron

Steel Rebar (B500) rebar diameter [mm]	Length $[m]$	Amount $[-]$	Volume $[m^3]$	Mass $[kg]$
8	3.2	19	0.0031	24.0
10	0.7	8	0.0004	3.5
16	1.8	35	0.0127	99.4

3.5 Environmental Impact

In table 3.4 the ECI values for the different types of steel reinforcement are presented. The values for the Dramix 5D steel fibres are obtained from the supplier (Piasecki, 2021) where values for the total of module A have been presented including values for Human Toxicity, and all Ecotoxicity impacts coming from the same supplier in a different document (Piasecki, 2022). These were not presented for module C and D. In chapter 8 when the different designs are compared to eachother this is held into account when coming to conclusions. For the steel rebars no representative values can be found from either supplier or manufacturer. Therefore for module A values have been taken from the course “CIE4100 Materials and Ecological Engineering” (Content page CIE4100 Materials and Ecological Engineering, 2020) presented by Prof. dr. H.M. Jonkers where values were presented for academic practise use. As this document does not provide values for module C and D, these values are assumed to be the same as for the Dramix 5D steel fibres.

Table 3.4: ECI values for steel reinforcement

Life stage	ECI Dramix 5D fibres $[€/kg]$	ECI Steel Rebars $[€/kg]$
A1 (Raw material supply)	nvt	nvt
A2 (Transport)	nvt	nvt
A3 (Manufacturing)	nvt	nvt
A1-A3 (Product stage)	0.1978	0.1628
C1 (Deconstruction demolition)	0.0002	0.0002
C2 (Transport)	0.0003	0.0003
C3 (Waste processing)	0.0001	0.0001
C4 (Disposal)	0.0002	0.0002
C1-C4 (End of life stage)	0.0008	0.0008
D (Benefits and loads beyond the system boundary) (Reuse, recovery, recycling, potential)	-0.0187	-0.0187
Total (A-D) (Cradle to gate with modules C1-C4 and D)	0.1798	0.1445

4 Material properties of the basalt reinforcement

To get a design using minibars or BFRP bars, it is important to categorise which material properties are needed for certain calculations. For both types of reinforcement different properties are required. All experiments in this research are performed at the company of Rutte Groep with their test-equipment and all basalt reinforcement is provided by ReforceTech from Norway.

4.1 Properties of minibar reinforced concrete

The technical characteristics that are already known regarding the Minibars are covered in table 4.1.

Table 4.1: Technical Characteristics of Basalt Minibars (ReforceTechb, 2021)

Material	Fibre Length	Fibre Diameter	Specific Gravity	Modulus of Elasticity	Tensile Strength
Basalt + thermoset resin	43 +/- 2 mm	0.70 mm	2.0 ± 0.1	42 GPa	> 1000 MPa

Other properties that are required for the design are dependent on the concrete and the fibre amount in kg/m^3. The properties that are required for the minibar reinforced are described here:

- The characteristic cube compressive strength $f_{ck,cube}$ $[MPa]$
  According to ReforceTech (the supplier of the materials), the characteristic cube compressive strength changes for different amounts of fibres added. For small amounts the strength is expected to increase and for bigger amounts the strength is expected to decrease from the original concrete strength class. The amount with which this strength changes is to be verified by performing compressive stress tests on cubes of 150x150x150 mm for as far as possible. Table 4.2 shows the different experiments including the quantities of each sample. This experiment will be executed according to the norm NEN-EN 12390-3 (NENb, 2019).
- The Elastic modulus E_{cm} $[MPa]$
  The elastic modulus of the concrete with the fibres can be obtained from the compression test of the cubes as well.
- The flexural tensile strength (limit or proportionality (LOP), residual) $f_{ct,L}^{f}$ $[MPa]$
  The flexural tensile strength can be determined with a CMOD (crack mouth opening displacement) test with a 3 point bending setup. For this experiment the samples will have a rectangular shape of 150x150x600 mm. This experiment will be executed according to the norm NEN-EN 14651 + A1 (NEN, 2007).
- The flow value f $[mm]$
  The flow value is obtained with a flow table test which will be executed according to NEN-EN 12350-5 (NENa, 2019). The flow value is important for the design of the quay wall, as the concrete has to be able to pour into the gaps between the bricks. A possible result when using a high dosage of fibres is that the concrete does not flow into the correct way (only the small parts of the mixture). For these flow tests an extra 10 L of each batch of concrete is needed. According to the supplier the workability should not be a problem. If it happens to be insufficient a solution would be to look at superplasticisers to improve workability.

Each experiment is repeated with different amounts of fibres. Different amounts of fibres are used for the tests as it is for this research it is unknown what the strength properties for certain mixtures are. The main focus lies around 15-55 kg fibres for a cubic metre of concrete. Tests are performed with 15, 20, 30 and 55 kg/m^3. The information about the different samples for each test is shown in the draft research proposal from ABT (ABT, 2022). Currently this proposal is being updated with the latest demands concerning the number of samples and the amounts of fibres for each sample. All experiments are performed with approximately 28 days strength concrete. Due to planning issues it is not always possible to test exactly 28 days after pouring the concrete.

Table 4.2: Experiments for minibar reinforced concrete

Experiment	Values obtained	Number of samples
Compressive strength tests	$f_{ck,cube}, E_{cm}$	52
3 point bending tests (CMOD)	$f^f_{ct,L}$	25
Flow table test	f	5
3/4 point bending tests	Cracking behaviour and capacity	4

Table 4.3: Experiments for steel fibre reinforced concrete

Experiment	Values obtained	Number of samples
Compressive strength tests	$f_{ck,cube}, E_{cm}$	10
3 point bending tests (CMOD)	$f^f_{ct,L}$	12
3/4 point bending tests	Cracking behaviour and capacity	4

4.2 Properties of BFRP bars

Part of this thesis project will also be a calculation for the amount of BFRP bars in the test samples for 3 and 4 point bending tests. The reason for this calculation is the capacity of the testing materials. The supplier of the testing equipment confirmed a capacity of 350 kN. Therefore with this calculation it can be determined whether the test bench is going to be able to apply enough pressure to enforce a failure mechanism on the samples. This calculation will be done based on the delivered properties of the BFRP bars by the supplier (ReforceTech). Figure 4.1 shows these properties for the different bar diameters. An interesting feature of the BFRP bars (referred to as “BasBars” by ReforceTech) is that the Tensile strength decreases with the bar diameter. B500 is used for the steel rebars with a characteristic strength of 550 MPa and a design yield strength of 435 MPa[2].

The properties that are required for a BasBar design have already been presented by ReforceTech as can be seen in figure 4.1. Where for the fibres the properties are dependent on the concrete strength properties, the BasBars have their own properties that can be used to calculate the strength capacities of a specimen. The stress strain relation is confirmed to be linear by ReforceTech. One possible problem with the stress strain relation being linear until failure is when the failure load is reached, brittle failure occurs. Later in the test results this is confirmed. To overcome brittle failure, in the design phase the tensile strength is not only reduced by using a safety factor ($\gamma_b = 1.2$), but with another 30%.

MECHANICAL PERFORMANCE

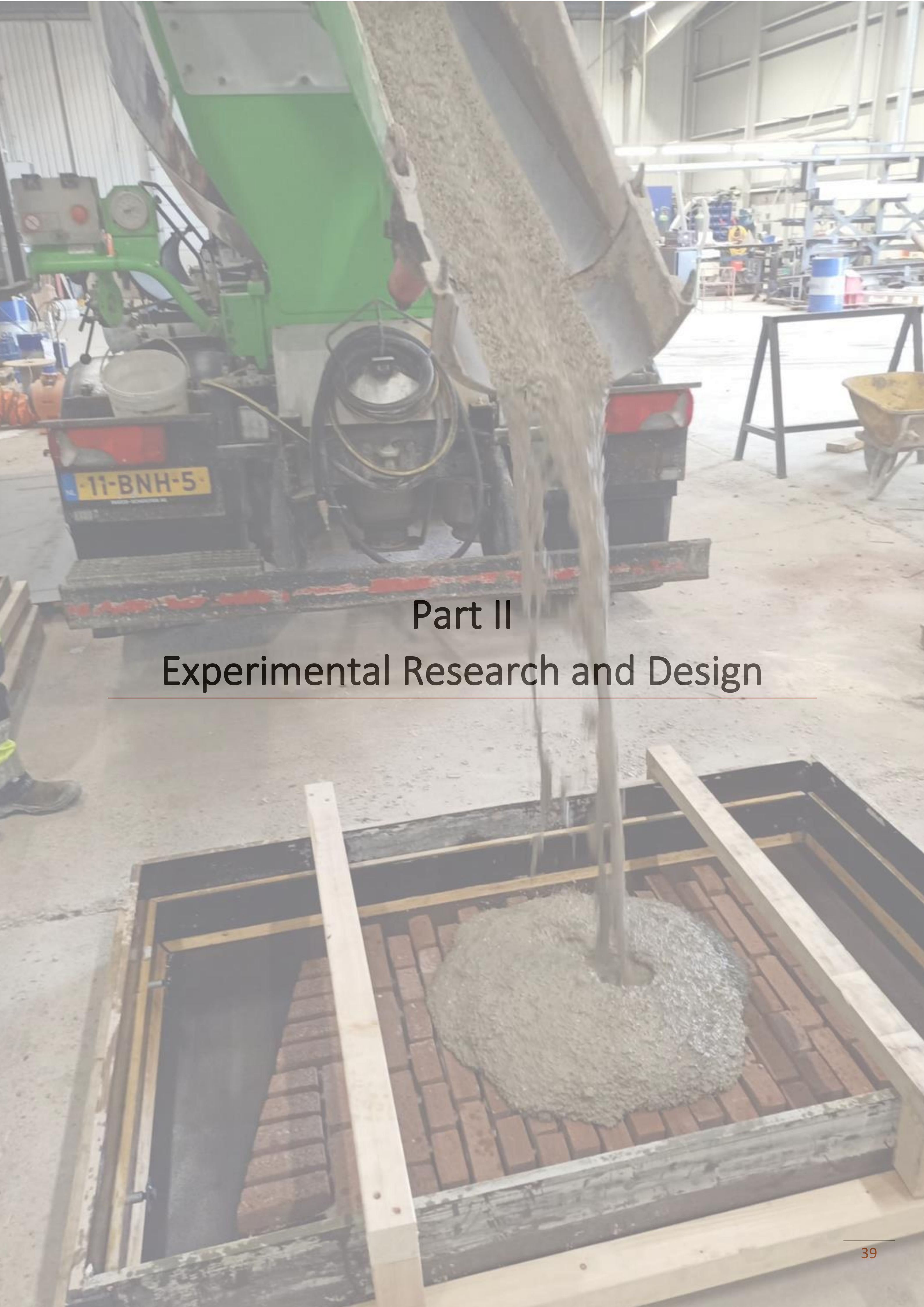
BasBar™ Size Chart - (Physical and Mechanical Properties)

Size	Nominal Diameter		Nominal Area		f*fu – Guar. Min. Tensile Strength		Ultimate Strain
	Mm	Inch	mm2	inch2	MPa	ksi	%
2	6	¼	31.67	0.049	904	131	2.1
3	10	⅜	71.26	0.110	848	123	2.0
4	13	½	126.7	0.196	795	115	1.8
5	16	⅝	197.9	0.307	745	108	1.7
6	19	¾	285.0	0.442	698	101	1.6
7	22	⅞	387.9	0.601	654	95	1.5
8	25	1	506.7	0.785	614	89	1.4
9	29	1⅛	641.3	0.994	576	84	1.3
10	32	1¼	791.7	1.227	542	79	1.2

Figure 4.1: Mechanical performance BasBars ReforceTech (ReforceTecha, 2021)

4.3 Other experiments with important results

- Cracking behaviour
  With a four point bending test the cracking behaviour is going to be monitored for a number of samples containing both minibars and BFRP bars. The results of these experiments can lead to a possible 3rd design with a combination of both types of reinforcement. This 3rd design is not part of this research, but in the future a 3rd design might be part of a follow-up research for which a set up can already be made in this thesis project. This is thus not necessarily a material property that is needed to be obtained in the current research goal/product and is therefore mentioned separately from the other experiments and properties in Appendix E.
- Experiments with steel reinforcement
  For each experiment explained above a similar or representative experiment is done with steel reinforcement. This way the direct changes in response of the different reinforcement materials are monitored and as mentioned the steel fibre design is validated.



Part II
Experimental Research and Design

5 Methods of testing and material use

This chapter is the first section of Part II of this research, where experimental research is used to calculate and produce designs with the different types of reinforcement. This chapter contains the concrete mixtures that are used for the experiments and the different test methods for the experiments that are performed.

5.1 Concrete Mixtures

The concrete mixtures that are used are made available by Ruttegroep. All mixtures that are used in this research are self-compacting mixtures using the plasticizers PW 3100 and SKY 648. A self-compacting mixture is required for the design of the aprons as no compacting measures are allowed when pouring the concrete. This is due to the bricks in the mould that have a lower density and the use of vibration needles for example could cause the bricks to start floating. The mixture should also be sufficiently flowable to fill the joints between the bricks.

The original mix obtained is used as the mixture without fibres for the design with the BFRP-bars. When fibres are added the mixtures change due to the addition of materials. Due to the shape of the fibres 43 mm in length, it is decided that the volume of fibres added is compensated by removing the same volume from the course fraction (4-8 mm).

The traditional concrete mixture (indicated with a T) is used as the main concrete mixture for all specimens in this research. The innovative concrete mixture (IPK) has been used for a couple of tests with the steel fibres. Those results are presented amongst the other results in Appendix A.

5.1.1 Traditional Concrete Mixture (T)

The traditional concrete mixture is presented in table 5.1, it contains the amounts of materials for the mixture without fibres and the changed mixtures for varying fibre amounts.

Table 5.1: Concrete mixtures for different designs

Fibre amount $[kg/m^3]$:	**Traditional mixture (no fibres)**	**20 (Basalt)**	**30 (Basalt)**	**45 (Steel)**
Material	$[kg/m^3]$	$[kg/m^3]$	$[kg/m^3]$	$[kg/m^3]$
Sand (0-4 mm)	877.5	877.5	877.5	877.5
Gravel (4-8 mm)	774.6	737.8	719.4	719.4
CEM I	78	78	78	78
CEM III A	331.5	331.5	331.5	331.5
Limestone flour	146.25	146.25	146.25	146.25
PW 3100	1.755	1.755	1.755	1.755
SKY 648	2.243	2.243	2.243	2.243
Minibars	-	20	30	-
Steel fibres	-	-	-	45
Water	154.4	154.4	154.4	144.4
Air content [%]	3.5	2.5	2.5	2.5
Total	2366	2349	2341	2396

5.1.2 ECI values concrete mixtures

The ECI value for a cubic metre of concrete depends on the materials that are used. In the mixtures presented in table 5.1 there are small differences leading to a different ECI value for each mixture as also explained in chapter 8. In Appendix F the ECI values for all the mixtures are presented in detail including the different modules and impact categories for each separate material used.

5.2 Test methods for material behaviour and properties

In this research various tests are performed. This chapter contains the different tests that are caried out during the research. In appendix B, all testing procedures are explained.

Concrete compression test

To obtain the concrete compressive strength f_c the European standard NEN-EN 12390-3 (NENb, 2019) is used.

Slump test (Flow table test)

To obtain the flow value f the European standard NEN-EN 12350-5 (NENa, 2019) is used.

Displacement controlled CMOD test

To obtain the flexural tensile strength of the fibered concrete the European standard EN 14651:2005+A1:2007 (NEN, 2007) and (NENc, 2019) are used. For the experiments in this research these norms are followed.

Force controlled 3 and 4 point bending test

To test the specimens with BFRP-bars, three and four point bending tests are performed. The cross-sections of all these specimens are 150x150 mm and the length varies between 600 and 1000 mm. Due to test bench and mould restrictions the beams could not be longer even though this was preferred to provide a better insight in the behaviour. The location of the reinforcement also differs per specimen to have a variety of results to see if concrete cover made a difference in testing (apart from increased or decreased lever-arm). These tests are force controlled, meaning that the applied force is gradually increased. This increase is measured in MPa and is equal to 0.05 MPa/s. This 0.05 MPa/s is based on the roller distance both upper and lower that are input values in the test bench. Based on the dimensions and these distances a linear stress is assumed and calculated with the sectional modules and the applied moment. This way a force increase converted from a constant stress increase is applied. Depending on the specimens dimensions this results in an actual force [kN] increase which is not the same for each specimen. The testing machine assumes a linear stress distribution similar as depicted in figure 5.1 (2), therefore the actual force increase can be calculated as follows from equations 5.1 -5.4. This calculated force is also the force displayed in the graphs with the results in chapter 6.1.4.

$$\Delta F_{3PB} = \frac{\Delta M}{l} 4 \qquad \text{(eq. 5.1)}$$

$$\Delta F_{4PB} = \frac{\Delta M}{a} 2 \qquad \text{(eq. 5.2)}$$

Where:

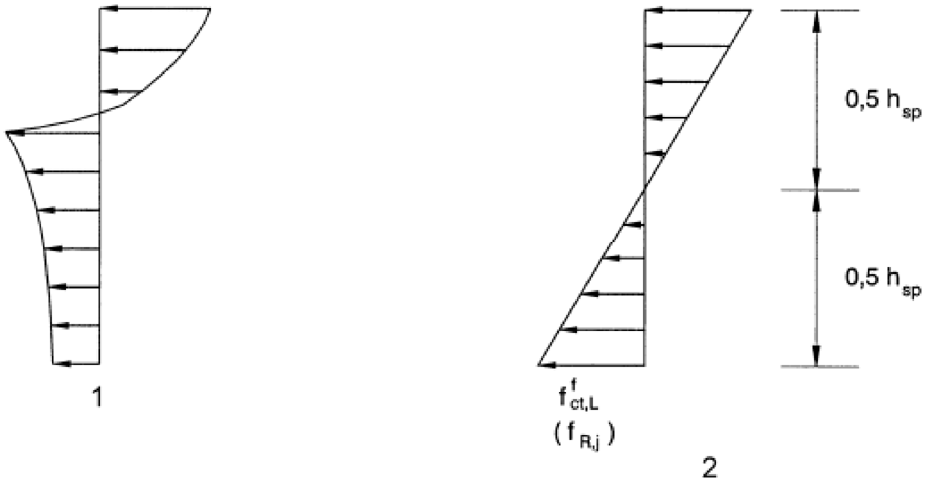
$$\Delta M = \Delta \sigma W = Moment\ increase\ per\ second\ [Nmm/s] \qquad \text{(eq. 5.3)}$$

$$l = distance\ between\ support\ rollers\ [mm]$$

$$\Delta\sigma = 0.05\ \mathrm{MPa/s}$$

$$W = \frac{1}{6} bh^2 = 562500\ mm^3 = sectional\ modulus \qquad \text{(eq. 5.4)}$$

$$a = distance\ from\ support\ roller\ to\ upper\ roller\ [mm]$$



Key

1 Real stress distribution

2 Assumed stress distribution

Figure 5.1: Real and assumed stress distribution

As a result of this assumed stress distribution, the calculated stress properties give a slight underestimation of the actual strength.

Specimens with a length of 600 and 1000 mm are prepared with either 1 or 2 reinforcement bars with diameters of 6 and 8 mm. All specimens have the same cross-section of 150x150 mm. The location of the reinforcement bars does differ per specimen. The different types of specimens are displayed in table 5.2.

In the third test batch this type of test is also performed on beams with fibres to check the moment capacity until failure of a regular fibre reinforced beam. This is done for both steel and minibars.

It must be noted here that force controlled tests are not in favour for these types of analysis. It is better to use displacement controlled tests. This is however not done in this research due to lack of expertise and equipment with the testing machine.

Mock-up

To further test the workability of the mixture two small scale mock-up tests are performed (one with steel fibres and one with minibars). For the mock-ups a pouring mould is used. This mould consists of a steel bottom plate with a pattern on top in which the bricks for the façade of the aprons can be placed. The following steps must be performed to ready the mould for the concrete:

- Place the bricks in the pattern (see figure 5.2) (for some pieces the bricks have to be sawn to the right size)
- Apply silver-sand in the joints between the bricks
  This sand is there to make sure a joint exists in the end result (figure 6.12) which can afterwards be sealed with a special mixture for the joints. The sand stops the concrete from flowing under the bricks. The thickness of the sand layer for the actual design is 20 mm. For the mock up a smaller thickness of 5 mm is used
- Oil is applied to all the sides and the part of the bottom plate that does not contain sand or bricks.

After preparing the mould, the concrete can be poured in with a concrete mixer truck as seen in figure 5.3. When demoulding the concrete test slab the results must be interpreted by looking at the gaps and possible damages due to demoulding. Chapter 6.2 shows the results of the two mock-up tests.

Figure 5.2: Pouring the concrete with the mixer truck

Figure 5.3: The mould with bricks laid into the pattern

6 Analysis of test results

6.1 Results

In this section the results are presented for the different tests that are performed. The results presented here are used in chapter 7 for the design calculations.

6.1.1 Results Concrete Compression Test

First test session

For the first test session the concrete mixtures where made in the shear mixer. The cubes where made with the self-compacting concrete with the traditional mixture. Table 6.1 shows the mean results from the regular cubes. The beams used for the CMOD tests are also used to obtain extra cubes. The mean results from those cubes are presented in table 6.2 . Appendix A shows all results for each test and each specimen. For the cubes with steel fibres the number of specimens and the mass of each cube is unknown as these tests had already been performed before this research and the administration only showed the mean compressive strengths.

Table 6.1: Results concrete compression tests (1st session + steel fibre cubes)

Fibre content	Concrete batch id.	Type of fibre	Nr. of specimens	f_{cm} $[MPa]$	ρ_{cm} $[kg/m^3]$
-	T1	-	3	67.8	2241
15	T1	Basalt	3	61.0	2200
30	T1	Basalt	3	69.5	2223
55	T1	Basalt	3	25.5	1850
35	T1	Steel	Unknown	95.6	Unknown
40	T1	Steel	Unknown	83.3	Unknown
45	T1	Steel	Unknown	88.5	Unknown
35	IPK1	Steel	Unknown	43.9	Unknown
40	IPK1	Steel	Unknown	36.7	Unknown
45	IPK1	Steel	Unknown	39.9	Unknown

Table 6.2: Results concrete compression tests (1st session extra cubes)

Fibre content	Concrete batch id.	Type of fibre	Nr. of specimens	f_{cm} $[MPa]$	ρ_{cm} $[kg/m^3]$
-	T1	-	6	73,2	2294
15	T1, T2	Basalt	8	60.58	2174
30	T1, T2	Basalt	8	66.63	2231
55	T1	Basalt	4	25.93	1840

Looking at the results from the Minibars, the results show that on average the cubes with no fibres perform the best and that by adding fibres the compressive strength drops. In chapter 5.1 the concrete mixture was designed to be C45/55 and the results presented here are higher. This was predicted due to the use of self-compacting concrete which was said to be increasing the concrete strength class by 1 or more.

The first set of results also shows densities that are significantly lower compared to the designed density. The concrete is very porous and thus the density dropped. As explained in chapter 5.1 this is partly due to the substitution of sand for fibres. Due to the low density of the fibres 1429 kg/m3, the volume is higher compared to steel fibres, meaning there are significantly more fibres present in the mixture. The shape of the fibres makes for a situation where the concrete mixture cannot fill enough pores. Therefore in the mixtures for session 2 only coarse material is substituted. This way, with more fine material the density increases. Another reason for the low density is the quality of the mixtures. The mixtures where not mixed consistently and not using the right amount of additives/water resulted in slight segregation of the mixture. Together this also caused the mixture with 55 kg/m3 fibres to perform worse compared to the rest.

When looking at the results for the steel fibre reinforced cubes, the results show that for the traditional mixture the compressive strength is around 15-20 MPa higher compared to the cube without fibres. This difference is possibly due to the mixture being slightly different and the concrete being made by a specialist. The tests were also performed before the current research started and therefore the only known test results are the mean compressive strengths. The innovative mixture (IPK) shows lower results which are also resulting in lower results in the CMOD tests presented in 6.1.3. It can therefore be said that these results are not relevant for the remainder of the research.

Second test session

The specimen for the second test session have again been made in the shear mixer. The fibres however have been added later in a regular concrete mixer to make sure the fibres would not be damaged. In table 6.3 the results for the compressive strength tests are shown. These values are the mean values of the concrete compressive strength as well as the density. All the cubes with fibres are obtained from the specimens used for the CMOD tests. From these specimens the end is sawn of in order to obtain 2 and in one case 3 cubes per beam.

Table 6.3: Results concrete compression tests (2nd session)

Fibre content	Concrete batch id.	Type of fibre	Nr. of specimens	f_{cm} $[MPa]$	ρ_{cm} $[kg/m^3]$	Standard deviation σ $[MPa]$
-	T1	-	3	72.78	2348	2.31
20	T1	Basalt	6	73.91	2348	1.09
30	T3	Basalt	7	59.44	2246	8.84
30	T4	Basalt	6	66.55	2324	2.66

It can be seen that the cubes with 20 kg/m3 minibars perform better compared to the cubes with 30 kg. It is expected that this is due to the difficulty of getting a good mixture in the small scale of these experiments, as well as the extra amount of fibres reducing the compressive strength of the concrete.

Third test session

The concrete compressive strength from the third session is lower compared to both the first and second test session. When looking at the results from the minibars in the fifth batch presented in figure 6.4, the density is significantly lower compared to the fourth batch. Possible causes can relate to the water/plasticizer usage in the mixture resulting in a sufficient workability but at the cost of a higher void content.

Table 6.4: Results concrete compression tests (3rd session)

Fibre content	Concrete batch id.	Type of fibre	Nr. of specimens	f_{cm} $[MPa]$	ρ_{cm} $[kg/m^3]$	Standard deviation σ $[MPa]$
30	T5	Basalt	4	53.72	2229	1.19
45	T2	Steel	4	58.15	2342	7.08

6.1.2 Results Slump Test

The results of the slump tests are displayed in table 6.5.

Table 6.5: Results Slump tests (all sessions)

Fibre content	Concrete batch id.	Slump value f $[mm]$
15	T1,T2	740
20	T1	700
30	T1,T2	660
30	T3,T4	640
55	T1	540

The mixture with 30 kg fibres have a slump value of 640-660 mm which is sufficient for a self-compacting concrete. The fibres do however tend to stick out at the top. With lower fibre dosages this is also the case but less. The fibres that are sticking out can be pressed into the concrete if required. This is done for the test specimens. The concrete from the mock-up tests has not been used to perform a slump test. The workability of these mixtures was however a big improvement over the earlier mixtures. It was easy to scoop through and it flowed in all edges and joints. Both the mixture with steel fibres and minibars are expected to have a slump value close to 750 mm.

6.1.3 Results Displacement Controlled CMOD Test

Results first test session

The results of the first test session are presented in table 6.6. The results with the minibars are significantly lower due to the use of the shear mixer resulting in broken fibres. The same technique is used for the steel fibres but those results are valid as the Dramix 5D fibres are not influenced by the mixing technique.

Table 6.6: Results CMOD tests (1st session)

Fibre content	Concrete batch id.	Type of fibre	$f_{fctm,fl}$ $[MPa]$	f_{R1} $[MPa]$	f_{R2} $[MPa]$	f_{R3} $[MPa]$	f_{R4} $[MPa]$
15	T1,T2	Basalt	6.99	5.07	3.84	2.45	1.74
30	T1,T2	Basalt	6.79	7.92	7.19	5.05	3.72
55	T1	Basalt	4.65	6.95	5.63	4.48	3.67
35	T1	Steel	7.65	6.32	8.91	7.98	5.74
40	T1	Steel	6.38	5.27	6.20	5.99	5.55
45	T1	Steel	6.70	8.45	11.62	11.41	8.92

Results second test session

When analysing the results from the second test session, it shows in table 6.7 that the 4th batch with 30 kg fibres performed the best. The differences between the 3rd and 4th batch can be explained when also looking at the results from the compressive strength tests. The compressive strength and the density of the 4th batch was higher compared to the third batch, showing that the mixture for the 3rd batch was not as good. As explained before, due to the small scale of the experiments and the limited capacity of the mixers, the mixtures differ a lot even if the same amounts of materials are used.

The use of the shear mixer in combination with a regular concrete mixer (to apply the fibres without braking them) has proven to work when comparing the results to the first test session. In chapter 7.1 it can also be seen from the calculations made, that the mixture with 30 kg/m3 minibars is sufficient to meet the strength requirements for the quay wall aprons. The third test session is therefore used to validate these outcomes.

Table 6.7: Results CMOD tests (2nd session)

Fibre content	Concrete batch id.	Type of fibre	$f_{fctm,fl}$ $[MPa]$	f_{R1} $[MPa]$	f_{R2} $[MPa]$	f_{R3} $[MPa]$	f_{R4} $[MPa]$
20	T1	Basalt	8.09	6.68	7.94	5.65	3.85

30	T3	Basalt	7.09	7.84	8.73	7.20	5.81
30	T4	Basalt	7.70	9.76	11.35	9.03	7.44

Third test session

The results for the minibars are presented in figure 6.1 and table 6.8 When comparing the results to those of the second test session it becomes clear that the cracking strength of the 5th batch with 30 kg/m3 Minibars is significantly lower. This can be explained by the lower concrete compressive strength which brings a lower tensile capacity as well. The tensile behaviour in the later stages however is still sufficient and even higher when looking at the values for the fr4 shown in table 6.7 and 6.8, meaning the ULS capacity is increased. Table 6.8 also contains the results for the steel fibre specimens. The results for the steel specimens are significantly worse. The reason for these bad results are expected to be related to the distribution of the fibres in the concrete as they may have sunk and are therefore not distributed evenly over the cross-section. These results are therefore neglected in the later design verification phase as earlier results have been produced that form a better representation of the capacities of the concrete mixture.

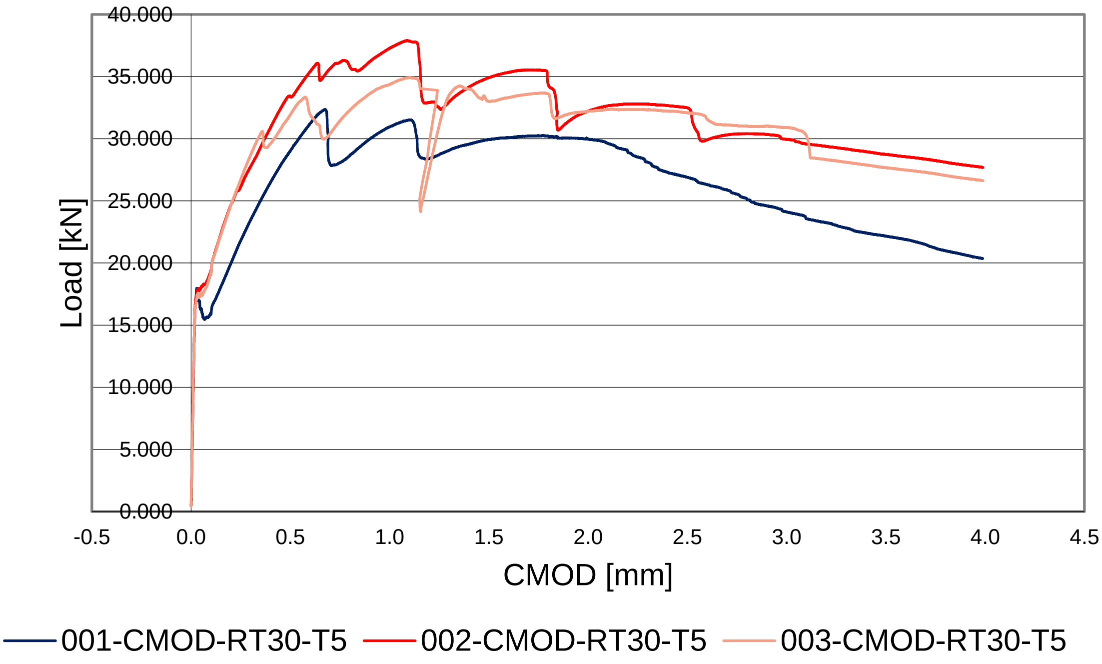


Figure 6.1: Results CMOD tests from third test session ReforceTech Minibars 30 kg/m3

Table 6.8: Results CMOD tests (3rd session)

Fibre content	Concrete batch id.	Type of fibre	$f_{fctm,fl}$ $[MPa]$	f_{R1} $[MPa]$	f_{R2} $[MPa]$	f_{R3} $[MPa]$	f_{R4} $[MPa]$
30	T5	Basalt	5.72	10.06	10.44	9.75	8.39
45	T2	Steel	5.45	3.34	3.68	3.69	3.50

6.1.4 Results Force Controlled Three/Four Point Bending Test

To test the capacities of beams with the BFRP-bars as reinforcement two different types of tests have been performed. Three point bending tests and four point bending tests. The choice between 3 and 4 point bending depends on the expected moment failure load in comparison with shear failure load.

Both these tests are force controlled, meaning that the force is gradually increased over time until the failure load is reached.

Results beams L = 1000 mm

Figure 6.2 and table 6.9 show the results for the specimens with a total length of 1000 mm and with a support distance of 900 mm. For one beam the support distance has been decreased to 788 mm. The force here is presented as a function of time as no data is available for deflection.

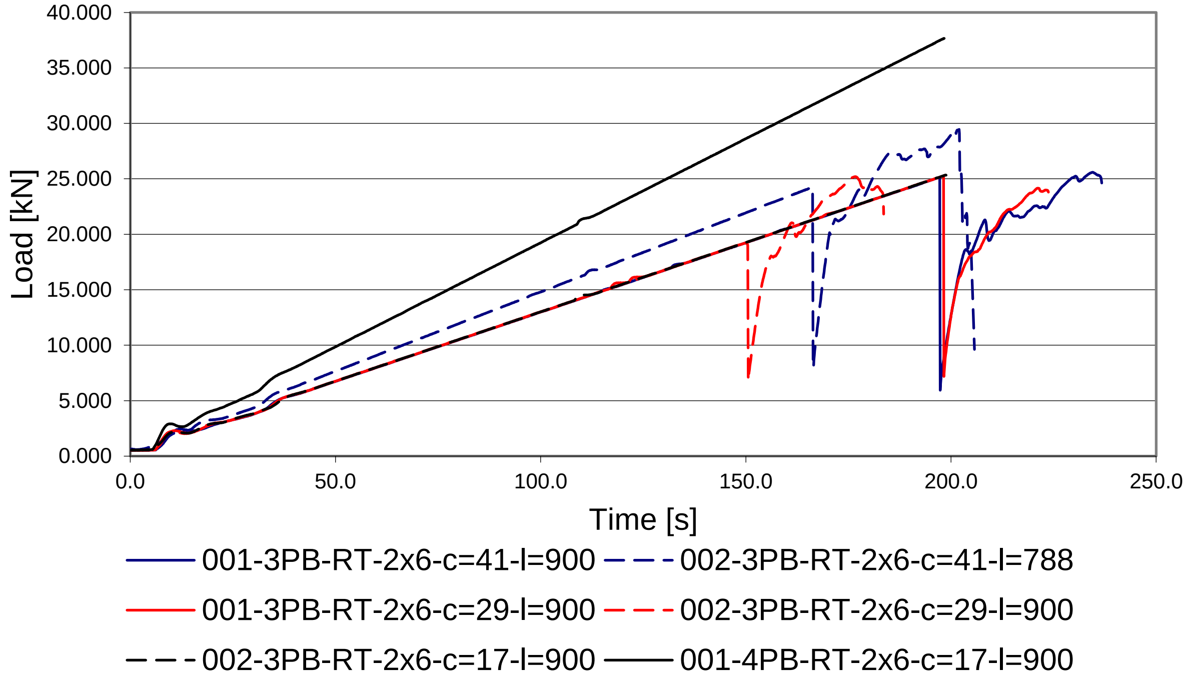
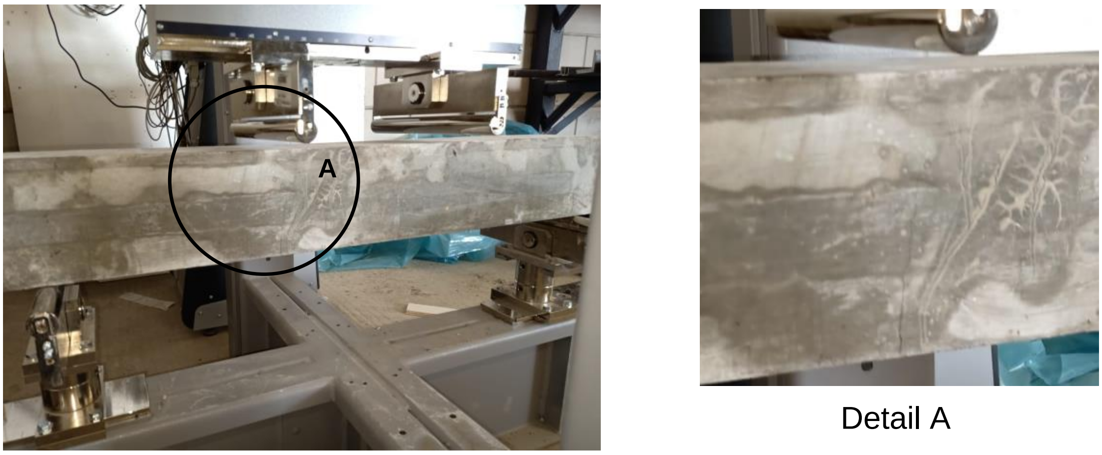


Figure 6.2: Results 3 and 4 point bending tests with basbars

Table 6.9: Results 3 and 4 point bending tests with basbars

ID	Type of test (3PB/4PB)	Type of reinforcement $(nx\phi)$	Roller distance [mm]	Distance from bottom to centre of bars [mm]	Expected moment capacity (converted to force applied) [kN]	Expected shear capacity (converted to force applied) [kN]	Actual applied load [kN]	Moment in cross-section
001	4PB	2x6	900	17	47.89	40.77	37.66	5.65
002	3PB	2x6	900	17	31.92	40.77	25.34	5.70
001	3PB	2x6	900	29	28.99	38.28	25.24	5.68
002	3PB	2x6	900	29	28.99	38.28	25.20	5.67
001	3PB	2x6	900	41	26.05	35.70	25.59	5.75
002	3PB	2x6	788	41	29.75	35.70	29.45	5.80

The first test performed was a four point bending test on the test specimen with a distance of 17 mm to the centre of the reinforcement. The applied force is lower than both the expected moment and shear capacity. The photo in figure 6.3 shows a single crack next to the left upper roller. The first thought was shear force failure, as reinforcement bars were still intact.



Detail A

Figure 6.3: Results of 4 point bending test with possible shear failure + detail A (turned out to be anchorage failure)

To overcome the same type of failure, the next specimens were tested with a three point bending test. The expected moment capacities of these beams lay lower compared to the shear capacities.

The next four tests however all failed at the same load (approx. 25.3 kN). The type of failure was at first unclear until the fourth beam clearly showed a bond slip failure. Figure 6.5 show the failure of these beams. From these pictures it can also be seen that the reinforcement bars stayed intact and that the concrete spalled of underneath the reinforcement.

Figures 6.4: Visualisation of concrete spalling off due to anchorage failure

The moment in the cross-sections at failure where all very similar therefore it can be concluded that the bond strength was causing the failure also in the beam shown in figure 6.4.

After concluding that the bond strength was the issue the last beam could be tested with a reduced span between the support rollers (788 mm instead of 900 mm) thus increasing the anchorage length of the bars to approx. 100 mm. The results of this test showed total failure of the BasBars as they snapped at the moment of failure. The specimen however also showed similar failure to the 2^{nd} -5^{th} beam, as the concrete below the bars spalled of. The snapping of the bars is a unwanted failure mechanism as it is a brittle failure. In the design section of the BasBar design in chapter 7.2 an additional safety factor is introduced to overcome this type of failure. This safety factor is an educated guess and is not based on experiments that point towards this value. Further research is needed to either approve with this factor or show that it is not necessary or if it can be closer to 1.0.

Figure 6.5: Brittle failure of the basbars

Results beams L = 600 mm

Figure 6.6 and 6.7 show results from three point bending tests performed on beams with a length of 600 mm. The results together with the expected results are presented in table 6.10. It can be seen that regardless of the amount of rebars (1 or 2) the resulting moments at failure in the cross-section stayed similar (around 6.5 kNm). From the figures it can be seen that at the moment of failure also the first crack forms, this can possibly be explained by the strain in the BasBars being similar to that of the concrete and keeping the concrete together until the anchorage of the BasBars fails. Looking at the results and the type of failure, the anchorage failure has a similar cause as for the beams with a length of 900 mm.

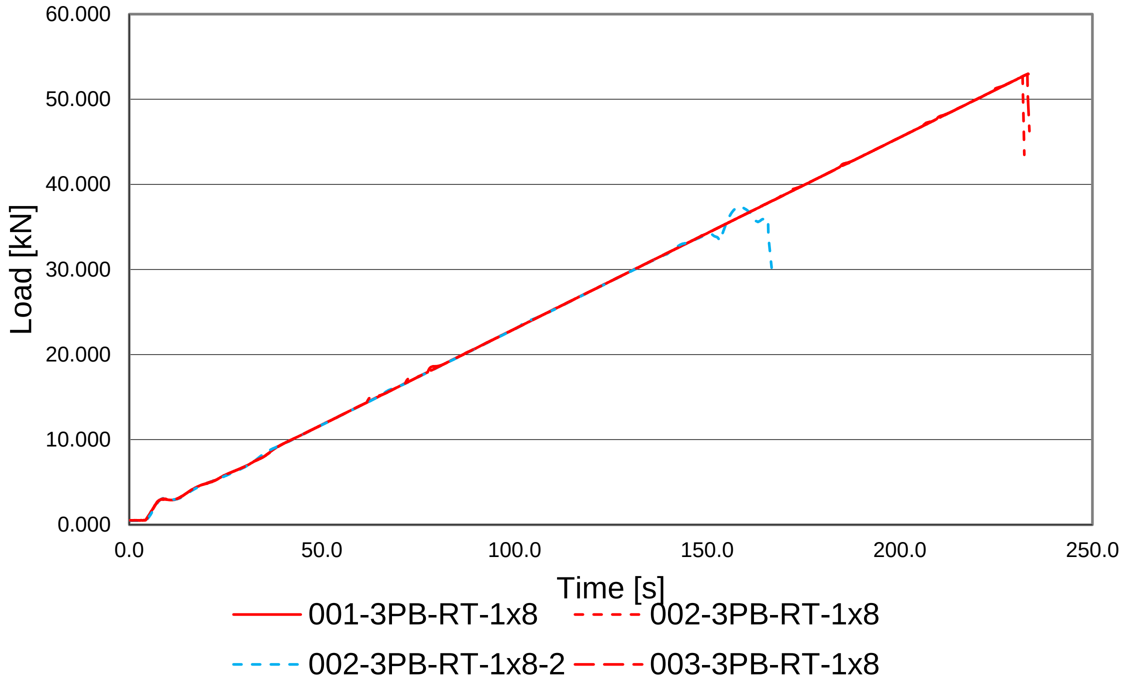


Figure 6.6: Results 3-point bending tests Beams l=600 mm with 1x8 BasBars

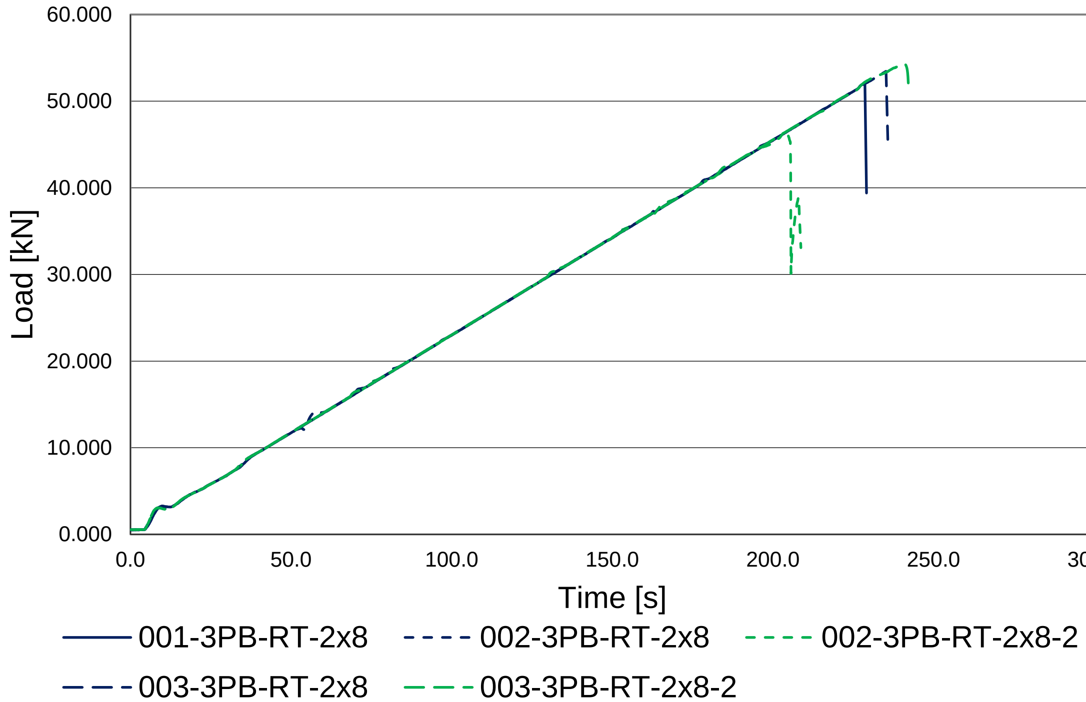


Figure 6.7: Results 3-point bending tests Beams l=600 mm with 1x8 BasBars

In the figures the different specimens are presented with different line-styles. For some of the specimens the test is run twice to see if this anchorage failure leaves the beams with a rest capacity. From the figures it can be seen that indeed the resulting capacities are in one case even higher than the original capacity indicating that the slight bond slip is picked up by the concrete and new 'grip' is found. However that effect cannot be expected to occur always as the bond is gone. Therefore this effect cannot be used for validation.

Table 6.10: Results 3 point bending tests beams with BasBars (l=600 mm)

ID	Type of test (3PB/4PB)	Type of reinforcement ($nx\phi$)	Roller distance [mm]	Distance from bottom to centre of bars [mm]	Expected moment capacity (converted to force applied) [kN]	Expected shear capacity (converted to force applied) [kN]	Actual applied load [kN]	Moment in cross-section
001	3PB	1x8	500	29	51.38	35.41	53.00	6.63
002	3PB	1x8	500	29	51.38	35.41	52.65	6.58
003	3PB	1x8	500	29	51.38	35.41	52.94	6.62
001	3PB	2x8	500	17	110.95	47.52	52.00	6.50
002	3PB	2x8	500	17	110.95	47.52	49.16	6.15
003	3PB	2x8	500	17	110.95	47.52	53.45	6.68

It must be noted with these results that some of the BasBars tended to start floating in the concrete after pouring the concrete in the mould. In the future this can be prevented by fixing the supports of the BasBars to the mould with glue. With other more viscous (less workable) mixtures this effect did not occur and therefore glue was deemed to be unnecessary.

Results beams l = 600 mm (minibars/Dramix 5D)

The three point bending test described before is also performed on beams with Minibars and Dramix 5D steel fibres. Again on beams with a length of 600 mm the tests are performed. In table 6.11 the results show that for the beams with the Minibars both the actual and expected capacities lie higher compared to those of the steel fibres. This difference is due to the lower outcomes of the CMOD tests for the steel fibres. Due to the possible segregation of the mixture, sinking of the steel fibres could have occurred causing uneven distribution of the fibres in the second batch. This might cause the actual applied load to be higher if the fibres concentrated at the bottom of the beam. For the expected moment capacity the highest of both SLS and ULS moment capacity is used as well as f_{ck} instead of f_{cd}.

Table 6.11: Results 3 point bending tests fibre reinforced beams (l=600 mm)

ID	Type of test (3PB/4PB)	Type of reinforcement	Roller distance [mm]	Expected moment capacity (converted to force applied) [kN]	Expected shear capacity (converted to force applied) [kN]	Actual applied load [kN]	Moment in cross-section
001	3PB	Basalt	500	45.65	93.55	47.23	5.90
002	3PB	Basalt	500	45.65	93.55	46.74	5.84
001	3PB	Steel	500	28.37	60.43	38.32	4.79
002	3PB	Steel	500	28.37	60.43	36.46	4.56

Results beams l = 850 mm (minibars/Dramix 5D)

To further test the fibres for both types also two four point bending tests are performed. The first test on a beam with minibars resulted in a significantly lower applied load compared to the expected capacity. The indicated failure mechanism looking at figure 6.8 moment which would mean that the calculated moment capacity is significantly lower. However in the latter tests the distance between the upper rollers has been reduced from 250 mm to 150 mm. As a result the applied moment is higher with the same applied force and the shear force stays the same. When looking at those results the applied load even increased and showed that the expected moment capacity is exceeded. The reasons for the lower results for the first beam are therefore unknown.

Figure 6.8: 4 point bending test on beam l = 850 mm (30 kg/m3 Minibars)

The beams with steel fibres again show similar moment capacities as for the three point bending tests with capacities around 4.8 kNm.

Table 6.12: Results 4 point bending tests fibre reinforced beams (l=850 mm)

ID	Type of test (3PB/4PB)	Type of reinforcement	Roller distance [mm]	Expected moment capacity (converted to force applied) [kN]	Expected shear capacity (converted to force applied) [kN]	Actual applied load [kN]	Moment in cross-section
001	4PB	Basalt	750	45.65	93.55	27.39	3.42
002	4PB	Basalt	750	32.60	93.55	38.03	6.66
001	4PB	Steel	750	20.26	60.43	27.55	4.82
002	4PB	Steel	750	20.26	60.43	31.54	5.52

It must be noted here that direct load transfer to the supports is not taken into account in any way. This is something further research should take into account when using these results. Due to the small span of the beam direct load transfer might cause the tests to show other types of failure.

6.2 Results Mock-up Test

The mock-up tests that are done are mostly a check to see whether the procedure of preparing the mould is correct and if changes should be made for better results. The second thing that is checked is whether the concrete flows between the bricks in the mould.

The pictures shown in this chapter can be analysed and conclusions are drawn concerning the preparation of the mould and the workability of the mixture. The picture in figure 6.9 shows an overview of the test specimen. The majority of the plate looks good however some damages are visible which are highlighted in the pictures in figures 6.9 – 6.12.

Figure 6.9: Mock-up test result

When looking at figure 6.12 the joints between the bricks show a clear border where the silver sand was applied resulting in a rough edge of concrete. This is a positive result showing that if the silver sand is applied in the correct way no concrete spills towards the top of the bricks and the joints can be sealed. Therefore it can be concluded that for both the mixture with 30 kg/m3 minibars and the mixture with 45 kg/m3 steel fibres the flowability is sufficient.

Figure 6.11 shows some damages and unwanted visual details around the edges of the bricks. These damages are mainly due lack of oil in the mould. The lack of oil has as a result that the concrete sticks to the steel of the mould causing damages when unmoulding. The unwanted visual details occur at the edge bricks on both the sides and the top. Here concrete has flown under the brick and leaves an edge of concrete on top of the bricks. Where the first problem explained can be solved by applying sufficient oil also in the edges the second problem might be solved by adding a tiny layer of silver sand under the bricks at the locations the bricks stick out at the edges.

Figure 6.10: Damages in the concrete on the edges of the bricks

Figure 6.11: Joints between the bricks where silver-sand has been applied in the correct way

Figure 6.13 shows two other types of damage. The first is the spalling of bricks. This is due to bricks not fitting in the mould. Some of the bricks had slightly broader edges resulting in being stuck in the mould and when demoulding the part that was clamped in the mould was torn of. To overcome this problem the bricks that are placed should be checked to see if they are not stuck. On the bottom of the plate another test is performed to see how the concrete would fair if no bricks where placed in the mould. As can be seen the concrete was torn of in a similar way as the brick above. Possibly due to lack of oil but it is also possible that the mould gripped the concrete in such a way that even with enough oil the result would not be great.

Figure 6.12: Brick damage and concrete damage

6.3 Material Properties

In this chapter the results from the experiments are used to calculate the necessary material properties.

6.3.1 Concrete compressive properties

The characteristic concrete strength (f_{ck}) follows from the simplified equation from table 3.1 from Eurocode 2 (NEN, 2020) depicted here in table 6.11. Note that only cube strengths are used and no cylindrical strengths.

$$f_{ck} = f_{cm} - 8 \qquad \text{(eq. 6.1)}$$

Where:

$f_{cm} = mean\ concrete\ compressive\ cube\ strength\ [MPa]$

The ultimate concrete strain can be derived from table 6.1-6.4 by using the obtained f_{cm} and equation 6.1.

The mean concrete modulus of elasticity (E_{cm}) is calculated with equation 6.2 obtained from table 6.13.

$$E_{cm} = 22[f_{cm}/10]^{0.3} \qquad \text{(eq. 6.2)}$$

6.3.2 Concrete tensile properties

Tables 6.6-6.8 show the results from the CMOD tests. These values are used to obtain stresses used to calculate the moment and shear capacities of the concrete elements. Figures 6.13 contains three stress and strain diagrams. These show the stress diagram for a cross-section for a certain value of the strain at the bottom (in the tensile zone). These three diagrams are used to calculate the moment capacities in chapter 7.1. For calculation of the moment capacities the RILEM TC for fibre reinforced concrete is used (RILEM TC, 2003).

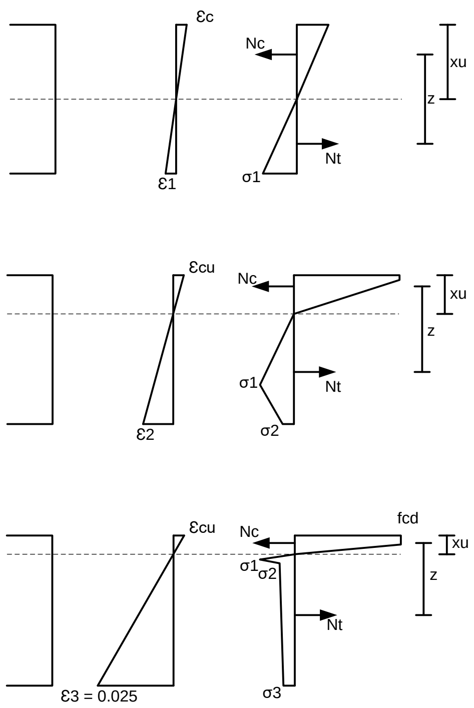


Figure 6.13: Stress-strain diagrams for cracking, SLS and ULS of a fibre reinforced member

There is a distinction between three different graphs due to the behaviour of the fibre reinforced concrete when loaded. In the beginning (until ε_1) the stress/strain diagram is linear and after cracking the tensile capacity of the fibre reinforced concrete drops with increasing strain. After a strain ε_2 a relatively constant strength of the fibre reinforced concrete is present until ultimate strain $\varepsilon_3 = 0.025$.

The different strains and corresponding stresses in the tensile zone are obtained from the results from the CMOD tests and equations 7.3, 7.4, 7.9 and 7.10.

Table 6.13: Equations and strength classes for concrete (NEN, 2011)

Sterkteklassen voor beton															Vergelijking/Verklaring
f_{ck} (MPa)	12	16	20	25	30	35	40	45	50	55	60	70	80	90	
$f_{ck,cube}$ (MPa)	15	20	25	30	37	45	50	55	60	67	75	85	95	105	
f_{cm} (MPa)	20	24	28	33	38	43	48	53	58	63	68	78	88	98	$f_{cm} = f_{ck}+8$(MPa)
f_{ctm} (MPa)	1,6	1,9	2,2	2,6	2,9	3,2	3,5	3,8	4,1	4,2	4,4	4,6	4,8	5,0	$f_{ctm}=0,30\times f_{ck}^{(2/3)}$ ≤C50/60 $f_{ctm}=2,12\cdot\ln(1+(f_{cm}/10))$ > C50/60
$f_{ctk,0,05}$ (MPa)	1,1	1,3	1,5	1,8	2,0	2,2	2,5	2,7	2,9	3,0	3,1	3,2	3,4	3,5	$f_{ctk;0,05} = 0,7\times f_{ctm}$ 5 % fractiel
$f_{ctk,0,95}$ (MPa)	2,0	2,5	2,9	3,3	3,8	4,2	4,6	4,9	5,3	5,5	5,7	6,0	6,3	6,6	$f_{ctk;0,95} = 1,3\times f_{ctm}$ 95 % fractiel
E_{cm} (GPa)	27	29	30	31	33	34	35	36	37	38	39	41	42	44	$E_{cm} = 22[(f_{cm})/10]^{0,3}$ (f_{cm} in MPa)
ε_{c1} (‰)	1,8	1,9	2,0	2,1	2,2	2,25	2,3	2,4	2,45	2,5	2,6	2,7	2,8	2,8	zie figuur 3.2 ε_{c1} (‰) $= 0,7\ f_{cm}^{0,31} \leq 2,8$
ε_{cu1} (‰)	3,5									3,2	3,0	2,8	2,8	2,8	zie figuur 3.2 voor $f_{ck} \geq 50$ MPa ε_{cu1}(‰)$=2,8+27[(98-f_{cm})/100]^4$
ε_{c2} (‰)	2,0									2,2	2,3	2,4	2, 5	2,6	zie figuur 3.3 voor $f_{ck} \geq 50$ MPa ε_{c2}(‰)$=2,0+0,085(f_{ck}-50)^{0,53}$
ε_{cu2} (‰)	3,5									3,1	2,9	2,7	2,6	2,6	zie figuur 3.3 voor $f_{ck} \geq 50$ MPa ε_{cu2}(‰)$=2,6+35[(90-f_{ck})/100]^4$
n	2,0									1,75	1,6	1,45	1,4	1,4	voor $f_{ck} \geq 50$ MPa $n=1,4+23,4[(90-f_{ck})/100]^4$
ε_{c3} (‰)	1,75									1,8	1,9	2,0	2,2	2,3	zie figuur 3.4 voor $f_{ck} \geq 50$ MPa ε_{c3}(‰)$=1,75+0,55[(f_{ck}-50)/40]$
ε_{cu3} (‰)	3,5									3,1	2,9	2,7	2,6	2,6	zie figuur 3.4 voor $f_{ck} \geq 50$ MPa ε_{cu3}(‰)$=2,6+35[(90-f_{ck})/100]^4$

7 Design of basalt reinforced aprons + new steel rebar design

In this chapter two designs are presented for the aprons. One with the minibars and one with the BFRP Bars. For both designs a moment capacity is calculated based on the known parameters from ReforceTech and the results from the experiments.

The design moments the fibre reinforced aprons are designed for are:

$$M_{Ed,crack} = n/a$$

$$M_{Ed,SLS} = 14.96\ kNm/m$$

$$M_{Ed,ULS} = 14.96\ kNm/m$$

The design moments the BFRP bar reinforced aprons are designed for are:

$$M_{Ed,y} = 14.96\ kNm/m$$

$$M_{Ed,x} = 8.00\ kNm/m$$

Tensile forces due to self-weight are not presented here as chapter 3 showed they were insignificantly small.

These values follow from the design of ABT for the steel fibre reinforced aprons. There, an average value for the capacity of a steel fibre reinforced apron of 14 kNm/m was assumed to be sufficient as only the collision load at a very specific location at the apron had the chance of exceeding the capacity. Note that in this research the resistances are calculated to be withholding all design forces. For the design cracking moment no value is taken as it would not matter whether the cracking moment capacity is below or above the design moments. If the cracking moment is above the given design moment this would mean that the apron does not crack. If the cracking capacity is lower and the SLS and ULS capacities are sufficient this could also lead to a sufficient design as even after cracking a moment capacity can be reached which is sufficient (this is in case of the fibre reinforced design). However for the first scenario mentioned where the cracking capacity would already be sufficient it does not hold if only the cracking capacity is sufficient. If for some reason cracks have already occurred and the moment capacity in SLS and/or ULS is not sufficient, the design might still fail. Therefore the main focus of the designs of the fibre reinforced aprons is with the SLS and ULS capacity (for the design with the BFRP bars the SLS and ULS capacity are always higher compared to the cracking moment and therefore governing).

The design shear force the aprons are designed for is:

$$V_{Ed} = V_{Ed,ps} = 50\ kN$$

The value for the shear force follows from the collision load of 50 kN. This load is spread over an area of 1000x500 mm and therefore acts as a punching load. The design is therefore validated for punching shear failure.

7.1 Calculation and verification of Minibar Reinforced Aprons

For the design of the minibar reinforced aprons the results from the CMOD tests are directly used to calculate the moment and shear capacities of the concrete. For all calculations the design thickness of 100 mm and a unit width of 1000 mm are assumed. The calculations for both the moment capacity as the shear capacity are based on (RILEM TC, 2003) which shows a design method for steel fibre reinforced concrete. Design methods are assumed to be equal for the minibars. The Rilem TC design methods are based on the eurocodes 1 (NEN, 2002) and 2 (NEN, 2011) + (NEN, 2020). The example calculation given in the Master

Thesis of (Abid & Franzén, 2011) about the design of steel reinforced concrete beams and slabs is used as a reference to make the calculations in this chapter.

7.1.1 Moment Capacity

The properties needed for the moment capacity calculations are obtained from table 6.7 and 6.8 in chapter 6.1. The following properties are needed for the calculation. They are obtained from the CMOD tests and the mean values are used for the different concrete batches:

$$f_{fctm,fl}\ [N/mm^2]$$

$$f_{R1}\ [N/mm^2]$$

$$f_{R4}\ [N/mm^2]$$

$$f_{ck}\ [N/mm^2]$$

According to Niek Pouwels (Pouwels, 2021), the mean values can be used as the governing design load is a load that is only applied for a short time (collision load).

Cracking moment

The cracking moment can be calculated using equations 7.1 – 7.3.

$M_{Rd,crack} = W_1 \cdot \sigma_1$ (eq. 7.1)

Where:

$W_1 = \frac{bh^2}{6}$ is the sectional modulus (eq. 7.2)

$\sigma_1 = 0.7 f_{fctm,fl}(1.6 - d)$ is the cracking stress (eq. 7.3)

$d = 0.1\ m$ is the effective depth in meters

The corresponding strain that belongs to the cracking stress is calculated using equations 7.4 and 7.5.

$\varepsilon_1 = \frac{\sigma_1}{E_c}$ (eq. 7.4)

Where:

$E_c = \frac{f_{cd}}{0.5\epsilon_u}$ (eq. 7.5)

$f_{cd} = \frac{f_{ck}}{\gamma_c}$ (eq. 7.6)

$\gamma_c = 1.5$

$\varepsilon_u = 3\ ‰\ for\ f_{ck} \leq 60\ MPa, \varepsilon_u = 3.2\ ‰\ for\ f_{ck} = 67\ MPa$

SLS and ULS moment

For both the SLS and ULS moment capacity the same formulas are used. The difference is the shape of the tensile zone in the concrete. Where the SLS capacity is taken at $\epsilon = \epsilon_2$, the ULS capacity is taken at $\epsilon = \epsilon_3$. In figure 7.1 the stress strain relation is depicted for a regular cross-section. Figures 7.2-7.4 contain the stress strain relations and the forces in the three situations calculated (so cracking, SLS and ULS).

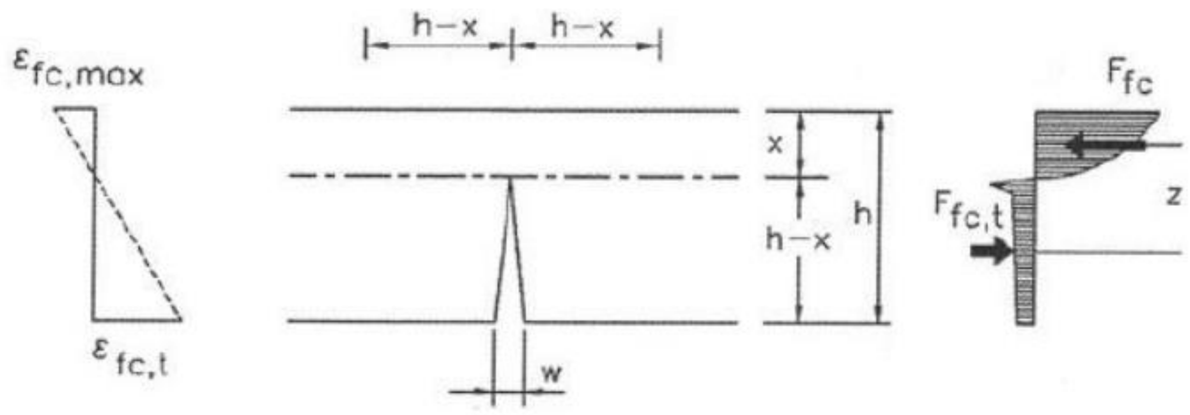


Figure 7.1: Stress strain diagram cracked cross-section

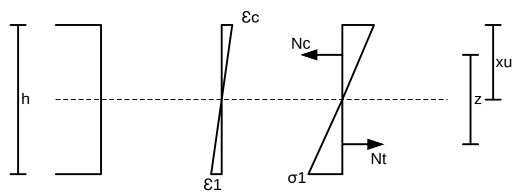


Figure 7.2: Stress strain diagram at moment of cracking ($\varepsilon = \varepsilon_1$)

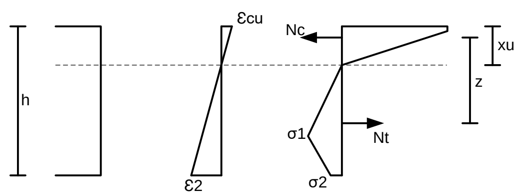


Figure 7.3: Stress strain diagram at SLS ($\varepsilon = \varepsilon_2$)

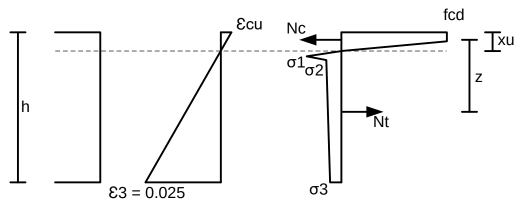


Figure 7.4: Stress strain diagram at ULS ($\varepsilon = \varepsilon_3$)

When not taking into account regular reinforcement bars and prestressing the moment capacity can be calculated according to equations 7.7-7.8.

$M_{Rd} = F_{fc,t}z$ (eq. 7.7)

Where:

$F_{fc,t}$ is the resulting residual tensile force of the fibres

$z = (1 - \beta)x + x_{\mathrm{T}}(h - x)$ is the internal lever arm (eq. 7.8)

β is centre of gravity for the concrete compressive zone (x)

x_T is the centre of gravity for the tensile zone of fibre stress given as a percentage of the height of the tensile zone ($h - x$)

The stress development in the tensile zone is assumed to be linear from the different points (ε_1 to ε_2 to ε_3) as shown in figure 7.2. The corresponding stresses and the strains are calculated using equations 7.9 – 7.10.

$\sigma_2 = 0.45 f_{R1} k_h$ (eq. 7.9)

Where:

$k_h = 1.0 - 0.6\frac{h[cm]-12.5}{47.5} = 1.0$ is the size factor (h = 12.5 cm which is the height at the notch in the CMOD tests)

$\sigma_3 = 0.37 f_{R4} k_h$ (eq. 7.10)

$\varepsilon_2 = \varepsilon_1 + 0.1‰$

$\varepsilon_3 = 25‰$`

Note that for the stresses (σ_1, σ_2 & σ_3) at first the direct results from the CMOD experiments are used and safety factors are added in the calculation. These factors do not have a name but are presented as numbers in equations 7.3, 7.9 and 7.10. For the calculations the mean values from the CMOD tests are used as well as the mean values from the compressive strength experiments. The latter are however reduced to a characteristic value as done in chapter 6.

Results for different fibre amounts

For the different amounts of fibres the test results from the CMOD and compressive strength test result in the moment capacities as displayed in table 7.1. Note that from chapter 6, only the relevant results are used for these calculations as some of the experiments provided values that are not representative. The first batch of results included specimens with 15, 30, and 55 kg/m3 fibres. Those results are not presented here as the calculations would not give the right representation.

Table 7.1: Moment capacities for different minibar reinforced concrete batches + steel fibres from first batch

Fibre amount $[kg/m^3]$ + mixture	$M_{Rd,crack}$ $[kNm/m]$	$M_{Rd,SLS}$ $[kNm/m]$	$M_{Rd,ULS}$ $[kNm/m]$	f_{ck} $[MPa]$
RT20 T1	13.94	15.30	9.96	65.91
RT30 T3	12.20	13.66	12.55	51.44
RT30 T4	13.25	15.13	15.60	58.55
RT30 T5	9.84	11.83	15.25	45.72
SV45 T1	13.08	15.18	16.31	80.50

As can be seen in table 7.1 the results show that the 4th batch with 30 kg/m3 minibars has a sufficient capacity to withstand the SLS and ULS design moments. However the 3rd batch does not have enough capacity. A reason for this is the concrete compressive strength. As seen in the last column the characteristic compressive strength of the third batch was significantly lower (51.44 compared to 59.62. A lower compressive strength has an impact on all values obtained from the CMOD test. This becomes clear when comparing to the batch with 20 kg/m3 minibars. The compressive strength here was 65.91 MPa compared to the 59.62 of the 4th batch. For the batch with 20 kg/m3 fibres this results in a higher cracking and SLS moment capacity. However 20 kg/m3 is not sufficient even with a higher compressive strength as the ULS capacity is lower (9.96 compared to 15.69. This drop is due to failure of the fibres. Where 30 kg was sufficient to have a capacity at ULS which was higher than it was for SLS, 20 kg shows the fibres losing their function in holding the concrete together. The failure mechanism is pulling out of the fibres, as a result the capacity drops with each fibre being pulled out.

It is expected that the lower concrete compressive capacity in batch 3 and 4 (30 kg/m3) is mainly due to the small scale of the experiment and the difficulty of mixing the concrete in two separate mixers (first a shear mixer for the self-compacting concrete and then a regular mixer for adding the fibres). With a lower fibre amount the mixing process was easier and thus the results were more consistent.

When mixing the concrete and the fibres in a mixer truck, the consistency increases as well as the ULS strength. However the cracking and SLS capacities are lower with the fifth batch due to a lower compressive strength. From previous tests it is shown that the compressive strength can be better and therefore the mixture should be checked for flaws. When that is done the mixture is validated.

7.1.2 Shear Capacity + Punching Shear

For the shear capacity of the fibre reinforced apron, again the value for f_{R4} is used. The total shear capacity is the added value of the capacity resulting from rebars, prestressing and the fibres. Since the first two are not present in this design, equations 7.11 – 7.14 can be used to calculate the shear resistance.

$$V_{Rd} = V_{Rd,c} + V_{fd} = (v_{min} + v_{fd})bd = (0.035k^{\frac{3}{2}}\sqrt{f_{ck}} + 0.7k_f k_1 \tau_{fd})bd \qquad \text{(eq. 7.11)}$$

Where:

$k_f = 1 + n\left(\frac{h_f}{b_w}\right)\left(\frac{h_f}{d}\right) \leq 1.5$ is the factor taking contribution of flanges in T-section into account ($n = 0$ for rectangular cross-sections as seen in equation 7.13 due to $b_f = b_w$ so $k_f = 1$) (eq. 7.12)

$$n = \frac{b_f - b_w}{h_f} \leq 3 \; and \; n \leq \frac{3b_w}{h_f} \qquad \text{(eq. 7.13)}$$

$k_1 = k = 1 + \sqrt{\frac{200}{d}} \leq 2$ is the factor taking size effect into account ($d < 200$ so $k = 2$)

$$\tau_{fd} = 0.12 f_{R4} \qquad \text{(eq. 7.14)}$$

As mentioned before the design must be validated for punching shear failure. There are two governing situations where in the first the collision load is applied at the side of the apron between two supports. This is the location where the maximum moment of 14.96 kNm/m occurs in the cross-section. In the second situation the load is applied in a corner of the plate. In this second situation the load is overlapping the support plate. In this situation there can be two scenarios, either the load is fully taken by the supports which is proven to have sufficient strength according to the support calculations from (Ingenieursburo Van Der Werf En Lankhorst, 2021) or the load is taken by the concrete. The moment in these two scenarios is set to 0 as the load is applied directly above the support.

For the first and second load situations the situations presented in figure 7.5 are applicable following from Eurocode 2 (NEN, 2011).

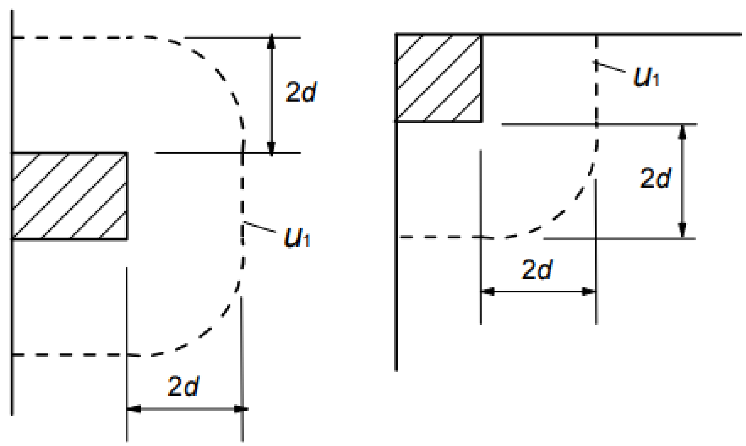


Figure 7.5: Load situations 1 and 2 with circumferences

For the punching failure check a design stress needs to be calculated. Following Eurocode 2 this is done according to equations 7.15 – 7.17.

$$v_{Ed} = \beta\frac{V_{Ed}}{u_1 d} \qquad \text{(eq. 7.15)}$$

Where:

$d = 100\ mm$ is the effective thickness of the apron (due to the fibres the entire thickness is effective)

u_1 is the control circumference depicted in figure 7.5.

$$\beta = 1 + k\frac{M_{Ed}}{V_{Ed}} \cdot \frac{u_1}{W_1} \qquad \text{(eq. 7.16)}$$

$$W_1 = \frac{c_1^2}{2} + c_1 c_2 + 4c_2 d + 16d^2 + 2\pi d c_1 \qquad \text{(eq. 7.17)}$$

$c_1 = 500\ mm$ (only relevant for load situation 1)

$c_2 = 1000\ mm$

k follows from table 7.2 following Eurocode 2.

Table 7.2: Values for k for rectangular areas of loading

c_1/c_2	$\leq 0,5$	1,0	2,0	$\geq 3,0$
k	0,45	0,60	0,70	0,80

The resulting design stresses and parameters for the calculation are presented in table 7.3 showing that load situation 2 is governing due to the decreased circumference.

Table 7.3: Design punching shear stresses for fibre reinforced concrete

Load situation	$u_1\ [mm]$	$\beta\ [-]$	$v_{Ed}\ [MPa]$
1	3128	1.28	0.20
2	1814	n/a	0.28

Table 7.4 shows the resulting shear capacities for the different batches together with the unity checks for punching shear failure.

Table 7.4: Shear capacities for different minibar reinforced concrete batches + steel fibres from first batch

Fibre amount $[kg/m^3]$ + mixture	$v_{min}\ [MPa]$	$v_{fd}\ [MPa]$	$v_{Rd}\ [MPa]$	$f_{ck}\ [MPa]$	U.C. Shear
RT20 T1	0.80	0.65	1.45	65.91	0.19
RT30 T3	0.71	0.98	1.68	51.44	0.16
RT30 T4	0.76	1.25	2.00	58.55	0.14
RT30 T5	0.67	1.40	2.07	45.72	0.13
SV45 T1	0.89	1.50	2.39	80.5	0.12

The values for the shear capacity are all sufficient to withstand the design collision/punching load of 50 kN.

7.2 Calculation and verification of BFRP Bar Reinforced Aprons

For the BFRP bar reinforced aprons the material and strength properties of the bars are directly taken from the supplier ReforceTech. For the different bar diameters the properties are enlisted in table…

When making a comparison with results from experiments it is important to use the resulting concrete compressive strength of the concrete cubes without fibres and to disregard safety factors in the resistance calculations.

7.2.1 Moment Capacity

The design for the moment capacity with BFRP bars consists of reinforcement in both X and Y direction. The governing moments are:

$$M_{Ed,y} = 14.96\ kNm/m$$

$$M_{Ed,x} = 8\ kNm/m$$

The reinforcement in y direction is placed closest to the edge and the reinforcement in x direction is placed next to it. The reason for this is the increased lever arm for the reinforcement in y direction. With a higher design moment in this direction, an increased lever arm results in less reinforcement. The moment in x direction is lower, thus already requires less reinforcement. Compared to the design with steel rebars, the bars can also be placed closer to the edge as corrosion does not play a part with the BasBars.

