TECHNICAL UNIVERSITY OF LIBEREC
Faculty of Textile Engineering

# HYBRID WOVEN STRUCTURES

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SUMMARY OF THE THESIS

**Title of the thesis:** **Woven Structures**

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**Field of study:** Textile Technics and Materials Engineering

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## Abstract:

With the advancement and continuing integration of composite materials and technology in today's modern industries, research in this field is becoming more and more significant.

Basalt fibers are very promising materials due to their fire resistance related to magmatic origin, superior mechanical properties and relatively low cost. On the other hand, being a relatively new kind of fiber, they are still not studied extensively. There are very few indications in technical papers about their behavior after aging treatments. The current study investigates the possibility of using basalt with other types of yarns and consequently the effect of hybrid woven structure on load bearing capacity and durability. This thesis conveys a better insight into characteristics of Basalt fibers specifically, alongside commonly used fibers to design and develop hybrid woven fabrics for Textile Reinforced Concrete (TRC) materials. Various combinations of basalt hybrid fabrics are investigated with respect to mechanical, thermal, acoustic, electrical and other functional properties. The influence of hybridization and structure of woven fabric is studied in detail. The tensile properties are predicted by using structural model and correlated to the results obtained through experiments.

This thesis also aims to investigate structural performance and durability aspects of TRC for its usability in the built environment. The present work provides a direction to study durability of different fiber-reinforced cement composites which can be ascertained/forecast by interfacial bonds and accelerated aging conditions. This study helps in gaining better insight into the specific material behavior of the concrete with hybrid reinforcement.

The main objective of the work is the investigation of hybridization effects in the load-bearing behavior of TRC. In the present work, the load-bearing behavior of TRC, which is a composite of a fine-grained concrete matrix and a reinforcement of high-performance fibers processed to textiles, when exposed to uniaxial tensile loading was investigated. The investigations are focused on reinforcement of hybrid woven fabrics. The bond behavior of textile reinforced concrete was characterized in this work by means of direct pull-out tests.

According to the results obtained, it can be concluded that the accelerated ageing test was too aggressive for textiles made of Jute (J) and Polyester (PET), leading to extensive degradation; however, Basalt (B) and Polypropylene (PP) textiles were found to be a promising alternative as they have superior durability properties in an alkaline environment without undergoing much strength loss. Despite the hydrophobic characteristics of PP fibers and their poor bond with the cement matrix, these fibers are considered as attractive for the reinforcement of cement matrices because of their high resistance to the alkaline environment of the cement matrix and a relatively lower cost.

In general the use of high strength fibers like basalt increases the strength and toughness of the cement composites providing strain-hardening behavior. Low modulus fiber such as PP and PET enhance mainly the ductility of the cement composites, but not its strength in a strain softening behavior. The PP and PET structure did not bond strongly with the cement matrix, resulting in relatively low composite performance. By the hybridization of PP and PET yarn with basalt, this problem can be solved. The B/PP or B/PET yarn combination in a hybrid fabric should be considered as reinforcement for cement composites.



**Keywords:** Hybrid woven fabrics, basalt, weavability, structural models, shear, yarn pull-out, accelerated aging, DMA, acoustic properties, electrical properties

# Anotace

Se zdokonalováním a trvalým začleňováním kompozitních materiálů a technologií v současném moderním průmyslu se výzkum v této oblasti stává čím dál více významnějším. Čedičová vlákna jsou velmi perspektivním materiálem díky jejich ohnivzdornosti spojené s lávovým původem, vynikajícím mechanickým vlastnostem a relativně nízké ceně. Na druhou stranu, tato vlákna doposud nebyla podrobena rozsáhlejšímu průzkumu, protože je možno je považovat za relativně nový typ vlákna. V technických článcích je možno nalézt jen omezené množství údajů o jejich chování po zpracování, jež je spojeno se stárnutím materiálu. Disertační práce prozkoumává možnosti využití čedičových vláken v kombinaci s jinými typy přízí a následně také vliv hybridní tkané struktury na nosnost kompozitu a dobu jeho životnosti. Tato disertační práce poskytuje podrobnější informace o vlastnostech čedičových vláken vedle běžně používaných vláken, a to pro návrh a vývoj hybridních tkaných textilií určených pro výrobu kompozitních materiálů, zejména betonu vyztuženého textilií (TRC). Zkoumány jsou různé kombinace čedičové hybridní tkaniny s ohledem na mechanické, tepelné, akustické, elektrické a jiné vlastnosti, přičemž vliv hybridizace a struktury tkaných textilií je studován detailněji. Mechanické vlastnosti jsou predikovány s použitím a strukturální modely korelovány s výsledky získanými z provedených experimentů.

Tato disertační práce dále cílí na vyšetření aspektů strukturální funkčnosti a životnosti TRC kompozitů pro jejich použití ve stavebnictví. Práce udává směr studia životnosti různých, vlákny vyztužených cementových kompozitů, která může být zjišťována resp. předpovídána na základě znalosti mezifázových vazeb a podmínek zrychleného stárnutí.

Hlavním cílem této práce je tedy průzkum hybridizačních efektů na nosné chování TRC kompozitu. V této studii je vyšetřeno nosné chování TRC kompozitu (kompozitní systém tvořený jemnozrnnou betonovou matricí a výztuží složenou z vysoce funkčních vláken zpracovaných do plošné textilie) při jednoosém namáhání tahem. Průzkum je zaměřen na výztužnou schopnost hybridní tkané struktury. Toto vazebné chování betonu vyztuženého textilií bylo sledováno v práci přímo pomocí vytrhávacího testu.

Na základě získaných výsledků může být shrnuto, že testy zrychleného stárnutí byly příliš agresivní pro textilie vyrobené z juty (J) a polyesteru (PET) vedoucí k jejich významné degradaci. Čedičové (B) a polypropylenové (PP) textilie však byly shledány slibnou alternativou ke zmíněným vláknům díky jejich výjimečné životnosti v alkalickém prostředí bez významných ztrát pevnosti. I přes hydrofobní charakter polypropylenových vláken a tedy jejich slabé interakci s cementovou matricí byla tato vlákna shledána jako atraktivní pro výztuž cementové matrice, a to díky jejich vysoké odolnosti k alkalickému prostředí cementové matrice a relativně nízké ceně.

Použití vysoce-pevnostních vláken jako jsou čedičová, obecně zvyšuje pevnost a tuhost cementových kompozitů poskytující mechanické zpevnění. Vlákna s nízkým modulem jako jsou polypropylen a polyester zlepšují zejména tažnost cementových kompozitů, ne však jejich pevnostně deformační chování. Struktury založené na kombinaci PP/PET se nepojí silně s cementovou matricí, což vede k relativně nízké funkčnosti kompozitu. Je tedy zřejmé, že hybridizace PP/PET příze s čedičem přináší řešení problému.Na druhou stranu kombinace B/P nebo B/PET v hybridní plošné textilii se zdá být dobrou volnou pro výztuž cementových kompozitů.



