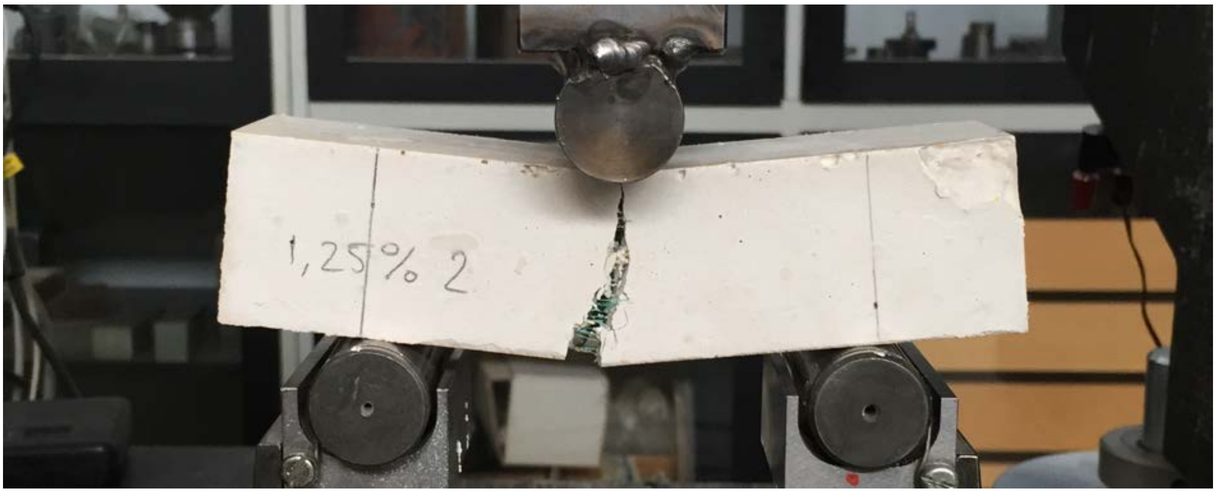
August 2016

Design of a ZeroWaste building material



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Chapter 1

Design of a ZeroWaste building material

1.1 Introduction

The design project covered in this report is based on the ongoing Ph.D. study by Ida Maria Gieysztor Bertelsen which include the reuse of fishing nets. Fibres of these fishing nets are therefore the starting point of development. These fibres are a sub-product of the process making plastic pills for reuse plastic, conducted by Plastix Global. Such fibres can be used for many different things, using them to improve material properties would however increase their value considerably and is then the first use to be attempted.
When used in composites to improve material properties fibres usually add strength and/or ductility, for the design project covered in this report, plaster will be used as the main material of the composites. Plaster is chosen based on three main reasons, it sets rapidly which is suitable for the duration of this project, it is very brittle and has a low tensile strength why the effect of the fibres should be easily recorded, finally though often procured by grinding stone it also occurs as a waste product of cleaning gas and so the composite could be made of strictly reused materials.
Plaster is generally mixed with fresh water, however fresh water is a valuable resource and should not be wasted. Mixing plaster with saline water will therefore be part of the design process in order to seek an even higher degree of sustainability.

A ZeroWaste building material is not only a material where each component of the material is sustainable, it must also be usable in construction, why the plaster composite proposed in this report will be evaluated upon malleability, compression strength, bending properties, and relevant visual observations.

1.2 Practical considerations

There are no set standards on casting nor testing plaster why the design of experiments for this study are based on hands-on experience and literature describing similar testing of mortar specimens.

1.2.1 Materials

Plaster

Plaster is a material that has been widely used through-out history, and is still used in construction mainly due to its fire resistance, sound insulation, and moisture transport abilities. However plaster is a very brittle material making it unsuitable for structural uses where announced fractures are wanted.

The plaster used in the specimens tested in relation to this study is ”Miller Modelgips” delivered from C. Flauenskjold A/S. This is the same plaster as used in the DTU course 11561 ”Construction Materials - use and testing”, to ensure some experience with the material and a potential for comparison with

previous tests. All information on the material is based on the course material Hansen (2016) and the information-ark accompanying the delivery. Material properties are given in table 1.2.1.
For casting this plaster a water to plaster relation of 7/16 is recommended.

Fibres

Glass fibres are commonly used in plaster composites to obtain the needed ductility for announced fracture. For the tests conducted in relation to this report the previously mentioned fishing net fibres will be used instead. The fishing net fibres are made from high density polyethylene (HDPE), the material properties are determined from previous studies by Ida Maria Gieysztor Bertelsen, and are given in table 1.2.1.