The design moment capacity is calculated using equations 7.18 – 7.22 The tensile force in the BasBars (N_{bt} $[kN/m]$) is set equal to the compressive force in the concrete (N_c [kN/m]) and from this balance the lever arm (z $[m]$) can be calculated. Note that the forces are in kN/m as a unit width of 1 m is taken. The balance of forces is presented in figures 7.6 and 7.7 for both x and y direction. In these calculations the yield strength of the reinforcement is reached with corresponding ultimate strains as presented in these figures.

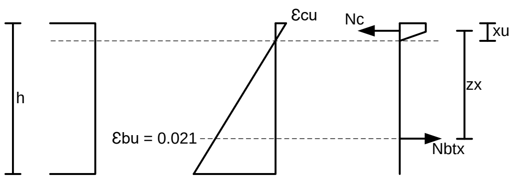


Figure 7.6: Strain diagram and balance of forces in x direction

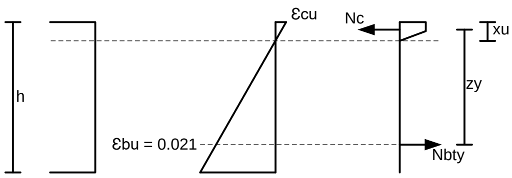


Figure 7.7: Strain diagram and balance of forces in y direction

$M_{Rd} = N_{bt} z\ [kNm/m]$ (eq. 7.18)

Where:

$N_{bt} = A_b n f_{bd}\ [kN/m]$ (eq. 7.19)

With:

$A_b = 31.67\ mm^2\ (only\ BasBars\ with\ \phi_b = 6\ mm\ are\ used)$

$n = number\ of\ rebars\ per\ meter\ [-/m]$

$f_{bd} = 0.7 \frac{f_{bu}}{\gamma_b} = 0.7 \frac{904}{1.2} = 527.33\ N/mm^2$

And:

$z_x = h - c_{nom} - 0.5\phi_b - \phi_b - \beta x_u$ (eq. 7.20)

$z_y = h - c_{nom} - 0.5\phi_b - \beta x_u$ (eq. 7.21)

With:

$h = 100\ mm$

$c_{nom} = 15\ mm = concrete\ cover\ to\ edge\ of\ first\ reinforcement$

$\beta = \frac{7}{18}$

$x_u = \frac{N_c}{\alpha f_{cd}}$ (eq. 7.22)

$N_c = N_{bt}$

$\alpha = 0.75 = shape\ factor\ concrete\ compression\ zone$

$f_{cd} = \frac{f_{ck}}{\gamma_c} = \frac{64.78}{1.5} = 43.19\ N/mm^2\ (result\ from\ compression\ tests)$

For different numbers of rebars the lever arms and the forces change. For both directions (x and y) the results for different numbers of rebars are presented in table 7.5.

Table 7.5: Design moment capacities for different numbers of rebars

Basalt Reinforcement	$N_{bt}\ [kN/m]$	$z\ [mm]$	$M_{Rd}\ [kNm/m]$
$n_{x_+} = n_{x_-} = 8$	133.6	74.4	9.94
$n_{y_+} = 14$	233.8	79.2	18.52
$n_{x_+} = n_{x_-} = 7$	116.9	74.6	8.72
$n_{y_+} = 12$	200.0	79.6	15.95
$n_{y_-} = 4$	66.8	82.6	5.52
$n_{x_+} = n_{x_-} = 6$	100.2	74.8	7.49
$n_{y\_+} = 11$	183.7	79.8	14.66
$n_{y_-} = 3$	50.1	81.4	4.08

From these results it shows that with $n_{y_+} = 12$, $n_{y_-} = 4$ and $n_{x_+} = n_{x_-} = 7$ the strength criteria for the moment capacity are met. In x direction the capacity $M_{Rd,x_+} = M_{Rd,x_-} = 8.72\ kNm/m$ results in unity checks equal to $UC_{M_{x_+}} = 0.92$ and $UC_{M_{x_-}} = 0.90$ and in y direction $M_{Rd,y_+} = 15.95\ kNm/m$ and $M_{Rd,y_-} = 5.52\ kNm/m$ result in $UC_{M_{y_+}} = 0.94$ and $UC_{M_{y_-}} = 0.86$.

7.2.2 Shear Capacity + Punching Shear

The shear capacity is calculated as presented in equations 7.23 – 7.27 For the shear capacity the concrete compressive strength and the percentage of reinforcement is important.

$v_{Rd} = \max(v_{min}; v_{Rd,max})$ (eq. 7.23)

Where:

$v_{min} = 0.035k^{\frac{3}{2}}\sqrt{f_{ck}} = 0.65\ MPa$ (eq. 7.24)

$v_{Rd,max} = C_{Rd}k(100\rho_b f_{ck})^{\frac{1}{3}}$ (eq. 7.25)

With:

$k = 1 + \sqrt{\frac{200}{d}} \leq 2$ (eq. 7.26)

$C_{Rd} = \frac{0.18}{\gamma_c} = 0.12$

$\rho_b = \frac{A_b n}{bd}$ (eq. 7.27)

Due to a decreased effective height as a result of the rebar placement the punching shear stress changes. The effective height can now be taken as the average of the effective heights in x and y direction. Note that only the main reinforcement (not the hogging reinforcement is taken into account here.

$d = \frac{1}{2}(d_x + d_y) = 79\ mm$

As a result the design stress increases to MPa as presented in table 7.6.

Table 7.6: Design punching shear stresses for BasBar reinforced concrete

Load situation	$u_1\ [mm]$	$\beta\ [-]$	$v_{Ed}\ [MPa]$
1	2996	1.31	0.28
2	1748	1	0.36

It is questionable if equation 7.25 still holds due to the lower modulus of elasticity of the BasBars. In this design however the v_{min} is governing most of the time as shown in table 7.7. This is due to the low reinforcement ratios. Even if equation 7.25 does not hold it would not matter in this situation.

Table 7.7: Shear capacities for different numbers of rebars

Basalt Reinforcement	$d\ [mm]$	$v_{Rd}\ [MPa]$	ρ_b	$UC_{ps}\ [-]$
$n_{x_+} = 8$	76	0.65	0.0033	0.55
$n_{y_+} = 14$	82	0.69	0.0054	0.52
$n_{x_+} = 7$	76	0.65	0.0029	0.55
$n_{y_+} = 12$	82	0.65	0.0046	0.55
$n_{x_+} = 6$	76	0.65	0.0025	0.55
$n_{y_+} = 11$	82	0.65	0.0042	0.55

7.2.3 Design details

The detailing of the design with the BFRP bars is for this research limited to the spacing, anchorage lengths, the concrete cover for the reinforcement and the overall design technical drawings.

Spacing

Following from the moment capacity calculation and the shear check the design with BasBars consists of 12 bars with $\phi_b = 6\ mm$ per meter in y direction and 7 in x direction. This design would result in a spacing between the centre of the BasBars of $s_{x_+} = 1000/7 = 143\ mm$, $s_{y\_} = 1000/250 = 250\ mm$ and $s_{y_+} = 1000/12 = 83.33\ mm$. Using more workable spacings is required, therefore $s_{x_+} = s_{x\_} = 140\ mm$, $s_{y\_} = 250\ mm$ and $s_{y_+} = 80\ mm$ are used.

Anchorage length

The anchorage length is calculated to be 100 mm in all directions. The calculation is presented in Appendix G.

Concrete cover

The concrete cover that is used I the design with the BasBars is 15 mm. This is equal to the nominal concrete cover as determined using chapter 4.4.1 from Eurocode 2 (NEN, 2011). This cover is equal to:

$c_{nom} = c_{min} + \Delta c_{dev}$ (eq. 7.28)

Calculations done in appendix G result in $c_{min} = 10, \Delta c_{dev} = 5\ \&\ c_{nom} = 15\ mm.$

Technical drawings

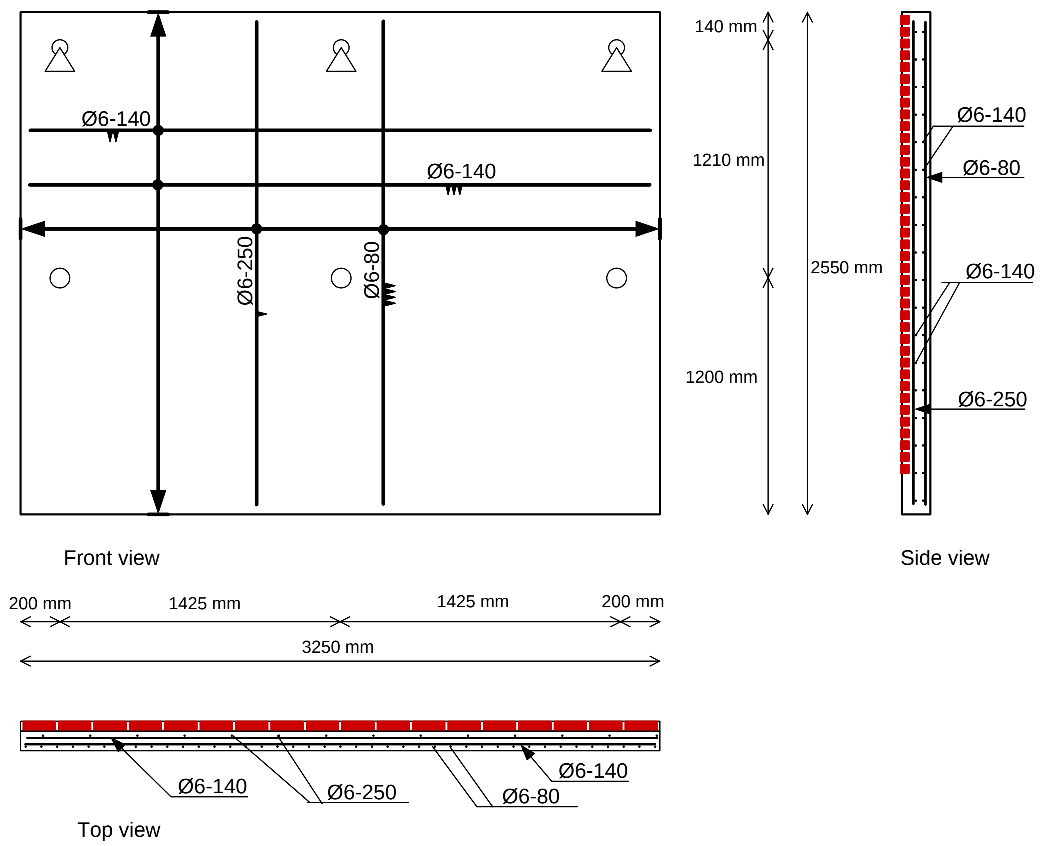


Figure 7.9: Technical drawing of BFRP-bar design (front, top and side view)

7.3 Calculation and verification of Steel Reinforced Aprons

In chapter 3 two steel designs are presented. One with the steel fibres which has been verified with the experiments in chapter 6 and the other with steel rebars. The design for that specific project is significantly different as mentioned before. Therefore in this chapter the design with steel rebars is reproduced for the same design criteria as is done for the basalt reinforced designs. The design calculation is the same as in chapter 7.2 for the BFRP bar design.

7.3.1 Moment and Shear Capacity

In the design with steel rebars the following parameters change:

$$A_s = 50.27\ mm^2\ (only\ rebars\ with\ \phi_s = 8\ mm\ are\ used)$$

$$f_{yd} = \frac{f_{yk}}{\gamma_b} = \frac{500}{1.15} = 435\ N/mm^2$$

$$c_{nom} = 40\ mm = concrete\ cover\ to\ edge\ of\ first\ reinforcement$$

The change in concrete cover is due to the risk of corrosion of the steel reinforcement. Following Eurocode 2 as done in 7.2.3 the Environmental Class increases from X0 to XC4 (for partially dry and wet conditions) and the strength class also moves up from S2 to S3 for a design lifespan of 50 years. This results in a $c_{min} = 35\ mm$ and with the deviation of 5 mm added, 40 mm is obtained. A design with the same design lifespan as for the BFRP-bars (100 years) the cover would be 50 mm which is not feasible with a thickness of 100 mm. This increase in concrete cover leads to a significant drop in lever arm and with a lower strength of the rebars the result is that more reinforcement is needed. There is however a small advantage as the reinforcement is placed close to the middle of the cross-section, no additional reinforcement is needed for moments in the other direction (so $M_{Ed,x\_}\ and\ M_{Ed,y\_}$).

All other equations and parameters stay the same. The resulting number of rebars and the corresponding capacities are displayed in table 7.8 and 7.10.

Table 7.8: Moment capacities of steel rebar design for different numbers of rebars

Steel Rebars	$N_{st}\ [kN/m]$	$z_+\ [mm]$	$z_-\ [mm]$	$M_{Rd_+}\ [kNm/m]$	$M_{Rd_-}\ [kNm/m]$
$n_x = 8$	174.9	45.90	49.90	8.03	8.73
$n_y = 14$	306.1	52.32	40.33	16.02	12.34
$n_x = 7$	153.1	46.16	50.16	7.07	7.68
$n_y = 13$	284.3	52.59	40.59	14.95	11.54

For the punching shear resistance the occurring stress again increases due to a decreased effective depth. With the steel rebars the effective depth $d = 52\ mm$.

Table 7.9: Design punching shear stresses for steel rebar reinforced concrete

Load situation	$u_1\ [mm]$	$\beta\ [-]$	$v_{Ed}\ [MPa]$
1	2827	1.37	0.46
2	1663	1	0.58

Table 7.10: Shear capacities of steel rebar design for different numbers of rebars

Steel Rebars	$d\ [mm]$	$v_{Rd,max}\ [MPa$	ρ_s	$UC_{ps}\ [-]$
$n_x = 8$	48	0.91	0.0084	0.64
$n_y = 14$	56	1.04	0.0126	0.56
$n_x = 7$	48	0.87	0.0073	0.66
$n_y = 13$	56	1.01	0.0117	0.57

When looking at the spacing of the reinforcement bars in y direction s = 75 mm would result in an average of 13.33 bars per meter. From table 7.8 and 7.10 it follows that this is sufficient as the moment resistance was already close to the design moment with 13 bars per meter. In x direction with 8 rebars per meter width a spacing of 125 mm is applied. Note that no technical drawing for this design is available as this design is only used for a material use comparison.

8 ECI calculation via LCA

8.1 LCA Procedure

The LCA procedure in this research contains the modules A, C and D. These modules are presented in figure 8.1. Here the Cradle to gate with options modules C1-C4 and D is used. Modules A1-A3 represent the product stage and govern the collection of raw material, transport and production. Module C4 represents the demolishing/crushing/smart crushing of the materials and the energy that is put into the material at the end of life. Category D represents the rest value of the material. If the result from crushing and separating is a material (secondary) that is as good as a primary material, then the value in category D can be taken as the value for module A1-A3.

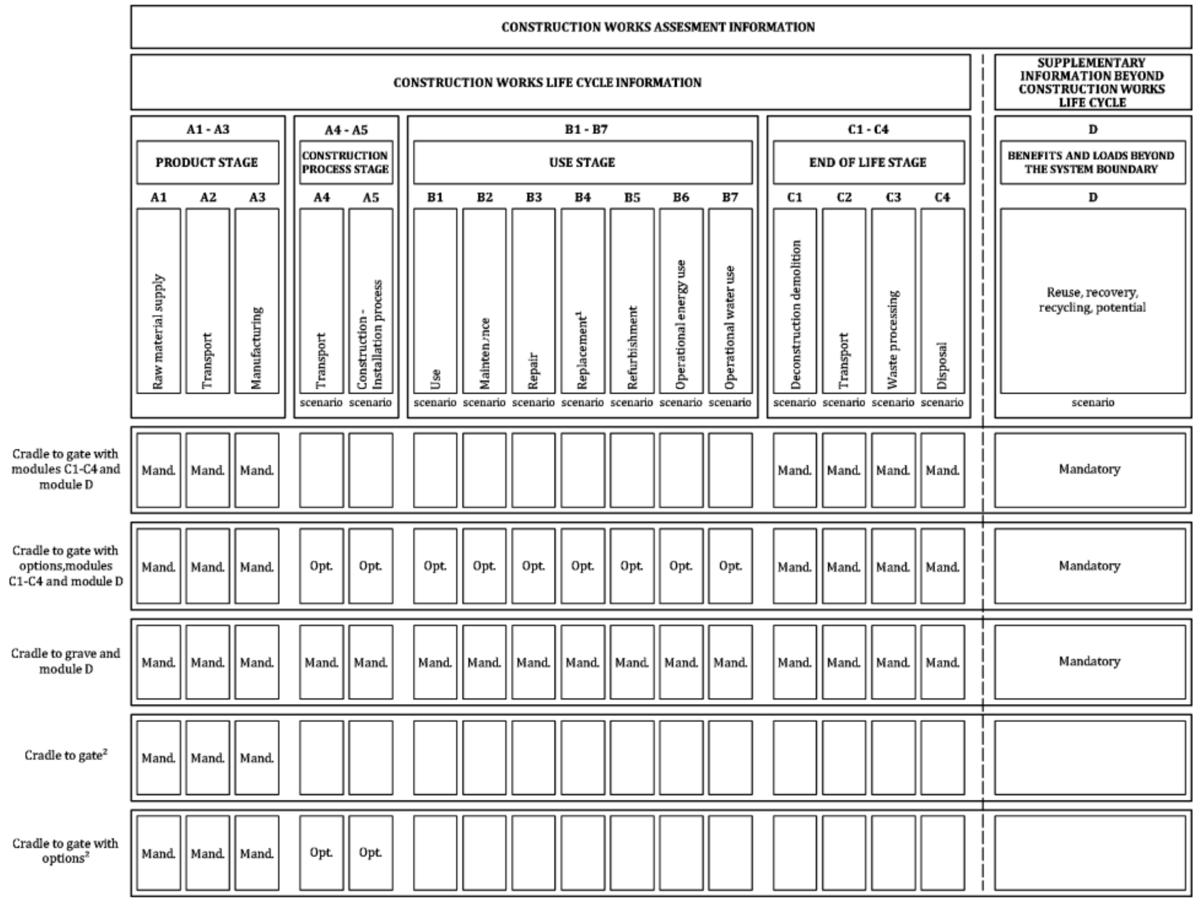


Figure 8.1: Types of EPD with respect to life cycle stages covered and life cycle stages and modules for the construction works assessment (NENd, 2019)

For each module the 11 (or more if possible and less if not found for certain materials) impact categories are compared. These impact categories are presented in table 8.1 with the needed information and monetary value. This monetary value is a standardized costs indicator for when a kilogram of a waste/harm-full product is produced. CO2 for example has a monetary value of 5 cents per kilogram emission and it is placed under global warming potential as the impact category.

Table 8.1: Impact categories used for ECI calculations

Impact Category	Unit	Monetary value €/kg
Abiotic Depletion Potential non-fuel (ADnf)	kg Sb eq	0.16
Abiotic Depletion Potential fossil-fuel (ADf)	kg Sb eq	0.16
Global Warming Potential (GWP)	kg CO_2 eq	0.05
Ozone Layer Depletion Potential (ODP)	kg CFC-11 eq	30
Photochemical Oxidation Potential (POCP)	kg C_2H_4 eq	2
Acidification Potential (AP)	kg SO_2 eq	4
Eutrophication Potential (EP)	kg PO_4^{2-} eq	9
Human Toxicity Potential (HT)	kg 1,4-DB eq	0.09
Ecotoxicity Potential, Fresh water (FAETP)	kg 1,4-DB eq	0.03
Ecotoxcity Potential, Marine water (MAETP)	kg 1,4-DB eq	0.0001
Ecotoxicity Potential, Terrestrial environment (TETP)	kg 1,4-DB eq	0.06
Water Depletion Potential (WDP)	m^3	n/a

For the materials in the concrete mixture it is assumed that they will all go through the smart crusher as explained in chapter 1.1 This process allows for full reuse as primary materials of the cement, filler and aggregates. The steel reinforcement can be separated using magnets and can be sold as scrap metal giving it a rest value (in terms of euro/kg or euro/m3) presented in module D. For the basalt rebars and fibres the rest value is different. The fibres and rebars cannot be send back to the factory and go through the fabrication process again, where the steel can be melted again the thermal process the basalt has been through is one way. However if after crushing the materials end up in the course/fine fraction of the aggregates, this does not reduce the value of the end product. This is one scenario that can be taken into account. In this research however it is assumed all the basalt material ends up separated and will have a rest value as presented in module D as provided by the EPD.

8.2 LCA results

In table 8.2 and 8.3 the results for the different designs are presented in terms of ECI value for one apron with an approximated volume of 0.83 m^3. In table 8.2 the values for HT, FAETP, MAETP and TETP have been removed from modules C and D. The reference lifespan is added for all designs. Here for both basalt reinforced designs both a lifespan of 50 years as well as 100 years is added for comparison. For this change between 50 and 100 years no changes in the concrete mixtures are taken into account. ECI-values for the standard mixture (without fibres) is also presented and indicates the base value due to material usage for the concrete itself.

Table 8.2: ECI values for different designs

1 apron ECI / yr	**Traditional mixture (no fibres) 50 yrs**	**BasBars 50 yrs**	**BasBars 100 yrs**	**B500 Steel 50 yrs**	**30 (Minibars) 50 yrs**	**30 (Minibars) 100 yrs**	**45 (Dramix 5D) 50 yrs**
A1-A3	0.36	0.48	0.24	0.59	0.54	0.27	0.51
C1-C4	0.02	0.04	0.02	0.02	0.02	0.01	0.02
D	-0.08	-0.09	-0.05	-0.10	-0.08	-0.04	-0.09
Total	0.30	0.43	0.21	0.51	0.48	0.24	0.44

When looking at the results it can be seen that the design with BasBars is performing better than both steel designs even when the lifespan is reduced to 50 years. In case of the Minibar design the results show that the design for 100 years performs better than the steel reinforced designs and the 50 year design performs intermediate. However even if the lifespan does not reach 100 years it can still be said that the designs perform better seeing as the toxicity values have not yet been added fully and the designs already lie close to eachother when assuming a lifespan of 50 years.

Part III
Discussions and Conclusions

9 Discussions, Conclusions and Recommendations

In this chapter a discussion is presented together with a conclusion answering the research question to end with some recommendations for possible further research or use of this research.

9.1 Discussions

In this chapter a reflection is given on the methodology and the execution of the research. This is done by going through all the steps taken to get to the conclusions presented further on in this chapter.

9.1.1 Literature study

In the first steps of this research a literature study is performed. The current quay wall apron design by ABT is used as a case study to form a foundation of the new reinforcement designs. This foundation consists of the design criteria/dimensions and the applied loads. Here it is assumed that these criteria stay the same for all designs elaborated in this research and thus small changes in self-weight are neglected. These assumptions are justified when looking at the impact of the self-weight of the structure since the self-weight does act in the direction transverse to that of the governing loads (in-plane vs out-of-plane).

After taking over these criteria for the new designs, research is performed into which properties are requested and how these are obtained. Here it is assumed that for the basalt reinforcement (so the Minibars and the BasBars) identical experiments can be performed as for steel reinforcement. These experiments contain CMOD-tests for the flexural strength of fibre reinforced concrete and bending tests for the rebars. From the certificates obtained from ReforceTech (the supplier/producer of the basalt reinforcement) it is confirmed that these experiments are the correct ways to determine the properties that are needed for design calculations.

Part of the literature study is also the collection of environmental data on the different materials that are used. This data is collected in the form of EPD's for the different (raw) materials. Where for the different materials used in the concrete mixtures and the basalt reinforcement full EPD's are available this cannot be said for the steel reinforcement. The EPD's obtained for the steel reinforcement do not contain values concerning Human Toxicity and Terrestrial/Marine-water/Fresh-water toxicity. Therefore these values are neglected for the other materials as well when comparing the designs later on. Here the assumption is made that this does not influence the end-result significantly. This is however something that should be investigated further to fully verify the results.

9.1.2 Experimental research

The experimental research concerning the different reinforcement types consisted of strength tests and an environmental impact comparison. This part of the research starts with the different concrete mixtures that are used. The mixtures are constantly updated and changed to overcome problems such as segregation or bad workability. In this process three test batches (consisting of numerous concrete batches) are prepared. For the first batch a shear mixer is used. This shear mixer however is said to be breaking the Minibars and thus the results of test session 1 have been neglected for further calculations. To overcome this problem the concrete for the second session has been transferred from the shear mixer to a regular mixer before adding the Minibars. The results of the second session therefore show strength values that are comparable to those of the steel fibres and it can be said that this mixing technique works. It is however still hard to get consistent mixtures so a point of discussion here is if this technique is to be used further on in the research. Therefore in the third session a mixer truck is used and this sees the results and the mixture to be more consistent for the Minibars. However lower strength values are obtained questioning the concrete mixture. The mixture itself therefore becomes part of the discussion as it is adjusted by a layman and should in fact be made and executed by a specialist. When looking at the results that are produced now regardless of the consistency there is potential and the assumption is therefore that if the mixture is perfected and executed by a specialist, that from all results the best parameters can be taken and assumed to form the potential strength parameters for the design. However this does need more research as is mentioned later on in the recommendations.

From the experiments performed on the BasBars it is shown that the concrete mixture has sufficient strength capacities when made without fibres but the experiments performed do have to be checked beforehand on different aspects. Where some beams failed due to lack of anchorage-length, this was not the assumed failure mechanism beforehand. The capacities of the BasBars where already confirmed and certificated and are less dependent on the concrete mixture (where all strength values in fibre reinforced concrete depend on the concrete strength). Therefore the design made with BasBars in chapter 7 can still be validated by the use of these known strength parameters together with the more consistent values obtained from the concrete mixtures without fibres. It must however be said that due to the significant lower density of the BasBars compared to the concrete mixture and the use of a mixture with small aggregates it is likely that the BasBars tend to float up. This should be encountered when this type of reinforcement is used, as also follows from the conclusions in the next part of this chapter.

When looking at the analysation of the test results and mainly the results of the bending tests it can be said that at some points it is difficult to separate different failure mechanisms. Due to the use of force controlled tests the testing machine stopped when detecting failure. It is better if displacement controlled tests are used instead of force controlled. That way the machine does not stop at failure and clearly shows crack patterns. Besides this, direct load transfer to the supports is not taken into account in this research. Especially in the small scale experiments with a small span direct load transfer can cause different outcomes to experiments. In further research this must be taken into account either by scaling up or making visible what the impact of direct load transfer can be to the test results of smaller specimens.

After performing the experiments and analysing the results, these results are used to calculate strength capacities. This is done in chapter 7 where official guidelines are followed to get to the results presented. However it must be noted that these results can be interpreted different by other parties. In this research the capacity of the Minibars mixture is deemed to be sufficient based on the different test results, other parties might need more verification as some results show lower capacities. Where the cause for lower values in this research is put with a low expertise level in execution it still must be proven that with a high expertise level by a (concrete) specialist results do indeed match earlier found values or even find improvements.

The next part of the experimental research is the comparison on environmental level. When looking at the results from the LCA calculations the following assumptions are kept in mind, where the designs with basalt reinforcement are claimed to have a lifespan of 100 years where the steel reinforced designs can only have a lifespan of 50 years. This leads to a result in favour of the basalt reinforcement. How these results might change in other conditions (other than in a water environment where risk of corrosion reduces the lifespan of steel reinforced designs) can be further investigated and are assumed to lead to designs in favour of steel reinforcement. It should also not be neglected that values for human toxicity etc (as mentioned above) are not taken into account in the comparison making the results less reliable from some perspectives.

9.2 Conclusions

In this thesis the following research question is answered: ***"Can the design of the prefab quay wall aprons be optimised in terms of environmental impact (ECI value) when Basalt Fibre Reinforced Polymer (BFRP) bars and/or minibars are used instead of steel rebars and steel fibres whilst the structural performance remains guaranteed?"***. To come to a conclusion the 5 presented sub-questions are answered in order to end with answering to the main research question.

- After setting up the research the first question before performing any experiments/tests is: 'Which material properties from the new reinforcement types are needed for the design of the quay wall aprons and which experiment has to be performed to obtain these properties?' To answer this question a distinction is made between fibre reinforced concrete and regular bar reinforced concrete. For fibre reinforced concrete both the compressive capacities of the concrete mixture as well as the flexural strength capacities are needed. These contain the compressive strength (fck), modulus and elasticity (Ec), Limit of Proportionality (LOP/fctmfl) + tensile capacities (fr1- fr4). The fck and Ec can be found with a cube compression test and the tensile and flexural strength can be found with the CMOD tests. For the bar reinforced concrete the material properties of the reinforcement can all be found and taken from certificates and documents. The concrete compressive capacities still need to be found by performing the same test as for the fibre reinforced concrete, so a concrete compression test. These two types of tests mentioned are therefore performed in this research together with 3 and 4 point bending test to look at detailing and cracking behaviour.

- With the parameters and corresponding tests the next questions are: 'What is the optimal amount of Minibars?' and 'What is the optimal distribution of BasBars?'.
  For the minibars the optimal fibre amount is found to be around 30 kg/m^3. This amount together with the right concrete mixture gives positives strength results in calculations for the moment- and shear capacities. This 30 kg/m^3 fibre content is aimed to perform similar to the steel fibre design consisting of 45 kg/m^3 Dramix 5D steel fibres. This design gives comparable capacities in the design calculations again with the right concrete mixture.
  In the case with the BasBar reinforcement mesh the design consists of reinforcement in x and y direction. The optimal spacing of BasBars in those directions are respectively 140 mm and 80 mm. For the design only bars with a diameter of 6 mm are used as they have the highest strength capacities. This design results in a use of 13 kg of BasBars per cubic meter of concrete compared to a steel design giving the same capacities whilst guaranteeing structural safety where 84 kg/m^3 is found.
- During this design phase the fourth question is also answered concerning the methods of verification of the designs. The different methods of verification used in this research are both theoretical and experimental. The fibre reinforced design is verified by performing tests to check the material parameters used for design calculations to then perform the validation by following the design codes and applying the right safety-factors. In the case of the design with BasBars the design is verified using the codes and guidelines combined with presented parameters for the reinforcement as these where already validated by the supplier/producer ReforceTech.
- The last sub-question that has to be answered before the main research question can be answered is 'After obtaining new designs which are verified and comparable to the steel reinforced designs in terms of strength, what is the difference in Environmental Cost Indicator (ECI) value?'. The differences in ECI value form the most important results in this thesis and provide the setup for the answer of the main research question. The ECI values that can be found in table 8.2 are again presented here in table 9.1. Note the distinction between the design lifespan of the different designs. For the steel reinforced designs the design lifespan could not exceed 50 years whereas the lifespan for the basalt reinforced designs is assumed to be 100 years. For this comparison also the values for basalt with a design life span of 50 years are presented. From this table it can be concluded that in the case the lifespan of the Minibar design is indeed 100 years, the ECI value (per year) is €0.24 compared to the €0.44 per year for the steel fibre design. The BasBar design shows even better results with €0.21 per year and the steel rebar design is worse with €0.51 per year.

Table 9.1: ECI values for different designs

1 apron ECI / yr	Traditional mixture (no fibres) 50 yrs	BasBars 50 yrs	BasBars 100 yrs	B500 Steel 50 yrs	30 (Minibars) 50 yrs	30 (Minibars) 100 yrs	45 (Dramix 5D) 50 yrs
A1-A3	0.36	0.48	0.24	0.59	0.54	0.27	0.51
C1-C4	0.02	0.04	0.02	0.02	0.02	0.01	0.02
D	-0.08	-0.09	-0.05	-0.10	-0.08	-0.04	-0.09
Total	0.30	0.43	0.21	0.51	0.48	0.24	0.44

All together it can be concluded that the design of the prefab quay wall aprons can indeed be optimised in terms of ECI value when BasBars or minibars are used instead of steel rebars and steel fibres. It is shown that structural performance remains guaranteed and given the circumstances (wet conditions) the ECI value for the basalt reinforced designs prove to be better than the steel reinforced designs under the circumstance that the Minibar reinforced design indeed has a lifespan of 100 years instead of 50. The BasBar design provides a better ECI value with a lifespan of 50 years compared to the steel reinforced designs.

9.3 Recommendations

The previous sections in this chapter present the final conclusion of the research. A ECI value comparison between different designs for a quay wall apron is made and it is found that basalt proves to perform better. When looking at the results and the entirety of the research, the following recommendations are given for future research.

Finetuning concrete mixtures

Firstly the concrete mixtures used for the experiments that are performed to form the results of this research should be finetuned in order to obtain more consistent results. In this research the results showed large deviations between different batches with the same contents. A concrete specialist can provide the expertise to get to more consistent and stronger batches. With finetuned mixtures new experiments must be performed to validate the mixtures. Together with finetuning these mixtures, the IPK mixture can also be investigated to see how it performs in terms of strength and environmental impact.

ECI values steel reinforcement

Secondly when checking or using the calculated ECI values it must be kept in mind that there are still values missing in this comparison. The toxicity values for steel fibres and steel rebars is only available for module A and not for modules C and D. In this research the values for the basalt reinforcement are added so if values for human toxicity can be found for steel reinforcement, together with a more representative EPD for steel rebars are found, a better comparison can be made between the designs in this research.

Minibars combined with BasBars

The combination of Minibars and BasBars in a hybrid variant is not a part of this research. Appendix E shows results that are performed with this combination. It must be noted that these experiments are performed with a concrete batch with broken fibres. Still the results showed positive crack patterns with multiple cracks over the length of the beam. It is therefore recommended to perform tests with low fibre amounts combined with rebars to use the strength potential of the bars combined with the positive cracking behaviour due to the fibres.

Recyclability of basalt reinforcement

Even though it is said that the making of the basalt reinforcement is a one way process, the material might still prove worth separating from concrete rubble at the end of life. It is however hard to separate the basalt reinforcement as it is similar in density to the concrete materials and it is not magnetic compared to steel. In follow-up research it is therefore recommended to experiment with this and see what rest-value the basalt has and what is the best method of extraction.

Extra experiments + EC0 Annex D

In this research the bending tests that are performed are all force-controlled. With displacement controlled tests the failure mechanism can be investigated in a better way as the crack patterns are better visualised. Therefore to investigate the failure of both beams with BasBars and Minibars it is advised to perform displacement controlled bending tests. In these experiments it is also recommended to use steel plates at the locations of the rollers. This to prevent a concentrated force injection.

Next to the bending tests it is also advised to perform pull-out tests as these are not performed in this research. A pull-out test can give additional information about the bond strength and if the same rules as for steel rebars can be applied.

For this research Annex D of Eurocode 0 (NENe, 2019) is not followed specifically. For further research this is recommended as it provides a better list of prerequisites on assisting/validating a design by performing experiments and tests.

Optimization of rebar designs

The rebar designs in this research are calculated assuming the maximum moment in the plate is occurring in the entire apron. However in certain areas of the plate this moment never exceeds certain values. The designs can therefore be slightly optimized so that less material is needed.

Preparing the mould

The mock-up presented in this research showed that the preparation before pouring the concrete can be optimized. With better fitting bricks, a different oil application technique and a better way of demoulding, a better result is expected with less damages. It is recommended for further use of these type of moulds (with a brick pattern), that a mould preparation guide is made with the correct way to overcome damages at the visible surface.

References

Abid, A., & Franzén, K. B. (2011). *Design of Fibre Reinforced Concrete Beams and Slabs.* Göteborg, Sweden: Chalmers University of Technology.

ABT. (2022). *Onderzoeksvoorstel Basaltvezelwapening.* ABT.

Baltussen, A. (2022). *20200919_Bepalingsmethode indicators Basalt Minibars.PNG.* Ecochain.

Banibayat, P., & Patnaik, A. (2014). *Variability of mechanical properties of basalt fiber reinforced polymer bars manufactured by wet-layup method.* Elsevier.

Content page CIE4100 Materials and Ecological Engineering. (2020). Retrieved from Brightspace TU Delft: https://brightspace.tudelft.nl/d2l/le/content/288949/Home

Fiore, V., Scalici, T., Bella, G. D., & Valenza, A. (2015). *Composites Part B.* Italy: Elsevier.

Ingenieursburo Van Der Werf En Lankhorst. (2021). *werk: 2822 Hangschorten IPK Amsterdam.*

Jamshaid, H., & Mishra, R. (2016). *A Green Material From Rock: Basalt Fiber - A Review.* Czech Republic;Pakistan: Taylor & Francis Group.

Mohamed, O. A., Hawat, W. A., & Keshawarz, M. (2021). *Durability and Mechanical Properties of Concrete Reinforced with Basalt Fiber-Reinforced Polymer (BFRP) Bars: Towards Sustainable Infrastructure.* MDPI.

NEN. (2002). *NEN-EN 1991 (en), Eurocode 1: Belastingen op constructies- Deel 1-1: Algemene belastingen - Volumieke gewichten, eigen gewicht en opgelegde belastingen voor gebouwen.* NEN.

NEN. (2007). *NEN-EN 14651 + A1 (en): Test method for metallic fibered concrete - Measuring the flexural tensile strength (limit or proportionality (LOP), residual).* NEN.

NEN. (2011). *NEN-EN 1992-1-1+C2 (nl) Eurocode 2: Ontwerp en berekening van betonconstructies - Deel 1-1: Algemene regels en regels voor gebouwen.* Delft: NEN.

NEN. (2020). *NEN-EN 1992-1-1+C2/NB+A1 (nl) National Annex to NEN-EN 1992-1-1+C2 Eurocode 2: Design of concrete structures - Part 1-1: General rules and rules for buildings.* NEN.

NEN. (2021). *NEN-EN 12390-1 (en) Testing hardened concrete - Part 1: Shape, dimensions and other requirements for specimens and moulds.* NEN.

NENa. (2019). *NEN-EN 12350-5 (en): Testing fresh concrete - Part 5: Flow table test.* NEN.

NENb. (2019). *NEN-EN 12390-3 (en): Testing hardened concrete - Part 3: Compressive strength of test specimens.* NEN.

NENc. (2019). *NEN-EN 12390-5 (en) Testing hardened concrete - Part 5: Flexural strength of test specimens.* NEN.

NENd. (2019). *NEN-EN 15804+A2 (en) Sustainability of construction works- Environmental product declarations - Core rules for the product category of construction products.* NEN.

NENe. (2019). *NEN-EN 1990+A1+A1/C2 (nl) Eurocode: Basis of structural design.* NEN.

Palys, T., & Atchison, C. (2014). *Research decisions: Quantitative, qualitative, and mixed method apporaches.* Nelson Education.

Piasecki, M. (2021). *Environmental Product Declaration Type III ITB No. 215/2021: Dramix® Steel fibers for Concrete Reinforcement.* Instytut Techniki Budowlanej (ITB).

Piasecki, M. (2022). *Research work no 01894/21/Z00NZF Environmental Cost Indicator (ECI) calculation for products: Dramix® - steel fibres for concrete reinforcement.* Instytut Techniki Budowlanej (ITB).

Pouwels, N. (2021). *210909_NOT_fase1_eisendocument_DEF_V1.1.* ABT.

ReforceTecha. (2021). *Product Data Sheet: BasBars.* Norway: ReforceTech.

ReforceTechb. (2021). *Product Data Sheet: MiniBars.* Norway: ReforceTech.

RILEM TC. (2003). *RILEM TC 162-TDF: 'Test and design methods for steel fibre reinforced concrete'.* TDF.

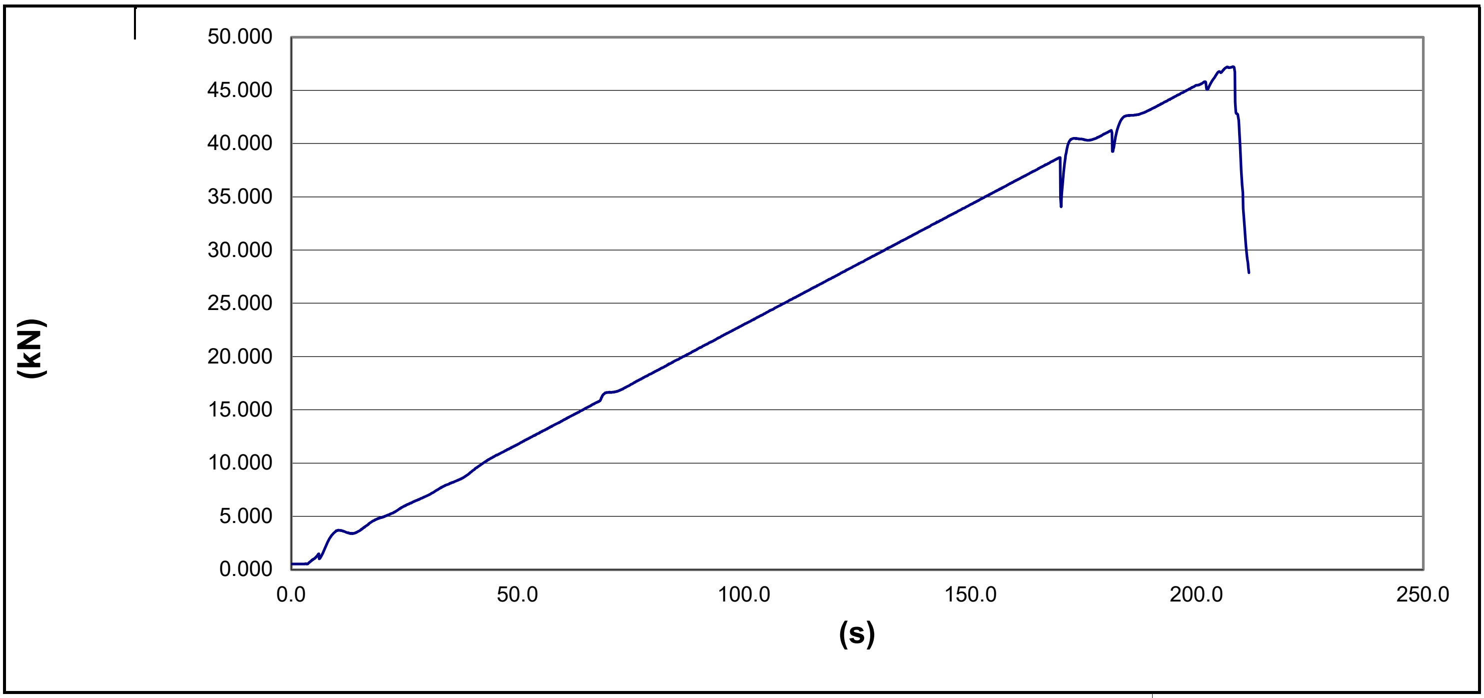
Wang, W., Wang, Y., Li, D., Liu, Y., & Li, Z. (2021). *Bond-slip behavior between basalt fiber reinforced plastic bars and recycled.* Elsevier.

Appendices

Appendix A Test Results

Flexural tests on beams: EN 12390-5

Certificate number	: 001-RT30-Bending-l=600			Certificate date	: -------
Testing machine	: C1701/FR s.n. 22000858				
Client	:				
Reference	:				
Specimen type	: Beam			Cement quantity [kg/m³]	:
Cement type	:			Test date	: 25/10/2022
Sample conditions:					
Condition when received	:			Condition at test time	:
Sampling location	:			Sampling date	: -------
Preparation method	:				
Specimen ID	:				
Dimensions	: *b(mm)*	: 150.00	*h(mm)* : 150.00	Mass [kg]	: 0.000
	l(mm)	600			:
Load Rate [MPa/s]	: 0.1		No of upper roll 1	"L" distance [mm]	500.0
Area [mm2]	: 4500.0	Specimen age	: 28 dd	Preparation date	: -------
Load [kN]	: 47.23			Strength [MPa]	: 10.49
	:				
Notes	:				



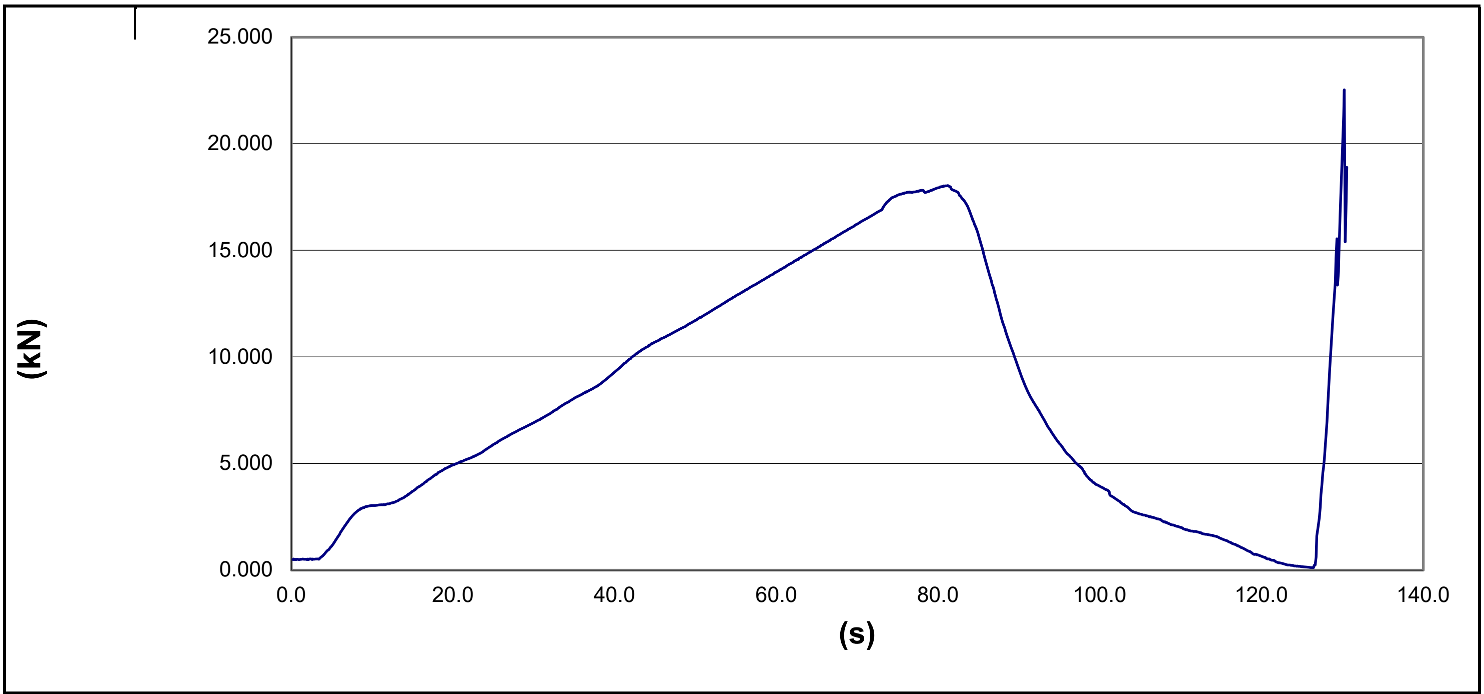
Operator

Operator01

	38.8		
Mcr	4.85	W	562500
Sigmacr	8.622222		

Flexural tests on beams: EN 12390-5

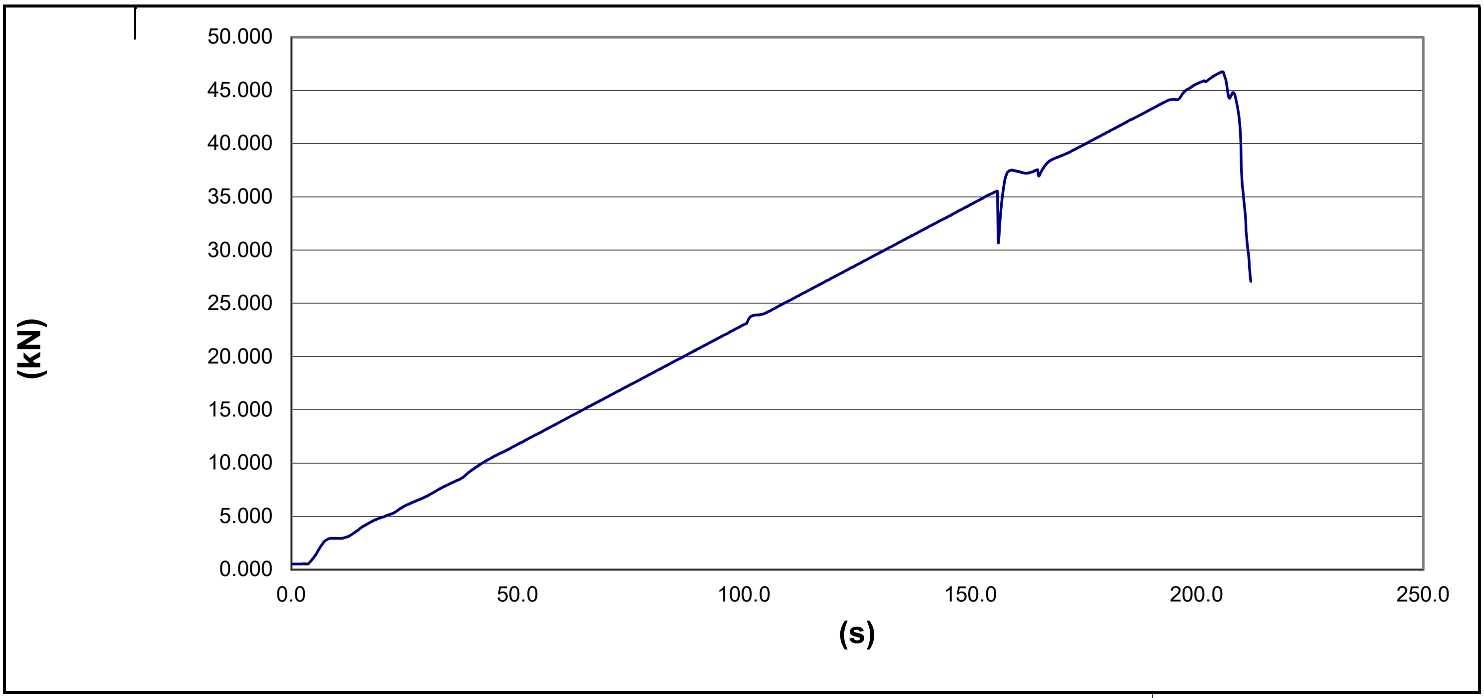
Certificate number	:	001-RT30-Bending-l=600			Certificate date	: -------
Testing machine	:	C1701/FR s.n. 22000858				
Client	:					
Reference	:					
Specimen type	:	Beam			Cement quantity [kg/m³]	:
Cement type	:				Test date	: 25/10/2022
Sample conditions:						
Condition when received	:				Condition at test time	:
Sampling location	:				Sampling date	: -------
Preparation method	:					
Specimen ID	:					
Dimensions	:	*b(mm)*	: 150.00	*h(mm)* : 150.00	Mass [kg]	: 0.000
		l(mm)	600			:
Load Rate [MPa/s]	:	0.1		No of upper roll 1	"L" distance [mm]	500.0
Area [mm2]	:	4500.0	Specimen age	: 28 dd	Preparation date	: -------
Load [kN]	:	22.53			Strength [MPa]	: 5.01
	:					
Notes	:					



Operator
Operator01

Flexural tests on beams: EN 12390-5

Certificate number	:	002-RT30-Bending-l=600				Certificate date	: --------
Testing machine	:	C1701/FR s.n. 22000858					
Client	:						
Reference	:						
Specimen type	:	Beam				Cement quantity [kg/m³]	:
Cement type	:					Test date	: 25/10/2022
Sample conditions:							
Condition when received	:					Condition at test time	:
Sampling location	:					Sampling date	: --------
Preparation method	:						
Specimen ID	:						
Dimensions	:	*b(mm)*	: 150.00	*h(mm)*	: 150.00	Mass [kg]	: 0.000
		l(mm)	600				:
Load Rate [MPa/s]	:	0.1		No of upper roll	1	"L" distance [mm]	500.0
Area [mm2]	:	4500.0	Specimen age	:	28 dd	Preparation date	: --------
Load [kN]	:	46.74				Strength [MPa]	: 10.39
	:						
Notes	:						



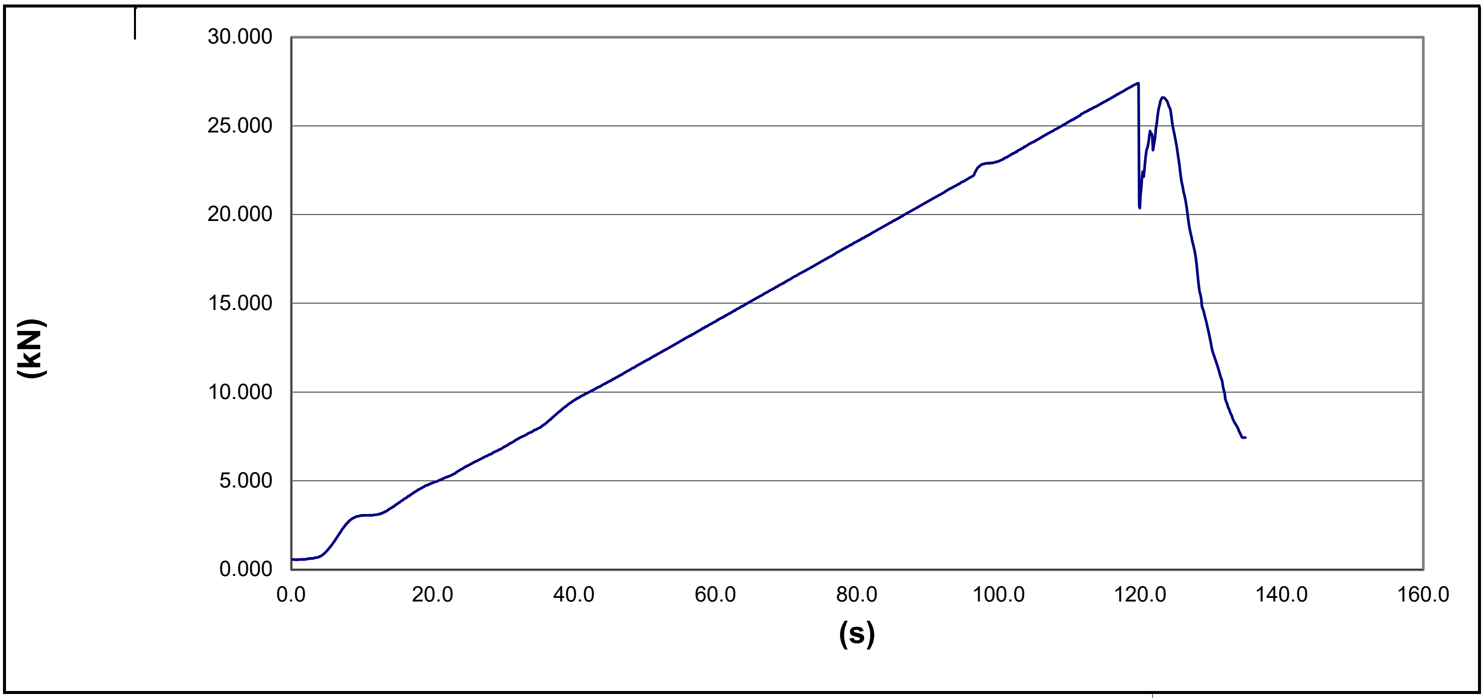
Operator

Operator01

	35.5		
Mcr	4.4375	W	562500
Sigmacr	7.888889		

Flexural tests on beams: EN 12390-5

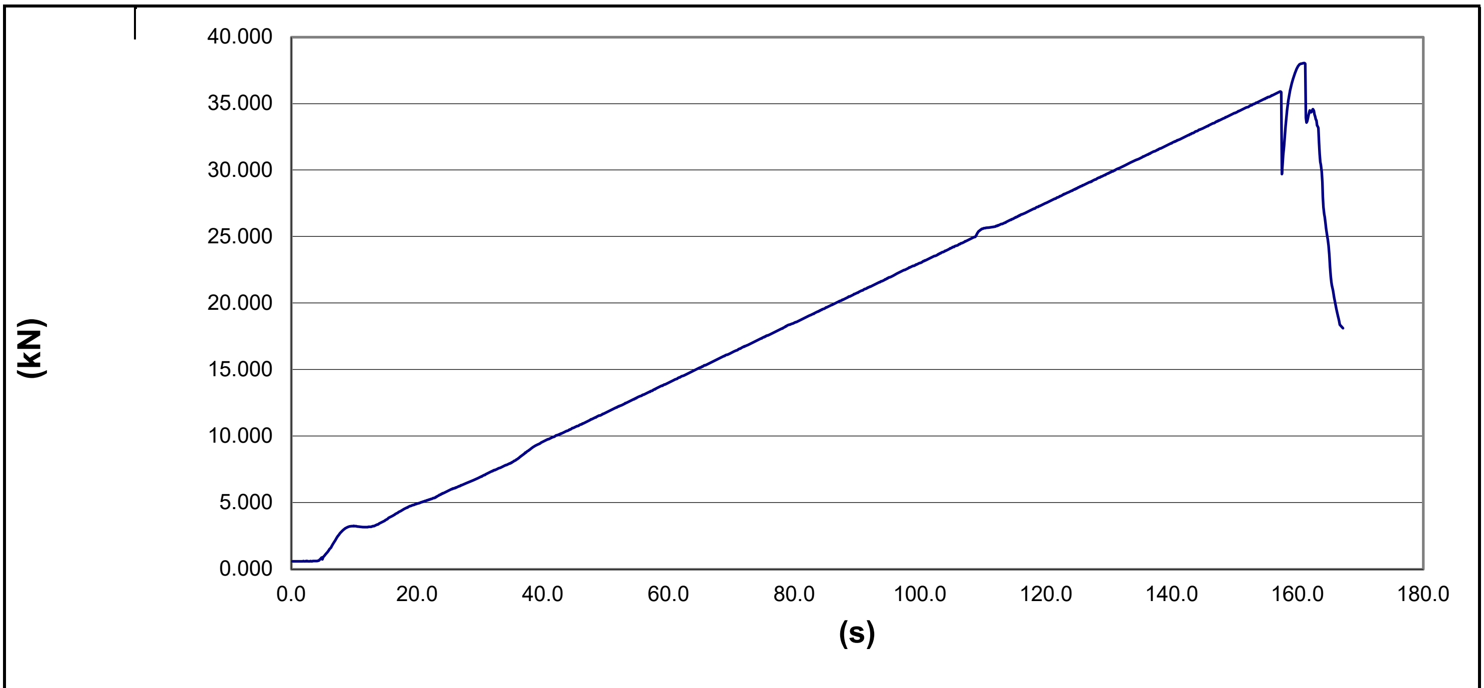
Certificate number	:	001-RT30-Bending-l=850			Certificate date	: --------
Testing machine	:	C1701/FR s.n. 22000858				
Client	:					
Reference	:					
Specimen type	:	Beam			Cement quantity [kg/m³]	:
Cement type	:				Test date	: 25/10/2022
Sample conditions:						
Condition when received	:				Condition at test time	:
Sampling location	:				Sampling date	: --------
Preparation method	:					
Specimen ID	:					
Dimensions	:	*b(mm)*	: 150.00	*h(mm)* : 150.00	Mass [kg]	: 0.000
		l(mm)	850			:
Load Rate [MPa/s]	:	0.1		No of upper roll 2	"L" distance [mm]	750.0
Area [mm2]	:	4500.0	Specimen age	: 28 dd	Preparation date	: --------
Load [kN]	:	27.39			Strength [MPa]	: 6.09
	:					
Notes	:					



Operator
Operator01

Flexural tests on beams: EN 12390-5

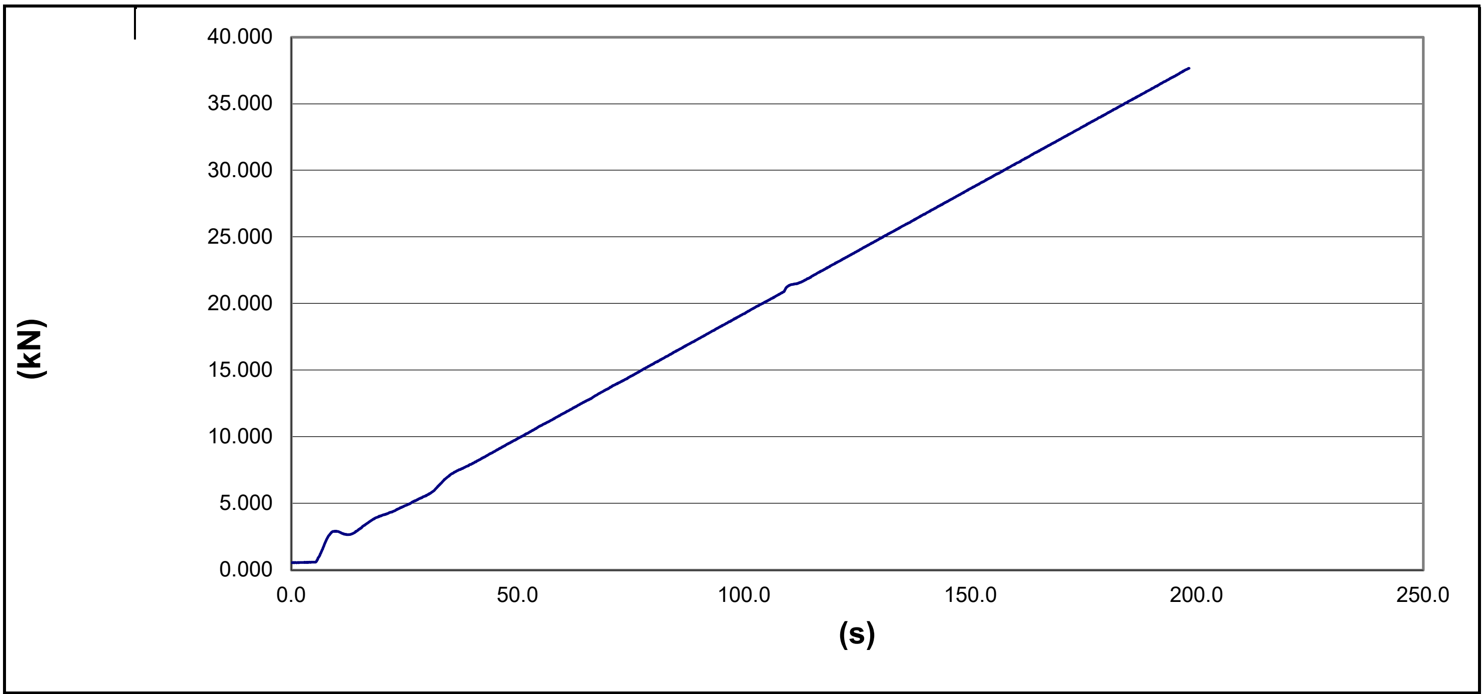
Certificate number	:	002-RT30-Bending-l=850			Certificate date	: --------
Testing machine	:	C1701/FR s.n. 22000858				
Client	:					
Reference	:					
Specimen type	:	Beam			Cement quantity [kg/m³]	:
Cement type	:				Test date	: 25/10/2022
Sample conditions:						
Condition when received	:				Condition at test time	:
Sampling location	:				Sampling date	: --------
Preparation method	:					
Specimen ID	:					
Dimensions	:	*b(mm)* : 150.00	*h(mm)* : 150.00		Mass [kg]	: 0.000
		l(mm) 850				:
Load Rate [MPa/s]	:	0.1	No of upper roll 2		"L" distance [mm]	750.0
Area [mm2]	:	4500.0	Specimen age : 28 dd		Preparation date	: --------
Load [kN]	:	38.03			Strength [MPa]	: 8.45
	:					
Notes	:					



Operator	
Operator01	

Flexural tests on beams: EN 12390-5

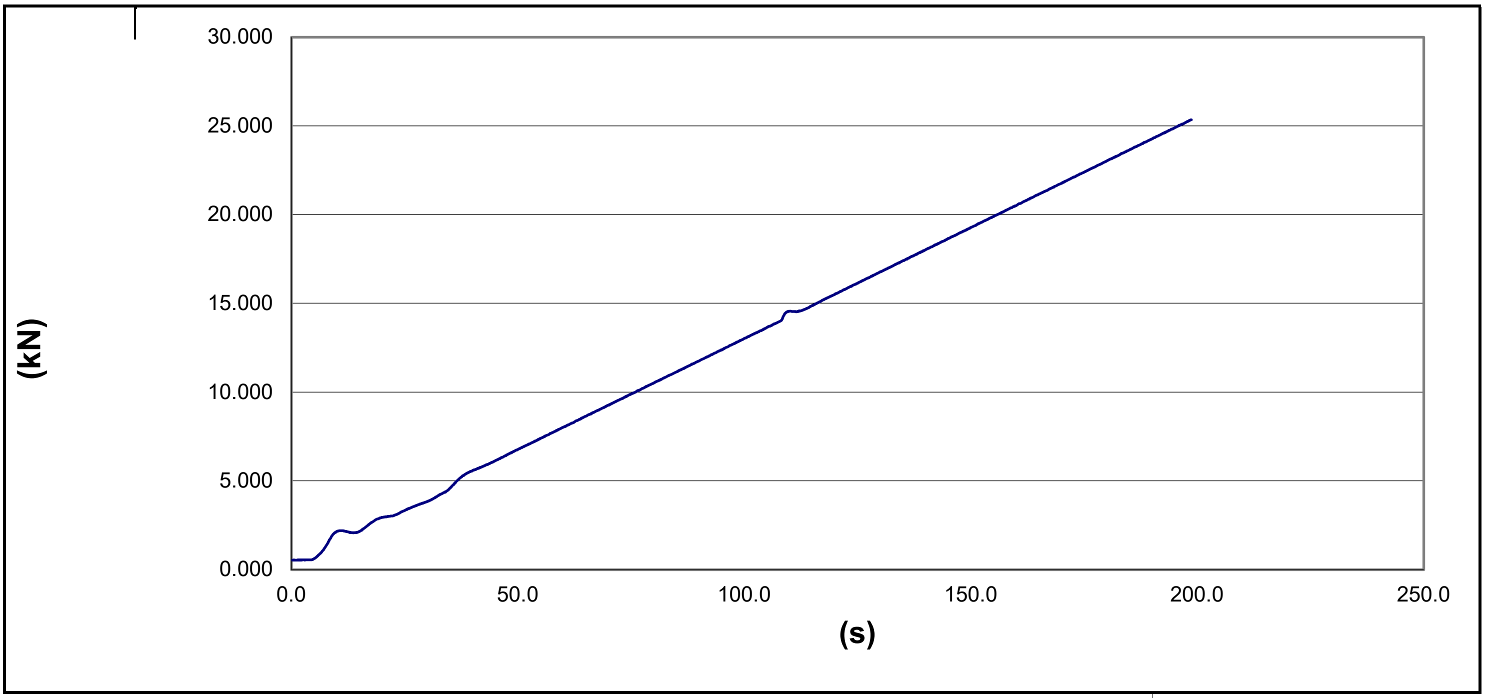
Certificate number	:	001-4PB-RT-2x6-c=17				Certificate date	: -------
Testing machine	:	C1701/FR s.n. 22000858					
Client	:						
Reference	:						
Specimen type	:	Beam				Cement quantity [kg/m³]	:
Cement type	:					Test date	: 22/08/2022
Sample conditions:							
Condition when received	:					Condition at test time	:
Sampling location	:					Sampling date	: -------
Preparation method	:						
Specimen ID	:						
Dimensions	:	*b(mm)*	: 150.00	*h(mm)*	: 150.00	Mass [kg]	: 0.000
		l(mm)	1000				:
Load Rate [MPa/s]	:	0.1		No of upper roll	2	"L" distance [mm]	900.0
Area [mm2]	:	3750.0	Specimen age	: 28 dd		Preparation date	: -------
Load [kN]	:	37.66				Strength [MPa]	: 10.04
	:						
Notes	:						



Operator
Operator01

Flexural tests on beams: EN 12390-5

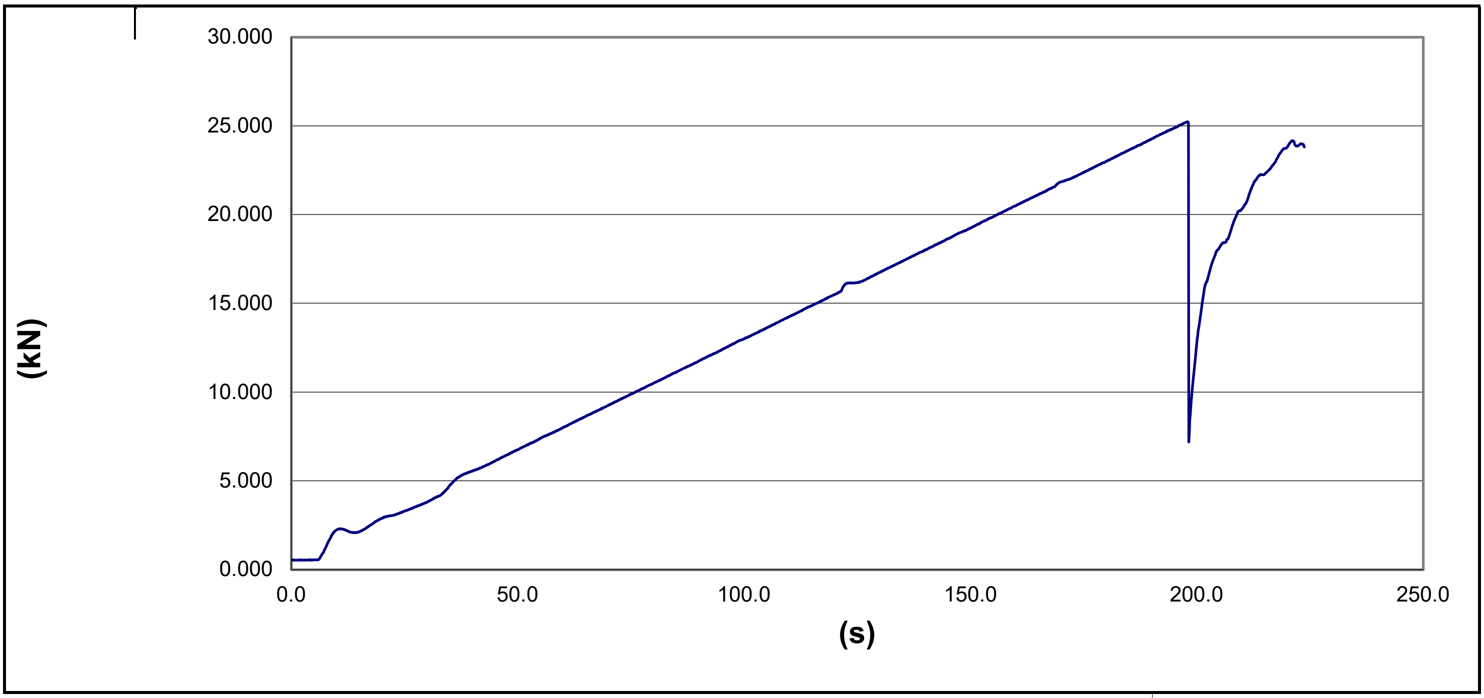
Certificate number	:	002-3PB-RT-2x6-c=17			Certificate date	: -------
Testing machine	:	C1701/FR s.n. 22000858				
Client	:					
Reference	:					
Specimen type	:	Beam			Cement quantity [kg/m³]	:
Cement type	:				Test date	: 24/08/2022
Sample conditions:						
Condition when received	:				Condition at test time	:
Sampling location	:				Sampling date	: -------
Preparation method	:					
Specimen ID	:					
Dimensions	:	*b(mm)*	: 150.00	*h(mm)* : 150.00	Mass [kg]	: 0.000
		l(mm)	1000			:
Load Rate [MPa/s]	:	0.1		No of upper roll 1	"L" distance [mm]	900.0
Area [mm2]	:	2500.0	Specimen age	: 28 dd	Preparation date	: -------
Load [kN]	:	25.34			Strength [MPa]	: 10.14
	:					
Notes	:					



Operator
Operator01

Flexural tests on beams: EN 12390-5

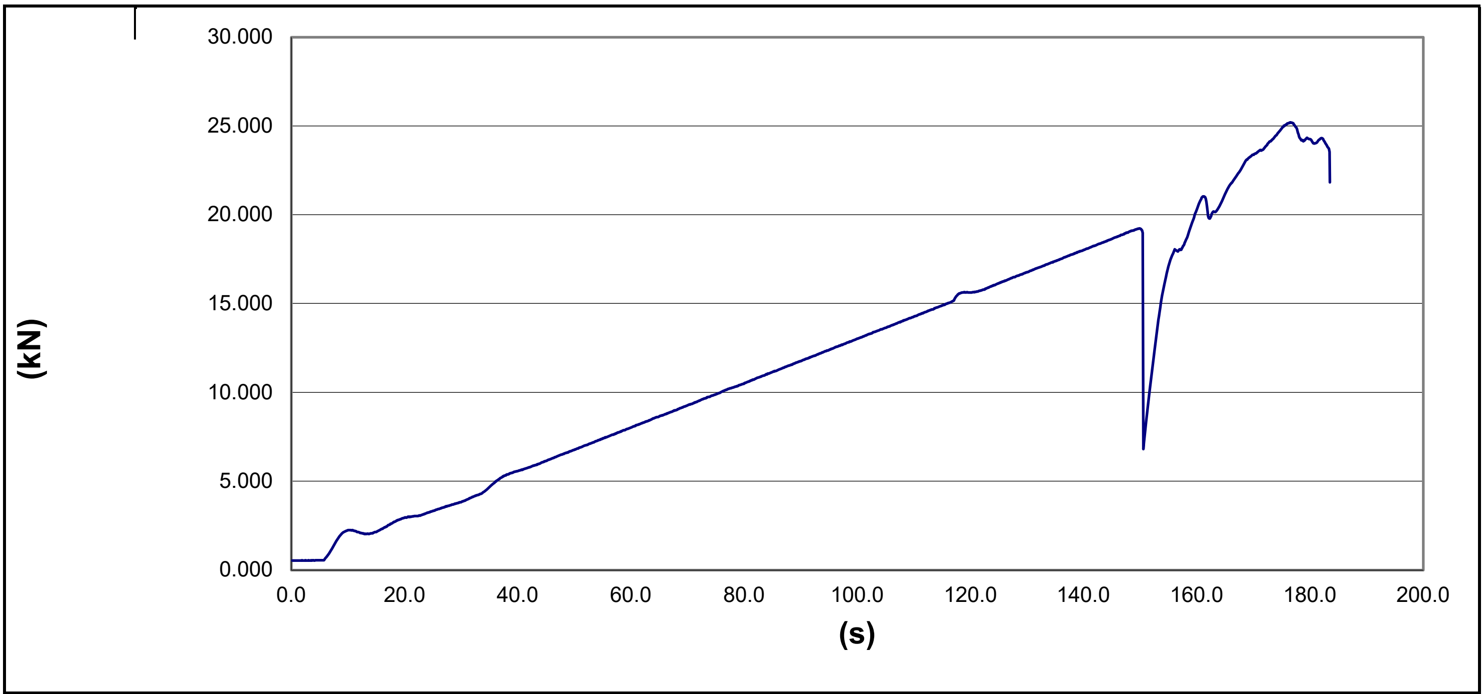
Certificate number	:	001-3PB-RT-2x6-c=29			Certificate date	: --------
Testing machine	:	C1701/FR s.n. 22000858				
Client	:					
Reference	:					
Specimen type	:	Beam			Cement quantity [kg/m³]	:
Cement type	:				Test date	: 24/08/2022
Sample conditions:						
Condition when received	:				Condition at test time	:
Sampling location	:				Sampling date	: --------
Preparation method	:					
Specimen ID	:					
Dimensions	:	*b(mm)*	: 150.00	*h(mm)* : 150.00	Mass [kg]	: 0.000
		l(mm)	1000			:
Load Rate [MPa/s]	:	0.1		No of upper roll 1	"L" distance [mm]	900.0
Area [mm2]	:	2500.0	Specimen age	: 28 dd	Preparation date	: --------
Load [kN]	:	25.24			Strength [MPa]	: 10.09
	:					
Notes	:					