**Klíčová slova**: Hybridní tkaniny, čedič, zpracovatelnost tkaním, strukturální modely, smyk, ytrhávání příze, zrychlené stárnutí, DMA, akustické vlastnosti, elektrické vlastnosti

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# 1 Introduction

The fast pace of technological advancement has always pushed engineering materials to their limits but in the last century the development of new materials is so fast as requirements for structures, automobiles etc. are changing rapidly. In the quest for ever more performance from existing materials, engineers have developed hybrid materials that in combination have characteristics superior to that of their individual constituents. Many of our modern technologies require material with unusual combination of properties that cannot be met by the conventional metal, ceramics and polymeric materials. This is especially true for materials that are needed for construction, transportation applications. Composites are emerging as realistic alternatives to the metal alloys in many applications like construction, automobiles, marine, aerospace applications, sports goods, etc.[1]. The fiber/textile is an important constituent in Fiber/textile Reinforced composites. FRCs find applications in construction industries, decking, window and door frames, sports equipment such as bicycle frames, baseball bats, exercise equipment and so on. They are also suited for many automotive applications. The textile composites are composed of two materials i.e., a textile skeleton for reinforcement (called perform) and a binding adhesive (called matrix) material to keep the skeleton integrated into a specific shape. The output and the scope of application for reinforced fibers within polymeric composites have been gradually expanding all over the world. Materials selection has always involved a number of compromises for the engineering designer. Of course, the material's properties are extremely important, since the performance of the structure or component to be designed relies in the properties of the material used in its construction. Polypropylene (PP) and Polyester (PET) are the two major synthetic fibers mainly used in industry. Polyester is made from Terepthalic acid (PTA) and Ethylene Glycol. Polypropylene is a polyolefin made from a polypropylene monomer obtained from naphtha. PP is a popular fiber due to its properties like low density i.e lightest fiber, easy process ability, excellent orientation characteristics, superior tensile properties, good chemical resistance, hydrophobicity, resistance to micro-organisms and the relatively inexpensive cost of production. Polyester fibers have high tenacity and elastic modulus as well as low water absorption and minimal shrinkage in comparison with other fibers. In composites, use of natural fibers such as ramie, jute, sisal, hemp, bamboo, oil palm fibers, banana etc is increasing to act as reinforcement. Among these fibers, jute is of particular interest as production of jute is excessive in tropical countries and composites made of jute fibers have moderate flexural and tensile properties compared with other natural fibers [2].

Glass and carbon fibers are widely used for making composites. Environment-friendly and cost effective composites have recently received considerable attention among the scientists. The use of glass and carbon as reinforcements in composites is currently thought of attributable to environmental concern though they have possessed excellent mechanical, thermal properties and durability. Concern for the environment, both in terms of limiting the use of finite resources and the need to manage waste disposal, has led to increasing pressure to recycle materials at the end of their useful life. As Fiber-reinforced polymer composites are widely applied in modem industry and many researches have been carried out to develop environmental fiber materials for the last decade. As a result, basalt fiber has taken notice of researchers as a new reinforcing fiber material [3]. Basalt fiber is extruded from melted basalt rock that consists mainly of Si and Al oxides. The tensile strength of single basalt fiber can be as high as carbon and also it has excellent thermal and chemical stability. Since its manufacturing process is simpler compared to that of glass fiber, basalt consumes less energy, and reduces environmental waste such as carbon dioxide through the manufacturing process.

Without retaining a specific shape, the properties of a composite cannot be utilized [4]. Woven structure is characterized by orthogonal interlacing of at least two sets of yarns called warp and weft. Woven fabrics are used in various technical textile applications. In particular, woven fabric composites offer better dimensional stability over a large range of temperatures, they provide more balanced properties in the fabric plane and the interlacing of yarns provides higher out-of-plane strength, which can take up the secondary loads due to load path eccentricities, local buckling, better impact resistance and tolerance etc. compared to the common unidirectional laminated composites. Incorporation of several different types of fibers into a single matrix has led to the development of hybrid composites. Hybrid composite materials have extensive engineering application where strength to weight ratio, low cost and ease of fabrication are required. Hybrid composites provide combination of properties such as tensile modulus, compressive strength and impact strength which cannot be realized in standard composite materials. Hybrid composites give the privilege to create a material bearing desirable properties among the combination of fibers, that is more cost effective and one can mitigate the non-desirable properties from the combination. It can help to tailor the requirement for specific materials. In comparison with conventional composites, hybrid composites exhibit balanced strength and stiffness, balanced thermal distortion stability, fire resistant behavior, reduced weight and/or cost, improved fatigue resistance, reduced notch sensitivity, improved fracture toughness and impact resistance [5]. Hybrid composites are used in application areas where special properties are required in preferential directions.

The applications related to construction industry have a vital involvement of composite materials over the past decade due to their multifold advantages. Textile reinforced concrete (TRC) is an innovative high performance composite material consisting of textiles embedded in a fine-grained concrete matrix. Textile Reinforced/Fiber-reinforced composites are gaining popularity within the civil construction sector. Applications like fiber-reinforced concrete, concrete retrofitting, concrete jacketing and internal and external reinforcement of composite concrete structures play an important role. TRC is rapidly replacing conventional materials due to its promising features.

## 2 Purpose and the aim of the thesis

The purpose of the thesis is to investigate structural performance and durability aspects of TRC for its usability in the built environment. This was expected to be done by studying the investigation of hybridization effects in the load-bearing and durability behavior of TRC. The idea of current research was to use the common polymeric fibers in the weft and warp along with basalt warp/weft so as to create hybrid woven structures and to further investigate the compatibility with cement in composite manufacturing. The major research objectives are:

### 2.1 To analyze the weavability problem during production of basalt hybrid fabrics

The purpose of this work is to study compatibility of basalt with other fibers in terms of weavability. The fibers in consideration are both thermoset and thermoplastic. Three types of weave structures were selected for the study i.e. plain, twill and matt weave. The structures produced were both hybrid and non-hybrid. During the sample production in weaving, behavior of each group was studied. For each combination of fibers monitoring, time study, breakages, efficiency and final settings were observed and noted. A special arrangement, during running of any combination of fibers was noted separately for future reference. Every weave and combination of fibers was allocated with separate time and special attention was given till the completion of each sample. All the record was maintained along with the working efficiency to keep up to date working of respective combinations. ANOVA is used to see the significance of fiber type and interlacement pattern on weavability.

### 2.2 To predict mechanical properties by using suitable computational tools and verify the predictability

Several methods are employed for the analysis and mechanical modeling of textile structures.

Different computational tools are used for modeling of the internal geometry and deformability of textile structures. Tensile properties of basalt hybrid fabrics are predicted by computational tool and verified with experimental data.

### 2.3 To investigate the effect of weave and fiber composition on mechanical, thermal and functional properties in basalt based hybrid woven structures.

The fabrics are investigated for mechanical and thermal properties. Tensile and shear testing was carried out. Shear testing was done by a biased tensile testing method and results were correlated with image processing based evaluation. Thermal properties were also investigated. Complex comparison of basalt fiber as a new type of reinforcement vis-a-vis other reinforcing fibres was made. For this reason basalt woven hybrid fabrics have been produced and the role of different reinforcing yarns in the structure and their properties and capabilities have been investigated. Polypropylene , Polyester and jute yarns have been used in the hybrid fabrics besides basalt yarn, and the mechanical characteristics of the hybrid fabrics have been investigated as a function of weave and fiber composition by tensile testing and dynamic mechanical testing respectively. Electrical resistivity of various hybrid woven structures was investigated as a function of fiber type and weave structure.

### 2.4 Study of thermo-mechanical charateristics of basalt hybrid fabrics

Dynamic mechanical analysis (DMA) yields information about the mechanical properties of a specimen placed, usually sinusoidal, oscillation as a function of time and temperature by subjecting it to a small, usually sinusoidal, oscillating force. The effect of fiber composition and weave structure in hybrid woven fabrics was evaluated. Thermal stability of samples were also analyzed by TGA(Thermal gravimetric analysis) .The effect of fiber composition was studied.

### 2.5 Study of acoustic properties of basalt hybrid fabrics

The acoustic impedance of a material is its most basic acoustic property. The sound absorption coefficient (SAC) for the frequency range from 50-1600 Hz and 500- 6400 Hz was evaluated. It is correlated to the air resistivity of various hybrid woven structures. Effect of weave structure and porosity was studied in detail. Relationship between elastic moduli and sound is also analyzed.

### 2.6 Study of durability under accelerated aging conditions

The degradation of fiber due to the alkaline solution in the cement matrix seriously decreases the durability and may cause premature failure of the TRC. Calcium hydroxide, which is the primary cause of alkaline environment in cement is used to study the accelerated aging of basalt as well as other thermoset and thermoplastic fiber yarns. In this case, the high concentration of alkali is the main cause of fibers damage. Particularly, weight loss and reduction in mechanical properties could appear. In this work, the effect of accelerated ageing on the tensile properties of textile reinforcement materials was investigated with different variables e.g. time, pH and type of alkali {$NaOH$ and $Ca(OH)_2$}.