Table 1.2.1: Material properties

Plaster		Fibres	
Elastic modulus [GPa]	Compressive strength [MPa]	Elastic modulus [GPa]	Tensile strength [MPa]
10	10	1	300-450

1.2.2 Mixing and casting

Plaster is usually mixed by adding the plaster powder to the water, not the other way around, Hagemann (1977). However since fibres were to be added in some specimens, it is known from previous experience, (Hansen, 2016), that fibres can be difficult to mix into plaster this way. Therefore it is decided that water should be added to the plaster powder, allowing for fibres to be mixed into the dry powder.
Plaster is expected to be processable for 5-10 minutes after it has been mixed, the time spend on mixing is known to have an influence on this time. Increased time spend on mixing decreases the time window for casting. It is decided that each batch shall be mixed for 15 seconds after the water has been added, this mixing is done in a HOBART kitchen machine. A manual mix is done to ensure an even mix.
Each batch consists of 1600 grams of plaster powder and 700 grams of water, enough for three specimens regardless if it is the cylinder or prism moulds. When cast, each mould is filled to 1/3 of the total volume, vibration of 55 Hz is then initiated and kept constant while the moulds are filled in small portions. The top of the moulds are swept so that the plaster levels with the mould. A metal top is held in place with clamps or weight for the cylinder and prism moulds respectively.
All equipment is cleaned immediately after use.
The entire process takes a total of 6.5 minutes. It is observed during cleaning that only approximately one more minute of process time can be allowed before the equipment no longer can be properly cleaned.

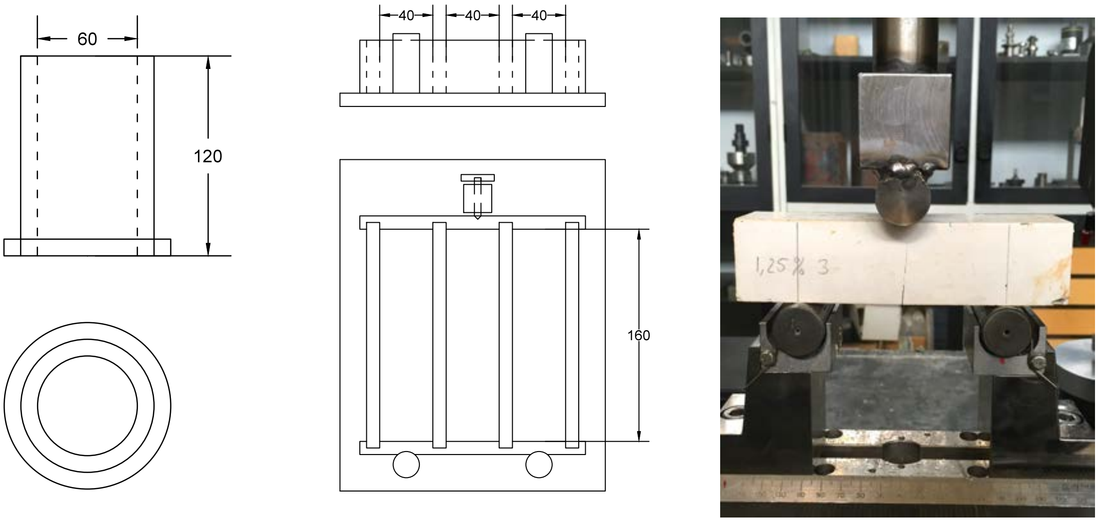
1.2.3 Structural tests

Cylinder compression tests

Specimens for the compression test are cast in cylinder moulds with a diameter of 60 mm and a height of 120 mm, as can be seen on figure 1.2.1(a).
Each specimen is tested in a TONI Industries compression machine. The dimensions of the specimens are given to the machine, the test is force controlled with a rate of 1 kN/sec for the time-dependant specimens and 0.5 kN/sec for the remaining tests.
Each specimen is by default tested until the machine registers a fracture in the material, defined as a sudden decrease in the force acting on the piston. Compression is continued for 10 mm deformation after fracture to clearly show the fracture behaviour of the specimen.

Beam bending tests

Specimens for the bending test are cast as prisms. These specimens are dimensioned and tested in correspondence with the standard testing of mortar prisms, Standard (2005).



(a) Drawing of the cylinder moulds with measurements relevant to the size of the specimen given.

(b) Drawing of the prism moulds with measurements relevant to the size of the specimen given.

(c) Picture of the set-up used for three-point bending of the prisms.

The specimens are 160 mm long and have a square cross section width 40 mm sides.
Testing is conducted on a 10 kN Instron machine with a Instron control system, in a three-point bending set-up according to Standard (2005) and shown on figure 1.2.1(c). The supports are 100 mm apart, the load is applied midway between the supports.
The test is deformation controlled with a rate of 1 mm/min. To obtain usable results for the ductile post-peak behaviour but conserve time, it is decided that each specimen will be tested to a deflection of 5 mm.