Operator
Operator01

Flexural tests on beams: EN 12390-5

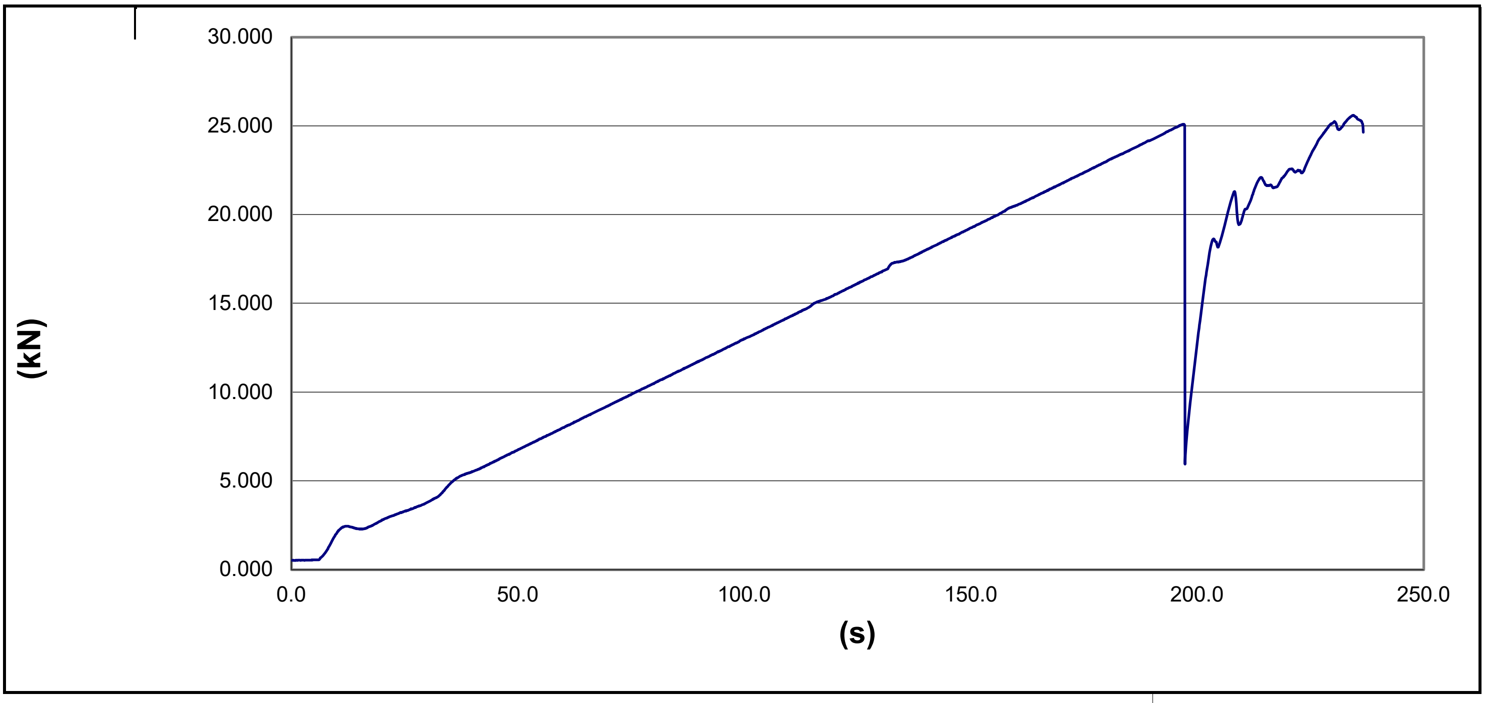
Certificate number	:	002-3PB-RT-2x6-c=29			Certificate date	: -------
Testing machine	:	C1701/FR s.n. 22000858				
Client	:					
Reference	:					
Specimen type	:	Beam			Cement quantity [kg/m³]	:
Cement type	:				Test date	: 24/08/2022
Sample conditions:						
Condition when received	:				Condition at test time	:
Sampling location	:				Sampling date	: -------
Preparation method	:					
Specimen ID	:					
Dimensions	:	*b(mm)*	: 150.00	*h(mm)* : 150.00	Mass [kg]	: 0.000
		l(mm)	1000			:
Load Rate [MPa/s]	:	0.1		No of upper roll 1	"L" distance [mm]	900.0
Area [mm2]	:	2500.0	Specimen age	: 28 dd	Preparation date	: -------
Load [kN]	:	25.20			Strength [MPa]	: 10.08
	:					
Notes	:					



Operator
Operator01

Flexural tests on beams: EN 12390-5

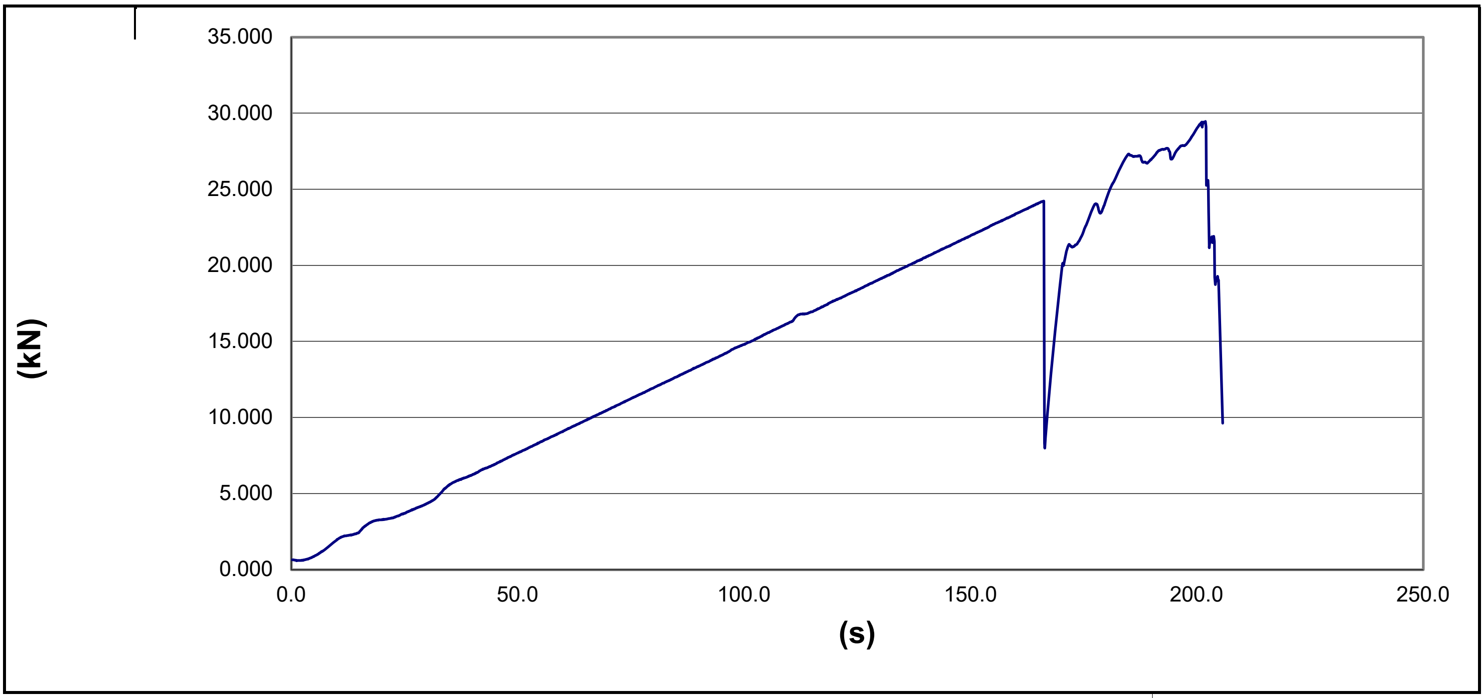
Certificate number	:	001-3PB-RT-2x6-c=41			Certificate date	:	-------
Testing machine	:	C1701/FR s.n. 22000858					
Client	:						
Reference	:						
Specimen type	:	Beam			Cement quantity [kg/m³]	:	
Cement type	:				Test date	:	24/08/2022
Sample conditions:							
Condition when received	:				Condition at test time	:	
Sampling location	:				Sampling date	:	-------
Preparation method	:						
Specimen ID	:						
Dimensions	:	*b(mm)*	: 150.00	*h(mm)* : 150.00	Mass [kg]	:	0.000
		l(mm)	1000			:	
Load Rate [MPa/s]	:	0.1		No of upper roll 1	"L" distance [mm]		900.0
Area [mm2]	:	2500.0	Specimen age	: 28 dd	Preparation date	:	-------
Load [kN]	:	25.59			Strength [MPa]	:	10.24
	:						
Notes	:						



Operator
Operator01

Flexural tests on beams: EN 12390-5

Certificate number	:	002-3PB-RT-2x6-c=41-l=788			Certificate date	: -------
Testing machine	:	C1701/FR s.n. 22000858				
Client	:					
Reference	:					
Specimen type	:	Beam			Cement quantity [kg/m³]	:
Cement type	:				Test date	: 24/08/2022
Sample conditions:						
Condition when received	:				Condition at test time	:
Sampling location	:				Sampling date	: -------
Preparation method	:					
Specimen ID	:					
Dimensions	:	*b(mm)*	: 150.00	*h(mm)* : 150.00	Mass [kg]	: 0.000
		l(mm)	1000			:
Load Rate [MPa/s]	:	0.1		No of upper roll 1	"L" distance [mm]	788.0
Area [mm2]	:	2855.3	Specimen age	: 28 dd	Preparation date	: -------
Load [kN]	:	29.45			Strength [MPa]	: 10.32
	:					
Notes	:					

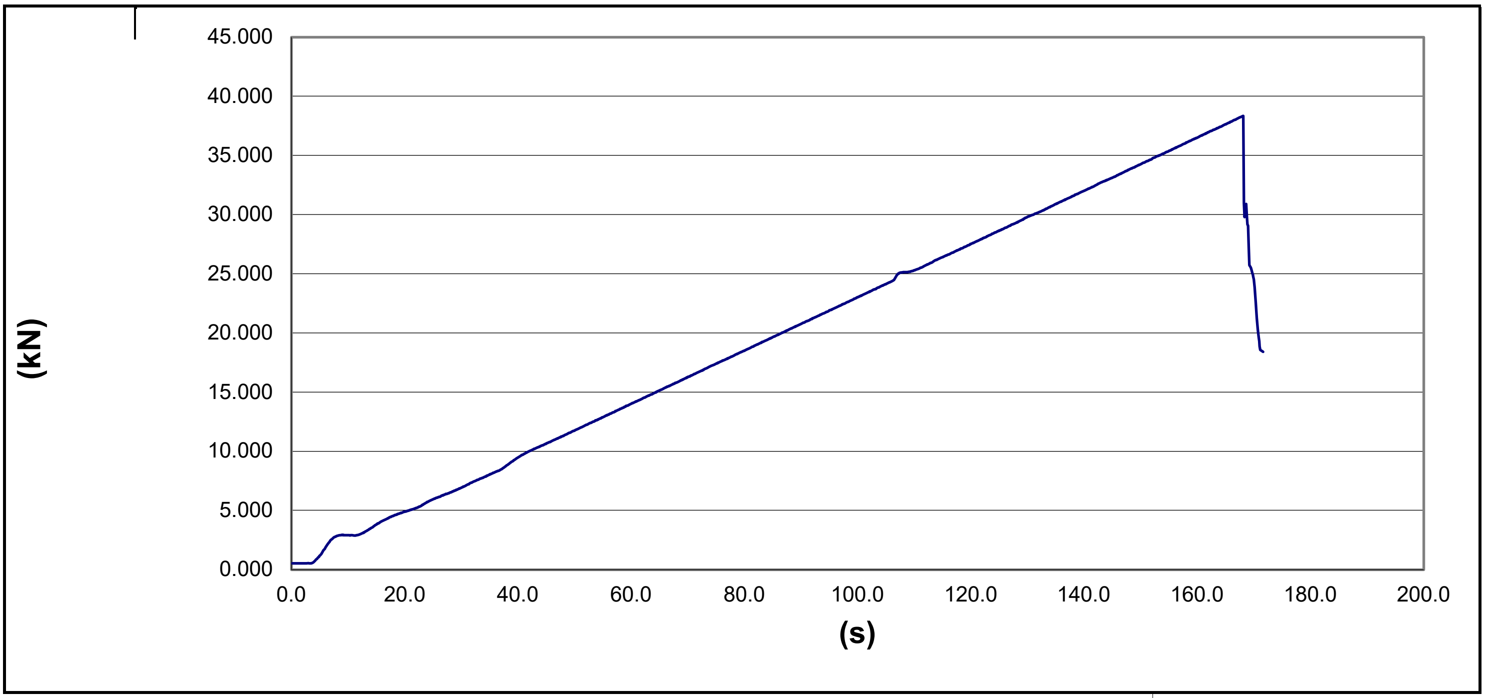


Operator

Operator01

Flexural tests on beams: EN 12390-5

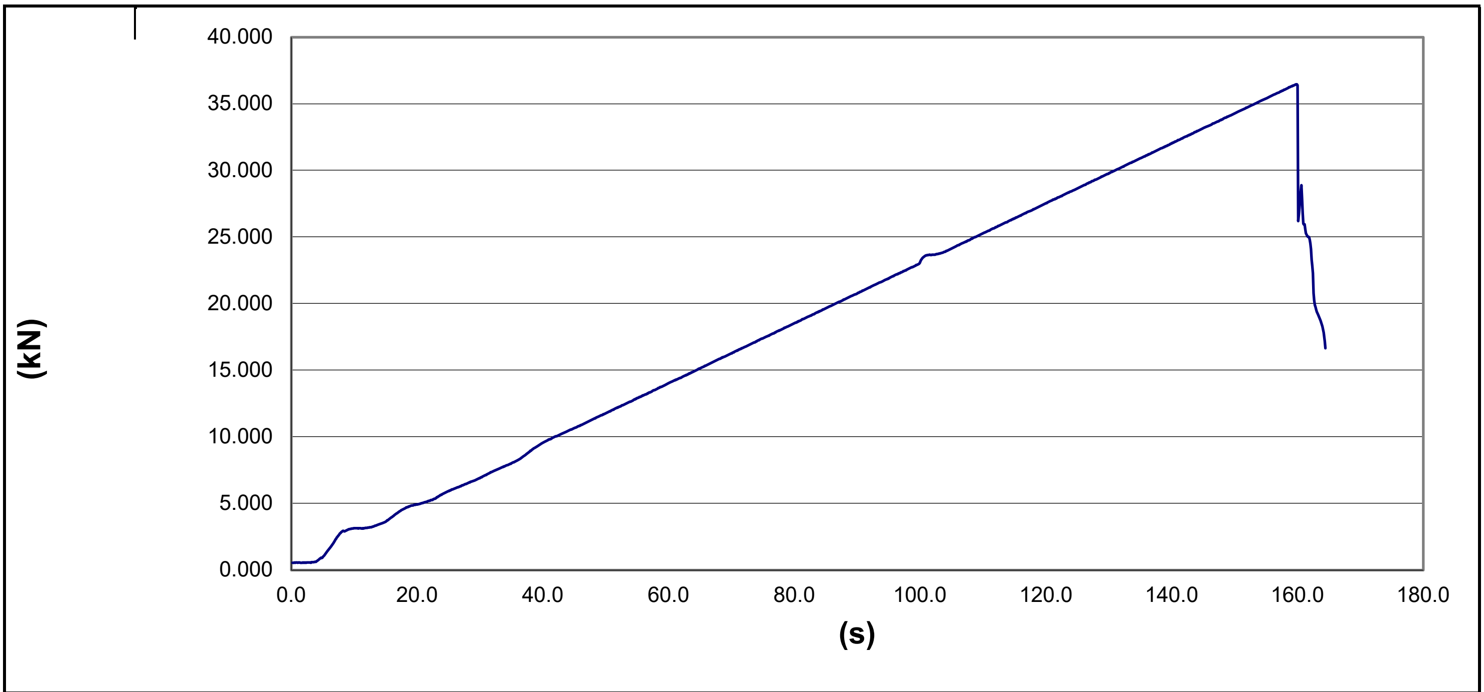
Certificate number	:	001-SV45-Bending-l=600			Certificate date	: --------
Testing machine	:	C1701/FR s.n. 22000858				
Client	:					
Reference	:					
Specimen type	:	Beam			Cement quantity [kg/m³]	:
Cement type	:				Test date	: 25/10/2022
Sample conditions:						
Condition when received	:				Condition at test time	:
Sampling location	:				Sampling date	: --------
Preparation method	:					
Specimen ID	:					
Dimensions	:	*b(mm)*	: 150.00	*h(mm)* : 150.00	Mass [kg]	: 0.000
		l(mm)	600			:
Load Rate [MPa/s]	:	0.1		No of upper roll 1	"L" distance [mm]	500.0
Area [mm2]	:	4500.0	Specimen age	: 28 dd	Preparation date	: --------
Load [kN]	:	38.32			Strength [MPa]	: 8.52
	:					
Notes	:					



Operator
Operator01

Flexural tests on beams: EN 12390-5

Certificate number	: 002-SV45-Bending-l=600			Certificate date	: -------
Testing machine	: C1701/FR s.n. 22000858				
Client	:				
Reference	:				
Specimen type	: Beam			Cement quantity [kg/m³]	:
Cement type	:			Test date	: 25/10/2022
Sample conditions:					
Condition when received	:			Condition at test time	:
Sampling location	:			Sampling date	: -------
Preparation method	:				
Specimen ID	:				
Dimensions	: *b(mm)*	: 150.00	*h(mm)* : 150.00	Mass [kg]	: 0.000
	l(mm)	600			:
Load Rate [MPa/s]	: 0.1		No of upper roll 1	"L" distance [mm]	500.0
Area [mm2]	: 4500.0	Specimen age	: 28 dd	Preparation date	: -------
Load [kN]	: 36.46			Strength [MPa]	: 8.10
	:				
Notes	:				

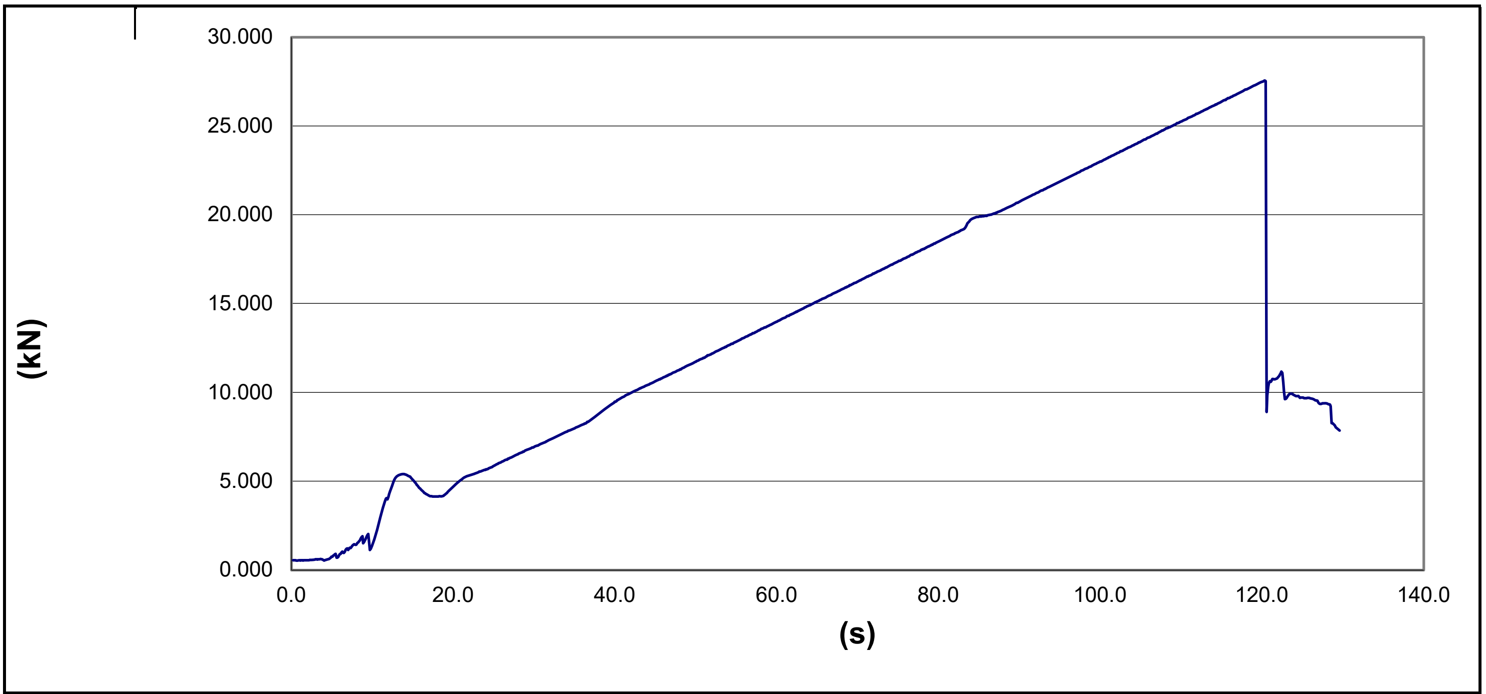


Operator

Operator01

Flexural tests on beams: EN 12390-5

Certificate number	:	001-SV45-Bending-l=850			Certificate date :	--------
Testing machine	:	C1701/FR s.n. 22000858				
Client	:					
Reference	:					
Specimen type	:	Beam			Cement quantity [kg/m³] :	
Cement type	:				Test date :	25/10/2022
Sample conditions:						
Condition when received	:				Condition at test time :	
Sampling location	:				Sampling date :	--------
Preparation method	:					
Specimen ID	:					
Dimensions	:	*b(mm)* : 150.00	*h(mm)* : 150.00		Mass [kg] :	0.000
		l(mm) 850			:	
Load Rate [MPa/s]	:	0.1	No of upper roll 2		"L" distance [mm]	750.0
Area [mm2]	:	4500.0	Specimen age : 28 dd		Preparation date :	--------
Load [kN]	:	27.55			Strength [MPa] :	6.12
	:					
Notes	:					

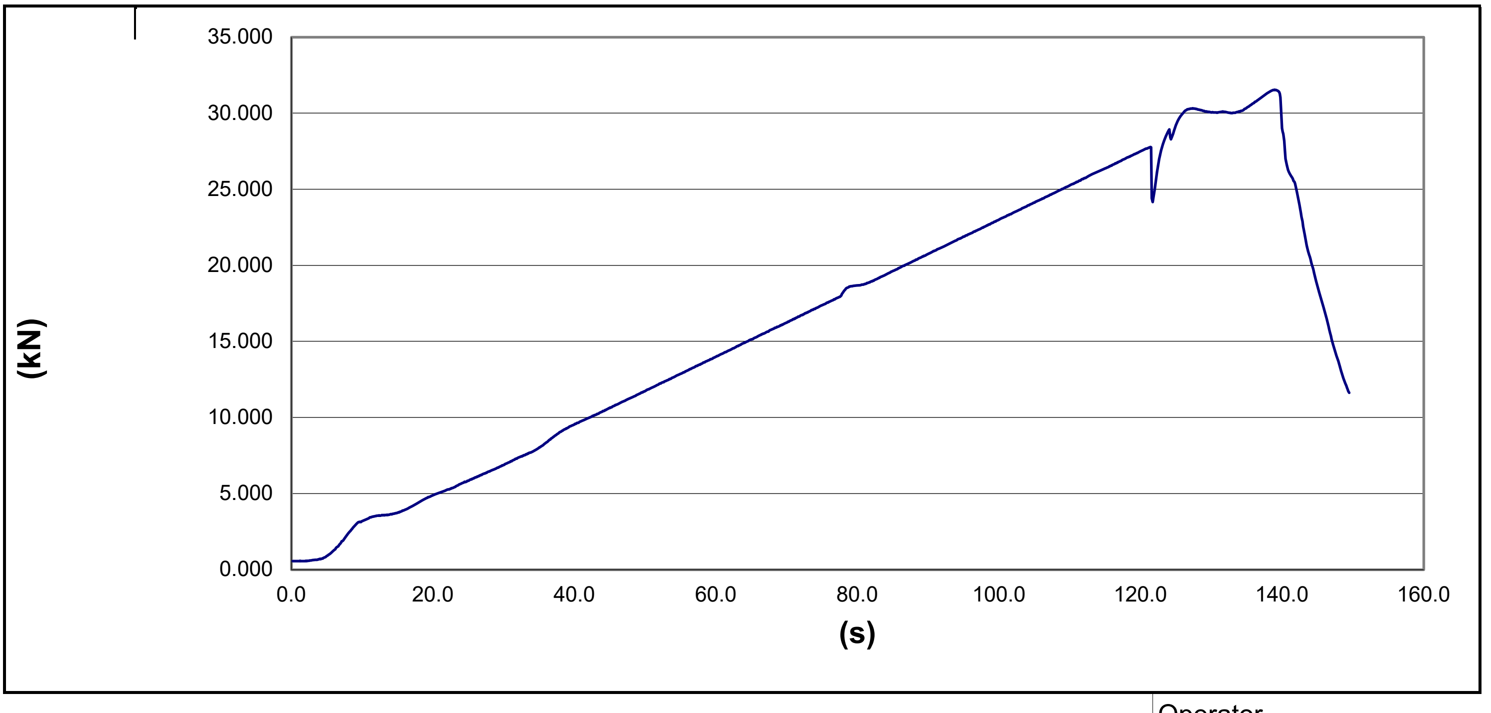


Operator

Operator01

Flexural tests on beams: EN 12390-5

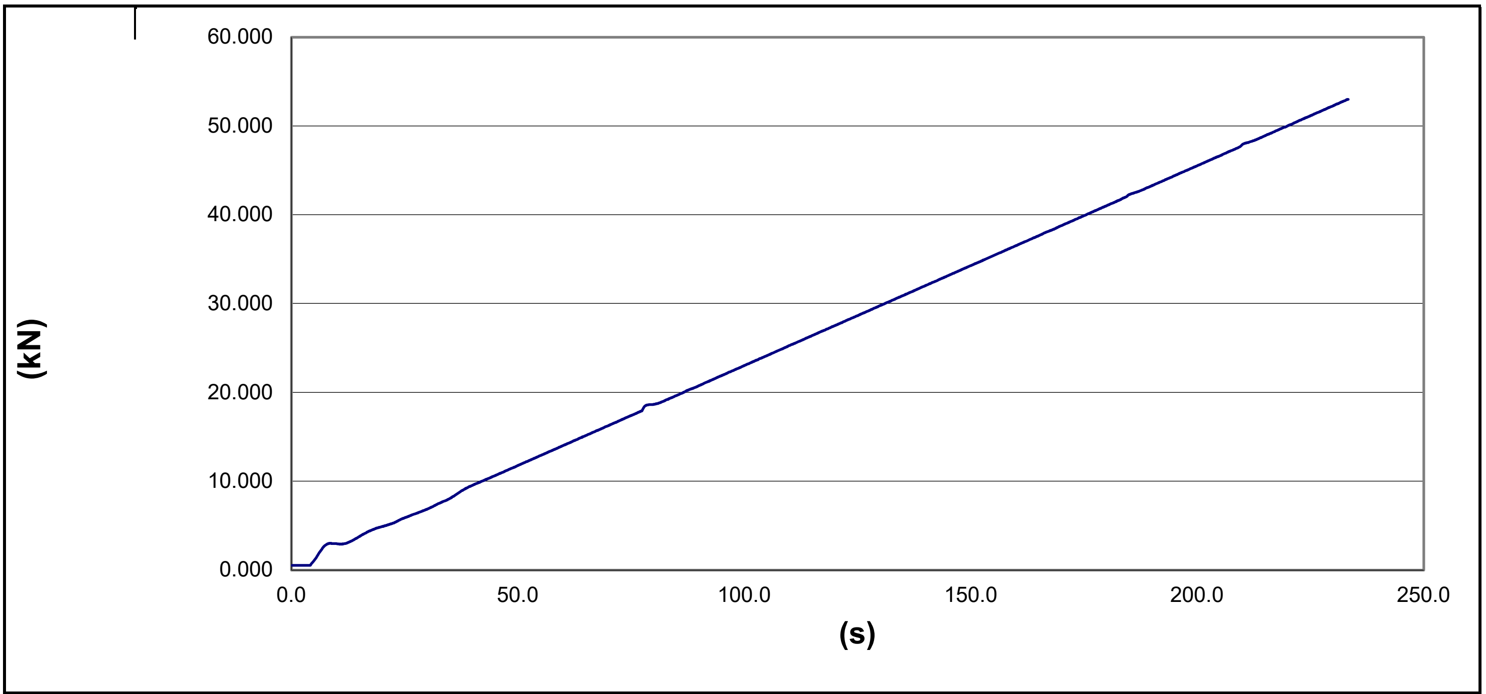
Certificate number	:	002-SV45-Bending-l=850			Certificate date :	-------
Testing machine	:	C1701/FR s.n. 22000858				
Client	:					
Reference	:					
Specimen type	:	Beam			Cement quantity [kg/m³] :	
Cement type	:				Test date :	25/10/2022
Sample conditions:						
Condition when received	:				Condition at test time :	
Sampling location	:				Sampling date :	-------
Preparation method	:					
Specimen ID	:					
Dimensions	:	*b(mm)* : 150.00	*h(mm)* : 150.00		Mass [kg] :	0.000
		l(mm) 850			:	
Load Rate [MPa/s]	:	0.1		No of upper roll 2	"L" distance [mm]	750.0
Area [mm2]	:	4500.0	Specimen age :	28 dd	Preparation date :	-------
Load [kN]	:	31.54			Strength [MPa] :	7.01
	:					
Notes	:					



Operator
Operator01

Flexural tests on beams: EN 12390-5

Certificate number	:	001-3PB-RT-1x6			Certificate date	: -------
Testing machine	:	C1701/FR s.n. 22000858				
Client	:					
Reference	:					
Specimen type	:	Beam			Cement quantity [kg/m³]	:
Cement type	:				Test date	: 22/08/2022
Sample conditions:						
Condition when received	:				Condition at test time	:
Sampling location	:				Sampling date	: -------
Preparation method	:					
Specimen ID	:					
Dimensions	:	*b(mm)*	: 150.00	*h(mm)* : 150.00	Mass [kg]	: 0.000
		l(mm)	600			:
Load Rate [MPa/s]	:	0.1		No of upper roll 1	"L" distance [mm]	500.0
Area [mm2]	:	4500.0	Specimen age	: 28 dd	Preparation date	: -------
Load [kN]	:	53.00			Strength [MPa]	: 11.78
	:					
Notes	:					

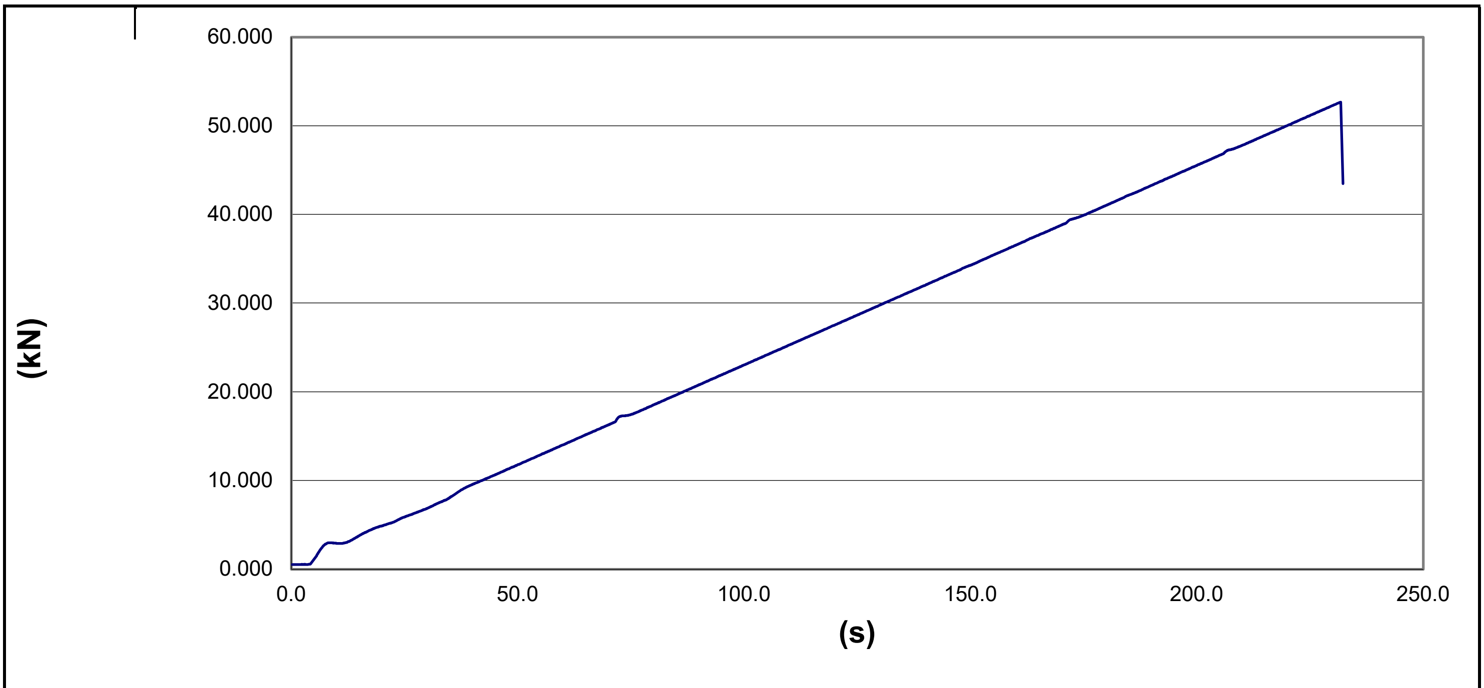


Operator

Operator01

Flexural tests on beams: EN 12390-5

Certificate number	:	001-3PB-RT-1x6			Certificate date	: -------
Testing machine	:	C1701/FR s.n. 22000858				
Client	:					
Reference	:					
Specimen type	:	Beam			Cement quantity [kg/m³]	:
Cement type	:				Test date	: 22/08/2022
Sample conditions:						
Condition when received	:				Condition at test time	:
Sampling location	:				Sampling date	: -------
Preparation method	:					
Specimen ID	:					
Dimensions	:	*b(mm)*	: 150.00	*h(mm)* : 150.00	Mass [kg]	: 0.000
		l(mm)	600			:
Load Rate [MPa/s]	:	0.1		No of upper roll 1	"L" distance [mm]	500.0
Area [mm2]	:	4500.0	Specimen age	: 28 dd	Preparation date	: -------
Load [kN]	:	52.65			Strength [MPa]	: 11.70
	:					
Notes	:					

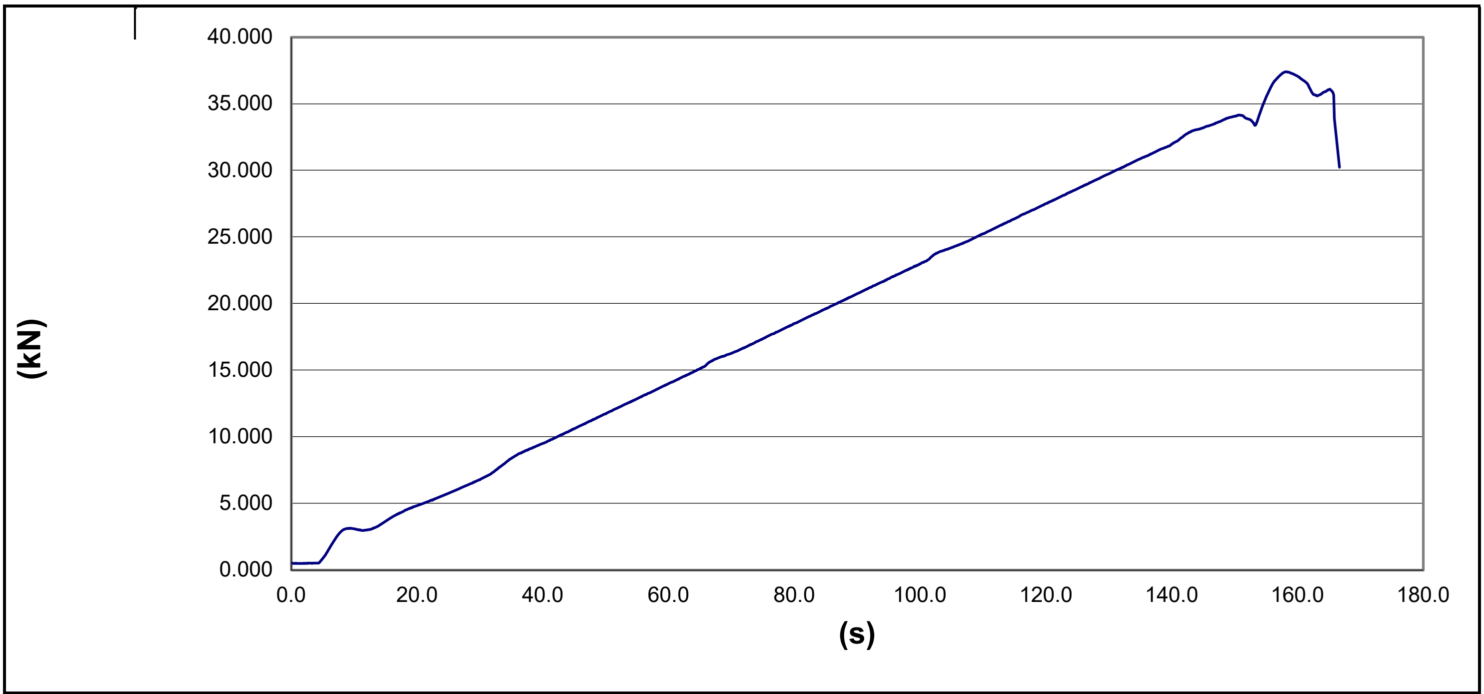


Operator

Operator01

Flexural tests on beams: EN 12390-5

Certificate number	:	002-3PB-RT-1x6-2			Certificate date	: -------
Testing machine	:	C1701/FR s.n. 22000858				
Client	:					
Reference	:					
Specimen type	:	Beam			Cement quantity [kg/m³]	:
Cement type	:				Test date	: 22/08/2022
Sample conditions:						
Condition when received	:				Condition at test time	:
Sampling location	:				Sampling date	: -------
Preparation method	:					
Specimen ID	:					
Dimensions	:	*b(mm)*	: 150.00	*h(mm)* : 150.00	Mass [kg]	: 0.000
		l(mm)	600			:
Load Rate [MPa/s]	:	0.1		No of upper roll 1	"L" distance [mm]	500.0
Area [mm2]	:	4500.0	Specimen age	: 28 dd	Preparation date	: -------
Load [kN]	:	37.40			Strength [MPa]	: 8.31
	:					
Notes	:					

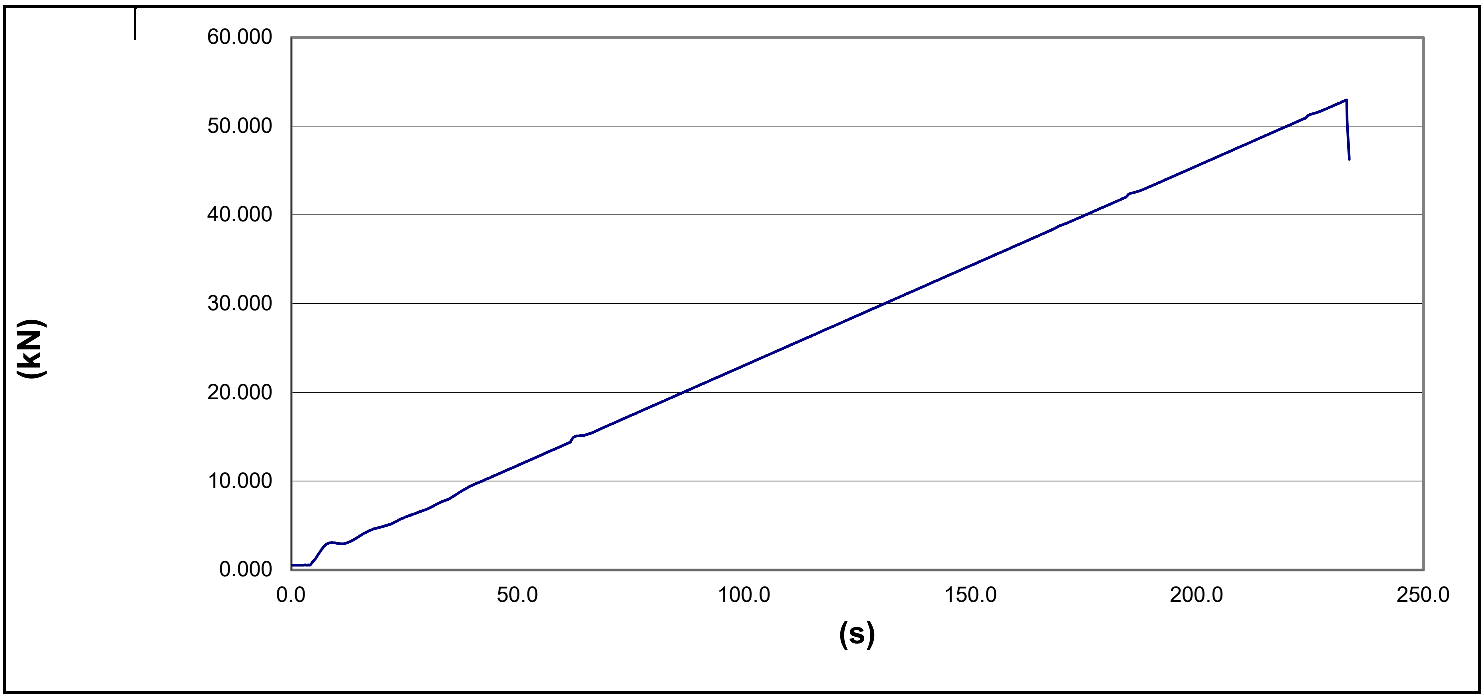


Operator

Operator01

Flexural tests on beams: EN 12390-5

Certificate number	:	003-3PB-RT-1x6				Certificate date	: -------
Testing machine	:	C1701/FR s.n. 22000858					
Client	:						
Reference	:						
Specimen type	:	Beam				Cement quantity [kg/m³]	:
Cement type	:					Test date	: 22/08/2022
Sample conditions:							
Condition when received	:					Condition at test time	:
Sampling location	:					Sampling date	: -------
Preparation method	:						
Specimen ID	:						
Dimensions	:	*b(mm)*	: 150.00	*h(mm)*	: 150.00	Mass [kg]	: 0.000
		l(mm)	600				:
Load Rate [MPa/s]	:	0.1		No of upper roll 1		"L" distance [mm]	500.0
Area [mm2]	:	4500.0	Specimen age	: 28 dd		Preparation date	: -------
Load [kN]	:	52.94				Strength [MPa]	: 11.76
	:						
Notes	:						

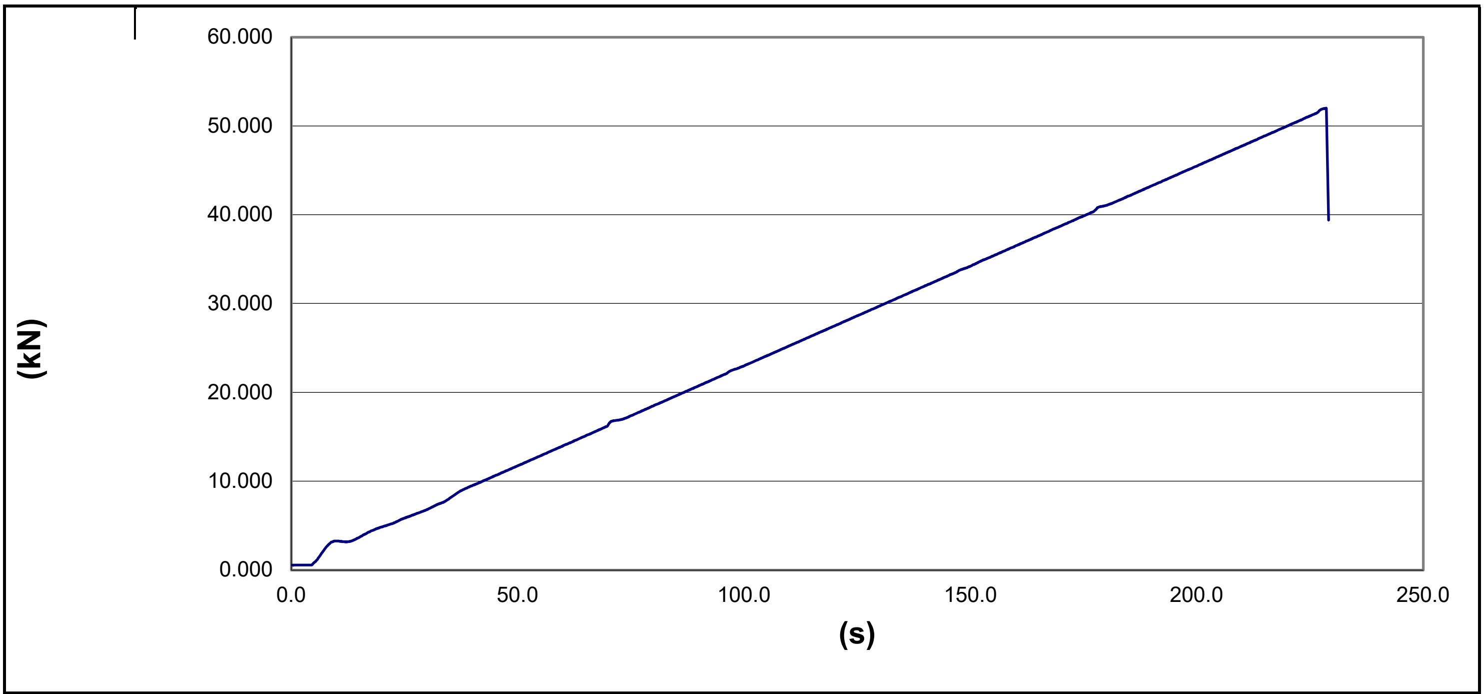


Operator

Operator01

Flexural tests on beams: EN 12390-5

Certificate number	:	001-3PB-RT-2x6			Certificate date	: -------
Testing machine	:	C1701/FR s.n. 22000858				
Client	:					
Reference	:					
Specimen type	:	Beam			Cement quantity [kg/m³]	:
Cement type	:				Test date	: 22/08/2022
Sample conditions:						
Condition when received	:				Condition at test time	:
Sampling location	:				Sampling date	: -------
Preparation method	:					
Specimen ID	:					
Dimensions	:	*b(mm)*	: 150.00	*h(mm)* : 150.00	Mass [kg]	: 0.000
		l(mm)	600			:
Load Rate [MPa/s]	:	0.1		No of upper roll 1	"L" distance [mm]	500.0
Area [mm2]	:	4500.0	Specimen age	: 28 dd	Preparation date	: -------
Load [kN]	:	52.00			Strength [MPa]	: 11.56
	:					
Notes	:					

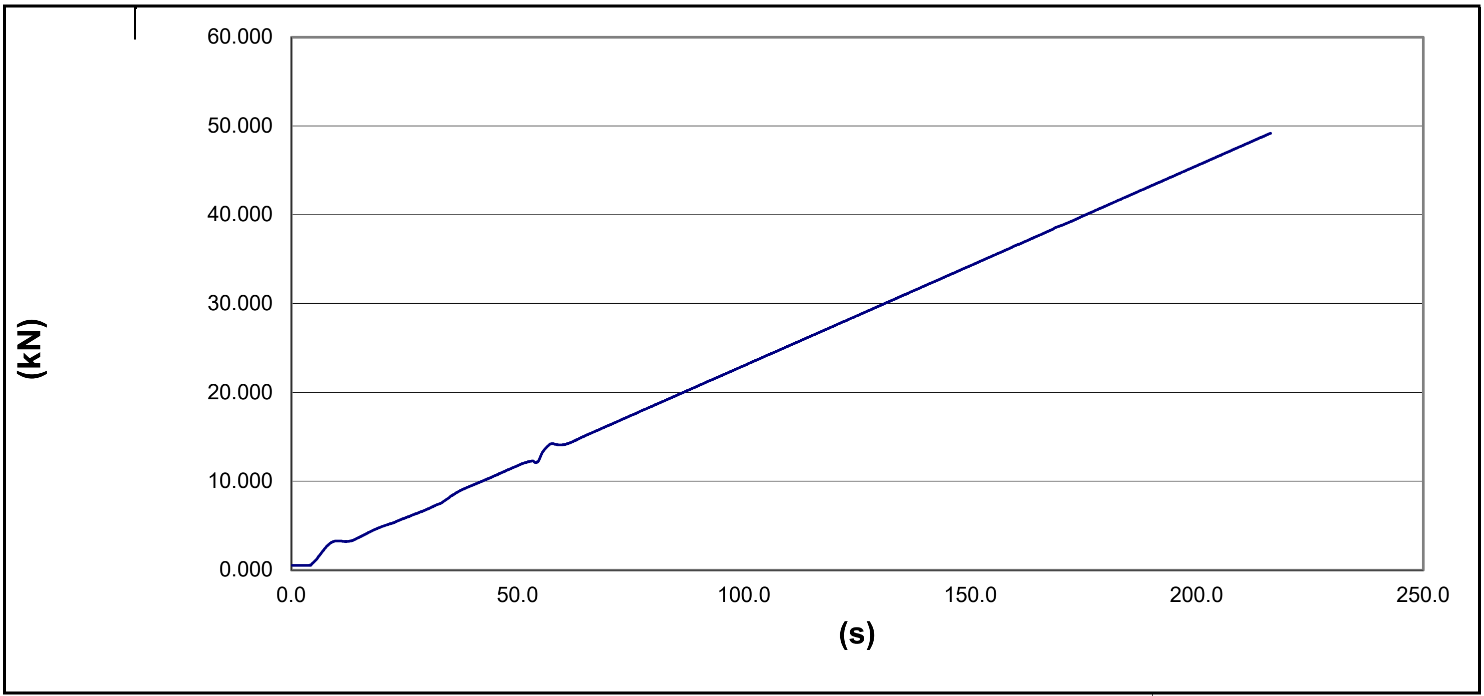


Operator

Operator01

Flexural tests on beams: EN 12390-5

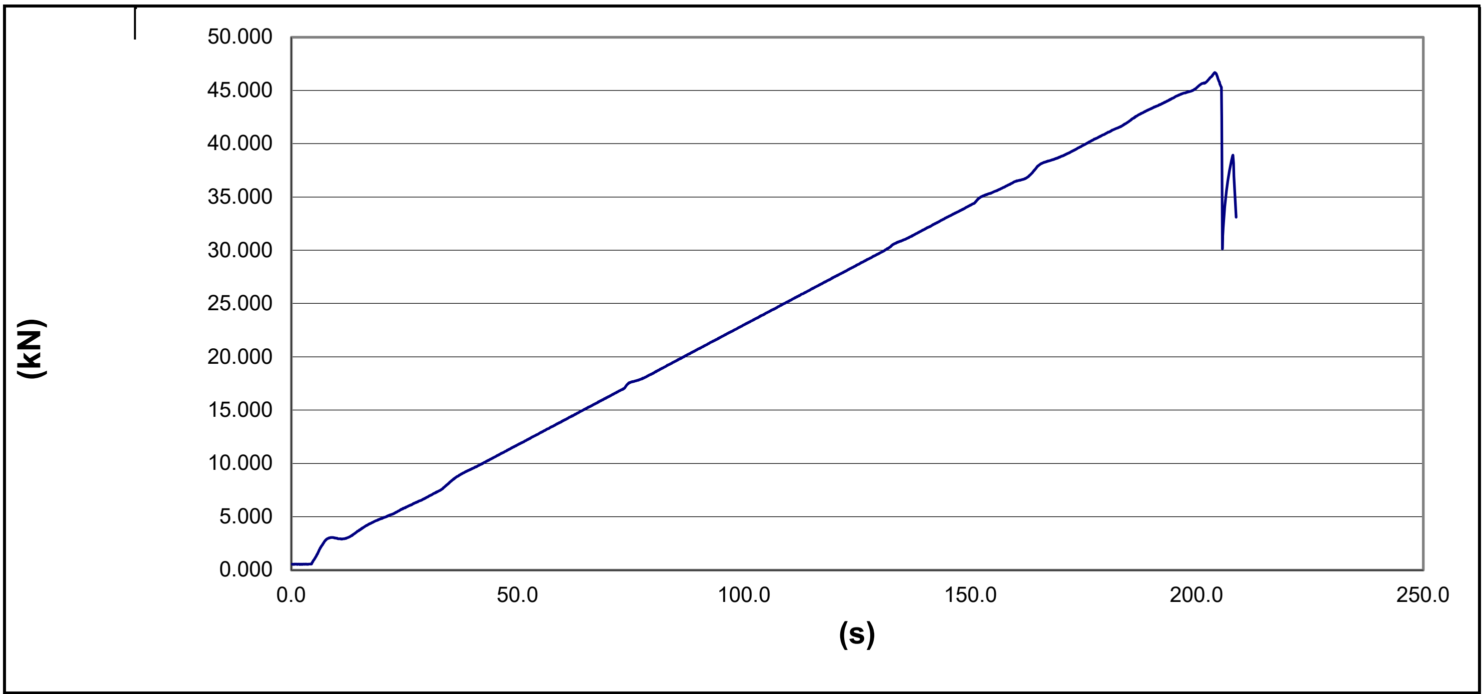
Certificate number	: 002-3PB-RT-2x6			Certificate date	: -------
Testing machine	: C1701/FR s.n. 22000858				
Client	:				
Reference	:				
Specimen type	: Beam			Cement quantity [kg/m³]	:
Cement type	:			Test date	: 22/08/2022
Sample conditions:					
Condition when received	:			Condition at test time	:
Sampling location	:			Sampling date	: -------
Preparation method	:				
Specimen ID	:				
Dimensions	: *b(mm)*	: 150.00	*h(mm)* : 150.00	Mass [kg]	: 0.000
	l(mm)	600			:
Load Rate [MPa/s]	: 0.1		No of upper roll 1	"L" distance [mm]	500.0
Area [mm2]	: 4500.0	Specimen age	: 28 dd	Preparation date	: -------
Load [kN]	: 49.16			Strength [MPa]	: 10.92
	:				
Notes	:				



Operator
Operator01

Flexural tests on beams: EN 12390-5

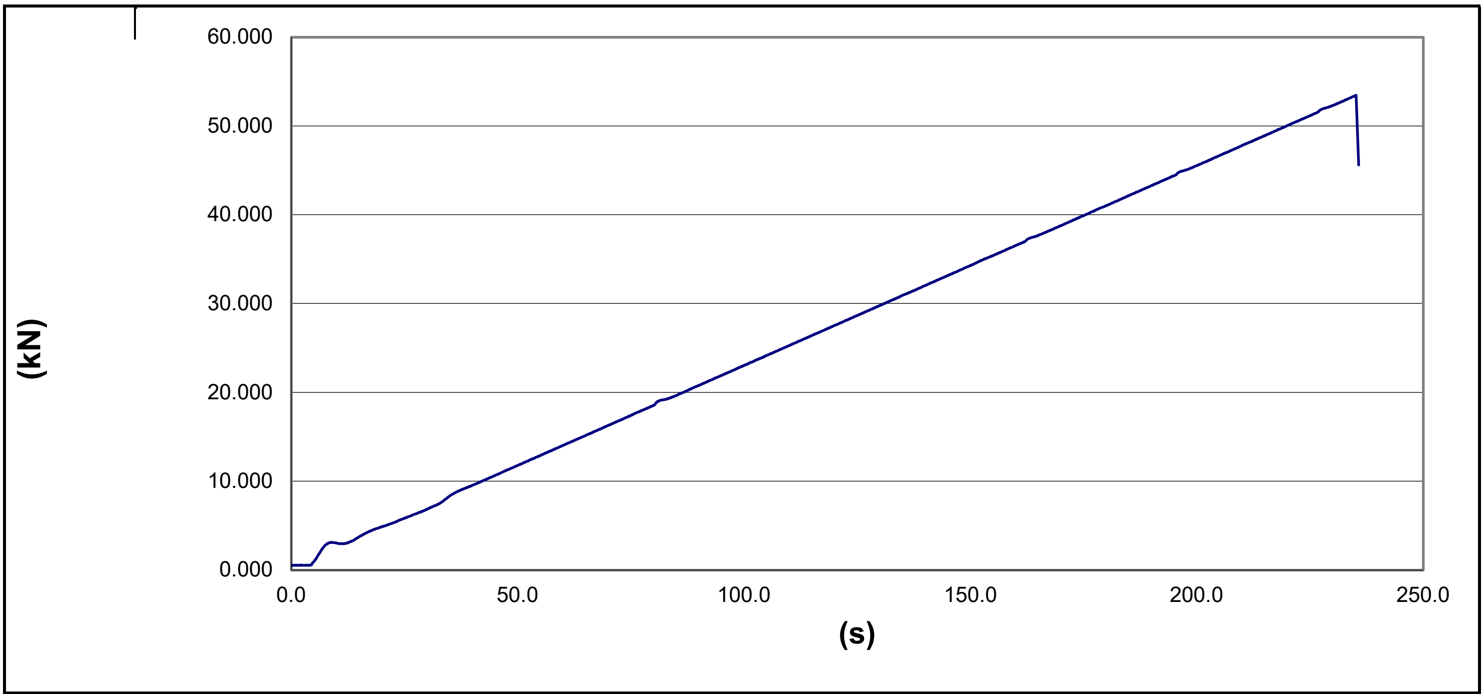
Certificate number	:	002-3PB-RT-2x6-2				Certificate date	: --------
Testing machine	:	C1701/FR s.n. 22000858					
Client	:						
Reference	:						
Specimen type	:	Beam				Cement quantity [kg/m³]	:
Cement type	:					Test date	: 22/08/2022
Sample conditions:							
Condition when received	:					Condition at test time	:
Sampling location	:					Sampling date	: --------
Preparation method	:						
Specimen ID	:						
Dimensions	:	*b(mm)*	: 150.00	*h(mm)*	: 150.00	Mass [kg]	: 0.000
		l(mm)	600				:
Load Rate [MPa/s]	:	0.1		No of upper roll	1	"L" distance [mm]	500.0
Area [mm2]	:	4500.0	Specimen age	: 28 dd		Preparation date	: --------
Load [kN]	:	46.67				Strength [MPa]	: 10.37
	:						
Notes	:						



Operator
Operator01

Flexural tests on beams: EN 12390-5

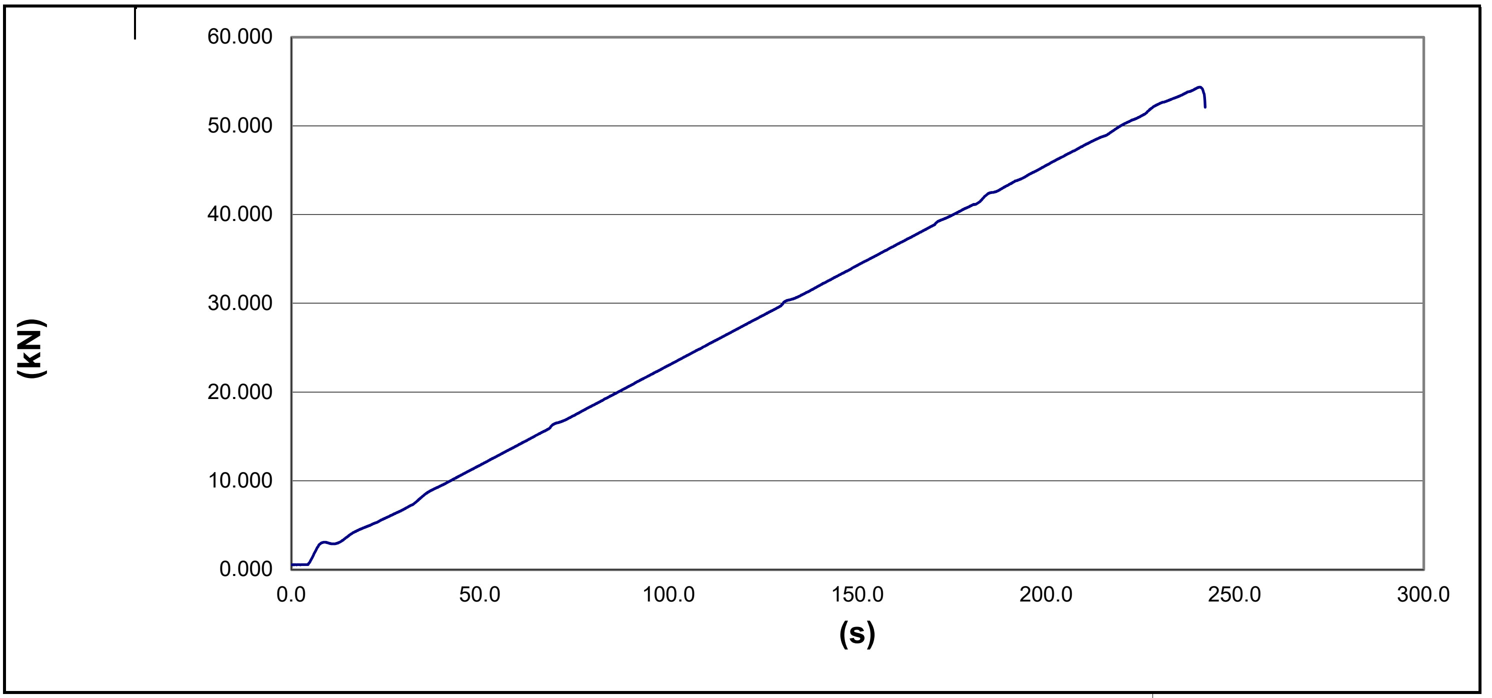
Certificate number	:	003-3PB-RT-2x6			Certificate date	: -------
Testing machine	:	C1701/FR s.n. 22000858				
Client	:					
Reference	:					
Specimen type	:	Beam			Cement quantity [kg/m³]	:
Cement type	:				Test date	: 22/08/2022
Sample conditions:						
Condition when received	:				Condition at test time	:
Sampling location	:				Sampling date	: -------
Preparation method	:					
Specimen ID	:					
Dimensions	:	*b(mm)*	: 150.00	*h(mm)* : 150.00	Mass [kg]	: 0.000
		l(mm)	600			:
Load Rate [MPa/s]	:	0.1		No of upper roll 1	"L" distance [mm]	500.0
Area [mm2]	:	4500.0	Specimen age	: 28 dd	Preparation date	: -------
Load [kN]	:	53.45			Strength [MPa]	: 11.88
	:					
Notes	:					



Operator
Operator01

Flexural tests on beams: EN 12390-5

Certificate number	: 003-3PB-RT-2x6-2				Certificate date	:	-------
Testing machine	: C1701/FR s.n. 22000858						
Client	:						
Reference	:						
Specimen type	: Beam				Cement quantity [kg/m³]	:	
Cement type	:				Test date	:	22/08/2022
Sample conditions:							
Condition when received	:				Condition at test time	:	
Sampling location	:				Sampling date	:	-------
Preparation method	:						
Specimen ID	:						
Dimensions	: *b(mm)*	: 150.00	*h(mm)*	: 150.00	Mass [kg]	:	0.000
	l(mm)	600				:	
Load Rate [MPa/s]	: 0.1		No of upper roll	1	"L" distance [mm]		500.0
Area [mm2]	: 4500.0	Specimen age	: 28 dd		Preparation date	:	-------
Load [kN]	: 54.35				Strength [MPa]	:	12.08
	:						
Notes	:						



Operator
Operator01

EN 14651

Test Organization	:	*Testing machine*	:

SPECIMEN DATA

Specimen ID	: 001-CMOD-RT20-T1	*Specimen type*	: balk
Specimen age [dd]	:	*Preparation date*	: 01/01/04
Curing	: water		
b [mm]	: 150	*h [mm]*	: 150
l [mm]	: 600	*Area [mm2]*	: 3125.0

Thickness after notch [mm]	: 125		
Notch width [mm]	: 3.6	*Notch date*	: 20/06/22
Surface preparation	: geen	*L [mm]*	: 500
Upper rollers number	: 1		

Preload [kN]	: 0.6	*Concrete type*	: C45/55
Fiber type	: Basaltvezels RT	*Fiber content*	: 20
Sampling date	: 01/05/22	*Sampling details*	:
Test date	: 20/06/22	*Test Location*	: Zaandam
Operator	:		

Deviations from standard	:
Declaration of conformity	:

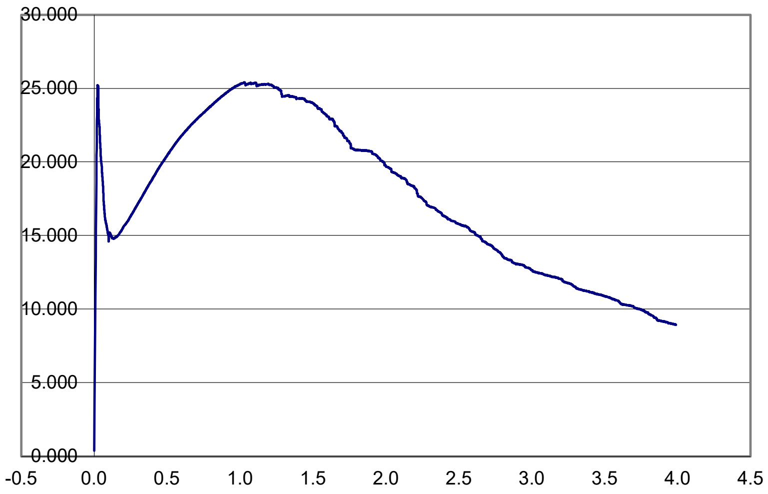
Certificate number	: 123456	*Certificate date*	: 20/06/22
Customer	:	*Reference*	:
Notes	:		

Start speed [mm/min]	: 0.05	*End Speed [mm/min]*	: 0.2
Speed change Thres. [mm/min]	: 0.1		
Target [mm]	: 4		

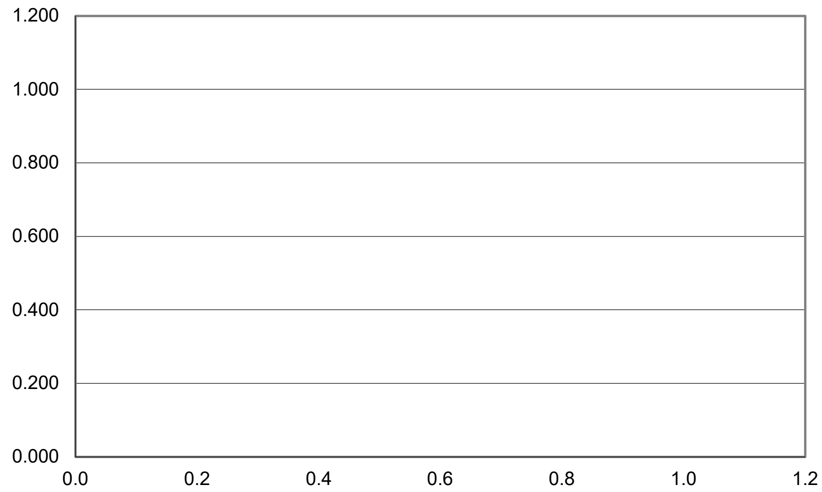
TEST RESULT

LOP [N/mm2]	:	8.07168335	*F0.5 [N/mm2]*	: 6.540158081
F1.5 [N/mm2]	:	7.679172363	*F2.5 [N/mm2]*	: 5.050819702
F3.5 [N/mm2]	:	3.486279907		

[kN]



CMOD [mm]



EN 14651

Test Organization	:		*Testing machine*	:	

SPECIMEN DATA

Specimen ID	:	002-CMOD-RT20-T1	*Specimen type*	:	balk
Specimen age [dd]	:		*Preparation date*	:	01/01/04
Curing	:	water			
b [mm]	:	150	*h [mm]*	:	150
l [mm]	:	600	*Area [mm2]*	:	3125.0

Thickness after notch [mm]	:	125			
Notch width [mm]	:	3.6	*Notch date*	:	20/06/22
Surface preparation	:	geen	*L [mm]*	:	500
Upper rollers number	:	1			

Preload [kN]	:	0.6	*Concrete type*	:	C45/55
Fiber type	:	Basaltvezels RT	*Fiber content*	:	20
Sampling date	:	01/05/22	*Sampling details*	:	
Test date	:	20/06/22	*Test Location*	:	Zaandam
Operator	:				

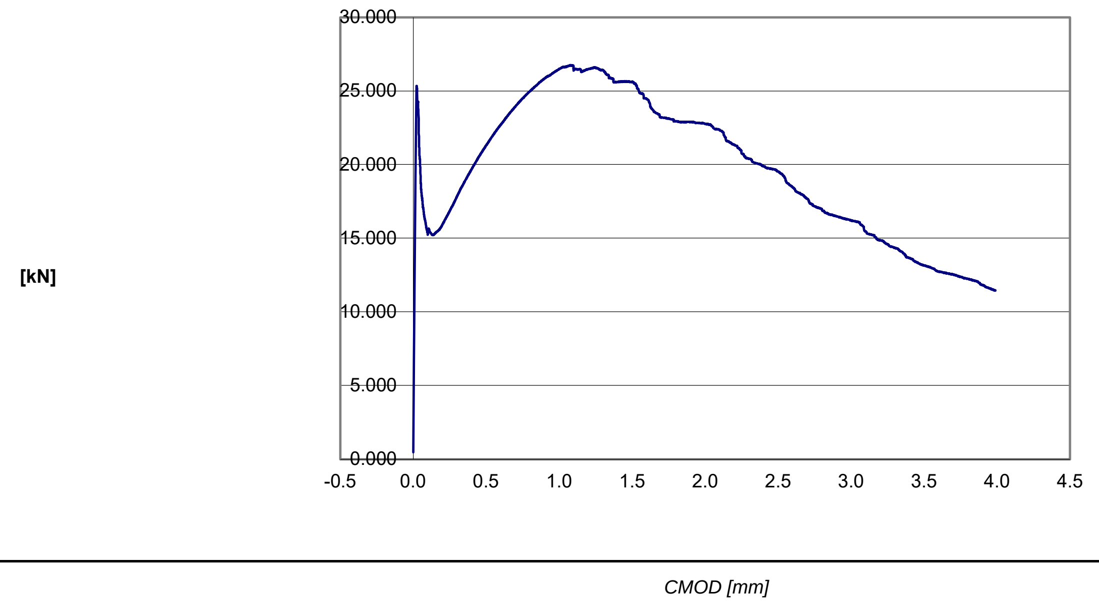
Deviations from standard	:
Declaration of conformity	:

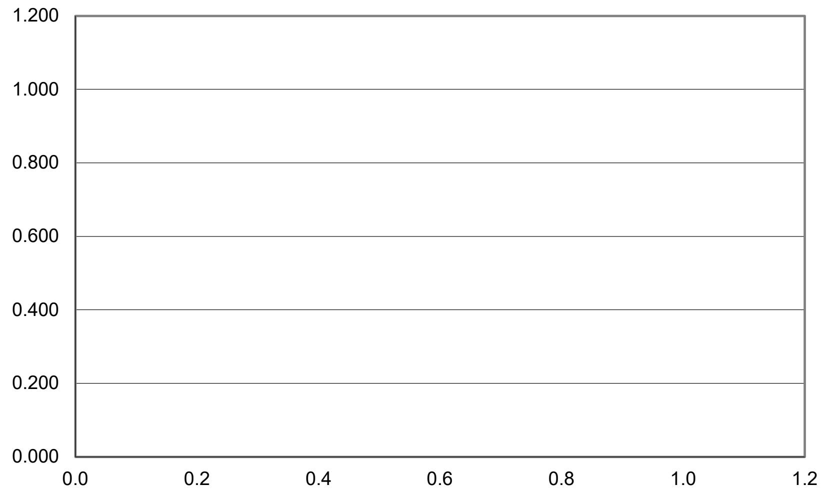
Certificate number	:	123456	*Certificate date*	:	20/06/22
Customer	:		*Reference*	:	
Notes	:				

Start speed [mm/min]	:	0.05	*End Speed [mm/min]*	:	0.2
Speed change Thres. [mm/min]	:	0.1			
Target [mm]	:	4			

TEST RESULT

LOP [N/mm2]	:	8.110262451	*F0.5 [N/mm2]*	:	6.817178955
F1.5 [N/mm2]	:	8.201970215	*F2.5 [N/mm2]*	:	6.25225708
F3.5 [N/mm2]	:	4.210835876			





EN 14651

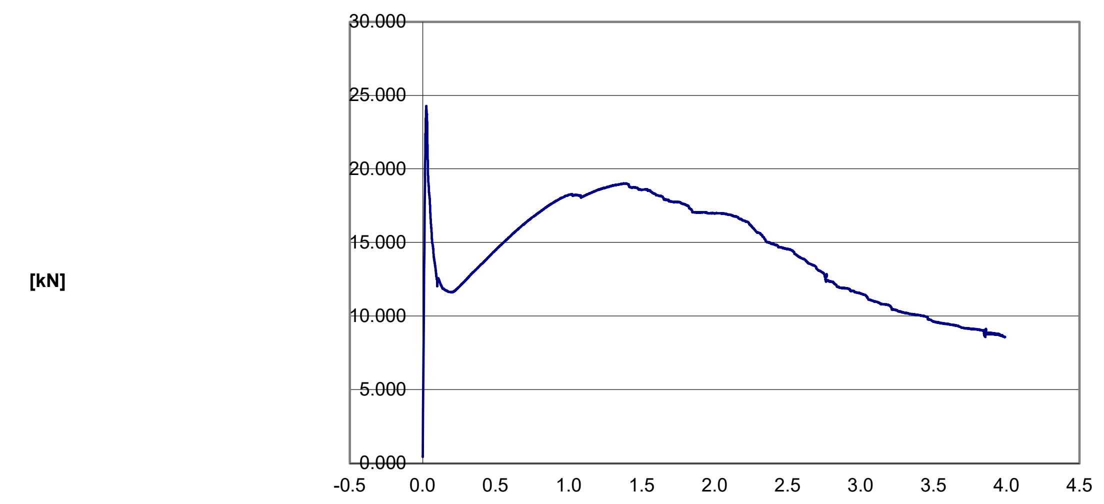
Test Organization	:		*Testing machine*	:	

SPECIMEN DATA

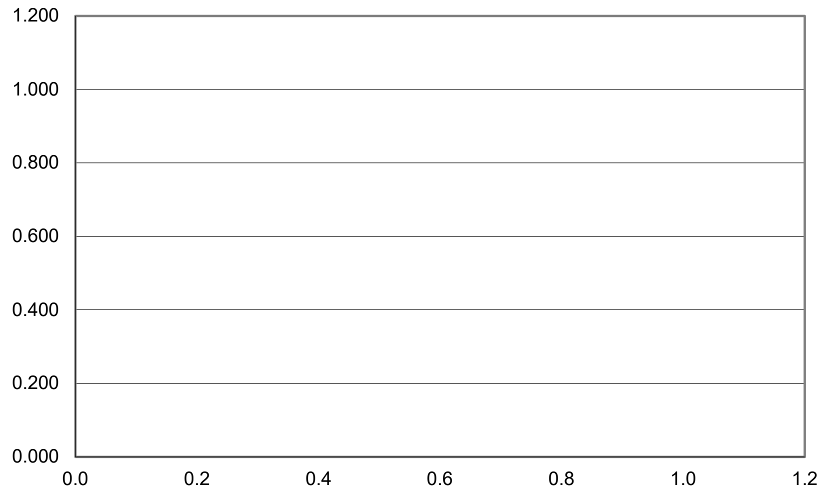
Specimen ID	:	003-CMOD-RT20-T1	*Specimen type*	:	balk
Specimen age [dd]	:		*Preparation date*	:	01/01/04
Curing	:	water			
b [mm]	:	150	*h [mm]*	:	150
l [mm]	:	600	*Area [mm2]*	:	3125.0
Thickness after notch [mm]	:	125			
Notch width [mm]	:	3.6	*Notch date*	:	20/06/22
Surface preparation	:	geen	*L [mm]*	:	500
Upper rollers number	:	1			
Preload [kN]	:	0.6	*Concrete type*	:	C45/55
Fiber type	:	Basaltvezels RT	*Fiber content*	:	20
Sampling date	:	01/05/22	*Sampling details*	:	
Test date	:	20/06/22	*Test Location*	:	Zaandam
Operator	:				
Deviations from standard	:				
Declaration of conformity	:				
Certificate number	:	123456	*Certificate date*	:	20/06/22
Customer	:		*Reference*	:	
Notes	:				
Start speed [mm/min]	:	0.05	*End Speed [mm/min]*	:	0.2
Speed change Thres. [mm/min]	:	0.1			
Target [mm]	:	4			