### 2.7 Compatibility study of basalt and other yarns with cement

Further aim of the work is to investigate the effect of using different yarns on load bearing capacity in a cement matrix system. The interaction between the cement matrix and reinforcement is characterized by the bond behavior. It is very important that there is good adhesion between the reinforcing fibers and the concrete or cement matrix, otherwise debonding may take place. Bond strength may dominate the mechanical properties of fiber-reinforced concrete. Thus the pull out strength from a cement matrix was evaluated for basalt and other types of yarns.

## 3 Overview of current state of problem

Current applications of textiles have crossed many barriers and reached limits beyond expectations Recently the composites based on technical textiles can be found in many industrial applications as storage and transport structures (tanks, pipes, hoses, etc.), automotive industry, for car frames and other automobile parts (manifold, wheels), sport equipment industry is employing high amounts of textile reinforced composites in the production of sporting goods and protective equipment (helmets, etc.). An interesting application is in building construction, as reinforcement of walls in order to develop strengthened structures with reduced thickness and subsequently low production costs [6-7]. By mixing two or more types of fiber in a matrix to form a hybrid composite it may be possible to create a material possessing the combined advantages of the individual components and simultaneously mitigating their less desirable qualities. It should, in addition, be possible to tailor the properties of such materials to suit specific requirements. The environmental issues have resulted in considerable interest in the development of new composite materials with addition of more than one reinforcement that are biodegradable resources, such as natural fibers as low-cost and environment-friendly alternative for synthetic fibers [8].

The methods of binding the individual fibers together are varied and have significant impact on both the manufacture of the component and structural performance of the composite. The main production processes employed in textile reinforcements are weaving, braiding, knitting and nonwovens production. Woven fabric is one of the most widely used materials in structural applications [9]. Woven structures formulate an important part of technical textiles and their applications. Weave structure helps in providing better and balanced properties in plane of fabric area where as interlacement of yarns provide out of plane strength which results in take up of secondary load due to load path eccentricities, load buckling, tolerance and better impact resistance in comparison with unidirectional laminated composites [10-14].

Growing environmental awareness throughout the world has triggered a paradigm shift towards designing materials compatible with the environment. Glass, Carbon, Kevlar and Boron fibers are being used as reinforcing materials in fiber-reinforced plastics, which have been widely accepted as materials for structural and nonstructural applications. However, these materials are resistant to biodegradation and can pose environmental problems. Basalt fiber is new special reinforced fiber [15-16]. Basalt is an igneous rock, which is solidified volcanic lava. In recent years, basalt received attention as a replacement for asbestos fibers. Basalt has emerged as a contender in the fiber reinforcement of composites. Basalt fiber (BF) is capable to withstand very high temperature and can be used in high performance applications. Basalt fiber is cheaper than carbon fibers, and exhibits a higher strength than glass [17]. Basalt based composites can replace steel (1kg of basalt reinforcement is equivalent to 9.6kg of steel) as lightweight concrete, which have comparable mechanical properties. As a result a lighter building is possible by using basalt fiber based bar instead of steel reinforcing bars. Composites, which are combinations of different materials leading to a new material, are often used in civil engineering. The reason is that the optimal plain material with regard to structural and economic performance does not often exist. Thus, it is necessary to combine the advantageous properties of single materials for instance load-bearing capacity, durability, weight and costs to eliminate mutually their drawbacks. The structural materials most often used in civil engineering are concrete and steel. Conventional steel in combination with reinforcement of concrete is most common for construction despite some of the historical disadvantages of vulnerability to corrosion attack and durability. In recent past, an attempt to improve sustainability of reinforced concrete came in the shape of development of TRC, which is by providing non-corrosive textile materials as reinforcement with fine grained concrete matrix. It has evolved as a perfect alternative with excellent properties of thin and light weight structures along with corrosion resistance. Textile composites have certain other advantages too like high strength-to-weight ratio, ease of handling, drapability, speed of installation, and visual impact, reversibility etc. Textiles are used in concrete to control cracking due to plastic shrinkage and drying shrinkage. They also reduce the permeability of concrete and thus reduce bleeding of water [18-21]. The composites behavior between textile reinforcement and concrete matrix determines important properties of the textile reinforced concrete, such as durability and load bearing capacity/structural performance. Despite the fact that TRC based research has revealed many promising attributes, it has yet to reach its recognition due to a lack of available design tools, standards and long-term behavior.

Many research work reported in literature mainly focused on glass, carbon and other fibers, but very little work is reported about use of Basalt fiber in hybrid fabrics. Also, very little work is done on hybrid woven fabrics, mainly focused on basalt and its weavability. Woven fabrics satisfy a wide range of needs and requirements and they are the main source of planar textile reinforcements. The physical and mechanical properties of these materials define the scope of their end use in a variety of applications. Therefore, it is crucial to have a better understanding of the parameters that influence the behavior of such hybrid woven materials. Information on usage of environment friendly material as basalt hybrid structure for composites, especially for TRC application is very limited. Pull-out tests is a common method applied to study the bond or pull-out behavior of reinforcement embedded in a matrix [22].Particularly, the effects of accelerated ageing are weight loss and reduction in mechanical properties [23-25]. . In the technical literature different studies are present, but the reported results appear somewhat contrasting

It is therefore necessary to study the effect of accelerated ageing on the tensile properties of textile reinforcement materials with different variables e.g. time, pH and type of alkali.

# 4 Studied Materials, Methods used

## 4.1 Materials

The details of fibers and yarns are given in Table 1.

Table 1: Properties of fibers and yarns used

| **Properties** | **Basalt** | **Polyester** | **Polypropylene** | **Jute** |
|---|---|---|---|---|
| Diameter of fibers (micron) | 12 | 22 | 34 | 18 |
| No. of filaments | 890 | 900 | 300 | -------- |
| Linear density of yarn (Tex) | 295 | 250 | 292 | 296 |
| TPM (Twists/m) | 20 | 24 | 30 | 180 |
| Tensile strength (N) | 92.75 | 57.44 | 88.91 | 41.43 |
| Tensile elongation (%) | 1.29 | 12.27 | 12.55 | 1.39 |
| Tenacity (N/tex) | 0.315 | 0.305 | 0.23 | 0.139 |
| Initial modulus (MPa) | 9,378 | 1069 | 721 | 3,741 |

***Cement and geopolymer for compatibility study***

A commercial ordinary portland cement (OPC) was used and green cement (GEOPOLYMER BAUCIS L110) produced by České lupkové závody, a.s was taken.

***Alkali for accelerated aging study***

The chemicals used for accelerated aging treatment are analytical grade NaOH (sodium hydroxide, Lach:ner.s.r.o, Czech Republic) and $Ca(OH)_2$ (Calcium hydroxide LACHMEMA.N.P.Brno, Czech Republic).

## 4.2 Methods

### *4.2.1 Preparation of samples*

The fabric samples produced are:
1. Plain weave, B/PP, B/PET and B/J,
2. Matt weave, B/PP, B/PET and B/J,
3. Twill weave, B/PP, B/PET and B/J.

Pure non-hybrid fabrics were also made for the comparison purposes. All fabric samples were made on the CCI sample loom with the same thread density for all fabrics approx. 12 threads/cm in warp and 8 threads/cm in weft.

(a) CCI Sample loom


(b) Industrial trial on Picanol rapier loom

Figure 1: CCI sample loom and commercial rapier loom for running the fabric samples

The weaving trials were first undertaken on CCI sample loom before weavability on commercial rapier loom so as to identify the efficiency of using basalt with other thermoplastic and thermoset yarns.

### *4.2.2 Characterization of the raw materials*

**Energy-dispersive X-ray analysis of basalt fiber**

Elemental detection via electron dot-mapping was conducted using energy dispersive X-ray (EDAX) analysis on the scanning electron microscope (SEM; VEGA TESCAN 3SBH) for basalt fiber so as to ascertain the chemical composition.

