



Experimental Study of the Influence of Pre-Stressing the Mesh on the Mechanical Properties of TRM.

Tomas Petri Bhose

Spain | 2016



ADVANCED MASTERS IN STRUCTURAL ANALYSIS  
OF MONUMENTS AND HISTORICAL CONSTRUCTIONS

# Master's Thesis

Tomas Petri Bhose

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Influence of Pre-Stressing  
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UNIVERSITAT POLITÈCNICA  
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University of Minho



Education and Culture

## Erasmus Mundus



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### **Experimental Study of the Influence of Pre-Stressing the Mesh on the Mechanical Properties of TRM.**

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Spain | 2016

## DECLARATION

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Year: 2016

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

I hereby declare that the MSc Consortium responsible for the Advanced Masters in Structural Analysis of Monuments and Historical Constructions is allowed to store and make available electronically the present MSc Dissertation.

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Dedication page (fully optional)

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## **ABSTRACT**

Textile-Reinforced Mortar (TRM) is very promising composite material to be used for strengthening of heritage structures. Its inorganic nature is making it totally compatible with historical masonry and adobe buildings as well as with low grade concrete elements.

TRM that can be also called Fabric-Reinforced Cementitious Matrix (FRCM), is composite material consisting matrix (mortar) and fibres (often arranged in textiles). During the last years TRM has been already used to strengthen masonry and concrete structures. This material is a promising alternative for other composite materials used in construction, as Fibre-Reinforced Polymer (FRP) and for some other more traditional strengthening techniques.

There has been already multiple studies related to TRM composites and its chemical and physical properties. Also many interesting studies have been done to find best possible testing methods, combination of different materials used as well as best application practices. It seems though that the effect of pre-stressing to the TRM composite has not been studied until today.

This work consists of the experimental study of the effect of the pre-stressing of textiles before the casting to the TRM, main focus in changes on mechanical properties and failure modes.

This study is also investigating how the different testing speeds in displacement controlled unidirectional tensile test is impacting to the results.

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## RESUMEN

El Textile-Reinforced Mortar (TRM) es un material compuesto prometedor para ser utilizado como refuerzo de estructuras históricas. Su naturaleza inorgánica lo convierte en un material totalmente compatible con mampostería antigua y edificios hechos de adobe, así como elementos de hormigón de bajas prestaciones.

El TRM, que también es conocido como Fabric-Reinforced Cementitious Matrix (FRCM), es un material compuesto consistente en una matriz (mortero) y fibras (habitualmente organizadas en tejidos). Durante los últimos años, el TRM ha sido utilizado para reforzar estructuras de mampostería y hormigón armado. Este material es una prometedora alternativa para otros materiales compuestos utilizados en la construcción, como el Fibre-Reinforced Polymer (FRP), y para otras técnicas tradicionales de refuerzo.

Existen múltiples estudios relacionados con los materiales compuestos tipo TRM y sus propiedades químicas y físicas. Además, se han realizado muchos estudios interesantes acerca de los posibles métodos de ensayo, combinación de diferentes materiales así como las mejores prácticas de aplicación. A pesar de ello, los efectos de pretensar el TRM no han sido estudiados hasta el momento.

Este trabajo consiste en el estudio experimental de los efectos del pretensar los tejidos antes de ejecutar el TRM, principalmente enfocados a los cambios en las propiedades mecánicas y los modos de fallo.

Además este estudio investiga la influencia que presenta la velocidad de ensayo bajo control por desplazamiento en los resultados.

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## TIIVISTELMÄ

Tekstiili vahvistetut laastit (TRM) ovat vielä suhteellisen uusia, mutta lupaavia materiaaleja käytettäväksi historiallisten rakenteiden vahvistamisessa. TRMn epäorgaaninen luonne tekee siitä hyvin yhteensopivan materiaalin erityisesti muurattujen tiili ja kivi rakenteiden kanssa. Tämän lisäksi se sopii hyvin käytettäväksi savitiili ja betoni rakenteiden vahvistukseen.

TRM jota usein kutsutaan myöskin nimellä tekstiili vahvistettu sementinomainen laasti (FRCM) on komposiitti materiaali joka koostuu sidosaineesta (laasti) sekä kuiduista joka on usein tekstiilin muodossa. Sidosaaineena käytetään usein laastia johon on lisätty lyhyitä kuidun pätkiä sekä lisäaineita jotka vahvistavat sidosta tekstiilin ja laastin välillä. Viimevuosina näitä materiaaleja on jo käytetty historiallisten rakenteiden vahvistamiseen ja sen katsotaankin olevan lupaava vaihtoehto kuitu vahvistetuille polymeereille (FRP) sekä perinteisemmille vahvistusmenetelmille.

TRM komposiittien kemikaalisia ja fysikaalisia ominaisuuksia on jo tutkittu useissa tutkimuksissa. Samoin erilaisista testaus menetelmistä, materiaali yhdistelmistä sekä implementointi tavoista on tutkimuksia tehtynä. Näyttäisi kuitenkin siltä, että tekstiili vahvistetun laastin esijännittämisen vaikutuksia itse komposiittiin ei ole vielä toistaiseksi tutkittu. Tämä raportti tutkii esijännittämisen vaikutuksia kyseiseen materiaaliin. Erityisesti tarkastellaan sen vaikutusta veto lujuteen, jäykkyyteen sekä tapaan jolla koepalat rikkoutuvat.

Tämän lisäksi tämä tutkimus tarkastelee eri testi nopeuksien vaikutusta vetolujuustestin tuloksiin.

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## 1 INTRODUCTION

### 1.1 Motivation for the present research

During the last centuries humans have been building new buildings with ever increasing speed. This has led in to the situation where the need of the conservation and restoration of existing infrastructure is getting more and more important. Also big part of the budgets in many developed countries is moving from the new constructions towards restoration work. More detailed information about the estimations of future investments for restoration work can be found from research by (P. Larrinaga, 2011).

Lately it has been also understood that existing buildings are part of our cultural heritage that can be considered as a living document of ancient knowledge as well as providing identity to the different cultures (ICOMOS). It is also bringing lot of value in monetary wise through the tourism industry. In some locations heritage structures are the main reason for tourists to visit bringing extra income to those communities. This all is promoting the value of historical monuments and constructions bringing more need to conserve those for the future generations as well.

During the past multiple techniques has been used to restore ancient structures with variable success. Some promising new materials have been later approved to be more damaging than conserving. This has led to the today's trend where minimum intervention approach is preferred (ICOMOS). In one side interventions should be avoided to keep the integrity of the historical buildings but same time it has been learned that one of the most effective way to destroy the old building is to leave it without any use. As today, many communities are trying to innovate new ideas how to use old buildings to avoid degradation and this is sometimes requiring new restoration and strengthening methods. Other reasons for need of repairing or strengthening could be settlement, seismic actions, change in environmental conditions, structural problems due to defects on design, materials or construction, building code changes or just deterioration because of ageing.

There is number of different strengthening methods available including conventional enlargement of existing elements or by building external supports. There is also many later invented techniques like repointing, post-stressing, grouting and externally bonded Fibre-Reinforced Polymers (FRP). All these techniques can be beneficial when used in correct ways in correct situations. Textile-Reinforced Mortar (TRM) is one of these promising techniques with some positive qualities that some other techniques are lacking. Due to its inorganic nature it is especially attractive to be used for historical structures where it is very important to have compatible chemical and physical properties with the parent materials. Multiple studies has been already done related to TRM and it has been also used in many locations. It has lot of possibilities due to its; inorganic nature, remarkable increment of both capacity and deformability, compatibility with historical materials and removability. By choosing right kind of application with matching material properties it can be used for concrete, masonry and adobe structures. It has also very promising possibilities in seismic areas where vernacular buildings can be

rather weakly constructed with poor materials. Besides all these positive properties one of the drawbacks that has been experienced is the cracking of the mortar that happens much before reaching to the ultimate capacity of the TRM. This will possibly expose the fibres to the direct sunlight, water and external physical impacts.

This work is studying how the pre-stressing of textiles would effect to the behaviour of the TRM composite. Especially how this will effect to the ultimate load, stiffness, failure mode and bonding. Another objective was to study the influence of different testing speeds used in displacement controlled unidirectional tensile test.

## 1.2 Objective of the research

Aim of this experiment is to study the effects of pre-stressing of textiles in Textile-Reinforced Mortar (TRM) to contribute to the conservation of our constructed historical heritage. Influence of different testing setups and also the influence of different testing speeds were measured. Finally results will be compared between unstressed and pre-stressed TRM to understand the effect for ultimate stress, failure mode and bonding strength.

First step was to design and built the pre-stressing system that would enable to pre-stress the textiles to produce pre-stressed Textile-Reinforced Mortar (PTRM) composite. Second step was to test the textiles to determine the adequate tensile load to be used during the casting. Third step was to produce the specimens by casting. Fourth step was to prepare the samples for testing by clueing steel plates on both ends of the samples to enable to connect the samples to the tensile testing device. Fifth step was to find optimal connecting mechanism during the tensile testing to minimize any possible bending moments towards the sample. Sixth step was to analyse the results by comparing unstressed and pre-stressed samples with different displacement velocities.

## 1.3 Outline of the thesis

The present report is divided in to five chapters. Main focus is to study how the pre-stressing of textile reinforced mortar is effecting for material properties to be used in cultural heritage structures.

Chapter 1 includes introduction, objectives and outline of this study. Here the importance of conserving of our built cultural heritage is highlighted and objectives of this study listed.

Chapter 2 is presenting the state of the art.

Chapter 3 focuses on experimental campaign, where testing setup is explained in detailed manner. This chapter covers also the results from the experimental campaign. In discussion part more information is added to explain the results including possible reasoning.

Chapter 4 presents final conclusions and introduces possible future research lines by the author.

## 2 STATE OF THE ART

This chapter covers general introduction of strengthening of historical structures with Textile-Reinforced Mortar (TRM), it is presenting the components of TRM and comparing it to the other common strengthening methods. State of the art chapter is also introducing most used testing methods and reasoning to the choices made for this experimental campaign.

### 2.1 Common repairing and strengthening methods

Like discussed in introduction section the value of historical buildings and monuments is crucial for many societies and indispensable concerning our global cultural heritage. To conserve this cultural heritage in best possible way there is constant need to innovate new and develop existing strengthening techniques. As there is multiple strengthening techniques available it is important to understand their adequacy and use them in correct surroundings.

In this section some most commonly used techniques are introduced shortly to give better understanding of benefits of TRM technique.

#### 2.1.1 Fibre-Reinforced Polymer (FRP)

From the beginning of the 1990s the FRP has been promising technique with many advantages like light weight, easiness to apply, immunity for corrosion, high tensile strength and flexibility. Soon it also appeared that there is multiple drawbacks especially when used in historical buildings. Some of these disadvantages are non-vapour permeability, stiffness that is much higher than in masonry, lack of fire resistance, non-applicability on wet surfaces or in low temperatures and being as non-reversible technique. FRP technique is also banned to be used in heritage interventions. (Pellergino Carlo, 2015)

FRP can be applied by using either Near Surface Mounted (NSM) or Externally Bonded Reinforcement (EBR) technique. These techniques can be also combined with pre-stressing.

Possible applications: beams, columns, slabs and walls.

Benefits:

- Lightweight
- Easy to apply
- Corrosion resistant
- High mechanical properties on both stiffness and strength
- Good fatigue behaviour

Disadvantages:

- Not always compatible with parent materials in historical structures
- Low resistance to fire
- Not possible to apply on wet surface or on cold environment
- Vulnerable for external physical damages
- Not vapour permeable
- No data available for its long term durability
- Toxic
- Relatively high cost



**Figure 1. Applying FRP.**

### **2.1.2 Repointing (Valluzzi, Binda, & Modena, 2005)**

Repointing is done by inserting reinforcement in to the mortar bed joint in masonry. As reinforcements steel rods or fibres can be used.

Possible applications: Masonry structures

Benefits:

- Reduce vertical cracking and creep

Disadvantages:

- Laborious to apply



**Figure 2. Repointing**

### **2.1.3 Grouting** (Binda, Modena, Baronio, & Abbaneo, 1997)

Grouting is commonly used to connect separated leafs in old masonry walls. It is applied by injecting liquid mortar or grout inside existing structure. The process starts from the bottom of the wall proceeding step by step until top of the wall is reached.

Possible applications: Masonry walls and columns

Benefits:

- Increasing flexural strength
- Connecting separated leafs

Disadvantages:

- Non-reversible



**Figure 3. Grouting**

### **2.1.4 Enlargement and overlays**

Addition of material on existing structure.

Possible applications: beams, columns, slabs and walls.

Benefits:

- Increase the stiffness, strength and ductility
- Compatible with parent material properties

Disadvantages:

- Increasing size and dead weight of the structure.



**Figure 4. Enlargement**

### **2.1.5 Post-tensioning**

Post-tensioning existing structural members.

Possible applications: Beams, columns, slabs and walls.

Benefits:

- Deflection reduction
- Crack width reduction
- Delay the yielding of the existing reinforcements
- Increase the stiffness and strength
- Increase the load-bearing capacity
- Increase the shear capacity
- Higher fatigue failure resistance

Disadvantages:

Sometimes difficult to apply or not acceptable due to aesthetic reasons.



**Figure 5. Post-tensioning**

### 2.1.6 Span length shortening

Reducing the span length with additional supports.

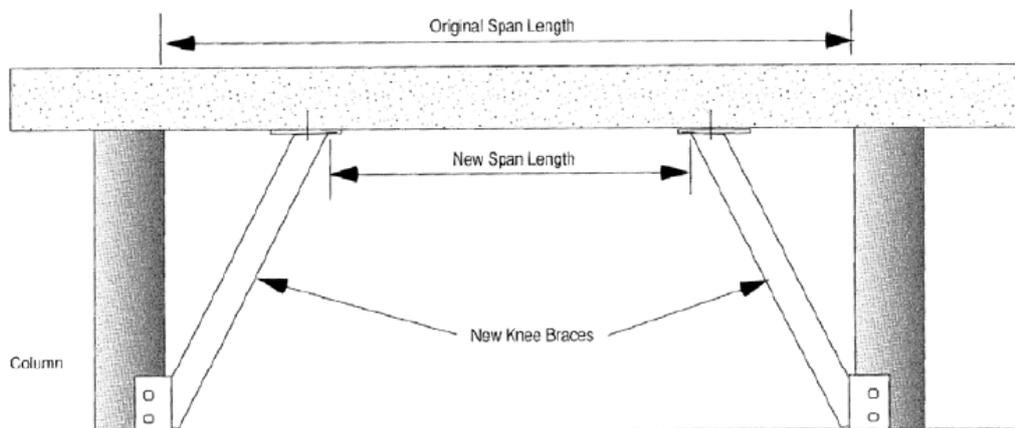
Possible applications: Slabs and beams

Benefits:

- Deflection reduction

Disadvantages

- Reducing the free space
- Aesthetic aspect



**Figure 6. Span length shortening.**

## 2.2 Textile-Reinforced Mortar (TRM)

TRM is composite material consisting matrix (mortar) and fibres (that are often replaced by textiles or nets). This combination and its inorganic nature is bringing multiple advantages like alkali-resistance, water vapour permeability, fire resistance, nontoxicity and easiness to apply also for more complex surfaces (P. Larrinaga, 2011). All these reasons are making TRM an attractive option for strengthening old structures. With right material choices TRM can be fairly compatible with parent materials.

In many studies TRM is called Fabric-Reinforced Cementitious Matrix (FRCM). These are both same material compositions where the traditional mortar is often placed with lime-based or cementitious mortar that is enriched with short fibres and additives. This is done to increase the bonding strength, reduce the crack size and to increase the bonding between textile and mortar.(D. Arboleda, Carozzi, Nanni, & Poggi, 2015)

The history of TRM could be considered to be started already millenniums ago when adobe structures were built combining mud based mortar with straws, Figure 7. This method is still in use in many developing countries in areas where lack of rain is allowing these structures last centuries.

The use of advanced composites in construction industry started only few decades ago. Most commonly used advanced composite has been Fibre-Reinforced Polymer (FRP) especially on concrete structures. There is multiple studies and guidelines done related to FRPs that is indicating the high interest of this material from the industry side. Due to earlier mentioned drawbacks on this material, especially on restoration purposes the interest seems to be moving from FRPs towards to TRMs.

Even the earliest researches of TRM were done already on 1980s it has been only after millennium when the real interest has grown to the point where multiple studies has been done and clear progress seen. There is still multiple unknowns on field of TRMs that makes designing work difficult. Happily there is multiple studies done and ongoing to find optimal testing processes to help future researches to standardize these materials for easier design work.



**Figure 7. Typical old adobe house where it was common to use mud straw mixture.**

## **2.3 TRM materials**

Textile-Reinforced Mortar (TRM) is made out of fibres that is mostly in form of textile or fabric and matrix that is mortar. Multiple kind of textiles that is possible to use in TRM are already studied but there is still lot of possibilities unexplored. First experiments with TRM were done with carbon and glass fibres but later basalt, steel wire, poly-paraphenylene benzobisoxazolo and vegetal fibres have been also giving very promising results.

Basalt has some advantages compared to carbon or glass fibres. With increasing demand by construction industry carbon is possibly not able to fill all this demand while basalt as most common rock type on earth's surface will not have this problem. When compared to glass fibres its mechanical properties are slightly better. Basalt has also perfectly elastic behaviour until the failure point. (Pello Larrinaga, Chastre, Biscaia, & San-Jos??, 2014)

### **2.3.1 Mortar**

Inorganic matrix used in TRMs are specially manufactured to have optimal workability and maximum chemical and mechanical bond between fabric and substrate. The difference to traditional mortars are mainly in some additives that has been added to reach earlier mentioned qualities. Some mortars have short fibres added as well to reach better bonding, higher flexural strength and reduce the crack size. In these mortars the short fibre quotient is less than 5%. There is both cement and lime based mortars available.