TEST RESULT

LOP [N/mm2]	:	7.773051758	*F0.5 [N/mm2]*	:	4.642138672
F1.5 [N/mm2]	:	5.948061523	*F2.5 [N/mm2]*	:	4.662314453
F3.5 [N/mm2]	:	3.08677002			



CMOD [mm]



EN 14651

Test Organization	:	*Testing machine*	:

SPECIMEN DATA

Specimen ID	: 001CMOD-RT15-T	*Specimen type*	: balk
Specimen age [dd]	:	*Preparation date*	: 01/01/04
Curing	: water		
b [mm]	: 150	*h [mm]*	: 150
l [mm]	: 600	*Area [mm2]*	: 3125.0

Thickness after notch [mm]	: 125		
Notch width [mm]	: 3.6	*Notch date*	: 20/06/22
Surface preparation	: geen	*L [mm]*	: 500
Upper rollers number	: 1		

Preload [kN]	: 0.6	*Concrete type*	: C45/55
Fiber type	: Basaltvezels Test	*Fiber content*	: 15
Sampling date	: 01/05/22	*Sampling details*	:
Test date	: 20/06/22	*Test Location*	: Zaandam
Operator	:		

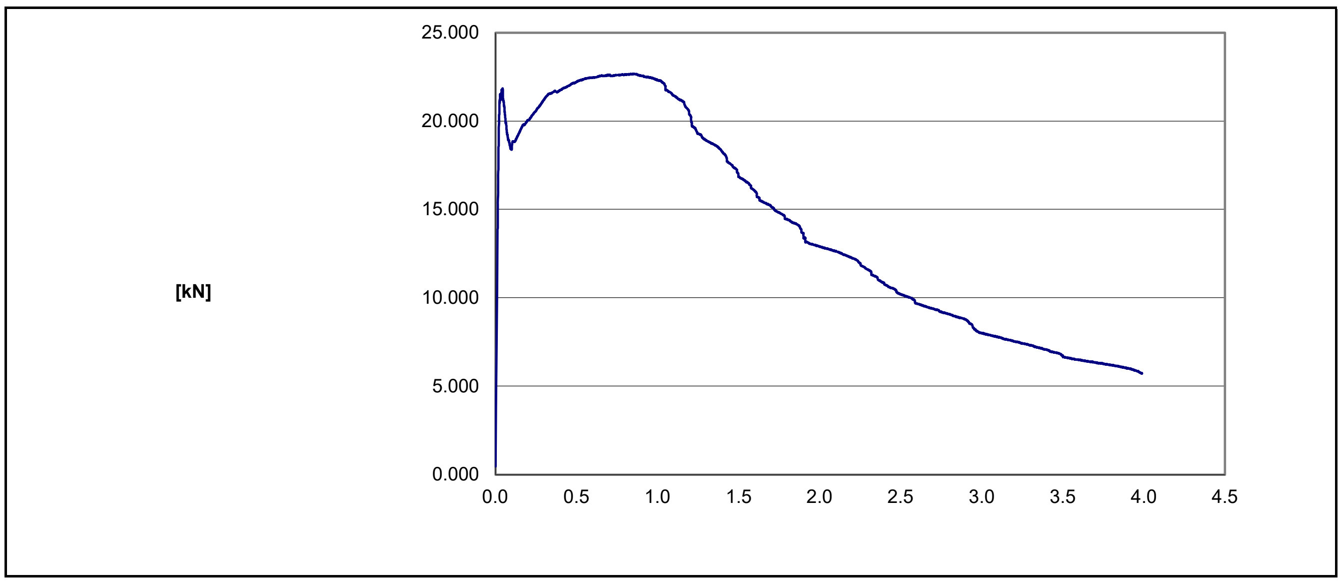
Deviations from standard	:
Declaration of conformity	:

Certificate number	: 123456	*Certificate date*	: 20/06/22
Customer	:	*Reference*	:
Notes	:		

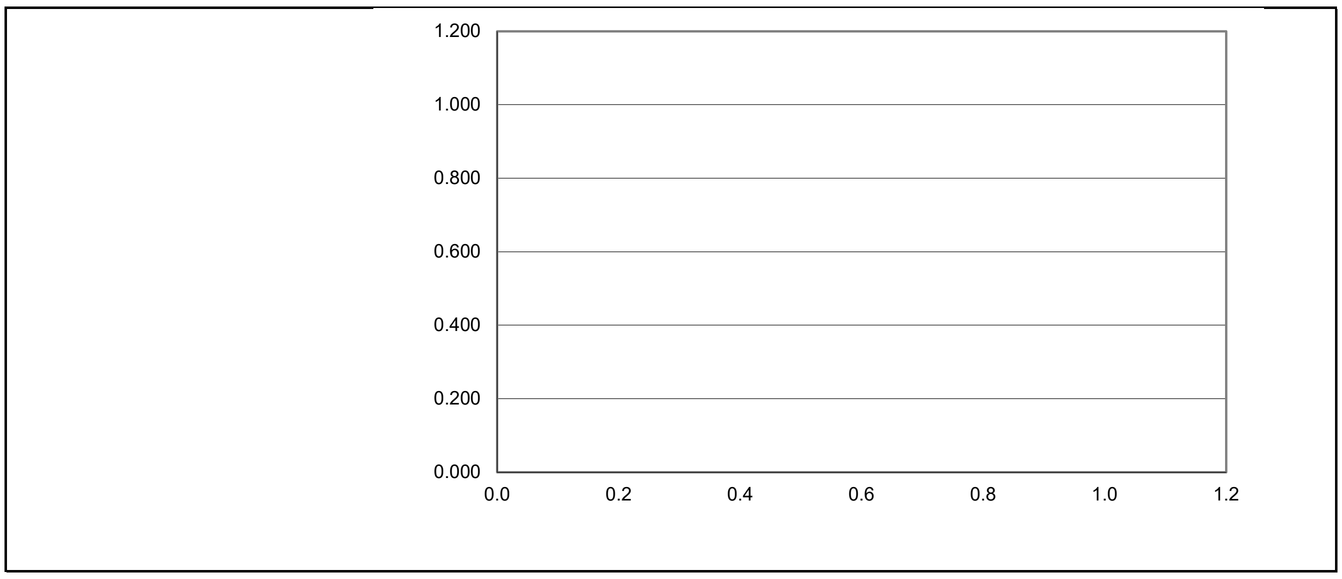
Start speed [mm/min]	: 0.05	*End Speed [mm/min]*	: 0.2
Speed change Thres. [mm/min]	: 0.1		
Target [mm]	: 4		

TEST RESULT

LOP [N/mm2]	:	6.991187134	*F0.5 [N/mm2]*	:	7.112241821
F1.5 [N/mm2]	:	5.397301025	*F2.5 [N/mm2]*	:	3.267839355
F3.5 [N/mm2]	:	2.150835419			



CMOD [mm]



EN 14651

Test Organization	:		*Testing machine*	:	

SPECIMEN DATA

Specimen ID	:	002CMOD-RT15-T	*Specimen type*	:	balk
Specimen age [dd]	:		*Preparation date*	:	01/01/04
Curing	:	water			
b [mm]	:	150	*h [mm]*	:	150
l [mm]	:	600	*Area [mm2]*	:	3125.0

Thickness after notch [mm]	:	125			
Notch width [mm]	:	3.6	*Notch date*	:	20/06/22
Surface preparation	:	geen	*L [mm]*	:	500
Upper rollers number	:	1			

Preload [kN]	:	0.6	*Concrete type*	:	C45/55
Fiber type	:	Basaltvezels RT	*Fiber content*	:	15
Sampling date	:	01/05/22	*Sampling details*	:	
Test date	:	20/06/22	*Test Location*	:	Zaandam
Operator	:				

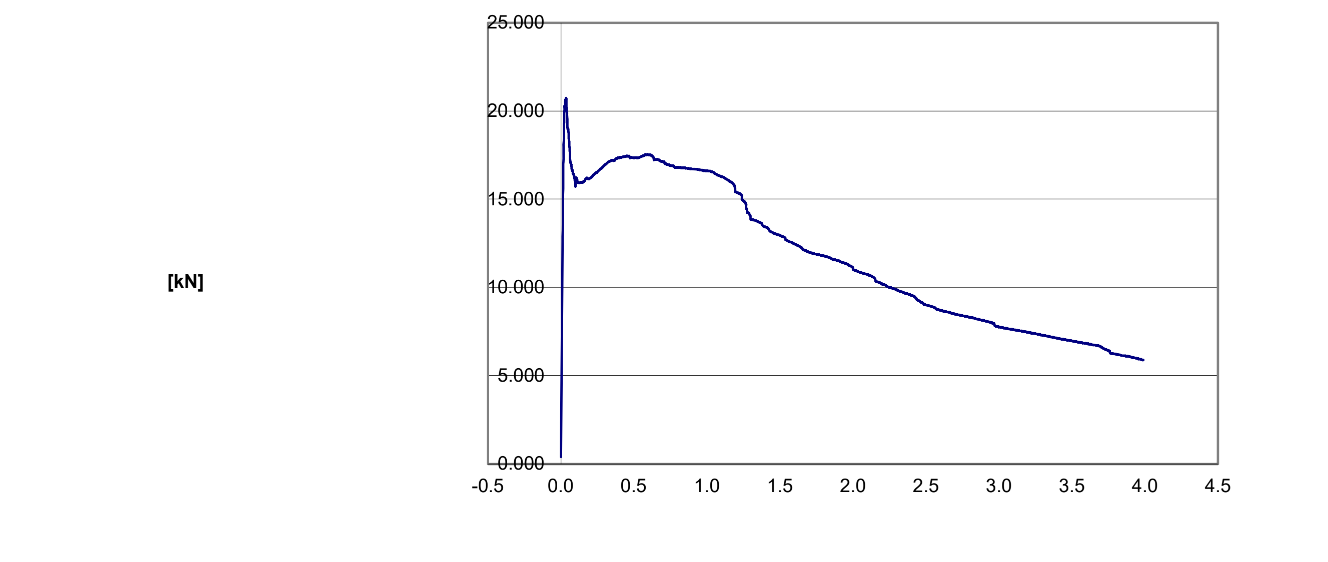
Deviations from standard	:	
Declaration of conformity	:	

Certificate number	:	123456	*Certificate date*	:	20/06/22
Customer	:		*Reference*	:	
Notes	:				

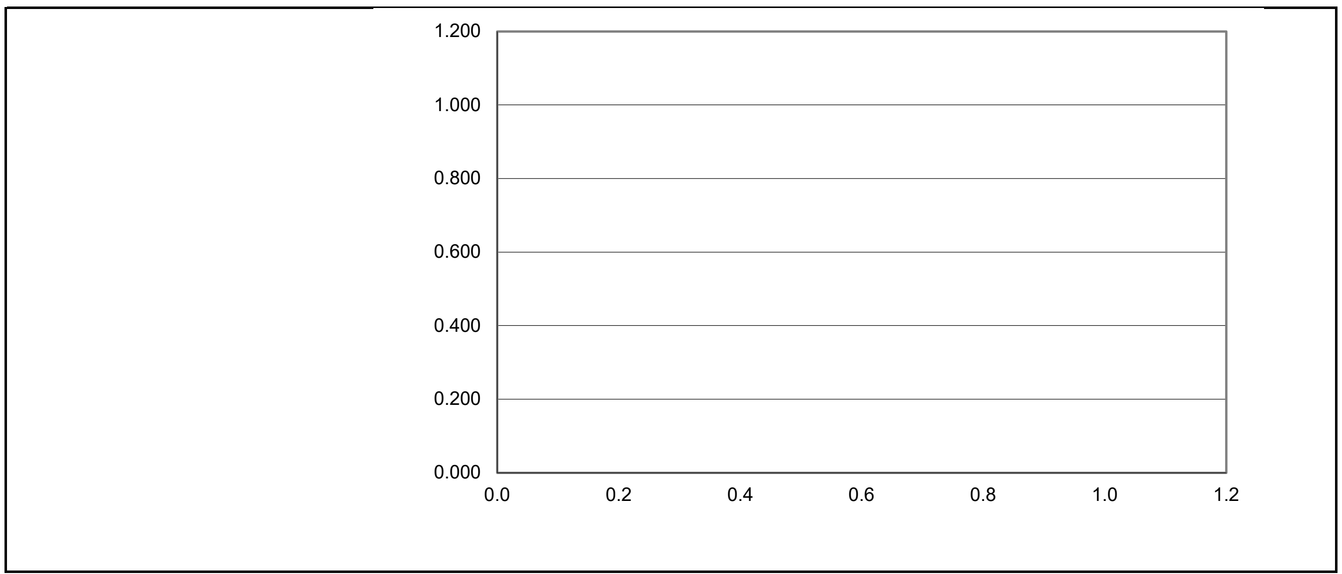
Start speed [mm/min]	:	0.05	*End Speed [mm/min]*	:	0.2
Speed change Thres. [mm/min]	:	0.1			
Target [mm]	:	4			

TEST RESULT

LOP [N/mm2]	:	6.639040527	*F0.5 [N/mm2]*	:	5.54954834
F1.5 [N/mm2]	:	4.151917725	*F2.5 [N/mm2]*	:	2.888180542
F3.5 [N/mm2]	:	2.233384857			



CMOD [mm]



EN 14651

Test Organization	:		*Testing machine*	:	

SPECIMEN DATA

Specimen ID	:	003CMOD-RT15-T	*Specimen type*	:	balk
Specimen age [dd]	:		*Preparation date*	:	01/01/04
Curing	:	water			
b [mm]	:	150	*h [mm]*	:	150
l [mm]	:	600	*Area [mm2]*	:	3125.0

Thickness after notch [mm]	:	125			
Notch width [mm]	:	3.6	*Notch date*	:	20/06/22
Surface preparation	:	geen	*L [mm]*	:	500
Upper rollers number	:	1			

Preload [kN]	:	0.6	*Concrete type*	:	C45/55
Fiber type	:	Basaltvezels RT	*Fiber content*	:	15
Sampling date	:	01/05/22	*Sampling details*	:	
Test date	:	20/06/22	*Test Location*	:	Zaandam
Operator	:				

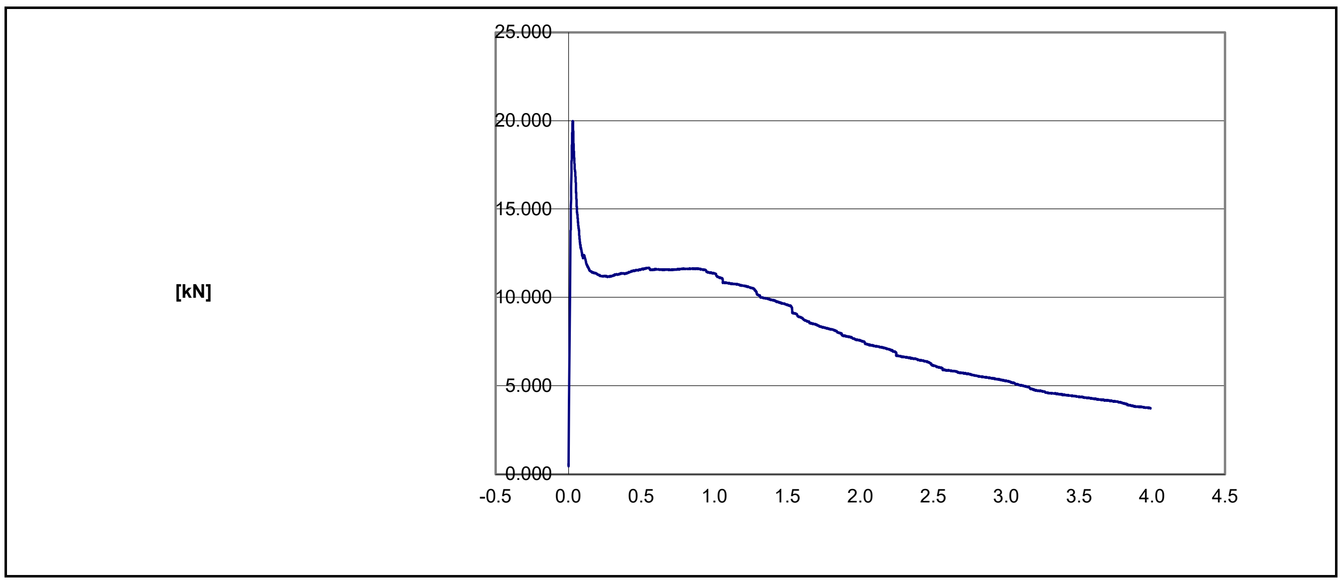
Deviations from standard	:	
Declaration of conformity	:	

Certificate number	:	123456	*Certificate date*	:	20/06/22
Customer	:		*Reference*	:	
Notes	:				

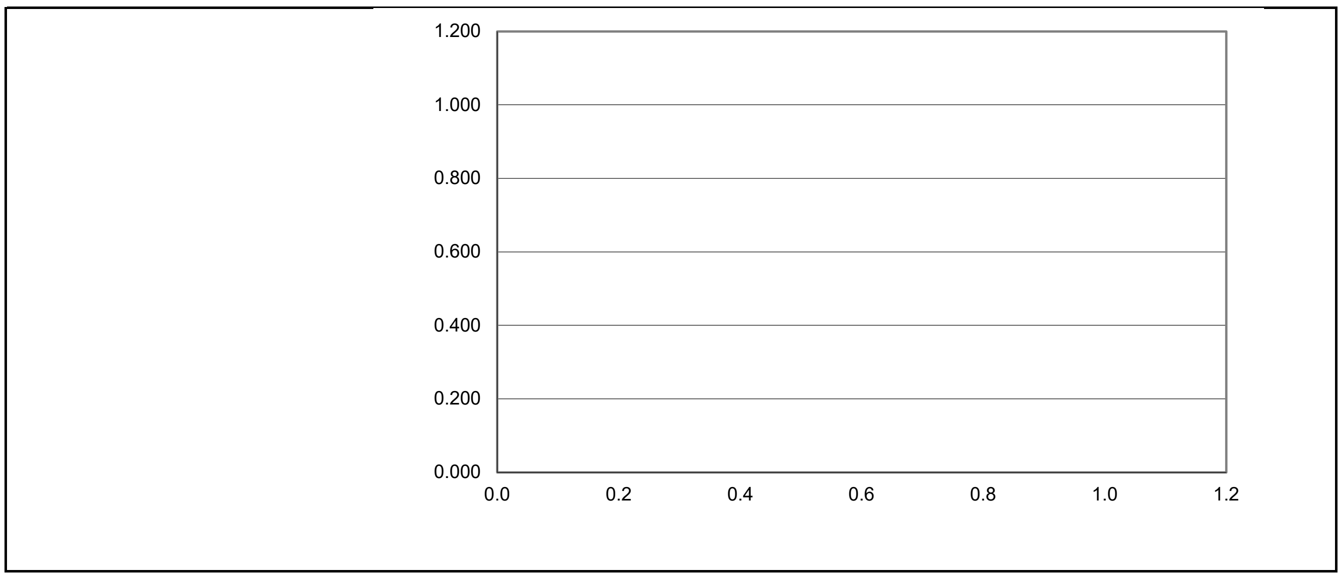
Start speed [mm/min]	:	0.05	*End Speed [mm/min]*	:	0.2
Speed change Thres. [mm/min]	:	0.1			
Target [mm]	:	4			

TEST RESULT

LOP [N/mm2]	:	6.393225708	*F0.5 [N/mm2]*	:	3.715349731
F1.5 [N/mm2]	:	3.06789093	*F2.5 [N/mm2]*	:	1.972234192
F3.5 [N/mm2]	:	1.403462524			



CMOD [mm]



EN 14651

Test Organization	:		*Testing machine*	:	

SPECIMEN DATA

Specimen ID	:	004CMOD-RT15-T	*Specimen type*	:	balk
Specimen age [dd]	:		*Preparation date*	:	01/01/04
Curing	:	water			
b [mm]	:	150	*h [mm]*	:	150
l [mm]	:	600	*Area [mm2]*	:	3125.0

Thickness after notch [mm]	:	125			
Notch width [mm]	:	3.6	*Notch date*	:	20/06/22
Surface preparation	:	geen	*L [mm]*	:	500
Upper rollers number	:	1			

Preload [kN]	:	0.6	*Concrete type*	:	C45/55
Fiber type	:	Basaltvezels RT	*Fiber content*	:	15
Sampling date	:	01/05/22	*Sampling details*	:	
Test date	:	20/06/22	*Test Location*	:	Zaandam
Operator	:				

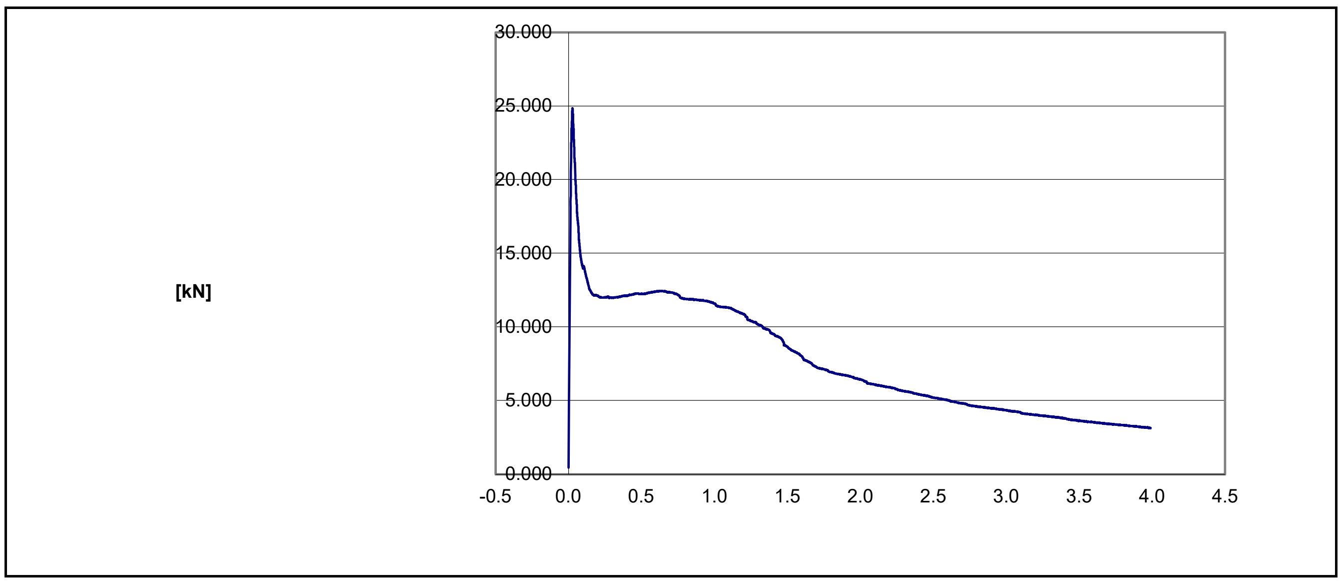
Deviations from standard	:	
Declaration of conformity	:	

Certificate number	:	123456	*Certificate date*	:	20/06/22
Customer	:		*Reference*	:	
Notes	:				

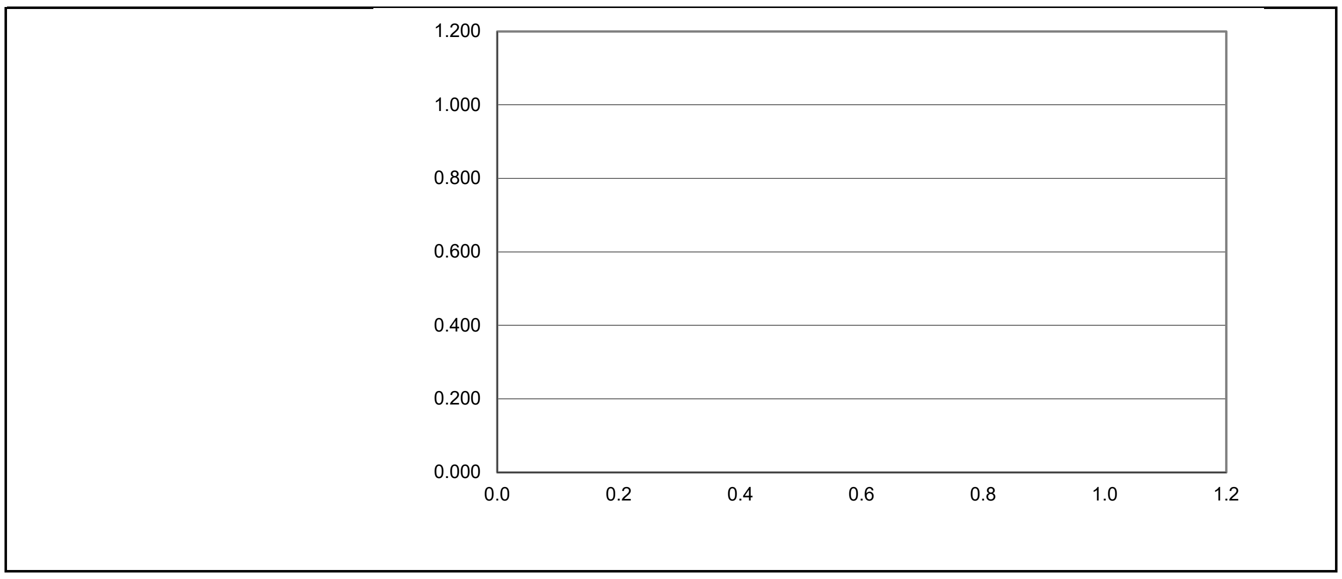
Start speed [mm/min]	:	0.05	*End Speed [mm/min]*	:	0.2
Speed change Thres. [mm/min]	:	0.1			
Target [mm]	:	4			

TEST RESULT

LOP [N/mm2]	:	7.94850708	*F0.5 [N/mm2]*	:	3.920688171
F1.5 [N/mm2]	:	2.768835144	*F2.5 [N/mm2]*	:	1.669381409
F3.5 [N/mm2]	:	1.165243149			



CMOD [mm]



EN 14651

Test Organization	:		*Testing machine*	:	

SPECIMEN DATA

Specimen ID	:	001CMOD-RT30-T	*Specimen type*	:	balk
Specimen age [dd]	:		*Preparation date*	:	01/01/04
Curing	:	water			
b [mm]	:	150	*h [mm]*	:	150
l [mm]	:	600	*Area [mm2]*	:	3125.0

Thickness after notch [mm]	:	125			
Notch width [mm]	:	3.6	*Notch date*	:	20/06/22
Surface preparation	:	geen	*L [mm]*	:	500
Upper rollers number	:	1			

Preload [kN]	:	0.6	*Concrete type*	:	C45/55
Fiber type	:	Basaltvezels RT	*Fiber content*	:	30
Sampling date	:	01/05/22	*Sampling details*	:	
Test date	:	20/06/22	*Test Location*	:	Zaandam
Operator	:				

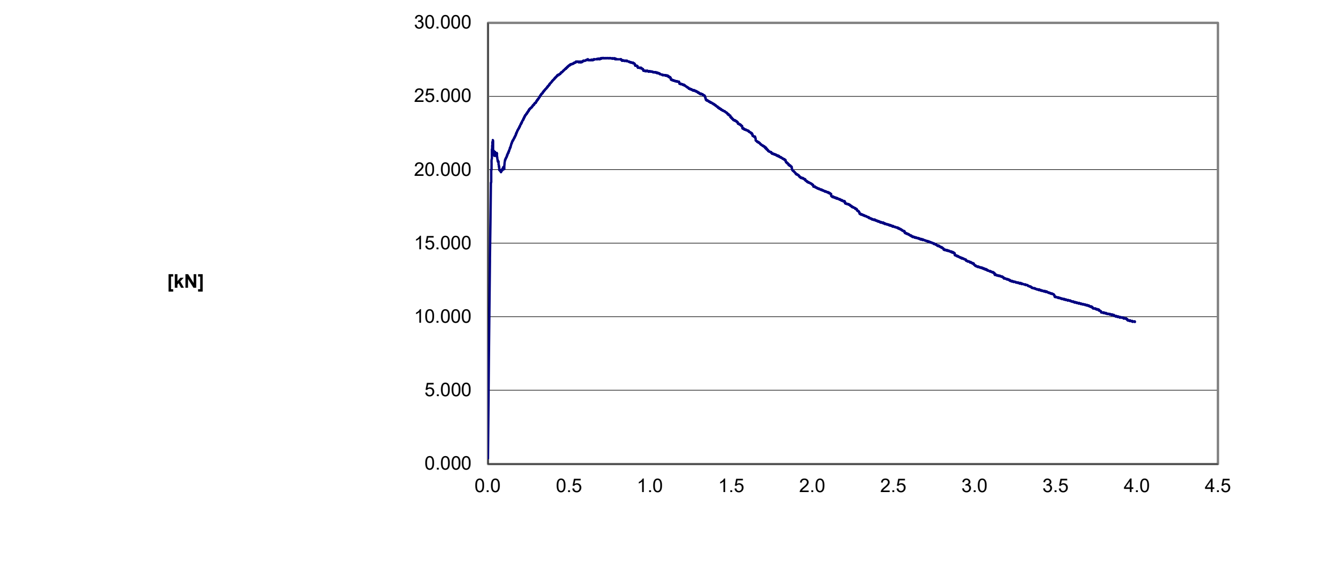
Deviations from standard	:	
Declaration of conformity	:	

Certificate number	:	123456	*Certificate date*	:	20/06/22
Customer	:		*Reference*	:	
Notes	:				

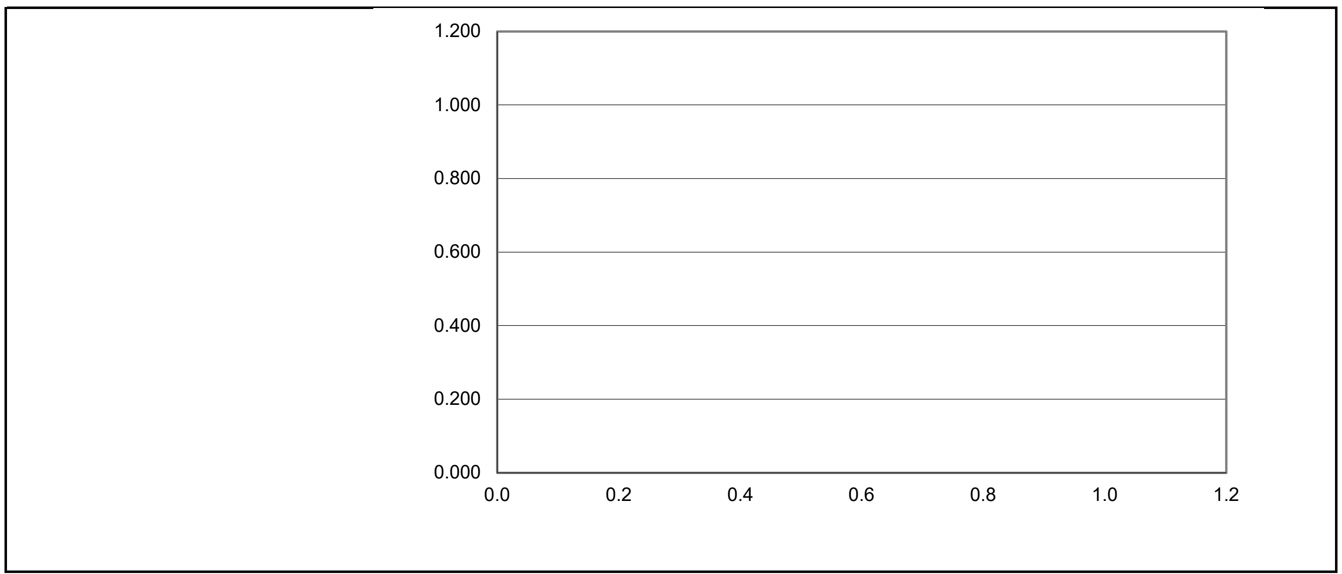
Start speed [mm/min]	:	0.05	*End Speed [mm/min]*	:	0.2
Speed change Thres. [mm/min]	:	0.1			
Target [mm]	:	4			

TEST RESULT

LOP [N/mm2]	:	7.047920532	*F0.5 [N/mm2]*	: 8.672987671
F1.5 [N/mm2]	:	7.535807495	*F2.5 [N/mm2]*	: 5.16973938
F3.5 [N/mm2]	:	3.634546509		



CMOD [mm]



EN 14651

Test Organization	:	*Testing machine*	:

SPECIMEN DATA

Specimen ID	: 002CMOD-RT30-T	*Specimen type*	: balk
Specimen age [dd]	:	*Preparation date*	: 01/01/04
Curing	: water		
b [mm]	: 150	*h [mm]*	: 150
l [mm]	: 600	*Area [mm2]*	: 3125.0

Thickness after notch [mm]	: 125		
Notch width [mm]	: 3.6	*Notch date*	: 20/06/22
Surface preparation	: geen	*L [mm]*	: 500
Upper rollers number	: 1		

Preload [kN]	: 0.6	*Concrete type*	: C45/55
Fiber type	: Basaltvezels RT	*Fiber content*	: 30
Sampling date	: 01/05/22	*Sampling details*	:
Test date	: 20/06/22	*Test Location*	: Zaandam
Operator	:		

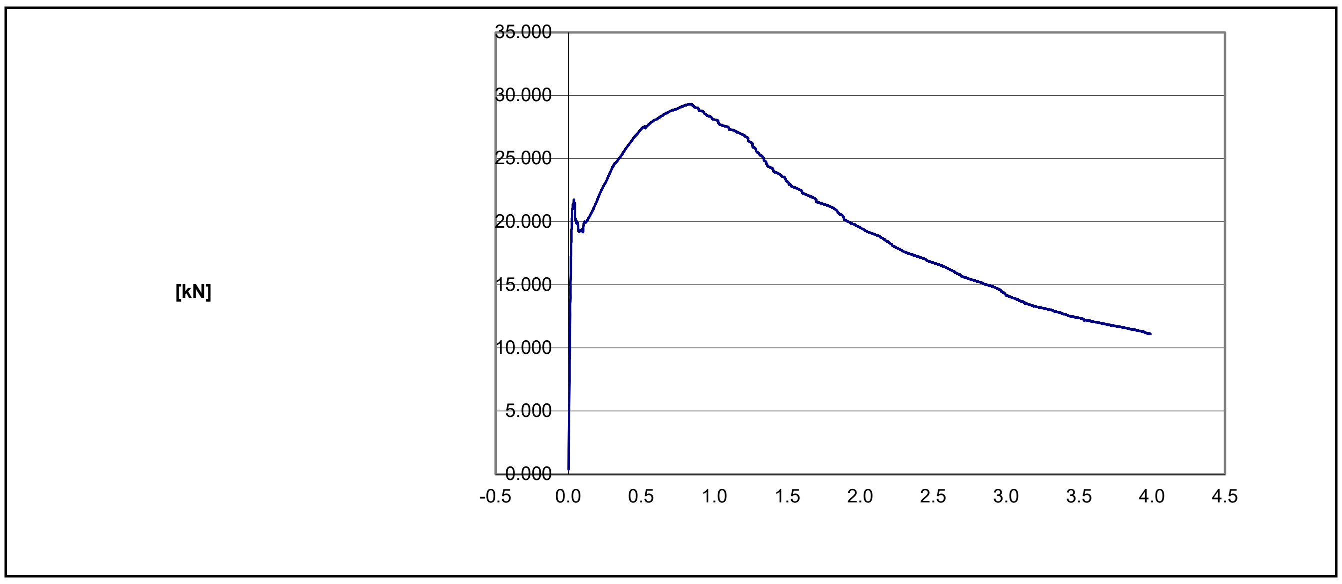
Deviations from standard	:
Declaration of conformity	:

Certificate number	: 123456	*Certificate date*	: 20/06/22
Customer	:	*Reference*	:
Notes	:		

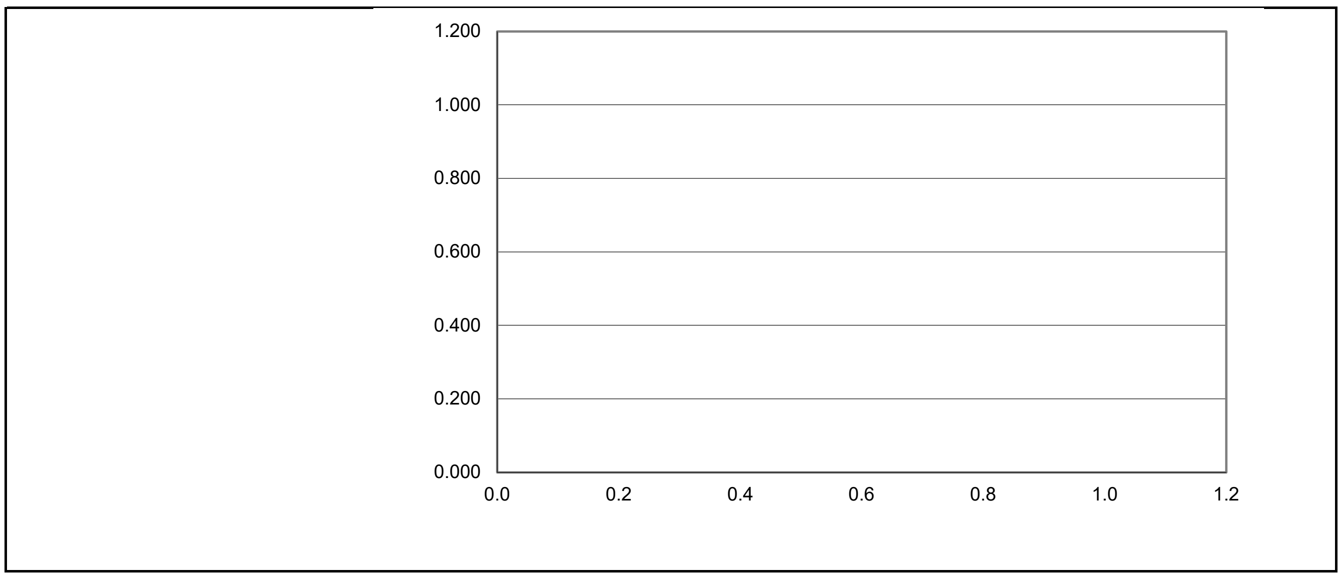
Start speed [mm/min]	: 0.05	*End Speed [mm/min]*	: 0.2
Speed change Thres. [mm/min]	: 0.1		
Target [mm]	: 4		

TEST RESULT

LOP [N/mm2]	:	6.963499756	*F0.5 [N/mm2]*	: 8.753640747
F1.5 [N/mm2]	:	7.416537476	*F2.5 [N/mm2]*	: 5.362277222
F3.5 [N/mm2]	:	3.95730896		



CMOD [mm]



EN 14651

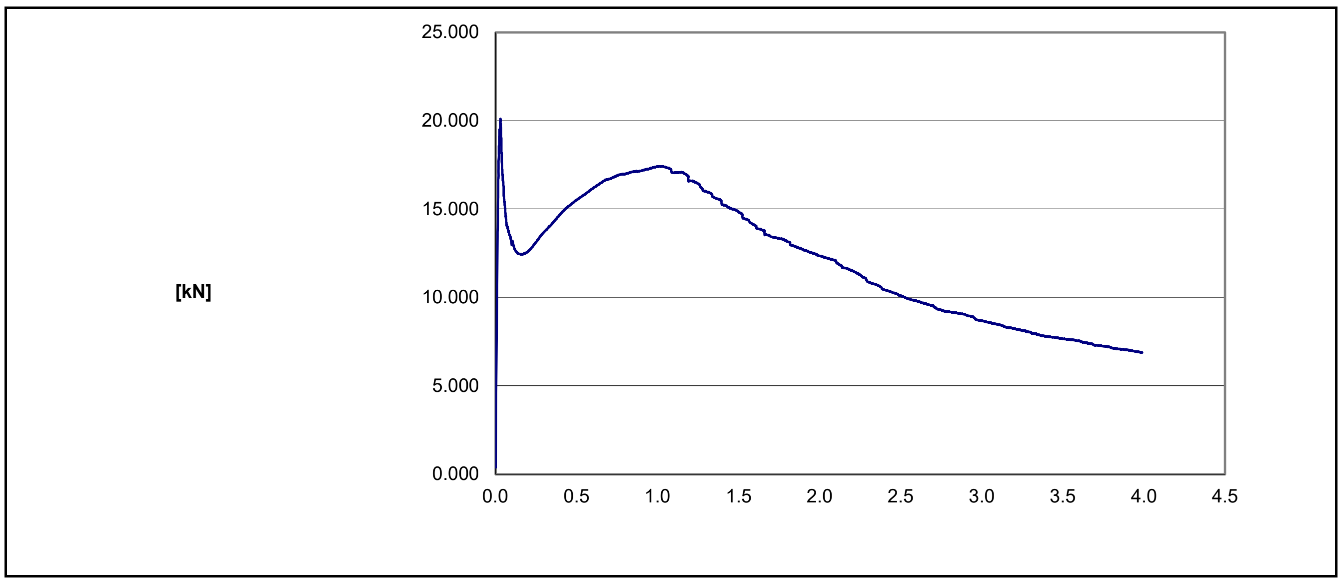
Test Organization	:		*Testing machine*	:	

SPECIMEN DATA

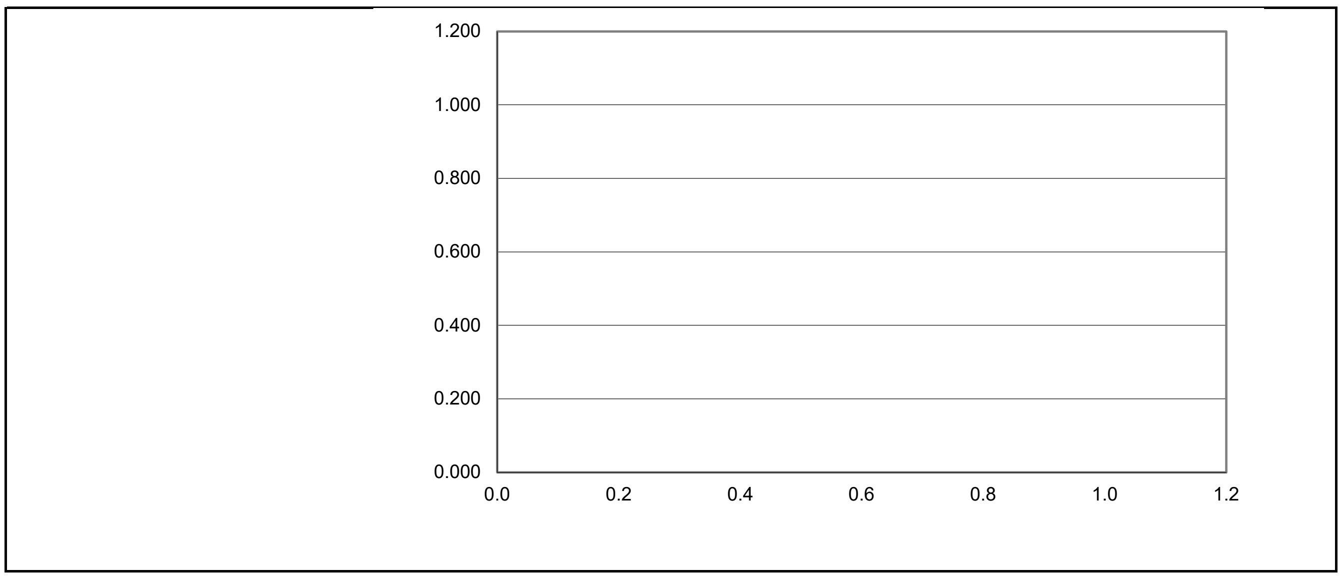
Specimen ID	:	003CMOD-RT30-T	*Specimen type*	:	balk
Specimen age [dd]	:		*Preparation date*	:	01/01/04
Curing	:	water			
b [mm]	:	150	*h [mm]*	:	150
l [mm]	:	600	*Area [mm2]*	:	3125.0
Thickness after notch [mm]	:	125			
Notch width [mm]	:	3.6	*Notch date*	:	20/06/22
Surface preparation	:	geen	*L [mm]*	:	500
Upper rollers number	:	1			
Preload [kN]	:	0.6	*Concrete type*	:	C45/55
Fiber type	:	Basaltvezels RT	*Fiber content*	:	30
Sampling date	:	01/05/22	*Sampling details*	:	
Test date	:	20/06/22	*Test Location*	:	Zaandam
Operator	:				
Deviations from standard	:				
Declaration of conformity	:				
Certificate number	:	123456	*Certificate date*	:	20/06/22
Customer	:		*Reference*	:	
Notes	:				
Start speed [mm/min]	:	0.05	*End Speed [mm/min]*	:	0.2
Speed change Thres. [mm/min]	:	0.1			
Target [mm]	:	4			

TEST RESULT

LOP [N/mm2]	: 6.437107544	*F0.5 [N/mm2]*	: 4.960608215
F1.5 [N/mm2]	: 4.746011047	*F2.5 [N/mm2]*	: 3.230993958
F3.5 [N/mm2]	: 2.455143738		



CMOD [mm]



EN 14651

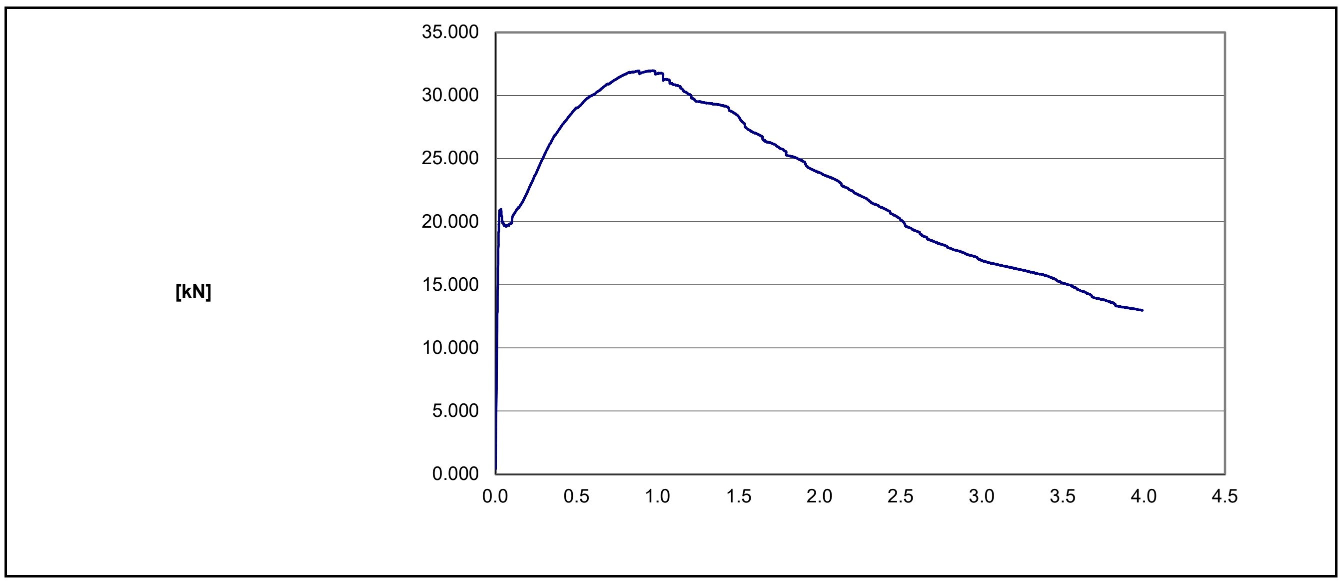
Test Organization	:	*Testing machine*	:

SPECIMEN DATA

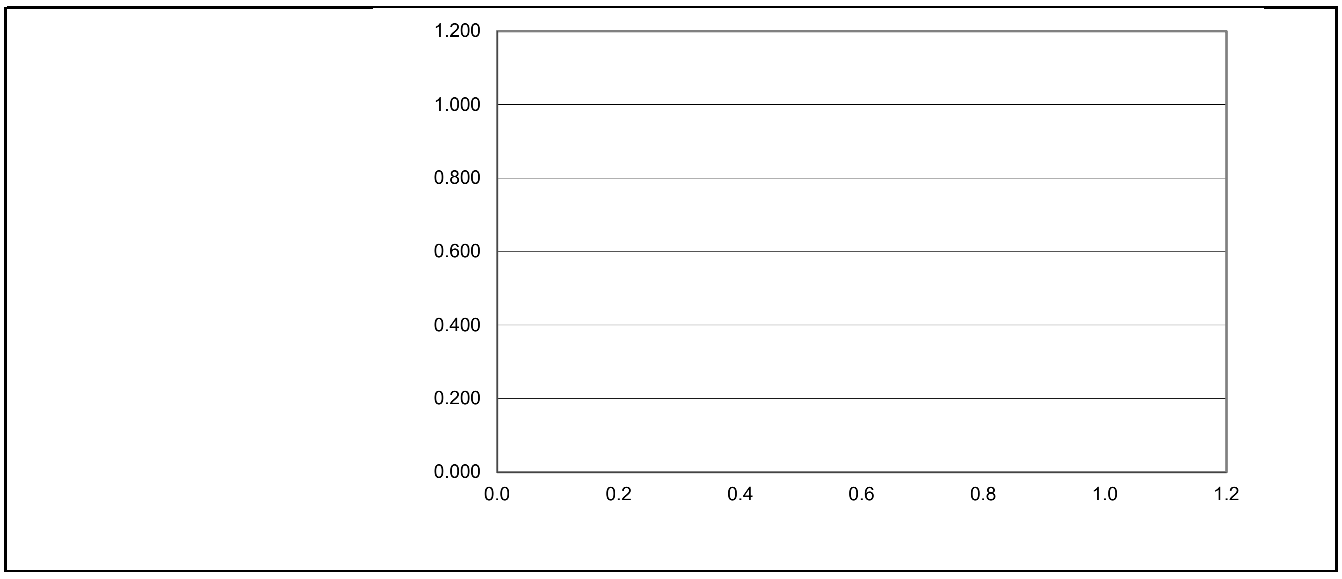
Specimen ID	: 004CMOD-RT30-T	*Specimen type*	: balk
Specimen age [dd]	:	*Preparation date*	: 01/01/04
Curing	: water		
b [mm]	: 150	*h [mm]*	: 150
l [mm]	: 600	*Area [mm2]*	: 3125.0
Thickness after notch [mm]	: 125		
Notch width [mm]	: 3.6	*Notch date*	: 20/06/22
Surface preparation	: geen	*L [mm]*	: 500
Upper rollers number	: 1		
Preload [kN]	: 0.6	*Concrete type*	: C45/55
Fiber type	: Basaltvezels RT	*Fiber content*	: 30
Sampling date	: 01/05/22	*Sampling details*	:
Test date	: 20/06/22	*Test Location*	: Zaandam
Operator	:		
Deviations from standard	:		
Declaration of conformity	:		
Certificate number	: 123456	*Certificate date*	: 20/06/22
Customer	:	*Reference*	:
Notes	:		
Start speed [mm/min]	: 0.05	*End Speed [mm/min]*	: 0.2
Speed change Thres. [mm/min]	: 0.1		
Target [mm]	: 4		

TEST RESULT

LOP [N/mm2]	:	6.71953125	*F0.5 [N/mm2]*	:	9.292860107
F1.5 [N/mm2]	:	9.061755371	*F2.5 [N/mm2]*	:	6.448074951
F3.5 [N/mm2]	:	4.846852722			



CMOD [mm]



EN 14651

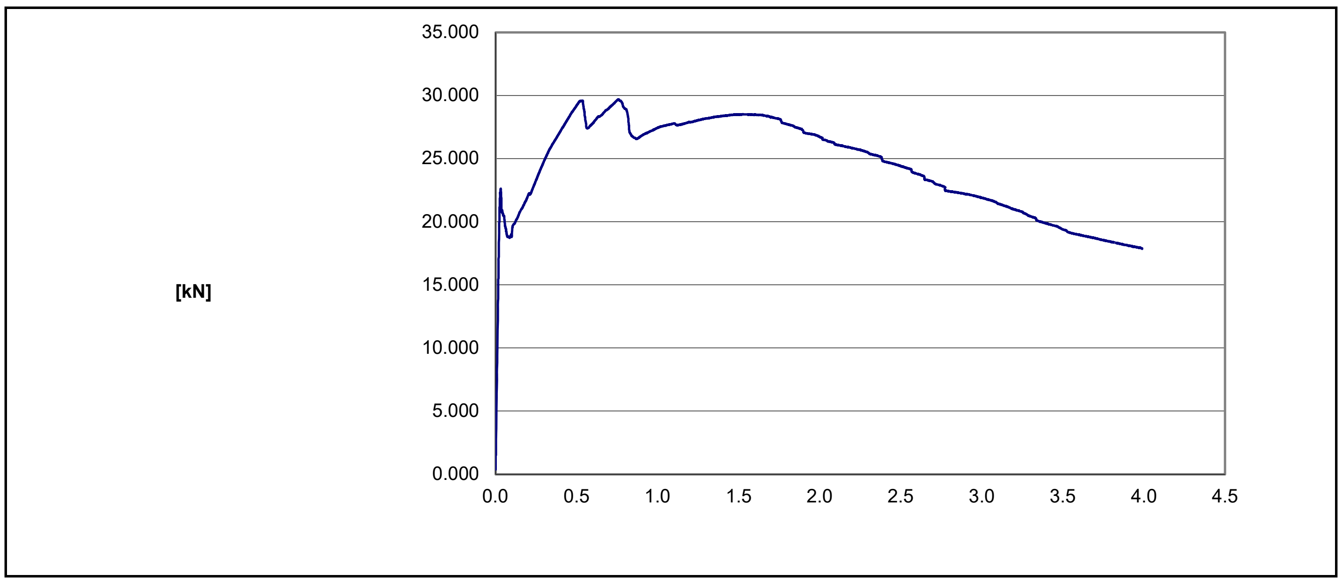
Test Organization	:		*Testing machine*	:	

SPECIMEN DATA

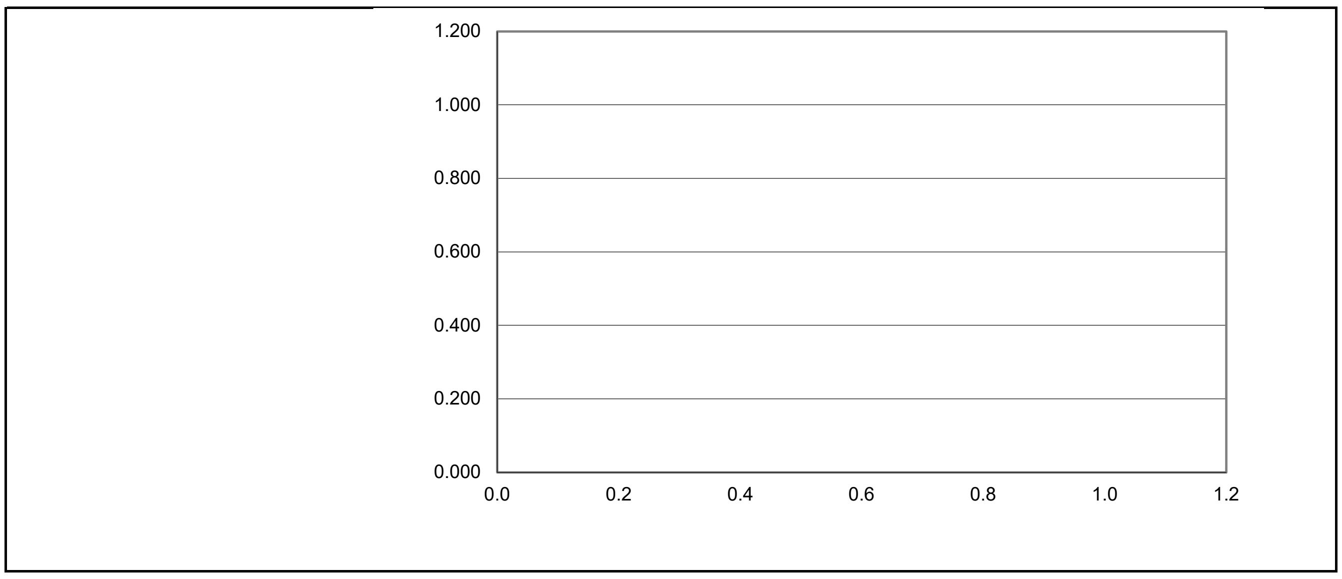
Specimen ID	:	001-CMOD-RT30-T3	*Specimen type*	:	balk
Specimen age [dd]	:		*Preparation date*	:	01/01/04
Curing	:	water			
b [mm]	:	150	*h [mm]*	:	150
l [mm]	:	600	*Area [mm2]*	:	3125.0
Thickness after notch [mm]	:	125			
Notch width [mm]	:	3.6	*Notch date*	:	20/06/22
Surface preparation	:	geen	*L [mm]*	:	500
Upper rollers number	:	1			
Preload [kN]	:	0.6	*Concrete type*	:	C45/55
Fiber type	:	Basaltvezels RT	*Fiber content*	:	30
Sampling date	:	01/05/22	*Sampling details*	:	
Test date	:	20/06/22	*Test Location*	:	Zaandam
Operator	:				
Deviations from standard	:				
Declaration of conformity	:				
Certificate number	:	123456	*Certificate date*	:	20/06/22
Customer	:		*Reference*	:	
Notes	:				
Start speed [mm/min]	:	0.05	*End Speed [mm/min]*	:	0.2
Speed change Thres. [mm/min]	:	0.1			
Target [mm]	:	4			

TEST RESULT

LOP [N/mm2]	:	7.236976929	*F0.5 [N/mm2]*	:	9.348095703
F1.5 [N/mm2]	:	9.116992188	*F2.5 [N/mm2]*	:	7.812903442
F3.5 [N/mm2]	:	6.206177979			



CMOD [mm]



EN 14651

Test Organization	:		*Testing machine*	:	

SPECIMEN DATA

Specimen ID	:	002-CMOD-RT30-T3	*Specimen type*	:	balk
Specimen age [dd]	:		*Preparation date*	:	01/01/04
Curing	:	water			
b [mm]	:	150	*h [mm]*	:	150
l [mm]	:	600	*Area [mm2]*	:	3125.0

Thickness after notch [mm]	:	125			
Notch width [mm]	:	3.6	*Notch date*	:	20/06/22
Surface preparation	:	geen	*L [mm]*	:	500
Upper rollers number	:	1			

Preload [kN]	:	0.6	*Concrete type*	:	C45/55
Fiber type	:	Basaltvezels RT	*Fiber content*	:	30
Sampling date	:	01/05/22	*Sampling details*	:	
Test date	:	20/06/22	*Test Location*	:	Zaandam
Operator	:				

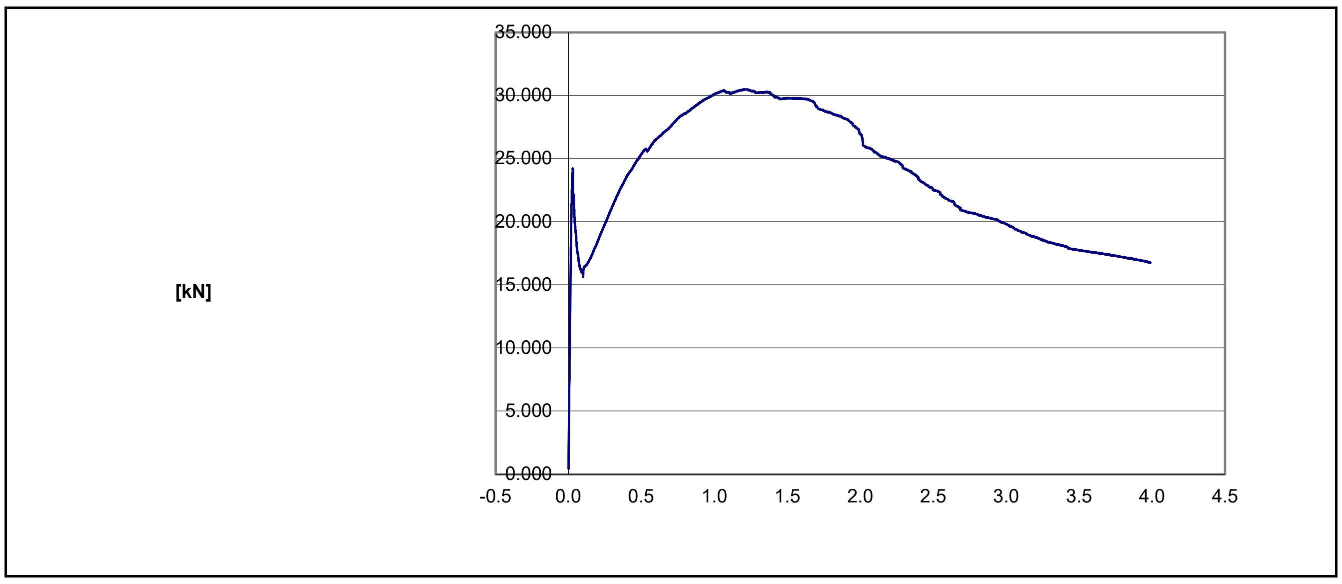
Deviations from standard	:	
Declaration of conformity	:	

Certificate number	:	123456	*Certificate date*	:	20/06/22
Customer	:		*Reference*	:	
Notes	:				

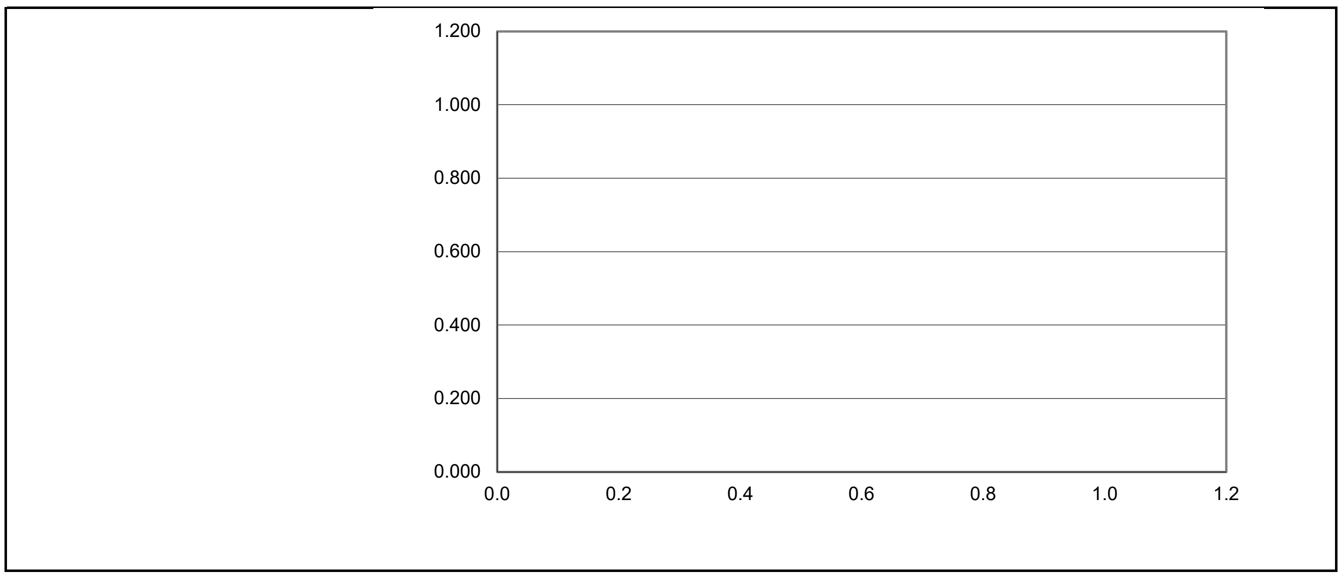
Start speed [mm/min]	:	0.05	*End Speed [mm/min]*	:	0.2
Speed change Thres. [mm/min]	:	0.1			
Target [mm]	:	4			

TEST RESULT

LOP [N/mm2]	:	7.743580322	*F0.5 [N/mm2]*	: 8.117749023
F1.5 [N/mm2]	:	9.533722534	*F2.5 [N/mm2]*	: 7.21350769
F3.5 [N/mm2]	:	5.683817139		



CMOD [mm]



EN 14651

Test Organization	:		*Testing machine*	:	

SPECIMEN DATA

Specimen ID	:	003-CMOD-RT30-T1	*Specimen type*	:	balk
Specimen age [dd]	:		*Preparation date*	:	01/01/04
Curing	:	water			
b [mm]	:	150	*h [mm]*	:	150
l [mm]	:	600	*Area [mm2]*	:	3125.0

Thickness after notch [mm]	:	125			
Notch width [mm]	:	3.6	*Notch date*	:	20/06/22
Surface preparation	:	geen	*L [mm]*	:	500
Upper rollers number	:	1			

Preload [kN]	:	0.6	*Concrete type*	:	C45/55
Fiber type	:	Basaltvezels RT	*Fiber content*	:	30
Sampling date	:	01/05/22	*Sampling details*	:	
Test date	:	20/06/22	*Test Location*	:	Zaandam
Operator	:				

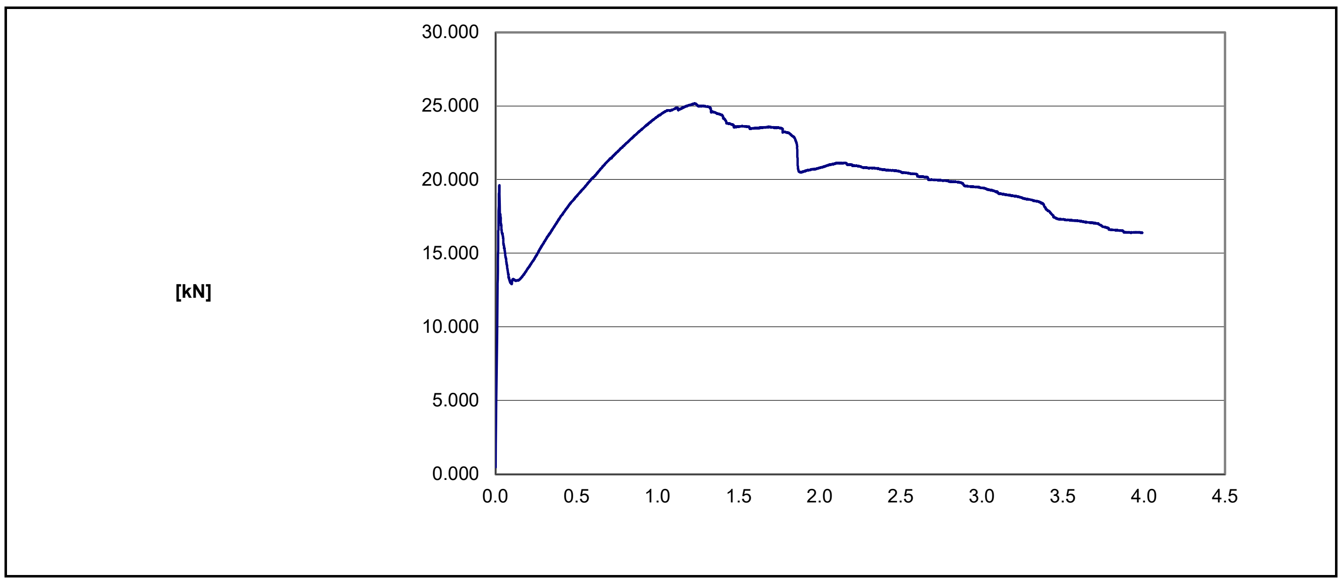
Deviations from standard	:	
Declaration of conformity	:	

Certificate number	:	123456	*Certificate date*	:	20/06/22
Customer	:		*Reference*	:	
Notes	:				

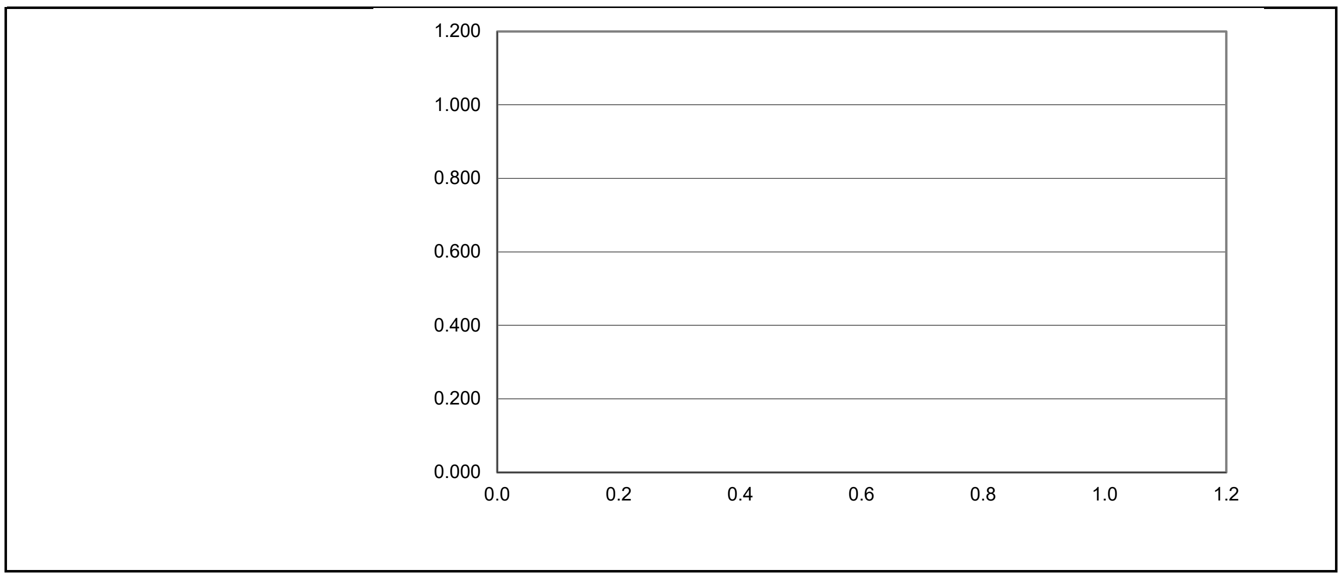
Start speed [mm/min]	:	0.05	*End Speed [mm/min]*	:	0.2
Speed change Thres. [mm/min]	:	0.1			
Target [mm]	:	4			

TEST RESULT

LOP [N/mm2]	:	6.283950806	*F0.5 [N/mm2]*	: 6.040007324
F1.5 [N/mm2]	:	7.549522095	*F2.5 [N/mm2]*	: 6.570079956
F3.5 [N/mm2]	:	5.537446899		



CMOD [mm]



EN 14651

Test Organization	:		*Testing machine*	:	

SPECIMEN DATA

Specimen ID	:	004-CMOD-RT30-T2	*Specimen type*	:	balk
Specimen age [dd]	:		*Preparation date*	:	01/01/04
Curing	:	water			
b [mm]	:	150	*h [mm]*	:	150
l [mm]	:	600	*Area [mm2]*	:	3125.0

Thickness after notch [mm]	:	125			
Notch width [mm]	:	3.6	*Notch date*	:	20/06/22
Surface preparation	:	geen	*L [mm]*	:	500
Upper rollers number	:	1			

Preload [kN]	:	0.6	*Concrete type*	:	C45/55
Fiber type	:	Basaltvezels RT	*Fiber content*	:	30
Sampling date	:	01/05/22	*Sampling details*	:	
Test date	:	20/06/22	*Test Location*	:	Zaandam
Operator	:				

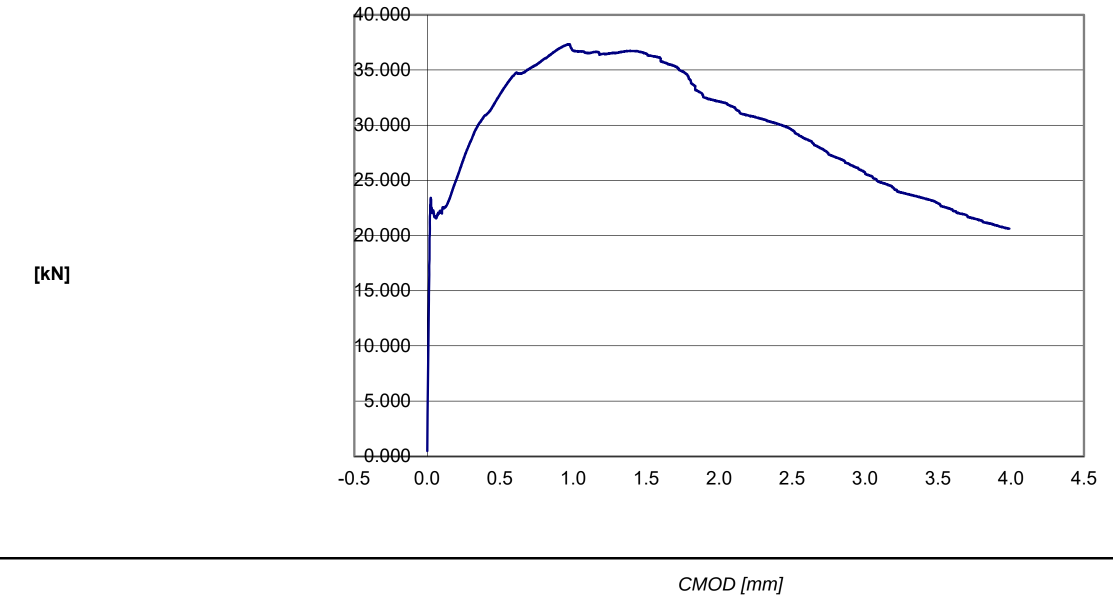
Deviations from standard	:	
Declaration of conformity	:	

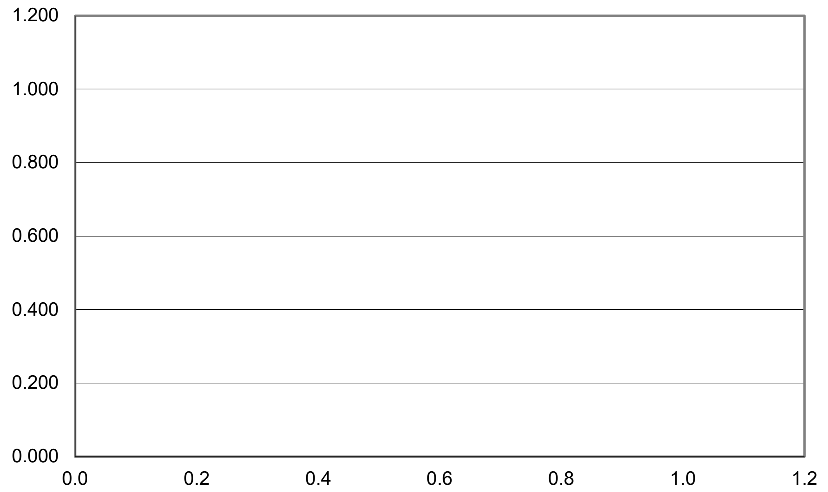
Certificate number	:	123456	*Certificate date*	:	20/06/22
Customer	:		*Reference*	:	
Notes	:				

Start speed [mm/min]	:	0.05	*End Speed [mm/min]*	:	0.2
Speed change Thres. [mm/min]	:	0.1			
Target [mm]	:	4			

TEST RESULT

LOP [N/mm2]	:	7.495406494	*F0.5 [N/mm2]*	:	10.50526367
F1.5 [N/mm2]	:	11.67715942	*F2.5 [N/mm2]*	:	9.457959595
F3.5 [N/mm2]	:	7.34133667			





EN 14651

Test Organization	:		*Testing machine*	:	

SPECIMEN DATA

Specimen ID	:	005-CMOD-RT30-T2	*Specimen type*	:	balk
Specimen age [dd]	:		*Preparation date*	:	01/01/04
Curing	:	water			
b [mm]	:	150	*h [mm]*	:	150
l [mm]	:	600	*Area [mm2]*	:	3125.0

Thickness after notch [mm]	:	125			
Notch width [mm]	:	3.6	*Notch date*	:	20/06/22
Surface preparation	:	geen	*L [mm]*	:	500
Upper rollers number	:	1			

Preload [kN]	:	0.6	*Concrete type*	:	C45/55
Fiber type	:	Basaltvezels RT	*Fiber content*	:	30
Sampling date	:	01/05/22	*Sampling details*	:	
Test date	:	20/06/22	*Test Location*	:	Zaandam
Operator	:				