**ATR–FTIR analysis of cements**

Attenuated total reflection (ATR) infrared spectroscopy (NicoletiZ10, Thermo Fisher Scientific Corporation) was used in order to understand the chemical structure of the cement. Transmission method was used with 16 scans for a background, 16 scans for a sample and the spectral range was 4000 -7500 cm$^{-1}$ with a resolution of 4/cm. Commercial Ordinary Portland Cement (OPC) and Geo Polymer Cement (GPC) were used and subjected to chemical analysis.

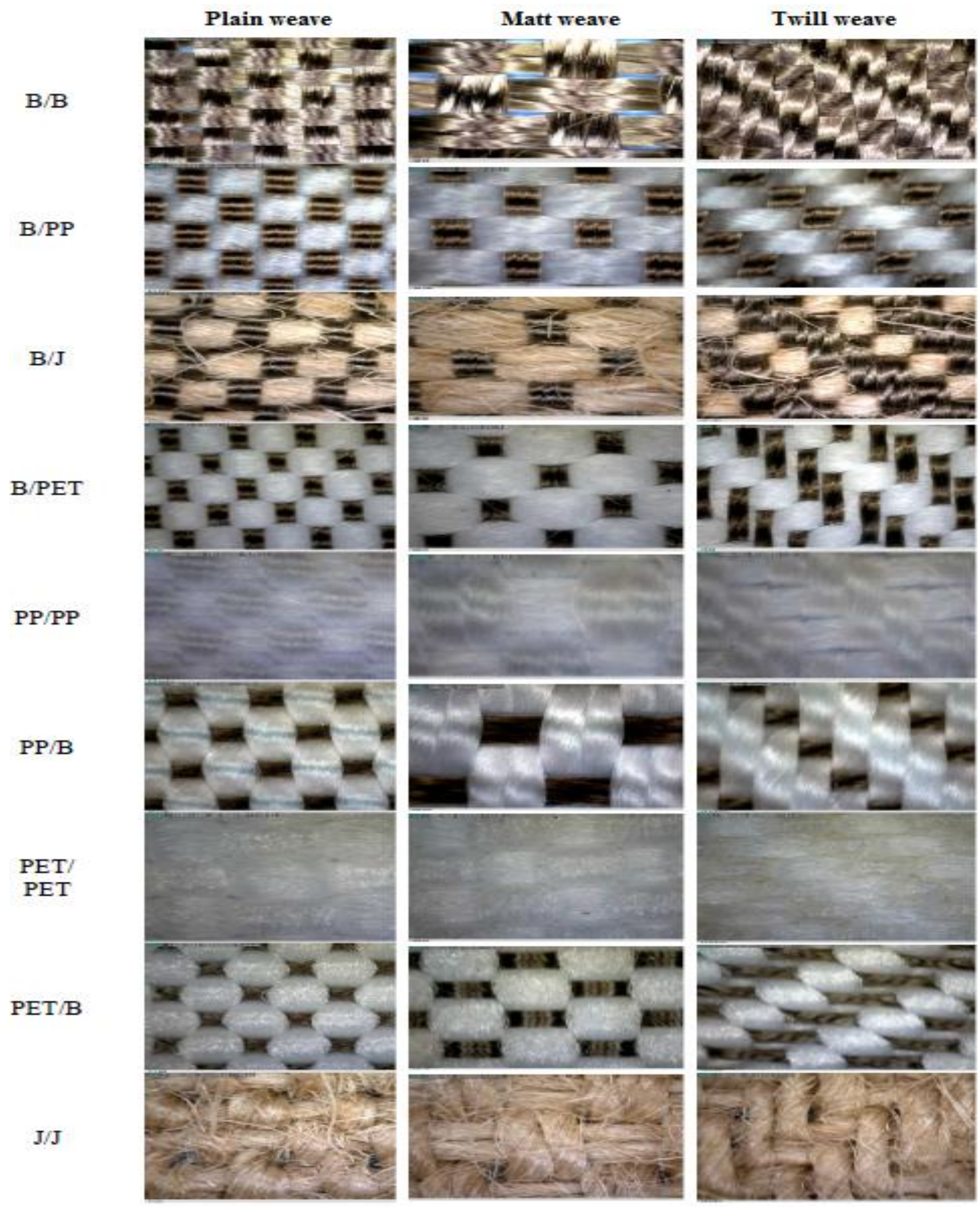


Figure 2: Photographs (Dinolite) of the structures developed with magnification 1280 x1024

**Inductively coupled plasma (ICP-OES) of cements**

Optical emission spectroscopy is done on Perkin Elmer optima 2100 DV. In this work, ICP analysis was used for cement prepared by direct suspension of the powder in dilute acid medium. The aim of this investigation was to develop a rapid method of quality control for such raw materials. The results showed that this technique is sensitive enough for each element of interest and no serious interferences were detected after a detailed inter-element interference study.

#### *4.2.3 Testing methods for fabrics*

**Mechanical properties**

**Static mechanical properties**

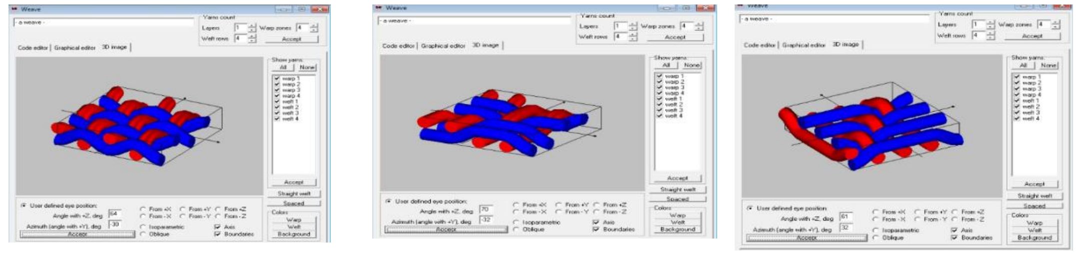
**Tensile test**

Tensile properties of all fabric samples in warp and weft direction were measured on a TIRA

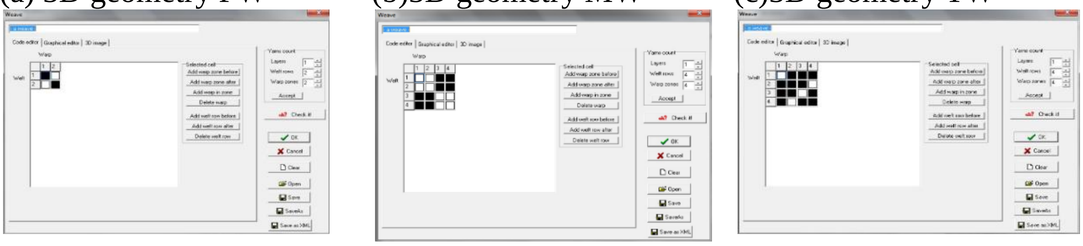
2300 (LaborTech s.r.o., Opava,Czech Republic) universal testing machine. The tensile testing speed was 100 mm/min. This test was performed according to EN ISO 13934-1. The specimen size for tensile testing was 20 cm x 5 cm as per standard. All tensile tests were performed at room temperature. For each sample, 20 measurements were done.

**Prediction of tensile properties using computational tools**

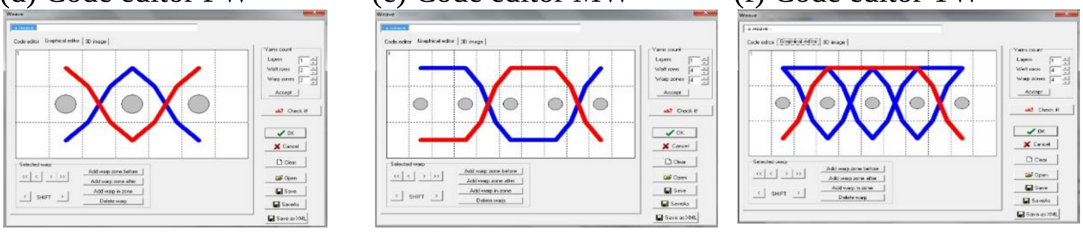
*WiseTex* is a computational tool for modeling of the internal geometry and deformability of textile structures. The model is a mechanical model, as it applies a yarn deformation energy minimization algorithm to predict the internal geometry of any 2D- and 3D-weave.