### 2.3.2 Fibres

First experiments with TRM were done with carbon and glass fibres but later also basalt, steel wire, poly-paraphenylene benzobisoxazolo and vegetal fibres has been taken into this field. Researches this far are indicating that TRM is promising technique to be used in heritage structures, (H??u??ler-Combe & Hartig, 2007), (Jesse & Curbach, 2000), (P. Larrinaga, 2011).

#### Basalt

Basalt is dark coloured, fine grained rock mainly composed of plagioclase and pyroxene minerals, Figure 8. It is formed by fast cooling of lava at the Earth's surface.

Basalt has huge potential as a future material. It underlies more of Earth's surface than any other rock type making it easily available material if industries will choose so. Even most of the basalt is found in ocean basins it also covers several percent of Earth's land surface as well. Most of the basalt is produced at divergent plate boundaries by volcanic eruptions. Some islands like Hawaii and Iceland are places where basalt is widely visible. Hawaiian Iceland is actually composed by layers after layers of basalt flows.

#### Basalt fibre

Use of basalt fibre for structural strengthening has started later than carbon and glass fibres. It has a similar chemical composition as glass fibre but it has better strength characteristic and it is highly resistant to alkaline, acidic and salt attack. Basalt has also wider temperature range for application (-269C to +650C), higher compression and shear strength than carbon or aramid fibres.

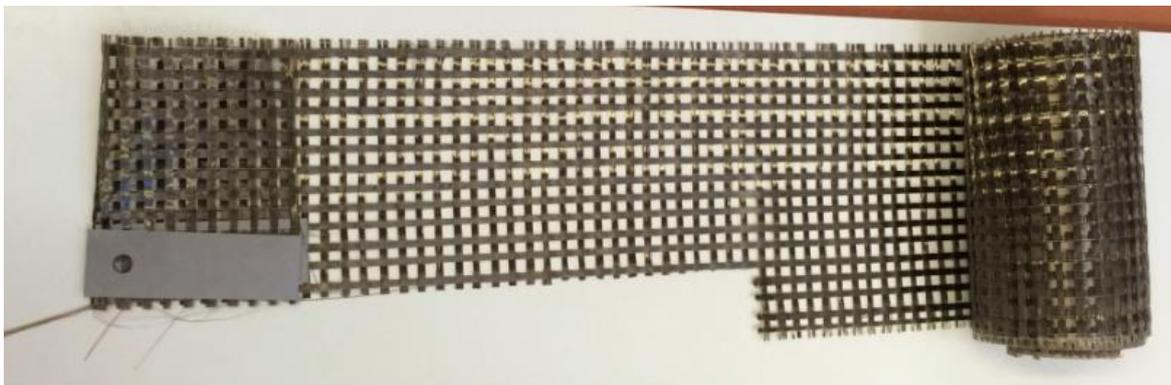
Basalt fibre is produced by melt drawing at 1500 C° temperature.



**Figure 8. Basalt stone.**



**Figure 9. Basalt fibre.**



**Figure 10. Commercially available basalt fibre textile.**

## Hemp

Industrial hemp is variety of cannabis plant that is grown for fibre and seed production, Figure 11. Cultivation of hemp for industrial purposes has been started over 10000 years ago. Traditionally hemp fibres were used for ropes, sail canvases and even paper production but due to its very coarse fibre it was not that much used for clothing. Nowadays more advanced processing techniques are enabling the use of hemp in much more wider range of end products.

Hemp is known as very fast growing plant that is producing very strong and durable fibres and these qualities are making it very interesting material for restoration purposes as well.



**Figure 11. Hemp plant.**



**Figure 12. Commercial products of hemp.**

## **2.4 Applications of TRM**

When doing restoration work for heritage structures there is some extra properties to be taken into account. The fact that old materials are often more ductile and vapour than some modern materials can lead to the situation where restoration work is doing more harm than good. As an example in some locations where Portland cement has been used it is actually breaking the parent material faster than it would have weathered without restoration work. This is happening due to incompatible mechanical properties with parent material while Portland cement is much harder than lime based mortars used earlier. Portland cement is also blocking the water to move through the mortar that can also lead various problems. These learnings from earlier experiments has to be remembered when introducing new materials for restoration world of historical buildings.

With Fibre-Reinforced Polymer (FRP) there is similar risks as Portland cement due to its stiffness and non-vapour permeability. In general FRP is more suitable when strengthening reinforced concrete structures but extra caution should be considered when this is designed to be used for historical masonry or for low-grade concrete structures.

For these reasons TRM is getting more and more interesting option to be used in restoration of historical structures. In TRM organic matrix is placed with inorganic matrix (mortar) giving material vapour permeability, more similar stiffness with historical materials, non-toxicity and resistance against fire and external physical impacts. This inorganic matrix can be either lime based or cement based

mortar depending on the parent material to get best possible compatibility. Fibres in TRM are in textile format to enable a good impregnation.

TRM applying technique is fairly simple. After cleaning and repairing the surface the first layer of mortar is spread on the surface. Then the textile is placed on top of this mortar (Figure 13) before laying the second layer of the mortar. This simple process is enabling to use TRM in various kind of locations. Most suitable parent materials for use of TRM are masonry, adobe and concrete.



**Figure 13. Applying TRM.**

In many case Textile-Reinforced Mortar (TRM) or Fabric-Reinforced Cementitious Matrix (FRCM) could be used instead of more traditional strengthening techniques or Fibre-Reinforced Polymers (FRP). TRM has some benefits comparing to the more traditional strengthening techniques; it is light weight, it does not increase the stiffness that much and in many times it is easier to apply. When comparing to FRPs it has better resilience for humidity, high temperatures and physical damages. FRP has often very different chemical and physical properties with historical materials, it has also poor flexibility and water permeability that can lead variable problems during the time.

TRM has already been used in multiple locations to increase the load bearing capacity of the existing structures (P. Larrinaga, 2011). There is also many great researches done to find right kind of combinations of different textiles and different kind of mortars.

TRM can be used to increase the shear and flexural resistance, increase the deformation capacity subjected to seismic loading and to increase out-of-plane or in-plane strength of structural elements.

## 2.5 TRM in heritage structures

TRM is very promising technique to be used especially for heritage structures. Major part of our built heritage is made out of masonry and TRM has very compatible chemical and physical properties with masonry. It is vapour permeable, it has similar stiffness with the parent material, it has good fire resistance and it is fully reversible technique. TRM's inorganic matrix is not penetrating into the substrate and that way not causing any damage to the parent material.

This all is making TRM with its inorganic nature a very promising technique for heritage interventions. Even it is not as light weight as FRP it is still much lighter than many of the traditional strengthening techniques. While it is relatively new material it is still lacking some codes and guidelines but as now there is already many good researches done like (Hegger, Will, Bruckermann, & Voss, 2006) about its load-bearing behaviour, (Bernat, Gil, Roca, & Escrig, 2013) about eccentric loading on TRM strengthened brickwork walls and (Escrig, Gil, Bernat-Maso, & Puigvert, 2015) about TRM shear strengthened reinforced concrete beams.

## 2.6 Testing methods

Even TRM is showing some promising result from different researches it is still relatively new composite material. One of the reasons it is not more widely used is the difficulty of designing the strengthening of heritage structure with TRM without clear standards. We are still missing standards for load transfer mechanism, specimen geometry, fabrication and strain measurement technique.

Research community has been developing different setups for tensile testing of TRM with different geometries of specimens, various gripping systems and strain measurements and how to connect the specimen to the unidirectional tensile testing system with minimum bending moment. In this section some of these different setup are introduced from earlier researches like (Diana Arboleda, Carozzi, Nanni, & Poggi, 2016; Contamine, Si Larbi, & Hamelin, 2011; Hartig, Jesse, & Häußler-Combe, 2010; Hartig, Jesse, Schicktanz, & Häußler-Combe, 2011). All these mentioned variables plus the production of the mortar is influencing to the measured tensile load-bearing capacity of the composite.

### 2.6.1 Specimen geometry

Shape of the specimen is influencing to the results and earlier researches like (Hartig et al., 2011) has been comparing these earlier studies, Figure 14. One reason to find optimal shape for specimen is to control the cracking area in specimen. This is important to secure the bonding between textile and matrix and to be able to place the strain measurement device on the area where crack will appear.

For this experiment plate shape of specimens were used due to easiness of the production.

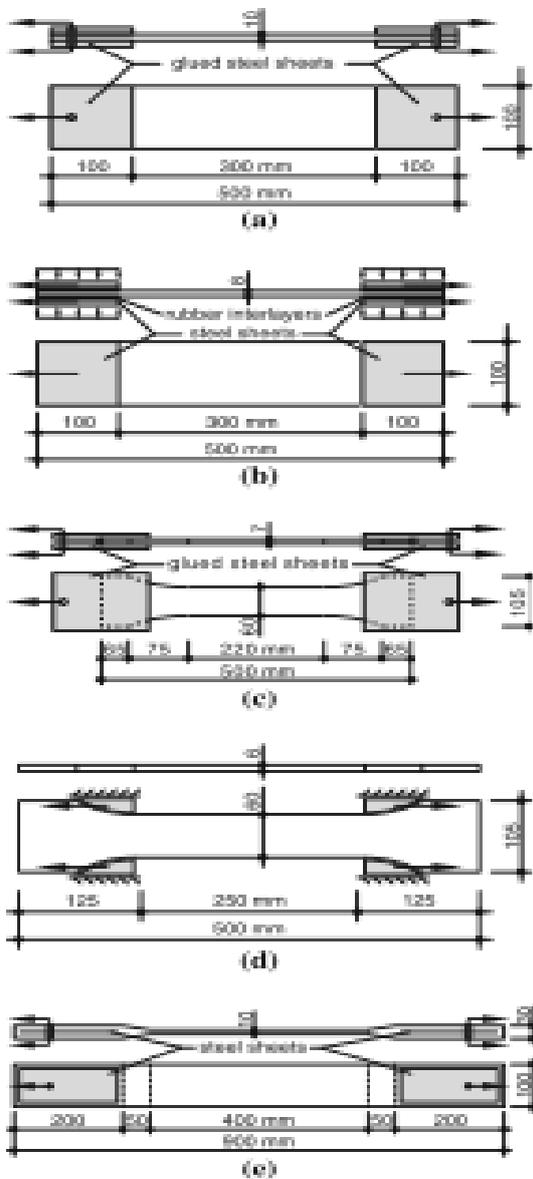


Figure 14. Different specimen shapes. (Hartig et al., 2011)

## 2.6.2 Gripping methods

There is different techniques for the load application to the specimen. The method where steel plates are connected to the specimen with adhesive is called clevis method and it is recommended by "RILEM Technical Committee 232-TDT" and study done by (D. Arboleda et al., 2015). Another commonly known methods are perforated steel plate where steel plate is casted inside the specimen and the method that is using steel flanges.

Figure 15

In this experiment clevis method was used that is shown in

Figure 15 c.

Many researches has been studying the influence of testing setups. (De Santis & De Felice, 2015) is interesting study where the effects of different clamping methods and testing setups on the results are studied widely.

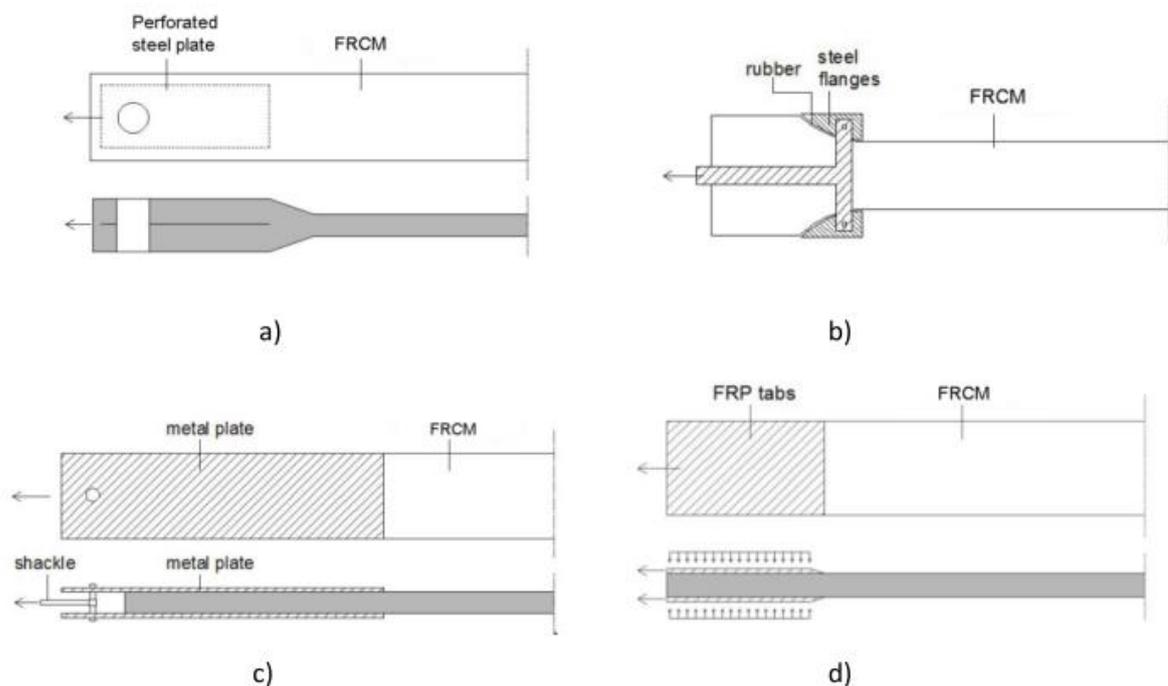


Figure 15. Grip setups: a) Steel plate inside specimen; b) steel flanges; c) clued steel plates (clevis); d) clamping grips. (D. Arboleda et al., 2015)

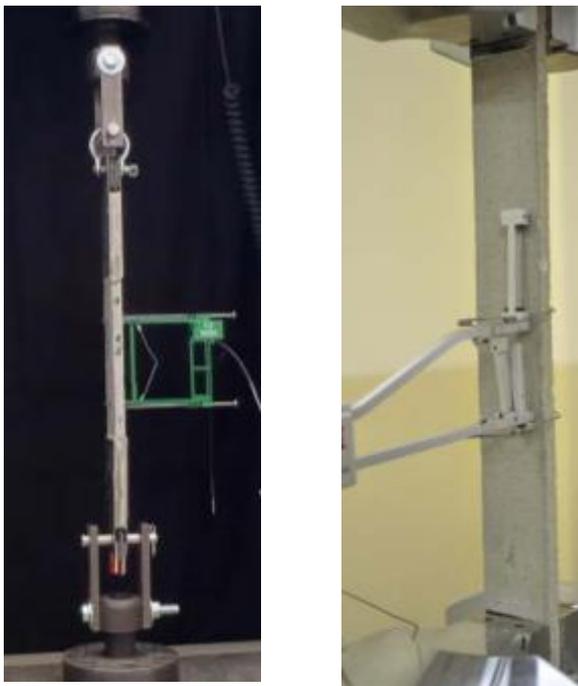
### 2.6.3 Connection to the tensile testing device

The connection to the tensile testing system can have great impact to the results. Clamping can break the mortar or create extra bonding strength that is not existing when used TRM in practice while connection with adhesive can cause slipping due to too short bonding length. Also different kind of connections can cause unwanted bending moments if end connections are not having multiple degree of freedom.

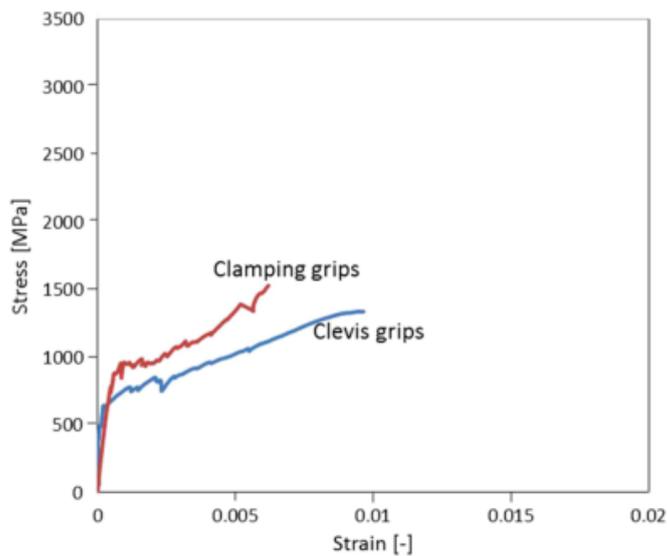
In study done by (D. Arboleda et al., 2015) two different gripping methods are compared, clamping grips and clevis grip, Figure 16. In that study it was shown that with clamping grip it is possible to

reach maximum strength but this method is not allowing natural slipping between textile and matrix. For this reason clevis method is recommended. Figure 17

When using clevis method it is important to have connection with multiple degree of freedom for this reason the upper end of the specimen is connected with shackle to minimize forced bending moment.



**Figure 16. Different tensile testing setups. Clevis method and clamping method.**



**Figure 17. Difference between two testing methods, clamping and clevis.** (D. Arboleda et al., 2015)

#### 2.6.4 Strain measuring

In general there is two commonly used ways to measure displacement and calculate the strain, point-to-point instruments like extensometer used in this experiment and linear variable differential transformers (LVDT). The challenge of measuring exact displacement is due to high number of variables present.

From earlier researches it is shown (D. Arboleda et al., 2015; Contamine et al., 2011) that in optimal setup four LVDTs would be used to measure strain from both sides of the specimen. While this is not always possible the earlier researches has shown that with single extensometer with sufficient gauge length the strain can be measured with high accuracy as well.