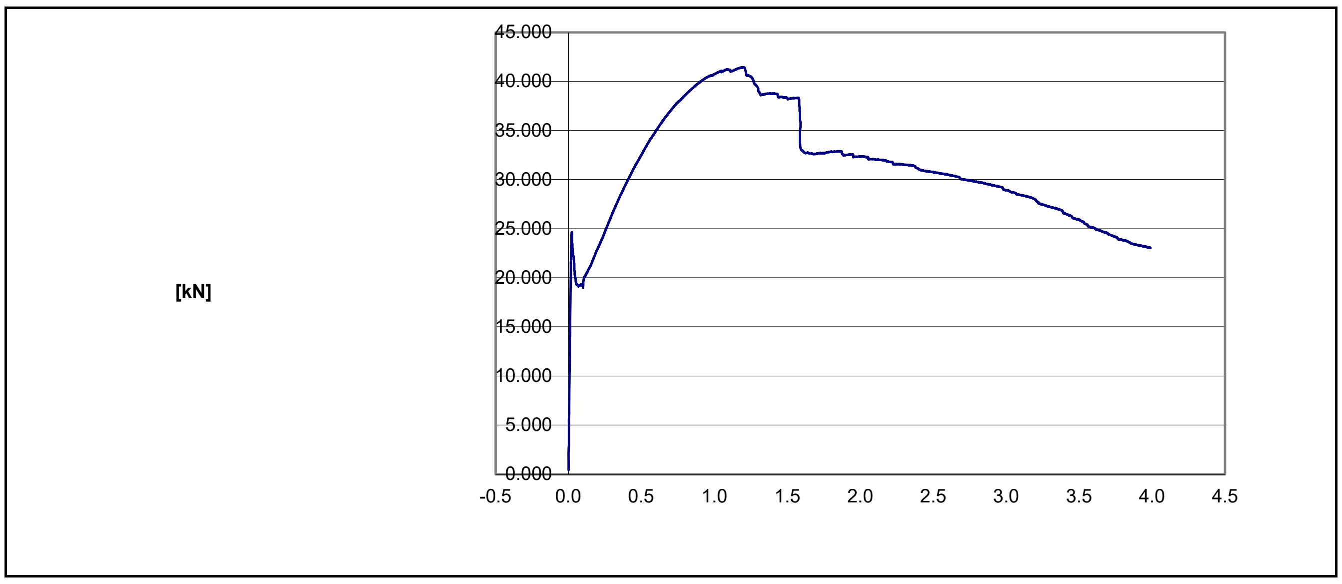
Deviations from standard	:	
Declaration of conformity	:	

Certificate number	:	123456	*Certificate date*	:	20/06/22
Customer	:		*Reference*	:	
Notes	:				

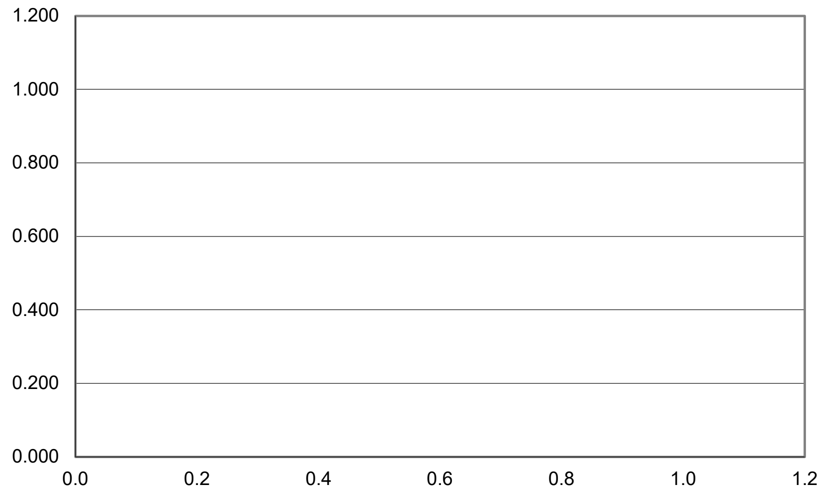
Start speed [mm/min]	:	0.05	*End Speed [mm/min]*	:	0.2
Speed change Thres. [mm/min]	:	0.1			
Target [mm]	:	4			

TEST RESULT

LOP [N/mm2]	:	7.88663269	*F0.5 [N/mm2]*	:	10.41227295
F1.5 [N/mm2]	:	12.25685303	*F2.5 [N/mm2]*	:	9.851019287
F3.5 [N/mm2]	:	8.290148315			



CMOD [mm]



EN 14651

Test Organization	:		*Testing machine*	:	

SPECIMEN DATA

Specimen ID	:	006-CMOD-RT30-T4	*Specimen type*	:	balk
Specimen age [dd]	:		*Preparation date*	:	01/01/04
Curing	:	water			
b [mm]	:	150	*h [mm]*	:	150
l [mm]	:	600	*Area [mm2]*	:	3125.0

Thickness after notch [mm]	:	125			
Notch width [mm]	:	3.6	*Notch date*	:	20/06/22
Surface preparation	:	geen	*L [mm]*	:	500
Upper rollers number	:	1			

Preload [kN]	:	0.6	*Concrete type*	:	C45/55
Fiber type	:	Basaltvezels RT	*Fiber content*	:	30
Sampling date	:	01/05/22	*Sampling details*	:	
Test date	:	20/06/22	*Test Location*	:	Zaandam
Operator	:				

Deviations from standard	:	
Declaration of conformity	:	

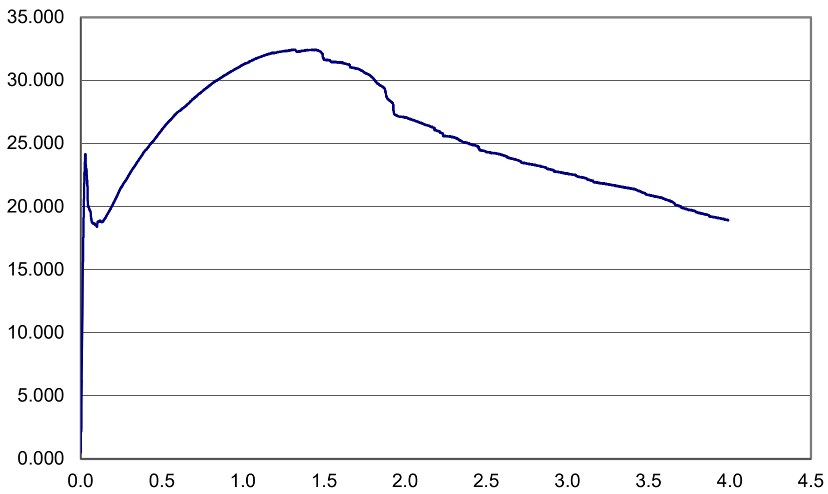
Certificate number	:	123456	*Certificate date*	:	20/06/22
Customer	:		*Reference*	:	
Notes	:				

Start speed [mm/min]	:	0.05	*End Speed [mm/min]*	:	0.2
Speed change Thres. [mm/min]	:	0.1			
Target [mm]	:	4			

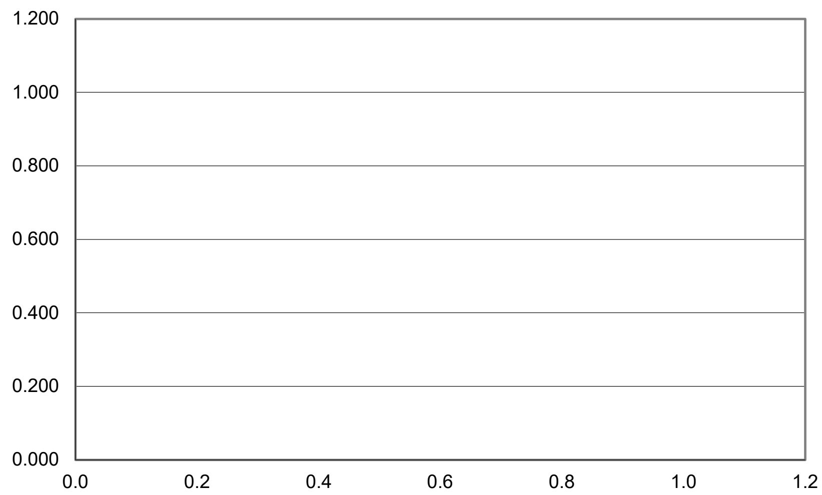
TEST RESULT

LOP [N/mm2]	:	7.729581909	*F0.5 [N/mm2]*	: 8.347694702
F1.5 [N/mm2]	:	10.12316284	*F2.5 [N/mm2]*	: 7.784606934
F3.5 [N/mm2]	:	6.691446533		

[kN]



CMOD [mm]



EN 14651

Test Organization	:	*Testing machine*	:

SPECIMEN DATA

Specimen ID	: 001-CMOD-RT30-T5	*Specimen type*	: balk
Specimen age [dd]	:	*Preparation date*	: 01/01/04
Curing	: water		
b [mm]	: 150	*h [mm]*	: 150
l [mm]	: 600	*Area [mm2]*	: 3125.0

Thickness after notch [mm]	: 125		
Notch width [mm]	: 3.6	*Notch date*	: 20/06/22
Surface preparation	: geen	*L [mm]*	: 500
Upper rollers number	: 1		

Preload [kN]	: 0.6	*Concrete type*	: C45/55
Fiber type	: Basaltvezels RT	*Fiber content*	: 30
Sampling date	: 01/05/22	*Sampling details*	:
Test date	: 20/06/22	*Test Location*	: Zaandam
Operator	:		

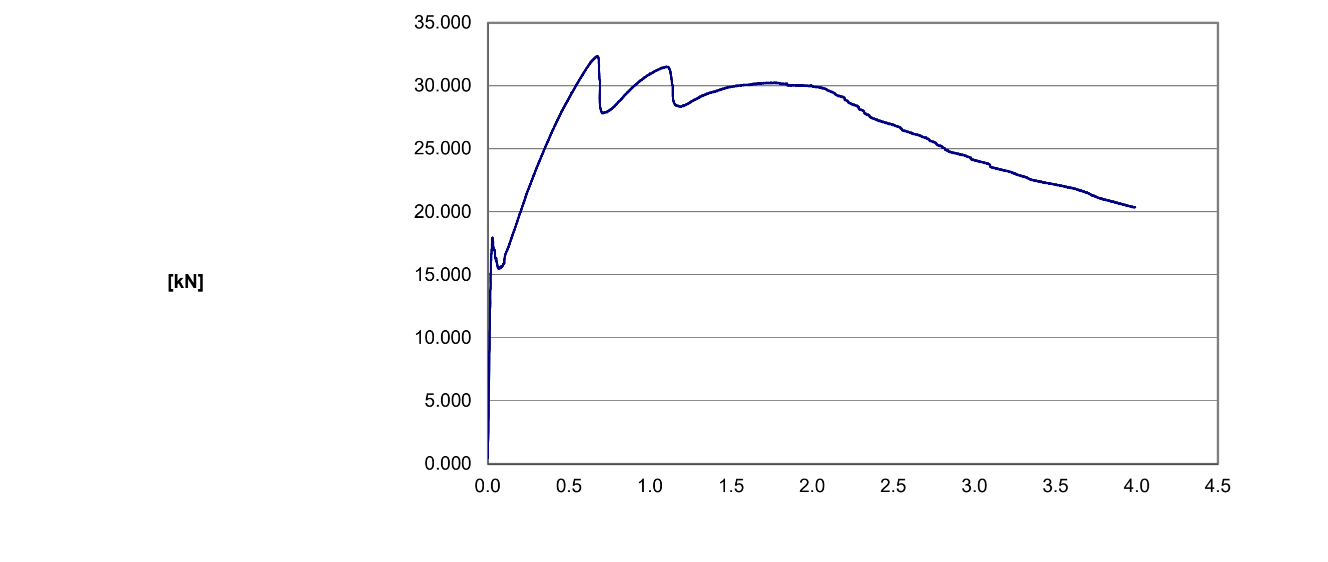
Deviations from standard	:
Declaration of conformity	:

Certificate number	: 123456	*Certificate date*	: 20/06/22
Customer	:	*Reference*	:
Notes	:		

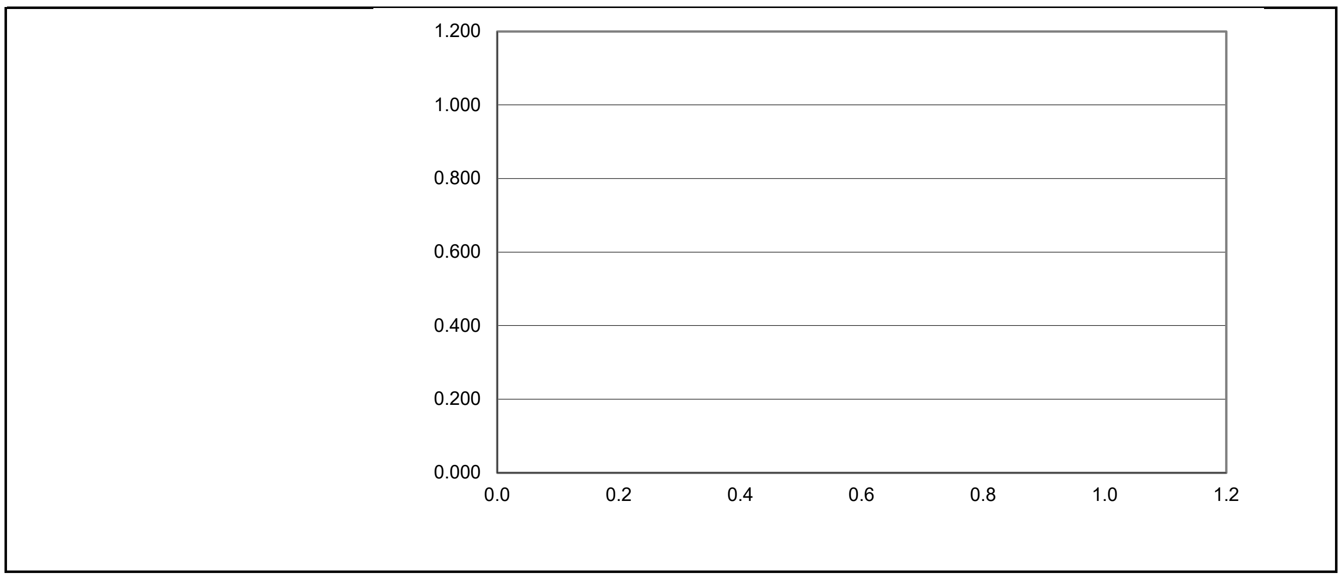
Start speed [mm/min]	: 0.05	*End Speed [mm/min]*	: 0.2
Speed change Thres. [mm/min]	: 0.1		
Target [mm]	: 4		

TEST RESULT

LOP [N/mm2]	:	5.746983643	*F0.5 [N/mm2]*	:	9.290583496
F1.5 [N/mm2]	:	9.578547363	*F2.5 [N/mm2]*	:	8.608275146
F3.5 [N/mm2]	:	7.091424561			



CMOD [mm]



EN 14651

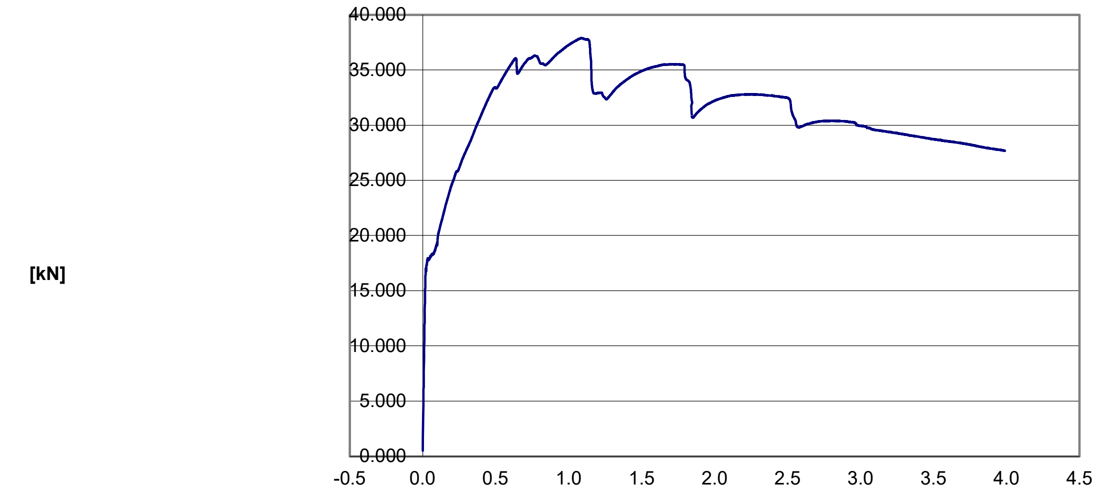
Test Organization	:	*Testing machine*	:

SPECIMEN DATA

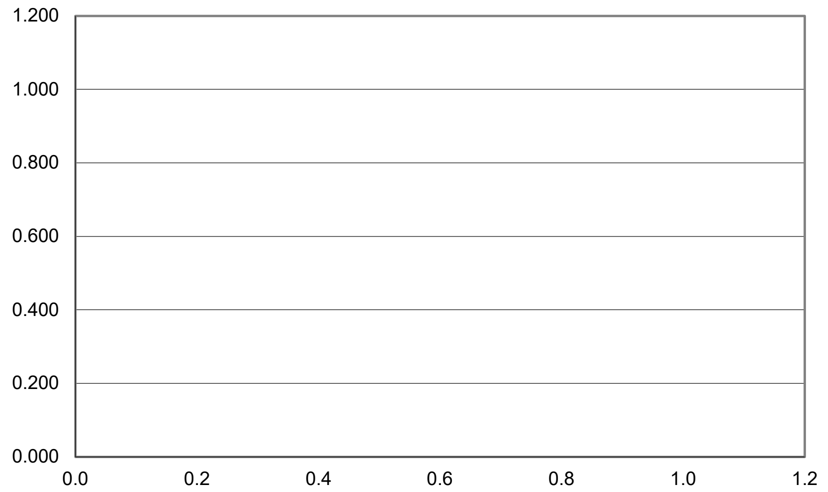
Specimen ID	: 002-CMOD-RT30-T5	*Specimen type*	: balk
Specimen age [dd]	:	*Preparation date*	: 01/01/04
Curing	: water		
b [mm]	: 150	*h [mm]*	: 150
l [mm]	: 600	*Area [mm2]*	: 3125.0
Thickness after notch [mm]	: 125		
Notch width [mm]	: 3.6	*Notch date*	: 20/06/22
Surface preparation	: geen	*L [mm]*	: 500
Upper rollers number	: 1		
Preload [kN]	: 0.6	*Concrete type*	: C45/55
Fiber type	: Basaltvezels RT	*Fiber content*	: 30
Sampling date	: 01/05/22	*Sampling details*	:
Test date	: 20/06/22	*Test Location*	: Zaandam
Operator	:		
Deviations from standard	:		
Declaration of conformity	:		
Certificate number	: 123456	*Certificate date*	: 20/06/22
Customer	:	*Reference*	:
Notes	:		
Start speed [mm/min]	: 0.05	*End Speed [mm/min]*	: 0.2
Speed change Thres. [mm/min]	: 0.1		
Target [mm]	: 4		

TEST RESULT

LOP [N/mm2]	:	5.757938232	*F0.5 [N/mm2]*	:	10.68082642
F1.5 [N/mm2]	:	11.1705481	*F2.5 [N/mm2]*	:	10.39102905
F3.5 [N/mm2]	:	9.193322144			



CMOD [mm]



EN 14651

Test Organization	:	*Testing machine*	:

SPECIMEN DATA

Specimen ID	: 003-CMOD-RT30-T5	*Specimen type*	: balk
Specimen age [dd]	:	*Preparation date*	: 01/01/04
Curing	: water		
b [mm]	: 150	*h [mm]*	: 150
l [mm]	: 600	*Area [mm2]*	: 3125.0

Thickness after notch [mm]	: 125		
Notch width [mm]	: 3.6	*Notch date*	: 20/06/22
Surface preparation	: geen	*L [mm]*	: 500
Upper rollers number	: 1		

Preload [kN]	: 0.6	*Concrete type*	: C45/55
Fiber type	: Basaltvezels RT	*Fiber content*	: 30
Sampling date	: 01/05/22	*Sampling details*	:
Test date	: 20/06/22	*Test Location*	: Zaandam
Operator	:		

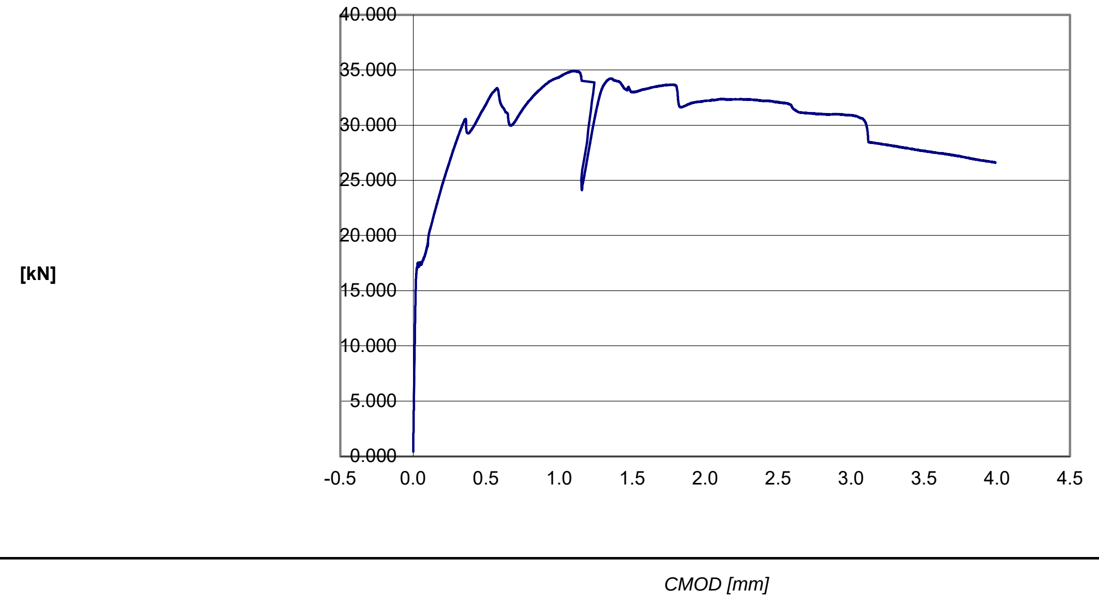
Deviations from standard	:
Declaration of conformity	:

Certificate number	: 123456	*Certificate date*	: 20/06/22
Customer	:	*Reference*	:
Notes	:		

Start speed [mm/min]	: 0.05	*End Speed [mm/min]*	: 0.2
Speed change Thres. [mm/min]	: 0.1		
Target [mm]	: 4		

TEST RESULT

LOP [N/mm2]	:	5.630939331	*F0.5 [N/mm2]*	:	10.22184509
F1.5 [N/mm2]	:	10.56483276	*F2.5 [N/mm2]*	:	10.26402954
F3.5 [N/mm2]	:	8.851728			



27.66165

3.45770625
390625

8.851728

EN 14651

Test Organization	:	*Testing machine*	:

SPECIMEN DATA

Specimen ID	: 3.1	*Specimen type*	: balk
Specimen age [dd]	:	*Preparation date*	: 01/01/04
Curing	: water		
b [mm]	: 150	*h [mm]*	: 150
l [mm]	: 600	*Area [mm2]*	: 3125.0

Thickness after notch [mm]	: 125		
Notch width [mm]	: 3.6	*Notch date*	: 20/06/22
Surface preparation	: geen	*L [mm]*	: 500
Upper rollers number	: 1		

Preload [kN]	: 0.6	*Concrete type*	: C45/55
Fiber type	: 5D	*Fiber content*	: 45
Sampling date	: 01/05/22	*Sampling details*	:
Test date	: 20/06/22	*Test Location*	: zaandaam
Operator	:		

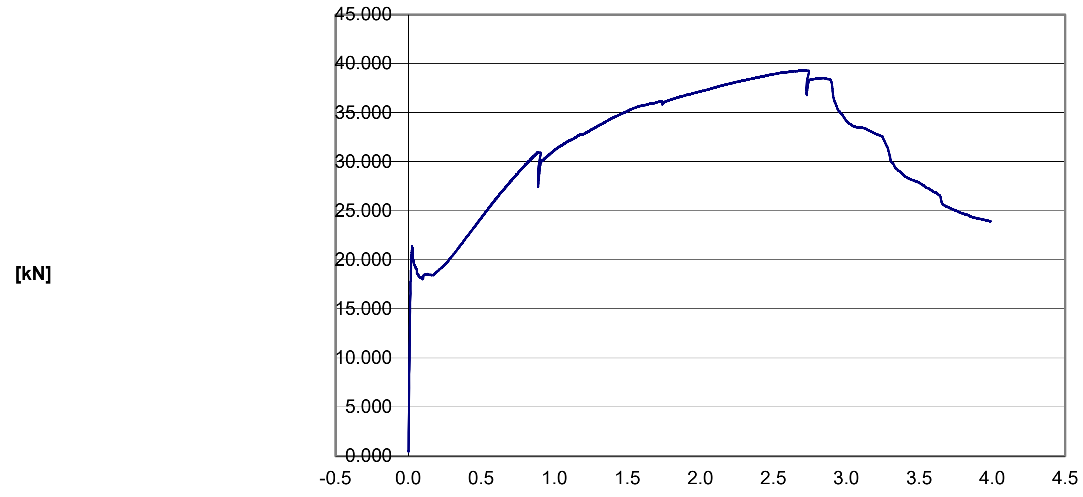
Deviations from standard	:
Declaration of conformity	:

Certificate number	: 123456	*Certificate date*	: 20/06/22
Customer	:	*Reference*	:
Notes	:		

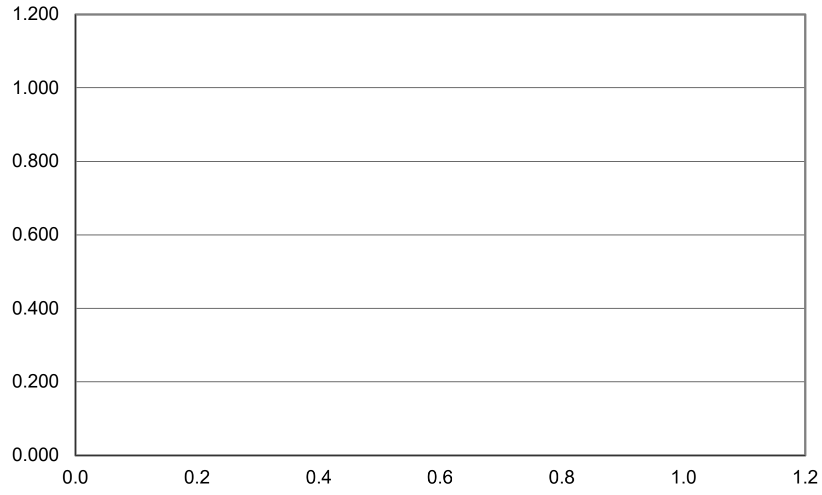
Start speed [mm/min]	: 0.05	*End Speed [mm/min]*	: 0.2
Speed change Thres. [mm/min]	: 0.1		
Target [mm]	: 4		

TEST RESULT

LOP [N/mm2]	:	6.855159302	*F0.5 [N/mm2]*	: 7.775907593
F1.5 [N/mm2]	:	11.24614014	*F2.5 [N/mm2]*	: 12.4565625
F3.5 [N/mm2]	:	8.920424805		



CMOD [mm]



EN 14651

Test Organization	:		*Testing machine*	:	

SPECIMEN DATA

Specimen ID	:	3.2 T	*Specimen type*	:	balk
Specimen age [dd]	:		*Preparation date*	:	01/01/04
Curing	:	water			
b [mm]	:	150	*h [mm]*	:	150
l [mm]	:	600	*Area [mm2]*	:	3125.0

Thickness after notch [mm]	:	125			
Notch width [mm]	:	3.6	*Notch date*	:	20/06/22
Surface preparation	:	geen	*L [mm]*	:	500
Upper rollers number	:	1			

Preload [kN]	:	0.6	*Concrete type*	:	C45/55
Fiber type	:	5D	*Fiber content*	:	45
Sampling date	:	01/05/22	*Sampling details*	:	
Test date	:	20/06/22	*Test Location*	:	zaandaam
Operator	:				

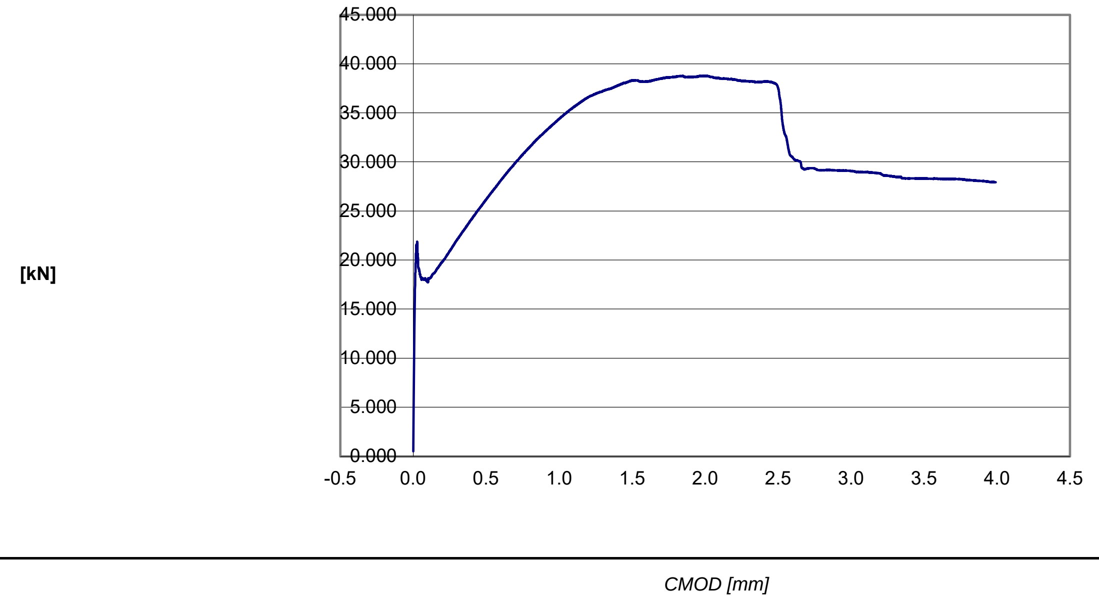
Deviations from standard	:	
Declaration of conformity	:	

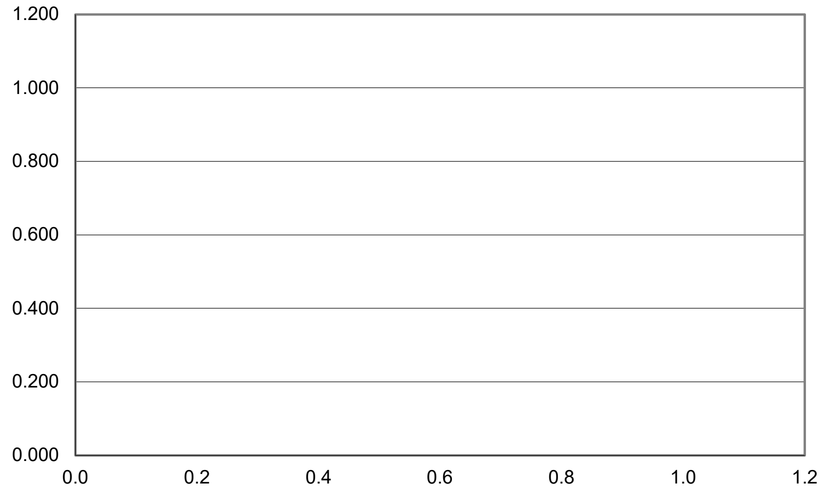
Certificate number	:	123456	*Certificate date*	:	20/06/22
Customer	:		*Reference*	:	
Notes	:				

Start speed [mm/min]	:	0.05	*End Speed [mm/min]*	:	0.2
Speed change Thres. [mm/min]	:	0.1			
Target [mm]	:	4			

TEST RESULT

LOP [N/mm2]	:	7.003450928	*F0.5 [N/mm2]*	:	8.379072266
F1.5 [N/mm2]	:	12.25891846	*F2.5 [N/mm2]*	:	12.01243652
F3.5 [N/mm2]	:	9.061379395			





EN 14651

Test Organization	:	*Testing machine*	:

SPECIMEN DATA

Specimen ID	: 3.3 T	*Specimen type*	: balk
Specimen age [dd]	:	*Preparation date*	: 01/01/04
Curing	: water		
b [mm]	: 150	*h [mm]*	: 150
l [mm]	: 600	*Area [mm2]*	: 3125.0

Thickness after notch [mm]	: 125		
Notch width [mm]	: 3.6	*Notch date*	: 20/06/22
Surface preparation	: geen	*L [mm]*	: 500
Upper rollers number	: 1		

Preload [kN]	: 0.6	*Concrete type*	: C45/55
Fiber type	: 5D	*Fiber content*	: 45
Sampling date	: 01/05/22	*Sampling details*	:
Test date	: 20/06/22	*Test Location*	: zaandaam
Operator	:		

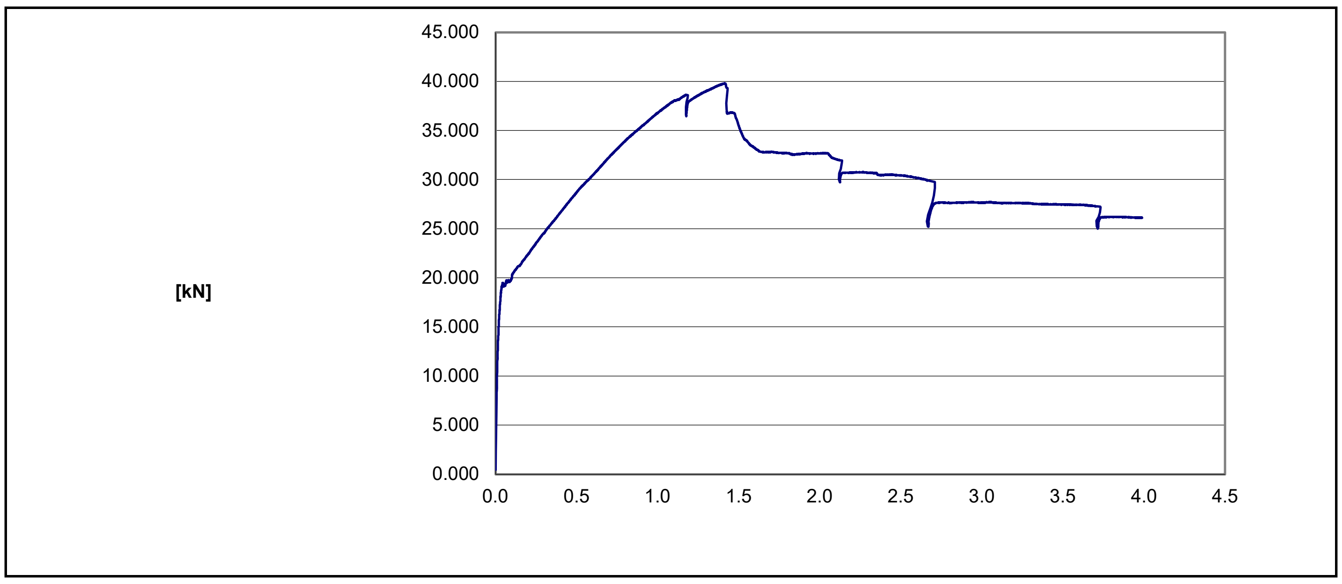
Deviations from standard	:
Declaration of conformity	:

Certificate number	: 123456	*Certificate date*	: 20/06/22
Customer	:	*Reference*	:
Notes	:		

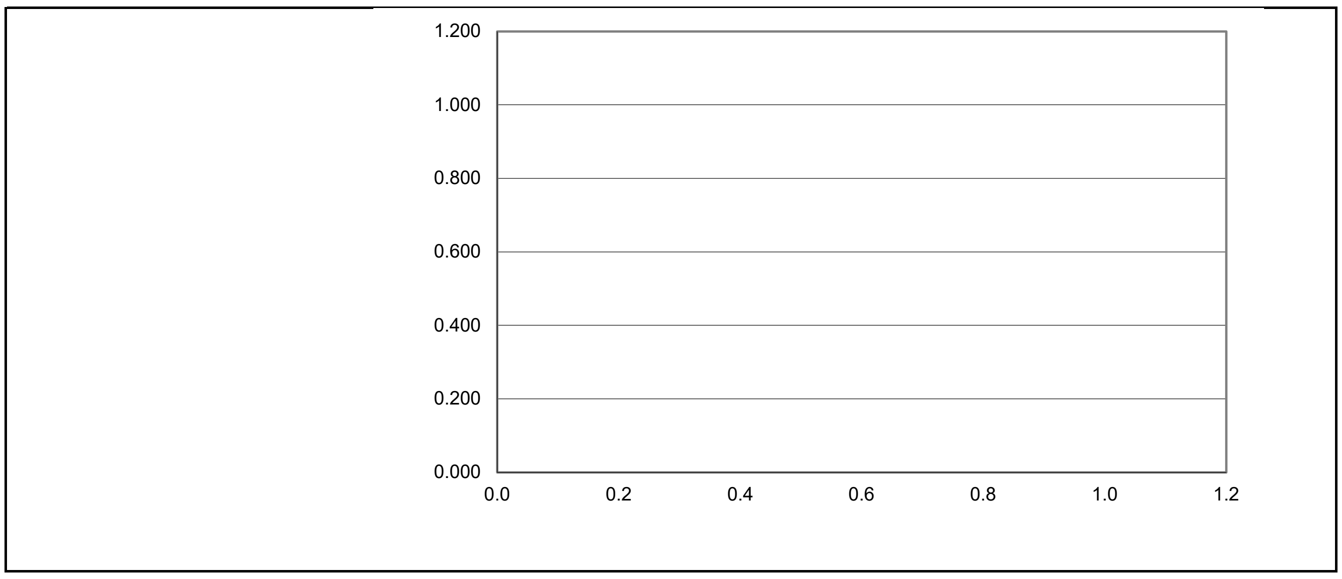
Start speed [mm/min]	:	0.05	*End Speed [mm/min]*	: 0.2
Speed change Thres. [mm/min]	:	0.1		
Target [mm]	:	4		

TEST RESULT

LOP [N/mm2]	:	6.238493042	*F0.5 [N/mm2]*	:	9.18598999
F1.5 [N/mm2]	:	11.35213379	*F2.5 [N/mm2]*	:	9.739907227
F3.5 [N/mm2]	:	8.793479614			



CMOD [mm]



EN 14651

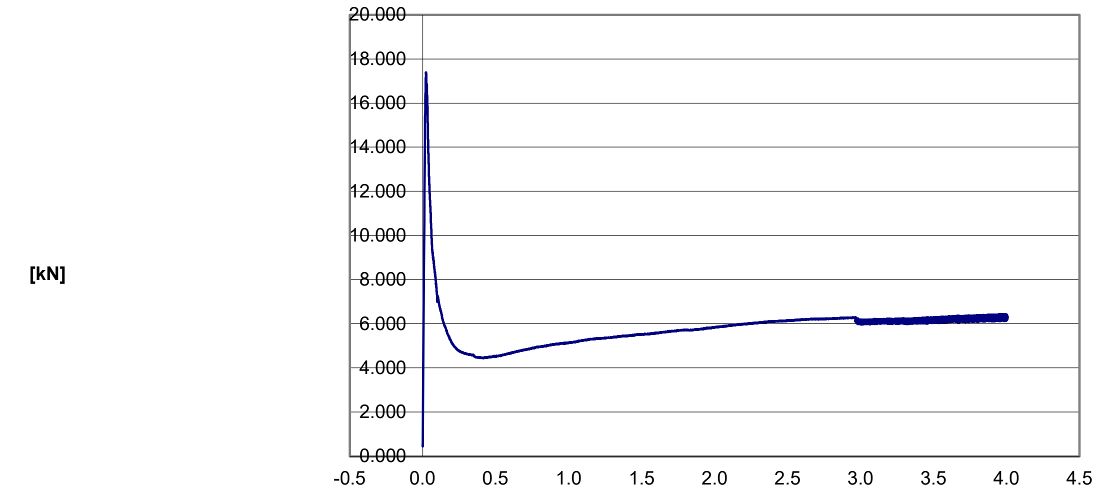
Test Organization	:	*Testing machine*	:

SPECIMEN DATA

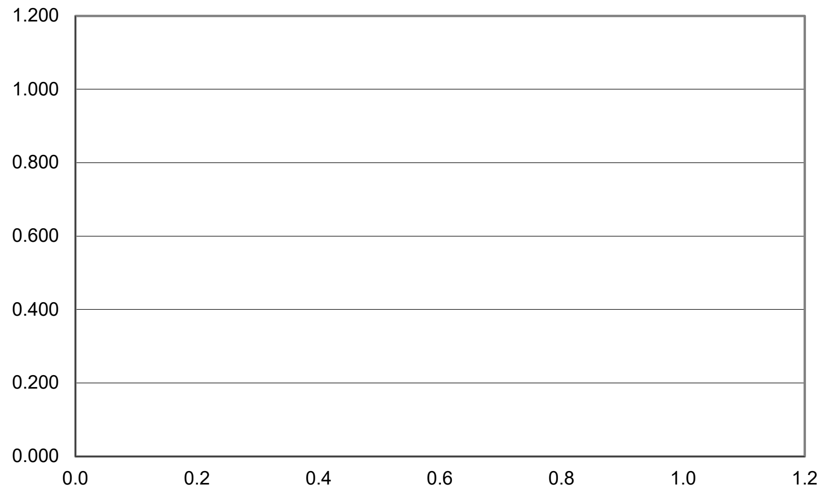
Specimen ID	: 001-CMOD-SV45-T5	*Specimen type*	: balk
Specimen age [dd]	:	*Preparation date*	: 01/01/04
Curing	: water		
b [mm]	: 150	*h [mm]*	: 150
l [mm]	: 600	*Area [mm2]*	: 3125.0
Thickness after notch [mm]	: 125		
Notch width [mm]	: 3.6	*Notch date*	: 20/06/22
Surface preparation	: geen	*L [mm]*	: 500
Upper rollers number	: 1		
Preload [kN]	: 0.6	*Concrete type*	: C45/55
Fiber type	: Basaltvezels RT	*Fiber content*	: 45
Sampling date	: 01/05/22	*Sampling details*	:
Test date	: 20/06/22	*Test Location*	: Zaandam
Operator	:		
Deviations from standard	:		
Declaration of conformity	:		
Certificate number	: 123456	*Certificate date*	: 20/06/22
Customer	:	*Reference*	:
Notes	:		
Start speed [mm/min]	: 0.05	*End Speed [mm/min]*	: 0.2
Speed change Thres. [mm/min]	: 0.1		
Target [mm]	: 4		

TEST RESULT

LOP [N/mm2]	:	5.563300171	*F0.5 [N/mm2]*	: 1.449628906
F1.5 [N/mm2]	:	1.767254639	*F2.5 [N/mm2]*	: 1.968540649
F3.5 [N/mm2]	:	2.007320557		



CMOD [mm]



EN 14651

Test Organization	:		*Testing machine*	:	

SPECIMEN DATA

Specimen ID	:	002-CMOD-SV45-T2	*Specimen type*	:	balk
Specimen age [dd]	:		*Preparation date*	:	01/01/04
Curing	:	water			
b [mm]	:	150	*h [mm]*	:	150
l [mm]	:	600	*Area [mm2]*	:	3125.0

Thickness after notch [mm]	:	125			
Notch width [mm]	:	3.6	*Notch date*	:	20/06/22
Surface preparation	:	geen	*L [mm]*	:	500
Upper rollers number	:	1			

Preload [kN]	:	0.6	*Concrete type*	:	C45/55
Fiber type	:	Dramix 5D staalvezels	*Fiber content*	:	45
Sampling date	:	01/05/22	*Sampling details*	:	
Test date	:	20/06/22	*Test Location*	:	Zaandam
Operator	:				

Deviations from standard	:	
Declaration of conformity	:	

Certificate number	:	123456	*Certificate date*	:	20/06/22
Customer	:		*Reference*	:	
Notes	:				

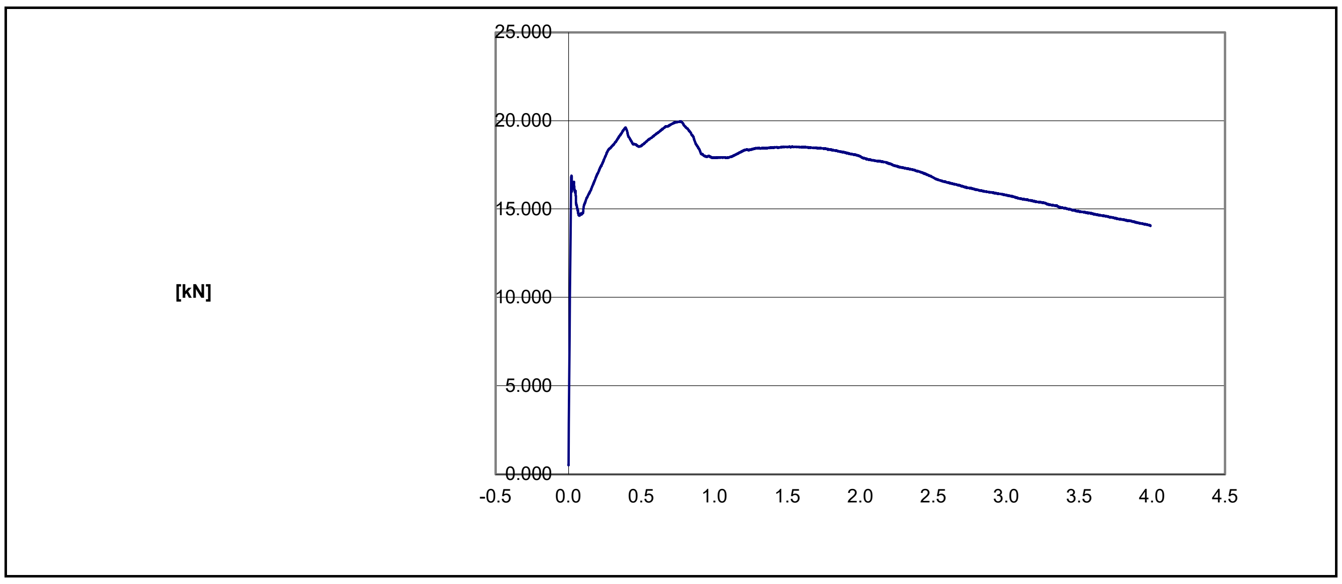
Start speed [mm/min]	:	0.05	*End Speed [mm/min]*	:	0.2
Speed change Thres. [mm/min]	:	0.1			
Target [mm]	:	4			

TEST RESULT

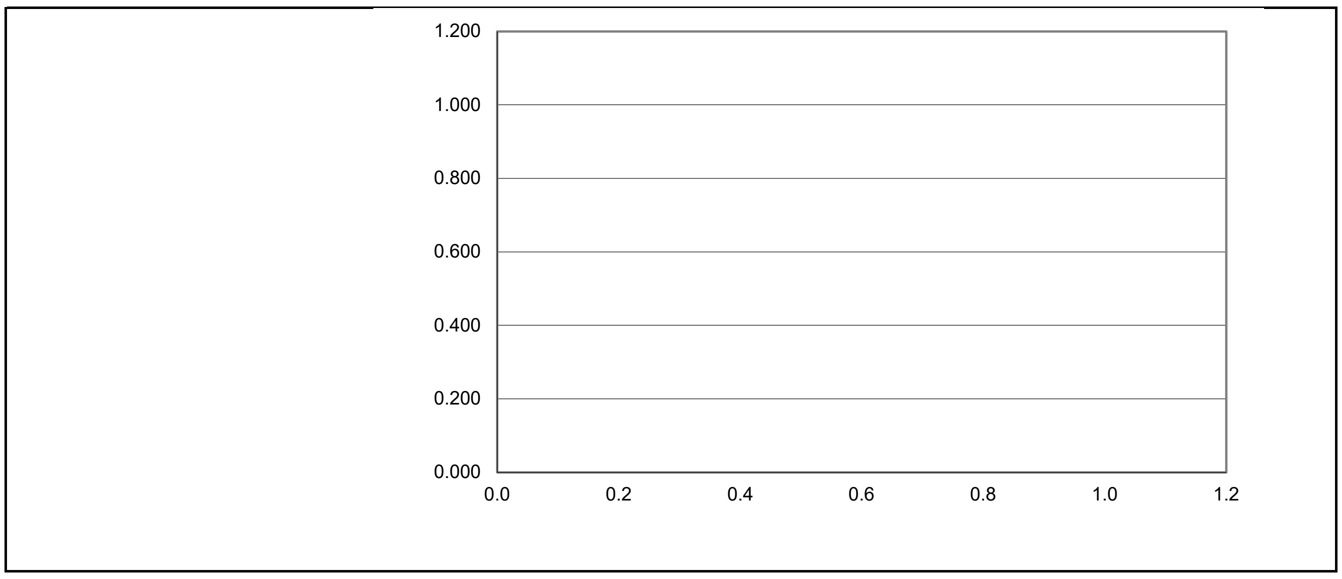
LOP [N/mm2] : 5.407284546 *F0.5 [N/mm2]* : 5.948361816

F1.5 [N/mm2] : 5.924517212 *F2.5 [N/mm2]* : 5.374269409

F3.5 [N/mm2] : 4.75432312



CMOD [mm]



EN 14651

Test Organization	:		*Testing machine*	:	

SPECIMEN DATA

Specimen ID	:	003-CMOD-SV45-T2	*Specimen type*	:	balk
Specimen age [dd]	:		*Preparation date*	:	01/01/04
Curing	:	water			
b [mm]	:	150	*h [mm]*	:	150
l [mm]	:	600	*Area [mm2]*	:	3125.0

Thickness after notch [mm]	:	125			
Notch width [mm]	:	3.6	*Notch date*	:	20/06/22
Surface preparation	:	geen	*L [mm]*	:	500
Upper rollers number	:	1			

Preload [kN]	:	0.6	*Concrete type*	:	C45/55
Fiber type	:	Dramix 5D staalvezels	*Fiber content*	:	45
Sampling date	:	01/05/22	*Sampling details*	:	
Test date	:	20/06/22	*Test Location*	:	Zaandam
Operator	:				

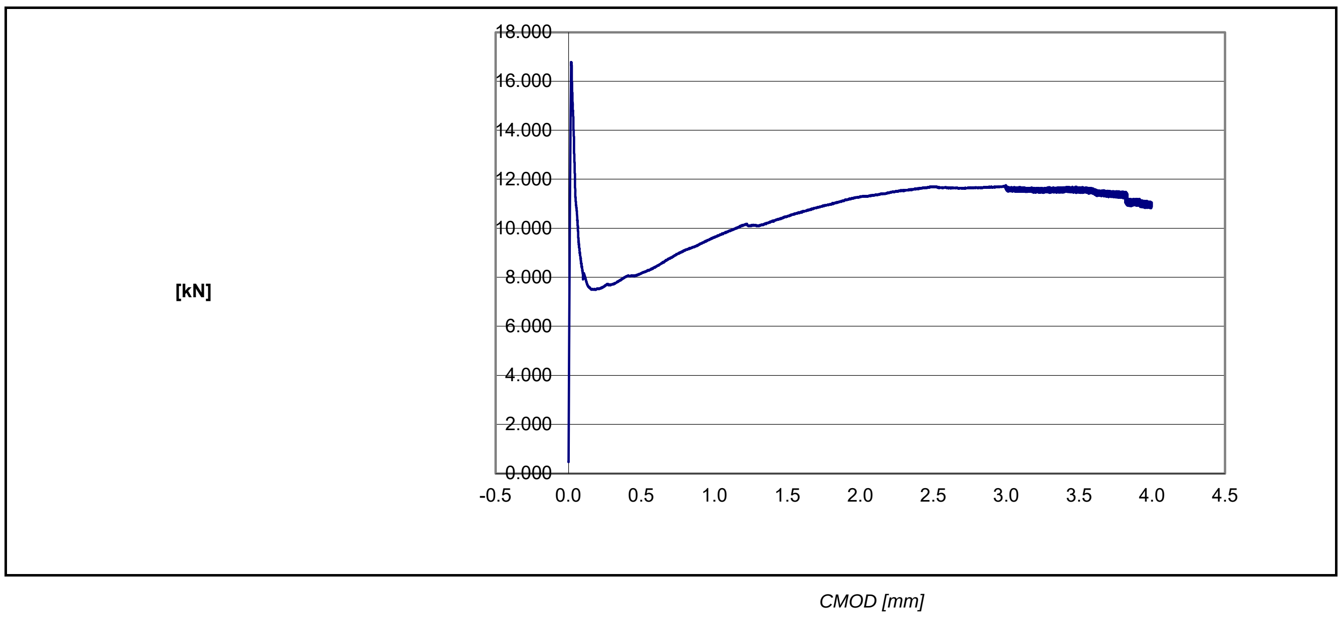
Deviations from standard	:	
Declaration of conformity	:	

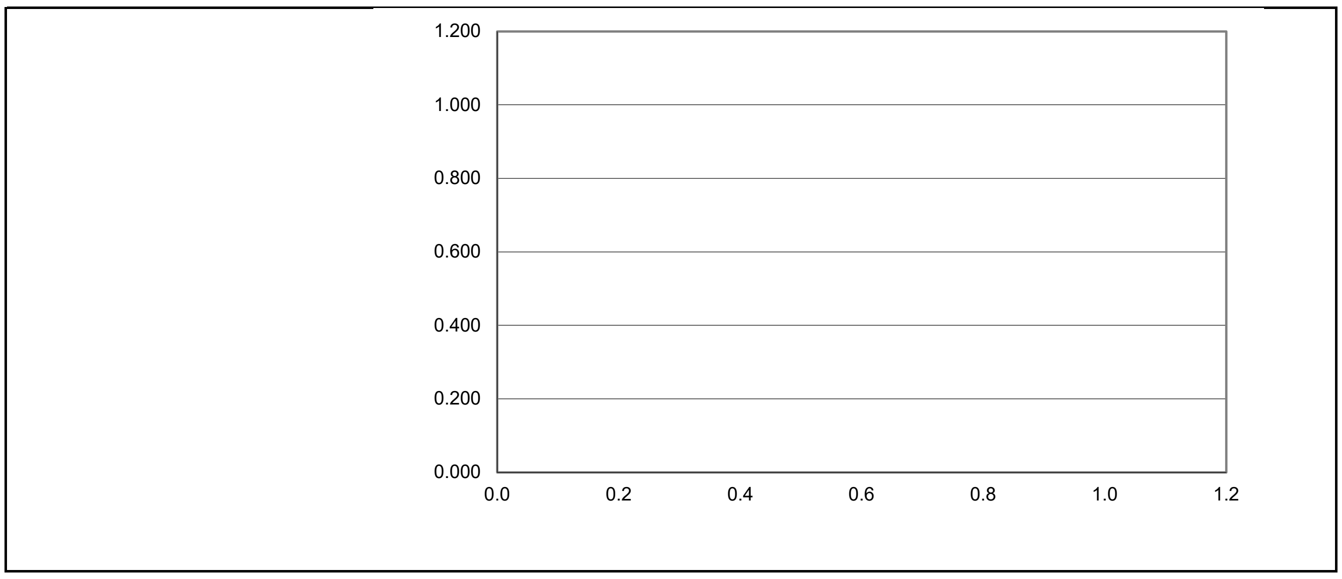
Certificate number	:	123456	*Certificate date*	:	20/06/22
Customer	:		*Reference*	:	
Notes	:				

Start speed [mm/min]	:	0.05	*End Speed [mm/min]*	:	0.2
Speed change Thres. [mm/min]	:	0.1			
Target [mm]	:	4			

TEST RESULT

LOP [N/mm2]	:	5.368717041	*F0.5 [N/mm2]*	: 2.611972351
F1.5 [N/mm2]	:	3.356641846	*F2.5 [N/mm2]*	: 3.738147278
F3.5 [N/mm2]	:	3.730810852		





	001-RT15-T1	002-RT15-T1	003-RT15-T1
Mass [kg]	7.2287	7.5716	7.4741
Strength [Mpa]	59.56	69.25	54.26
Density [kg/m3]	2141.837037	2243.437037	2214.548148

fcm T1 [Mpa]	61.02
fck T1 [Mpa]	53.02
rho	2199.940741

	001-RT30-T1	002-RT30-T1	003-RT30-T1
Mass [kg]	7.3553	7.5441	7.6067
Strength [Mpa]	66.79	69.31	72.36
Density [kg/m3]	2179.348148	2235.288889	2253.837037

fcm T1 [Mpa]	69.49
fck T1 [Mpa]	61.49
rho	2222.824691

	001-RT55-T1	002-RT55-T1	003-RT55-T1
Mass [kg]	6.3119	6.2383	6.1853
Strength [Mpa]	24.13	26.59	25.72
Density [kg/m3]	1870.192593	1848.385185	1832.681481

fcm T1 [Mpa]	25.48
fck T1 [Mpa]	17.48
rho	1850.419753

	001-CUBE-T1	002-CUBE-T1	003-CUBE-T1
Mass [kg]	7.6409	7.563	7.4864
Strength [Mpa]	70.61	68.04	64.61
Density [kg/m3]	2263.97037	2240.888889	2218.192593

fcm T1 [Mpa]	67.75
fck T1 [Mpa]	59.75
rho	2241.017284

	001-RT20-T1-1	001-RT20-T1-2
Mass [kg]	7.7289	7.9206
Strength [Mpa]	73.72	73.89
Density [kg/m3]	2290.044444	2346.844444

	002-RT20-T1-1	002-RT20-T1-2
Mass [kg]	8.0061	7.9226
Strength [Mpa]	73.7	72
Density [kg/m3]	2372.177778	2347.437037

	003-RT20-T1-1	003-RT20-T1-2
Mass [kg]	8.0114	7.9549
Strength [Mpa]	74.89	75.28
Density [kg/m3]	2373.748148	2357.007407

fcm [Mpa]	73.91
fck [Mpa]	65.91
rho	2347.876543

	001-RT30-T3-1	001-RT30-T3-2
Mass [kg]	7.4483	7.3837
Strength [Mpa]	57.48	53.86
Density [kg/m3]	2206.903704	2187.762963

	002-RT30-T3-1	002-RT30-T3-2
Mass [kg]	7.8095	7.5954
Strength [Mpa]	59.15	58.67
Density [kg/m3]	2313.925926	2250.488889

	003-RT30-T3-1	003-RT30-T3-2	003-RT30-T3-3
Mass [kg]	7.6078	7.6084	7.6022
Strength [Mpa]	61.56	63.2	62.19
Density [kg/m3]	2254.162963	2254.340741	2252.503704

	004-RT30-T4-1	004-RT30-T4-2
Mass [kg]	7.9432	7.809
Strength [Mpa]	68.58	67.62
Density [kg/m3]	2353.540741	2313.777778

	005-RT30-T4-1	005-RT30-T4-2
Mass [kg]	7.7692	7.7351
Strength [Mpa]	67.38	66.9
Density [kg/m3]	2301.985185	2291.881481

	006-RT30-T4-1	006-RT30-T4-2
Mass [kg]	8.0306	7.7754
Strength [Mpa]	65.03	63.8
Density [kg/m3]	2379.437037	2303.822222

	001-RT30-T5	002-RT30-T5	003-RT30-T5	004-RT30-T5
Mass [kg]	7.5426	7.5024	7.5225	7.5201
Strength [Mpa]	52.02	54.13	53.69	55.02
Density [kg/m3]	2234.844444	2222.933333	2228.888889	2228.17778

fcm T3 [Mpa]	59.44
fck T3 [Mpa]	51.44
rho	2245.726984

fcm T4 [Mpa]	66.55
fck T4 [Mpa]	58.55
rho	2324.074074

fcm T5 [Mpa]	53.72
fck T5 [Mpa]	45.72
rho	2228.711111

	001-SV45-T2	002-SV45-T2	003-SV45-T2	004-SV45-T2
Mass [kg]	7.9458	7.9154	7.8723	7.8893
Strength [Mpa]	63.15	58.07	56.66	56.71
Density [kg/m3]	2354.311111	2345.303704	2332.533333	2337.57037

fcm T5 [Mpa]	58.65
fck T5 [Mpa]	50.65
rho	2342.42963

Appendix B Testing Procedures

Concrete Compression Test

To obtain the concrete compressive strength f_c the European standard NEN-EN 12390-3 (NENb, 2019) is used. The apparatus, test specimens and procedure are as follows.

Apparatus

A compression testing machine, conforming to European standard NEN-EN 12390-4 is used.

Test specimens

The test is carried out with cubes with a dimension of 150x150x150 mm. The test specimens meet the requirements of the European standard NEN-EN 12390-1 (NEN, 2021)

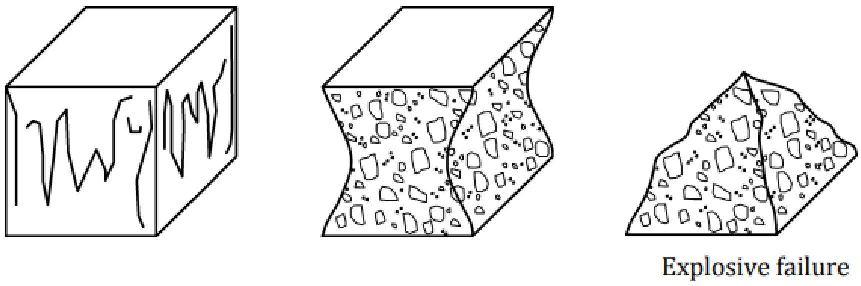
In this research tests are also performed on cubes sawn off from specimens used for CMOD tests (as described in chapter 5.2.3). The condition of these specimens is noted in the report.

Procedure

If the bearing surfaces are clean of any material from previous tests, the specimen is placed in the testing machine within the designated square indicated with lines engraved in the test machine bearing surface. The specimen is placed with the top surface from casting placed to one of the sides. Once placed the loading starts.

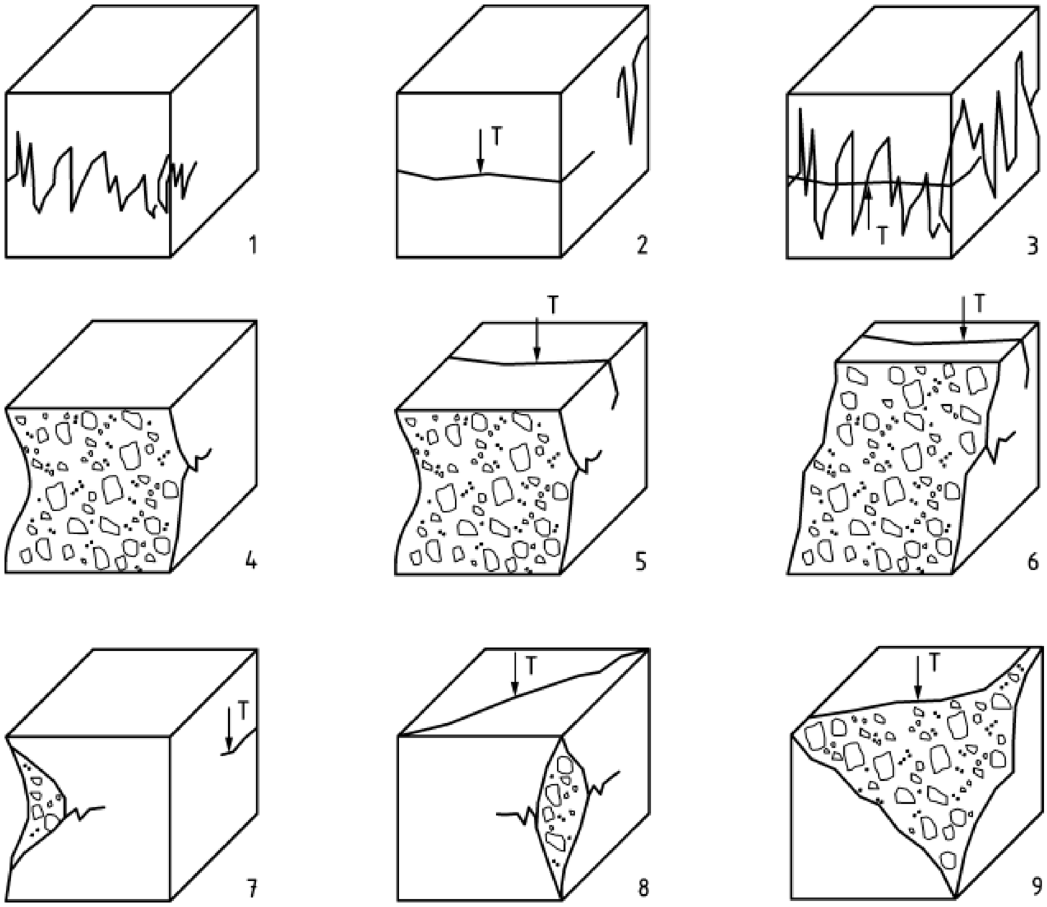
A manually controlled testing machine is used for the compression tests. During loading the load increase is kept constant within the range of 0.6 +- 0.2 MPa/s. Manually the rate of loading is changed to keep constant load increase. The testing machine keeps track of the required speed and manually this speed is acquired +- 10%.

Once the testing machine shows the failure load and strength the machine is manually turned off to prevent the specimen from being crushed. The type of failure is then assessed using figures AB.1 and AB.2 . These indicate in which cases the test showed a satisfactory failure. If failure is unsatisfactory this is recorded with a reference to the concerning failure pattern.



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

Figure AB.1: Satisfactory cube failure patterns



Key

T = tensile crack

Figure AB.2: Unsatisfactory cube failure patterns

Test results

The concrete compressive strength is obtained from the testing machine indicating the failure load and strength. The failure load can be used to manually calculate the strength with equation AB.1.

$$f_c = \frac{F}{A_c} \qquad \text{(eq. AB.1)}$$

Where:

$f_c = compressive\ strength\ [MPa]$

$F = maximum\ load\ at\ failure\ [N]$

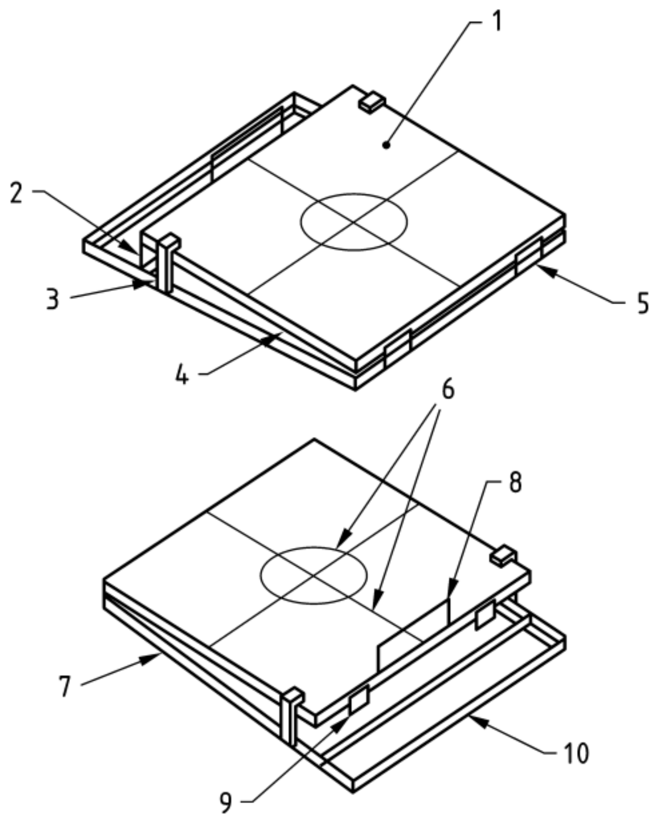
$A_c = Cross\ sectional\ area\ of\ the\ specimen\ [mm^2]$

Slump Test (Flow Table Test)

To obtain the flow value f the European standard NEN-EN 12350-5 (NENa, 2019) is used. The apparatus, sampling and procedure are as follows.

Apparatus

The flow table as shown in figure AB.3 is a plate with a metal surface with a minimum thickness of 2 mm and a mass of 16 +-0.5 kg. The centre of the table consists of a cross with lines that run parallel to the edges and a central circle with a diameter of 210 +- 1 mm.



Key

1	metal plate	6	markings
2	fall limited to (40 ± 1) mm	7	base frame
3	upper stop	8	lifting handle
4	table top	9	lower stop
5	external hinges	10	foot rests

Figure AB.3: Slump test table

This circle is a reference to place the hollow cone which is shown in figure AB.4 including its dimensions.

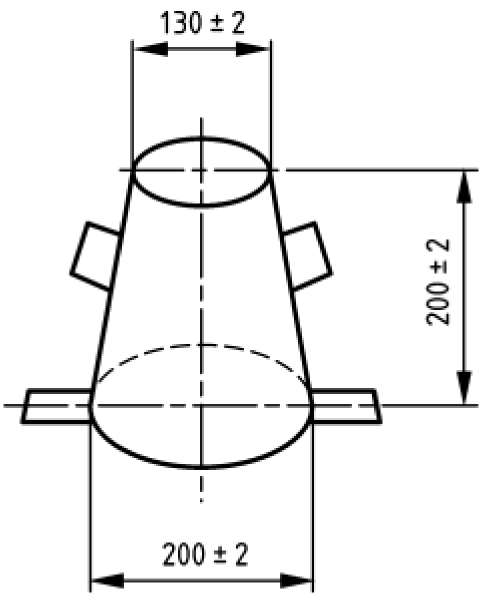


Figure AB.4: Slump test cone

Sampling

The concrete sample that is used for the test is re-mixed before carrying out the test. This is done with a scoop or shovel e.g. After the re-mixing the testing procedure can be followed.

Procedure

The hollow cone is dampened and is placed on a cleaned flow table. Note that no superfluous moisture may be used to clean the table or dampen the cone. Now the cone is positioned inside the circle and pressed down to prevent concrete from flowing out underneath. The cone is then filled with concrete all the way to the top. After filling up wait between 10 and 30 second before starting the test.

The test is then performed by raising the cone in a smooth motion. In this research self-compacting concrete is used, therefore the lifting handle and the lower and upper stop are not used during the testing procedure.

Once the spread is stabilized the measurement is performed. The dimensions of the concrete spread d_1 and d_2 are measured and used to obtain the flow rate.

Test results

The flow rate is given by equation AB.2.

$$f = \frac{d_1+d_2}{2} \qquad \text{(eq. AB.2)}$$

Where:

$f = flow\ rate\ [mm]$

$d_1, d_2 = concrete\ spread\ dimensions\ [mm]$

This result must be reported to the nearest 10 mm.

Displacement Controlled CMOD Test

To obtain the flexural tensile strength of the fibered concrete the European standard EN 14651:2005+A1:2007 (NEN, 2007) and (NENc, 2019) are used. For the experiments in this research these norms are followed, leading to the following test procedure and preparation of the test specimens.

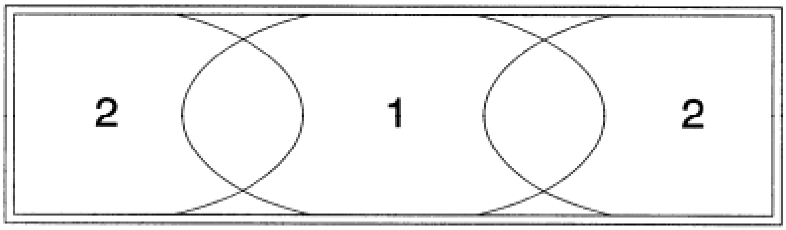
Test specimens

Restrictions in terms of dimensions of the test specimens:

- The samples have a nominal size (width and depth) of 150 mm and a length L so that 550 mm <= L <= 700 mm according to EN 12390-1 (NEN, 2021).
- Maximum aggregate size is 32 mm.
- The fibres are no longer than 60 mm.

Filling the mould:

- As shown in figure AB.5 the mould should be filled up to approximately 90% in area 1 before filling up in area 2.
- Since self-compacting concrete is used, the mould is filled and levelled off without any compaction.



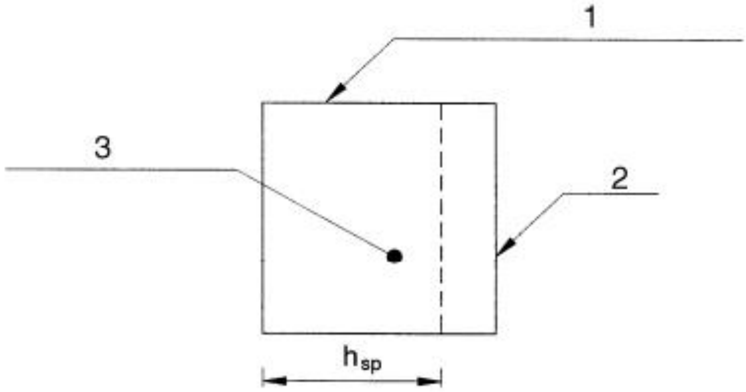
Key

1 and 2 order of filling

Figure AB.5: Filling procedure for CMOD-test

Notching of the test specimens:

- Wet sawing is used to notch the test specimens
- The notched side is not the top or bottom side (after casting), as seen in figure AB.6
- The width of the notch is <= 5 mm (3.5 mm with the machine used in this research) and the remaining height of the cross-section (hsp) is 125 +- 1 mm.



Key

1 Top surface during casting

2 Notch

3 Cross-section of test specimen

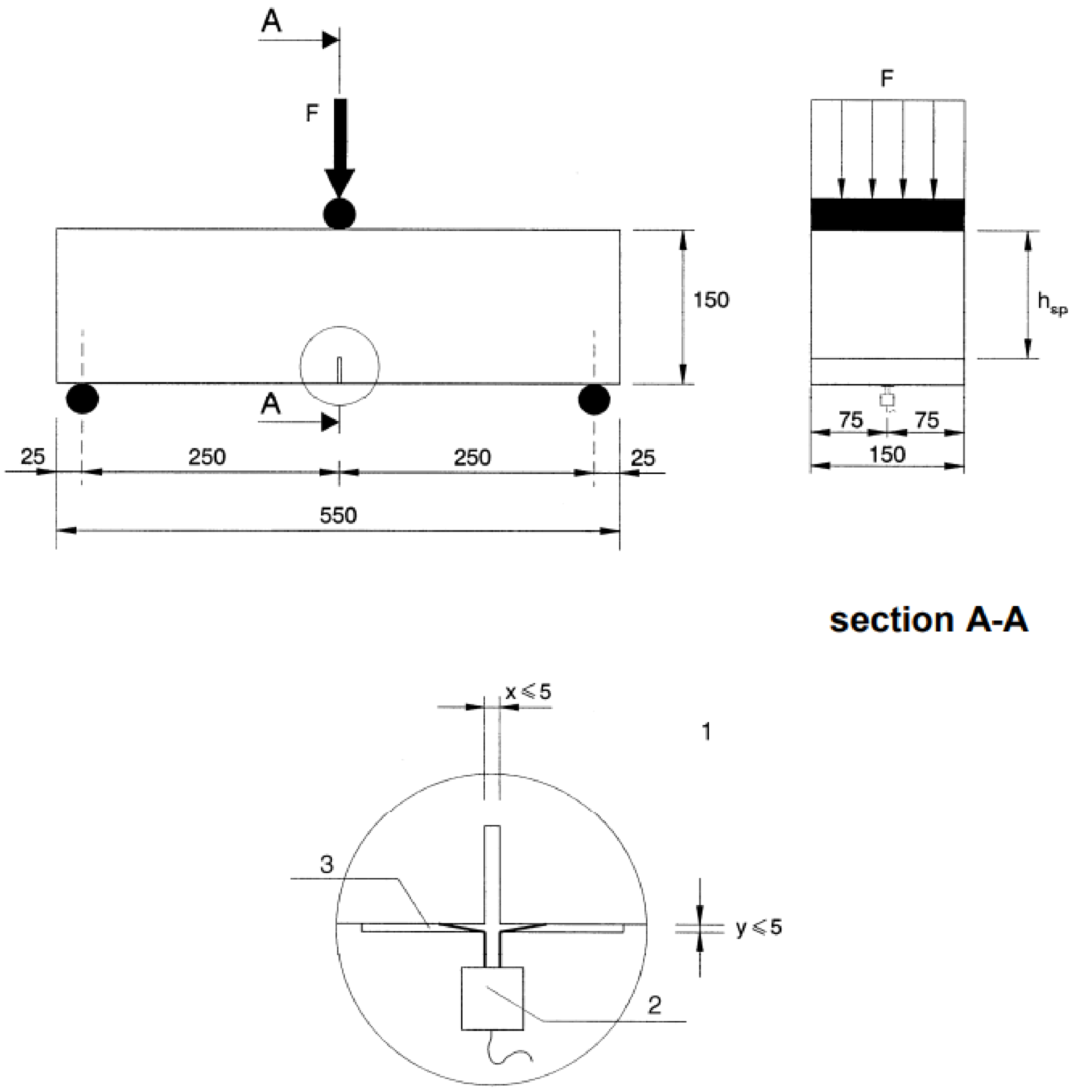
Figure AB.6: Notch in test specimen

Testing procedure

For the preparation and positioning of the test specimens a different procedure is followed as a different sensor is used to measure the crack mouth opening displacement (CMOD):

- Two metal pieces with a small slot are glued to the test specimens in the middle of the width at the edge of the notch. These pieces and the location are visible in figure AB.7. The distance between the slots is between 3 and 4 mm.
- The specimen is placed with the notch facing downwards on top of the supporting rollers. The horizontal distance between the rollers is set at 3*d equalling 450 mm.