(a) 3D geometry PW (b)3D geometry MW (c)3D geometry TW



(d) Code editor PW (e) Code editor MW (f) Code editor TW



(g) Graphical editor PW (h) Graphical editor MW (i) Graphical editor TW

Figure 3 : Weave structure (a-c) 3D image, (d-f) code editor and (g-i) graphical editor.

**Shear test**

In this work, a picture frame was used to analyze the in-plane shear behavior of all fabric samples. Shear properties of all fabrics were measured on tensile testing machine by picture frame method under small angular displacements (15 degrees), however jamming of the fibers and wrinkling of the material, which occurred at large angular displacements would not have been observable. It is an effective way for characterizing in-plane shear property of fabrics. Testing yields load and displacement data, which can be used to determine the shear modulus as a function of the materials angular displacement.

The frame is extended diagonally along opposing corners using simple tensile testing equipment as shown in Figure 4. Shear test was performed on TIRA (LaborTech s.r.o., Opava,Czech Republic) with a crosshead speed of 10 mm/min. The nonlinear behavior of shear force versus shear angle and the deformation mechanism were analyzed. Load–displacement(axial force- displacement curves of intra-ply shear tests are analyzed. For each sample type, 10 measurements were taken.

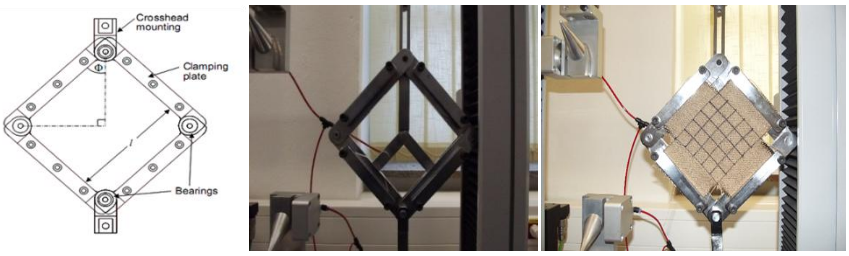
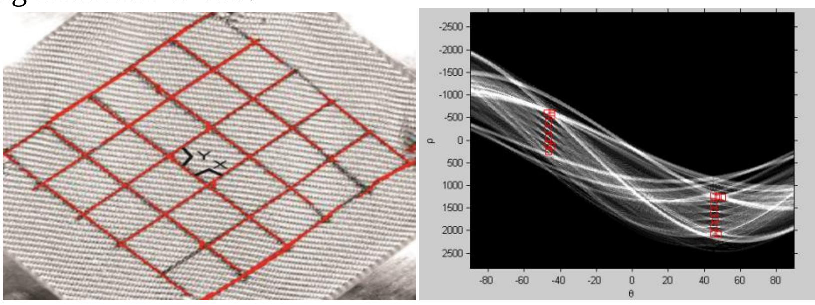



Figure 4: Picture frame fixture design and clamping of sample in fixture

**Image analysis using MATLAB for determination of shear angle**

A special program was developed in MATLAB 7.10 (R 2010a) using Hough's transform to find the angle between the lines on the specimens. This image was analyzed to obtain shear angle and displacement of the specimen during the test. The image file string is examined and then the appropriate image reading function is called by MATLAB imread. As the images taken were colored, the images were converted to grayscale and then normalized to a matrix of values ranging from zero to one.



**(a)** **(b)**

Figure 5. Determination of shear angle using image analysis.

Figure 5 shows the main idea of Hough transform applied to find the shear angle in image analysis technique. The Hough transform is widely used in image analysis, computer vision and digital image processing to find shapes in a binary digital image. This approach is preferred when the objective is to find lines or curves in an image. The parameter ρ represents the distance between line and origin, θ is the angle of the vector from origin to this point. In Figure 5(a), the X, Y angle is presented on gray image for better understanding in sample and shear angle is calculated using this information. Figure 5 (a) shows the points where the lines intersect giving the distance and angle. This distance and angle indicate the line which bisects the points being tested at each 5 mm displacement in every 30 seconds interval. It helps researchers to understand more about detections of angles using houghs transform. In Fig 5(b), the points in Hough's histogram are clearly shown.

**Dynamic mechanical properties**

DMA facilitates in material selection for specific end-use applications. The task of evaluating new materials and projecting their performance for specific applications is a challenging one for engineers and designers. Tensile mode is ideal for investigating thin specimens, such as films/fibers, thin materials in the low-to medium modulus range. The DMA was performed on a DMA 40XT RMI equipment. The samples were tested using tensile mode at a frequency of 1 Hz in temperature scan mode. The DMA test was executed in the temperature range of 27 to 100°C at a heating rate of 3°C/min. This test was performed according to EN ISO 6721-1. All of the samples were investigated in the warp direction. For each sample, five measurements were done.

## Transmission and Thermal Properties

### Air Permeability

All the samples were conditioned in standard atmospheric temperature of about 20° ± 2°C and 65 ± 2% relative humidity for 24 h before subjecting to testing. The Air permeability of the samples were analyzed by using the air Permeability Tester, FX 3300 air permeability tester 111 according to standard ISO 9237(1995). The measurement was performed at a constant drop of 200 Pa (20 $cm^2$ test area) in the standard atmosphere. The averages of 20 measurements for each sample were taken, and mean values of the thermal properties were calculated. To confirm repeatability, measurements were performed thrice at an interval of 30 days for all the samples. The precision of the instrument was measured up to two decimal places for the same fabric that was tested in similar conditions and the accuracy was approximately 14.

### Thermal conductivity and resistance

Measurement of the thermal insulation properties of the fabrics was done by means of Alambeta according to ISO EN31092 standard.The values of thermal conductivity, thermal resistance and fabric thickness under a 200 Pa contact pressure were determined.

Measurement of thermal properties of fabrics are also done by TCi according to the standard test method EN 61326-2-4:2006. TCI developed by C-Therm is a device for conveniently measuring the thermal conductivity of a small sample by using the MTPS (modified transient plane source) method. The tests of thermal properties were repeated five times. The means and SD of data were calculated for all tests.

### Electrical properties

Electrical resistivity (also known as resistivity, specific electrical resistance or volume resistivity) is an intrinsic property that quantifies how strongly a given material opposes the flow of electric current. A low resistivity indicates a material that readily allows the movement of electric charge. Electrical resistance measurement was done on a measuring device (ohmmeter) 4339B High Resistance Meter. The electrical volume and surface resistivity of the samples tested were measured according to the standard ASTM D257-07, at temperature 22.3°C and relative humidity 40.7%. Measurement results were recorded out after 60 s from the moment of placing the electrodes on the textile sample. Voltage value was maintained at 100V. Volume resistivity is measured by applying a voltage potential across opposite sides of the sample and measuring the resultant current through the sample.

### Acoustic properties

The amount of research conducted on sound absorption properties of woven fabrics in comparison to nonwoven and spacer textile fabrics is very limited. The sound absorption coefficient of woven fabrics is significantly lower than that of nonwoven textiles. Despite this fact, woven fabrics are preferred in end-uses, where nonwoven textiles cannot be used due to both technical and economic reasons. This work deals with the study of the acoustic characteristics of woven fabrics in relation to fabric structural parameters and air flow resistivity. In this work acoustical characteristics of hybrid woven fabrics including sound absorption coefficient and factors affecting sound absorption coefficient via the impedance tube method are determined. In order to achieve the objectives of the research, sound absorption coefficient of hybrid woven fabric samples was determined. In this work, the sound absorption of all fabrics samples were calculated using two terms, namely sound absorption coefficient (SAC) and noise reduction coefficient (NRC) using impedance tube method. The performance of all fabrics samples were analyzed for acoustic absorption.Acoustic property was measured by using two-microphone impedance tube according to ASTM E1050-08. The following measurement methods are divided according to the size of evaluated samples. The device is used to determine the sound absorption coefficient, SAC (α) of circular samples with a diameter of 100 mm for the frequency range from 50-1600 Hz and 29mm for the determination of sound absorption coefficient, SAC (α) of circular samples for the frequency range of 500-6400Hz. For comparison among fabrics mid frequency range is used i.e 250-2000 Hz. Among the factors which effect acoustic properties, the air flow resistance is the major contributing parameter in various materials. It is therefore important to consider the flow resistance of an acoustic sample, which is calculated .Correlation between acoustic impedance and modulus was calculated.