1.3 Preliminary compression tests

1.3.1 Time-dependent tests

The time-dependant test series is the first specimens that are cast. This series therefore have two purposes, one is to determine the wanted setting time of the specimens in the future series, the second purpose is to get familiar with the casting process so that future specimens can be cast as consistently as possible.
The expected compressive strength for the used plaster is 10 MPa and it is expected that 72 hours of setting time will be adequate.

A total of 8 cylinders are successfully cast and tested. While testing only one cylinder for each time interval, the compressive strength measured is of limited use, however observing how the setting of the cylinders quite clearly showed how the water evaporate from the voids of the plaster. The specimens are de-moulded after one hour where the specimens are firm and all there is left for the plaster to gain full strength is the voids drying out. Testing after the first hour the specimen still feels wet throughout, as the setting time increases the specimen starts to dry from the outside in. At three hours setting time the difference in moisture is quite clear when inspecting the fracture , when passing 48 hours the specimens start to seem dried out to a reasonable extend and the 72 hours setting time is decided for the further testing.

1.3.2 Saline water tests

To exploit the possibilities of using saline water instead of fresh water when mixing plaster. Knowing that saline water is an accelerator to the setting process of plaster this test is also conducted in cylinders

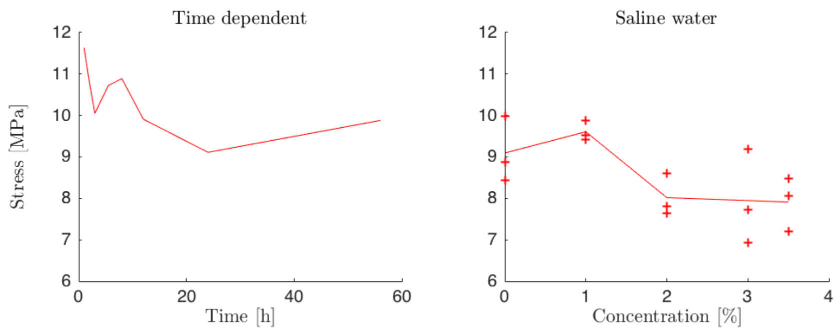


Figure 1.3.1: Compressive strength of the time-dependant and saline cylinders.

since they are the easier to cast. Since ocean water is known to have an average salinity of 3.5%. A series of specimens are planned where the salinity of the water used for mixing increase by 1%. Initially the series was planned to 5% however 3% proved to be setting very fast and was almost not possible to cast. The 3.5% series was therefore the last series to be cast allowing the test to cover salinity from fresh water to average ocean water.
All saline water specimens are de-moulded after 1 hour and left to set for a total of 48 hours before testet. As already mentioned the setting process is accelerated when saline water is used, the process is accelerated to such an extend that the equipment could not be cleaned for the 3% and the 3.5% saline water. Even before knowing the strength effects of saline water, it is certain that any salinity above 2% of the water used for mixing will accelerate the setting process to such an extend that proper casting would be impossible. As seen from figure **??** the compressive strength also seem to decrease for high salinity.

1.4 Fibre tests

Before focusing on the composite specimens, there are some important observations to make on the fibres: The fibres are of very different length, they vary from approximately 1 mm to 50 mm. The fibres are of different colours, in this study it is not clarified if each colour also means different thickness or material properties. The fibres are dirty, one gets greasy fingers when handling the fibres.
These inconsistencies are hard to evaluate in theory, to clarify if the fibres can be used untreated it is decided to make two series of fibre composites, one with cleaned fibres, and one with uncleaned fibres. For both series of specimens the difference in fibre lengths are assumed to be evenly distributed in a batch.
The effect of the fibres will be studied through different fibre concentrations measured as percentage by weight. A series of both cylinder and beam specimens with fibre concentrations from 0.0% to 2.0% with intervals of 0.25% is therefore planned for both the cleaned and uncleaned fibres. For the clean fibre series additional batches of 3% and 4% are made to investigate a potential upper limit for the fibre concentration.

To clean the fibres a volume of 1.5 litres is distributed into three large buckets where they are manually separated while hot water is running through them and filling the bucket with water. The fibres are then left for approximately 12 hours for the dirt to deposit. Then the fibres are collected from the top with minimum disturbance of the water. The process is then repeated two additional times before the fibres are laid out to dry.