- Next is placing the sensor by clamping it between the slots in the metal pieces. The positioned specimen is visible in schematic drawings in figure AB.7.



Key

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

Figure AB.7: Test specimen CMOD-test

The testing procedure goes as follows:

- Start the test programme with a preload of 0.5 kN including a preload pause.
- Once preload is reached and testing is paused reset CMOD channel to 0 mm and continue the test.
- In the first part of the test the machine shall be operated so that the CMOD increases with a constant rate of 0.05 mm/min and after CMOD = 0.1 the speed is increased to 0.2 mm/min.
- The test is terminated at CMOD = 4 mm
- In case the minimum load value in the interval CMODFL to CMOD = 0.5 mm should not be less than 30% of the load value corresponding to CMOD = 0.5 mm. If this is the case the testing procedure is checked for instabilities.
- In case the crack starts outside the notched area, the test is rejected.

Expression of results

The results from the CMOD contain the limit of proportionality (LOP) and residual flexural tensile strengths at CMOD = 0.5, 1.5, 2.5 and 3.5 mm. These values are calculated by the computer after the test. The specimens dimensions are therefore entered before the test (these remain the same for each CMOD test carried out in this research).

The LOP and residual tensile strength can also be calculated manually if the load at certain CMOD values is known. The limit of proportionality is given by equation AB.3 and the residual flexural tensile strength is given by equation AB.4 for the different values of CMOD. The LOP can be described as the strength from where plastic deformation of the specimen occurs.

$$f_{ct,L}^{f} = \frac{6M_L l}{bh_{sp}^2} = \frac{3F_L l}{2bh_{sp}^2} \qquad \text{(eq. AB.3)}$$

Where:

$f_{ct,L}^{f} = LOP\ [N/mm^2]$

$F_L = load\ corresponding\ to\ LOP\ [N]$

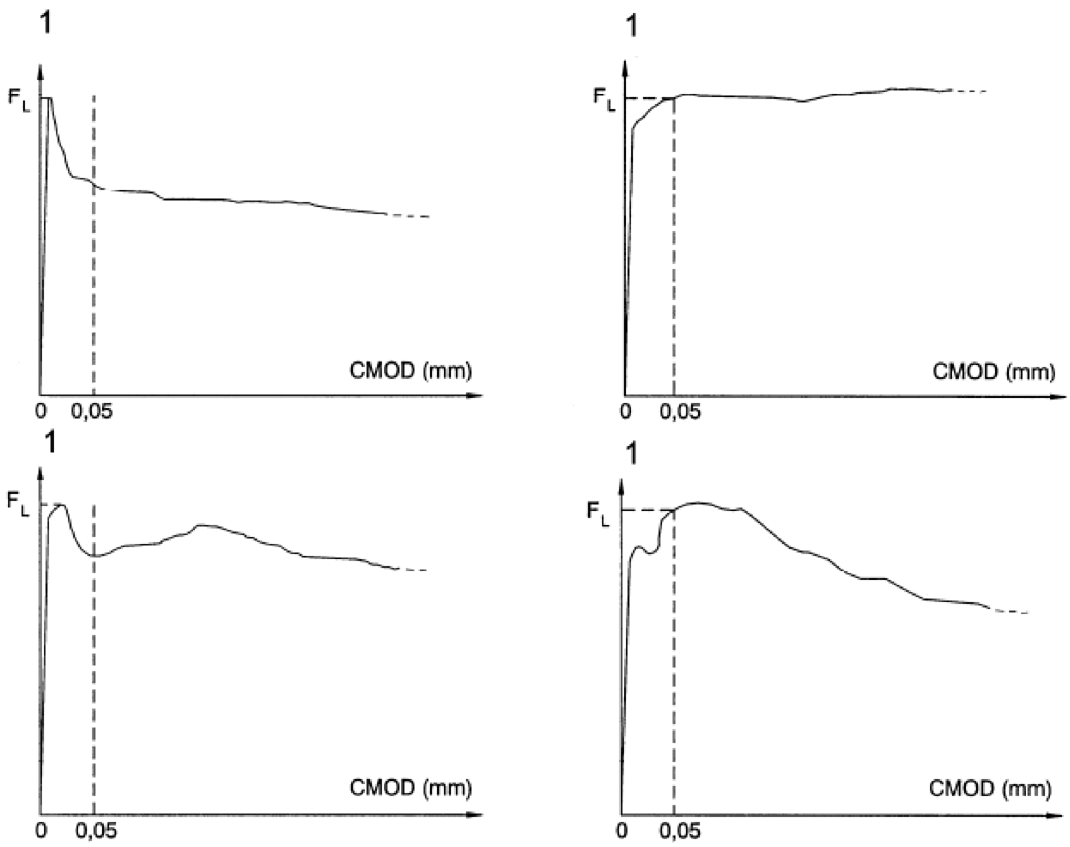
$l = width\ between\ support\ rollers\ [mm]$

$b = width\ of\ specimen = 150\ mm$

$h_{sp} = distance\ between\ top\ of\ the\ notch\ and\ top\ of\ the\ specimen = 125\ mm$

$M_L = bending\ moment\ [kNm]\ corresponding\ to\ load\ at\ LOP$

Note that the load FL is the highest load in the interval between CMOD = 0 and 0.05 mm and not necessarily the load at CMOD = 0.05 mm this is shown in figure AB.8.



Key

1 Load F

Figure AB.8: Possible CMOD-curves + indication of F_L

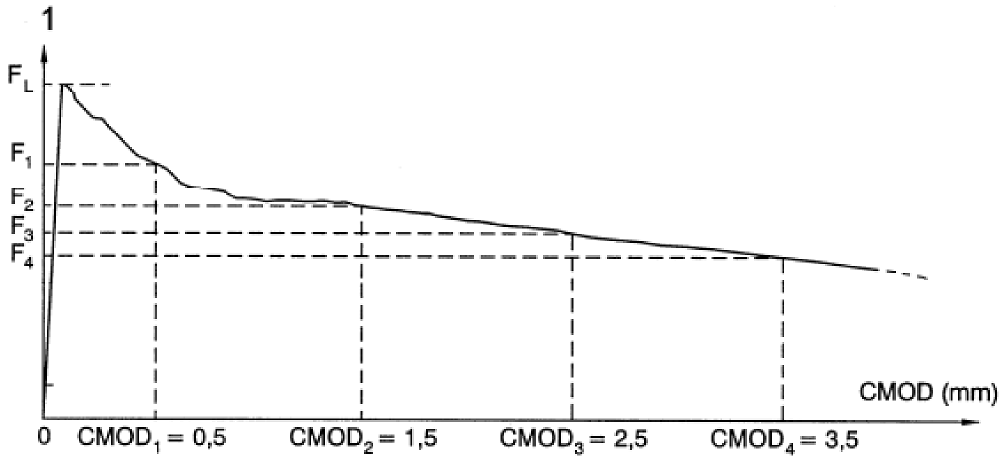
$$f_{R,j} = \frac{6M_j l}{bh_{sp}^2} = \frac{3F_j l}{2bh_{sp}^2} \quad \text{(eq. AB.4)}$$

Where:

$f_{R,j} = Residual\ flexural\ tensile\ strength\ [N/mm^2]\ corresponding\ with\ CMOD = CMOD_j\ (j = 1{,}2{,}3{,}4)$

$F_j = load\ [N]\ corresponding\ with\ CMOD = CMOD_j\ (j = 1{,}2{,}3{,}4)$

$M_J = bending\ moment\ [Nmm]\ corresponding\ to\ the\ load\ F_j\ (j = 1{,}2{,}3{,}4)$

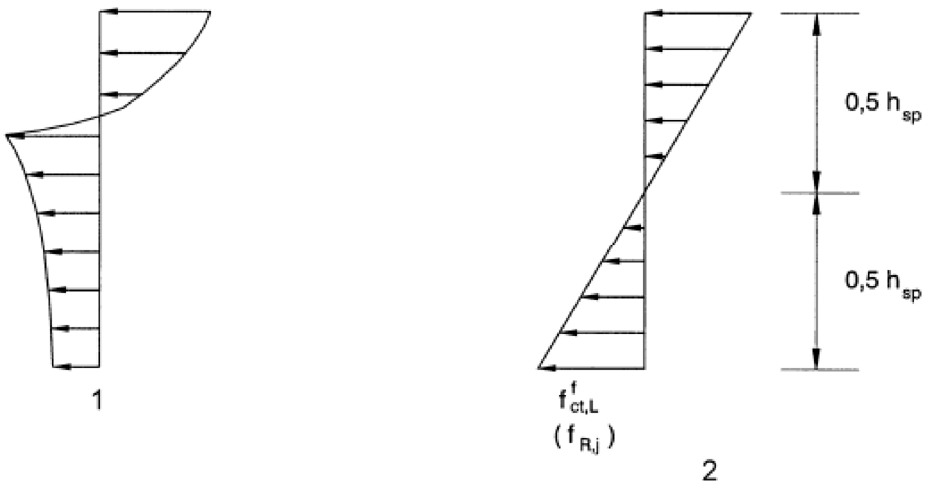


Key

1 Load F

Figure AB.9: CMOD curve + indications for $CMOD_1$ – $CMOD_4$

For the calculation of the LOP and the residual flexural tensile strength a linear stress distribution is assumed in the above equations. Figure AB.10 shows the real stress distribution and the assumed stress distribution.



Key

1 Real stress distribution

2 Assumed stress distribution

Figure AB.10: Real and assumed stress distribution

Appendix C Calculations of expected test results

> $restart;$

> $ffctmfl := 5.72; fR1 := 10.06; fR2 := 10.44; fR3 := 9.75; fR4 := 8.39; fck := 45.72; fcd := \frac{fck}{1.0};$

$$ffctmfl := 5.72$$
$$fR1 := 10.06$$
$$fR2 := 10.44$$
$$fR3 := 9.75$$
$$fR4 := 8.39$$
$$fck := 45.72$$
$$fcd := 45.72000000 \quad \textbf{(1)}$$

> $h1 := 150; d1 := 125; b1 := 150; kh := 1;$

$$h1 := 150$$
$$d1 := 125$$
$$b1 := 150$$
$$kh := 1 \quad \textbf{(2)}$$

> $sigma1 := 0.7 \cdot ffctmfl \cdot \left(1.6 - \frac{d1}{1000}\right); sigma2 := 0.45 \cdot fR1 \cdot kh; sigma3 := 0.37 \cdot fR4 \cdot kh;$

$$\sigma 1 := 5.905900000$$
$$\sigma 2 := 4.5270$$
$$\sigma 3 := 3.1043 \quad \textbf{(3)}$$

> $Ec := \frac{fcd}{\frac{0.003}{2}}; Ecm := 22 \cdot \left(\frac{fck + 8}{10}\right)^{0.3} \cdot 1000;$

$$Ec := 30480.00000$$
$$Ecm := 36430.36159 \quad \textbf{(4)}$$

> $varepsilon1 := \frac{sigma1}{Ec}; varepsilon2 := varepsilon1 + \frac{0.1}{1000}; varepsilon3 := \frac{25}{1000};$

$$\varepsilon 1 := 0.0001937631234$$
$$\varepsilon 2 := 0.0002937631234$$
$$\varepsilon 3 := \frac{1}{40} \quad \textbf{(5)}$$

> $Ft1(\mathrm{varepsilon}) := 0.5 \cdot sigma1 \cdot b \cdot (h - x1) \cdot \left(\frac{\mathrm{varepsilon}}{varepsilon1}\right):$

> $Fc1(\mathrm{varepsilon}) := \left(\frac{0.5 \cdot b \cdot x1 \cdot Ec \cdot \mathrm{varepsilon} \cdot x1}{h - x1}\right):$

> $eq1 := Ft1(\mathrm{varepsilon}) = Fc1(\mathrm{varepsilon}):$

> $x1x := solve(eq1, x1):$

> $x1 := x1x:$

> $Ft2(\mathrm{varepsilon}) := 0.5 \cdot sigma1 \cdot b \cdot (h - x2) \cdot \left(\frac{varepsilon1}{\mathrm{varepsilon}}\right) + \frac{1}{\mathrm{varepsilon}} \Bigg(0.5 \cdot \Bigg(2 \cdot sigma1$
$- \frac{(sigma1 - sigma2) \cdot (\mathrm{varepsilon} - varepsilon1)}{varepsilon2 - varepsilon1}\Bigg) \cdot b \cdot (h - x2) \cdot (\mathrm{varepsilon}$

$- varepsilon1)\Big)$:

> $Fc2(\text{varepsilon}) := \left(\frac{0.5 \cdot b \cdot x2 \cdot Ec \cdot \text{varepsilon} \cdot x2}{h - x2}\right)$:

> $eq2 := Ft2(\text{varepsilon}) = Fc2(\text{varepsilon})$:

> $x2x := solve(eq2, x2)$:

> $x2 := x2x[1]$:

> $Ft3(\text{varepsilon}) := \frac{0.5 \cdot sigma1 \cdot b \cdot (h - x3) \cdot varepsilon1}{\text{varepsilon}} + \frac{0.5 \cdot (sigma1 + sigma2) \cdot b \cdot (h - x3) \cdot (varepsilon2 - varepsilon1)}{\text{varepsilon}} + \frac{1}{\text{varepsilon}} \left(0.5 \cdot \left(2 \cdot sigma2 - \frac{(sigma2 - sigma3) \cdot (\text{varepsilon} - varepsilon2)}{varepsilon3 - varepsilon2}\right) \cdot b \cdot (h - x3) \cdot (\text{varepsilon} - varepsilon2)\right)$:

> $Fc3(\text{varepsilon}) := \left(\frac{0.5 \cdot b \cdot x3 \cdot Ec \cdot \text{varepsilon} \cdot x3}{h - x3}\right)$:

> $eq3 := Ft3(\text{varepsilon}) = Fc3(\text{varepsilon})$:

> $x3x := solve(eq3, x3)$:

> $x3 := x3x[1]$:

> $ec2(\text{varepsilon}) := \frac{x2}{h - x2} \cdot \text{varepsilon}$: $ec3(\text{varepsilon}) := \frac{x3}{h - x3} \cdot \text{varepsilon}$: $ec4(\text{varepsilon}) := \frac{x4}{h - x4} \cdot \text{varepsilon}$:

> $\text{alpha}(\text{varepsilon}) := \min\left(\frac{1}{ec4(\text{varepsilon})} \cdot (ec4(\text{varepsilon}) - 0.25 \cdot eu), 0.75\right)$:

> $Ft4(\text{varepsilon}) := \frac{0.5 \cdot sigma1 \cdot b \cdot (h - x4) \cdot varepsilon1}{\text{varepsilon}} + \frac{0.5 \cdot (sigma1 + sigma2) \cdot b \cdot (h - x4) \cdot (varepsilon2 - varepsilon1)}{\text{varepsilon}} + \frac{1}{\text{varepsilon}} \left(0.5 \cdot \left(2 \cdot sigma2 - \frac{(sigma2 - sigma3) \cdot (\text{varepsilon} - varepsilon2)}{varepsilon3 - varepsilon2}\right) \cdot b \cdot (h - x4) \cdot (\text{varepsilon} - varepsilon2)\right)$:

> $Fc4(\text{varepsilon}) := \text{alpha}(\text{varepsilon}) \cdot b \cdot x4 \cdot fcd$:

> $eq4 := Ft4(\text{varepsilon}) = Fc4(\text{varepsilon})$:

> $x4x := solve(eq4, x4)$:

Warning, solutions may have been lost

> $x4 := x4x[2]$:

> $Ft5(\text{varepsilon}) := \frac{0.5 \cdot sigma1 \cdot b \cdot (h - x5) \cdot varepsilon1}{\text{varepsilon}} + \frac{0.5 \cdot (sigma1 + sigma2) \cdot b \cdot (h - x5) \cdot (varepsilon2 - varepsilon1)}{\text{varepsilon}} + \frac{1}{\text{varepsilon}} \left(0.5 \cdot \left(2 \cdot sigma2 - \frac{(sigma2 - sigma3) \cdot (\text{varepsilon} - varepsilon2)}{varepsilon3 - varepsilon2}\right) \cdot b \cdot (h - x5) \cdot (\text{varepsilon} - varepsilon2)\right)$:

> $Fc5(\text{varepsilon}) := 0.75 \cdot b \cdot x5 \cdot fcd$:

> $eq5 := Ft5(\text{varepsilon}) = Fc5(\text{varepsilon})$:

> $x5 := solve(eq5, x5)$:

> $h := 150; b := 150; eu := 0.003;$

$$h := 150$$
$$b := 150$$
$$eu := 0.003 \tag{6}$$

> $eq0 := ec3(\text{varepsilon}) = \frac{eu}{2}$:

> $e0x := solve(eq0, \text{varepsilon});$

$$e0x := 0.00006806045979, 0.0002295345401, 0.008004876523, 0.1498120506 \tag{7}$$

> $e0 := e0x[3];$

$$e0 := 0.008004876523 \tag{8}$$

> $eq01 := ec4(\text{varepsilon}) = eu$:

> $e01x := solve(eq01, \text{varepsilon});$

$$e01x := 0.1303422453, 0.02747468192 \tag{9}$$

> $e01 := e01x[2];$

$$e01 := 0.02747468192 \tag{10}$$

> $with(plots)$:

> $B1 := plot([0, varepsilon1 + 0.000001], [x1, x1], colour = blue, labels = ['\text{varepsilon}', 'xu\ [mm]'], labeldirections = ['horizontal', 'vertical'])$:

> $B2 := plot(x2, \text{varepsilon} = varepsilon1 + 0.000001 .. varepsilon2, colour = blue)$:

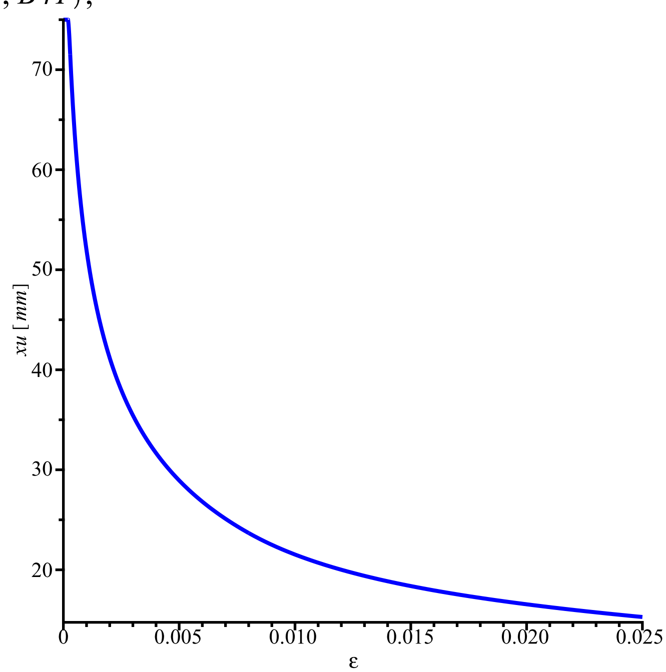
> $B3 := plot(x3, \text{varepsilon} = varepsilon2 .. e0, colour = blue)$:

> $B4 := plot(x4, \text{varepsilon} = e0 .. e01, colour = blue)$:

> $B41 := plot(x4, \text{varepsilon} = e0 .. varepsilon3, colour = blue)$:

> $B5 := plot(x5, \text{varepsilon} = e01 .. varepsilon3, colour = blue)$:

> $display(B1, B2, B3, B41);$



$$> A := plot\left(\frac{Ft1(\text{varepsilon})}{1000}, \text{varepsilon} = 0\,..varepsilon1 + 0.000001, colour = blue\right):$$

$$> AA := plot\left(\frac{Fc1(\text{varepsilon})}{1000}, \text{varepsilon} = 0\,..varepsilon1 + 0.000001, colour = red\right):$$

$$> C := plot\left(\frac{Ft2(\text{varepsilon})}{1000}, \text{varepsilon} = varepsilon1 + 0.000001\,..varepsilon2, colour = blue\right):$$

$$> CC := plot\left(\frac{Fc2(\text{varepsilon})}{1000}, \text{varepsilon} = varepsilon1 + 0.000001\,..varepsilon2, colour = red\right):$$

$$> F := plot\left(\frac{Ft3(\text{varepsilon})}{1000}, \text{varepsilon} = varepsilon2\,..e0, colour = blue\right):$$

$$> FF := plot\left(\frac{Fc3(\text{varepsilon})}{1000}, \text{varepsilon} = varepsilon2\,..e0, colour = red\right):$$

$$> G := plot\left(\frac{Ft4(\text{varepsilon})}{1000}, \text{varepsilon} = e0\,..e01, colour = blue\right):$$

$$> G1 := plot\left(\frac{Ft4(\text{varepsilon})}{1000}, \text{varepsilon} = e0\,..varepsilon3, colour = blue\right):$$

$$> GG := plot\left(\frac{Fc4(\text{varepsilon})}{1000}, \text{varepsilon} = e0\,..e01, colour = red\right):$$

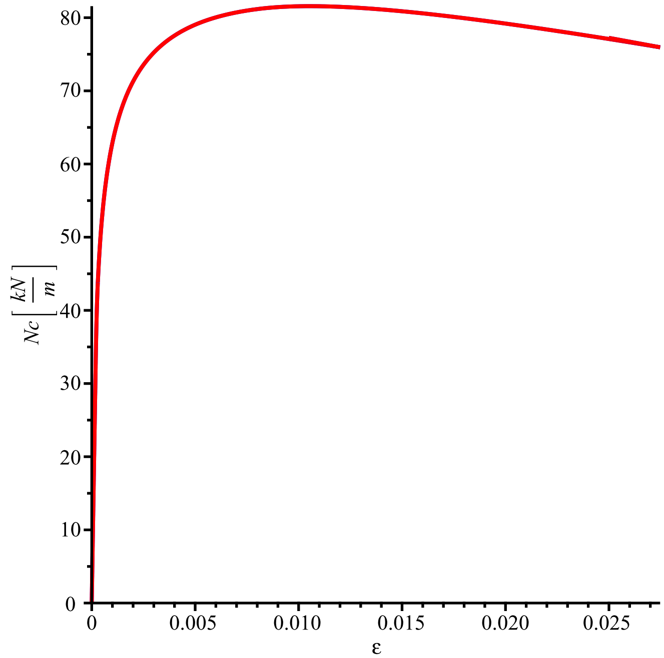
$$> GG1 := plot\left(\frac{Fc4(\text{varepsilon})}{1000}, \text{varepsilon} = e0\,..varepsilon3, colour = red\right):$$

$$> GGG := plot\left(\frac{Ft5(\text{varepsilon})}{1000}, \text{varepsilon} = e01\,..varepsilon3, colour = blue\right):$$

$$> GGGG := plot\left(\frac{Fc5(\text{varepsilon})}{1000}, \text{varepsilon} = e01\,..varepsilon3, colour = red\right):$$

$$> display(C, CC):$$

$$> display\left(A, AA, C, CC, F, FF, G, GG, GGG, GGGG, labels = \left[\text{'varepsilon'}, 'Nc\left[\frac{kN}{m}\right]'\right], labeldirections = ['horizontal', 'vertical']\right);$$



$$> A11(\text{varepsilon}) := \frac{sigma1 \cdot 0.5 \cdot \text{varepsilon} \cdot \text{varepsilon}}{varepsilon1} :$$

$$> A12 := 0.5 \cdot sigma1 \cdot varepsilon1 :$$

$$> sigma21(\text{varepsilon}) := sigma1 - \frac{(sigma1 - sigma2) \cdot (\text{varepsilon} - varepsilon1)}{varepsilon2 - varepsilon1} :$$

$$> A21(\text{varepsilon}) := sigma21(\text{varepsilon}) \cdot (\text{varepsilon} - varepsilon1) :$$

$$> A22 := sigma2 \cdot (varepsilon2 - varepsilon1) :$$

$$> A31(\text{varepsilon}) := 0.5 \cdot (sigma1 - sigma21(\text{varepsilon})) \cdot (\text{varepsilon} - varepsilon1) :$$

$$> A32 := 0.5 \cdot (sigma1 - sigma2) \cdot (varepsilon2 - varepsilon1) :$$

$$> sigma31(\text{varepsilon}) := sigma2 - \frac{(sigma2 - sigma3) \cdot (\text{varepsilon} - varepsilon2)}{varepsilon3 - varepsilon2} :$$

$$> sigma32(\text{varepsilon}) := sigma2 + \frac{(sigma2 - sigma3) \cdot (\text{varepsilon} - varepsilon2)}{varepsilon3 - varepsilon2} :$$

> **if** $(sigma2 > sigma3)$ **then** $sigma4(\text{varepsilon}) := sigma31(\text{varepsilon})$
> **else** $sigma4(\text{varepsilon}) := sigma32(\text{varepsilon})$ **end if**:

$$> A41(\text{varepsilon}) := sigma2 \cdot (\text{varepsilon} - varepsilon2) :$$

$$> A51(\text{varepsilon}) := 0.5 \cdot \text{abs}(sigma2 - sigma4(\text{varepsilon})) \cdot (\text{varepsilon} - varepsilon2) :$$

$$> \text{beta}(\text{varepsilon}) :=$$

$$\min\left(\frac{1}{\left(ec4(\text{varepsilon}) - \frac{1}{2} \cdot eu\right) + \frac{1}{4} \cdot eu} \left(\frac{\left(ec4(\text{varepsilon}) - \frac{1}{2} \cdot eu\right) \cdot 1}{2} \cdot \left(ec4(\text{varepsilon}) - \frac{1}{2} \cdot eu\right) + \frac{1}{4} \cdot eu \cdot \left(\frac{1}{6} \cdot eu + \left(ec4(\text{varepsilon}) - \frac{1}{2} \cdot eu\right)\right)\right)\right.$$

$$\cdot \frac{1}{ec4(\text{varepsilon})}, \frac{7}{18}\Bigg):$$

$$> z1(\text{varepsilon}) := \frac{\left(\frac{(h - x1)\cdot 2}{3} + \frac{x1\cdot 2}{3}\right)\cdot \text{varepsilon}}{\text{varepsilon}}:$$

$$> z2(\text{varepsilon}) := \frac{2}{3}\cdot x2 + \left(\left(\frac{2}{3}\cdot A12\cdot varepsilon1 + A21(\text{varepsilon})\cdot\left(\frac{1}{2}\cdot(\text{varepsilon} - varepsilon1) + varepsilon1\right) + A31(\text{varepsilon})\cdot\left(\frac{1}{3}\cdot(\text{varepsilon} - varepsilon1) + varepsilon1\right)\right)\cdot(h - x2)\right) \Big/ ((A12 + A21(\text{varepsilon}) + A31(\text{varepsilon}))\cdot\text{varepsilon}):$$

$$> z31(\text{varepsilon}) := \frac{2}{3}\cdot x3 + \left(\left(\frac{2}{3}\cdot A12\cdot varepsilon1 + A22\cdot\left(varepsilon1 + \frac{1}{2}\cdot(varepsilon2 - varepsilon1)\right) + A32\cdot\left(varepsilon1 + \frac{1}{3}\cdot(varepsilon2 - varepsilon1)\right) + A41(\text{varepsilon})\cdot\left(\frac{1}{2}\cdot(\text{varepsilon} - varepsilon2) + varepsilon2\right) + A51(\text{varepsilon})\cdot\left(\frac{1}{3}\cdot(\text{varepsilon} - varepsilon2) + varepsilon2\right)\right)\cdot(h - x3)\right) \Big/ ((A12 + (A22 + A32) + (A41(\text{varepsilon}) + A51(\text{varepsilon})))\cdot\text{varepsilon}):$$

$$> z32(\text{varepsilon}) := \frac{2}{3}\cdot x3 + \left(\left(\frac{2}{3}\cdot A12\cdot varepsilon1 + A22\cdot\left(varepsilon1 + \frac{1}{2}\cdot(varepsilon2 - varepsilon1)\right) + A32\cdot\left(varepsilon1 + \frac{1}{3}\cdot(varepsilon2 - varepsilon1)\right) + A41(\text{varepsilon})\cdot\left(\frac{1}{2}\cdot(\text{varepsilon} - varepsilon2) + varepsilon2\right) + A51(\text{varepsilon})\cdot\left(\frac{2}{3}\cdot(\text{varepsilon} - varepsilon2) + varepsilon2\right)\right)\cdot(h - x3)\right) \Big/ ((A12 + (A22 + A32) + (A41(\text{varepsilon}) + A51(\text{varepsilon})))\cdot\text{varepsilon}):$$

$>$ **if** $(sigma2 > sigma3)$ **then** $z3(\text{varepsilon}) := z31(\text{varepsilon})$ **else** $z3(\text{varepsilon}) := z32(\text{varepsilon})$ **end if**:

$$> z41(\text{varepsilon}) := (1 - \text{beta}(\text{varepsilon}))\cdot x4 + \left(\left(\frac{2}{3}\cdot A12\cdot varepsilon1 + A22\cdot\left(varepsilon1 + \frac{1}{2}\cdot(varepsilon2 - varepsilon1)\right) + A32\cdot\left(varepsilon1 + \frac{1}{3}\cdot(varepsilon2 - varepsilon1)\right) + A41(\text{varepsilon})\cdot\left(\frac{1}{2}\cdot(\text{varepsilon} - varepsilon2) + varepsilon2\right) + A51(\text{varepsilon})\cdot\left(\frac{1}{3}\cdot(\text{varepsilon} - varepsilon2) + varepsilon2\right)\right)\cdot(h - x4)\right) \Big/ ((A12 + (A22 + A32) + (A41(\text{varepsilon}) + A51(\text{varepsilon})))\cdot\text{varepsilon}):$$

$$> z42(\text{varepsilon}) := (1 - \text{beta}(\text{varepsilon}))\cdot x4 + \Bigg(\Bigg(\frac{2}{3}\cdot A12\cdot varepsilon1 + A22\cdot\left(varepsilon1 + \frac{1}{2}\cdot(varepsilon2 - varepsilon1)\right) + A32\cdot\Bigg(varepsilon1 + \frac{1}{3}\cdot(varepsilon2$$

$- varepsilon1) \Big) + A41(\text{varepsilon}) \cdot \Big(\frac{1}{2} \cdot (\text{varepsilon} - varepsilon2) + varepsilon2 \Big) + A51(\text{varepsilon}) \cdot \Big(\frac{2}{3} \cdot (\text{varepsilon} - varepsilon2) + varepsilon2 \Big) \Big) \cdot (h - x4) \Big) \Big/ ((A12 + (A22 + A32) + (A41(\text{varepsilon}) + A51(\text{varepsilon}))) \cdot \text{varepsilon}) :$

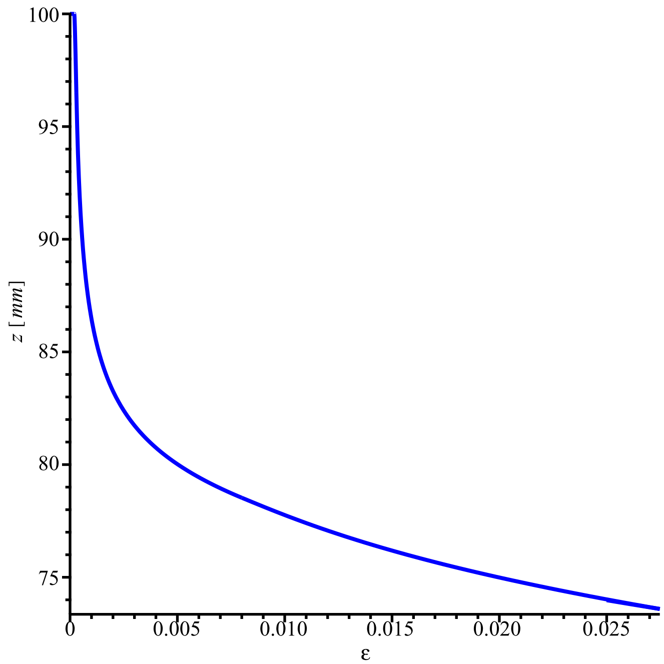
> **if** $(sigma2 > sigma3)$ **then** $z4(\text{varepsilon}) := z41(\text{varepsilon})$ **else** $z4(\text{varepsilon}) := z42(\text{varepsilon})$ **end if**:

> $z51(\text{varepsilon}) := (1 - \text{beta}(\text{varepsilon})) \cdot x5 + \Big(\Big(\frac{2}{3} \cdot A12 \cdot varepsilon1 + A22 \cdot \Big(varepsilon1 + \frac{1}{2} \cdot (varepsilon2 - varepsilon1) \Big) + A32 \cdot \Big(varepsilon1 + \frac{1}{3} \cdot (varepsilon2 - varepsilon1) \Big) + A41(\text{varepsilon}) \cdot \Big(\frac{1}{2} \cdot (\text{varepsilon} - varepsilon2) + varepsilon2 \Big) + A51(\text{varepsilon}) \cdot \Big(\frac{1}{3} \cdot (\text{varepsilon} - varepsilon2) + varepsilon2 \Big) \Big) \cdot (h - x5) \Big) \Big/ ((A12 + (A22 + A32) + (A41(\text{varepsilon}) + A51(\text{varepsilon}))) \cdot \text{varepsilon}) :$

> $z52(\text{varepsilon}) := (1 - \text{beta}(\text{varepsilon})) \cdot x5 + \Big(\Big(\frac{2}{3} \cdot A12 \cdot varepsilon1 + A22 \cdot \Big(varepsilon1 + \frac{1}{2} \cdot (varepsilon2 - varepsilon1) \Big) + A32 \cdot \Big(varepsilon1 + \frac{1}{3} \cdot (varepsilon2 - varepsilon1) \Big) + A41(\text{varepsilon}) \cdot \Big(\frac{1}{2} \cdot (\text{varepsilon} - varepsilon2) + varepsilon2 \Big) + A51(\text{varepsilon}) \cdot \Big(\frac{2}{3} \cdot (\text{varepsilon} - varepsilon2) + varepsilon2 \Big) \Big) \cdot (h - x5) \Big) \Big/ ((A12 + (A22 + A32) + (A41(\text{varepsilon}) + A51(\text{varepsilon}))) \cdot \text{varepsilon}) :$

> **if** $(sigma2 > sigma3)$ **then** $z5(\text{varepsilon}) := z51(\text{varepsilon})$ **else** $z5(\text{varepsilon}) := z52(\text{varepsilon})$ **end if**:

```
> with(plots) :
> Z1 := plot(z1(varepsilon), varepsilon = 0.00000001 ..varepsilon1, colour = blue, labels = [
      'varepsilon','z [mm]'], labeldirections = ['horizontal','vertical']) :
> Z2 := plot(z2(varepsilon), varepsilon = varepsilon1 ..varepsilon2, colour = blue) :
> Z3 := plot(z3(varepsilon), varepsilon = varepsilon2 ..e0, colour = blue) :
> Z4 := plot(z4(varepsilon), varepsilon = e0 ..e01, colour = blue) :
> Z41 := plot(z4(varepsilon), varepsilon = e0 ..varepsilon3, colour = blue) :
> Z5 := plot(z5(varepsilon), varepsilon = e01 ..varepsilon3, colour = blue) :
> display(Z1, Z2, Z3, Z4, Z5);
```



>

> $M1 := plot\left(\frac{z1(\text{varepsilon})\cdot Fc1(\text{varepsilon})}{1000000}, \text{varepsilon} = 0.00000001\,..varepsilon1, colour = blue, labels = \left[\text{'varepsilon'}, 'MRd\left[\frac{kNm}{m}\right]'\right], labeldirections = ['horizontal', 'vertical']\right):$

> $M2 := plot\left(\frac{z2(\text{varepsilon})\cdot Fc2(\text{varepsilon})}{1000000}, \text{varepsilon} = varepsilon1 + 0.000001\,..varepsilon2, colour = blue\right):$

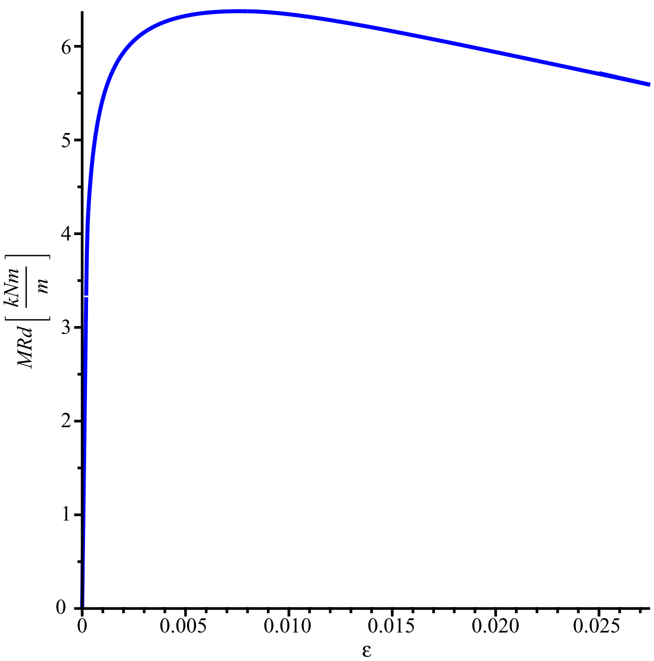
> $M3 := plot\left(\frac{z3(\text{varepsilon})\cdot Fc3(\text{varepsilon})}{1000000}, \text{varepsilon} = varepsilon2\,..e0, colour = blue\right):$

> $M4 := plot\left(\frac{z4(\text{varepsilon})\cdot Ft4(\text{varepsilon})}{1000000}, \text{varepsilon} = e0\,..e01, colour = blue\right):$

> $M41 := plot\left(\frac{z4(\text{varepsilon})\cdot Ft4(\text{varepsilon})}{1000000}, \text{varepsilon} = e0\,..varepsilon3, colour = blue\right):$

> $M5 := plot\left(\frac{z5(\text{varepsilon})\cdot Fc5(\text{varepsilon})}{1000000}, \text{varepsilon} = e01\,..varepsilon3, colour = blue\right):$

> $display(M1, M2, M3, M4, M5);$



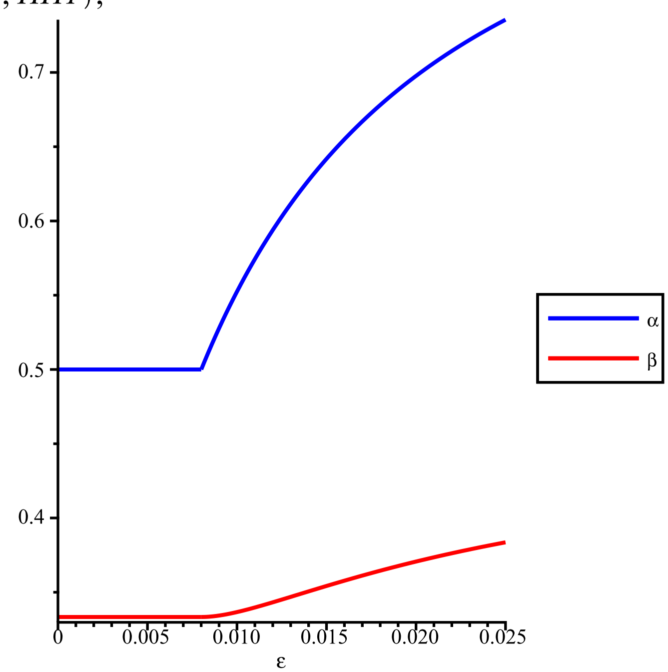
> $H := plot(\text{alpha}(\text{varepsilon}), \text{varepsilon} = e0..varepsilon3, colour = blue, legend = \text{'alpha'}, legendstyle = [location = right])$:

> $H1 := plot\left([0, e0], \left[\frac{1}{2}, \frac{1}{2}\right], colour = blue\right)$:

> $HH := plot(\text{beta}(\text{varepsilon}), \text{varepsilon} = e0..varepsilon3, colour = red, legend = \text{'beta'}, legendstyle = [location = right])$:

> $HH1 := plot\left([0, e0], \left[\frac{1}{3}, \frac{1}{3}\right], colour = red\right)$:

> $display(H, H1, HH, HH1)$;



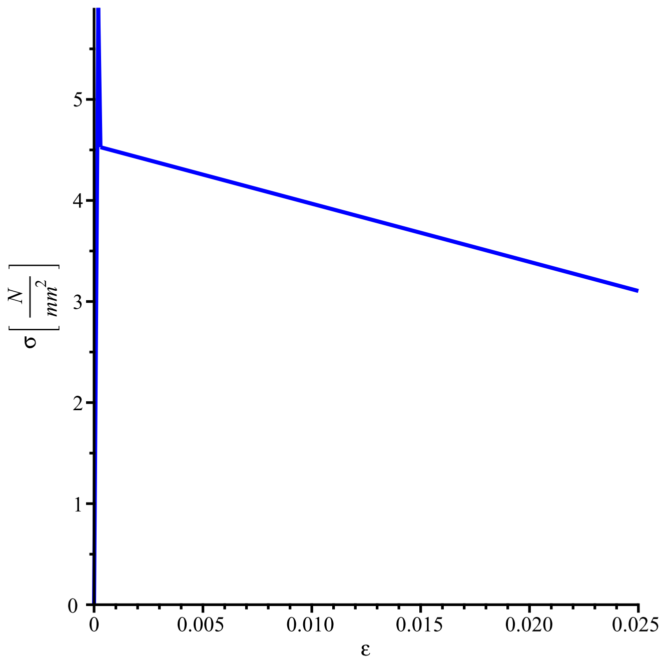
> $S1 := plot\left([0, varepsilon1], [0, sigma1], colour = blue, labels = \left[\text{'varepsilon'}, \text{'sigma}\left[\frac{N}{mm^2}\right]\text{'}\right],\right.$

labeldirections = ['*horizontal*','*vertical*']) :

> $S2 := plot([varepsilon1, varepsilon2], [sigma1, sigma2], colour = blue)$:

> $S3 := plot([varepsilon2, varepsilon3], [sigma2, sigma3], colour = blue)$:

> $display(S1, S2, S3)$;



> varepsilon := *varepsilon1*;

$$\varepsilon := 0.0001937631234 \qquad (11)$$

> $Mcr := \frac{z1(\text{varepsilon}) \cdot Fc1(\text{varepsilon})}{1000000}$;

$$Mcr := 3.322068751 \qquad (12)$$

> varepsilon := *varepsilon2*;

$$\varepsilon := 0.0002937631234 \qquad (13)$$

> $MSLS := \frac{z2(\text{varepsilon}) \cdot Fc2(\text{varepsilon})}{1000000}$;

$$MSLS := 4.228810477 \qquad (14)$$

> varepsilon := *varepsilon3*;

$$\varepsilon := \frac{1}{40} \qquad (15)$$

> $MULS := \frac{z4(\text{varepsilon}) \cdot Fc4(\text{varepsilon})}{1000000}$;

$$MULS := 5.705687436 \qquad (16)$$

> $VRd := (vmin + vfd) \cdot b \cdot d$; $vmin := 0.035 \cdot k^{\frac{3}{2}} \cdot \text{sqrt}(fck)$; $vfd := 0.7 \cdot kf \cdot k \cdot tau1$;

$$VRd := 150\ (vmin + vfd)\ d$$

$$vmin := 0.2366579811\ k^{3/2}$$

$$vfd := 0.7\ kf\ k\ \tau 1 \qquad (17)$$

> $d := h$;

(18)

$$d := 150 \quad \textbf{(18)}$$

>

> $k := \min\left(1 + \mathrm{sqrt}\left(\frac{200}{d}\right), 2\right); kf := 1 : tau1 := 0.12 \cdot fR4;$

$$k := 2$$

$$\tau 1 := 1.0068 \quad \textbf{(19)}$$

> $\frac{evalf(VRd)}{1000}; evalf(vmin); vfd;$

$$46.77502169$$

$$0.6693698529$$

$$1.40952 \quad \textbf{(20)}$$

> $Fvrd := \frac{evalf(VRd \cdot 2)}{1000};$

$$Fvrd := 93.55004338 \quad \textbf{(21)}$$

> $Mmax := \max(MSLS, MULS);$

$$Mmax := 5.705687436 \quad \textbf{(22)}$$

> $Fmrd600 := \frac{4 \cdot Mmax \cdot 1000^2}{500 \cdot 1000};$

$$Fmrd600 := 45.64549948 \quad \textbf{(23)}$$

> $Fmrd850 := \frac{2 \cdot Mmax \cdot 1000^2}{350 \cdot 1000};$

$$Fmrd850 := 32.60392820 \quad \textbf{(24)}$$

>

>

> $restart;$

> $ffctmfl := 5.45; fR1 := 3.34; fR2 := 3.68; fR3 := 3.69; fR4 := 3.50; fck := 58.15; fcd := \frac{fck}{1.0};$

$$ffctmfl := 5.45$$
$$fR1 := 3.34$$
$$fR2 := 3.68$$
$$fR3 := 3.69$$
$$fR4 := 3.50$$
$$fck := 58.15$$
$$fcd := 58.15000000 \quad \textbf{(1)}$$

> $h1 := 150; d1 := 125; b1 := 150; kh := 1;$

$$h1 := 150$$
$$d1 := 125$$
$$b1 := 150$$
$$kh := 1 \quad \textbf{(2)}$$

> $sigma1 := 0.7 \cdot ffctmfl \cdot \left(1.6 - \frac{d1}{1000}\right); sigma2 := 0.45 \cdot fR1 \cdot kh; sigma3 := 0.37 \cdot fR4 \cdot kh;$

$$\sigma1 := 5.627125000$$
$$\sigma2 := 1.5030$$
$$\sigma3 := 1.2950 \quad \textbf{(3)}$$

> $Ec := \frac{fcd}{\frac{0.003}{2}}; Ecm := 22 \cdot \left(\frac{fck + 8}{10}\right)^{0.3} \cdot 1000;$

$$Ec := 38766.66667$$
$$Ecm := 38777.66330 \quad \textbf{(4)}$$

> $varepsilon1 := \frac{sigma1}{Ec}; varepsilon2 := varepsilon1 + \frac{0.1}{1000}; varepsilon3 := \frac{25}{1000};$

$$\varepsilon1 := 0.0001451536973$$
$$\varepsilon2 := 0.0002451536973$$
$$\varepsilon3 := \frac{1}{40} \quad \textbf{(5)}$$

> $Ft1(\mathrm{varepsilon}) := 0.5 \cdot sigma1 \cdot b \cdot (h - x1) \cdot \left(\frac{\mathrm{varepsilon}}{varepsilon1}\right):$

> $Fc1(\mathrm{varepsilon}) := \left(\frac{0.5 \cdot b \cdot x1 \cdot Ec \cdot \mathrm{varepsilon} \cdot x1}{h - x1}\right):$

> $eq1 := Ft1(\mathrm{varepsilon}) = Fc1(\mathrm{varepsilon}):$

> $x1x := solve(eq1, x1):$

> $x1 := x1x:$

> $Ft2(\mathrm{varepsilon}) := 0.5 \cdot sigma1 \cdot b \cdot (h - x2) \cdot \left(\frac{varepsilon1}{\mathrm{varepsilon}}\right) + \frac{1}{\mathrm{varepsilon}} \Bigg(0.5 \cdot \Bigg(2 \cdot sigma1$
$- \frac{(sigma1 - sigma2) \cdot (\mathrm{varepsilon} - varepsilon1)}{varepsilon2 - varepsilon1}\Bigg) \cdot b \cdot (h - x2) \cdot (\mathrm{varepsilon}$

$- varepsilon1)\Big) :$

$> Fc2(\mathrm{varepsilon}) := \left(\frac{0.5 \cdot b \cdot x2 \cdot Ec \cdot \mathrm{varepsilon} \cdot x2}{h - x2}\right) :$

$> eq2 := Ft2(\mathrm{varepsilon}) = Fc2(\mathrm{varepsilon}) :$

$> x2x := solve(eq2, x2) :$

$> x2 := x2x[1] :$

$$> Ft3(\mathrm{varepsilon}) := \frac{0.5 \cdot sigma1 \cdot b \cdot (h - x3) \cdot varepsilon1}{\mathrm{varepsilon}} + \frac{0.5 \cdot (sigma1 + sigma2) \cdot b \cdot (h - x3) \cdot (varepsilon2 - varepsilon1)}{\mathrm{varepsilon}} + \frac{1}{\mathrm{varepsilon}} \left(0.5 \cdot \left(2 \cdot sigma2 - \frac{(sigma2 - sigma3) \cdot (\mathrm{varepsilon} - varepsilon2)}{varepsilon3 - varepsilon2}\right) \cdot b \cdot (h - x3) \cdot (\mathrm{varepsilon} - varepsilon2)\right) :$$

$> Fc3(\mathrm{varepsilon}) := \left(\frac{0.5 \cdot b \cdot x3 \cdot Ec \cdot \mathrm{varepsilon} \cdot x3}{h - x3}\right) :$

$> eq3 := Ft3(\mathrm{varepsilon}) = Fc3(\mathrm{varepsilon}) :$

$> x3x := solve(eq3, x3) :$

$> x3 := x3x[1] :$

$$> ec2(\mathrm{varepsilon}) := \frac{x2}{h - x2} \cdot \mathrm{varepsilon} : ec3(\mathrm{varepsilon}) := \frac{x3}{h - x3} \cdot \mathrm{varepsilon} : ec4(\mathrm{varepsilon}) := \frac{x4}{h - x4} \cdot \mathrm{varepsilon} :$$

$$> \mathrm{alpha}(\mathrm{varepsilon}) := \min\left(\frac{1}{ec4(\mathrm{varepsilon})} \cdot (ec4(\mathrm{varepsilon}) - 0.25 \cdot eu), 0.75\right) :$$

$$> Ft4(\mathrm{varepsilon}) := \frac{0.5 \cdot sigma1 \cdot b \cdot (h - x4) \cdot varepsilon1}{\mathrm{varepsilon}} + \frac{0.5 \cdot (sigma1 + sigma2) \cdot b \cdot (h - x4) \cdot (varepsilon2 - varepsilon1)}{\mathrm{varepsilon}} + \frac{1}{\mathrm{varepsilon}} \left(0.5 \cdot \left(2 \cdot sigma2 - \frac{(sigma2 - sigma3) \cdot (\mathrm{varepsilon} - varepsilon2)}{varepsilon3 - varepsilon2}\right) \cdot b \cdot (h - x4) \cdot (\mathrm{varepsilon} - varepsilon2)\right) :$$

$> Fc4(\mathrm{varepsilon}) := \mathrm{alpha}(\mathrm{varepsilon}) \cdot b \cdot x4 \cdot fcd :$

$> eq4 := Ft4(\mathrm{varepsilon}) = Fc4(\mathrm{varepsilon}) :$

$> x4x := solve(eq4, x4) :$

Warning, solutions may have been lost

$> x4 := x4x[2] :$

$$> Ft5(\mathrm{varepsilon}) := \frac{0.5 \cdot sigma1 \cdot b \cdot (h - x5) \cdot varepsilon1}{\mathrm{varepsilon}} + \frac{0.5 \cdot (sigma1 + sigma2) \cdot b \cdot (h - x5) \cdot (varepsilon2 - varepsilon1)}{\mathrm{varepsilon}} + \frac{1}{\mathrm{varepsilon}} \left(0.5 \cdot \left(2 \cdot sigma2 - \frac{(sigma2 - sigma3) \cdot (\mathrm{varepsilon} - varepsilon2)}{varepsilon3 - varepsilon2}\right) \cdot b \cdot (h - x5) \cdot (\mathrm{varepsilon} - varepsilon2)\right) :$$

> $Fc5(\text{varepsilon}) := 0.75 \cdot b \cdot x5 \cdot fcd :$

> $eq5 := Ft5(\text{varepsilon}) = Fc5(\text{varepsilon}) :$

> $x5 := solve(eq5, x5) :$

> $h := 150; b := 150; eu := 0.003;$

$$h := 150$$

$$b := 150$$

$$eu := 0.003 \tag{6}$$

> $eq0 := ec3(\text{varepsilon}) = \frac{eu}{2} :$

> $e0x := solve(eq0, \text{varepsilon});$

$$e0x := 0.0001869426001, 0.03148030210, 0.3267651398, -0.0001093123127 \tag{7}$$

> $e0 := e0x[2];$

$$e0 := 0.03148030210 \tag{8}$$

> $eq01 := ec4(\text{varepsilon}) = eu :$

> $e01x := solve(eq01, \text{varepsilon});$

$$e01x := 0.2113150592, 0.1469303826 \tag{9}$$

> $e01 := e01x[2];$

$$e01 := 0.1469303826 \tag{10}$$

> $with(plots) :$

> $B1 := plot([0, varepsilon1 + 0.000001], [x1, x1], colour = blue, labels = [\text{'varepsilon'}, \text{'}xu\ [mm]\text{'}], labeldirections = [\text{'horizontal'}, \text{'vertical'}]) :$

> $B2 := plot(x2, \text{varepsilon} = varepsilon1 + 0.000001\ ..varepsilon2, colour = blue) :$

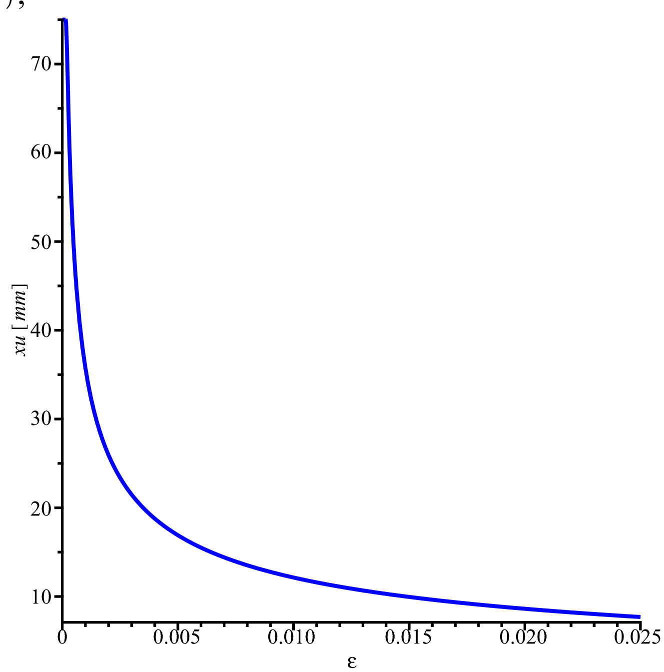
> $B3 := plot(x3, \text{varepsilon} = varepsilon2\ ..varepsilon3, colour = blue) :$

> $B4 := plot(x4, \text{varepsilon} = e0\ ..e01, colour = blue) :$

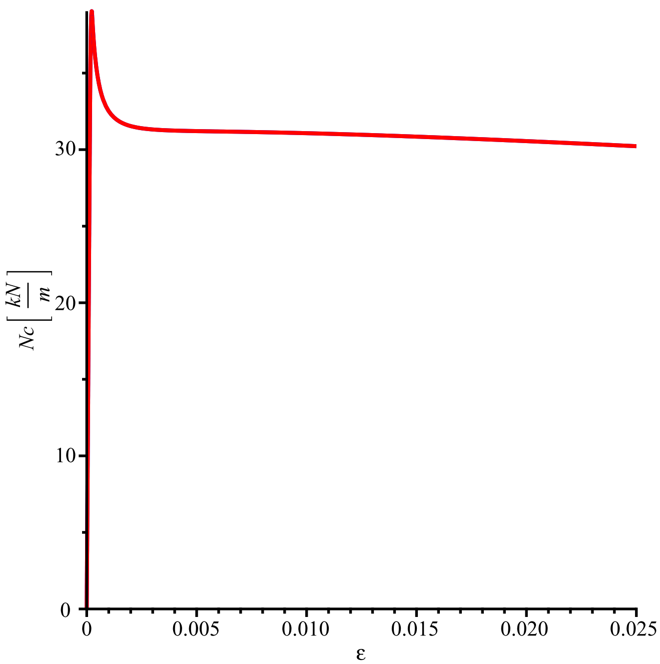
> $B41 := plot(x4, \text{varepsilon} = e0\ ..varepsilon3, colour = blue) :$

> $B5 := plot(x5, \text{varepsilon} = e01\ ..varepsilon3, colour = blue) :$

> $display(B1, B2, B3);$



```
> A := plot(Ft1(varepsilon)/1000, varepsilon = 0 .. varepsilon1 + 0.000001, colour = blue) :
> AA := plot(Fc1(varepsilon)/1000, varepsilon = 0 .. varepsilon1 + 0.000001, colour = red) :
> C := plot(Ft2(varepsilon)/1000, varepsilon = varepsilon1 + 0.000001 .. varepsilon2, colour
      = blue) :
> CC := plot(Fc2(varepsilon)/1000, varepsilon = varepsilon1 + 0.000001 .. varepsilon2, colour
      = red) :
> F := plot(Ft3(varepsilon)/1000, varepsilon = varepsilon2 .. varepsilon3, colour = blue) :
> FF := plot(Fc3(varepsilon)/1000, varepsilon = varepsilon2 .. varepsilon3, colour = red) :
> G := plot(Ft4(varepsilon)/1000, varepsilon = e0 .. e01, colour = blue) :
> G1 := plot(Ft4(varepsilon)/1000, varepsilon = e0 .. varepsilon3, colour = blue) :
> GG := plot(Fc4(varepsilon)/1000, varepsilon = e0 .. e01, colour = red) :
> GG1 := plot(Fc4(varepsilon)/1000, varepsilon = e0 .. varepsilon3, colour = red) :
> GGG := plot(Ft5(varepsilon)/1000, varepsilon = e01 .. varepsilon3, colour = blue) :
> GGGG := plot(Fc5(varepsilon)/1000, varepsilon = e01 .. varepsilon3, colour = red) :
> display(C, CC) :
> display(A, AA, C, CC, F, FF, labels = ['varepsilon','Nc [kN/m]'], labeldirections = ['horizontal',
      'vertical']);
```



$> A11(\text{varepsilon}) := \dfrac{sigma1 \cdot 0.5 \cdot \text{varepsilon} \cdot \text{varepsilon}}{varepsilon1}$:

$> A12 := 0.5 \cdot sigma1 \cdot varepsilon1$:

$> sigma21(\text{varepsilon}) := sigma1 - \dfrac{(sigma1 - sigma2) \cdot (\text{varepsilon} - varepsilon1)}{varepsilon2 - varepsilon1}$:

$> A21(\text{varepsilon}) := sigma21(\text{varepsilon}) \cdot (\text{varepsilon} - varepsilon1)$:

$> A22 := sigma2 \cdot (varepsilon2 - varepsilon1)$:

$> A31(\text{varepsilon}) := 0.5 \cdot (sigma1 - sigma21(\text{varepsilon})) \cdot (\text{varepsilon} - varepsilon1)$:

$> A32 := 0.5 \cdot (sigma1 - sigma2) \cdot (varepsilon2 - varepsilon1)$:

$> sigma31(\text{varepsilon}) := sigma2 - \dfrac{(sigma2 - sigma3) \cdot (\text{varepsilon} - varepsilon2)}{varepsilon3 - varepsilon2}$:

$> sigma32(\text{varepsilon}) := sigma2 + \dfrac{(sigma2 - sigma3) \cdot (\text{varepsilon} - varepsilon2)}{varepsilon3 - varepsilon2}$:

> **if** $(sigma2 > sigma3)$ **then** $sigma4(\text{varepsilon}) := sigma31(\text{varepsilon})$
else $sigma4(\text{varepsilon}) := sigma32(\text{varepsilon})$ **end if**:

$> A41(\text{varepsilon}) := sigma2 \cdot (\text{varepsilon} - varepsilon2)$:

$> A51(\text{varepsilon}) := 0.5 \cdot \text{abs}(sigma2 - sigma4(\text{varepsilon})) \cdot (\text{varepsilon} - varepsilon2)$:

> beta(varepsilon) :=

$$\min\left(\frac{1}{\left(ec4(\text{varepsilon}) - \frac{1}{2} \cdot eu\right) + \frac{1}{4} \cdot eu}\left(\frac{\left(ec4(\text{varepsilon}) - \frac{1}{2} \cdot eu\right) \cdot 1}{2} \cdot \left(ec4(\text{varepsilon}) - \frac{1}{2} \cdot eu\right) + \frac{1}{4} \cdot eu \cdot \left(\frac{1}{6} \cdot eu + \left(ec4(\text{varepsilon}) - \frac{1}{2} \cdot eu\right)\right)\right)\right)$$

$$\cdot \frac{1}{ec4(\text{varepsilon})}, \frac{7}{18}\Bigg):$$

$$> z1(\text{varepsilon}) := \frac{\left(\frac{(h - x1)\cdot 2}{3} + \frac{x1\cdot 2}{3}\right)\cdot \text{varepsilon}}{\text{varepsilon}}:$$

$$> z2(\text{varepsilon}) := \frac{2}{3}\cdot x2 + \left(\left(\frac{2}{3}\cdot A12\cdot varepsilon1 + A21(\text{varepsilon})\cdot\left(\frac{1}{2}\cdot(\text{varepsilon} - varepsilon1) + varepsilon1\right) + A31(\text{varepsilon})\cdot\left(\frac{1}{3}\cdot(\text{varepsilon} - varepsilon1) + varepsilon1\right)\right)\cdot(h - x2)\right) \Big/ ((A12 + A21(\text{varepsilon}) + A31(\text{varepsilon}))\cdot\text{varepsilon}):$$

$$> z31(\text{varepsilon}) := \frac{2}{3}\cdot x3 + \left(\left(\frac{2}{3}\cdot A12\cdot varepsilon1 + A22\cdot\left(varepsilon1 + \frac{1}{2}\cdot(varepsilon2 - varepsilon1)\right) + A32\cdot\left(varepsilon1 + \frac{1}{3}\cdot(varepsilon2 - varepsilon1)\right) + A41(\text{varepsilon})\cdot\left(\frac{1}{2}\cdot(\text{varepsilon} - varepsilon2) + varepsilon2\right) + A51(\text{varepsilon})\cdot\left(\frac{1}{3}\cdot(\text{varepsilon} - varepsilon2) + varepsilon2\right)\right)\cdot(h - x3)\right) \Big/ ((A12 + (A22 + A32) + (A41(\text{varepsilon}) + A51(\text{varepsilon})))\cdot\text{varepsilon}):$$

$$> z32(\text{varepsilon}) := \frac{2}{3}\cdot x3 + \left(\left(\frac{2}{3}\cdot A12\cdot varepsilon1 + A22\cdot\left(varepsilon1 + \frac{1}{2}\cdot(varepsilon2 - varepsilon1)\right) + A32\cdot\left(varepsilon1 + \frac{1}{3}\cdot(varepsilon2 - varepsilon1)\right) + A41(\text{varepsilon})\cdot\left(\frac{1}{2}\cdot(\text{varepsilon} - varepsilon2) + varepsilon2\right) + A51(\text{varepsilon})\cdot\left(\frac{2}{3}\cdot(\text{varepsilon} - varepsilon2) + varepsilon2\right)\right)\cdot(h - x3)\right) \Big/ ((A12 + (A22 + A32) + (A41(\text{varepsilon}) + A51(\text{varepsilon})))\cdot\text{varepsilon}):$$

> **if** $(sigma2 > sigma3)$ **then** $z3(\text{varepsilon}) := z31(\text{varepsilon})$ **else** $z3(\text{varepsilon}) := z32(\text{varepsilon})$ **end if**:

$$> z41(\text{varepsilon}) := (1 - \text{beta}(\text{varepsilon}))\cdot x4 + \left(\left(\frac{2}{3}\cdot A12\cdot varepsilon1 + A22\cdot\left(varepsilon1 + \frac{1}{2}\cdot(varepsilon2 - varepsilon1)\right) + A32\cdot\left(varepsilon1 + \frac{1}{3}\cdot(varepsilon2 - varepsilon1)\right) + A41(\text{varepsilon})\cdot\left(\frac{1}{2}\cdot(\text{varepsilon} - varepsilon2) + varepsilon2\right) + A51(\text{varepsilon})\cdot\left(\frac{1}{3}\cdot(\text{varepsilon} - varepsilon2) + varepsilon2\right)\right)\cdot(h - x4)\right) \Big/ ((A12 + (A22 + A32) + (A41(\text{varepsilon}) + A51(\text{varepsilon})))\cdot\text{varepsilon}):$$

$$> z42(\text{varepsilon}) := (1 - \text{beta}(\text{varepsilon}))\cdot x4 + \Bigg(\Bigg(\frac{2}{3}\cdot A12\cdot varepsilon1 + A22\cdot\left(varepsilon1 + \frac{1}{2}\cdot(varepsilon2 - varepsilon1)\right) + A32\cdot\Bigg(varepsilon1 + \frac{1}{3}\cdot(varepsilon2$$

$$- varepsilon1) \Big) + A41(\text{varepsilon}) \cdot \left(\frac{1}{2} \cdot (\text{varepsilon} - varepsilon2) + varepsilon2 \right) + A51(\text{varepsilon}) \cdot \left(\frac{2}{3} \cdot (\text{varepsilon} - varepsilon2) + varepsilon2 \right) \Big) \cdot (h - x4) \Big) \Big/ ((A12 + (A22 + A32) + (A41(\text{varepsilon}) + A51(\text{varepsilon}))) \cdot \text{varepsilon}) :$$

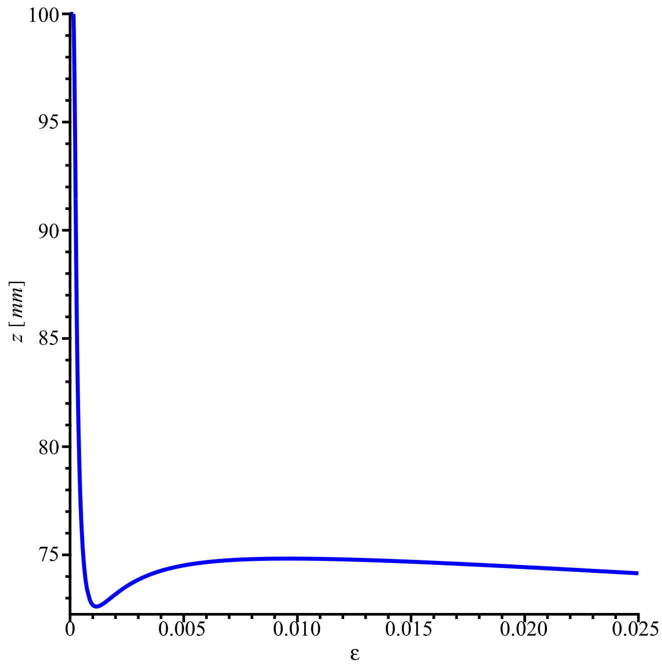
> **if** $(sigma2 > sigma3)$ **then** $z4(\text{varepsilon}) := z41(\text{varepsilon})$ **else** $z4(\text{varepsilon}) := z42(\text{varepsilon})$ **end if**:

> $$z51(\text{varepsilon}) := (1 - \text{beta}(\text{varepsilon})) \cdot x5 + \Bigg(\bigg(\frac{2}{3} \cdot A12 \cdot varepsilon1 + A22 \cdot \left(varepsilon1 + \frac{1}{2} \cdot (varepsilon2 - varepsilon1) \right) + A32 \cdot \left(varepsilon1 + \frac{1}{3} \cdot (varepsilon2 - varepsilon1) \right) + A41(\text{varepsilon}) \cdot \left(\frac{1}{2} \cdot (\text{varepsilon} - varepsilon2) + varepsilon2 \right) + A51(\text{varepsilon}) \cdot \left(\frac{1}{3} \cdot (\text{varepsilon} - varepsilon2) + varepsilon2 \right) \bigg) \cdot (h - x5) \Bigg) \Big/ ((A12 + (A22 + A32) + (A41(\text{varepsilon}) + A51(\text{varepsilon}))) \cdot \text{varepsilon}) :$$

> $$z52(\text{varepsilon}) := (1 - \text{beta}(\text{varepsilon})) \cdot x5 + \Bigg(\bigg(\frac{2}{3} \cdot A12 \cdot varepsilon1 + A22 \cdot \left(varepsilon1 + \frac{1}{2} \cdot (varepsilon2 - varepsilon1) \right) + A32 \cdot \left(varepsilon1 + \frac{1}{3} \cdot (varepsilon2 - varepsilon1) \right) + A41(\text{varepsilon}) \cdot \left(\frac{1}{2} \cdot (\text{varepsilon} - varepsilon2) + varepsilon2 \right) + A51(\text{varepsilon}) \cdot \left(\frac{2}{3} \cdot (\text{varepsilon} - varepsilon2) + varepsilon2 \right) \bigg) \cdot (h - x5) \Bigg) \Big/ ((A12 + (A22 + A32) + (A41(\text{varepsilon}) + A51(\text{varepsilon}))) \cdot \text{varepsilon}) :$$

> **if** $(sigma2 > sigma3)$ **then** $z5(\text{varepsilon}) := z51(\text{varepsilon})$ **else** $z5(\text{varepsilon}) := z52(\text{varepsilon})$ **end if**:

```
> with(plots) :
> Z1 := plot(z1(varepsilon), varepsilon = 0.00000001 ..varepsilon1, colour = blue, labels = [
    'varepsilon','z [mm]'], labeldirections = ['horizontal','vertical']) :
> Z2 := plot(z2(varepsilon), varepsilon = varepsilon1 ..varepsilon2, colour = blue) :
> Z3 := plot(z3(varepsilon), varepsilon = varepsilon2 ..varepsilon3, colour = blue) :
> Z4 := plot(z4(varepsilon), varepsilon = e0 ..e01, colour = blue) :
> Z41 := plot(z4(varepsilon), varepsilon = e0 ..varepsilon3, colour = blue) :
> Z5 := plot(z5(varepsilon), varepsilon = e01 ..varepsilon3, colour = blue) :
> display(Z1, Z2, Z3);
```



>

> $M1 := plot\left(\frac{z1(\text{varepsilon}) \cdot Fc1(\text{varepsilon})}{1000000}, \text{varepsilon} = 0.00000001 \,..\, varepsilon1, colour = blue, labels = \left[\text{'varepsilon'}, \text{'}MRd\left[\frac{kNm}{m}\right]\text{'}\right], labeldirections = [\text{'}horizontal\text{'}, \text{'}vertical\text{'}]\right):$

> $M2 := plot\left(\frac{z2(\text{varepsilon}) \cdot Fc2(\text{varepsilon})}{1000000}, \text{varepsilon} = varepsilon1 + 0.000001 \,..\, varepsilon2, colour = blue\right):$

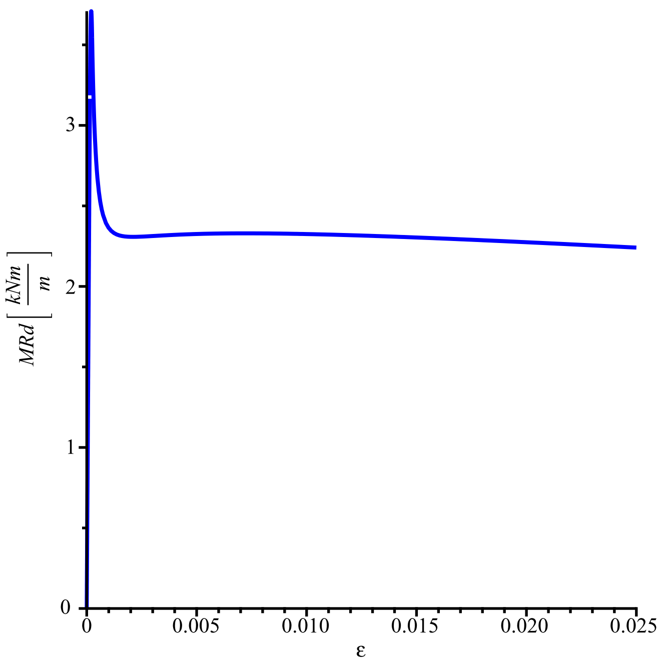
> $M3 := plot\left(\frac{z3(\text{varepsilon}) \cdot Fc3(\text{varepsilon})}{1000000}, \text{varepsilon} = varepsilon2 \,..\, varepsilon3, colour = blue\right):$

> $M4 := plot\left(\frac{z4(\text{varepsilon}) \cdot Ft4(\text{varepsilon})}{1000000}, \text{varepsilon} = e0 \,..\, e01, colour = blue\right):$

> $M41 := plot\left(\frac{z4(\text{varepsilon}) \cdot Ft4(\text{varepsilon})}{1000000}, \text{varepsilon} = e0 \,..\, varepsilon3, colour = blue\right):$

> $M5 := plot\left(\frac{z5(\text{varepsilon}) \cdot Fc5(\text{varepsilon})}{1000000}, \text{varepsilon} = e01 \,..\, varepsilon3, colour = blue\right):$

> $display(M1, M2, M3);$



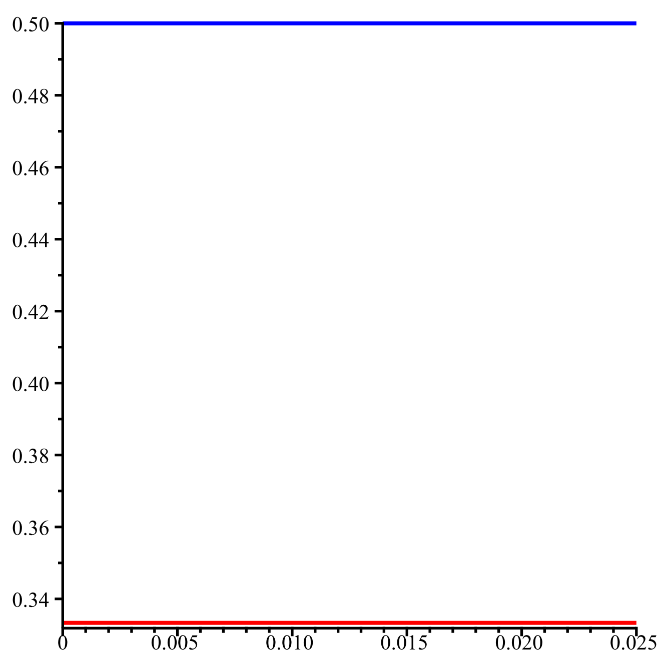
> $H := plot(\text{alpha}(\text{varepsilon}), \text{varepsilon} = e0..varepsilon3, colour = blue, legend = \text{'alpha'}, legendstyle = [location = right])$:

> $H1 := plot\left([0, varepsilon3], \left[\frac{1}{2}, \frac{1}{2}\right], colour = blue\right)$:

> $HH := plot(\text{beta}(\text{varepsilon}), \text{varepsilon} = e0..varepsilon3, colour = red, legend = \text{'beta'}, legendstyle = [location = right])$:

> $HH1 := plot\left([0, varepsilon3], \left[\frac{1}{3}, \frac{1}{3}\right], colour = red\right)$:

> $display(H1, HH1)$;