**Thermal stability**

Thermal analysis includes a group of analytical methods in which the properties of a substance or a polymeric material are measured as a function of temperature. The thermal behavior of hybrid and non-hybrid woven fabrics were studied under thermos-gravimetric analysis (TGA). The thermos-gravimetric analysis was performed on Mettler Toledo in air from 30$^{o}$C to 600$^{o}$C at heating rate of 10$^{o}$C/min. For each sample, decomposition temperatures and the maximum rates of decomposition were determined. Melting points were determined by Stuart SMP3. It is an easy and accurate visual way to determine melting points of different substances. Results were verified by DSC. The differential scanning calorimetry was performed on DSC 6 Perkin Elmer instrument from 30$^{o}$C to 300$^{o}$C at heating rate of 10$^{o}$C/min.

## 4.3 Characterization of load bearing capacity and durability of yarns in cement composites

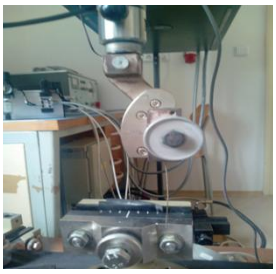
**Preparation of cement matrix**

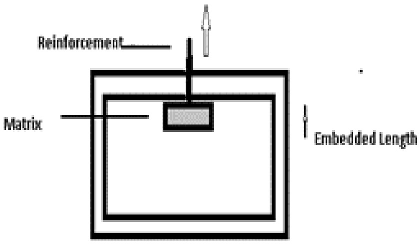
The OPC pastes were prepared by mixing the cement with distilled water. The water to cement ratio (w/c) of 0.4 was maintained. The samples were thoroughly mixed using glass rod for ten minutes and then allowed to hydrate in air-tight plastic containers. Preparation of geopolymer(GPC) mixture is typically used with 5 parts by weight of GPC cement and 4 parts by weight of alkali (NaOH) as recommended by supplier.

**Yarn pull out test**

At present, no standard test setup to investigate the pull-out behavior of TRC is available; as such, relevant experimental work from literature was revealed to help establish an experimental setup. Direct pull-out tests are included in this research to characterize the complex pull-out behavior of a textile structure embedded in a concrete matrix with a particular focus on B, PP, PET and J based TRC. More specifically, the pull-out of a single yarn from the textile woven fabrics was carried out which resulted in a representative smeared pull-out behavior of the yarn embedded woven structure. The pull-out test primarily gives information on the compatibility/interfacial behavior between the yarns selected for the reinforcement and the cement matrix. From this test, estimates can be derived for the failure behavior, and thus for the durability and load bearing capacity The pull-out tests encompassed the evaluation of both pull-out and rupture of the textile material as failure modes. So strand/yarn in cement test, is used to quantitatively analyze this test. The yarn specimens were embedded into cement slab of 40x40x10 mm. The yarn is precisely placed in the center of the specimen. The yarn lengths have to be set so as to ensure protruding ends, for mounting in a tensile tester. It is important to protect the protruding yarn ends from the exposure to avoid strength losses. The specimens were demolded after 48 h and then dried again for 48 h at room temperature. Five specimens were produced for each yarn in order to obtain a representative trend of the pull-out behavior. The yarn was pulled out from the cement by

*TIRA 2300 (LaborTech s.r.o., Opava,Czech Republic)* universal testing machine at the rate of 2.0 mm/min. The experimental setup developed to conduct the pull-out tests is illustrated in Figure 6. In the standard pull-out test, load applied to the yarn end is recorded as a function of the displacement of other end with respect to a ‘‘stationary’’ point in the cement block, usually at the substrate or grips holding the matrix. The test was conducted according to force control such that the load was applied by a pneumatic jack on top of the rigid frame structure. The force-displacement curves and the peak pull-out forces were recorded.






(a) TIRA tester (b)Experimental set up

Figure 6: Pull out test method

**Accelerated aging in alkaline solution**

The action of aqueous sodium hydroxide and calcium hydroxide solutions 10 g/L (w/V) on B, PET, PP and J yarns were investigated under a variety of conditions of pH and time. For this purpose, loss in weight (W), breaking load, % elongation to break and scanning electron micrographs of the yarn surfaces were studied. Tensile tests were conducted on specimens before and after ageing treatment, given that the materials could be tested based on their level of degradation. Furthermore, the interpretation of the experimental results involved the documentation of visual observations before and after testing. To measure weight loss properties, the specimens were weighed by a digital balance to a precision of ±0.1%. Then the dried specimens were fully immersed into alkali solutions for 1 week and 2 week at room temperature. The samples were then reweighed after drying. 2 m length of each yarn, were immersed in three separate tight plastic cylindrical containers in order to avoid any evaporative loss, containing NaOH (98% concentrated) and $Ca(OH)_2$ (96% concentrated) with 10, 11 and 12 pH in separate containers at room temperature. The specimens have to be straight during all the test and the solution level is marked on the container, in order to monitor possible evaporation. Once removed from the alkaline solution, the test specimens were treated with acetic acid (100 mL) to neutralize the remaining hydroxide and rinsed in distilled water to remove any alkali sticking to the surface and visually examining prior to commencing tensile testing. These yarns were dried in oven for 30 min and finally air-dried for 24 hours before further use. NaOH is a strong alkali and used for checking accelerated ageing effect more rapidly.

**Scanning Electron Microscope (SEM) for characterizing surface degradation**

SEM was used for morphological analysis and for investigating the surface degradation of alkali treated samples. SEM images were prepared with different magnifications ranging from 2.5 KX to 50 KX. The microstructures of yarns were prepared on a Vegas-Tescan Scanning Electron Microscope (SEM) with accelerating voltage of 20 kV. The surfaces of the samples were coated with gold by means of a plasma sputtering apparatus prior to SEM investigation. SEM provides detailed high resolution images of the samples by a focused electron beam across the surface and detecting secondary or backscattered electron signal. It provides images with magnifications up to ~ x 50, 000 allowing sub-micron-scale features to be seen i.e. well beyond the range of optical microscopes.

**Statistical analysis with ANOVA**

All the measurements were made under standard atmospheric conditions. The means and standard deviations (SD) of data were calculated for all the tests. The upper and lower (±) 95% confidence interval of the mean is specified for the values in the figures. The tested data were statistically analyzed using data analysis software ORIGIN LAB (origin pro 8), MATLAB & Minitab statistical package. The one-sample t-confidence interval and test procedures are used to make inferences about population parameters i.e. population mean based on data from a random sample and is also used for hypothesis testing for population mean. The results were evaluated statistically according to two-way variance analysis (ANOVA), and the factors were the 'fibre type' and 'weave pattern'. The Minitab statistical package was used to execute the statistical analysis. All test results were statistically assessed at significance level, p-value, $0.05 \leq$ p-value $\leq 0.01$. If the p-value is smaller than or equals 0.05, the effect of weave structure and fiber type are considered to be significant.

## 5 Summary of the results achieved

### 5.1 Weavability study

Basalt is a relatively new material for the weaving industry. There is no established setting available to run such a yarn. In the case with some of the other materials like cotton, polyester or blends of both for instance runs extensively across the industry. The advantage of extensively used fibers are that, there is always a reference of settings available from where one can start the initial running and then fine tuning can be done, which was not the case with basalt. Basalt is a relatively stronger yarn as compared to others used in this work, and thus it was difficult to handle weft insertion. Once initial settings for basalt were optimized, it was successful in running compared to all the other yarns.