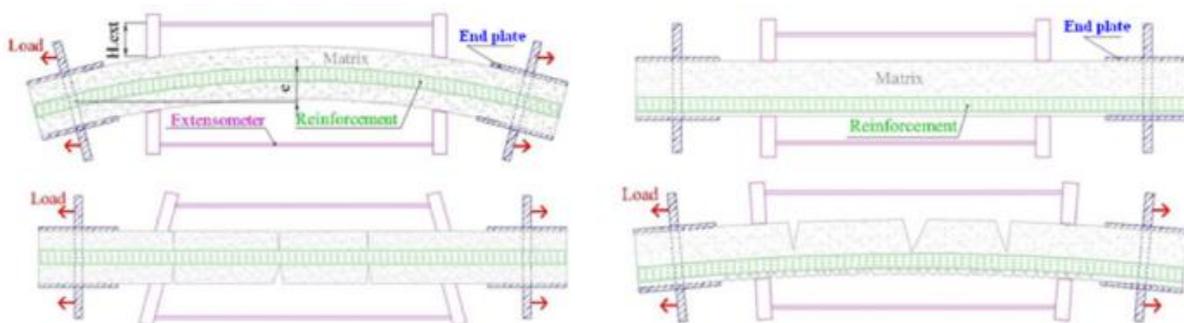
If displacement is taken directly from the tensile testing device it will include all the connection parts as well and that's why giving false results. In another hand the extensometer that is commonly used has only 50 mm gauge length that is likely to miss the cracking area.



**Figure 18. Extensometer.**

Another challenge is sample itself that might not be fully straight. This is causing eccentricity that will lead to some bending during the tensile test. If this happens the extensometer will be either convex or concave side of the specimen giving false result. When placed on convex side the results can give negative values in the beginning of the strain graph and in opposite measuring from the concave side can give values that are too high. Also if the reinforcement is not exactly in middle of the specimen this could lead to the bending creating same phenomenon. Thirdly the end plates that might move during the cluing process might make sample eccentric leading again to the bending effect.

Figure 19 taken from the research done by (Contamine et al., 2011) is showing these possible defects caused by unwanted bending.



**Figure 19. Possible bending effect during tensile testing.**

## 2.7 Failure mechanism

Ideally the stress-strain curve from tensile test of FRCM should have three linear phases, this is clearly explained in (Carozzi & Poggi, 2015). First phase is presenting the uncracked state where stress-

strain curve reflects the elastic modulus of the matrix and textile together. Second phase is indicating the formation of cracks showing reduction on stress level. Here the tensile load is transferred from composite to the textile. Third phase reflects the tensile strength of the textile. Second and third phase are heavily dependent of bonding strength between matrix and textile.

### 3 EXPERIMENTAL CAMPAIGN

In this experimental study the purpose is to compare if it is possible to increase the strength of the TRM and delay the cracking point of the mortar by pre-stressing the fibres. It was also studied if testing speed is influencing to the results. To be able to compare difference between unstressed and pre-stressed TRM, 15 samples were produced of all specific type, 45 samples all together, and then tested by displacement controlled unidirectional tensile test.

As textiles, basalt fibre and hemp fibre were used and specimens of both fibres were produced both unstressed and pre-stressed. In each TRM sample three tows of fibres were used.

Basalt was chosen as it has alkali resistant properties and its physical properties are closer to historically used materials than carbon. It has reasonable flexibility and good resistance towards fatigue. Comparison to glass fibres it is not toxic for humans, it is completely inert and it has less effect for climate change. It is widely available and easy to manufacture. Basalt is also much more economical than carbon.

Hemp was chosen while it is easily available especially in developing countries where basalt could be more difficult to find. In some seismically active countries hemp could be an option when retrofitting vernacular buildings to be more seismic resistant.

The experimental campaign was done in the laboratory of UPC, Terrassa campus.

#### 3.1 TRM materials used in this experiment

##### 3.1.1 Mortar

Inorganic cementitious fibre reinforced mortar was chosen to reach better chemical and mechanical bonding between mortar and textiles. The used repair mortar is enriched with short fibres and additives.

Sika MonoTop-612 is a cementitious, silicafume containing, fibre reinforced, polymer modified one-component repair mortar.

- Pot life (25C): 50-60 minutes
- Aggregate / cement ration: 2.4%
- Polymer content: 8% by weight of cement
- Compressive strength after 7 days: 30-40N/mm<sup>2</sup>
- Compressive strength after 28 days: 40-50N/mm<sup>2</sup>
- Tensile strength after 7 days: 3-4 N/mm<sup>2</sup>

- Tensile strength after 28 days: 4-5 N/mm<sup>2</sup>



**Figure 20. Cementitious mortar.**

### **3.1.2 Textile**

For textiles basalt and hemp were used in this experiment. It was decided to use three tows in each sample leaving 1 cm space between tows. The spaces between tows are enabling mortar to impregnate properly in to the fibre net and to guarantee the good matrix-reinforcement adhesion.

For basalt fibre, commercially available basalt net textile was chosen.

Hemp textile was done from commercially available strings by connecting five strings together.

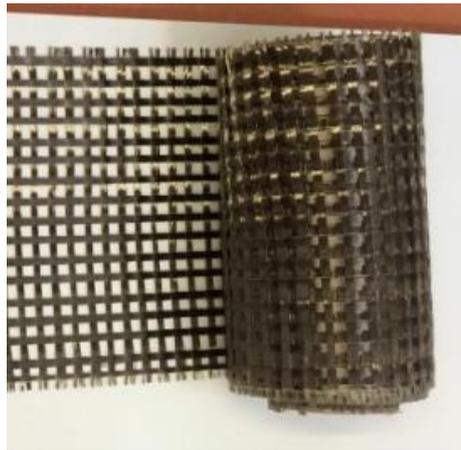
#### *3.1.2.1 Basalt fibre*

For this experiment commercially available basalt fibre was used.

Fidbasalt grid 300 C95

Balanced grid basalt fibre sheet for structural strengthening

- Ultimate tensile strength: 3080 MPa
- Young's modulus: 95 GPa
- Ultimate tensile strain: 3.15 %
- Density: 2.8 g/cm<sup>3</sup>



**Figure 21. Basalt fibre.**

### 3.1.2.2 Hemp

In this experiment a commercially available hemp was used.

Rombull, [www.rombull.es](http://www.rombull.es)

- Thickness: 0,5 mm
- 90 m in one roll
- Ultimate tensile strength: 8.5 Kg



**Figure 22. Ball of yarn, hemp.**



**Figure 23. Hemp strings.**

## 3.2 Pre-stressing system

### 3.2.1 Designing and assembling

To be able to pre-stress the fibres a pre-stressing system was built. By using already available materials from laboratory it was decided to build a rigid frame from steel beams and use that to pre-stress the fibres to be casted inside the mortar. Two strength gages were used to control the implemented tensile load.

From available materials four I-shape steel beams (20 cm x 20 cm) were chosen to build a rigid frame. Two shorter beams with 144 cm length were used on the end of the frame and two longer beams with 300 cm length were used as longitudinal structures. Beams were connected to each other with 20 mm thick bolts through the already existing holes. Figure 24



**Figure 24. Process to build the pre-stressing system.**

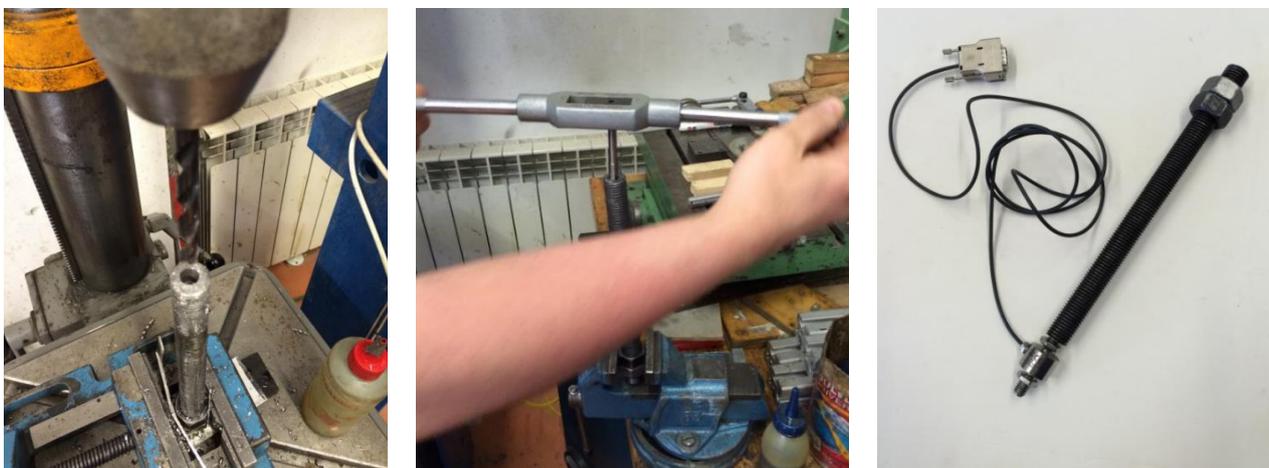
After rigid frame was done the next task was to find solution how to pre-stress the textile inside this rigid frame. Again from the available materials it was decided to use two U-shape steel bars 65 cm long each to work as an adapter between rigid frame and textile nets. One U-shape frame was fixed directly to the one end of the rigid frame and another one was left loose to be penetrated with 20 mm thick steel rods. These steel rods were used to adjust the load on textiles.

After first dry trial it was noticed that with this setup it would be very difficult to cast samples in a place. The process, where first layer of mortar would be laid and only after that fibre nets would fixed in to the pre-stressing device and adjusted to the agreed load level would take too much time and cause mortar to dry. So the system was needed to be developed further in a way that it would be possible to prepare the fibre nets fully ready and pre-stressed with the right load before starting the casting. To enable this it was agreed to lift one I-beam 10 cm from the ground to be able to slide the casting form under it to be placed against already pre-stressed fibres. Figure 25



**Figure 25. One I-beam was lifted to allow sliding the form under the textiles. U-shape beams were used as adapter between textiles and rigid frame.**

To adjust the load on textiles two load cells were introduced to the system. To get these load cells connected two steel rods were needed to be cut from the middle where load cells would be placed. Holes were drilled on both sides of the cut steel rod and threads were inserted to allow load cells to be screwed in. Figure 26



**Figure 26. Steel rods were prepared to insert load cells into the system.**

### 3.2.2 Load adjusting system

For pre-stressing the system was needed to develop to get exactly wanted load on textiles before casting.

For this purpose two U-shape beams were connected to the both ends of the rigid frames. One end was fixed while another was left to be adjusted to be able to load the fibres. Adjustable U-beam was

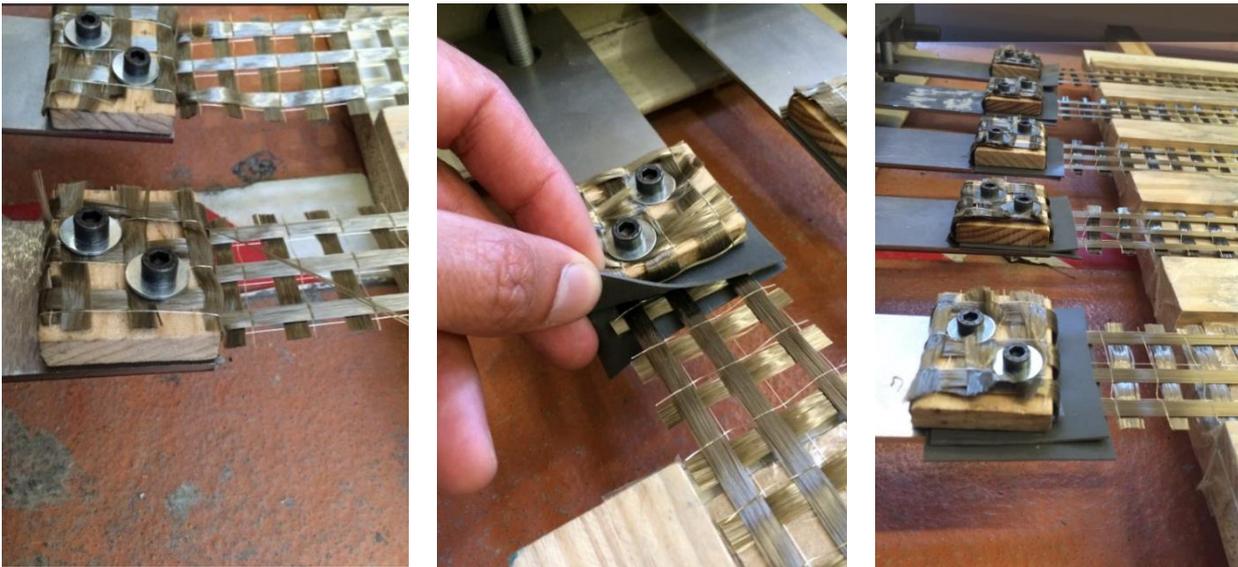
connected to the rigid frame with two steel rods where load cells were inserted. Load cells were implemented on both sides of the U-beam and then connected to the software to be able to control the load amount. To get the wanted tension on fibres two bolts were tighten in turns to increase the load. Load amount was followed through the software. Figure 27



**Figure 27. Load cells and pre-stressing system.**

### **3.2.3 Connecting textiles to the pre-stressing system**

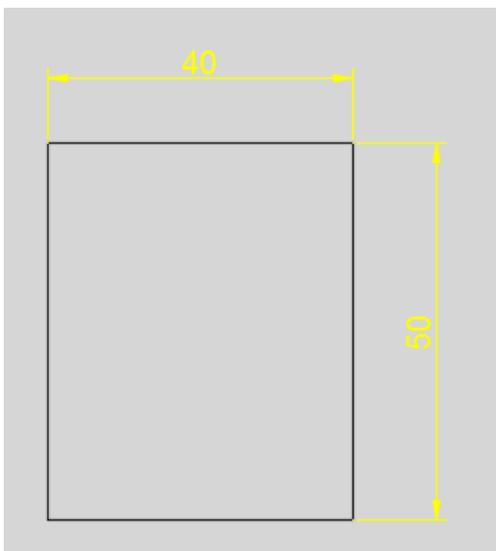
The first setup to connect the textiles to the U-beam was done by rolling the textile around the wooden piece and screwed to the steel plates which were connected to the U-beam with multiple degree of freedom. After first trial it was noticed that fibres were cut from the edge of the steel plates due to sharp corner. To fix this problem steel plates were polished and 1 mm thick rubber mats were implemented between fibres and steel, and fibres and wood pieces.



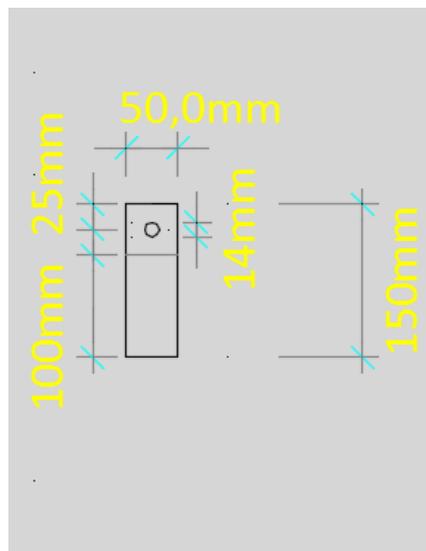
**Figure 28. The connection between textile and U-beam.**

Size of the wooden pieces used to connect textiles were 5 cm x 4 cm x 1 cm (Figure 29) and textile was rolled fully around the specimen so that bottom side was covered with two layers to secure that there is enough friction.

Metal plates that were used to connect nets to the U-beam were 3 mm thick. Figure 30



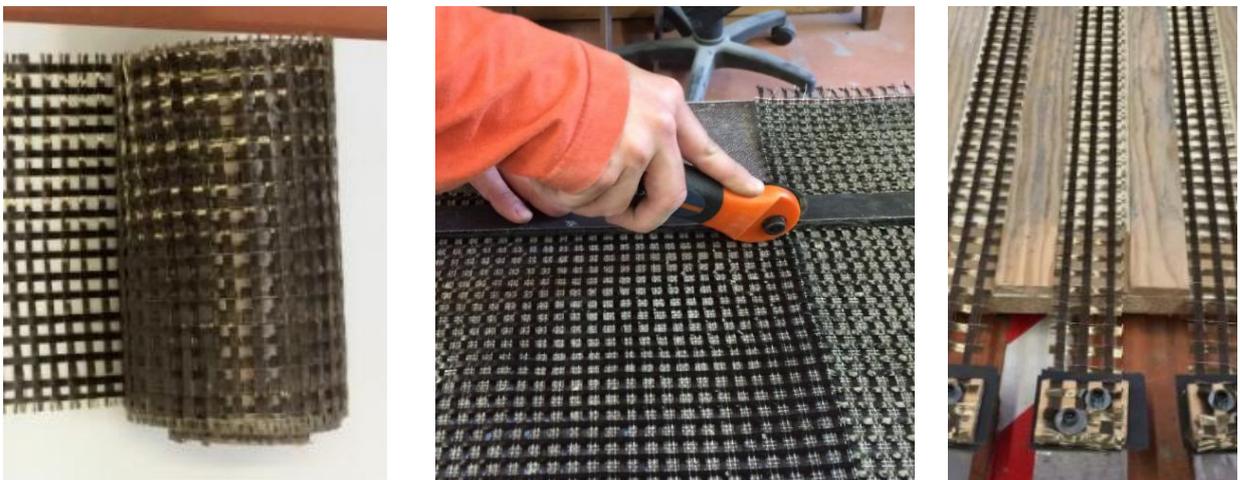
**Figure 29. Size of the wooden piece.**



**Figure 30. Size of the steel plate.**

### 3.2.4 Preparing fibre nets

The size of the mould is 5 cm x 140 cm and textile nets needs to be cut to fit perfectly in to this mould. Basalt net is having one centimetre wide tows with one centimetre spacing making it possible to have three tows in five centimetre wide mould. For this reason the basalt net was cut with special tool taking care that each 5 cm wide net had three tows in it. For length 25 cm extra was left on both ends to allow the connection around the wooden piece making the total length of each textile 190 cm. Figure 31



**Figure 31. Preparing basalt nets.**

The hemp that was used came as ball of yarn and it was decided to produce three tows with five strings in each into each sample. The process to make these tows hemp strings were stretched between two pegs with five folds and then the ends were tied together. After that it was possible to place these readymade tows into the pre-stressing system. Figure 32



**Figure 32. Preparing hemp strings.**

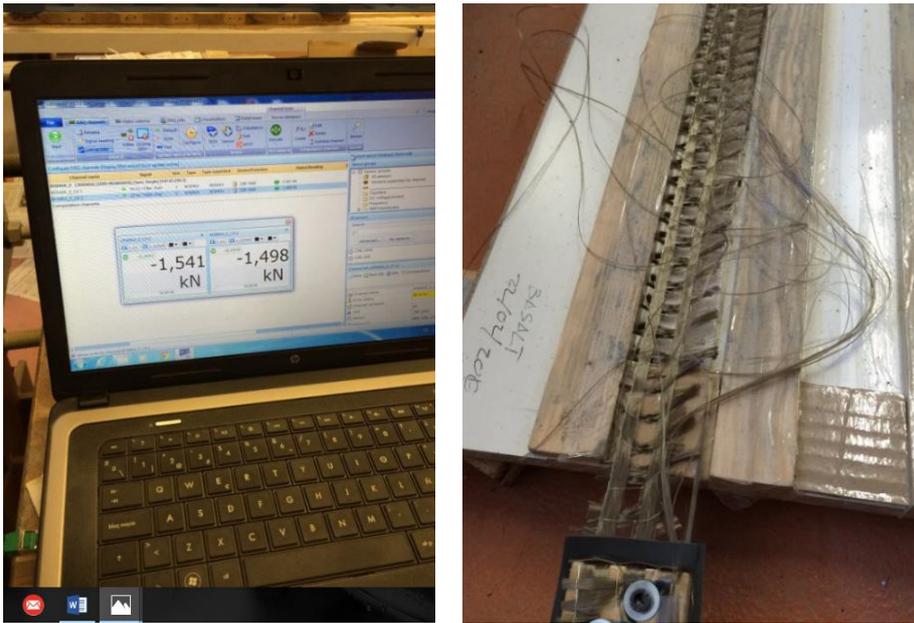
### **3.2.5 Pre-stressing**

After the pre-stressing system was done it was possible to try how much load different textiles can take to decide the load level for the final TRM specimens.