1.5 Results

1.5.1 Compression tests

Compression tests of the cylinders with cleaned fibres shows a relatively unchanged compression strength for fibre concentrations between 0% and 2% with and average strength of 10.16 MPa. At 3 and 4% the

fibre concentration seem to have become so large that the strength of the composite is lowered, at 4% the mean compressive strength is at only 6.45 MPa, which is approximately 60% of the compressive strength at lower fibre concentrations. Furthermore the fracture is no longer well defined for the highest fibre concentrations.
Compression tests of the uncleaned fibres show less ductility as most of the specimens don't show a well defined fracture. Notice that the uncleaned fibre specimens show less compressive strength than the cleaned fibre specimens, 7.73 MPa on average from 0% to 2%. This indicates that the dirt on the fibres has a non beneficial influence on the strength of the cylinders. However it must be noted that the strength of the reference specimens are also lower than it was for the cleaned fibre reference specimens. This is first of all due to a change in the set-up resulting in the first specimens being tested with a shear load, before it was noted and corrected. This would lead to a lower compressive strength, so whether the lower strength is only caused by this, or whether this cast in general had less compressive strength is not clear and so to really be usable results, further studies with testing of more specimens should be conducted.

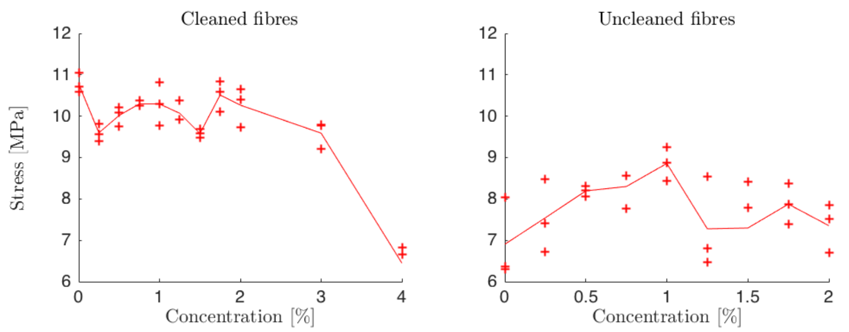


Figure 1.5.1: Compressive strength of the cleaned and uncleaned fibre cylinders.

1.5.2 Bending tests

Results from the beam testing are evaluated on five different parameters based on the deformation-load plot, shown conceptually on figure 1.5.2. The curve can roughly be separated into two main behaviours, left of the first vertical dashed line is the linear elastic behaviour, right of this line is the ductile post-peak behaviour. In the linear elastic behaviour three values are considered, the elastic modulus [kN/mm], the first fracture load [kN], and the deformation equivalent to the first fracture load [mm]. In the ductile post-peak behaviour two values are considered, the second fracture load [kN] and the fracture energy [Nm].

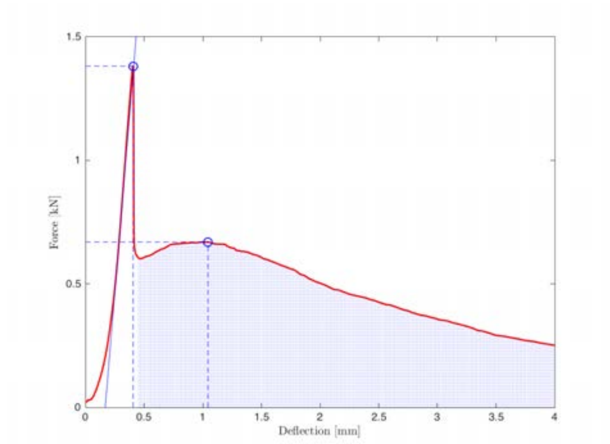


Figure 1.5.2: A typical deformation-load curve for the bending of a fibre reinforced plaster beam. In the linear elastic zone: The elastic modulus is shown with a blue line along the slope of the first peak, the first fracture point is shown with a blue circle at the top of the first peak, corresponding load and deflection values are shown with dashed lines. In the ductile post-peak behaviour zone: The second fracture point is shown with a blue circle on the highest point of the 'tail', the fracture energy is the area under the 'tail' shown with the blue hatch.