The results of weavability efficiency was analyzed with the help of MINITAB® statistical software package (MINITAB, State College, PA; http://www.minitab.com/en-US/default.aspx). The output of analysis of variance (ANOVA) is given in Table 4.11. The ANOVA results show that there is significant difference (*p* value of less than 0.05 at α level = 0.05) in weave and yarn material.

Table 2: Analysis of variance output for Efficiency

| **Source** | **DF** | **Adj SS** | **Adj MS** | **F-value** | **P-Value** |
|---|---|---|---|---|---|
| Regression | 9 | 2412.72 | 268.080 | 128.58 | 0.00 |
| Float | 1 | 133.39 | 133.389 | 63.98 | 0.000 |
| Materials | 8 | 2279.33 | 284.917 | 136.65 | 0.000 |
| Error | 17 | 35.44 | 2.085 | | |
| Total | 26 | 2448.17 | | | |

| S | R-sq | R-sq(adj) | R-sq(pred) |
|---|---|---|---|
| 1.44394 | 98.55% | 97.79% | 96.36% |

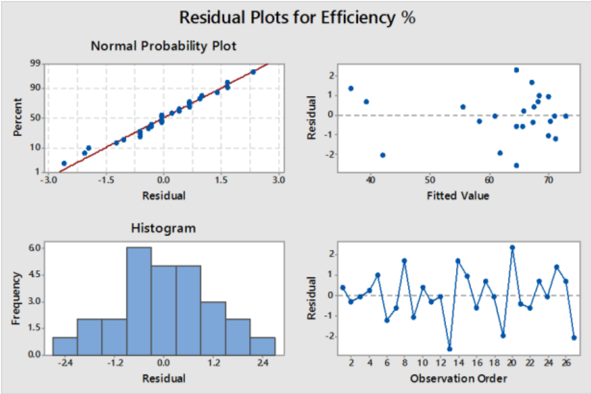


Figure 7: Residual Plots for Efficiency %

For the Efficiency data, the histogram does not follow a normal curve. Evaluate the normal probability plot to assess whether the residuals are normal. For the Efficiency data, the residuals appear to follow a straight line. No evidence of nonnormality, skewness, outliers, or unidentified variables exists. For the Efficiency data, the residuals appear to be randomly scattered around zero. No evidence of nonconstant variance, missing terms, outliers, or influential point's exists. For the Efficiency data, the residuals appear to be randomly scattered about zero. No evidence exists that the error terms are correlated with one another.

## 5.2 Characterization of fiber and cement raw materials

### Energy-Dispersive X-Ray Analysis of Basalt

Table 3 shows the summary of elements detected in energy-dispersive X-ray (EDAX) analysis. Spectral analysis detected number of elements in basalt. Presence of silica (Si) (24.58 wt%) and oxygen (O) (32.98 wt%) was found to be dominant as compared to other elements.

Table 3: Elemental composition of basalt.

| Element | Wt% |
|---|---|
| C | 12.37 |
| O | 32.98 |
| Na | 1.64 |
| Mg | 2.16 |
| Al | 8.69 |
| Si | 24.58 |
| K | 1.34 |
| Ca | 6.03 |
| Ti | 0.81 |
| Fe | 9.40 |
| Total: | 100.00 |

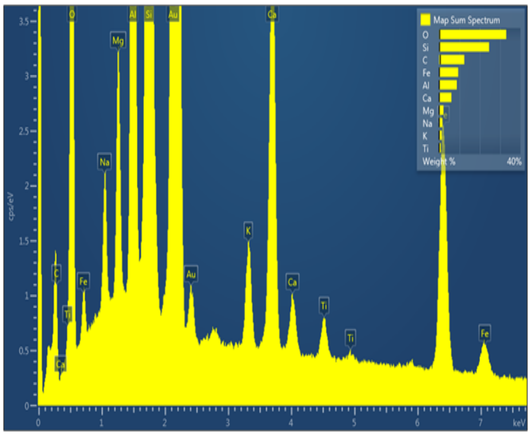


Figure 8: Energy-Dispersive X-Ray Analysis of Basalt

### Inductively coupled plasma (ICP-OES) analysis of cement

The conventional chemical analysis of cements generally involves tedious procedures for sample preparation. In this study, the concentrations of elements in cement samples were determined by ICP-OES method. This method is designed to determine the composition of a wide variety of materials, with excellent sensitivity (Measurement uncertainty of less than 1% relative). The results are shown in Table 4, and are in good agreement with certified values, except for Si. Probably this result is related to their more pronounced refractory behavior. It is known that Si is used in cement mainly as the tri- and di-calcium silicate phase and requires additional power to obtain proper atomization and excitation.

Table 4: Metal contents (concentration) of used cements.

| Components | GPC | OPC |
|---|---|---|
| | mg/kg | mg/kg |
| Be | 3.41 | 1.11 |
| Cu | 20.1 | 172 |
| Cr | 117 | 75.4 |
| Ni | 52.9 | 45.4 |
| Pb | 32.7 | 73.2 |
| Fe | 3595 | 16777 |
| Mg | 19957 | 10178 |
| Ca | 91329 | 415569 |
| Na | 3432 | 2042 |
| Mn | 1744 | 525 |
| Al | 79410 | 23497 |
| B | 270681 | 170867 |
| Ti | 3514 | 1586 |
| V | 90.1 | 39.5 |
| Zn | 40.8 | 274 |
| Sr | 199 | 773 |
| Ba | 345 | 341 |
| K | 5567 | 7882 |

**FTIR of OPC &GPC**

Cement contains several chemical components with functional groups, such as Si-O, $SO_4$, $H_2O$, OH, Al-O and $CO_3$, which are infrared active.

The FTIR spectrum of the anhydrous OPC Figure 9(a) shows peaks at 1616 $cm^{-1}$ which correspond to stretching and bending modes of water absorbed. The carbonates ($CaCO_3$) peak at 1421 $cm^{-1}$ and 878 $cm^{-1}$ are observed due to the reactions of atmospheric $CO_2$ with calcium hydroxide. The triplet bands appearing at wave number 1151-1092 $cm^{-1}$ are due to $\nu_3$ modes of $-SO_4^{-2}$. The vibration modes are often denoted by $\upsilon_1$ (systematic stretch), $\upsilon_2$(bending), $\upsilon_3$(asymmetric stretch). The strong band at 917$cm^{-1}$ is due to Si-O asymmetric stretching vibration of $C_3S$ and/or $C_2S$ (Tricalcium silicate (3CaO.$SiO_2$/Dicalcium silicate 2CaO.$SiO_2$). The band assignments are in good agreement with those reported in the previous studies.Figure 9(b) shows the FTIR-spectra of GPC. The stretching vibration of O-C-O was still detected in each of the GPC samples at 1424$cm^{-1}$ which was attributed to the carbonation reaction. The carbonation process occurred because an excessive amount of Na was available from the alkaline activator solution where it reacted with $CO_2$ from the atmosphere. These bands are connected with the presence of $CaCO_3$ and $Na_2CO_3$. The band attributed to asymmetric stretching vibration of Si-O-Si and Al-O-Si around area 1011–1027 $cm^{-1}$ indicated the formation of aluminosilicate gel. Besides that, symmetric stretching vibrations Si-O-Si were located at 778–798 $cm^{-1}$. At 583–721 $cm^{-1}$, symmetric stretching vibrations of Si-O-Si and Al-O-Si were identified. In the meantime, the bending vibrations of Si-O-Si and O-Si-O were found at area 467–479 $cm^{-1}$.