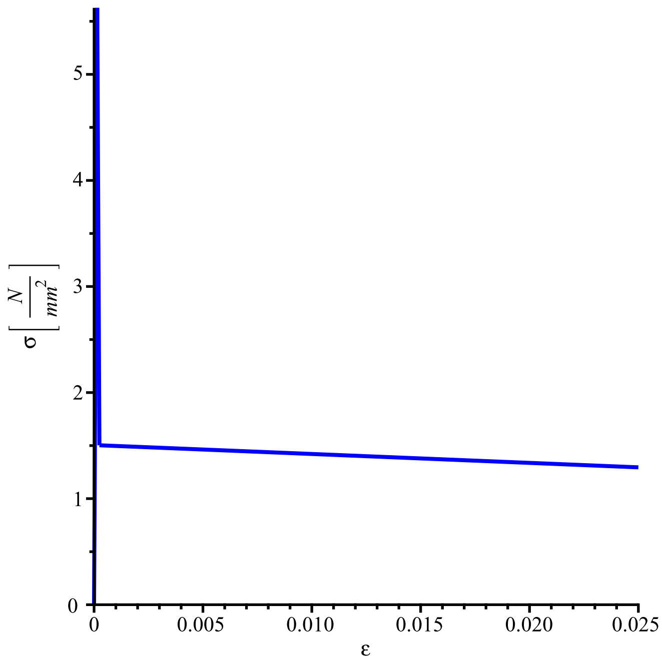
> $S1 := plot\left([0, varepsilon1], [0, sigma1], colour = blue, labels = \left[\text{'varepsilon','sigma}\left[\frac{N}{mm^2}\right]\text{'}\right],\right.$

$labeldirections = ['horizontal','vertical']\Big)$:

> $S2 := plot([varepsilon1, varepsilon2], [sigma1, sigma2], colour = blue)$:

> $S3 := plot([varepsilon2, varepsilon3], [sigma2, sigma3], colour = blue)$:

> $display(S1, S2, S3);$



> varepsilon := $varepsilon1$;

$$\varepsilon := 0.0001451536973 \quad (11)$$

> $Mcr := \frac{z1(\text{varepsilon}) \cdot Fc1(\text{varepsilon})}{1000000}$;

$$Mcr := 3.165257812 \quad (12)$$

> varepsilon := $varepsilon2$;

$$\varepsilon := 0.0002451536973 \quad (13)$$

> $MSLS := \frac{z2(\text{varepsilon}) \cdot Fc2(\text{varepsilon})}{1000000}$;

$$MSLS := 3.546253549 \quad (14)$$

> varepsilon := $varepsilon3$;

$$\varepsilon := \frac{1}{40} \quad (15)$$

> $MULS := \frac{z4(\text{varepsilon}) \cdot Fc4(\text{varepsilon})}{1000000}$;

$$MULS := 2.239664466 \quad (16)$$

> $VRd := (vmin + vfd) \cdot b \cdot d;\ vmin := 0.035 \cdot k^{\frac{3}{2}} \cdot \mathrm{sqrt}(fck);\ vfd := 0.7 \cdot kf \cdot k \cdot tau1;$

$$VRd := 150\ (vmin + vfd)\ d$$
$$vmin := 0.2668965155\ k^{3/2}$$
$$vfd := 0.7\ kf\ k\ \tau 1 \quad (17)$$

> $d := h;$

(18)

$$d := 150 \qquad \textbf{(18)}$$

>

> $k := \min\left(1 + \mathrm{sqrt}\left(\frac{200}{d}\right), 2\right); kf := 1 : tau1 := 0.12 \cdot fR4;$

$$k := 2$$

$$\tau 1 := 0.4200 \qquad \textbf{(19)}$$

> $\frac{evalf(VRd)}{1000}; evalf(vmin); vfd;$

$$30.21519024$$

$$0.7548973437$$

$$0.58800 \qquad \textbf{(20)}$$

> $Fvrd := \frac{evalf(VRd \cdot 2)}{1000};$

$$Fvrd := 60.43038048 \qquad \textbf{(21)}$$

> $Mmax := \max(MSLS, MULS);$

$$Mmax := 3.546253549 \qquad \textbf{(22)}$$

> $Fmrd600 := \frac{4 \cdot Mmax \cdot 1000^2}{500 \cdot 1000};$

$$Fmrd600 := 28.37002839 \qquad \textbf{(23)}$$

> $Fmrd850 := \frac{2 \cdot Mmax \cdot 1000^2}{350 \cdot 1000};$

$$Fmrd850 := 20.26430600 \qquad \textbf{(24)}$$

>

>

Appendix D Calculation sheets of fibre capacities (Maple)

> $restart;$

> $ffctmfl := 7.70; fR1 := 9.76; fR2 := 11.35; fR3 := 9.03; fR4 := 7.44; fck := 58.55; fcd := \frac{fck}{1.5};$

$$ffctmfl := 7.70$$
$$fR1 := 9.76$$
$$fR2 := 11.35$$
$$fR3 := 9.03$$
$$fR4 := 7.44$$
$$fck := 58.55$$
$$fcd := 39.03333334 \quad (1)$$

> $h1 := 150; d1 := 125; b1 := 150; kh := 1;$

$$h1 := 150$$
$$d1 := 125$$
$$b1 := 150$$
$$kh := 1 \quad (2)$$

> $sigma1 := 0.7 \cdot ffctmfl \cdot \left(1.6 - \frac{d1}{1000}\right); sigma2 := 0.45 \cdot fR1 \cdot kh; sigma3 := 0.37 \cdot fR4 \cdot kh;$

$$\sigma1 := 7.950250000$$
$$\sigma2 := 4.3920$$
$$\sigma3 := 2.7528 \quad (3)$$

> $Ec := \frac{fcd}{\frac{0.003}{2}}; Ecm := 22 \cdot \left(\frac{fck + 8}{10}\right)^{0.3} \cdot 1000;$

$$Ec := 26022.22223$$
$$Ecm := 38847.85989 \quad (4)$$

> $varepsilon1 := \frac{sigma1}{Ec}; varepsilon2 := varepsilon1 + \frac{0.1}{1000}; varepsilon3 := \frac{25}{1000};$

$$\varepsilon1 := 0.0003055177198$$
$$\varepsilon2 := 0.0004055177198$$
$$\varepsilon3 := \frac{1}{40} \quad (5)$$

> $Ft1(\mathrm{varepsilon}) := 0.5 \cdot sigma1 \cdot b \cdot (h - x1) \cdot \left(\frac{\mathrm{varepsilon}}{varepsilon1}\right):$

> $Fc1(\mathrm{varepsilon}) := \left(\frac{0.5 \cdot b \cdot x1 \cdot Ec \cdot \mathrm{varepsilon} \cdot x1}{h - x1}\right):$

> $eq1 := Ft1(\mathrm{varepsilon}) = Fc1(\mathrm{varepsilon}):$

> $x1x := solve(eq1, x1):$

> $x1 := x1x:$

> $Ft2(\mathrm{varepsilon}) := 0.5 \cdot sigma1 \cdot b \cdot (h - x2) \cdot \left(\frac{varepsilon1}{\mathrm{varepsilon}}\right) + \frac{1}{\mathrm{varepsilon}} \Bigg(0.5 \cdot \Bigg(2 \cdot sigma1$
$- \frac{(sigma1 - sigma2) \cdot (\mathrm{varepsilon} - varepsilon1)}{varepsilon2 - varepsilon1}\Bigg) \cdot b \cdot (h - x2) \cdot (\mathrm{varepsilon}$

$$- varepsilon1) \Big) :$$

$$> Fc2(\mathrm{varepsilon}) := \left(\frac{0.5 \cdot b \cdot x2 \cdot Ec \cdot \mathrm{varepsilon} \cdot x2}{h - x2} \right) :$$

$$> eq2 := Ft2(\mathrm{varepsilon}) = Fc2(\mathrm{varepsilon}) :$$

$$> x2x := solve(eq2, x2) :$$

$$> x2 := x2x[1] :$$

$$> Ft3(\mathrm{varepsilon}) := \frac{0.5 \cdot sigma1 \cdot b \cdot (h - x3) \cdot varepsilon1}{\mathrm{varepsilon}} + \frac{0.5 \cdot (sigma1 + sigma2) \cdot b \cdot (h - x3) \cdot (varepsilon2 - varepsilon1)}{\mathrm{varepsilon}} + \frac{1}{\mathrm{varepsilon}} \left(0.5 \cdot \left(2 \cdot sigma2 - \frac{(sigma2 - sigma3) \cdot (\mathrm{varepsilon} - varepsilon2)}{varepsilon3 - varepsilon2} \right) \cdot b \cdot (h - x3) \cdot (\mathrm{varepsilon} - varepsilon2) \right) :$$

$$> Fc3(\mathrm{varepsilon}) := \left(\frac{0.5 \cdot b \cdot x3 \cdot Ec \cdot \mathrm{varepsilon} \cdot x3}{h - x3} \right) :$$

$$> eq3 := Ft3(\mathrm{varepsilon}) = Fc3(\mathrm{varepsilon}) :$$

$$> x3x := solve(eq3, x3) :$$

$$> x3 := x3x[1] :$$

$$> ec2(\mathrm{varepsilon}) := \frac{x2}{h - x2} \cdot \mathrm{varepsilon} : ec3(\mathrm{varepsilon}) := \frac{x3}{h - x3} \cdot \mathrm{varepsilon} : ec4(\mathrm{varepsilon}) := \frac{x4}{h - x4} \cdot \mathrm{varepsilon} :$$

$$> \mathrm{alpha}(\mathrm{varepsilon}) := \min\left(\frac{1}{ec4(\mathrm{varepsilon})} \cdot (ec4(\mathrm{varepsilon}) - 0.25 \cdot eu), 0.75 \right) :$$

$$> Ft4(\mathrm{varepsilon}) := \frac{0.5 \cdot sigma1 \cdot b \cdot (h - x4) \cdot varepsilon1}{\mathrm{varepsilon}} + \frac{0.5 \cdot (sigma1 + sigma2) \cdot b \cdot (h - x4) \cdot (varepsilon2 - varepsilon1)}{\mathrm{varepsilon}} + \frac{1}{\mathrm{varepsilon}} \left(0.5 \cdot \left(2 \cdot sigma2 - \frac{(sigma2 - sigma3) \cdot (\mathrm{varepsilon} - varepsilon2)}{varepsilon3 - varepsilon2} \right) \cdot b \cdot (h - x4) \cdot (\mathrm{varepsilon} - varepsilon2) \right) :$$

$$> Fc4(\mathrm{varepsilon}) := \mathrm{alpha}(\mathrm{varepsilon}) \cdot b \cdot x4 \cdot fcd :$$

$$> eq4 := Ft4(\mathrm{varepsilon}) = Fc4(\mathrm{varepsilon}) :$$

$$> x4x := solve(eq4, x4) :$$

Warning, solutions may have been lost

$$> x4 := x4x[2] :$$

$$> Ft5(\mathrm{varepsilon}) := \frac{0.5 \cdot sigma1 \cdot b \cdot (h - x5) \cdot varepsilon1}{\mathrm{varepsilon}} + \frac{0.5 \cdot (sigma1 + sigma2) \cdot b \cdot (h - x5) \cdot (varepsilon2 - varepsilon1)}{\mathrm{varepsilon}} + \frac{1}{\mathrm{varepsilon}} \left(0.5 \cdot \left(2 \cdot sigma2 - \frac{(sigma2 - sigma3) \cdot (\mathrm{varepsilon} - varepsilon2)}{varepsilon3 - varepsilon2} \right) \cdot b \cdot (h - x5) \cdot (\mathrm{varepsilon} - varepsilon2) \right) :$$

> $Fc5(\text{varepsilon}) := 0.75 \cdot b \cdot x5 \cdot fcd$:

> $eq5 := Ft5(\text{varepsilon}) = Fc5(\text{varepsilon})$:

> $x5 := solve(eq5, x5)$:

> $h := 100;\ b := 1000;\ eu := 0.003;$

$$h := 100$$
$$b := 1000$$
$$eu := 0.003 \tag{6}$$

> $eq0 := ec3(\text{varepsilon}) = \frac{eu}{2}$:

> $e0x := solve(eq0, \text{varepsilon})$:

> $e0 := e0x[2];$

$$e0 := 0.006982201558 \tag{7}$$

> $eq01 := ec4(\text{varepsilon}) = eu$:

> $e01x := solve(eq01, \text{varepsilon})$:

> $e01 := e01x[2];$

$$e01 := 0.02432693421 \tag{8}$$

> $with(plots)$:

> $B1 := plot([0, varepsilon1 + 0.000001], [x1, x1], colour = blue, labels = [\text{'varepsilon'}, \text{'}xu\ [mm]\text{'}], labeldirections = [\text{'horizontal'}, \text{'vertical'}])$:

> $B2 := plot(x2, \text{varepsilon} = varepsilon1 + 0.000001 .. varepsilon2, colour = blue)$:

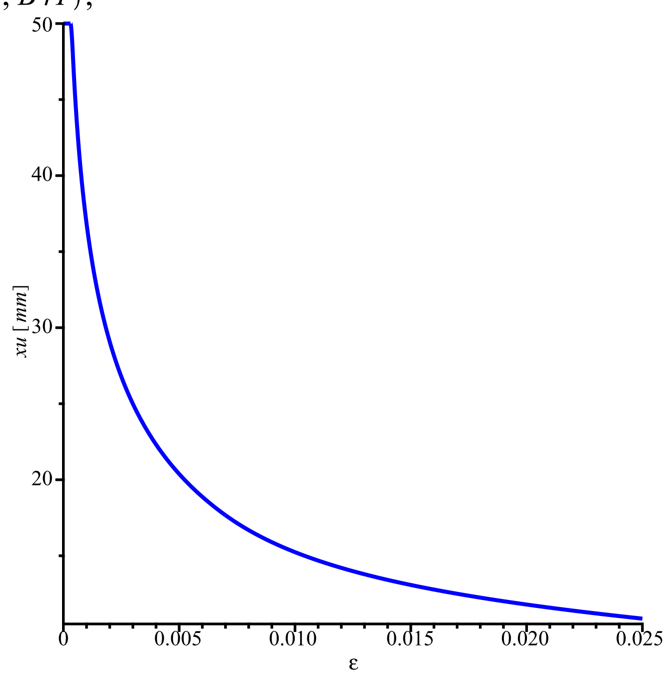
> $B3 := plot(x3, \text{varepsilon} = varepsilon2 .. e0, colour = blue)$:

> $B4 := plot(x4, \text{varepsilon} = e0 .. e01, colour = blue)$:

> $B41 := plot(x4, \text{varepsilon} = e0 .. varepsilon3, colour = blue)$:

> $B5 := plot(x5, \text{varepsilon} = e01 .. varepsilon3, colour = blue)$:

> $display(B1, B2, B3, B41);$



> $A := plot\left(\frac{Ft1(\text{varepsilon})}{1000}, \text{varepsilon} = 0 .. varepsilon1 + 0.000001, colour = blue\right)$:

$$> AA := plot\left(\frac{Fc1(\text{varepsilon})}{1000}, \text{varepsilon} = 0 .. varepsilon1 + 0.000001, colour = red\right) :$$

$$> C := plot\left(\frac{Ft2(\text{varepsilon})}{1000}, \text{varepsilon} = varepsilon1 + 0.000001 .. varepsilon2, colour = blue\right) :$$

$$> CC := plot\left(\frac{Fc2(\text{varepsilon})}{1000}, \text{varepsilon} = varepsilon1 + 0.000001 .. varepsilon2, colour = red\right) :$$

$$> F := plot\left(\frac{Ft3(\text{varepsilon})}{1000}, \text{varepsilon} = varepsilon2 .. e0, colour = blue\right) :$$

$$> FF := plot\left(\frac{Fc3(\text{varepsilon})}{1000}, \text{varepsilon} = varepsilon2 .. e0, colour = red\right) :$$

$$> G := plot\left(\frac{Ft4(\text{varepsilon})}{1000}, \text{varepsilon} = e0 .. e01, colour = blue\right) :$$

$$> G1 := plot\left(\frac{Ft4(\text{varepsilon})}{1000}, \text{varepsilon} = e0 .. varepsilon3, colour = blue\right) :$$

$$> GG := plot\left(\frac{Fc4(\text{varepsilon})}{1000}, \text{varepsilon} = e0 .. e01, colour = red\right) :$$

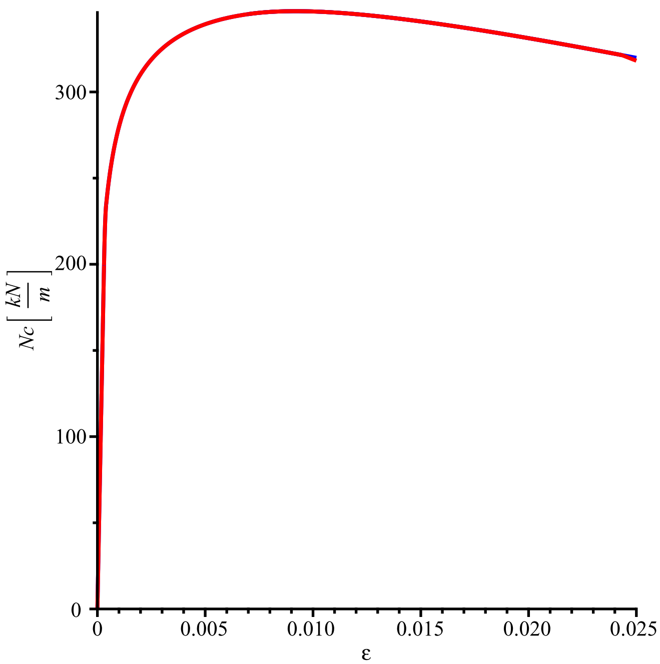
$$> GG1 := plot\left(\frac{Fc4(\text{varepsilon})}{1000}, \text{varepsilon} = e0 .. varepsilon3, colour = red\right) :$$

$$> GGG := plot\left(\frac{Ft5(\text{varepsilon})}{1000}, \text{varepsilon} = e01 .. varepsilon3, colour = blue\right) :$$

$$> GGGG := plot\left(\frac{Fc5(\text{varepsilon})}{1000}, \text{varepsilon} = e01 .. varepsilon3, colour = red\right) :$$

$$> display(C, CC) :$$

$$> display\left(A, AA, C, CC, F, FF, G, GG, G1, GG1, labels = \left['\text{varepsilon}', 'Nc\left[\frac{kN}{m}\right]'\right], labeldirections = ['horizontal', 'vertical']\right);$$



$$> A11(\text{varepsilon}) := \frac{sigma1 \cdot 0.5 \cdot \text{varepsilon} \cdot \text{varepsilon}}{varepsilon1} :$$

$$> A12 := 0.5 \cdot sigma1 \cdot varepsilon1 :$$

$$> sigma21(\text{varepsilon}) := sigma1 - \frac{(sigma1 - sigma2) \cdot (\text{varepsilon} - varepsilon1)}{varepsilon2 - varepsilon1} :$$

$$> A21(\text{varepsilon}) := sigma21(\text{varepsilon}) \cdot (\text{varepsilon} - varepsilon1) :$$

$$> A22 := sigma2 \cdot (varepsilon2 - varepsilon1) :$$

$$> A31(\text{varepsilon}) := 0.5 \cdot (sigma1 - sigma21(\text{varepsilon})) \cdot (\text{varepsilon} - varepsilon1) :$$

$$> A32 := 0.5 \cdot (sigma1 - sigma2) \cdot (varepsilon2 - varepsilon1) :$$

$$> sigma31(\text{varepsilon}) := sigma2 - \frac{(sigma2 - sigma3) \cdot (\text{varepsilon} - varepsilon2)}{varepsilon3 - varepsilon2} :$$

$$> sigma32(\text{varepsilon}) := sigma2 + \frac{(sigma2 - sigma3) \cdot (\text{varepsilon} - varepsilon2)}{varepsilon3 - varepsilon2} :$$

> **if** $(sigma2 > sigma3)$ **then** $sigma4(\text{varepsilon}) := sigma31(\text{varepsilon})$
> **else** $sigma4(\text{varepsilon}) := sigma32(\text{varepsilon})$ **end if**:

$$> A41(\text{varepsilon}) := sigma2 \cdot (\text{varepsilon} - varepsilon2) :$$

$$> A51(\text{varepsilon}) := 0.5 \cdot \text{abs}(sigma2 - sigma4(\text{varepsilon})) \cdot (\text{varepsilon} - varepsilon2) :$$

$$> \text{beta}(\text{varepsilon}) :=$$

$$\min\left(\frac{1}{\left(ec4(\text{varepsilon}) - \frac{1}{2} \cdot eu\right) + \frac{1}{4} \cdot eu}\left(\frac{\left(ec4(\text{varepsilon}) - \frac{1}{2} \cdot eu\right) \cdot 1}{2} \cdot \left(ec4(\text{varepsilon}) - \frac{1}{2} \cdot eu\right) + \frac{1}{4} \cdot eu \cdot \left(\frac{1}{6} \cdot eu + \left(ec4(\text{varepsilon}) - \frac{1}{2} \cdot eu\right)\right)\right)\right.$$

$$\cdot \frac{1}{ec4(\text{varepsilon})}, \frac{7}{18}\Bigg):$$

$$> z1(\text{varepsilon}) := \frac{\left(\frac{(h - x1)\cdot 2}{3} + \frac{x1\cdot 2}{3}\right)\cdot \text{varepsilon}}{\text{varepsilon}}:$$

$$> z2(\text{varepsilon}) := \frac{2}{3}\cdot x2 + \left(\left(\frac{2}{3}\cdot A12\cdot varepsilon1 + A21(\text{varepsilon})\cdot\left(\frac{1}{2}\cdot(\text{varepsilon} - varepsilon1) + varepsilon1\right) + A31(\text{varepsilon})\cdot\left(\frac{1}{3}\cdot(\text{varepsilon} - varepsilon1) + varepsilon1\right)\right)\cdot(h - x2)\right) \Big/ ((A12 + A21(\text{varepsilon}) + A31(\text{varepsilon}))\cdot\text{varepsilon}):$$

$$> z31(\text{varepsilon}) := \frac{2}{3}\cdot x3 + \left(\left(\frac{2}{3}\cdot A12\cdot varepsilon1 + A22\cdot\left(varepsilon1 + \frac{1}{2}\cdot(varepsilon2 - varepsilon1)\right) + A32\cdot\left(varepsilon1 + \frac{1}{3}\cdot(varepsilon2 - varepsilon1)\right) + A41(\text{varepsilon})\cdot\left(\frac{1}{2}\cdot(\text{varepsilon} - varepsilon2) + varepsilon2\right) + A51(\text{varepsilon})\cdot\left(\frac{1}{3}\cdot(\text{varepsilon} - varepsilon2) + varepsilon2\right)\right)\cdot(h - x3)\right) \Big/ ((A12 + (A22 + A32) + (A41(\text{varepsilon}) + A51(\text{varepsilon})))\cdot\text{varepsilon}):$$

$$> z32(\text{varepsilon}) := \frac{2}{3}\cdot x3 + \left(\left(\frac{2}{3}\cdot A12\cdot varepsilon1 + A22\cdot\left(varepsilon1 + \frac{1}{2}\cdot(varepsilon2 - varepsilon1)\right) + A32\cdot\left(varepsilon1 + \frac{1}{3}\cdot(varepsilon2 - varepsilon1)\right) + A41(\text{varepsilon})\cdot\left(\frac{1}{2}\cdot(\text{varepsilon} - varepsilon2) + varepsilon2\right) + A51(\text{varepsilon})\cdot\left(\frac{2}{3}\cdot(\text{varepsilon} - varepsilon2) + varepsilon2\right)\right)\cdot(h - x3)\right) \Big/ ((A12 + (A22 + A32) + (A41(\text{varepsilon}) + A51(\text{varepsilon})))\cdot\text{varepsilon}):$$

$$> \textbf{if}\ (sigma2 > sigma3)\ \textbf{then}\ z3(\text{varepsilon}) := z31(\text{varepsilon})\ \textbf{else}\ z3(\text{varepsilon}) := z32(\text{varepsilon})\ \textbf{end if}:$$

$$> z41(\text{varepsilon}) := (1 - \text{beta}(\text{varepsilon}))\cdot x4 + \left(\left(\frac{2}{3}\cdot A12\cdot varepsilon1 + A22\cdot\left(varepsilon1 + \frac{1}{2}\cdot(varepsilon2 - varepsilon1)\right) + A32\cdot\left(varepsilon1 + \frac{1}{3}\cdot(varepsilon2 - varepsilon1)\right) + A41(\text{varepsilon})\cdot\left(\frac{1}{2}\cdot(\text{varepsilon} - varepsilon2) + varepsilon2\right) + A51(\text{varepsilon})\cdot\left(\frac{1}{3}\cdot(\text{varepsilon} - varepsilon2) + varepsilon2\right)\right)\cdot(h - x4)\right) \Big/ ((A12 + (A22 + A32) + (A41(\text{varepsilon}) + A51(\text{varepsilon})))\cdot\text{varepsilon}):$$

$$> z42(\text{varepsilon}) := (1 - \text{beta}(\text{varepsilon}))\cdot x4 + \Bigg(\Bigg(\frac{2}{3}\cdot A12\cdot varepsilon1 + A22\cdot\left(varepsilon1 + \frac{1}{2}\cdot(varepsilon2 - varepsilon1)\right) + A32\cdot\Bigg(varepsilon1 + \frac{1}{3}\cdot(varepsilon2$$

$- varepsilon1)\Big) + A41(\text{varepsilon}) \cdot \left(\frac{1}{2} \cdot (\text{varepsilon} - varepsilon2) + varepsilon2\right)$
$+ A51(\text{varepsilon}) \cdot \left(\frac{2}{3} \cdot (\text{varepsilon} - varepsilon2) + varepsilon2\right)\Big) \cdot (h - x4)\Big) \Big/ ((A12$
$+ (A22 + A32) + (A41(\text{varepsilon}) + A51(\text{varepsilon}))) \cdot \text{varepsilon}) :$

> **if** $(sigma2 > sigma3)$ **then** $z4(\text{varepsilon}) := z41(\text{varepsilon})$ **else** $z4(\text{varepsilon}) := z42(\text{varepsilon})$ **end if**:

> $z51(\text{varepsilon}) := (1 - \text{beta}(\text{varepsilon})) \cdot x5 + \Big(\Big(\frac{2}{3} \cdot A12 \cdot varepsilon1 + A22 \cdot \Big(varepsilon1 + \frac{1}{2} \cdot (varepsilon2 - varepsilon1)\Big) + A32 \cdot \Big(varepsilon1 + \frac{1}{3} \cdot (varepsilon2 - varepsilon1)\Big) + A41(\text{varepsilon}) \cdot \left(\frac{1}{2} \cdot (\text{varepsilon} - varepsilon2) + varepsilon2\right) + A51(\text{varepsilon}) \cdot \left(\frac{1}{3} \cdot (\text{varepsilon} - varepsilon2) + varepsilon2\right)\Big) \cdot (h - x5)\Big) \Big/ ((A12 + (A22 + A32) + (A41(\text{varepsilon}) + A51(\text{varepsilon}))) \cdot \text{varepsilon}) :$

> $z52(\text{varepsilon}) := (1 - \text{beta}(\text{varepsilon})) \cdot x5 + \Big(\Big(\frac{2}{3} \cdot A12 \cdot varepsilon1 + A22 \cdot \Big(varepsilon1 + \frac{1}{2} \cdot (varepsilon2 - varepsilon1)\Big) + A32 \cdot \Big(varepsilon1 + \frac{1}{3} \cdot (varepsilon2 - varepsilon1)\Big) + A41(\text{varepsilon}) \cdot \left(\frac{1}{2} \cdot (\text{varepsilon} - varepsilon2) + varepsilon2\right) + A51(\text{varepsilon}) \cdot \left(\frac{2}{3} \cdot (\text{varepsilon} - varepsilon2) + varepsilon2\right)\Big) \cdot (h - x5)\Big) \Big/ ((A12 + (A22 + A32) + (A41(\text{varepsilon}) + A51(\text{varepsilon}))) \cdot \text{varepsilon}) :$

> **if** $(sigma2 > sigma3)$ **then** $z5(\text{varepsilon}) := z51(\text{varepsilon})$ **else** $z5(\text{varepsilon}) := z52(\text{varepsilon})$ **end if**:

> *with*(*plots*) :

> *Z1* := *plot*(*z1*(varepsilon), varepsilon = 0.00000001 ..*varepsilon1*, *colour* = *blue*, *labels* = ['varepsilon','*z* [*mm*]'], *labeldirections* = ['*horizontal*','*vertical*']) :

> *Z2* := *plot*(*z2*(varepsilon), varepsilon = *varepsilon1* ..*varepsilon2*, *colour* = *blue*) :

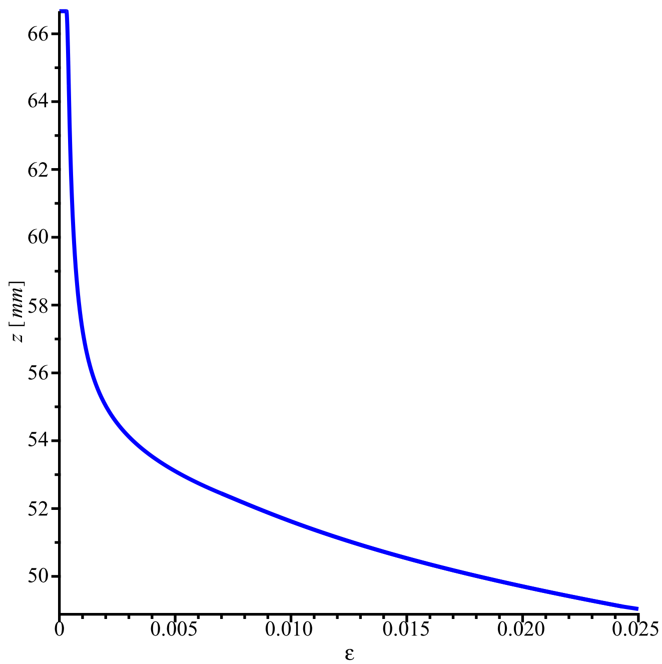
> *Z3* := *plot*(*z3*(varepsilon), varepsilon = *varepsilon2* ..*e0*, *colour* = *blue*) :

> *Z4* := *plot*(*z4*(varepsilon), varepsilon = *e0* ..*e01*, *colour* = *blue*) :

> *Z41* := *plot*(*z4*(varepsilon), varepsilon = *e0* ..*varepsilon3*, *colour* = *blue*) :

> *Z5* := *plot*(*z5*(varepsilon), varepsilon = *e01* ..*varepsilon3*, *colour* = *blue*) :

> *display*(*Z1*, *Z2*, *Z3*, *Z4*, *Z41*);



>

> $M1 := plot\left(\frac{z1(\text{varepsilon}) \cdot Fc1(\text{varepsilon})}{1000000}, \text{varepsilon} = 0.00000001 \,..varepsilon1, colour = blue, labels = \left[\text{'varepsilon'}, 'MRd\left[\frac{kNm}{m}\right]'\right], labeldirections = ['horizontal', 'vertical']\right):$

> $M2 := plot\left(\frac{z2(\text{varepsilon}) \cdot Fc2(\text{varepsilon})}{1000000}, \text{varepsilon} = varepsilon1 + 0.000001 \,..varepsilon2, colour = blue\right):$

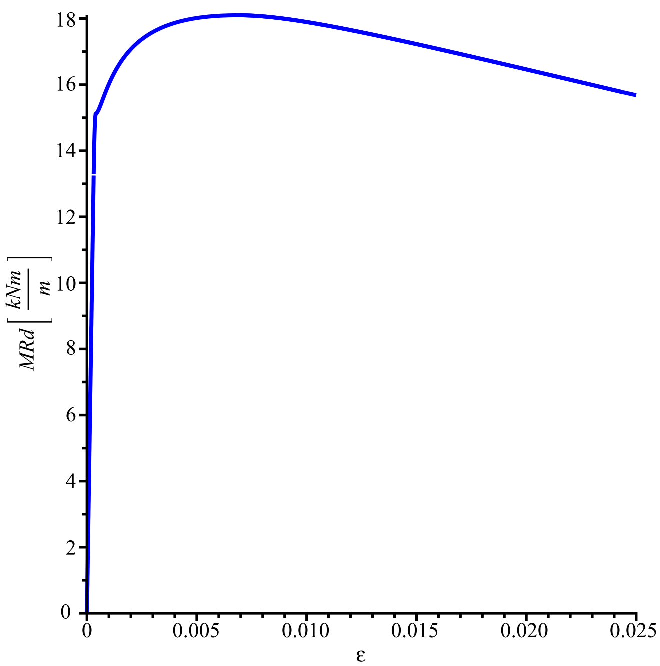
> $M3 := plot\left(\frac{z3(\text{varepsilon}) \cdot Fc3(\text{varepsilon})}{1000000}, \text{varepsilon} = varepsilon2 \,..e0, colour = blue\right):$

> $M4 := plot\left(\frac{z4(\text{varepsilon}) \cdot Ft4(\text{varepsilon})}{1000000}, \text{varepsilon} = e0 \,..e01, colour = blue\right):$

> $M41 := plot\left(\frac{z4(\text{varepsilon}) \cdot Ft4(\text{varepsilon})}{1000000}, \text{varepsilon} = e0 \,..varepsilon3, colour = blue\right):$

> $M5 := plot\left(\frac{z5(\text{varepsilon}) \cdot Fc5(\text{varepsilon})}{1000000}, \text{varepsilon} = e01 \,..varepsilon3, colour = blue\right):$

> $display(M1, M2, M3, M4, M41);$



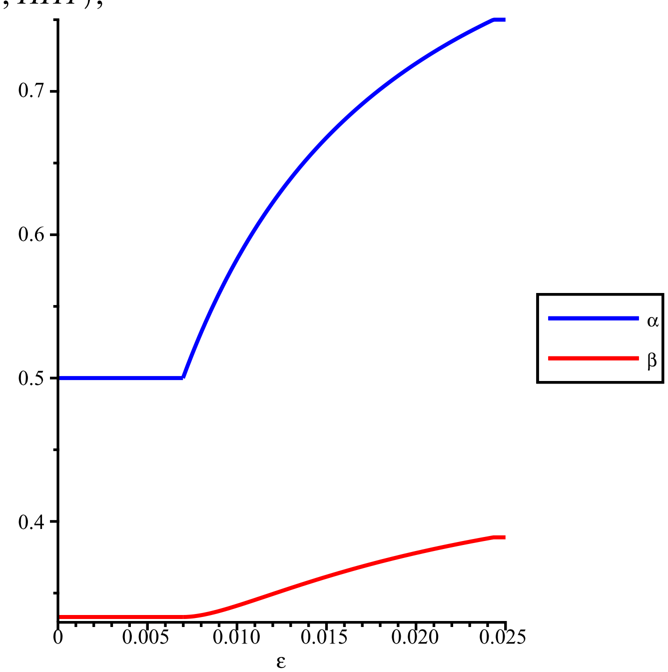
> $H := plot(\text{alpha}(\text{varepsilon}), \text{varepsilon} = e0 .. varepsilon3, colour = blue, legend = \text{'alpha'}, legendstyle = [location = right])$:

> $H1 := plot\left([0, e0], \left[\frac{1}{2}, \frac{1}{2}\right], colour = blue\right)$:

> $HH := plot(\text{beta}(\text{varepsilon}), \text{varepsilon} = e0 .. varepsilon3, colour = red, legend = \text{'beta'}, legendstyle = [location = right])$:

> $HH1 := plot\left([0, e0], \left[\frac{1}{3}, \frac{1}{3}\right], colour = red\right)$:

> $display(H, H1, HH, HH1);$



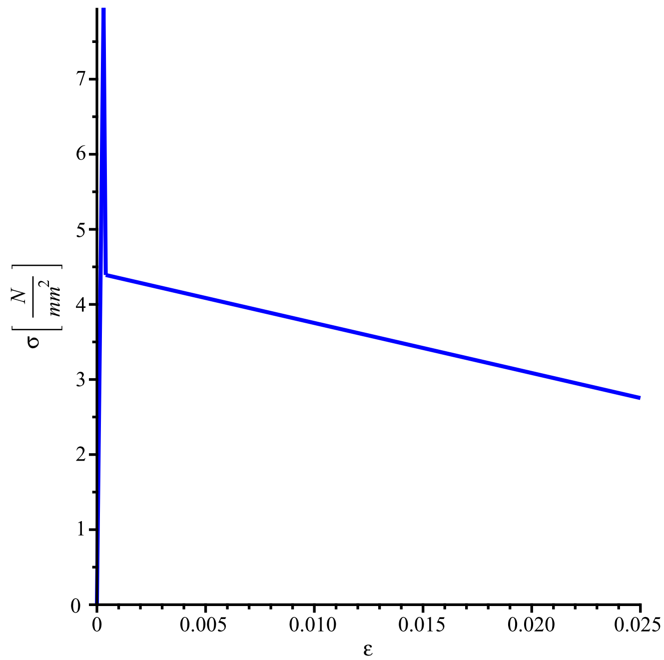
> $S1 := plot\left([0, varepsilon1], [0, sigma1], colour = blue, labels = \left[\text{'varepsilon','sigma}\left[\frac{N}{mm^2}\right]\text{'}\right],\right.$

$labeldirections = ['horizontal','vertical']\Big)$:

> $S2 := plot([varepsilon1, varepsilon2], [sigma1, sigma2], colour = blue)$:

> $S3 := plot([varepsilon2, varepsilon3], [sigma2, sigma3], colour = blue)$:

> $display(S1, S2, S3)$;



> varepsilon := $varepsilon1$;

$$\varepsilon := 0.0003055177198 \tag{9}$$

> $Mcr := \frac{z1(\text{varepsilon}) \cdot Fc1(\text{varepsilon})}{1000000}$;

$$Mcr := 13.25041667 \tag{10}$$

> varepsilon := $varepsilon2$;

$$\varepsilon := 0.0004055177198 \tag{11}$$

> $MSLS := \frac{z2(\text{varepsilon}) \cdot Fc2(\text{varepsilon})}{1000000}$;

$$MSLS := 15.12562857 \tag{12}$$

> varepsilon := $varepsilon3$;

$$\varepsilon := \frac{1}{40} \tag{13}$$

> $MULS := \frac{z4(\text{varepsilon}) \cdot Fc4(\text{varepsilon})}{1000000}$;

$$MULS := 15.60030317 \tag{14}$$

> $VRd := (vmin + vfd) \cdot b \cdot d; vmin := 0.035 \cdot k^{\frac{3}{2}} \cdot \mathrm{sqrt}(fck); vfd := 0.7 \cdot kf \cdot k \cdot tau1;$

$$VRd := 1000\ (vmin + vfd)\ d$$

$$vmin := 0.2678129011\ k^{3/2}$$

$$vfd := 0.7\ kf\ k\ \tau 1 \tag{15}$$

> $d := h$;

(16)

$$d := 100 \tag{16}$$

>

> $k := \min\left(1 + \mathrm{sqrt}\left(\frac{200}{d}\right), 2\right); kf := 1 : tau1 := 0.12 \cdot fR4;$

$$k := 2$$

$$\tau 1 := 0.8928 \tag{17}$$

> $\frac{evalf(VRd)}{1000}; evalf(vmin); vfd;$

$$200.7409274$$

$$0.7574892736$$

$$1.24992 \tag{18}$$

> $restart;$

> $ffctmfl := 7.60; fR1 := 8.45; fR2 := 11.62; fR3 := 11.41; fR4 := 8.92; fck := 80.5; fcd := \frac{fck}{1.5};$

$$ffctmfl := 7.60$$
$$fR1 := 8.45$$
$$fR2 := 11.62$$
$$fR3 := 11.41$$
$$fR4 := 8.92$$
$$fck := 80.5$$
$$fcd := 53.66666667 \quad \textbf{(1)}$$

> $h1 := 150; d1 := 125; b1 := 150; kh := 1;$

$$h1 := 150$$
$$d1 := 125$$
$$b1 := 150$$
$$kh := 1 \quad \textbf{(2)}$$

> $sigma1 := 0.7 \cdot ffctmfl \cdot \left(1.6 - \frac{d1}{1000}\right); sigma2 := 0.45 \cdot fR1 \cdot kh; sigma3 := 0.37 \cdot fR4 \cdot kh;$

$$\sigma 1 := 7.847000000$$
$$\sigma 2 := 3.8025$$
$$\sigma 3 := 3.3004 \quad \textbf{(3)}$$

> $Ec := \frac{fcd}{\frac{0.003}{2}}; Ecm := 22 \cdot \left(\frac{fck + 8}{10}\right)^{0.3} \cdot 1000;$

$$Ec := 35777.77778$$
$$Ecm := 42316.10266 \quad \textbf{(4)}$$

> $varepsilon1 := \frac{sigma1}{Ec}; varepsilon2 := varepsilon1 + \frac{0.1}{1000}; varepsilon3 := \frac{25}{1000};$

$$\varepsilon 1 := 0.0002193260869$$
$$\varepsilon 2 := 0.0003193260869$$
$$\varepsilon 3 := \frac{1}{40} \quad \textbf{(5)}$$

> $Ft1(\mathrm{varepsilon}) := 0.5 \cdot sigma1 \cdot b \cdot (h - x1) \cdot \left(\frac{\mathrm{varepsilon}}{varepsilon1}\right):$

> $Fc1(\mathrm{varepsilon}) := \left(\frac{0.5 \cdot b \cdot x1 \cdot Ec \cdot \mathrm{varepsilon} \cdot x1}{h - x1}\right):$

> $eq1 := Ft1(\mathrm{varepsilon}) = Fc1(\mathrm{varepsilon}):$

> $x1x := solve(eq1, x1):$

> $x1 := x1x:$

> $Ft2(\mathrm{varepsilon}) := 0.5 \cdot sigma1 \cdot b \cdot (h - x2) \cdot \left(\frac{varepsilon1}{\mathrm{varepsilon}}\right) + \frac{1}{\mathrm{varepsilon}} \Bigg(0.5 \cdot \Bigg(2 \cdot sigma1$
$- \frac{(sigma1 - sigma2) \cdot (\mathrm{varepsilon} - varepsilon1)}{varepsilon2 - varepsilon1}\Bigg) \cdot b \cdot (h - x2) \cdot (\mathrm{varepsilon}$

$- varepsilon1) \Big) :$

$> \ Fc2(\mathrm{varepsilon}) := \left(\frac{0.5 \cdot b \cdot x2 \cdot Ec \cdot \mathrm{varepsilon} \cdot x2}{h - x2} \right) :$

$> \ eq2 := Ft2(\mathrm{varepsilon}) = Fc2(\mathrm{varepsilon}) :$

$> \ x2x := solve(eq2, x2) :$

$> \ x2 := x2x[1] :$

$$> \ Ft3(\mathrm{varepsilon}) := \frac{0.5 \cdot sigma1 \cdot b \cdot (h - x3) \cdot varepsilon1}{\mathrm{varepsilon}} + \frac{0.5 \cdot (sigma1 + sigma2) \cdot b \cdot (h - x3) \cdot (varepsilon2 - varepsilon1)}{\mathrm{varepsilon}} + \frac{1}{\mathrm{varepsilon}} \left(0.5 \cdot \left(2 \cdot sigma2 - \frac{(sigma2 - sigma3) \cdot (\mathrm{varepsilon} - varepsilon2)}{varepsilon3 - varepsilon2} \right) \cdot b \cdot (h - x3) \cdot (\mathrm{varepsilon} - varepsilon2) \right) :$$

$> \ Fc3(\mathrm{varepsilon}) := \left(\frac{0.5 \cdot b \cdot x3 \cdot Ec \cdot \mathrm{varepsilon} \cdot x3}{h - x3} \right) :$

$> \ eq3 := Ft3(\mathrm{varepsilon}) = Fc3(\mathrm{varepsilon}) :$

$> \ x3x := solve(eq3, x3) :$

$> \ x3 := x3x[1] :$

$$> \ ec2(\mathrm{varepsilon}) := \frac{x2}{h - x2} \cdot \mathrm{varepsilon} : ec3(\mathrm{varepsilon}) := \frac{x3}{h - x3} \cdot \mathrm{varepsilon} : ec4(\mathrm{varepsilon}) := \frac{x4}{h - x4} \cdot \mathrm{varepsilon} :$$

$$> \ \mathrm{alpha}(\mathrm{varepsilon}) := \min\left(\frac{1}{ec4(\mathrm{varepsilon})} \cdot (ec4(\mathrm{varepsilon}) - 0.25 \cdot eu), 0.75 \right) :$$

$$> \ Ft4(\mathrm{varepsilon}) := \frac{0.5 \cdot sigma1 \cdot b \cdot (h - x4) \cdot varepsilon1}{\mathrm{varepsilon}} + \frac{0.5 \cdot (sigma1 + sigma2) \cdot b \cdot (h - x4) \cdot (varepsilon2 - varepsilon1)}{\mathrm{varepsilon}} + \frac{1}{\mathrm{varepsilon}} \left(0.5 \cdot \left(2 \cdot sigma2 - \frac{(sigma2 - sigma3) \cdot (\mathrm{varepsilon} - varepsilon2)}{varepsilon3 - varepsilon2} \right) \cdot b \cdot (h - x4) \cdot (\mathrm{varepsilon} - varepsilon2) \right) :$$

$> \ Fc4(\mathrm{varepsilon}) := \mathrm{alpha}(\mathrm{varepsilon}) \cdot b \cdot x4 \cdot fcd :$

$> \ eq4 := Ft4(\mathrm{varepsilon}) = Fc4(\mathrm{varepsilon}) :$

$> \ x4x := solve(eq4, x4) :$

Warning, solutions may have been lost

$> \ x4 := x4x[2] :$

$$> \ Ft5(\mathrm{varepsilon}) := \frac{0.5 \cdot sigma1 \cdot b \cdot (h - x5) \cdot varepsilon1}{\mathrm{varepsilon}} + \frac{0.5 \cdot (sigma1 + sigma2) \cdot b \cdot (h - x5) \cdot (varepsilon2 - varepsilon1)}{\mathrm{varepsilon}} + \frac{1}{\mathrm{varepsilon}} \left(0.5 \cdot \left(2 \cdot sigma2 - \frac{(sigma2 - sigma3) \cdot (\mathrm{varepsilon} - varepsilon2)}{varepsilon3 - varepsilon2} \right) \cdot b \cdot (h - x5) \cdot (\mathrm{varepsilon} - varepsilon2) \right) :$$

> $Fc5(\text{varepsilon}) := 0.75 \cdot b \cdot x5 \cdot fcd$:

> $eq5 := Ft5(\text{varepsilon}) = Fc5(\text{varepsilon})$:

> $x5 := solve(eq5, x5)$:

> $h := 100;\ b := 1000;\ eu := 0.003;$

$$h := 100$$
$$b := 1000$$
$$eu := 0.003 \tag{6}$$

> $eq0 := ec3(\text{varepsilon}) = \frac{eu}{2}$:

> $e0x := solve(eq0, \text{varepsilon})$:

> $e0 := e0x[2];$

$$e0 := 0.01081994020 \tag{7}$$

> $eq01 := ec4(\text{varepsilon}) = eu$:

> $e01x := solve(eq01, \text{varepsilon})$:

> $e01 := e01x[2];$

$$e01 := 0.03489283987 \tag{8}$$

> $with(plots)$:

> $B1 := plot([0, varepsilon1 + 0.000001], [x1, x1], colour = blue, labels = [\text{'varepsilon'}, \text{'}xu\ [mm]\text{'}], labeldirections = [\text{'}horizontal\text{'}, \text{'}vertical\text{'}])$:

> $B2 := plot(x2, \text{varepsilon} = varepsilon1 + 0.000001\ ..varepsilon2, colour = blue)$:

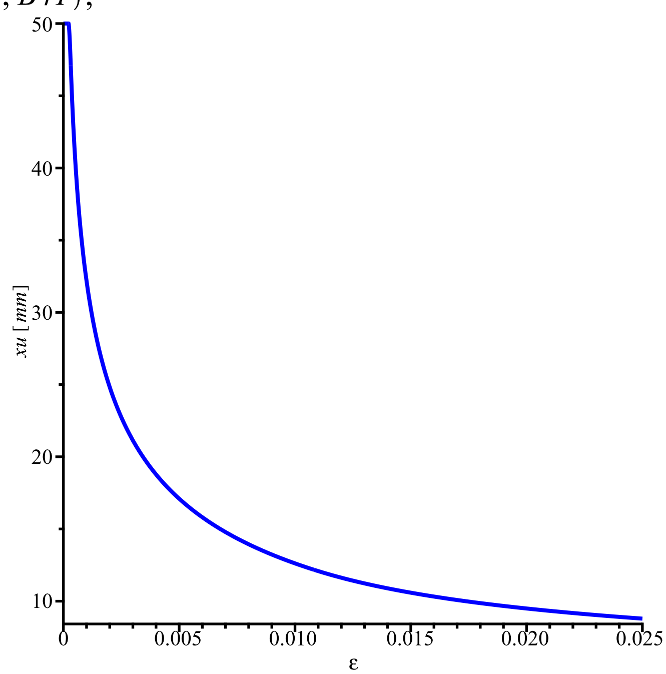
> $B3 := plot(x3, \text{varepsilon} = varepsilon2\ ..e0, colour = blue)$:

> $B4 := plot(x4, \text{varepsilon} = e0\ ..e01, colour = blue)$:

> $B41 := plot(x4, \text{varepsilon} = e0\ ..varepsilon3, colour = blue)$:

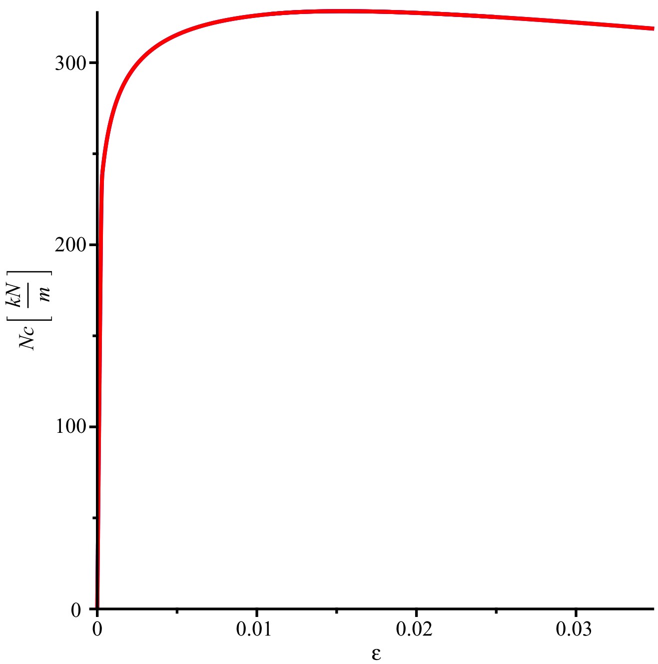
> $B5 := plot(x5, \text{varepsilon} = e01\ ..varepsilon3, colour = blue)$:

> $display(B1, B2, B3, B41);$



> $A := plot\left(\frac{Ft1(\text{varepsilon})}{1000}, \text{varepsilon} = 0\ ..varepsilon1 + 0.000001, colour = blue\right)$:

```
> AA := plot(Fc1(varepsilon)/1000, varepsilon = 0 .. varepsilon1 + 0.000001, colour = red) :
> C := plot(Ft2(varepsilon)/1000, varepsilon = varepsilon1 + 0.000001 .. varepsilon2, colour
      = blue) :
> CC := plot(Fc2(varepsilon)/1000, varepsilon = varepsilon1 + 0.000001 .. varepsilon2, colour
      = red) :
> F := plot(Ft3(varepsilon)/1000, varepsilon = varepsilon2 .. e0, colour = blue) :
> FF := plot(Fc3(varepsilon)/1000, varepsilon = varepsilon2 .. e0, colour = red) :
> G := plot(Ft4(varepsilon)/1000, varepsilon = e0 .. e01, colour = blue) :
> G1 := plot(Ft4(varepsilon)/1000, varepsilon = e0 .. varepsilon3, colour = blue) :
> GG := plot(Fc4(varepsilon)/1000, varepsilon = e0 .. e01, colour = red) :
> GG1 := plot(Fc4(varepsilon)/1000, varepsilon = e0 .. varepsilon3, colour = red) :
> GGG := plot(Ft5(varepsilon)/1000, varepsilon = e01 .. varepsilon3, colour = blue) :
> GGGG := plot(Fc5(varepsilon)/1000, varepsilon = e01 .. varepsilon3, colour = red) :
> display(C, CC) :
> display(A, AA, C, CC, F, FF, G, GG, G1, GG1, labels = ['varepsilon','Nc [kN/m]'], labeldirections
      = ['horizontal','vertical']);
```



> $A11(\text{varepsilon}) := \dfrac{sigma1 \cdot 0.5 \cdot \text{varepsilon} \cdot \text{varepsilon}}{varepsilon1}$:

> $A12 := 0.5 \cdot sigma1 \cdot varepsilon1$:

> $sigma21(\text{varepsilon}) := sigma1 - \dfrac{(sigma1 - sigma2) \cdot (\text{varepsilon} - varepsilon1)}{varepsilon2 - varepsilon1}$:

> $A21(\text{varepsilon}) := sigma21(\text{varepsilon}) \cdot (\text{varepsilon} - varepsilon1)$:

> $A22 := sigma2 \cdot (varepsilon2 - varepsilon1)$:

> $A31(\text{varepsilon}) := 0.5 \cdot (sigma1 - sigma21(\text{varepsilon})) \cdot (\text{varepsilon} - varepsilon1)$:

> $A32 := 0.5 \cdot (sigma1 - sigma2) \cdot (varepsilon2 - varepsilon1)$:

> $sigma31(\text{varepsilon}) := sigma2 - \dfrac{(sigma2 - sigma3) \cdot (\text{varepsilon} - varepsilon2)}{varepsilon3 - varepsilon2}$:

> $sigma32(\text{varepsilon}) := sigma2 + \dfrac{(sigma2 - sigma3) \cdot (\text{varepsilon} - varepsilon2)}{varepsilon3 - varepsilon2}$:

> **if** $(sigma2 > sigma3)$ **then** $sigma4(\text{varepsilon}) := sigma31(\text{varepsilon})$
else $sigma4(\text{varepsilon}) := sigma32(\text{varepsilon})$ **end if**:

> $A41(\text{varepsilon}) := sigma2 \cdot (\text{varepsilon} - varepsilon2)$:

> $A51(\text{varepsilon}) := 0.5 \cdot \text{abs}(sigma2 - sigma4(\text{varepsilon})) \cdot (\text{varepsilon} - varepsilon2)$:

> $\text{beta}(\text{varepsilon}) :=$

$$\min\left(\frac{1}{\left(ec4(\text{varepsilon}) - \frac{1}{2} \cdot eu\right) + \frac{1}{4} \cdot eu}\left(\frac{\left(ec4(\text{varepsilon}) - \frac{1}{2} \cdot eu\right) \cdot 1}{2} \cdot \left(ec4(\text{varepsilon}) - \frac{1}{2} \cdot eu\right) + \frac{1}{4} \cdot eu \cdot \left(\frac{1}{6} \cdot eu + \left(ec4(\text{varepsilon}) - \frac{1}{2} \cdot eu\right)\right)\right)\right.$$

$$\cdot \frac{1}{ec4(\text{varepsilon})}, \frac{7}{18}\Bigg):$$

$$> z1(\text{varepsilon}) := \frac{\left(\frac{(h - x1)\cdot 2}{3} + \frac{x1\cdot 2}{3}\right)\cdot \text{varepsilon}}{\text{varepsilon}}:$$

$$> z2(\text{varepsilon}) := \frac{2}{3}\cdot x2 + \left(\left(\left(\frac{2}{3}\cdot A12\cdot varepsilon1 + A21(\text{varepsilon})\cdot\left(\frac{1}{2}\cdot(\text{varepsilon} - varepsilon1) + varepsilon1\right) + A31(\text{varepsilon})\cdot\left(\frac{1}{3}\cdot(\text{varepsilon} - varepsilon1) + varepsilon1\right)\right)\right)\cdot(h - x2)\right) \Big/ ((A12 + A21(\text{varepsilon}) + A31(\text{varepsilon}))\cdot \text{varepsilon}):$$

$$> z31(\text{varepsilon}) := \frac{2}{3}\cdot x3 + \left(\left(\left(\frac{2}{3}\cdot A12\cdot varepsilon1 + A22\cdot\left(varepsilon1 + \frac{1}{2}\cdot(varepsilon2 - varepsilon1)\right) + A32\cdot\left(varepsilon1 + \frac{1}{3}\cdot(varepsilon2 - varepsilon1)\right) + A41(\text{varepsilon})\cdot\left(\frac{1}{2}\cdot(\text{varepsilon} - varepsilon2) + varepsilon2\right) + A51(\text{varepsilon})\cdot\left(\frac{1}{3}\cdot(\text{varepsilon} - varepsilon2) + varepsilon2\right)\right)\right)\cdot(h - x3)\right) \Big/ ((A12 + (A22 + A32) + (A41(\text{varepsilon}) + A51(\text{varepsilon})))\cdot \text{varepsilon}):$$

$$> z32(\text{varepsilon}) := \frac{2}{3}\cdot x3 + \left(\left(\left(\frac{2}{3}\cdot A12\cdot varepsilon1 + A22\cdot\left(varepsilon1 + \frac{1}{2}\cdot(varepsilon2 - varepsilon1)\right) + A32\cdot\left(varepsilon1 + \frac{1}{3}\cdot(varepsilon2 - varepsilon1)\right) + A41(\text{varepsilon})\cdot\left(\frac{1}{2}\cdot(\text{varepsilon} - varepsilon2) + varepsilon2\right) + A51(\text{varepsilon})\cdot\left(\frac{2}{3}\cdot(\text{varepsilon} - varepsilon2) + varepsilon2\right)\right)\right)\cdot(h - x3)\right) \Big/ ((A12 + (A22 + A32) + (A41(\text{varepsilon}) + A51(\text{varepsilon})))\cdot \text{varepsilon}):$$

> **if** $(sigma2 > sigma3)$ **then** $z3(\text{varepsilon}) := z31(\text{varepsilon})$ **else** $z3(\text{varepsilon}) := z32(\text{varepsilon})$ **end if**:

$$> z41(\text{varepsilon}) := (1 - \text{beta}(\text{varepsilon}))\cdot x4 + \left(\left(\left(\frac{2}{3}\cdot A12\cdot varepsilon1 + A22\cdot\left(varepsilon1 + \frac{1}{2}\cdot(varepsilon2 - varepsilon1)\right) + A32\cdot\left(varepsilon1 + \frac{1}{3}\cdot(varepsilon2 - varepsilon1)\right) + A41(\text{varepsilon})\cdot\left(\frac{1}{2}\cdot(\text{varepsilon} - varepsilon2) + varepsilon2\right) + A51(\text{varepsilon})\cdot\left(\frac{1}{3}\cdot(\text{varepsilon} - varepsilon2) + varepsilon2\right)\right)\right)\cdot(h - x4)\right) \Big/ ((A12 + (A22 + A32) + (A41(\text{varepsilon}) + A51(\text{varepsilon})))\cdot \text{varepsilon}):$$

$$> z42(\text{varepsilon}) := (1 - \text{beta}(\text{varepsilon}))\cdot x4 + \left(\left(\left(\frac{2}{3}\cdot A12\cdot varepsilon1 + A22\cdot\left(varepsilon1 + \frac{1}{2}\cdot(varepsilon2 - varepsilon1)\right) + A32\cdot\left(varepsilon1 + \frac{1}{3}\cdot(varepsilon2\right.\right.\right.\right.$$

$- varepsilon1)\Big) + A41(\text{varepsilon})\cdot\left(\frac{1}{2}\cdot(\text{varepsilon} - varepsilon2) + varepsilon2\right)$
$+ A51(\text{varepsilon})\cdot\left(\frac{2}{3}\cdot(\text{varepsilon} - varepsilon2) + varepsilon2\right)\Big)\cdot(h - x4)\Big) \Big/ ((A12$
$+ (A22 + A32) + (A41(\text{varepsilon}) + A51(\text{varepsilon})))\cdot\text{varepsilon})$:

> **if** $(sigma2 > sigma3)$ **then** $z4(\text{varepsilon}) := z41(\text{varepsilon})$ **else** $z4(\text{varepsilon}) :=$
> $z42(\text{varepsilon})$ **end if**:

> $z51(\text{varepsilon}) := (1 - \text{beta}(\text{varepsilon}))\cdot x5 + \Big(\Big(\frac{2}{3}\cdot A12\cdot varepsilon1 + A22\cdot\Big(varepsilon1$
> $+ \frac{1}{2}\cdot(varepsilon2 - varepsilon1)\Big) + A32\cdot\Big(varepsilon1 + \frac{1}{3}\cdot(varepsilon2$
> $- varepsilon1)\Big) + A41(\text{varepsilon})\cdot\left(\frac{1}{2}\cdot(\text{varepsilon} - varepsilon2) + varepsilon2\right)$
> $+ A51(\text{varepsilon})\cdot\left(\frac{1}{3}\cdot(\text{varepsilon} - varepsilon2) + varepsilon2\right)\Big)\cdot(h - x5)\Big) \Big/ ((A12$
> $+ (A22 + A32) + (A41(\text{varepsilon}) + A51(\text{varepsilon})))\cdot\text{varepsilon})$:

> $z52(\text{varepsilon}) := (1 - \text{beta}(\text{varepsilon}))\cdot x5 + \Big(\Big(\frac{2}{3}\cdot A12\cdot varepsilon1 + A22\cdot\Big(varepsilon1$
> $+ \frac{1}{2}\cdot(varepsilon2 - varepsilon1)\Big) + A32\cdot\Big(varepsilon1 + \frac{1}{3}\cdot(varepsilon2$
> $- varepsilon1)\Big) + A41(\text{varepsilon})\cdot\left(\frac{1}{2}\cdot(\text{varepsilon} - varepsilon2) + varepsilon2\right)$
> $+ A51(\text{varepsilon})\cdot\left(\frac{2}{3}\cdot(\text{varepsilon} - varepsilon2) + varepsilon2\right)\Big)\cdot(h - x5)\Big) \Big/ ((A12$
> $+ (A22 + A32) + (A41(\text{varepsilon}) + A51(\text{varepsilon})))\cdot\text{varepsilon})$:

> **if** $(sigma2 > sigma3)$ **then** $z5(\text{varepsilon}) := z51(\text{varepsilon})$ **else** $z5(\text{varepsilon}) :=$
> $z52(\text{varepsilon})$ **end if**:

> *with*(*plots*) :

> $Z1 := plot(z1(\text{varepsilon}), \text{varepsilon} = 0.00000001 ..varepsilon1, colour = blue, labels = [$
> 'varepsilon','z [mm]'], labeldirections = ['horizontal','vertical']) :

> $Z2 := plot(z2(\text{varepsilon}), \text{varepsilon} = varepsilon1 ..varepsilon2, colour = blue)$:

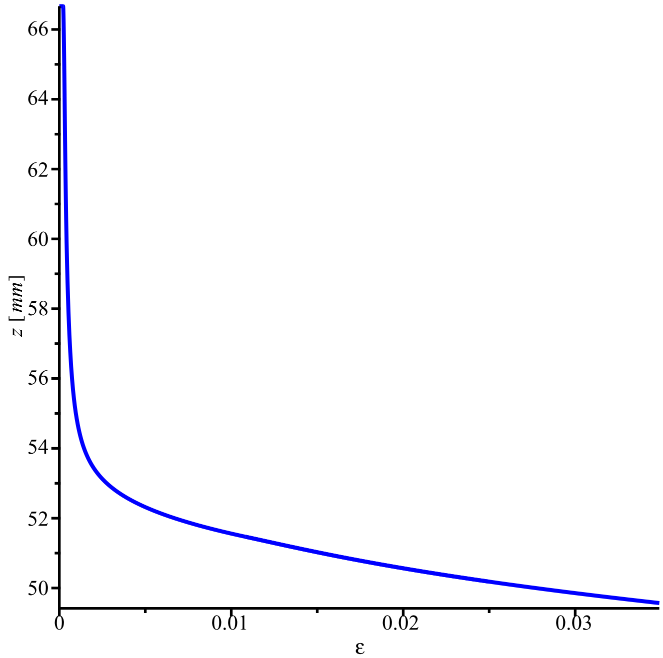
> $Z3 := plot(z3(\text{varepsilon}), \text{varepsilon} = varepsilon2 ..e0, colour = blue)$:

> $Z4 := plot(z4(\text{varepsilon}), \text{varepsilon} = e0 ..e01, colour = blue)$:

> $Z41 := plot(z4(\text{varepsilon}), \text{varepsilon} = e0 ..varepsilon3, colour = blue)$:

> $Z5 := plot(z5(\text{varepsilon}), \text{varepsilon} = e01 ..varepsilon3, colour = blue)$:

> $display(Z1, Z2, Z3, Z4, Z41)$;



>

> $M1 := plot\left(\frac{z1(\text{varepsilon}) \cdot Fc1(\text{varepsilon})}{1000000}, \text{varepsilon} = 0.00000001 \,..varepsilon1, colour = blue, labels = \left[\text{'varepsilon'}, 'MRd\left[\frac{kNm}{m}\right]'\right], labeldirections = [\text{'horizontal'}, \text{'vertical'}]\right):$

> $M2 := plot\left(\frac{z2(\text{varepsilon}) \cdot Fc2(\text{varepsilon})}{1000000}, \text{varepsilon} = varepsilon1 + 0.000001 \,..varepsilon2, colour = blue\right):$

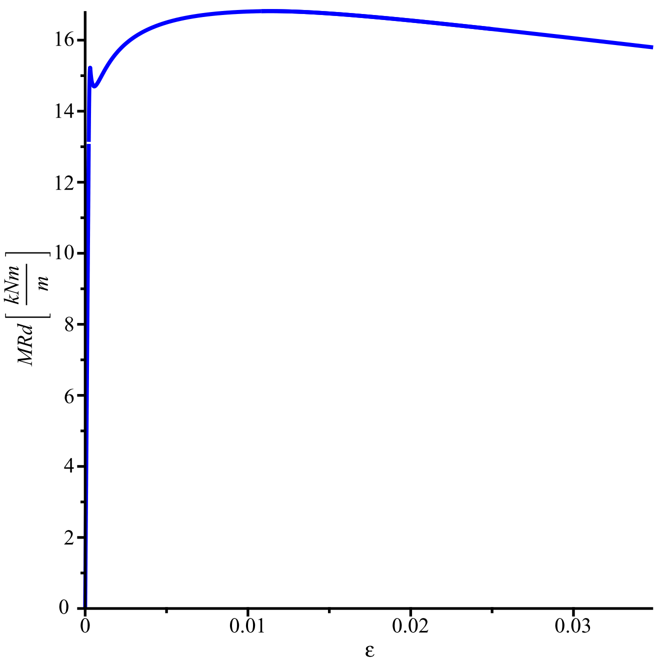
> $M3 := plot\left(\frac{z3(\text{varepsilon}) \cdot Fc3(\text{varepsilon})}{1000000}, \text{varepsilon} = varepsilon2 \,..e0, colour = blue\right):$

> $M4 := plot\left(\frac{z4(\text{varepsilon}) \cdot Ft4(\text{varepsilon})}{1000000}, \text{varepsilon} = e0 \,..e01, colour = blue\right):$

> $M41 := plot\left(\frac{z4(\text{varepsilon}) \cdot Ft4(\text{varepsilon})}{1000000}, \text{varepsilon} = e0 \,..varepsilon3, colour = blue\right):$

> $M5 := plot\left(\frac{z5(\text{varepsilon}) \cdot Fc5(\text{varepsilon})}{1000000}, \text{varepsilon} = e01 \,..varepsilon3, colour = blue\right):$

> $display(M1, M2, M3, M4, M41);$



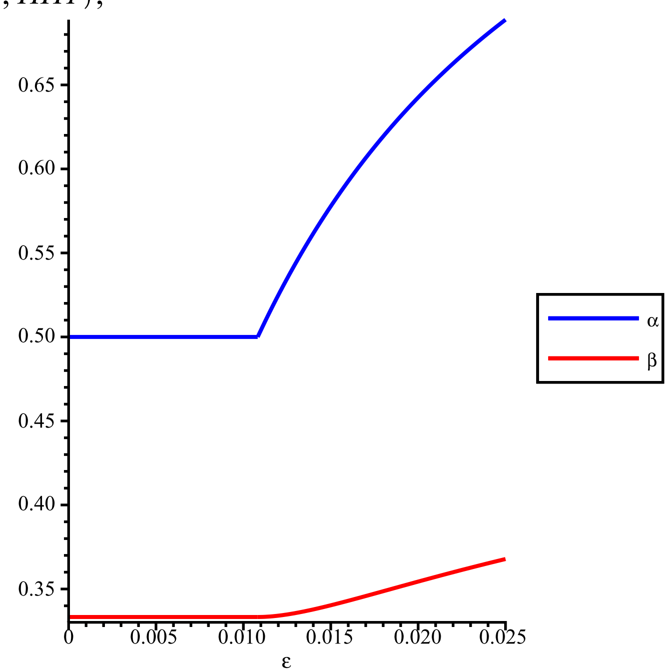
> $H := plot(\alpha(\varepsilon), \varepsilon = e0 .. \varepsilon 3, colour = blue, legend = \text{'alpha'}, legendstyle = [location = right])$:

> $H1 := plot\left([0, e0], \left[\frac{1}{2}, \frac{1}{2}\right], colour = blue\right)$:

> $HH := plot(\beta(\varepsilon), \varepsilon = e0 .. \varepsilon 3, colour = red, legend = \text{'beta'}, legendstyle = [location = right])$:

> $HH1 := plot\left([0, e0], \left[\frac{1}{3}, \frac{1}{3}\right], colour = red\right)$:

> $display(H, H1, HH, HH1);$



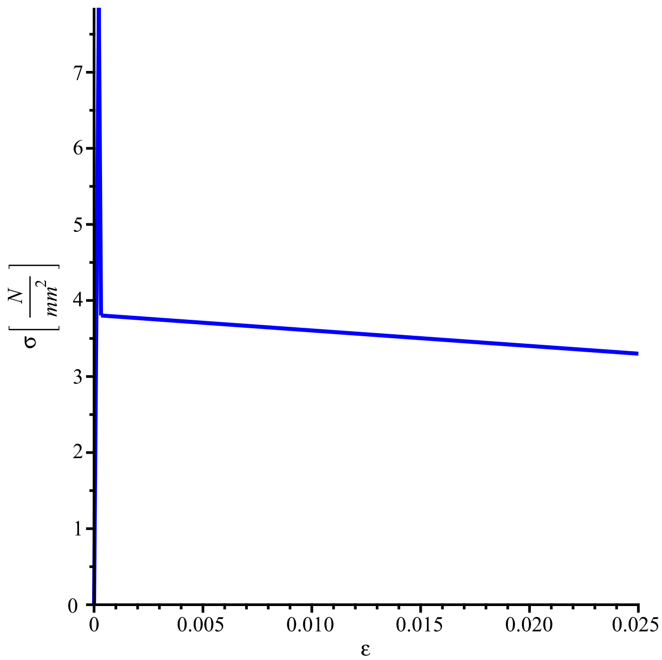
> $S1 := plot\left([0, \varepsilon 1], [0, \sigma 1], colour = blue, labels = \left[\text{'varepsilon'},\text{'sigma}\left[\frac{N}{mm^2}\right]\text{'}\right],\right.$

$labeldirections = ['horizontal','vertical']\Big)$:

> $S2 := plot([varepsilon1, varepsilon2], [sigma1, sigma2], colour = blue)$:

> $S3 := plot([varepsilon2, varepsilon3], [sigma2, sigma3], colour = blue)$:

> $display(S1, S2, S3);$



> varepsilon $:= varepsilon1;$

$$\varepsilon := 0.0002193260869 \tag{9}$$

> $Mcr := \frac{z1(\text{varepsilon}) \cdot Fc1(\text{varepsilon})}{1000000};$

$$Mcr := 13.07833334 \tag{10}$$

> varepsilon $:= varepsilon2;$

$$\varepsilon := 0.0003193260869 \tag{11}$$

> $MSLS := \frac{z2(\text{varepsilon}) \cdot Fc2(\text{varepsilon})}{1000000};$

$$MSLS := 15.17913390 \tag{12}$$

> varepsilon $:= varepsilon3;$

$$\varepsilon := \frac{1}{40} \tag{13}$$

> $MULS := \frac{z4(\text{varepsilon}) \cdot Fc4(\text{varepsilon})}{1000000};$

$$MULS := 16.31128149 \tag{14}$$

> $VRd := (vmin + vfd) \cdot b \cdot d; vmin := 0.035 \cdot k^{\frac{3}{2}} \cdot \text{sqrt}(fck); vfd := 0.7 \cdot kf \cdot k \cdot tau1;$

$$VRd := 1000\ (vmin + vfd)\ d$$

$$vmin := 0.3140262728\ k^{3/2}$$

$$vfd := 0.7\ kf\ k\ \tau1 \tag{15}$$

> $d := h;$

(16)

$$d := 100 \tag{16}$$

>

> $k := \min\left(1 + \mathrm{sqrt}\left(\frac{200}{d}\right), 2\right); kf := 1 : tau1 := 0.12 \cdot fR4;$

$$k := 2$$

$$\tau 1 := 1.0704 \tag{17}$$

> $\frac{evalf(VRd)}{1000}; evalf(vmin); vfd;$

$$238.6760428$$

$$0.8882004276$$

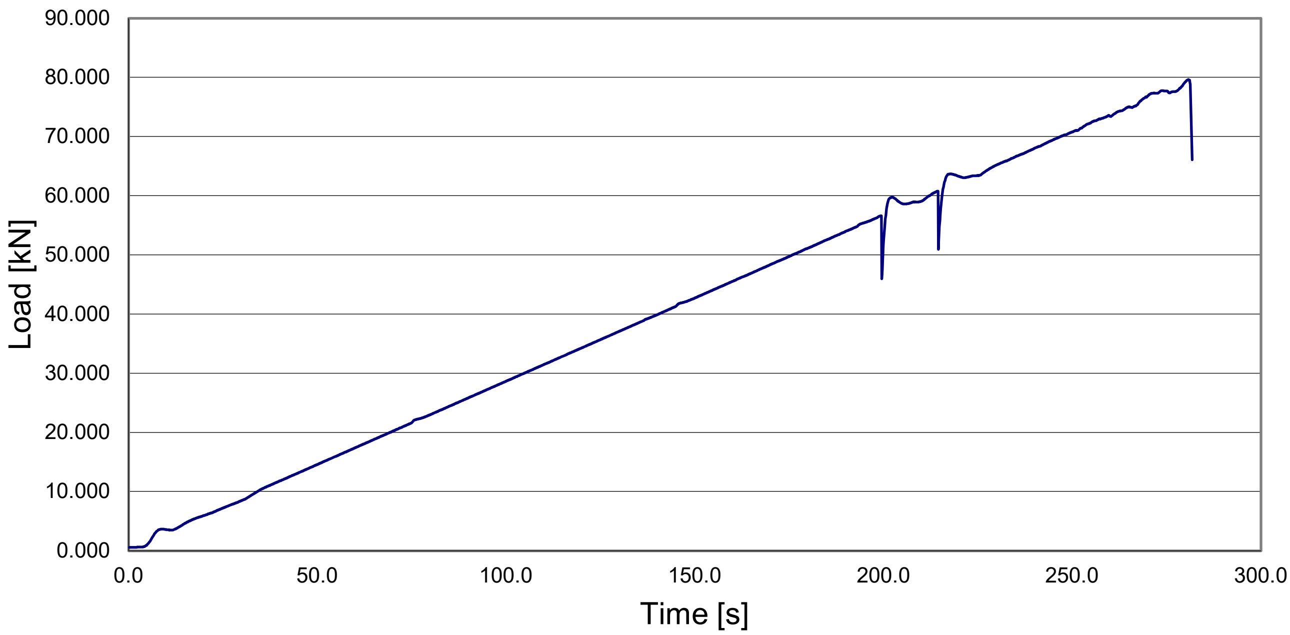
$$1.49856 \tag{18}$$

Appendix E Extra experiments with hybrid variants

Flexural tests on beams: EN 12390-5

Certificate number	:	001-4PBH-RT15-2x6-T			Certificate date	:	-------
Testing machine	:	C1701/FR s.n. 22000858					
Client	:						
Reference	:						
Specimen type	:	Beam			Cement quantity [kg/m³]	:	
Cement type	:				Test date	:	29/06/2022
Sample conditions:							
Condition when received	:				Condition at test time	:	
Sampling location	:				Sampling date	:	-------
Preparation method	:						
Specimen ID	:						
Dimensions	:	*b(mm)*	: 150.00	*h(mm)* : 150.00	Mass [kg]	:	0.000
		l(mm)	800			:	
Load Rate [MPa/s]	:	0.1		No of upper roll 2	"L" distance [mm]		600.0
Area [mm2]	:	5625.0	Specimen age	: 28 dd	Preparation date	:	-------
Load [kN]	:	79.64			Strength [MPa]	:	14.16
	:						
Notes	:						

(kN)