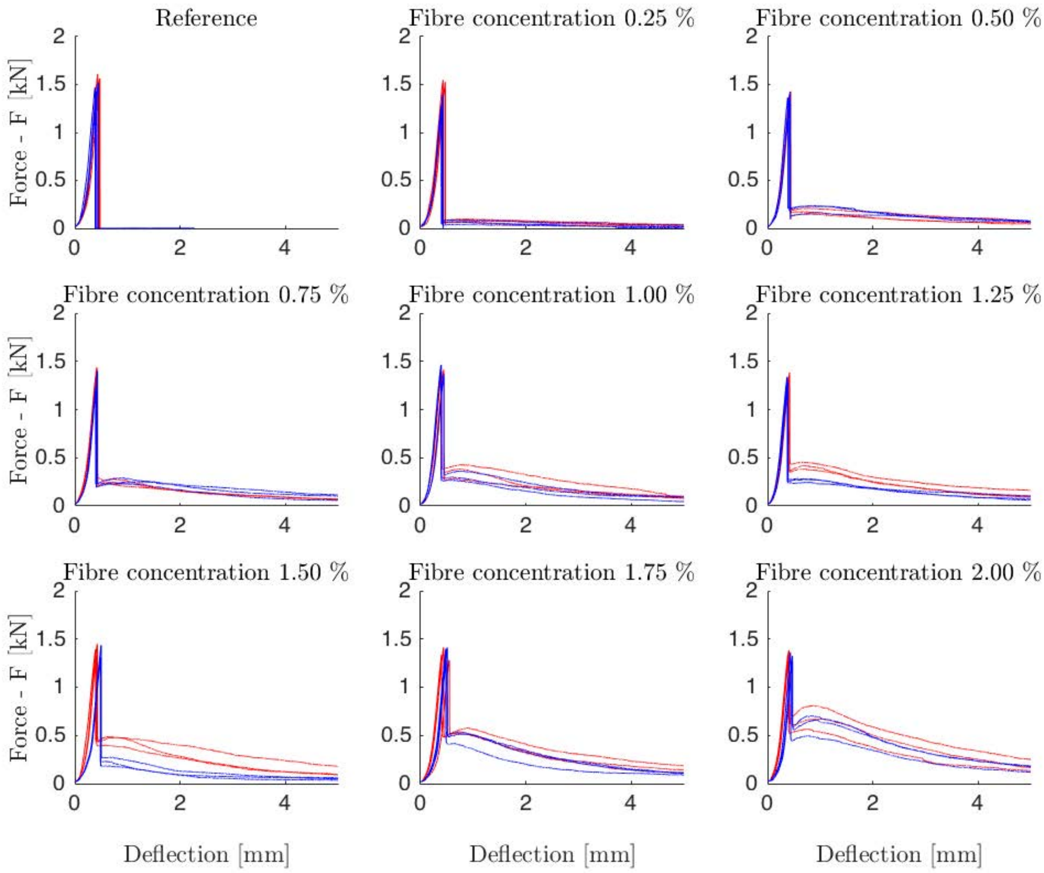


Figure 1.5.3: Deformation-load curves for all the tested prism specimens. The cleaned fibre specimens are shown with red curves, the uncleaned fibre specimens are shown with blue curves.

The deformation-load curves for all the tested specimens are shown on figure 1.5.3. From these curves it is seen how the reference specimens with no fibres have a completely brittle fracture with not ductile post-peak behaviour at all and so how the ductile behaviour and so the fracture energy increase as fibres are added to the plaster.
From this figure it is also seen how the uncleaned fibre specimens (blue curves) are generally showing a little flatter curves than the cleaned fibre specimens (red curves). To further illustrate the development of each of the previously described parameters they are shown on figure 1.5.4.