#### **3.2.5.1 Basalt**

First trial was done until 1kN for each fibre net. While there was five lines of fibre nets and two load gages each load gage was loaded with 2,5kN. Based on the manufacturer's information the basalt net was supposed to withstand this load. In reality singular fibres started to brake with this load causing the stress decreasing as soon as wanted load was reached.

Next trial was done with 1,5kN on each load gage giving 3kN load for the system with five separate fibre nets. With this load each fibre net was tensioned with 0,6kN load. Even with this load singular fibres were breaking reducing the load. After two hours the load was dropped with 0,4kN leaving 0,52kN on each fibre net and after 19 hours load was reduced with 0,7kN leaving only 0,46kN tension on each fibre net.



**Figure 33. Pre-stressing test with basalt textile.**

With further studies it was found that earlier research result was supporting this effect. In (Pello Larrinaga, Chastre, San-Jos??, & Garmendia, 2013) study the difference between the data given by manufacturer and the experimental results is clearly shown, Figure 34. This is due to fact that in reality it is very difficult to load all fibres equally and most likely some fibres are taking more load than others. This is causing the phenomenon where rapture is happening in individual fibres and not simultaneously in all tows. Due to the information that was taken from this research and from the dry-trial it was decided to pre-stress the basalt fibre of each line to the 350N to avoid cutting singular fibres with pre-stressing. This gives total load of 1,75kN for the system and 875N for each two load cells.

Average results of basalt textile under pure tensile load.

	Filament – given by the manufacturer	Textile – experimental <sup>a</sup>
Ultimate tensile strength, $\sigma_{fu}$ (MPa)	2100	1160 (0.025)
Young's modulus, $E_f$ (GPa)	89	67 (0.054)
Ultimate tensile strain, $\epsilon_f$ (%)	3.14	1.82 (0.054)

<sup>a</sup> COV between brackets.

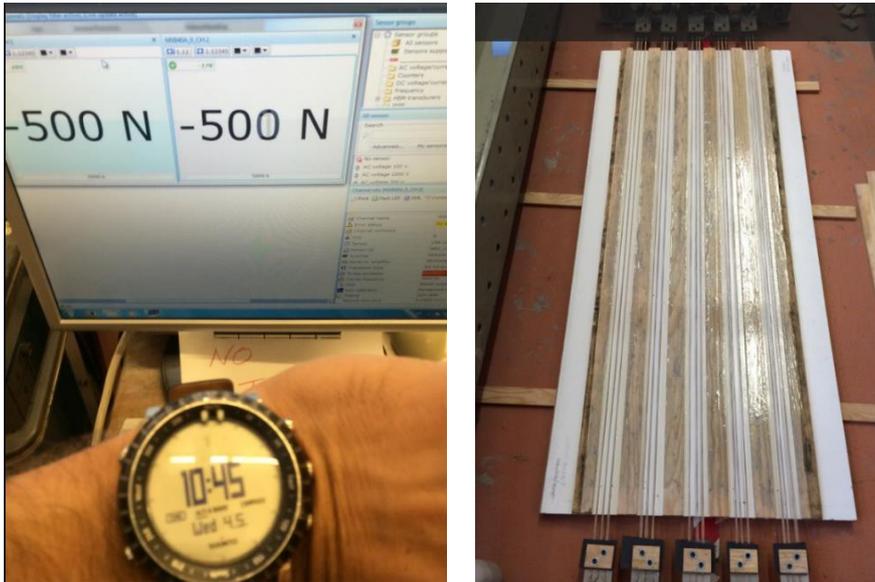
**Figure 34. Basalt tensile test carried by (Pello Larrinaga et al., 2013)**

### 3.2.5.2 Hemp

Test pre-stressing was done for three tows five threads in each tow to find out how much load it can take. It was found out that after 502N per sample, singular threads started to break. After this load was

decreasing even when stress-tightening bolts were tightened. Same time new threads were getting broken.

Due to this result it was decided to use 200N load for each specimen to avoid braking threads. To get this 1kN total load for five specimens was applied giving 500N for two load cells each. Figure 35



**Figure 35. Pre-stressing test for the hemp.**

### **3.3 Preparing specimens**

All specimens were manufactured in same way by using same kind of rectangular shaped flat mould with dimensions of 400 mm x 50 mm x 10 mm (length, width, thickness). Form that was used to cast samples had five moulds with dimensions of 1400 mm x 50 mm x 10 mm, allowing to cast 15 samples at once, Figure 36. While the moulds were 1400 mm long the samples were cut to the 400 mm sizes after curing time.

For all specimens one layer of textile was implemented through the whole length of the specimen. This textile layer was placed in middle of the specimen.



**Figure 36. Casting form with five moulds.**

### 3.3.1 Preparing moulds

Before casting moulds were cleaned, taped with clear packing tape and bussed with vaseline, Figure 37. This all was done to easy the un moulding process.



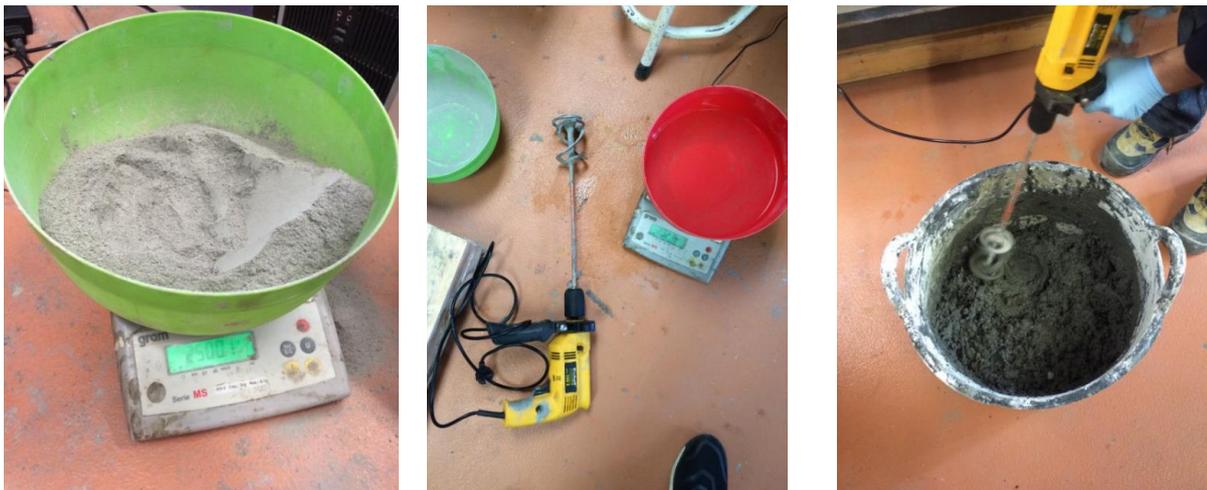
**Figure 37. Preparing moulds.**

### 3.3.2 Casting

In this experiment Sika MonoTop-612 cementitious, silica fume containing, fibre reinforced, polymer modified one-component repair mortar was used. This mortar was chosen to increase the bonding between textiles and mortar. Cementitious mortar with short fibres and additives is much stronger than

traditional mortars both on tensile and compressive strengths. Also the short fibres inside mortar should decrease the cracking size.

During the casting process 16.6% water / cement ratio was used. All quantities were measured exactly with electric scale to control the quality of the mortar. Finally cement and water were mixed with slow speed electric mixer. Figure 38

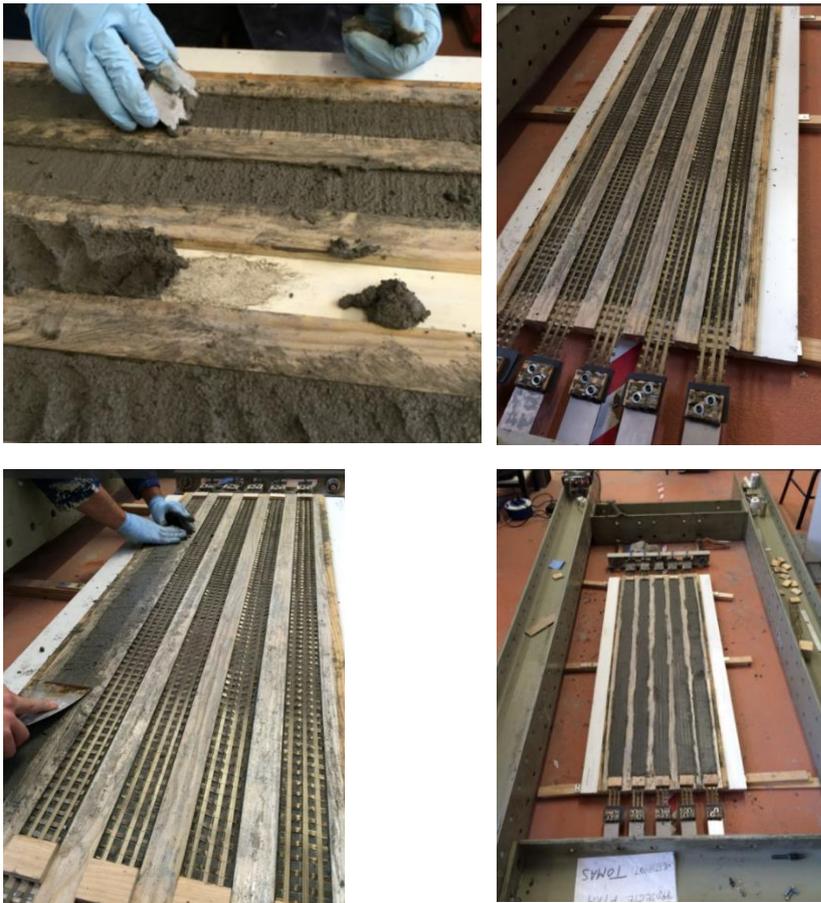


**Figure 38. Process to mix the mortar.**

### 3.3.2.1 *Pre-stressed specimens*

Casting was done by using manual impregnation technique. Firstly 5mm layer of mortar was placed evenly on base of the moulds. After all five moulds were prepared with this base layer the form was moved to be placed against pre-stressed textiles. Top layer with 5mm thickness was then placed against textile taking extra care that mortar will impregnate thoroughly through textile cells to secure good bonding between mortar and textile. Lastly the surface was smoothed with the finishing trowel.

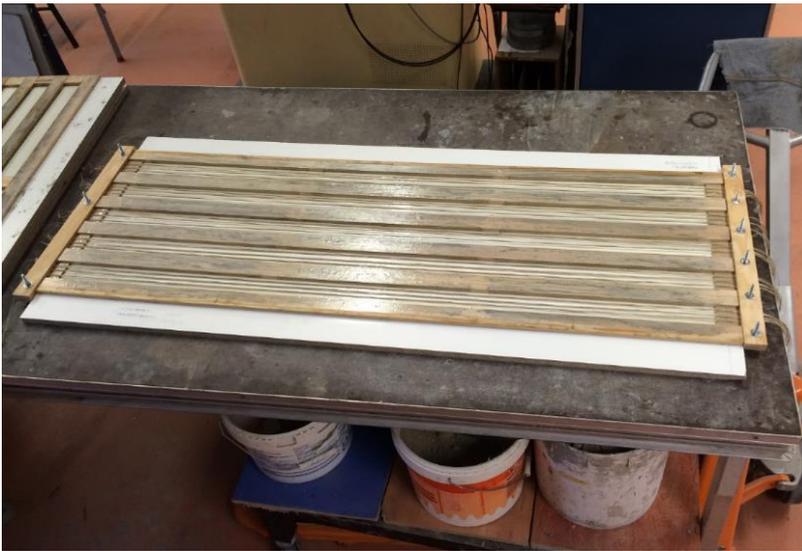
All samples were cured at least 28 days before testing but to speed up the process of casting all samples the form was moved from the pre-stressing system and samples unmoled after 14 days to allow reuse of the moulds.



**Figure 39 – Casting process.**

### 3.3.2.2 *Unstressed hemp specimens*

Unstressed hemp samples were done in similar method except instead of pre-stressing system the hemp tows were clamped between wooden strips. After lining the hemp strings with the right spacing between wooden strips those strips were screwed together. With these wooden strips it was possible to line all the hemp tows evenly and then easily place top of the first layer of mortar. Wooden strips kept the strings also straight when laying second layer of mortar. Extra care was taken to keep tows straight and to make sure that all hemp strings are perfectly against the mortar.



**Figure 40. System to line unstressed hemp strings evenly.**



**Figure 41. The process to cast unstressed hemp specimens.**

### 3.3.3 Unmoulding process

Unmoulding process was also developing during the process. The first set that was pre-stressed basalt specimens were unmoulded with sliding. Wooden piece was placed on one end of the specimen and hammered softly out from the mould.

This process turned out to be too rough creating some small cracks on some specimens. So the next set of specimens that were unstressed hemp different approach was tried. This time specimens removed from the mould by pushing from one end with piece of stick.

Even with this method there was some cracking appearing possibly due to bending. So with the last set of specimens that were pre-stressed hemp the mould was dismantled. In the end this method would be recommended in future experiments to avoid cracking. Figure 42



**Figure 42. Unmoulding process was developing from sliding the specimens with hammer to dismantling the mould.**

### 3.3.4 Cutting specimens

After unmoulding samples were cut to the 40 cm long pieces. Cutting was done by using angle grinder. Extra care was taken to avoid any bending during this process. Figure 43



**Figure 43. Cutting specimens.**



**Figure 44. Specimens in right size.**

### 3.3.5 Gripping method

After the specimens were cut to the right sizes next step was to glue steel plates on both ends on both sides of the specimens to allow them to be connected to unidirectional tensile testing device. For this purpose steel plates and special mould to level samples to the steel plates were earlier manufactured.

Firstly the steel plates were roughen with grinding wheel and cleaned with alcohol. Secondly first layer of steel plates were placed on mould and epoxy adhesive spread evenly on those. Thirdly specimens were lined on steel plates taking care that adhesive was contacting both sides through the whole cluing area. Figure 45

After this same method was applied to the steel plates glued on other side of the specimens.



**Figure 45. Cluing the steel plates on specimens.**



**Figure 46. Samples ready for testing.**

### 3.3.6 Mortar samples

From each cast of mortar prismatic samples of the matrix were also produced for determining their tensile and compressive strength. To do this three point bending tests and compressive tests were carried out.

Figure 47



Figure 47. Mortar sample without textile.

## 3.4 Experimental setup

### 3.4.1 Clevis grip

All specimens were prepared for tensile test by preparing them to be equal size and by adding the connection steel plates on both ends, Figure 48. Clevis grip method was used where two 3mm thick steel plates are glued to the both end of the specimen with epoxy adhesive. Due to available steel plates 100mm bonding length was used instead of recommended 150mm (D. Arboleda et al., 2015). In the end this bonding length seemed to be enough for this particular experiment while no specimen was failing due to bonding between steel plates and specimen.

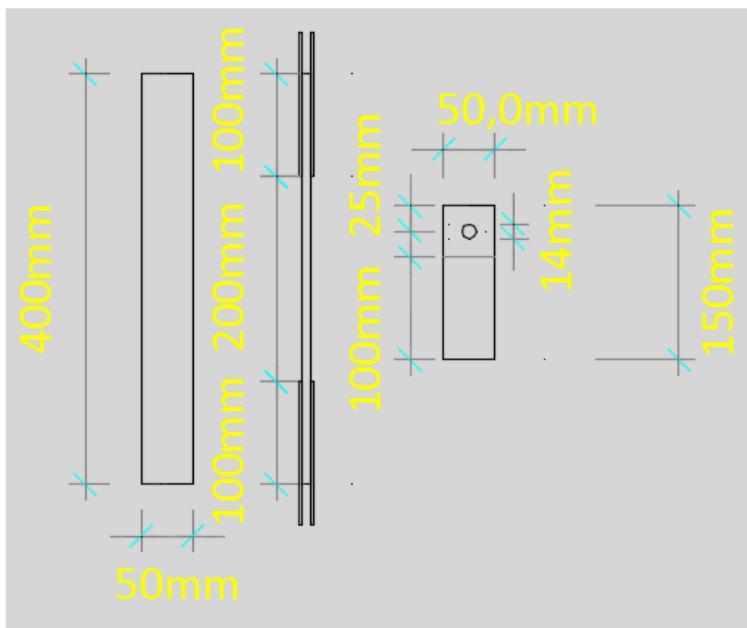


Figure 48. Clevis grip system.