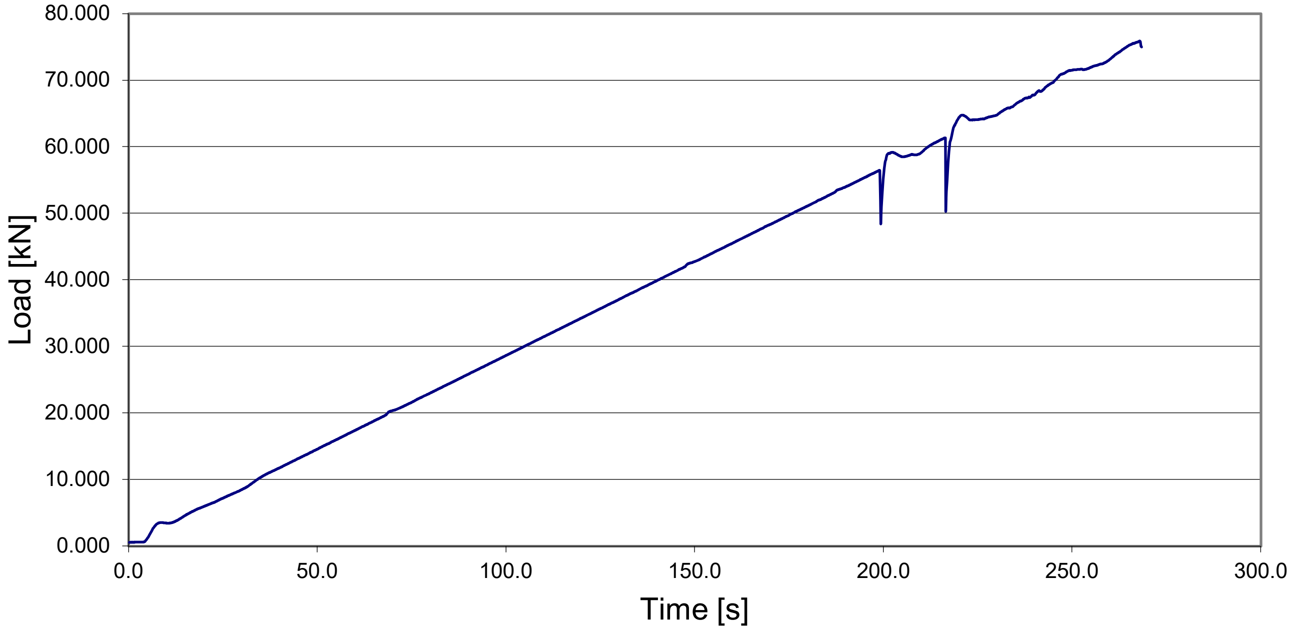


Operator

Operator01

Flexural tests on beams: EN 12390-5

Certificate number	: 002-4PBH-RT15-2x6-T			Certificate date	: -------
Testing machine	: C1701/FR s.n. 22000858				
Client	:				
Reference	:				
Specimen type	: Beam			Cement quantity [kg/m³]	:
Cement type	:			Test date	: 29/06/2022
Sample conditions:					
Condition when received	:			Condition at test time	:
Sampling location	:			Sampling date	: -------
Preparation method	:				
Specimen ID	:				
Dimensions	: *b(mm)*	: 150.00 *h(mm)*	: 150.00	Mass [kg]	: 0.000
	l(mm)	800			:
Load Rate [MPa/s]	: 0.1		No of upper roll 2	"L" distance [mm]	600.0
Area [mm2]	: 5625.0	Specimen age	: 28 dd	Preparation date	: -------
Load [kN]	: 75.88			Strength [MPa]	: 13.49
	:				
Notes	:				

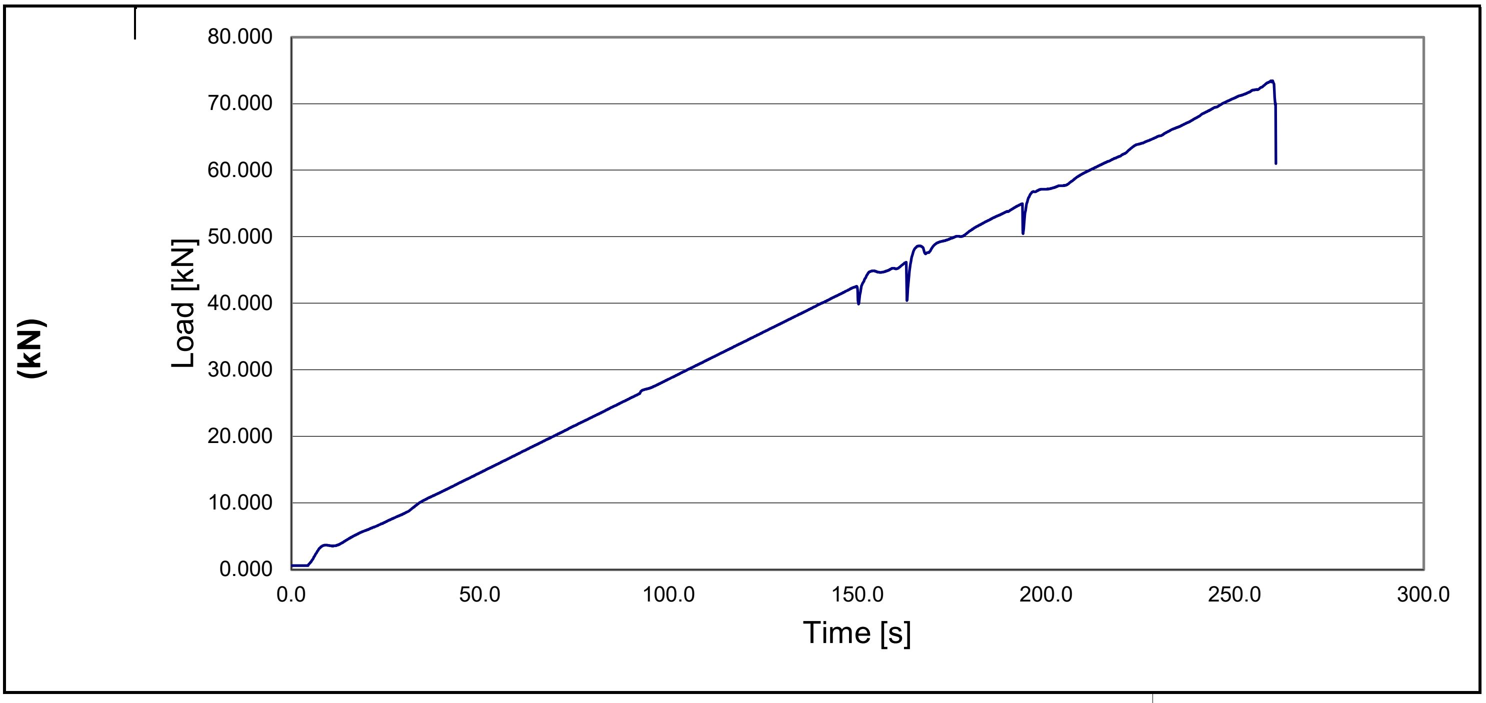


Operator

Operator01

Flexural tests on beams: EN 12390-5

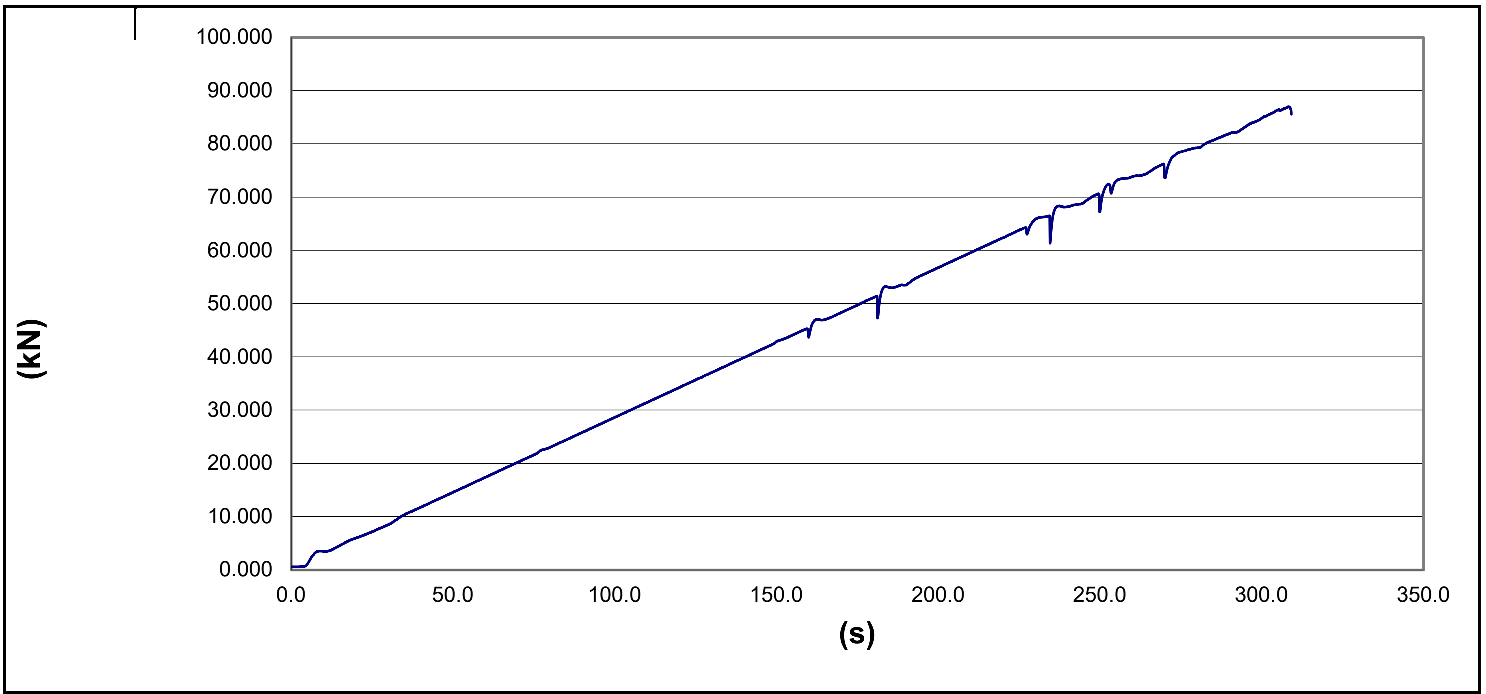
Certificate number	: 001-4PBH-RT30-2x6-T			Certificate date	: -------
Testing machine	: C1701/FR s.n. 22000858				
Client	:				
Reference	:				
Specimen type	: Beam			Cement quantity [kg/m³]	:
Cement type	:			Test date	: 29/06/2022
Sample conditions:					
Condition when received	:			Condition at test time	:
Sampling location	:			Sampling date	: -------
Preparation method	:				
Specimen ID	:				
Dimensions	: *b(mm)*	: 150.00	*h(mm)* : 150.00	Mass [kg]	: 0.000
	l(mm)	800			:
Load Rate [MPa/s]	: 0.1		No of upper roll 2	"L" distance [mm]	600.0
Area [mm2]	: 5625.0	Specimen age	: 28 dd	Preparation date	: -------
Load [kN]	: 73.46			Strength [MPa]	: 13.06
	:				
Notes	:				



Operator
Operator01

Flexural tests on beams: EN 12390-5

Certificate number	:	002-4PBH-RT30-2x6-T			Certificate date :	-------
Testing machine	:	C1701/FR s.n. 22000858				
Client	:					
Reference	:					
Specimen type	:	Beam			Cement quantity [kg/m³] :	
Cement type	:				Test date :	29/06/2022
Sample conditions:						
Condition when received	:				Condition at test time :	
Sampling location	:				Sampling date :	-------
Preparation method	:					
Specimen ID	:					
Dimensions	:	*b(mm)*	: 150.00	*h(mm)* : 150.00	Mass [kg] :	0.000
		l(mm)	800		:	
Load Rate [MPa/s]	:	0.1		No of upper roll 2	"L" distance [mm]	600.0
Area [mm2]	:	5625.0	Specimen age	: 28 dd	Preparation date :	-------
Load [kN]	:	86.97			Strength [MPa] :	15.46
	:					
Notes	:					

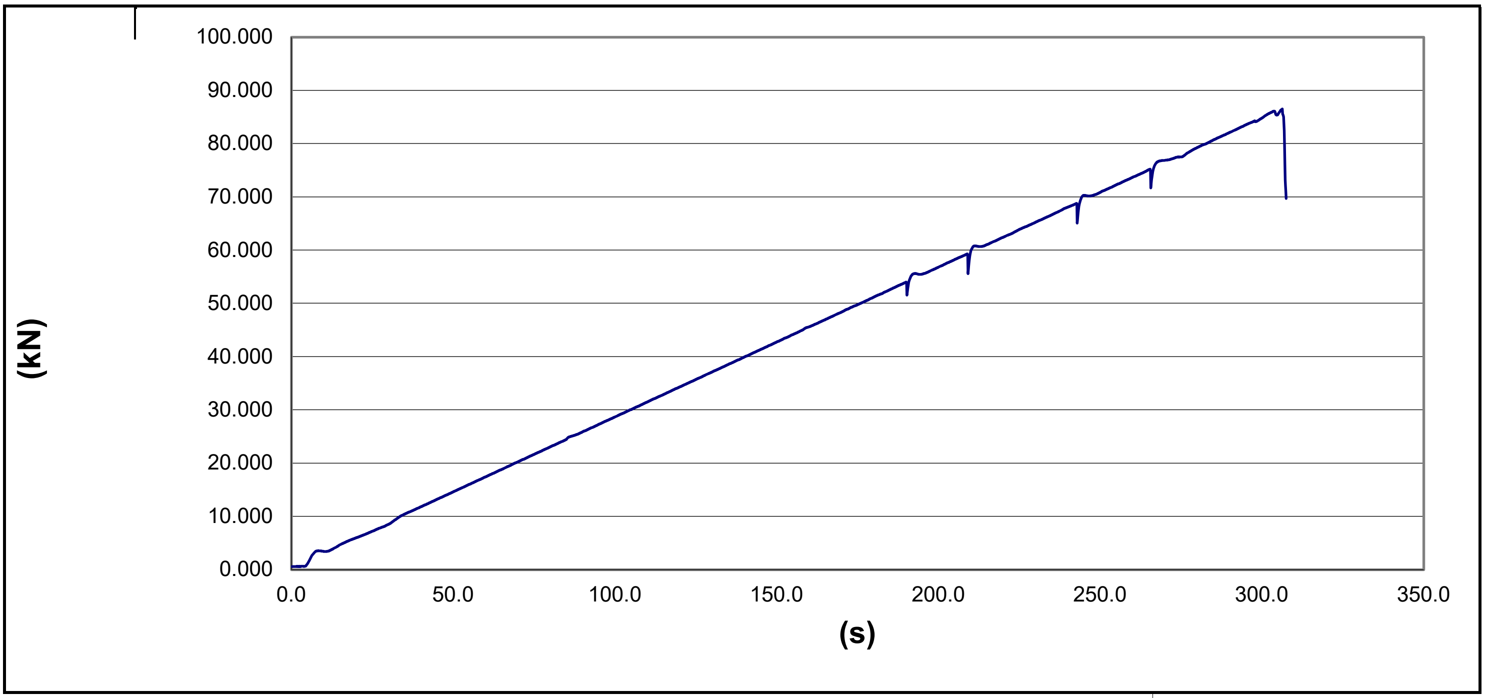


Operator

Operator01

Flexural tests on beams: EN 12390-5

Certificate number	: 002-4PBH-SV40-2x6-T				Certificate date	:	-------
Testing machine	: C1701/FR s.n. 22000858						
Client	:						
Reference	:						
Specimen type	: Beam				Cement quantity [kg/m³]	:	
Cement type	:				Test date	:	29/06/2022
Sample conditions:							
Condition when received	:				Condition at test time	:	
Sampling location	:				Sampling date	:	-------
Preparation method	:						
Specimen ID	:						
Dimensions	: *b(mm)*	: 150.00	*h(mm)*	: 150.00	Mass [kg]	:	0.000
	l(mm)	800				:	
Load Rate [MPa/s]	: 0.1		No of upper roll	2	"L" distance [mm]		600.0
Area [mm2]	: 5625.0	Specimen age	: 28 dd		Preparation date	:	-------
Load [kN]	: 86.515				Strength [MPa]	:	15.381
	:						
Notes	:						

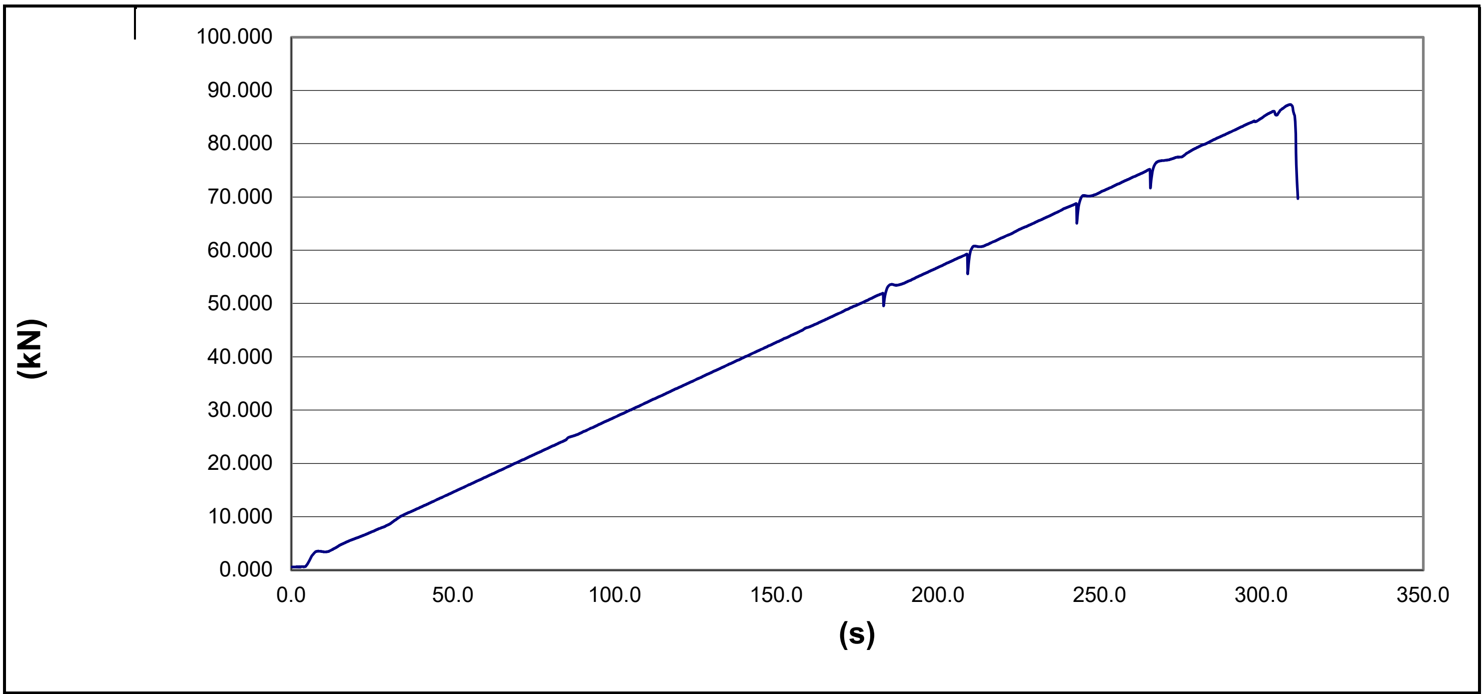


Operator

Operator01

Flexural tests on beams: EN 12390-5

Certificate number	:	002-4PBH-SV40-2x6-T				Certificate date	: -------
Testing machine	:	C1701/FR s.n. 22000858					
Client	:						
Reference	:						
Specimen type	:	Beam				Cement quantity [kg/m³]	:
Cement type	:					Test date	: 29/06/2022
Sample conditions:							
Condition when received	:					Condition at test time	:
Sampling location	:					Sampling date	: -------
Preparation method	:						
Specimen ID	:						
Dimensions	:	*b(mm)*	: 150.00	*h(mm)*	: 150.00	Mass [kg]	: 0.000
		l(mm)	800				:
Load Rate [MPa/s]	:	0.1		No of upper roll	2	"L" distance [mm]	600.0
Area [mm2]	:	5625.0	Specimen age	: 28 dd		Preparation date	: -------
Load [kN]	:	87.35				Strength [MPa]	: 15.53
	:						
Notes	:						



Operator

Operator01

8.735

Appendix F ECI values Excel

	0.16	0.16	0.05	30	2	4	9	0.09	0.03	0.0001	0.06	
Basalt		0.00007686										
A1	5.44E-06	1.83E-02	1.89E+00	1.58E-07	2.66E-03	5.92E-03	1.03E-03	2.03E+00	1.60E-01	6.82E+01	1.81E-03	4.37E-01
A2	5.49E-07	1.48E-03	1.99E-01	3.70E-08	1.18E-04	8.87E-04	1.80E-04	8.03E-02	2.33E-03	8.26E+00	2.79E-04	2.48E-02
A3	1.42E-07	4.82E-04	1.09E-01	9.53E-09	4.83E-05	2.51E-04	4.34E-05	4.46E-02	6.63E-03	8.26E+00	1.43E-04	2.41E+00
C1	9.28E-09	1.90E-04	1.75E-02	4.99E-09	2.79E-05	2.09E-04	4.70E-05	9.91E-03	1.38E-04	4.66E-01	1.64E-05	2.31E-03
C2	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
C3	9.05E-10	5.71E-06	8.32E-04	1.47E-10	8.15E-07	6.18E-06	1.40E-06	3.17E-04	4.58E-06	1.53E-02	4.36E-06	1.73E-03
C4	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
D	-2.33E-08	-2.88E-05	-4.20E-03	-3.76E-10	-3.04E-06	-2.41E-05	-4.19E-06	-1.88E-03	-2.68E-05	-1.17E-01	-9.79E-06	-6.06E-02
Staalvezels												
A1	5.57E-04	3.17E-03	5.77E-01	3.96E-08	1.38E-04	2.37E-03	1.15E-03	7.30E-01	1.55E+00	5.32E+00	2.54E-04	6.86E-03
A2	0.00E+00	3.51E-05	6.82E-03	0.00E+00	3.53E-06	5.25E-05	9.30E-06					1.00E-06
A3	1.74E-03	1.32E-03	2.97E-01	7.57E-09	3.50E-05	1.03E-03	1.70E-03					3.58E-04
C1	1.94E-05	1.44E-05	2.52E-03	2.89E-11	1.19E-05	2.31E-06	9.61E-08					9.48E-06
C2	0.00E+00	1.88E-05	3.20E-03	0.00E+00	1.48E-06	2.21E-05	3.90E-06					4.20E-07
C3	1.29E-05	9.61E-06	1.68E-03	1.92E-11	7.94E-06	1.53E-06	6.39E-08					6.30E-06
C4	6.00E-05	6.24E-06	3.00E-03	1.15E-10	6.50E-07	3.50E-06	1.72E-06					1.00E-05
D	-2.18E-04	-1.05E-03	-2.36E-01	-4.49E-09	-1.02E-04	-9.11E-04	-3.17E-04					-1.01E-04
Stalen staven												
A1	1.10E-06	1.30E-02	1.50E+00	6.00E-08	1.20E-03	5.10E-03	7.00E-04	5.50E-01	1.80E-02	5.00E+01	2.70E-02	6.86E-03
A2												
A3												
C1	1.94E-05	1.44E-05	2.52E-03	2.89E-11	1.19E-05	2.31E-06	9.61E-08					9.48E-06
C2	0.00E+00	1.88E-05	3.20E-03	0.00E+00	1.48E-06	2.21E-05	3.90E-06					4.20E-07
C3	1.29E-05	9.61E-06	1.68E-03	1.92E-11	7.94E-06	1.53E-06	6.39E-08					6.30E-06
C4	6.00E-05	6.24E-06	3.00E-03	1.15E-10	6.50E-07	3.50E-06	1.72E-06					1.00E-05
D	-2.18E-04	-1.05E-03	-2.36E-01	-4.49E-09	-1.02E-04	-9.11E-04	-3.17E-04					-1.01E-04

8.70E-07	2.93E-03	9.45E-02	4.74E-06	5.32E-03	2.37E-02	9.27E-03	1.83E-01	4.80E-03	6.82E-03	1.09E-04	0.00E+00	0.33013221	
8.78E-08	2.37E-04	9.95E-03	1.11E-06	2.36E-04	3.55E-03	1.62E-03	7.23E-03	6.99E-05	8.26E-04	1.67E-05	0.00E+00	0.023731638	
2.27E-08	7.71E-05	5.45E-03	2.86E-07	9.66E-05	1.00E-03	3.91E-04	4.01E-03	1.99E-04	8.26E-04	8.58E-06	0.00E+00	0.012066109	0.36593
1.48E-09	3.04E-05	8.75E-04	1.50E-07	5.58E-05	8.36E-04	4.23E-04	8.92E-04	4.14E-06	4.66E-05	9.84E-07	0.00E+00	0.003163975	
0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0	
1.45E-10	9.14E-07	4.16E-05	4.41E-09	1.63E-06	2.47E-05	1.26E-05	2.85E-05	1.37E-07	1.53E-06	2.62E-07	0.00E+00	0.000111927	
0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0	0.003276
-3.73E-09	-4.61E-06	-2.10E-04	-1.13E-08	-6.08E-06	-9.64E-05	-3.77E-05	-1.69E-04	-8.04E-07	-1.17E-05	-5.87E-07	0.00E+00	-0.000537104	-0.00054
												0.368668755	
8.91E-05	5.07E-04	2.89E-02	1.19E-06	2.76E-04	9.48E-03	1.04E-02	6.57E-02	4.65E-02	5.32E-04	1.52E-05	0.00E+00	0.1623	
0.00E+00	5.61E-06	3.41E-04	0.00E+00	7.06E-06	2.10E-04	8.37E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.0006	
2.78E-04	2.11E-04	1.49E-02	2.27E-07	7.00E-05	4.12E-03	1.53E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.0348	0.1978
3.10E-06	2.31E-06	1.26E-04	8.67E-10	2.38E-05	9.24E-06	8.65E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.0002	
0.00E+00	3.01E-06	1.60E-04	0.00E+00	2.96E-06	8.84E-05	3.51E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.0003	
2.06E-06	1.54E-06	8.40E-05	5.76E-10	1.59E-05	6.12E-06	5.75E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.0001	
9.60E-06	9.99E-07	1.50E-04	3.45E-09	1.30E-06	1.40E-05	1.55E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.0002	0.0008
-3.49E-05	-1.68E-04	-1.18E-02	-1.35E-07	-2.04E-04	-3.64E-03	-2.85E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	-0.0187	-0.0187
												0.1798	
1.76E-07	2.08E-03	7.50E-02	1.80E-06	2.40E-03	2.04E-02	6.30E-03	4.95E-02	5.40E-04	5.00E-03	1.62E-03	0.00E+00	0.1628	
0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.0000	
0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.0000	0.1628
3.10E-06	2.31E-06	1.26E-04	8.67E-10	2.38E-05	9.24E-06	8.65E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.0002	
0.00E+00	3.01E-06	1.60E-04	0.00E+00	2.96E-06	8.84E-05	3.51E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.0003	
2.06E-06	1.54E-06	8.40E-05	5.76E-10	1.59E-05	6.12E-06	5.75E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.0001	
9.60E-06	9.99E-07	1.50E-04	3.45E-09	1.30E-06	1.40E-05	1.55E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.0002	0.0008
-3.49E-05	-1.68E-04	-1.18E-02	-1.35E-07	-2.04E-04	-3.64E-03	-2.85E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	-0.0187	-0.0187
												0.1449	
												0.144893986	
3.68E-04	7.23E-04	4.40E-02	1.42E-06	3.53E-04	1.38E-02	2.57E-02	6.57E-02	4.65E-02	5.32E-04	1.52E-05	0.00E+00		
3.82E-04	7.31E-04	4.46E-02	1.42E-06	3.97E-04	1.39E-02	2.58E-02	6.57E-02	4.65E-02	5.32E-04	1.52E-05	0.00E+00		

Abiotic De non fuel (A	Abiotic De fuel (ADf)	Global Wa (GWP)	Ozone Lay (ODP)	Photocher (POCP)	Acidificati (AP)	Eutrophica (EP)	Human To (HT)	Ecotoxicity (FAETP)	Ecotoxcity (MAETP)	Ecotoxicity (TETP)	Water Depletion Potential (WDP)
kg Sb eq	kg Sb eq	kg CO2 eq	kg CFC-11	kg C2H4 e	kg SO2 eq	kg PO42- e	kg 1,4-DB (	kg 1,4-DB (	kg 1,4-DB (	kg 1,4-DB (	M3
0.16	0.16	0.05	30	2	4	9	0.09	0.03	0.0001	0.06	

Design Material	Traditional mixture (no fibres) $[kg/m^3]$	Basalt rebar	Steel rebar	30 (Basalt) $[kg/m^3]$	45 (Steel) $[kg/m^3]$
Sand (0-4 mm)	877.5	877.4469	877.49965	877.5	877.5
Gravel (4-8 mm)	774.6	774.5532	774.59969	719.4	759.6
CEM I	78	77.99528	77.999969	78	78
CEM III A	331.5	331.48	331.49987	331.5	331.5
Limestone flour	146.25	146.2412	146.24994	146.25	146.3
PW 3100	1.755	1.754894	1.7549993	1.755	1.755
SKY 648	2.243	2.242864	2.2429991	2.243	2.243
Basalt fibres/rebar	0	13	0	30	0
Steel fibres	0	0	0	0	45
Water	154.4	154.3907	154.39994	154.4	144.4
Steel rebar	0	0	84.18	0	0
Air content [%]	3.5	3.5	3.5	2.5	2.5
Total	2366.248	2379.105	2450.427	2341.048	2386.298

A1

Impact category	Material / Process Type		Abiotic Dep non fuel (AI	Abiotic Dep fuel (ADf)	Global Warı (GWP)	Ozone Laye (ODP)	Photochem (POCP)	Acidificatic (AP)	Eutrophica (EP)	Human To: (HT)	Ecotoxicity (FAETP)	Ecotoxcity (MAETP)	Ecotoxicity (TETP)	Water Depletion Potential (WDP)
Unit			kg Sb eq	kg Sb eq	kg CO2 eq	kg CFC-11 (	kg C2H4 eq	kg SO2 eq	kg PO42- e	kg 1,4-DB (	kg 1,4-DB (	kg 1,4-DB (	kg 1,4-DB (	M3
	Monetary value / impact category eq		0.16	0.16	0.05	30	2	4	9	0.09	0.03	0.0001	0.06	
				7.69E-05										
Raw materials:		Unit:												
Sand, sea 0-4 mm NL	Aggregate Fine - primary	kg	3.55E-07	1.73E-02	2.64E+00	5.08E-08	2.08E-03	2.54E-02	5.73E-03	9.83E-01	3.19E-02	1.85E+02	1.28E-02	0.00E+00
Gravel, sea >4 mm NL	Aggregate Coarse - primary	kg	5.27E-07	6.22E-02	9.55E+00	4.52E-08	7.32E-03	9.36E-02	2.12E-02	3.51E+00	1.50E-01	7.16E+02	4.98E-02	0.00E+00
CEM I NL	Cement	kg	1.73E-03	1.66E+00	8.54E+02	2.41E-05	1.10E-01	1.56E+00	2.31E-01	5.55E+01	1.23E+00	5.86E+03	1.10E+00	5.83E+01
CEM IIIA NL	Cement	kg	2.19E-03	1.44E+00	5.22E+02	2.11E-05	9.42E-02	1.31E+00	1.64E-01	5.24E+01	1.24E+00	5.60E+03	7.22E-01	4.61E+01
Limestone powder NL	Filler	kg	8.66E-05	2.22E-01	3.11E+01	2.79E-06	9.65E-03	9.20E-02	1.86E-02	5.58E+00	1.32E-01	4.99E+02	5.05E-02	2.50E+00
Plasticizer - water reducer	Chemical Admixture	kg	1.27E-01	1.54E+01	1.25E+03	2.10E-04	1.27E+00	7.41E+00	6.26E-01	8.92E+02	1.64E+01	5.01E+04	1.84E+00	9.72E+02
Super plasticizer - high range v	Chemical Admixture	kg	1.27E-01	1.54E+01	1.25E+03	2.10E-04	1.27E+00	7.41E+00	6.26E-01	8.92E+02	1.64E+01	5.01E+04	1.84E+00	9.72E+02
Basalt fibres/rebar	Reinforcement	kg	5.44E-06	1.83E-02	1.89E+00	1.58E-07	2.66E-03	5.92E-03	1.03E-03	2.03E+00	1.60E-01	6.82E+01	1.81E-03	4.37E-01
Steel fibres	Reinforcement	kg	5.57E-04	3.17E-03	5.77E-01	3.96E-08	1.38E-04	2.37E-03	1.15E-03	7.30E-01	1.55E+00	5.32E+00	2.54E-04	6.86E-03
Tap water	Water	kg	9.58E-06	2.46E-03	3.37E-01	3.54E-08	2.06E-04	1.66E-03	2.11E-04	1.33E-01	2.89E-03	9.15E+00	3.98E-03	4.30E+01
Steel rebar	Reinforcement	kg	1.10E-06	1.30E-02	1.50E+00	6.00E-08	1.20E-03	5.10E-03	7.00E-04	5.50E-01	1.80E-02	5.00E+01	2.70E-02	6.86E-03

Traditional mixture (no fibres)	Basalt rebar	Steel rebar	30 (Basalt)	45 (Steel)
0.35	0.35	0.35	0.35	0.35
1.13	1.13	1.13	1.05	1.11
4.46	4.46	4.46	4.46	4.46
12.79	12.79	12.79	12.79	12.79
0.40	0.40	0.40	0.40	0.40
0.33	0.33	0.33	0.33	0.33
0.42	0.42	0.42	0.42	0.42
0.00	4.29	0.00	9.90	0.00
0.00	0.00	0.00	0.00	7.30
0.01	0.01	0.01	0.01	0.01
0.00	0.00	13.71	0.00	0.00
19.89	24.19	33.60	29.72	27.18

Design Material	Traditional mixture (no fibres) $[kg/m^3]$	Basalt rebar	Steel rebar	30 (Basalt) $[kg/m^3]$	45 (Steel) $[kg/m^3]$
Sand (0-4 mm)	877.5	877.4469	877.49965	877.5	877.5
Gravel (4-8 mm)	774.6	774.5532	774.59969	719.4	759.6
CEM I	78	77.99528	77.999969	78	78
CEM III A	331.5	331.48	331.49987	331.5	331.5
Limestone flour	146.25	146.2412	146.24994	146.25	146.3
PW 3100	1.755	1.754894	1.7549993	1.755	1.755
SKY 648	2.243	2.242864	2.2429991	2.243	2.243
Basalt fibres/rebar	0	13	0	30	0
Steel fibres	0	0	0	0	45
Water	154.4	154.3907	154.39994	154.4	144.4
Steel rebar	0	0	84.18	0	0
Air content [%]	3.5	3.5	3.5	2.5	2.5
Total	2366.248	2379.105	2450.427	2341.048	2386.298

A2

Impact category	Material / Process Type		Abiotic Dep non fuel (AI	Abiotic Dep fuel (ADf)	Global Warı (GWP)	Ozone Laye (ODP)	Photochem (POCP)	Acidificatic (AP)	Eutrophica (EP)	Human To: (HT)	Ecotoxicity (FAETP)	Ecotoxcity (MAETP)	Ecotoxicity (TETP)	Water Depletion Potential (WDP)
Unit			kg Sb eq	kg Sb eq	kg CO2 eq	kg CFC-11 (	kg C2H4 eq	kg SO2 eq	kg PO42- e	kg 1,4-DB (	kg 1,4-DB (	kg 1,4-DB (	kg 1,4-DB (	M3
	Monetary value / impact category eq		0.16	0.16	0.05	30	2	4	9	0.09	0.03	0.0001	0.06	
				7.69E-05										
Raw materials:		Unit:												
Sand, sea 0-4 mm NL	Aggregate Fine - primary	kg	1.71E-04	4.92E-02	6.69E+00	1.19E-06	4.04E-03	2.94E-02	5.78E-03	2.82E+00	8.22E-02	2.96E+02	9.96E-03	3.64E-01
Gravel, sea >4 mm NL	Aggregate Coarse - primary	kg	1.71E-04	4.92E-02	6.69E+00	1.19E-06	4.04E-03	2.94E-02	5.78E-03	2.82E+00	8.22E-02	2.96E+02	9.96E-03	3.64E-01
CEM I NL	Cement	kg	1.71E-04	4.92E-02	6.69E+00	1.19E-06	4.04E-03	2.94E-02	5.78E-03	2.82E+00	8.22E-02	2.96E+02	9.96E-03	3.64E-01
CEM IIIA NL	Cement	kg	1.71E-04	4.92E-02	6.69E+00	1.19E-06	4.04E-03	2.94E-02	5.78E-03	2.82E+00	8.22E-02	2.96E+02	9.96E-03	3.64E-01
Limestone powder NL	Filler	kg	1.71E-04	4.92E-02	6.69E+00	1.19E-06	4.04E-03	2.94E-02	5.78E-03	2.82E+00	8.22E-02	2.96E+02	9.96E-03	3.64E-01
Plasticizer - water reducer	Chemical Admixture	kg	1.71E-04	4.92E-02	6.69E+00	1.19E-06	4.04E-03	2.94E-02	5.78E-03	2.82E+00	8.22E-02	2.96E+02	9.96E-03	3.64E-01
Super plasticizer - high range v	Chemical Admixture	kg	1.71E-04	4.92E-02	6.69E+00	1.19E-06	4.04E-03	2.94E-02	5.78E-03	2.82E+00	8.22E-02	2.96E+02	9.96E-03	3.64E-01
Basalt fibres/rebar	Reinforcement	kg	5.49E-07	1.48E-03	1.99E-01	3.70E-08	1.18E-04	8.87E-04	1.80E-04	8.03E-02	2.33E-03	8.26E+00	2.79E-04	2.48E-02
Steel fibres	Reinforcement	kg	0.00E+00	3.51E-05	6.82E-03	0.00E+00	3.53E-06	5.25E-05	9.30E-06					1.00E-06
Tap water	Water	kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Steel rebar	Reinforcement	kg												

Traditional mixture (no fibres)	Basalt rebar	Steel rebar	30 (Basalt)	45 (Steel)
0.71	0.71	0.71	0.71	0.71
0.62	0.62	0.62	0.58	0.61
0.06	0.06	0.06	0.06	0.06
0.27	0.27	0.27	0.27	0.27
0.12	0.12	0.12	0.12	0.12
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00
0.00	0.31	0.00	0.71	0.00
0.00	0.00	0.00	0.00	0.03
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00
1.78	2.09	1.78	2.45	1.80

Design Material	Traditional mixture (no fibres) $[kg/m^3]$	Basalt rebar	Steel rebar	30 (Basalt) $[kg/m^3]$	45 (Steel) $[kg/m^3]$
Sand (0-4 mm)	877.5	877.4469	877.49965	877.5	877.5
Gravel (4-8 mm)	774.6	774.5532	774.59969	719.4	759.6
CEM I	78	77.99528	77.999969	78	78
CEM III A	331.5	331.48	331.49987	331.5	331.5
Limestone flour	146.25	146.2412	146.24994	146.25	146.3
PW 3100	1.755	1.754894	1.7549993	1.755	1.755
SKY 648	2.243	2.242864	2.2429991	2.243	2.243
Basalt fibres/rebar	0	13	0	30	0
Steel fibres	0	0	0	0	45
Water	154.4	154.3907	154.39994	154.4	144.4
Steel rebar	0	0	84.18	0	0
Air content [%]	3.5	3.5	3.5	2.5	2.5
Total	2366.248	2379.105	2450.427	2341.048	2386.298

A3

Impact category	Material / Process Type		Abiotic Dep non fuel (AI	Abiotic Dep fuel (ADf)	Global Warı (GWP)	Ozone Laye (ODP)	Photochem (POCP)	Acidificatic (AP)	Eutrophica (EP)	Human To: (HT)	Ecotoxicity (FAETP)	Ecotoxcity (MAETP)	Ecotoxicity (TETP)	Water Depletion Potential (WDP)
Unit			kg Sb eq	kg Sb eq	kg CO2 eq	kg CFC-11 (	kg C2H4 eq	kg SO2 eq	kg PO42- e	kg 1,4-DB (	kg 1,4-DB (	kg 1,4-DB (	kg 1,4-DB (	M3
	Monetary value / impact category eq		0.16	0.16	0.05	30	2	4	9	0.09	0.03	0.0001	0.06	
				7.69E-05										
Raw materials:		Unit:												
Sand, sea 0-4 mm NL	Aggregate Fine - primary	kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Gravel, sea >4 mm NL	Aggregate Coarse - primary	kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CEM I NL	Cement	kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CEM IIIA NL	Cement	kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Limestone powder NL	Filler	kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Plasticizer - water reducer	Chemical Admixture	kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Super plasticizer - high range v	Chemical Admixture	kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Basalt fibres/rebar	Reinforcement	kg	1.42E-07	4.82E-04	1.09E-01	9.53E-09	4.83E-05	2.51E-04	4.34E-05	4.46E-02	6.63E-03	8.26E+00	1.43E-04	2.41E+00
Steel fibres	Reinforcement	kg	1.74E-03	1.32E-03	2.97E-01	7.57E-09	3.50E-05	1.03E-03	1.70E-03					3.58E-04
Tap water	Water	kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Steel rebar	Reinforcement	kg												

Traditional mixture (no fibres)	Basalt rebar	Steel rebar	30 (Basalt)	45 (Steel)
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00
0.00	0.16	0.00	0.36	0.00
0.00	0.00	0.00	0.00	1.57
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00
0.00	0.16	0.00	0.36	1.57

Design Material	Traditional mixture (no fibres) $[kg/m^3]$	Basalt rebar	Steel rebar	30 (Basalt) $[kg/m^3]$	45 (Steel) $[kg/m^3]$
Sand (0-4 mm)	877.5	877.4469	877.49965	877.5	877.5
Gravel (4-8 mm)	774.6	774.5532	774.59969	719.4	759.6
CEM I	78	77.99528	77.999969	78	78
CEM III A	331.5	331.48	331.49987	331.5	331.5
Limestone flour	146.25	146.2412	146.24994	146.25	146.3
PW 3100	1.755	1.754894	1.7549993	1.755	1.755
SKY 648	2.243	2.242864	2.2429991	2.243	2.243
Basalt fibres/rebar	0	13	0	30	0
Steel fibres	0	0	0	0	45
Water	154.4	154.3907	154.39994	154.4	144.4
Steel rebar	0	0	84.18	0	0
Air content [%]	3.5	3.5	3.5	2.5	2.5
Total	2366.248	2379.105	2450.427	2341.048	2386.298

A1-A3

Impact category	Material / Process Type		Abiotic Dep non fuel (AI	Abiotic Dep fuel (ADf)	Global Warı (GWP)	Ozone Laye (ODP)	Photochem (POCP)	Acidificatic (AP)	Eutrophica (EP)	Human To: (HT)	Ecotoxicity (FAETP)	Ecotoxcity (MAETP)	Ecotoxicity (TETP)	Water Depletion Potential (WDP)
Unit			kg Sb eq	kg Sb eq	kg CO2 eq	kg CFC-11 (	kg C2H4 eq	kg SO2 eq	kg PO42- e	kg 1,4-DB (	kg 1,4-DB (	kg 1,4-DB (	kg 1,4-DB (	M3
	Monetary value / impact category eq		0.16	0.16	0.05	30	2	4	9	0.09	0.03	0.0001	0.06	
				7.69E-05										
Raw materials:		Unit:												
Sand, sea 0-4 mm NL	Aggregate Fine - primary	kg	1.71E-04	6.65E-02	9.33E+00	1.24E-06	6.12E-03	5.48E-02	1.15E-02	3.80E+00	1.14E-01	4.81E+02	2.28E-02	3.64E-01
Gravel, sea >4 mm NL	Aggregate Coarse - primary	kg	1.72E-04	1.11E-01	1.62E+01	1.24E-06	1.14E-02	1.23E-01	2.70E-02	6.33E+00	2.32E-01	1.01E+03	5.98E-02	3.64E-01
CEM I NL	Cement	kg	1.90E-03	1.71E+00	8.61E+02	2.53E-05	1.14E-01	1.59E+00	2.37E-01	5.83E+01	1.31E+00	6.16E+03	1.11E+00	5.87E+01
CEM IIIA NL	Cement	kg	2.36E-03	1.49E+00	5.29E+02	2.23E-05	9.82E-02	1.34E+00	1.70E-01	5.52E+01	1.32E+00	5.90E+03	7.32E-01	4.65E+01
Limestone powder NL	Filler	kg	2.58E-04	2.71E-01	3.78E+01	3.98E-06	1.37E-02	1.21E-01	2.44E-02	8.40E+00	2.14E-01	7.95E+02	6.05E-02	2.86E+00
Plasticizer - water reducer	Chemical Admixture	kg	1.27E-01	1.54E+01	1.26E+03	2.11E-04	1.27E+00	7.44E+00	6.32E-01	8.95E+02	1.65E+01	5.04E+04	1.85E+00	9.72E+02
Super plasticizer - high range v	Chemical Admixture	kg	1.27E-01	1.54E+01	1.26E+03	2.11E-04	1.27E+00	7.44E+00	6.32E-01	8.95E+02	1.65E+01	5.04E+04	1.85E+00	9.72E+02
Basalt fibres/rebar	Reinforcement	kg	6.13E-06	2.03E-02	2.20E+00	2.05E-07	2.83E-03	7.06E-03	1.25E-03	2.15E+00	1.69E-01	8.47E+01	2.23E-03	2.87E+00
Steel fibres	Reinforcement	kg	2.30E-03	4.52E-03	8.81E-01	4.72E-08	1.77E-04	3.45E-03	2.86E-03	7.30E-01	1.55E+00	5.32E+00	2.54E-04	7.22E-03
Tap water	Water	kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Steel rebar	Reinforcement	kg	1.10E-06	1.30E-02	1.50E+00	6.00E-08	1.20E-03	5.10E-03	7.00E-04	5.50E-01	1.80E-02	5.00E+01	2.70E-02	6.86E-03

Traditional mixture (no fibres)	Basalt rebar	Steel rebar	30 (Basalt)	45 (Steel)
1.06	1.06	1.06	1.06	1.06
1.76	1.76	1.76	1.63	1.72
4.52	4.52	4.52	4.52	4.52
13.06	13.06	13.06	13.06	13.06
0.51	0.51	0.51	0.51	0.51
0.33	0.33	0.33	0.33	0.33
0.43	0.43	0.43	0.43	0.43
0.00	4.76	0.00	10.98	0.00
0.00	0.00	0.00	0.00	8.90
0.00	0.00	0.00	0.00	0.00
0.00	0.00	13.71	0.00	0.00
21.67	26.43	35.38	32.53	30.54

C1

Impact category	Material / Process Type		Abiotic Dep non fuel (AI	Abiotic Dep fuel (ADf)	Global Warı (GWP)	Ozone Laye (ODP)	Photochem (POCP)	Acidificatic (AP)	Eutrophica (EP)	Human To: (HT)	Ecotoxicity (FAETP)	Ecotoxcity (MAETP)	Ecotoxicity (TETP)	Water Depletion Potential (WDP)
Unit			kg Sb eq	kg Sb eq	kg CO2 eq	kg CFC-11 (	kg C2H4 eq	kg SO2 eq	kg PO42- e	kg 1,4-DB (	kg 1,4-DB (	kg 1,4-DB (	kg 1,4-DB (	M3
	Monetary value / impact category eq		0.16	0.16	0.05	30	2	4	9	0.09	0.03	0.0001	0.06	

Design	Traditional mixture (no fibres)	Basalt rebar	Steel rebar	30 (Basalt)	45 (Steel)
Material	$[kg/m^3]$			$[kg/m^3]$	$[kg/m^3]$
Sand (0-4 mm)	877.5	877.4469	877.49965	877.5	877.5
Gravel (4-8 mm)	774.6	774.5532	774.59969	719.4	759.6
CEM I	78	77.99528	77.999969	78	78
CEM III A	331.5	331.48	331.49987	331.5	331.5
Limestone flour	146.25	146.2412	146.24994	146.25	146.3
PW 3100	1.755	1.754894	1.7549993	1.755	1.755
SKY 648	2.243	2.242864	2.2429991	2.243	2.243
Basalt fibres/rebar	0	13	0	30	0
Steel fibres	0	0	0	0	45
Water	154.4	154.3907	154.39994	154.4	144.4
Steel rebar	0	0	84.18	0	0
Air content [%]	3.5	3.5	3.5	2.5	2.5
Total	2366.248	2379.105	2450.427	2341.048	2386.298

7.69E-05

Raw materials:		Unit:												
Sand, sea 0-4 mm NL	Aggregate Fine - primary	kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Gravel, sea >4 mm NL	Aggregate Coarse - primary	kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CEM I NL	Cement	kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CEM IIIA NL	Cement	kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Limestone powder NL	Filler	kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Plasticizer - water reducer	Chemical Admixture	kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Super plasticizer - high range v	Chemical Admixture	kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Basalt fibres/rebar	Reinforcement	kg	9.28E-09	1.90E-04	1.75E-02	4.99E-09	2.79E-05	2.09E-04	4.70E-05	9.91E-03	1.38E-04	4.66E-01	1.64E-05	2.31E-03
Steel fibres	Reinforcement	kg	1.94E-05	1.44E-05	2.52E-03	2.89E-11	1.19E-05	2.31E-06	9.61E-08					9.48E-06
Tap water	Water	kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Steel rebar	Reinforcement	kg	1.94E-05	1.44E-05	2.52E-03	2.89E-11	1.19E-05	2.31E-06	9.61E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.48E-06

Traditional mixture (no fibres)	Basalt rebar	Steel rebar	30 (Basalt)	45 (Steel)
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00
0.00	0.04	0.00	0.09	0.00
0.00	0.00	0.00	0.00	0.01
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.01	0.00	0.00
0.00	0.04	0.01	0.09	0.01

C2

Impact category	Material / Process Type		Abiotic Dep non fuel (Al	Abiotic Deg fuel (ADf)	Global Warı (GWP)	Ozone Laye (ODP)	Photochem (POCP)	Acidificatic (AP)	Eutrophica (EP)	Human To: (HT)	Ecotoxicity (FAETP)	Ecotoxicity (MAETP)	Ecotoxicity (TETP)	Water Depletion Potential (WDP)
Unit			kg Sb eq	kg Sb eq	kg CO2 eq	kg CFC-11 ε	kg C2H4 eq	kg SO2 eq	kg PO42- e	kg 1,4-DB ε	kg 1,4-DB ε	kg 1,4-DB ε	kg 1,4-DB ε	M3
	Monetary value / impact category eq		0.16	0.16	0.05	30	2	4	9	0.09	0.03	0.0001	0.06	

Design	Traditional mixture (no fibres)	Basalt rebar	Steel rebar	30 (Basalt)	45 (Steel)
Material	$[kg/m^3]$			$[kg/m^3]$	$[kg/m^3]$
Sand (0-4 mm)	877.5	877.4469	877.49965	877.5	877.5
Gravel (4-8 mm)	774.6	774.5532	774.59969	719.4	759.6
CEM I	78	77.99528	77.999969	78	78
CEM III A	331.5	331.48	331.49987	331.5	331.5
Limestone flour	146.25	146.2412	146.24994	146.25	146.3
PW 3100	1.755	1.754894	1.7549993	1.755	1.755
SKY 648	2.243	2.242864	2.2429991	2.243	2.243
Basalt fibres/rebar	0	13	0	30	0
Steel fibres	0	0	0	0	45
Water	154.4	154.3907	154.39994	154.4	144.4
Steel rebar	0	0	84.18	0	0
Air content [%]	3.5	3.5	3.5	2.5	2.5
Total	2366.248	2379.105	2450.427	2341.048	2386.298

7.69E-05

Raw materials:		Unit:												
Sand, sea 0-4 mm NL	Aggregate Fine - primary	kg	1.71E-04	4.92E-02	6.69E+00	1.19E-06	4.04E-03	2.94E-02	5.78E-03	2.82E+00	8.22E-02	2.96E+02	9.96E-03	3.64E-01
Gravel, sea >4 mm NL	Aggregate Coarse - primary	kg	1.71E-04	4.92E-02	6.69E+00	1.19E-06	4.04E-03	2.94E-02	5.78E-03	2.82E+00	8.22E-02	2.96E+02	9.96E-03	3.64E-01
CEM I NL	Cement	kg	1.71E-04	4.92E-02	6.69E+00	1.19E-06	4.04E-03	2.94E-02	5.78E-03	2.82E+00	8.22E-02	2.96E+02	9.96E-03	3.64E-01
CEM IIIA NL	Cement	kg	1.71E-04	4.92E-02	6.69E+00	1.19E-06	4.04E-03	2.94E-02	5.78E-03	2.82E+00	8.22E-02	2.96E+02	9.96E-03	3.64E-01
Limestone powder NL	Filler	kg	1.71E-04	4.92E-02	6.69E+00	1.19E-06	4.04E-03	2.94E-02	5.78E-03	2.82E+00	8.22E-02	2.96E+02	9.96E-03	3.64E-01
Plasticizer - water reducer	Chemical Admixture	kg	1.71E-04	4.92E-02	6.69E+00	1.19E-06	4.04E-03	2.94E-02	5.78E-03	2.82E+00	8.22E-02	2.96E+02	9.96E-03	3.64E-01
Super plasticizer - high range v	Chemical Admixture	kg	1.71E-04	4.92E-02	6.69E+00	1.19E-06	4.04E-03	2.94E-02	5.78E-03	2.82E+00	8.22E-02	2.96E+02	9.96E-03	3.64E-01
Basalt fibres/rebar	Reinforcement	kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Steel fibres	Reinforcement	kg	0.00E+00	1.88E-05	3.20E-03	0.00E+00	1.48E-06	2.21E-05	3.90E-06					4.20E-07
Tap water	Water	kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Steel rebar	Reinforcement	kg	0.00E+00	1.88E-05	3.20E-03	0.00E+00	1.48E-06	2.21E-05	3.90E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.20E-07

Traditional mixture (no fibres)	Basalt rebar	Steel rebar	30 (Basalt)	45 (Steel)
0.71	0.71	0.71	0.71	0.71
0.62	0.62	0.62	0.58	0.61
0.06	0.06	0.06	0.06	0.06
0.27	0.27	0.27	0.27	0.27
0.12	0.12	0.12	0.12	0.12
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.01
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.02	0.00	0.00
1.78	1.78	1.81	1.74	1.79

C3

Impact category	Material / Process Type		Abiotic Dep non fuel (Al	Abiotic Deg fuel (ADf)	Global Warı (GWP)	Ozone Laye (ODP)	Photochem (POCP)	Acidificatic (AP)	Eutrophica (EP)	Human To: (HT)	Ecotoxicity (FAETP)	Ecotoxicity (MAETP)	Ecotoxicity (TETP)	Water Depletion Potential (WDP)
Unit			kg Sb eq	kg Sb eq	kg CO2 eq	kg CFC-11 ε	kg C2H4 eq	kg SO2 eq	kg PO42- e	kg 1,4-DB ε	kg 1,4-DB ε	kg 1,4-DB ε	kg 1,4-DB ε	M3
	Monetary value / impact category eq		0.16	0.16	0.05	30	2	4	9	0.09	0.03	0.0001	0.06	

Design	Traditional mixture (no fibres)	Basalt rebar	Steel rebar	30 (Basalt)	45 (Steel)
Material	$[kg/m^3]$			$[kg/m^3]$	$[kg/m^3]$
Sand (0-4 mm)	877.5	877.4469	877.49965	877.5	877.5
Gravel (4-8 mm)	774.6	774.5532	774.59969	719.4	759.6
CEM I	78	77.99528	77.999969	78	78
CEM III A	331.5	331.48	331.49987	331.5	331.5
Limestone flour	146.25	146.2412	146.24994	146.25	146.3
PW 3100	1.755	1.754894	1.7549993	1.755	1.755
SKY 648	2.243	2.242864	2.2429991	2.243	2.243
Basalt fibres/rebar	0	13	0	30	0
Steel fibres	0	0	0	0	45
Water	154.4	154.3907	154.39994	154.4	144.4
Steel rebar	0	0	84.18	0	0
Air content [%]	3.5	3.5	3.5	2.5	2.5
Total	2366.248	2379.105	2450.427	2341.048	2386.298

7.69E-05

Raw materials:		Unit:												
Sand, sea 0-4 mm NL	Aggregate Fine - primary	kg	1.02E-04	5.86E-03	8.30E-01	8.34E-08	7.38E-04	5.51E-03	5.97E-04	8.48E-01	1.53E-02	7.03E+01	3.28E-03	7.29E-01
Gravel, sea >4 mm NL	Aggregate Coarse - primary	kg	1.02E-04	5.86E-03	8.30E-01	8.34E-08	7.38E-04	5.51E-03	5.97E-04	8.48E-01	1.53E-02	7.03E+01	3.28E-03	7.29E-01
CEM I NL	Cement	kg	1.02E-04	5.86E-03	8.30E-01	8.34E-08	7.38E-04	5.51E-03	5.97E-04	8.48E-01	1.53E-02	7.03E+01	3.28E-03	7.29E-01
CEM IIIA NL	Cement	kg	1.02E-04	5.86E-03	8.30E-01	8.34E-08	7.38E-04	5.51E-03	5.97E-04	8.48E-01	1.53E-02	7.03E+01	3.28E-03	7.29E-01
Limestone powder NL	Filler	kg	1.02E-04	5.86E-03	8.30E-01	8.34E-08	7.38E-04	5.51E-03	5.97E-04	8.48E-01	1.53E-02	7.03E+01	3.28E-03	7.29E-01
Plasticizer - water reducer	Chemical Admixture	kg	1.02E-04	5.86E-03	8.30E-01	8.34E-08	7.38E-04	5.51E-03	5.97E-04	8.48E-01	1.53E-02	7.03E+01	3.28E-03	7.29E-01
Super plasticizer - high range v	Chemical Admixture	kg	1.02E-04	5.86E-03	8.30E-01	8.34E-08	7.38E-04	5.51E-03	5.97E-04	8.48E-01	1.53E-02	7.03E+01	3.28E-03	7.29E-01
Basalt fibres/rebar	Reinforcement	kg	9.05E-10	5.71E-06	8.32E-04	1.47E-10	8.15E-07	6.18E-06	1.40E-06	3.17E-04	4.58E-06	1.53E-02	4.36E-06	1.73E-03
Steel fibres	Reinforcement	kg	1.29E-05	9.61E-06	1.68E-03	1.92E-11	7.94E-06	1.53E-06	6.39E-08					6.30E-06
Tap water	Water	kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Steel rebar	Reinforcement	kg	1.29E-05	9.61E-06	1.68E-03	1.92E-11	7.94E-06	1.53E-06	6.39E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.30E-06

Traditional mixture (no fibres)	Basalt rebar	Steel rebar	30 (Basalt)	45 (Steel)
0.14	0.14	0.14	0.14	0.14
0.12	0.12	0.12	0.11	0.12
0.01	0.01	0.01	0.01	0.01
0.05	0.05	0.05	0.05	0.05
0.02	0.02	0.02	0.02	0.02
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.01	0.00	0.00
0.34	0.35	0.35	0.34	0.35

C4

Impact category	Material / Process Type		Abiotic Dep non fuel (Al	Abiotic Deg fuel (ADf)	Global Warı (GWP)	Ozone Laye (ODP)	Photochem (POCP)	Acidificatic (AP)	Eutrophica (EP)	Human To: (HT)	Ecotoxicity (FAETP)	Ecotoxicity (MAETP)	Ecotoxicity (TETP)	Water Depletion Potential (WDP)
Unit			kg Sb eq	kg Sb eq	kg CO2 eq	kg CFC-11 ε	kg C2H4 eq	kg SO2 eq	kg PO42- e	kg 1,4-DB ε	kg 1,4-DB ε	kg 1,4-DB ε	kg 1,4-DB ε	M3
	Monetary value / impact category eq		0.16	0.16	0.05	30	2	4	9	0.09	0.03	0.0001	0.06	

Design	Traditional mixture (no fibres)	Basalt rebar	Steel rebar	30 (Basalt)	45 (Steel)
Material	$[kg/m^3]$			$[kg/m^3]$	$[kg/m^3]$
Sand (0-4 mm)	877.5	877.4469	877.49965	877.5	877.5
Gravel (4-8 mm)	774.6	774.5532	774.59969	719.4	759.6
CEM I	78	77.99528	77.999969	78	78
CEM III A	331.5	331.48	331.49987	331.5	331.5
Limestone flour	146.25	146.2412	146.24994	146.25	146.3
PW 3100	1.755	1.754894	1.7549993	1.755	1.755
SKY 648	2.243	2.242864	2.2429991	2.243	2.243
Basalt fibres/rebar	0	13	0	30	0
Steel fibres	0	0	0	0	45
Water	154.4	154.3907	154.39994	154.4	144.4
Steel rebar	0	0	84.18	0	0
Air content [%]	3.5	3.5	3.5	2.5	2.5
Total	2366.248	2379.105	2450.427	2341.048	2386.298

7.69E-05

Raw materials:		Unit:												
Sand, sea 0-4 mm NL	Aggregate Fine - primary	kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Gravel, sea >4 mm NL	Aggregate Coarse - primary	kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CEM I NL	Cement	kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CEM IIIA NL	Cement	kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Limestone powder NL	Filler	kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Plasticizer - water reducer	Chemical Admixture	kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Super plasticizer - high range v	Chemical Admixture	kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Basalt fibres/rebar	Reinforcement	kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Steel fibres	Reinforcement	kg	6.00E-05	6.24E-06	3.00E-03	1.15E-10	6.50E-07	3.50E-06	1.72E-06					1.00E-05
Tap water	Water	kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Steel rebar	Reinforcement	kg	6.00E-05	6.24E-06	3.00E-03	1.15E-10	6.50E-07	3.50E-06	1.72E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.00E-05

Traditional mixture (no fibres)	Basalt rebar	Steel rebar	30 (Basalt)	45 (Steel)
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.01
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.02	0.00	0.00
0.00	0.00	0.02	0.00	0.01

D

Impact category	Material / Process Type		Abiotic Dep non fuel (Al	Abiotic Deg fuel (ADf)	Global Warı (GWP)	Ozone Laye (ODP)	Photochem (POCP)	Acidificatic (AP)	Eutrophica (EP)	Human To: (HT)	Ecotoxicity (FAETP)	Ecotoxicity (MAETP)	Ecotoxicity (TETP)	Water Depletion Potential (WDP)
Unit			kg Sb eq	kg Sb eq	kg CO2 eq	kg CFC-11 ε	kg C2H4 eq	kg SO2 eq	kg PO42- e	kg 1,4-DB ε	kg 1,4-DB ε	kg 1,4-DB ε	kg 1,4-DB ε	M3
	Monetary value / impact category eq		0.16	0.16	0.05	30	2	4	9	0.09	0.03	0.0001	0.06	

Design	Traditional mixture (no fibres)	Basalt rebar	Steel rebar	30 (Basalt)	45 (Steel)
Material	$[kg/m^3]$			$[kg/m^3]$	$[kg/m^3]$
Sand (0-4 mm)	877.5	877.4469	877.49965	877.5	877.5
Gravel (4-8 mm)	774.6	774.5532	774.59969	719.4	759.6
CEM I	78	77.99528	77.999969	78	78

7.69E-05

Raw materials:		Unit:												
Sand, sea 0-4 mm NL	Aggregate Fine - primary	kg	-2.15E-04	-2.85E-02	-4.22E+00	-3.68E-07	-3.12E-03	-2.40E-02	-3.91E-03	-1.95E+00	3.03E-02	-1.26E+02	-1.02E-02	-6.20E+01
Gravel, sea >4 mm NL	Aggregate Coarse - primary	kg	-2.15E-04	-2.85E-02	-4.22E+00	-3.68E-07	-3.12E-03	-2.40E-02	-3.91E-03	-1.95E+00	3.03E-02	-1.26E+02	-1.02E-02	-6.20E+01
CEM I NL	Cement	kg	-1.85E-05	-3.37E-01	-1.18E+02	-2.93E-06	-2.37E-02	-2.37E-01	-4.43E-02	-8.52E+00	-1.95E-01	-8.26E+02	-2.00E-01	0.00E+00

Traditional mixture (no fibres)	Basalt rebar	Steel rebar	30 (Basalt)	45 (Steel)
-0.47	-0.47	-0.47	-0.47	-0.47
-0.42	-0.42	-0.42	-0.39	-0.41
-0.64	-0.64	-0.64	-0.64	-0.64

CEM III A	331.5	331.48	331.49987	331.5	331.5
Limestone flour	146.25	146.2412	146.24994	146.25	146.3
PW 3100	1.755	1.754894	1.7549993	1.755	1.755
SKY 648	2.243	2.242864	2.2429991	2.243	2.243
Basalt fibres/rebar	0	13	0	30	0
Steel fibres	0	0	0	0	45
Water	154.4	154.3907	154.39994	154.4	144.4
Steel rebar	0	0	84.18	0	0
Air content [%]	3.5	3.5	3.5	2.5	2.5
Total	2366.248	2379.105	2450.427	2341.048	2386.298

CEM IIIA NL	Cement	kg	-1.85E-05	-3.37E-01	-1.18E+02	-2.93E-06	-2.37E-02	-2.37E-01	-4.43E-02	-8.52E+00	-1.95E-01	-8.26E+02	-2.00E-01	0.00E+00	-2.72	-2.72	-2.72	-2.72	-2.72
Limestone powder NL	Filler	kg	-1.85E-05	-3.37E-01	-1.18E+02	-2.93E-06	-2.37E-02	-2.37E-01	-4.43E-02	-8.52E+00	-1.95E-01	-8.26E+02	-2.00E-01	0.00E+00	-1.20	-1.20	-1.20	-1.20	-1.20
Plasticizer - water reducer	Chemical Admixture	kg	-1.85E-05	-3.37E-01	-1.18E+02	-2.93E-06	-2.37E-02	-2.37E-01	-4.43E-02	-8.52E+00	-1.95E-01	-8.26E+02	-2.00E-01	0.00E+00	-0.01	-0.01	-0.01	-0.01	-0.01
Super plasticizer - high range v	Chemical Admixture	kg	-1.85E-05	-3.37E-01	-1.18E+02	-2.93E-06	-2.37E-02	-2.37E-01	-4.43E-02	-8.52E+00	-1.95E-01	-8.26E+02	-2.00E-01	0.00E+00	-0.02	-0.02	-0.02	-0.02	-0.02
Basalt fibres/rebar	Reinforcement	kg	-2.33E-08	-2.88E-05	-4.20E-03	-3.76E-10	-3.04E-06	-2.41E-05	-4.19E-06	-1.88E-03	-2.68E-05	-1.17E-01	-9.79E-06	-6.06E-02	0.00	-0.01	0.00	-0.02	0.00
Steel fibres	Reinforcement	kg	-2.18E-04	-1.05E-03	-2.36E-01	-4.49E-09	-1.02E-04	-9.11E-04	-3.17E-04					-1.01E-04	0.00	0.00	0.00	0.00	-0.84
Tap water	Water	kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00	0.00	0.00	0.00	0.00
Steel rebar	Reinforcement	kg	-2.18E-04	-1.05E-03	-2.36E-01	-4.49E-09	-1.02E-04	-9.11E-04	-3.17E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	-1.01E-04	0.00	0.00	-1.57	0.00	0.00
														-5.49	-5.50	-7.07	-5.48	-6.33

1m3	**Traditional mixture (no fibres)**	**Basalt rebar**	**Steel rebar**	**30 (Basalt)**	**45 (Steel)**
A1-A3	21.68	26.43	35.39	32.53	30.54
C1-C4	2.13	2.17	2.19	2.17	2.15
D	-5.49	-5.50	-7.07	-5.48	-6.33
Total	18.31	23.11	30.51	29.23	26.37

1 apron EC	**Traditional mixture (no fibres)**	**Basalt rebar 50 yrs**	**Basalt rebar 100 yrs**	**Steel rebar 50 yrs**	**30 (Basalt) 50 yrs**	**30 (Basalt) 100 yrs**	**45 (Steel) 50 yrs**
A1-A3	17.97	0.44	0.22	0.59	0.54	0.27	0.51
C1-C4	1.76	0.04	0.02	0.04	0.04	0.02	0.04
D	-4.55	-0.09	-0.05	-0.12	-0.09	-0.05	-0.10
Total	15.18	0.38	0.19	0.51	0.48	0.24	0.44

0.82875

Anchorage length

The base anchorage length is described by equation AG.1. This is officially the norm for steel rebars. As confirmed by ReforceTech the BasBars are confirmed to have similar and even higher bond strengths compared to steel rebars.

$l_{b,rqd} = (\phi/4)(\sigma_{sd}/f_{bd})$ (eq. AG.1)

Where:

$\phi = bar\ diameter\ [mm]$

$\sigma_{sd} = design\ value\ of\ the\ stress\ in\ the\ point\ from\ where\ the\ anchorage\ is\ measured\ [MPa]$

$f_{bd} = 2.25\eta_1\eta_2 f_{ctd}$ (eq. AG.2)

Where:

$\eta_1 = coeficient\ for\ quality\ of\ attachment\ \eta_1 = 1.0\ for\ good\ circomstances\ \&\ \eta_1 = 0.7\ for\ other\ circomstances\ (\eta_1 = 0.7\ is\ assumed\ as\ bars\ are\ not\ ribbed)$

$\eta_2 = determined\ by\ bar\ diameter\ \eta_2 = 1.0\ for\ \phi \leq 32\ mm\ \&\ \eta_2 = (132 - \phi)/100\ for\ \phi > 32\ mm$

$f_{ctd} = f_{ctk,0.05}/\gamma_c\ = design\ value\ of\ the\ tensile\ strength\ of\ the\ concrete$

The design value of the anchorage length is:

$l_{bd} = \alpha_1\alpha_2\alpha_3\alpha_4\alpha_5 l_{b,rqd} \geq l_{b,min}$ (eq. AG.3)

Where:

$\alpha_1,\ \alpha_2,\ \alpha_3,\ \alpha_4\ \&\ \alpha_5$ follow from table 8.2 and figure 8.4 from Eurocode 2 (NEN, 2020) depicted in table AG.1 and figure AG.1. Note that the product $(\alpha_2\alpha_3\alpha_5) \geq 0.7$.

$l_{b,min} \geq \max\{0.3l_{b,rqd}; 10\phi; 100\ mm\}$ for tensile anchorages (eq. AG.4)

Table AG.1: Values for the coefficients $\alpha_1, \alpha_2, \alpha_3, \alpha_4$ and α_5

Invloedsfactor	Type verankering	Wapeningsstaaf: Trekstaaf	Wapeningsstaaf: Drukstaaf
Vorm van de staaf	recht	$\alpha_1 = 1{,}0$	$\alpha_1 = 1{,}0$
	anders dan recht (zie figuur 8.1 (b), (c) en (d)	$\alpha_1 = 0{,}7$ als $c_d > 3\,\phi$ anders $\alpha_1 = 1{,}0$ (zie figuur 8.3 voor waarden van c_d)	$\alpha_1 = 1{,}0$
Betondekking	recht	$\alpha_2 = 1 - 0{,}15\,(c_d - \phi)/\phi$ $\geq 0{,}7$ $\leq 1{,}0$	$\alpha_2 = 1{,}0$
	anders dan recht (zie figuur 8.1 (b), (c) en (d))	$\alpha_2 = 1 - 0{,}15\,(c_d - 3\,\phi)/\phi$ $\geq 0{,}7$ $\leq 1{,}0$ (zie figuur 8.3 voor waarden van c_d)	$\alpha_2 = 1{,}0$
Opsluiting door dwarswapening, niet gelast aan de hoofdwapening	alle types	$\alpha_3 = 1 - K\lambda$ $\geq 0{,}7$ $\leq 1{,}0$	$\alpha_3 = 1{,}0$
Opsluiting door gelaste dwarswapening *	alle types, positie en afmeting als gespecificeerd in figuur 8.1 (e)	$\alpha_4 = 0{,}7$	$\alpha_4 = 0{,}7$
Opsluiting door dwarsdruk	alle types	$\alpha_5 = 1 - 0{,}04\,p$ $\geq 0{,}7$ $\leq 1{,}0$	–

waarin:

λ $= (\Sigma A_{st} - \Sigma A_{st,min})/ A_s$;

ΣA_{st} oppervlakte van de dwarsdoorsnede van de dwarswapening langs de rekenwaarde van de verankeringslengte l_{bd};

$\Sigma A_{st,min}$ oppervlakte van de dwarsdoorsnede van de minimale dwarswapening; $= 0{,}25\,A_s$ voor balken en 0 voor platen;

A_s oppervlakte van de doorsnede van een enkelvoudig verankerde staaf met maximale staafdiameter;

K waarden getoond in figuur 8.4;

p druk in dwarsrichting (MPa) in de uiterste grenstoestand langs l_{bd}.

* Zie ook 8.6: Voor directe opleggingen mag l_{bd} kleiner zijn genomen dan $l_{b,min}$, op voorwaarde dat er ten minste één dwarsdraad is gelast binnen de oplegging. Dit behoort ten minste op 15 mm vanaf de dagkant van de oplegging te zijn.

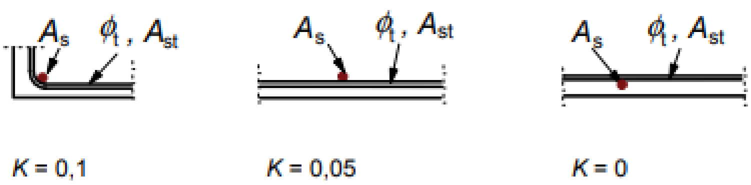


Figure AG.1: Values for K for beams and plates

In the design with BFRP-bars a bar diameter of 6 mm is used. From the SCIA Engineer model from Niek Pouwels it is derived that the governing moments occur between supports at the edges of the aprons, as shown in figures 3.X and 3.X. The governing anchorage length is found when looking at the supports as the place to start the anchorage. The available space here is 140 mm to the edge upwards 200 sideways as seen in the design configuration. The stress in the bars at these locations is assumed to be small enough (close to zero) resulting in $l_{b,qrd} < l_{b,min} = 100\ mm$. This is mainly due to the use of the small bar diameter of 6 mm. Therefore the anchorage length is taken to be 100 mm in all directions. The space left at the top and sides is however taken as 20 mm for execution reasons in order to be able to attach the bars together in both directions.

Note that pull-out tests have not been performed and are advised to be performed before use of the material and to confirm that the bond strengths are indeed similar and/or better than for steel rebars. If pull-out tests show that the bond strength is not sufficient and if other research shows that stresses are higher in the mentioned regions next to the edges of the apron, then the end of the bars must be bended to achieve sufficient bond strength.

Concrete cover

The concrete cover that is used I the design with the BasBars is 15 mm. This is equal to the nominal concrete cover as determined using chapter 4.4.1 from Eurocode 2 (NEN, 2011). This cover is equal to:

$$c_{nom} = c_{min} + \Delta c_{dev} \quad \text{(eq. AG.5)}$$

The minimum cover is calculated using equation AG.6.

$$c_{min} = \max \{c_{min,b}; c_{min,dur} + \Delta c_{dur,\gamma} - \Delta c_{dur,st} - \Delta c_{dur,add}; 10\ mm\} \quad \text{(eq. AG.5)}$$

Where:

$c_{min,b} = 6\ mm\ (diameter\ of\ the\ bar)$

$c_{min,dur} = 10\ mm$

For the minimum cover due to durability the environmental class X0 is assumed as corrosion of the BasBars is not relevant. For the construction class S2 is obtained from table 4.3 in Eurocode 2. After increasing S1 (the minimum strength class) to S3 due to having a design service life of 100 years and decreasing to S2 for having a strength class ≥ C45/55.

$\Delta c_{dur,\gamma}, \Delta c_{dur,st}$ & $\Delta c_{dur,add} = 0$ mm following Eurocode 2 these values can be set to 0 mm.

The Δc_{dev} can be obtained from the National Annex to Eurocode 2 chapter 4.4.1.3 (NEN, 2020) and is equal to 5 mm.

These values result in $c_{min} = 10, \Delta c_{dev} = 5$ & $c_{nom} = 15\ mm$.