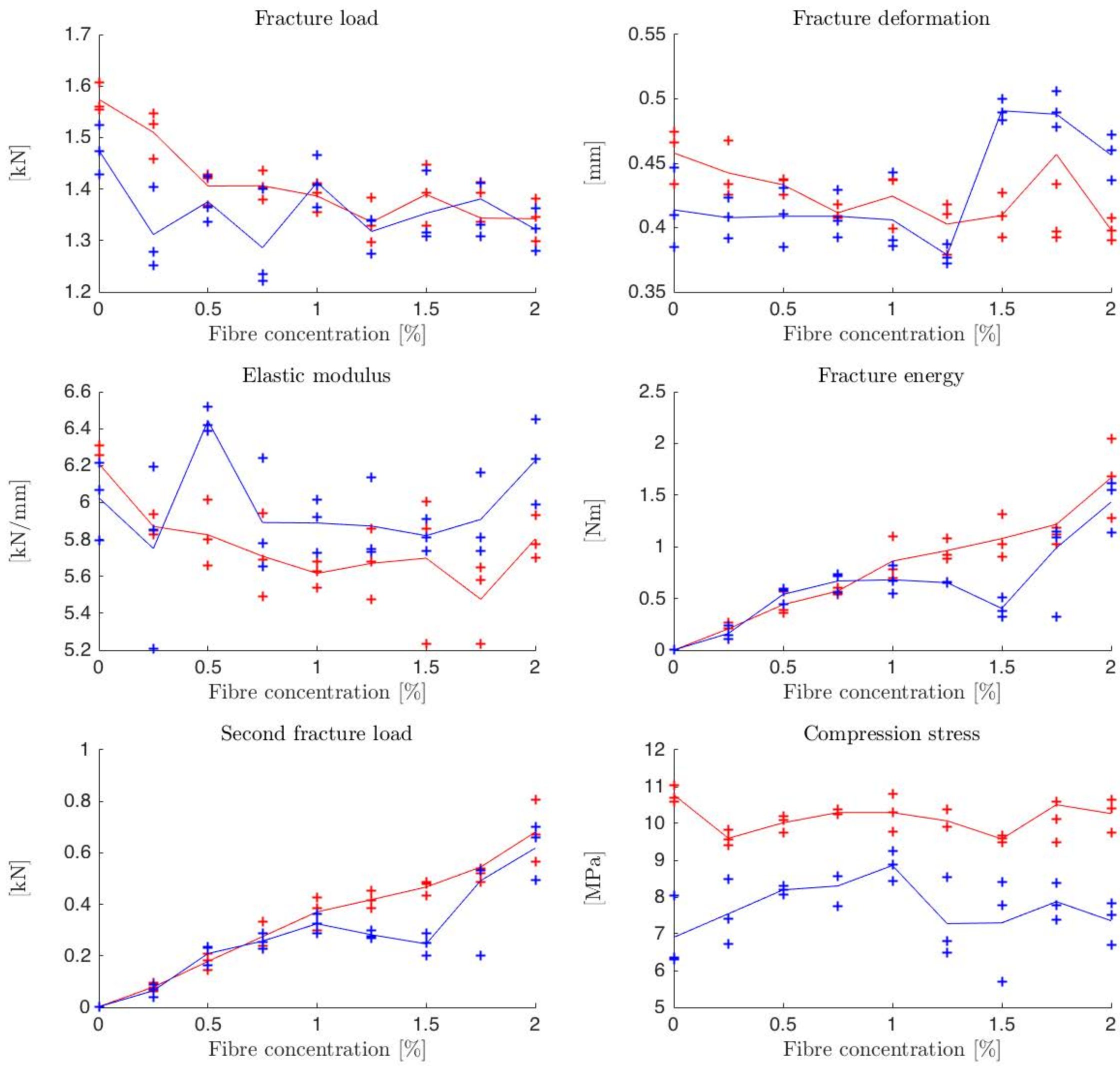


Figure 1.5.4: Comparison of cleaned and uncleaned specimens on each of the chosen parameters dependant on fibre concentration. The cleaned fibre specimens are shown with red curves, the uncleaned fibre specimens are shown with blue curves.

From figure 1.5.4 each of the parameters for evaluating the effect of increasing fibre concentrations in the specimens are shown separately together with the compressive strength of the corresponding cylinder tests.
Considering the cleaned fibre specimens (red curves), most noticeable is the decrease in first fracture load

and elastic modulus as well as the increase in second fracture load and fracture energy. Generally the uncleaned fibre specimens have the same behaviour as the cleaned fibre specimens however each of the values seem to be lower compared to using the same amount of cleaned fibres and there appear to be a greater variation in the results. For the elastic modulus however, the behaviour of the uncleaned fibres appear to be opposite to the one of the cleaned fibres and so the ealstic modulus increases with increasing concentration of uncleaned fibres. This indicates that the dirt on the fibres add to the stiffness of the plaster.

1.5.3 Observations

During the bending tests of the prism specimens, the crack-growth is visually inspected as the testing is conducted. For the reference specimens there is no visible crack-growth as the specimen completely splits in half as soon as a crack is initiated. For the lowest fibre concentration specimens there is no visible crack-growth in the definition of splitting the plaster, however these specimen do not separate at the point of fracture, why a crack-growth is somehow seen as the crack-width, especially at the bottom of the beam, increases. Already at a fibre concentration of 0.50% a visible crack growth in the material can be observed. The initial crack length is decreasing with an increasing concentration of fibres in the specimens.

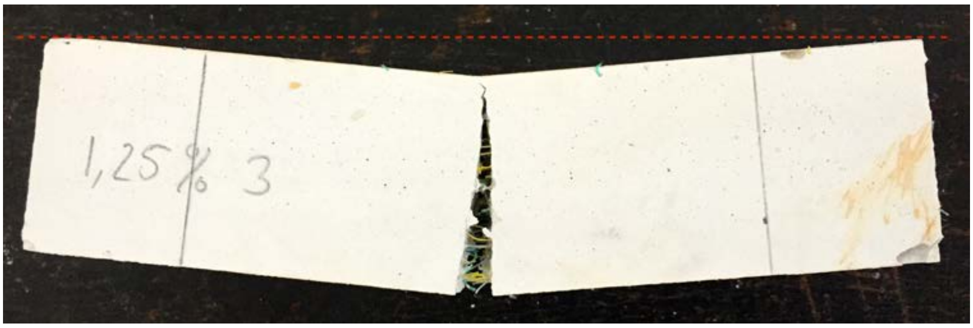


Figure 1.5.5: Remaining deformation of the bend prisms.