### 3.4.2 Connection to the tensile test system

First specimens were tested with pinned end support like recommended in earlier studies (D. Arboleda et al., 2015). After testing 12 specimens it was noticed that this system is still creating some bending effect. It seems that these thin specimens are very sensitive for bending and one challenge is to find system setup where bending would be minimized. In the end four different connection methods were used to remove the bending effect. In Figure 49 is shown the first two connection setups. The idea was to increase the degrees of freedom by implementing loose joint connections on both ends. Even after this unequal loading was inspected, during the loading the pinned bolt was tilting creating more load on one side of the specimen.



**Figure 49. First two connection setups (S1 and S2).**

The next version was done with single carabiner between the steel plates like shown in Figure 50. Firstly the carabiner used was too thick creating bending moment directly to steel plate but after changing this to the thinner one the results started to indicate direct tensile stress. In results these different connection setups are signed S1, S2, S3 and S4.



**Figure 50. Third and fourth connection setups (S3 and S4).**

### 3.4.3 Strain measurement

For measuring displacement the unidirectional tensile test system was set to record data with 50 Hz frequency. While this system is measuring total displacement of whole system, including steel elements and joints, separate clip-on extension meter was installed to measure only the free area of the specimen. This means the 200 mm space in specimen between the steel plates. This system was also set to record the data with 50 Hz frequency.

MTS extensometer has only 50 mm gage length, +25/-5 mm range it is able to catch only 50 mm from the needed 200 mm area. To overcome this problem extra system was created to record the data from total 200 mm free space of the specimens. This was done by connecting L-shape steel frames with magnets from the edge of the connector steel plates to extend the measuring space. Two aluminium bars were clued on both side of one L-frame to keep system in line. This system was done to eliminate the possibility of cracks appearing outside of measuring area. Figure 51



**Figure 51. Extra system to extend the gage length of the extensometer.**

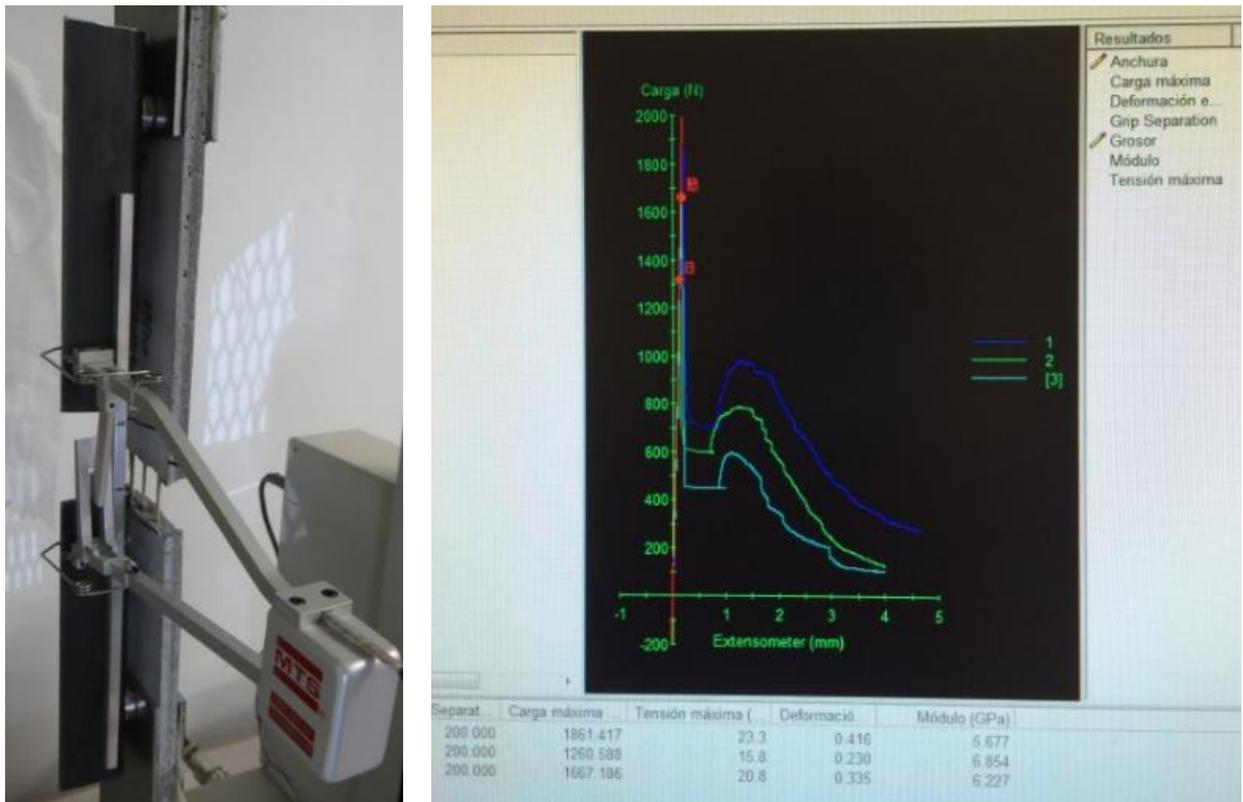


Figure 52 – Extension meter and load-displacement diagram.

### 3.4.4 Testing speed

Five different testing speeds were used to simulate different kind of real life scenarios. Low speed is trying to simulate possible settlement problems while the highest speed is closer to earthquake impact.

V1	0.2 mm/min
V2	1 mm/min
V3	5 mm/min
V4	25 mm/min
V5	100 mm/min

### 3.5 Results

45 TRM specimens were tested with displacement controlled unidirectional tensile test, 15 pre-stressed basalt specimens, 12 unstressed hemp specimens and 12 pre-stressed hemp specimens. The reason why there was only 12 specimens from unstressed and pre-stressed hemp was because three specimens from both categories got broken during the unmoulding.

In the end it was noticed from the results that some other specimens were also most likely cracked before test even it was not visible with naked eye. The specimens that didn't have clear drop of tensile stress after ultimate strength was marked as broken specimens. This happened only with pre-stressed basalt specimens indicating that pre-stressing kept the crack closed so that it was not possible to notice before testing.

In each category 5 different testing speeds were used from 0.2 mm/min to 100 mm/min. With pre-stressed basalt specimens it was possible to test three samples with each testing speed but with hemp specimens some testing speeds were used only twice due to fact that there was not enough specimens to do the test three times with each testing speed.

Because the main interest of this study is to compare the effect of the fabrics inside the TRM specimen the stress was determined by dividing the load with nominal section area of the fabric and not with the section area of the TRM specimen. This will not give the exactly right stress level to the fabric due to the fact that before the first crack appears the stress is mostly on matrix. Also in case of slipping of the textile relation to mortar the stress is not fully on textile. Nevertheless this will give us an option to compare the results between different textiles and between the unstressed and pre-stressed TRM.

Due to multiple variables with five different testing speeds, three different material composites, four different testing setups and un-cracked and cracked specimens it was important to eliminate the errors by comparing only samples that were comparable. Also in these results the categories that had only one specimen were neglected.

All specimens were cracked once from the matrix, perpendicular to the direction of the load following slipping phenomena after cracking. For the interest of this study the data was collected just before cracking, 0.1 seconds after cracking and from the point where maximum post load appeared. The data from 0.1 second after cracking was collected to understand how the pre-stressing is effecting to the stress and strain just after cracking.

Data from the tests were recorded with 50 Hz frequency.

### 3.5.1 Mortar samples

Flexural, tension and compression strength results from plain mortar samples that were taken from all casting patches are shown in Table 1. There is some reduction on strength between patches that seems to follow the trend with the curing time.

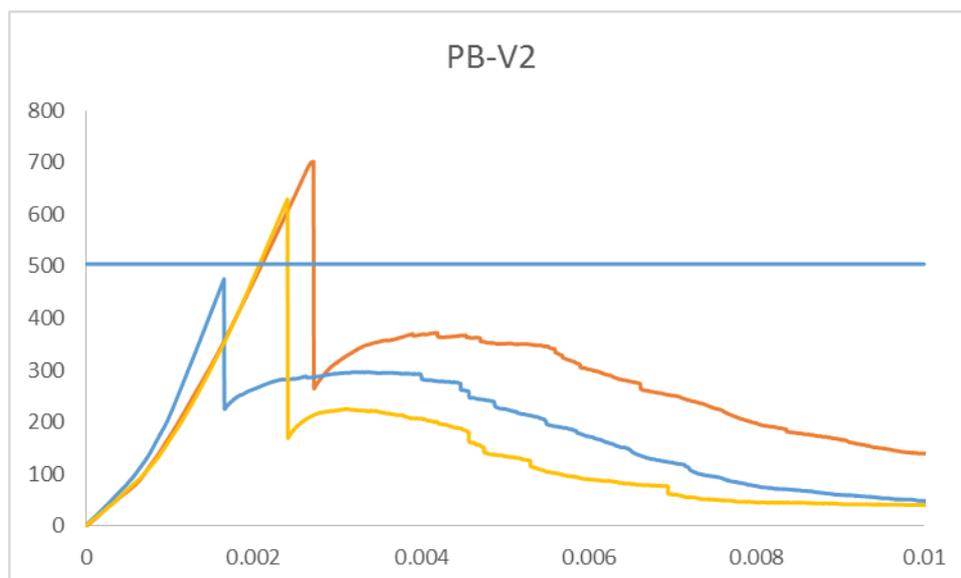
**Table 1. Results from mortar samples taken from each casting patch.**

		Curing time before test	Flexural Strength (MPa)	Tension Strength (MPa)	Average Compression Strength (Mpa)
Mortar for pre-stressed basalt	Average	45	6.74	2.97	45.77
	CV		0.12	0.12	0.03
Mortar for unstressed hemp	Average	42	6.56	2.90	39.24
	CV		0.05	0.05	0.05
Mortar for pre-stressed hemp	Average	30	4.96	2.19	35.22
	CV		0.04	0.04	0.07

From results from Table 1 it is possible to calculate the ultimate tensile strength for specimens without reinforcement. By multiplying the tension strength with cross area of the specimen and then dividing it with nominal area of textiles following ultimate tensile strengths were calculated.

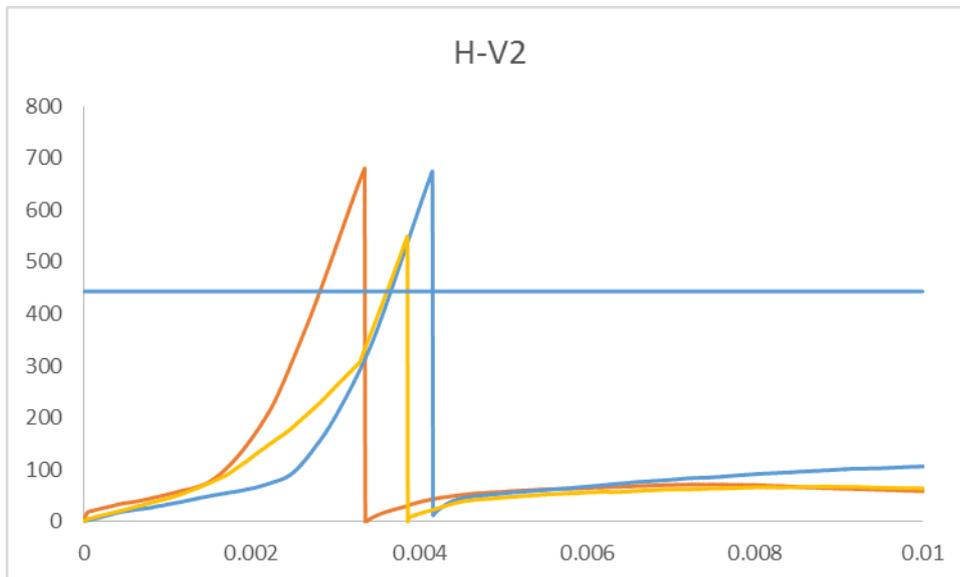
$$F_t = \delta_t \times A$$

Ultimate tensile strength for mortar used for pre-stressed basalt specimens is 504.33 Mpa.



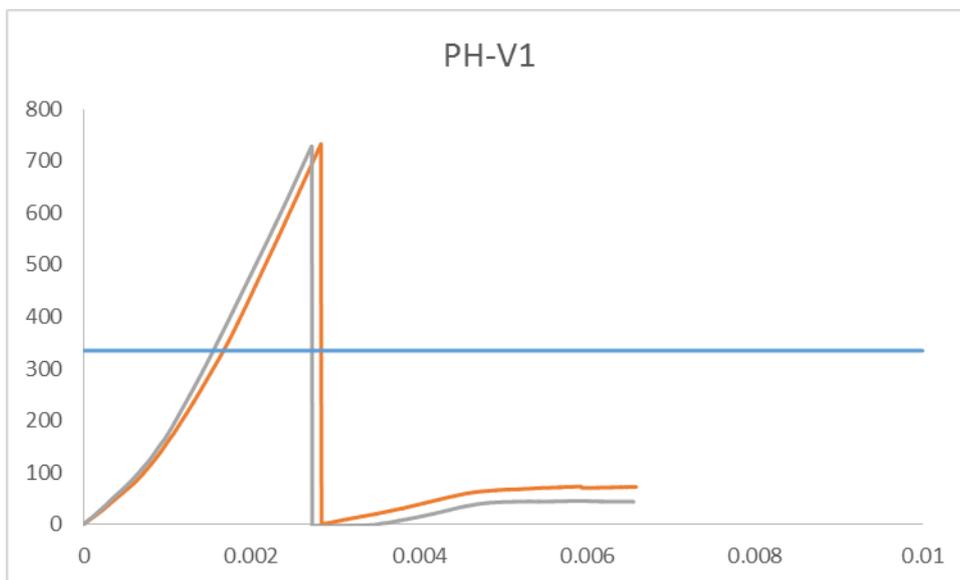
**Figure 53. Tensile test results of pre-stressed basalt TRM specimens with testing speed V2 and testing setup S4. Reference line indicating the strength of the mortar without reinforcement.**

Ultimate tensile strength for mortar used for unstressed hemp specimens is 443.12 Mpa.



**Figure 54. Tensile test results of unstressed hemp TRM specimens with testing speed V2 and testing setup S1 and S2. Reference line indicating the strength of the mortar without reinforcement.**

Ultimate tensile strength for mortar used for pre-stressed hemp specimens is 334.63 Mpa.



**Figure 55. Tensile test results of pre-stressed hemp specimens with testing speed V1 and testing setup S4. Reference line indicating the strength of the mortar without reinforcement.**

### 3.5.2 Data from tensile tests

During the tests load and displacement data was collected with 50 Hz frequency. From this data stress was calculated by dividing load with the nominal section area of the textile that was 2.65 mm<sup>2</sup> for

basalt and 2.945 mm<sup>2</sup> for hemp. Strain was calculated by dividing the results from extensometer with free space of the specimen that was 200 mm.

Equation to calculate stress.

$$\delta = \frac{F}{A}$$

Equation to calculate strain.

$$\varepsilon = \frac{\Delta L}{L}$$

Young's modulus, E was calculated like recommended by (ACI 549.4R-13)

$$E = \Delta f / \Delta \varepsilon = (0.90f_{fu} - 0.60f_{fu}) / (\varepsilon_{fat0.90ffu} - \varepsilon_{fat0.60ffu})$$

**Table 2. Stress-strain results from pre-stressed basalt specimens.**

Test S.	Sample	Ultimate stress		E extenso N/mm <sup>2</sup>	E system N/mm <sup>2</sup>	0.1s after ultimate		Ultimate post stress	
		Stress N/mm <sup>2</sup>	Strain			Stress N/mm <sup>2</sup>	Strain	Stress N/mm <sup>2</sup>	Strain
S3	PB1-V1*	388	0.00429	115672.7	128957.2	388	0.00430	388	0.00430
S3	PB2-V1*	256	0.01810			256	0.01811	256	0.01811
S2	PB3-V1*	351	0.00923	153230.4	207805.6	351	0.00923	351	0.00923
S4	PB4-V2	702	0.00105	736180.1	334360.7	265	0.00453	372	0.00667
S4	PB5-V2	476	0.00064	788260.0	408307.3	226	0.00364	297	0.00638
S4	PB6-V2	629	0.00088	787735.8	367100.2	169	0.00494	225	0.00549
S4	PB7-V3*	444	0.00637	107816.7	150943.4	443	0.00641	443	0.00641
S4	PB8-V3*	412	0.00625		291294.3	411	0.00629	411	0.00629
S4	PB9-V3*	559	0.00577	346996.3	230447.9	558	0.00581	558	0.00581
S4	PB10-V4*	438	0.00605	47990.9	162275.5	438	0.00624	438	0.00624
S4	PB11-V4	618	0.00108	571755.3	349406.0	233	0.00494	278	0.00576
S4	PB12-V4	793	0.00107	888243.8	370993.4	235	0.00445	303	0.00530
S4	PB13-V5	668	0.00100	813910.5	356304.2	269	0.00342	287	0.00406
S4	PB14-V5	840	0.00088	1009434.0	403773.6	562	0.00371	604	0.00423
S4	PB15-V5	775	0.00114	822102.4	346148.4	288	0.00659	315	0.00680

\*Broken samples.