From when the crack in the composite specimens are initiated, the crack-growth and widening of the crack can mean multiple things. Most plausible explanations are that the fibres either get pulled out of the specimen or they stretch when the plaster fracture. To further evaluate this cracked state the material of the fibres must be considered. As mentioned in the material section they have an elastic modulus of 1 GPa and a tensile strength of 300-450 MPa it is therefore unlikely that this test will pull the fibres to fracture. However it is quite a small elastic modulus and so a noticeable extension of the fibres would be expected if the forces in the plaster were properly transferred to the fibres. Assuming that the plaster part of the cross section at the point of fracture is completely separated, and that all force is then transferred to the fibres, these would extend with linear elastic behaviour. This behaviour would however mean that the crack width would decrease when the specimen was off-loaded. Though this is not measured during the off-load process, it is within what can be inspected visually not the case and the cracked specimen remains in the same shape as it was in at the maximum point of loading when removed from the machine. This behaviour suggest the other option, that the forces are not properly transferred to the fibres, they are instead pulled out of the specimen.

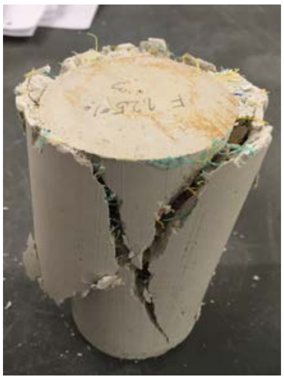
(a) Cylinder after compression test. Reference specimen with no added fibres.

(b) Cylinder after compression test. 0.25% fibre concentration.

(c) Cylinder after compression test. 0.50% fibre concentration.

(d) Cylinder after compression test. 0.75% fibre concentration.

(e) Cylinder after compression test. 1.00% fibre concentration.



(f) Cylinder after compression test. 1.25% fibre concentration.

(g) Cylinder after compression test. 1.50% fibre concentration.

(h) Cylinder after compression test. 1.75% fibre concentration.

(i) Cylinder after compression test. 2.00% fibre concentration.

(j) Cylinder after compression test. 3.00% fibre concentration.

(k) Cylinder after compression test. 4.00% fibre concentration.

Figure 1.5.6: Cylinders after compression to illustrate the effect of the fibre concentration. The shown specimens are cleaned fibre specimens, however the visually detected appearance of the uncleaned fibre specimens after fracture is much comparable.

1.6 Discussion

To be a well dimensioned building material ductility is wanted to such an extend that it will respond with an announced fracture with reserve when it fails. A typical deformation-load curve would have 'the second' fracture load as the highest point as it can be seen as point 1 on figure 1.6.1. This means that the linear elastic part of the curve ends and cracks develop before the material fail.

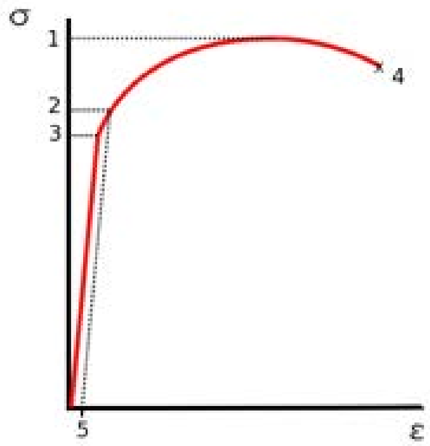


Figure 1.6.1: Example of a plastic behaviour deformation-load curve.

None of the tested specimens have shown this behaviour. However since there is a reasonable 'tail behaviour' of the high fibre concentration specimens the possibilities of further developing the material to have the wanted plastic behaviour should be considered. The increase in the second fracture load for each step up in fibre concentration, it could be investigated if the 3% fibre concentration would provide the plastic-behaviour wanted, the 4% concentration showed porousness to such an extend that it was almost falling apart and so the upper limit for fibre concentration is assumed to be somewhere between 3 and 4%.

Should increasing the fibre concentration not be sufficient, another way to obtain the wanted behaviour would be to lower the strength of the plaster so that the first fracture load would decrease to less than the second. This would obviously weaken the material, however it would be a safer material to use in construction since it would have both announced fracture and reserve.

The strength of the plaster is most easily lowered by increasing the water to plaster relation as can be seen from figure 1.6.2. As can be seen from the dashed readline on the figure, the water to plaster relation needs to be approximately 1.0. This is a large increase in the water to plaster relation and so the fibre contribution to the composite can only be assumed to be the same as in the present experiments.

Besides lowering the strength of the plaster, an increase in the water to plaster relation would also increase the malleability of the plaster and increase the time it takes to set. This would reopen investigation of using saline or brackish water. It could also allow for a higher fibre concentration, however since the upper limit was determined by porousness and not malleability while casting, it is unlikely that this limit would increase.

Regardless if the composite can be designed to have plastic-behaviour or not, then the effects of cleaning the fibres should be discussed, especially when the aim of developing a new building material is to safe resources and produce no waste, the required amount of fresh water to clean the fibres is not ideal. Using the uncleaned fibres would both lower the time- and freshwater consumption of the process, and then make the material more sustainable.

Based on the results displayed in figure 1.5.3 and 1.5.4 it is seen, as was already mentioned in the result section, that the uncleaned fibres tend to have slightly lower fracture loads, however the elastic modulus is seen to be slightly higher for the uncleaned fibres. Considering the previously mentioned alterations to reach a plastic behaviour, the lower first fracture load but almost identical second fracture load for the uncleaned fibres means the water to plaster relation would not have to be increased as much as earlier

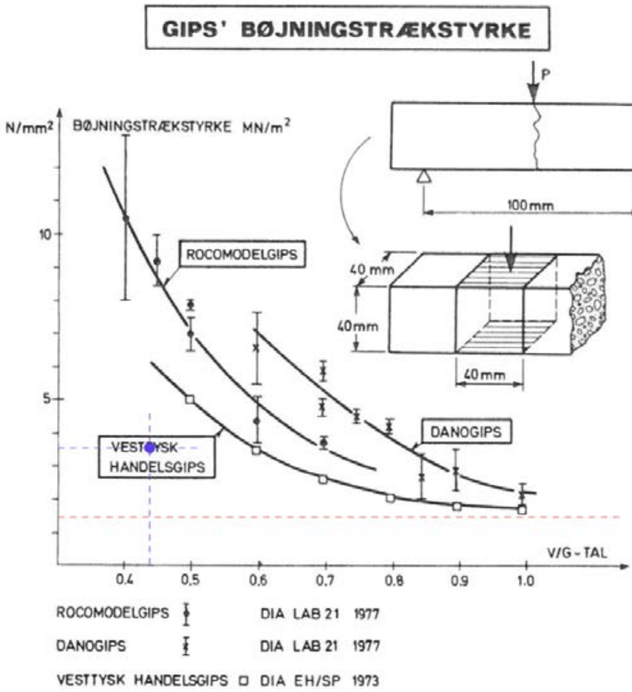


Figure 1.6.2: Experimentally determined bending tensile strength of plaster as a function the water to plaster relation. (Hagemann, 1977). The dashed blue line indicates the strength of the plaster used in the experiments, the dashed red line shows the needed strength of the plaster to create a plastic-behaviour composite.

mentioned, however the difference is quite small.
In general the differences are small, the biggest difference is that there seem to be more inconsistent results with the uncleaned fibres, though a study of more identical specimens would need to be conducted in order to determine this. Therefore a study of the dirt on the fibres in order to determine what it is made of would be beneficial together with more long term tests to ensure that it does not damage the material in other ways than observed in the experiments in relation to this report.

1.7 Conclusion

The time-dependant study is inconclusive, primarily because it is used as a tuning test. A setting time of 48 hours for the saline water specimens and 72 hours for the fibre specimens is decided.
The saline water series show a considerable effect on the setting time of the plaster, showing that a salinity above approximately 3% can be considered impossible to cast properly. The strength seem to decrease with increased salinity.
The fibre composites are tested in both a cleaned fibre and uncleaned fibre series that shows that the strength of the composite is lowered with the uncleaned fibres. All fibre concentrations show an increased strength in the post peak behaviour, however not even the highest fibre concentrations show a plastic behaviour.
Since a plastic behaviour would be preferable in regards of achieving a ductile building material with announced fracture and reserve, multiple consideration to how this could be achieved are discussed, most straight forward seem to be experimenting with lowering the strength of the plaster.
Wanting to lower the strength of the plaster both mixing with saline water and using uncleaned fibres are not necessarily out of the question. Based on the conducted studies a building material made from plaster and reused fishing net fibres is not successfully designed, however the tested composite has shown tendencies worth pursuing. Suggestions for further studies are mentioned bellow.

1.7.1 Future studies

A combination of high fibre concentrations with a higher water to plaster relation should be investigated in order to obtain a material with theoretical plastic behaviour.
For more detail and easier comparison to other materials the stress distribution in the bended beams should be further investigated so that it is known or at least estimated for the post cracked cross section.
In order to minimize the use of fresh water, further studies of using the uncleaned fibres as well as using brackish water for mixing should be conducted. The use of brackish water could be beneficial in regards to bringing down the first fracture load, the higher water to plaster relation needed for the same purpose would also help the malleability when using saline water. Already ongoing experiments with electrolysis conducted by Ida Maria Gieysztor Bertelsen of the uncleaned fibres do however suggest that some of the dirt might be salt which would mean that the effects of saline water might be stronger than seen in this report.

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