**Table 3. Stress-strain results from unstressed hemp specimens.**

Test S.	Sample	Ultimate stress		E extenso N/mm <sup>2</sup>	E system N/mm <sup>2</sup>	0.1s after ultimate		Ultimate post stress	
		Stress N/mm <sup>2</sup>	Strain			Stress N/mm <sup>2</sup>	Strain	Stress N/mm <sup>2</sup>	Strain
S3	H1-V1	335	0.00069	521847.9	194413.9	-25	0.00315	59	0.01839
S2	H2-V1	449	0.00123	385156.4	311687.3	-10	0.00419	71	0.01644
S2	H3-V2	680	0.00057	2404873.7	449262.1	-3	0.00327	72	0.01017
S1	H4-V2	675	-0.00007		470644.0	12	0.00053	114	0.01726
S1	H5-V2	549	-0.00020		423345.8	5	0.00197	67	0.01217
S1	H6-V3	631	0.00073	829237.8	431658.0	6	0.00571	135	0.01834
S1	H7-V3	469	-0.00101		423933.7	7	0.00149	69	0.01123

S1	H8-V4	473	-0.00121		389167.8	25	0.00099	150	0.01614
S1	H9-V4	650	-0.00011		353392.4	2	0.00443	49	0.01388
S1	H10-V5	723	0.00003		427946.2	20	0.00340	115	0.01046
S1	H11-V5	640	0.00122	644543.9	60806.0	2	0.00574	47	0.01060
S1	H12-V5**	140	0.06407		13628.93761	135	0.06488	135	0.06488

**Table 4. Stress-strain results from pre-stressed hemp specimens.**

Test S.	Sample	Ultimate stress		E extenso N/mm <sup>2</sup>	E system N/mm <sup>2</sup>	0.1s after ultimate		Ultimate post stress	
		Stress N/mm <sup>2</sup>	Strain			Stress N/mm <sup>2</sup>	Strain	Stress N/mm <sup>2</sup>	Strain
S4	PH1-V1	733	0.00050	1842105.3	349490.3	-1	0.00251	73	0.00576
S4	PH2-V1	728	0.00055	1559544.0	335901.8	-4	0.00319	45	0.00636
S4	PH3-V2	891	0.00030		317344.5	-1	0.00643	27	0.00798
S4	PH4-V2	828	0.00018	3904923.6	342037.1	-4	0.00106	75	0.00722
S4	PH5-V2	747	0.00091	1093213.0	337005.5	47	0.00183	170	0.00743
S4	PH6-V3	666	0.00000		196744.2	1	0.00039	84	0.00819
S1	PH7-V3	264	-0.00137		286330.5	60	-0.00383	152	0.00470
S1	PH8-V4	242	-0.00153		199633.1	61	-0.00318	86	-0.00098
S1	PH9-V4*	127	0.01410			126	0.01431	126	0.01431
S1	PH10-V5	369	-0.00142		301739.5	53	-0.00184	56	-0.00138
S1	PH11-V5	545	-0.00030			80	-0.00051	112	0.00426
S1	PH12-V5**	178	0.01233	16893.5	25435.1	161	0.01299	161	0.01299

From these results it is possible to see how strain is sometimes giving negative values due to abnormal behaviour from extensometer. This phenomenon is explained earlier in strain measuring section. Because of this reason it was decided to ignore the results from extensometer and calculate the strain from the results taken from displacement controlled tensile testing system. This is not giving exactly the right strain for the specimens but it enables us to compare the results between different types of specimens.

In following results strain is calculated this way and divided with the whole length of the specimen that was 400 mm

### 3.5.2.1 Graphs from tensile tests.

#### Pre-stressed basalt TRM

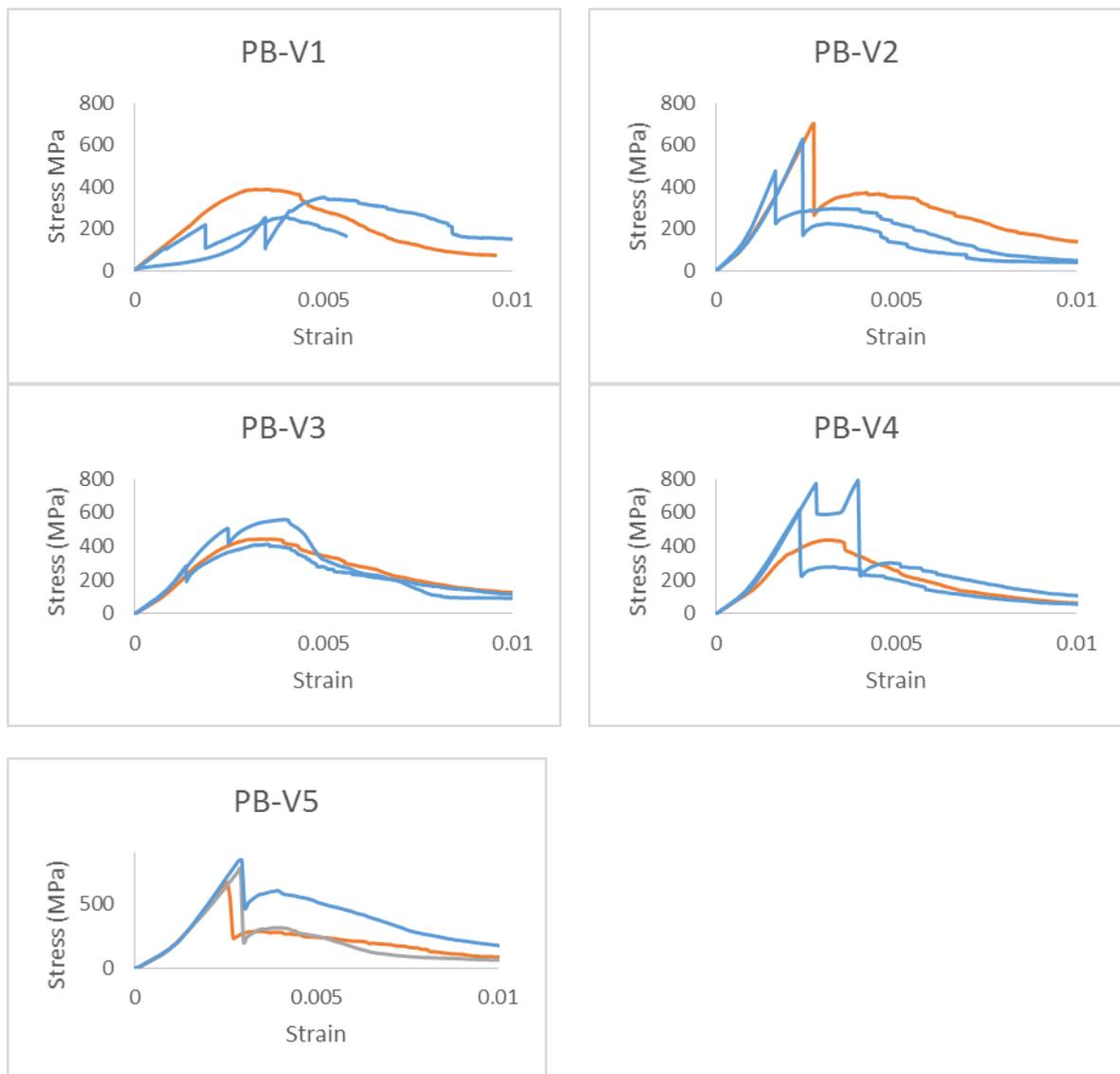
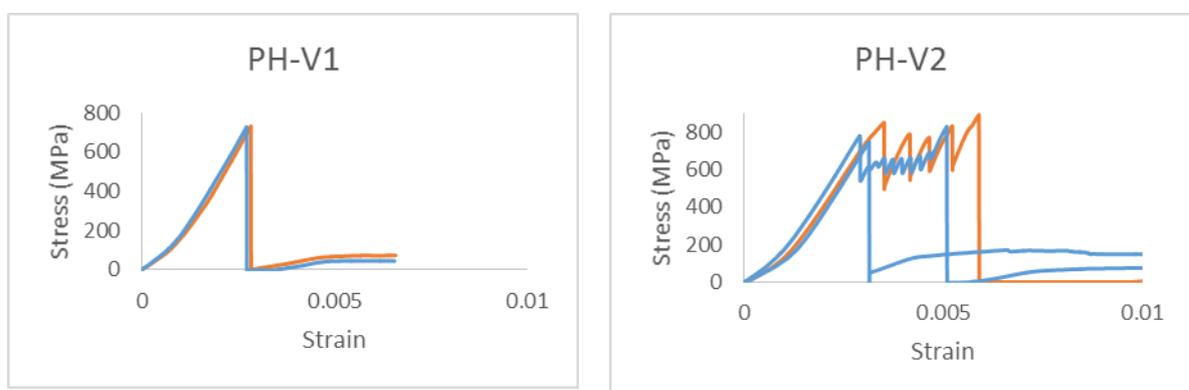


Figure 56. Pre-stressed basalt TRM specimens tested with different testing speeds.

### Pre-stressed hemp TRM



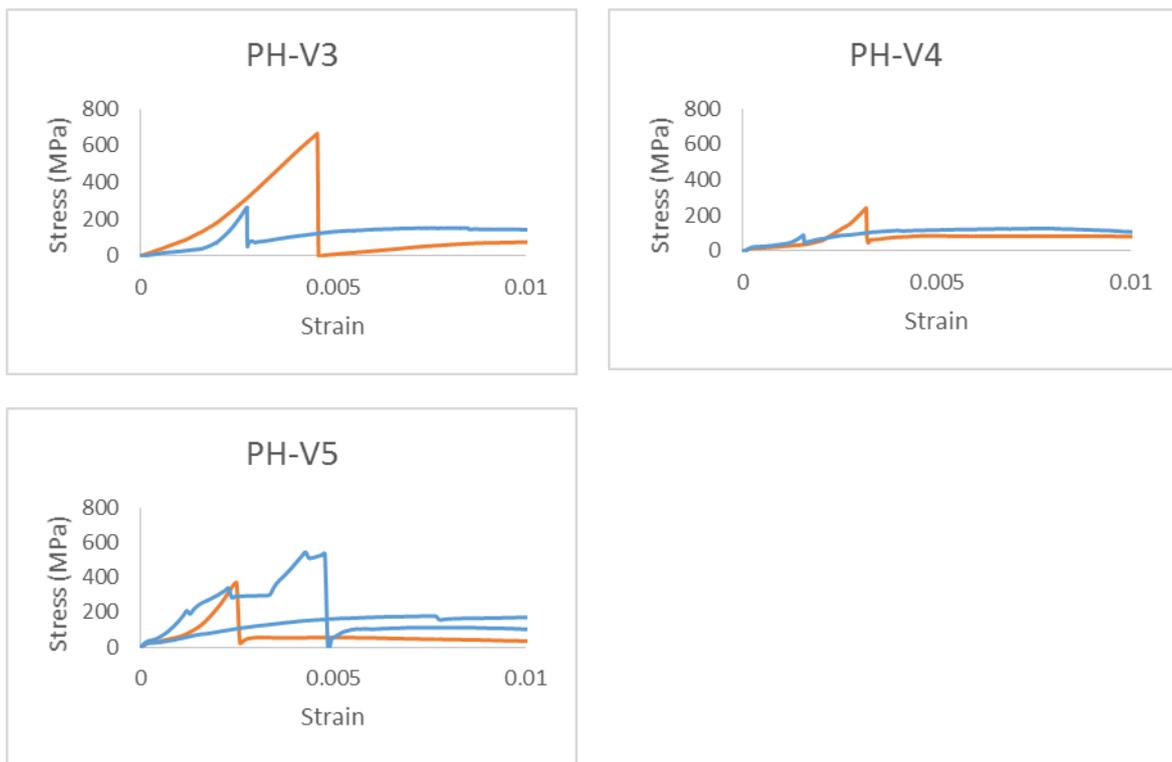
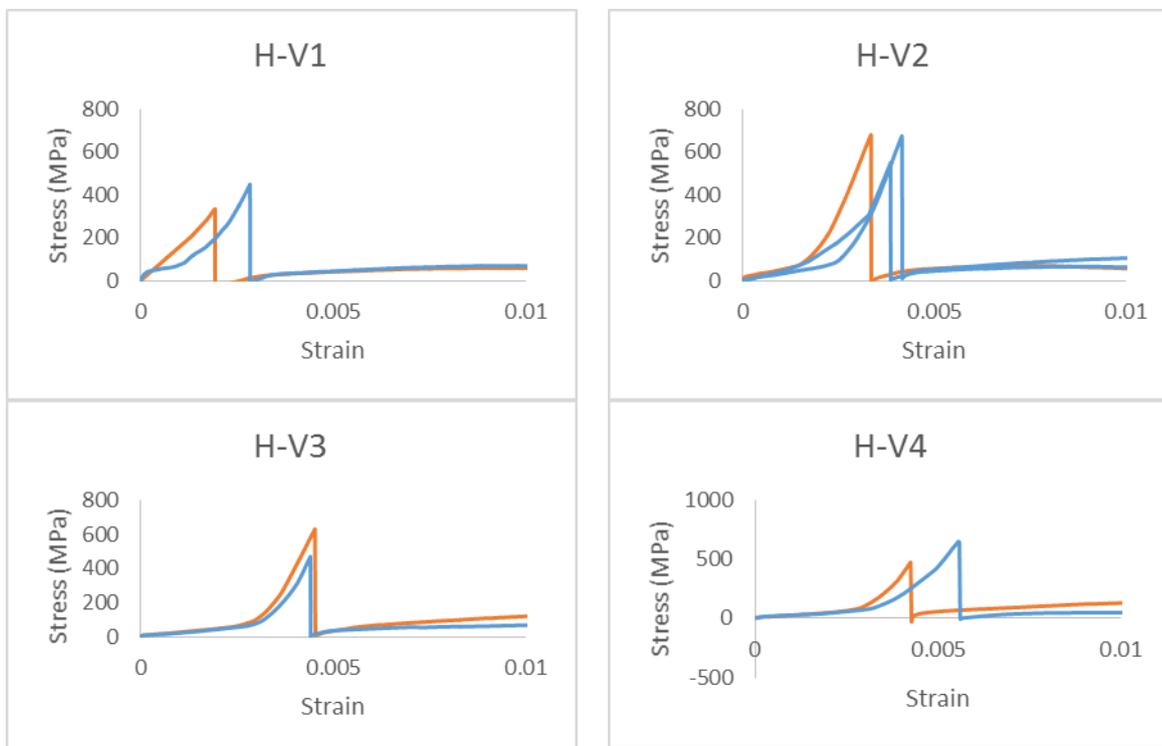
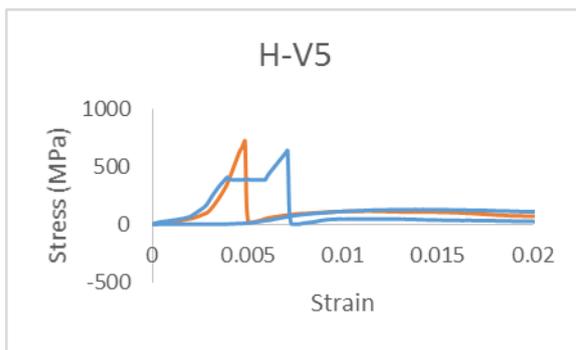


Figure 57. Pre-stressed hemp TRM specimens tested with different testing speeds.

### Unstressed hemp TRM

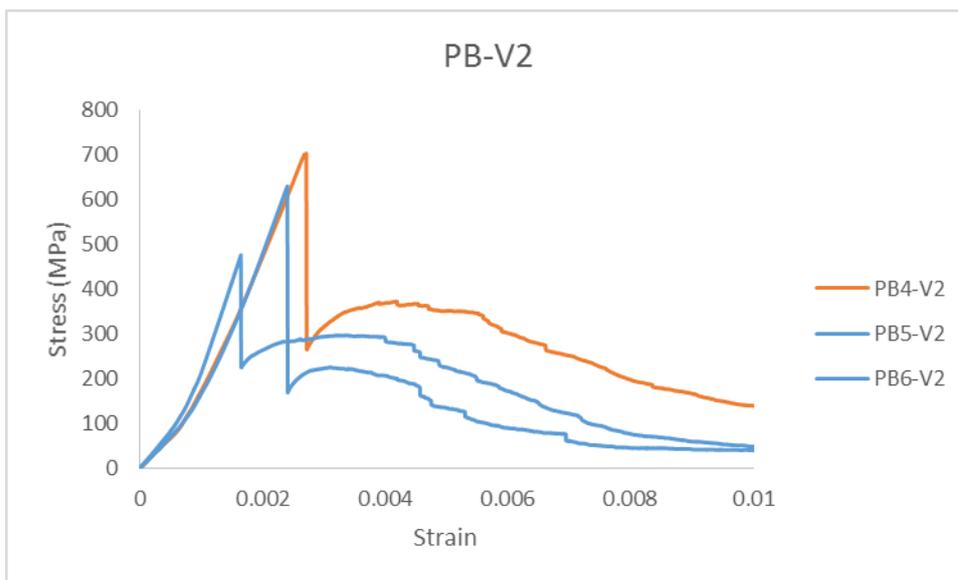




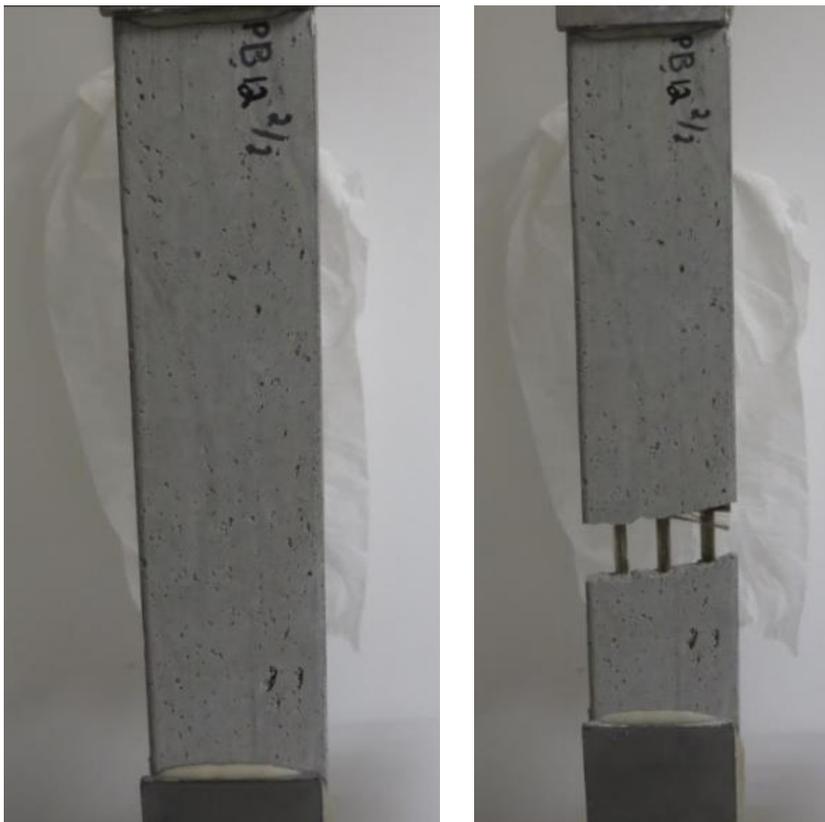
**Figure 58. Hemp TRM specimens tested with different testing speeds.**

### 3.5.3 Failure mechanism of TRM

In this experiment failure happened by cracking followed by slipping between textile and mortar. Figure 59 and Figure 60.



**Figure 59. Failure mode with one crack followed by slipping between textile and matrix.**



**Figure 60 – All specimens were cracked once followed by slipping between textile and matrix.**

### **3.5.4 Influence of pre-stressing**

#### *3.5.4.1 Unstressed versus pre-stressed hemp TRM*

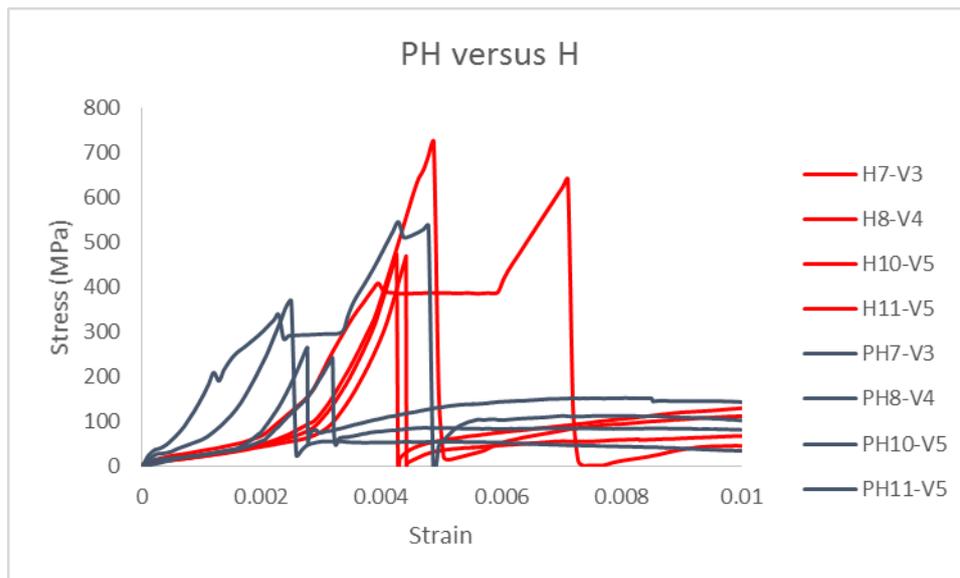
When comparing effect of pre-stressing for ultimate stress, only fully comparable results are found between unstressed and pre-stressed hemp specimens with testing speeds V3, V4 and V5 with four samples. One sample with V3 and V4 from both unstressed and pre-stressed hemp and two samples from each with V5. All these samples were tested with setup 1 (S1). Table 5. Other samples were either tested with different testing setup or cracked during unmoulding and for those reasons not comparable.

When comparing these results between unstressed and pre-stressed hemp specimens it is seen that pre-stressing is reducing the ultimate strength that appears just before cracking. On the contrary the stress just after cracking is higher with pre-stressed specimens.

In a point of cracking the strain is smaller in pre-stressed specimens indicating higher stiffness. Table 5

**Table 5. Comparing unstressed and pre-stressed hemp specimens tested with same testing setup (S1).**

Sample	Ultimate stress		0.1s after ultimate stress		Ultimate post stress	
	Stress N/mm <sup>2</sup>	Strain	Stress N/mm <sup>2</sup>	Strain	Stress N/mm <sup>2</sup>	Strain
H7-V3	469	0.00441	8	0.00444	69	0.01074
H8-V4	473	0.00425	28	0.00436	150	0.01384
H10-V5	723	0.00487	22	0.00529	115	0.01146
H11-V5	640	0.00711	2	0.00753	47	0.01178
<b>Average</b>	<b>576</b>	<b>0.00516</b>	<b>15</b>	<b>0.00541</b>	<b>95</b>	<b>0.01195</b>
PH7-V3	264	0.00276	66	0.00278	152	0.00810
PH8-V4	242	0.00318	68	0.00329	86	0.00472
PH10-V5	369	0.00249	59	0.00291	56	0.00324
PH11-V5	545	0.00428	89	0.00520	112	0.00820
<b>Average</b>	<b>355</b>	<b>0.00318</b>	<b>71</b>	<b>0.00355</b>	<b>102</b>	<b>0.00607</b>



**Figure 61. Comparison between unstressed hemp and pre-stressed hemp specimens tested with comparable testing speed and testing setups (S1).**

When comparing the strains between pre-stressed and unstressed hemp samples it seems that pre-stressing is increasing the stiffness of the sample that is seen with decrease of the strain. This is clearly visible in the following graphs where specimens with same testing speeds and same testing setup (S1) are compared. The ultimate stresses are also higher with unstressed hemp specimens.

Pre-stressed hemp (PH) is shown with blue and unstressed hemp (H) is shown with red.

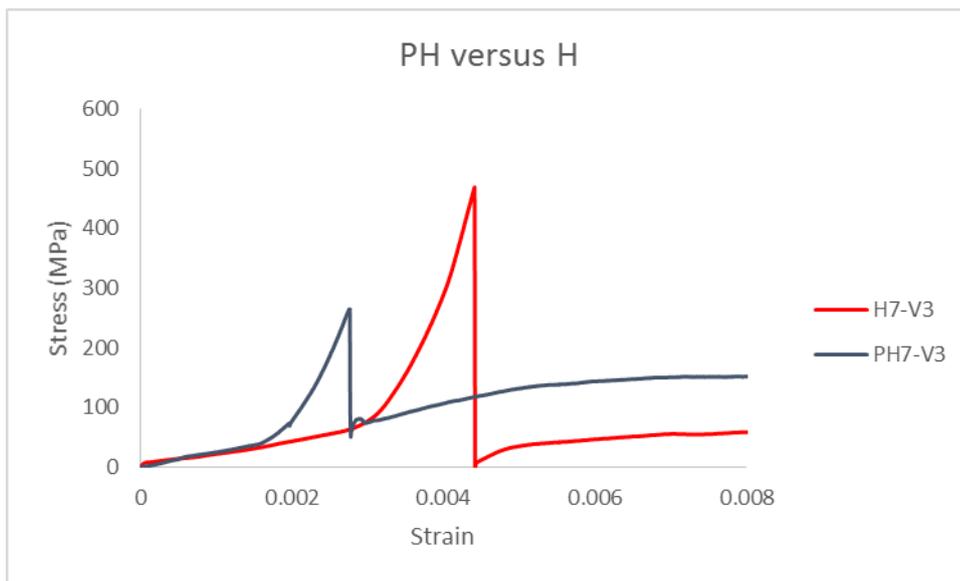


Figure 62. Stress-strain curves of specimens H7 and PH7. Testing setup 1

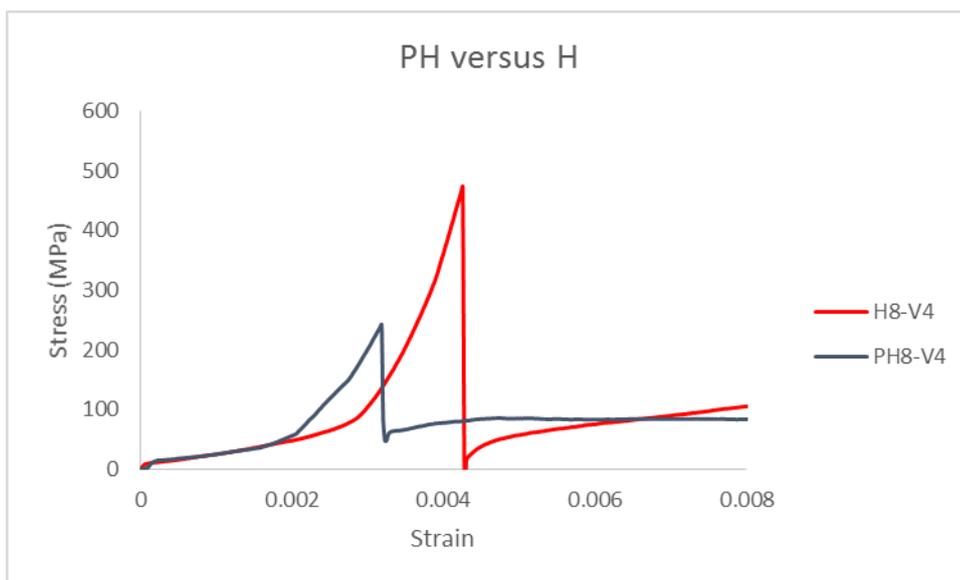
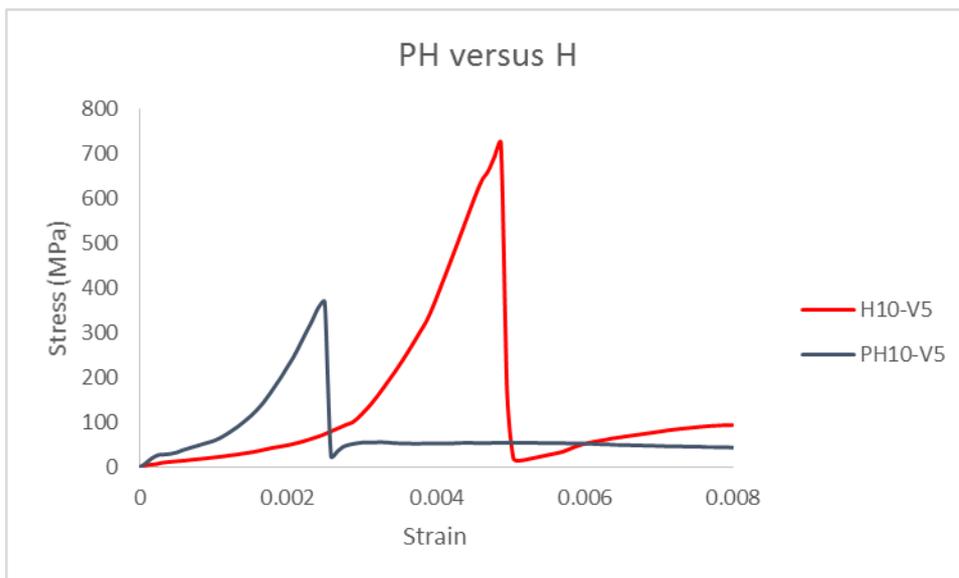
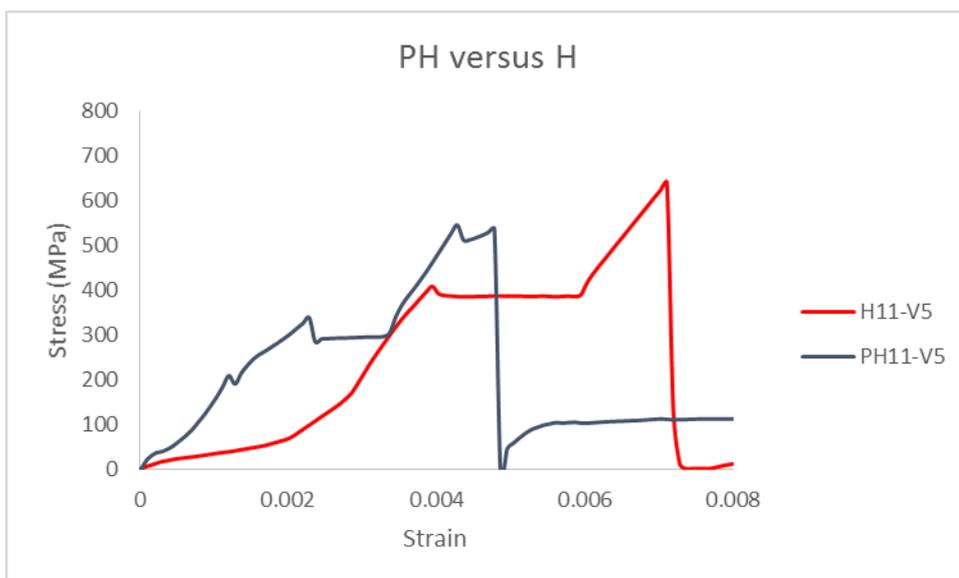


Figure 63. Stress-strain curves of specimens H8 (S1) and PH8 (S1).



**Figure 64. Stress-strain curves of specimens H10 (S1) and PH10 (S1).**



**Figure 65. Stress-strain curves of specimen H11 (S1) and PH11 (S1).**

### 3.5.4.2 Unstressed versus pre-stressed basalt

Pre-stressed basalt samples (PB) were compared with results from the unstressed basalt samples (B) that were tested earlier in another study. Here the testing speeds were comparable but testing setup is different so ultimate stress should be excluded from comparison. Unstressed specimens were tested with testing setup 1 (S1) and pre-stressed specimens were tested with testing setup 4 (S4). As mentioned earlier the testing setup 4 (S4) had less bending effect leading to the higher tensile stress.

These graphs are showing that in pre-stressed specimens the textiles are effective in earlier phase than in unstressed specimens making pre-stressed specimens stiffer.

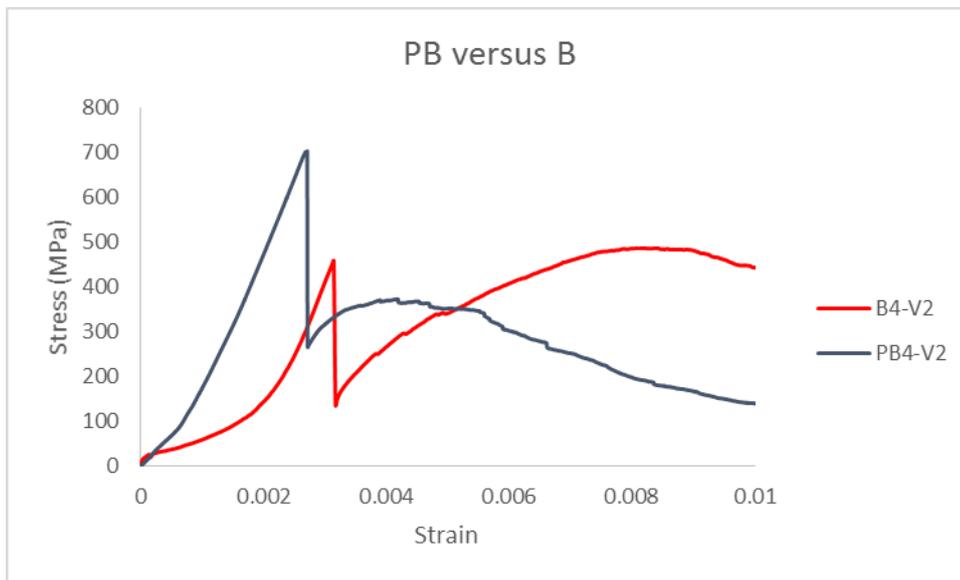


Figure 66. Stress-strain curves of specimen B4 (S1) and PB4 (S4).

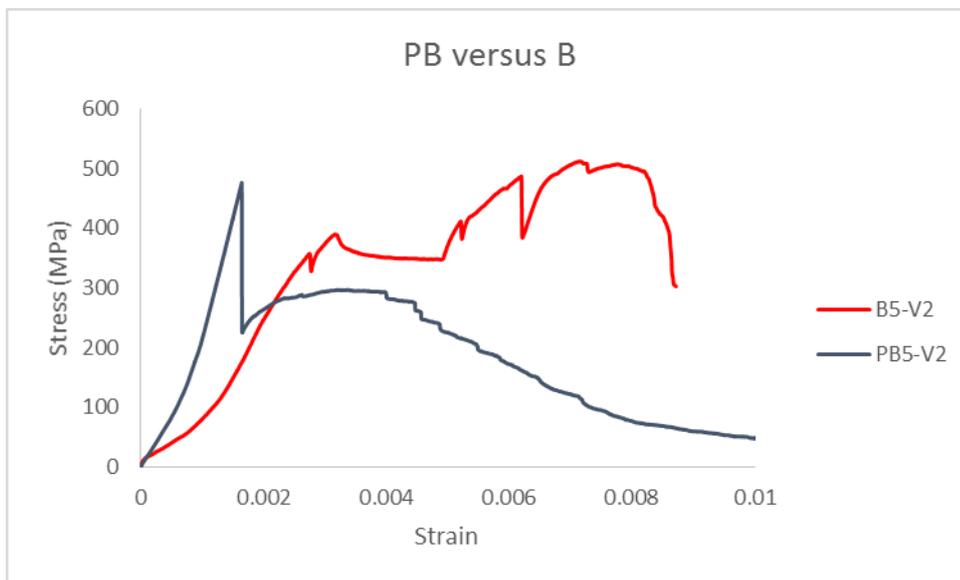


Figure 67. Stress-strain curves of specimen B5 (S1) and PB5 (S4).

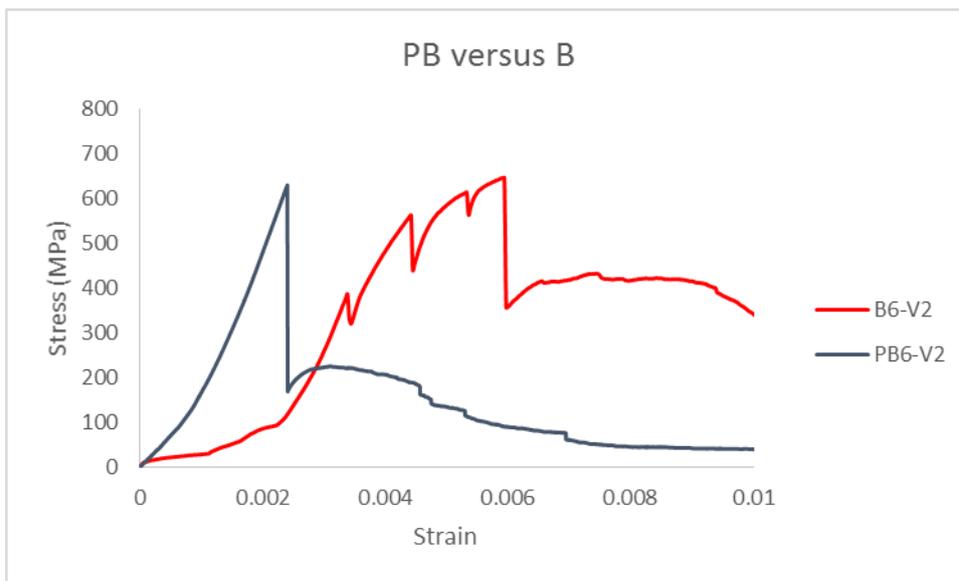


Figure 68. Stress-strain curves of specimen B6 (S1) and PB6 (S4).

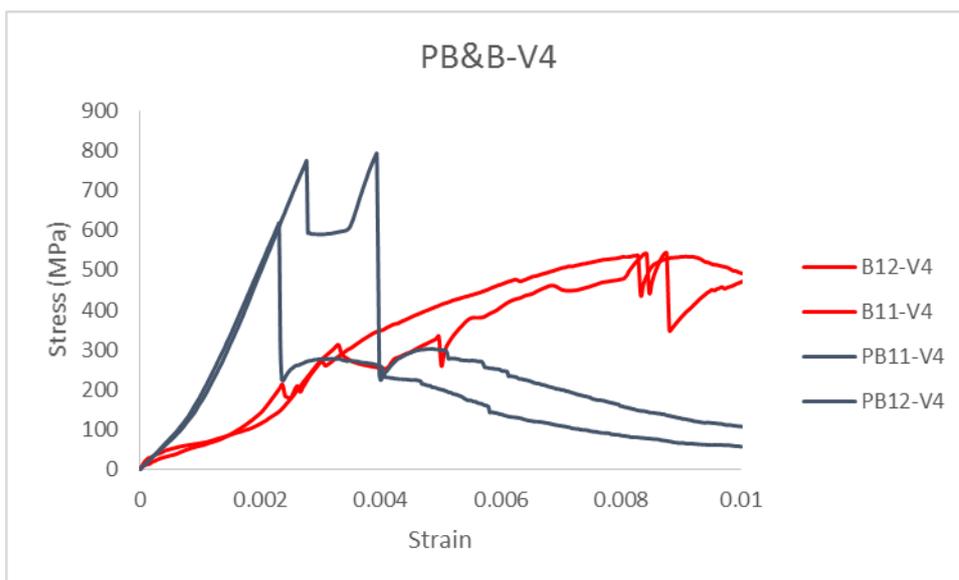


Figure 69. Stress-strain curves of B (S1) and PB (S4) with testing speed V4.

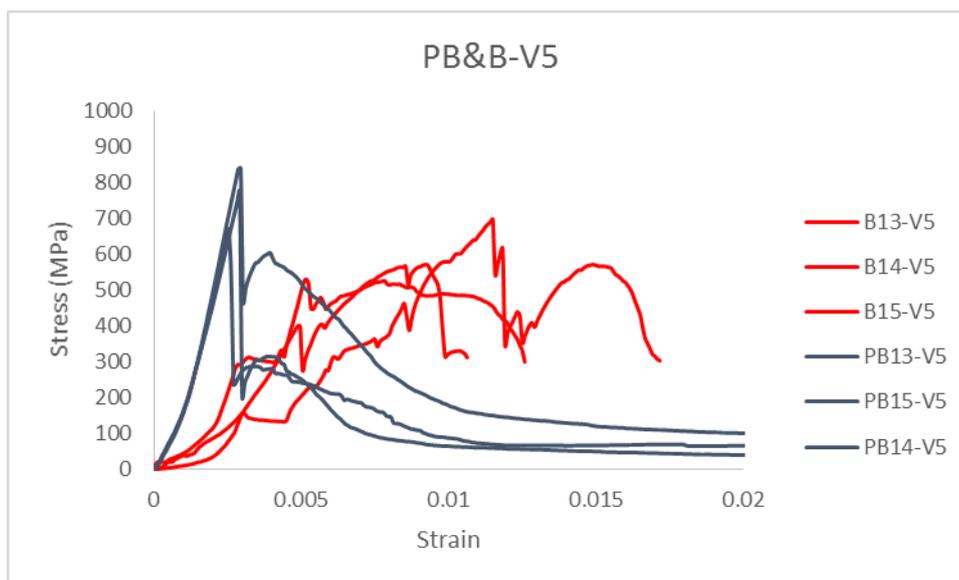


Figure 70. Stress-strain curves of B (S1) and PB (S4) with testing speed V5.

### 3.5.5 Influence of testing speed

Five different testing speeds were used; V1 = 0.2 mm/min, V2 = 1 mm/min, V3 = 5 mm/min, V4 = 25 mm/min and V5 = 100 mm/min. From the results specimens that were uncracked and tested with testing setup 4 (S4) were compared in Table 6. It is seen that with increasing testing speed the ultimate load is also increasing.

Table 6. Comparing effect of testing speed to the ultimate load between samples that were tested with same testing setup. In this case only results from testing setup 4 (S4) were used. Empty cells indicate results that were not comparable.

Material	V1=0.2mm/min		V2=1mm/min		V3=5mm/min		V4=25mm/min		V5=100mm/min	
	Average	St.Dev	Average	St.Dev	Average	St.Dev	Average	St.Dev	Average	St.Dev
	N		N		N		N		N	
PB-FRCM			1596.3	0.157			1869.0	0.124	2017.0	0.093
PH-FRCM	2152	0.003	2421.3	0.072						

\*PB, pre-stressed basalt

\*PH, pre-stressed hemp

### 3.5.6 Influence of testing setup

During the experiment testing setup was changed four times. It seemed that even the system was supposed to allow multi degree of freedom it still created some bending moment to the samples. The

problem was noticed when some samples gave negative displacement values during the tensile test. In reality this should not happen but displacement should increase when load is applied. The idea was to find testing setup that would create minimum bending moment.

Most clearly the impact of testing setup is shown on pre-stressed hemp specimens were the last 6 specimens were tested with system 1 (S1) and the first 6 specimens with system 4 (S4). When testing setup was changed to remove the bending effect the ultimate tensile load was increased. Table 7

**Table 7 – Influence of testing setup. Comparing testing setup 4 (S4) and testing setup 1 (S1).**

System	Material	Ult. Load (N)	Average (N)
S4	PH1-V1	2159	
S4	PH2-V1	2145	
S4	PH3-V2	2624	
S4	PH4-V2	2439	
S4	PH5-V2	2201	
S4	PH6-V3	1962	2255
S1	PH7-V3	778	
S1	PH8-V4	713	
S1	PH10-V5	1086	
S1	PH11-V5	1605	1046

### 3.5.7 Comparison between pre-stressed basalt and pre-stressed hemp

When comparing test results between pre-stressed basalt and pre-stressed hemp it shows that hemp is having higher ultimate stress than basalt. Then when comparing results 0.1 second after cracking results are showing that now basalt has higher stress than hemp. Table 8

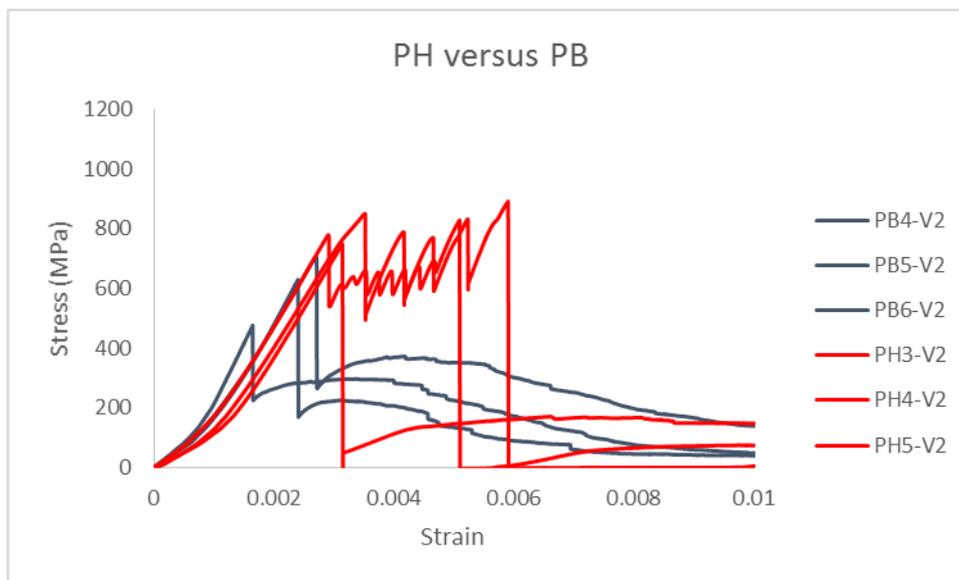
This is indicating that hemp has higher initial bonding than basalt (even hemp has only unidirectional tows) but after cracking the basalt seems to have higher bonding strength.

**Table 8. Comparing pre-stressed basalt and pre-stressed hemp. All specimens tested with testing setup 4 (S4).**

Sample	Ultimate stress		0.1s after ultimate stress		Ultimate post stress	
	Stress N/mm <sup>2</sup>	Strain	Stress N/mm <sup>2</sup>	Strain	Stress N/mm <sup>2</sup>	Strain
PB4-V2	702	0.00272	265	0.00272	372	0.00419
PB5-V2	476	0.00165	226	0.00165	297	0.00339
PB6-V2	629	0.00241	169	0.00241	225	0.00310

<b>Average</b>	<b>602</b>	<b>0.00226</b>	<b>220</b>	<b>0.00226</b>	<b>298</b>	<b>0.00356</b>
PH3-V2	891	0.00591	0	0.00592	27	0.01171
PH4-V2	828	0.00510	0	0.00511	75	0.01011
PH5-V2	747	0.00315	52	0.00316	170	0.00663
<b>Average</b>	<b>822</b>	<b>0.00472</b>	<b>17</b>	<b>0.00473</b>	<b>91</b>	<b>0.00948</b>

Figure 71 is showing how the stress of pre-stressed hemp specimens are going close to zero after cracking. This is indicating the larger cracks while the fibres are not responding immediately after cracking. With pre-stressed basalt specimens it is evident that fibres are taking more load immediately after cracking.



**Figure 71. Comparing stress-strain curves between pre-stressed basalt and pre-stressed hemp specimens. All specimens tested with testing setup 4 (S4).**

## 3.6 Discussions

The objective of this experiment was to study the effect of pre-stressing and effect of testing speed for textile reinforced matrix (TRM) specimens. It could be said that the study succeeded partly to reach to its objectives while the results are indicating same patterns but same time the high number of variables made quantity of comparable results rather small. If we list all these variables (5 testing speeds, 4 testing setups, unstressed and pre-stressed specimens, basalt and hemp specimens and uncracked and cracked specimens) we will reach for 160 different categories. During result analysing different variables were eliminated by comparing only samples which were comparable and this why the number of specimens that were actually comparable covered sometimes only two or three samples. Even though, it was still possible to find patterns related to different testing setups, different testing speeds and for effect of pre-stressing.

### 3.6.1 Influence of pre-stressing

It seems that pre-stressing is effecting to the TRM by reducing the ultimate strength but same time increasing the post strength. It also seems that textiles are effective from the beginning of the tensile test compared to the unstressed specimens where it seems that in the first phase tensile strength is on mortar and only after while textiles are taking some load as well. Pre-stressing also seems to reduce the crack size just after the cracking.

There might be multiple reasons why pre-stressing is reducing the of ultimate strength of TRM. One reason could be that pre-stressing is making textiles straighter and more even reducing the friction between matrix and textile. Another reason might be that pre-stressing is creating initial bonding stress between textile and mortar. In this way the textile and mortar will have higher bonding stress and textiles will start slipping when this ultimate bonding strength is reached.

With basalt specimens testing results are indicating that pre-stressing is reducing the bonding strength between the textile and mortar especially after the first crack appears. While unstressed basalt samples seems to crack from multiple places in pre-stressed specimens there were only one crack and after that failure was happening with slipping between textile and mortar.

With hemp specimens results are indicating that pre-stressing is reducing the ultimate strength of TRM specimens but increasing the strength just after cracking. For ultimate post stress there is no real difference.

### 3.6.2 Influence of testing speed

Five different testing speeds were used;  $V1 = 0.2$  mm/min,  $V2 = 1$  mm/min,  $V3 = 5$  mm/min,  $V4 = 25$  mm/min and  $V5 = 100$  mm/min. From the results specimens that were uncracked and tested with testing setup 4 (S4) were compared in Table 6. It seems that there is tendency that with increasing

testing speed the ultimate load is also increasing. Unfortunately the small number of comparable specimens are not allowing us to get quantitative results.

### **3.6.3 Influence of testing setup**

When analysing the results it was evident how sensitive the results are for the testing setup. Even the smallest eccentricity is reducing the ultimate tensile strength. This eccentricity can be caused by the curvature of the specimen, eccentricity of the textile inside the matrix, displacement of the gripping plates or from the connection mechanism to the tensile testing machine. Out of these variables it was possible to manipulate only the connection part while all other variables were already fixed when testing started.

During the testing it was noticed that the original testing setup was still creating some bending moment. This was due to fact that the gripping plates were newer perfectly in line and even the slightest difference between the holes in these plates created a situation where testing setup was adding more load on one side of the specimen. Due to this the testing setup was changed four times during the test to achieve balanced loading for the gripping plates on both side of the specimen. The best result was finally received with setup where metal carabiners were placed middle of the gripping plates.

### **3.6.4 Strain measuring**

In general there is two commonly used ways to measure displacement and calculate the strain, point-to-point instruments like extension meter used in this experiment and linear variable differential transformers (LVDT). The challenge of measuring exact displacement is due to high number of variables present. Following is covering some of these variables and how they will effect to the results.

Firstly these measuring systems are recording displacement only from the surface of the mortar and that's why not catching the possible telescopic behaviour of the fibres neither the slipping between the fibres and mortar. This will also leave the question while calculating the stress if it should be calculated towards mortar or towards textile.

Secondly the specimens are hardly ever perfectly straight and while applying the unidirectional tensile load these specimens are forced to straighten. This will create bending load that will effect to the cracking load. This bending phenomena will also introduce an error on the displacement figure that is measured from one side of the sample. Depending on if the measuring system is implemented on the convex or concave side of the specimen it will give either too low or too high figures respectively.

Thirdly the extensometer length is smaller than the specimen size. In this experiment the L-frame steel plates were introduced to cover the total length of the specimen. Even this system was giving some

promising results it was still influenced by the bending by giving negative figures due to this straightening effect.

Fourthly the bending after cracking can change the lining of the separated mortar elements corrupting the absolute displacement figures.

Fifthly the release of huge energy during the first crack appearing will create impact that sometimes causes the unwanted movement or sliding on the extension meter.

Sixthly four different connection methods were used during this experiment to reduce the bending effect and to find optimal connection method to be used in coming experiments. These different methods are impacting to the displacement results and that's why not fully comparable to each other.

### **3.6.5 Pre-stressed hemp versus pre-stressed basalt**

Before cracking the behaviour of pre-stressed hemp and pre-stressed basalt seems to be rather similar where textiles are effective already from the beginning of the tensile test. The ultimate stress, just before cracking is higher on hemp specimens. This is possibly indicating higher initial bonding strength between hemp and mortar than basalt and mortar. After this basalt seems to have better friction with mortar possibly due to transversal fibres. Also the ultimate post stress is higher with basalt specimens.

#### 4 CONCLUSION AND POSSIBILITIES FOR FURTHER STUDIES

Experiment is indicating that pre-stressing is reducing the strain before cracking and decreasing the cracking size. It also seems that pre-stressing is reducing the initial bonding strength between textile and matrix. With basalt samples it was clear that pre-stressing was keeping minor cracks closed. Unfortunately same time it seems that pre-stressing is actually weakening the connection between mortar and textile. While unstressed basalt samples were getting cracked in multiple places pre-stressed samples broke only from one place and then slipping was failure mode after this. This could be due to fact that with pre-stressing textile is getting very strait and even almost like razorblade.

With hemp, experiment is showing better initial bonding between textile and matrix than for basalt but after the initial connection is lost the bonding with unidirectional fibres are lower. One possible problem was the small diameter of hemp strings, only 0.5 mm. With bigger diameter the bonding could be good enough to counter less slipping and more cracks on mortar.

It would be very interesting to do some further studies with hemp that would be double diameter for the one used in this experiment with transversal tows. Also it would interesting to try if evenly distributed knots on fibre would increase the bonding enough to avoid slipping. This would reduce ultimate strength of the fibre but it might still be enough to get perfectly useful material to be used in historical buildings, especially for masonry and adobe structures.

Results with basalt are indicating that some kind of treatment like resin on basalt would be needed to increase the bonding strength between basalt textile and mortar. It would be also interesting to study how long bonding length would be enough to avoid slipping and to reach to the ultimate tensile strength of the textile.

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