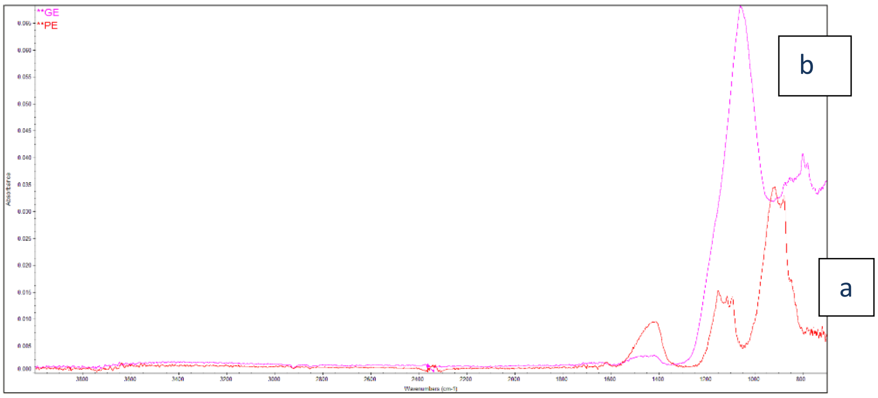



Figure 9: FTIR spectra of used cement materials (a) OPC, (b) GPC.

### 5.3 Accelerated aging in alkaline solution

The degradation of fiber due to the alkaline solution in the cement matrix seriously decreases the durability and may cause premature failure of the concrete composite. Calcium hydroxide is the primary cause of alkaline environment in cement. After a careful scientific research, accelerated aging tests were made to evaluate the weight loss and the loss of mechanical properties of B, PP, PET and J fibers, in order to quantify their performance limits. 5 samples for each category were tested and their averages is reported.

**Visual observations**

The external appearance of the yarns specimens was examined pre- and post-alkali treatment, for comparison of color, surface degradation and change in shape. In Basalt yarn, no significant visible change of color or surface texture were observed after 7 days of immersion in pH=10, pH=11 and pH=12 of two types of alkali namely NaOH and $Ca(OH)_2$. The Jute samples degradation was marked by color change. These samples lost a great deal of stiffness to the point that they broke prior to removal from the solution. For those exposed to pH 12, the observed degradation was similar to the pH 11 samples, yet these could be further tested in tension. The PP and PET specimens also lost a significant amount of physical stiffness. Effect of sodium hydroxide is stronger in all samples as compared to calcium hydroxide.

**Weight loss %**

The specimen's weight was measured both before and after the aging in order to evaluate weight loss. The calculated weight loss are given in Table 5.

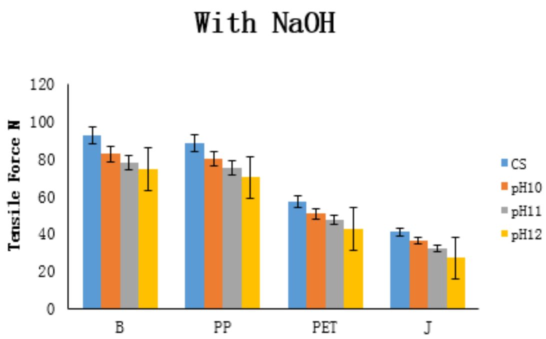
Table 5: % Weight loss.

| Reinforcement Type | Weight loss [%] (1 week) | | | | | | Weight loss [%] (2 week) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | NaOH | | | $Ca(OH)_2$ | | | NaOH | | | Ca $(OH)_2$ | | |
| | pH 10 | pH 11 | pH 12 | pH 10 | pH 11 | pH 12 | pH 10 | pH 11 | pH 12 | pH 10 | pH 11 | pH 12 |
| **B** | 0.4 | 0.8 | 1.0 | 0.3 | 0.5 | 0.7 | 1.0 | 1.1 | 1.5 | 0.8 | 1.0 | 1.2 |
| **PP** | 1.4 | 1.6 | 1.7 | 0.9 | 1.0 | 1.1 | 1.8 | 2.0 | 2.4 | 1.5 | 1.8 | 2.0 |
| **PET** | 2.8 | 3.2 | 3.5 | 2.0 | 2.5 | 3.0 | 3.5 | 4.0 | 5.1 | 3.0 | 3.5 | 4.2 |
| **J** | 4.7 | 6.2 | 7.2 | 4.1 | 5.0 | 5.2 | 7.0 | 9.5 | 14 | 5.5 | 7.0 | 8.5 |

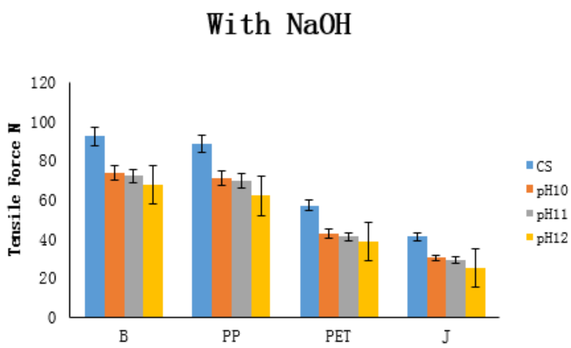
These results reflect the conditions for a range of pH and duration of alkali treatment in aqueous sodium hydroxide and calcium hydroxide solution. The weight loss increases with increasing treatment time, pH and use of stronger alkali (NaOH). The weight loss of basalt fiber is minimum as it is least affected by alkali followed by PP fiber.

### Tensile test of alkali treated yarns

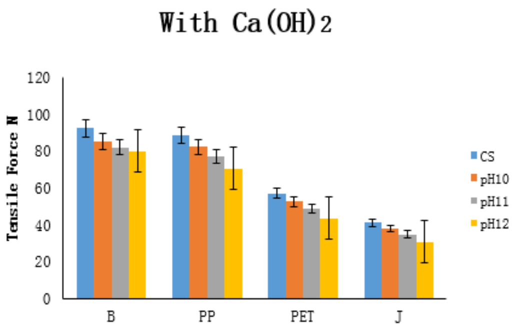
After the aging in alkali solution, tensile tests were made in order to evaluate the maximum load $F_{max}$ and the ultimate tensile elongation % of all the yarns before and after the aging, comparing the values obtained from controlled sample. ASTM E 2098-00 standard test method was used for this test. The graphical representation of strength loss is given in Figure 10 & 11.



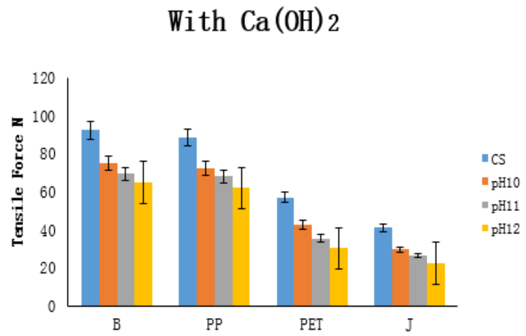

1 week treatment with NaOH




2 weeks treatment with NaOH

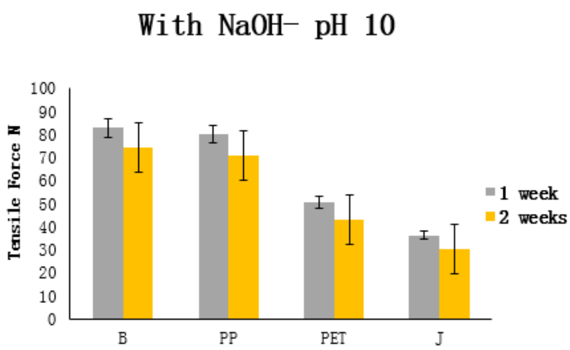


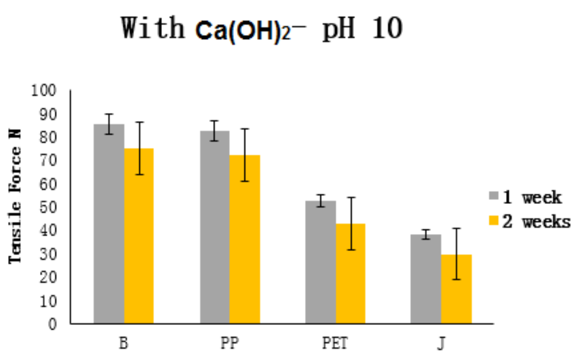

1 week treatment with $Ca(OH)_2$




2 weeks treatment with $Ca(OH)_2$

Figure 10: Effect of pH on degradation of yarn after alkali treatment.



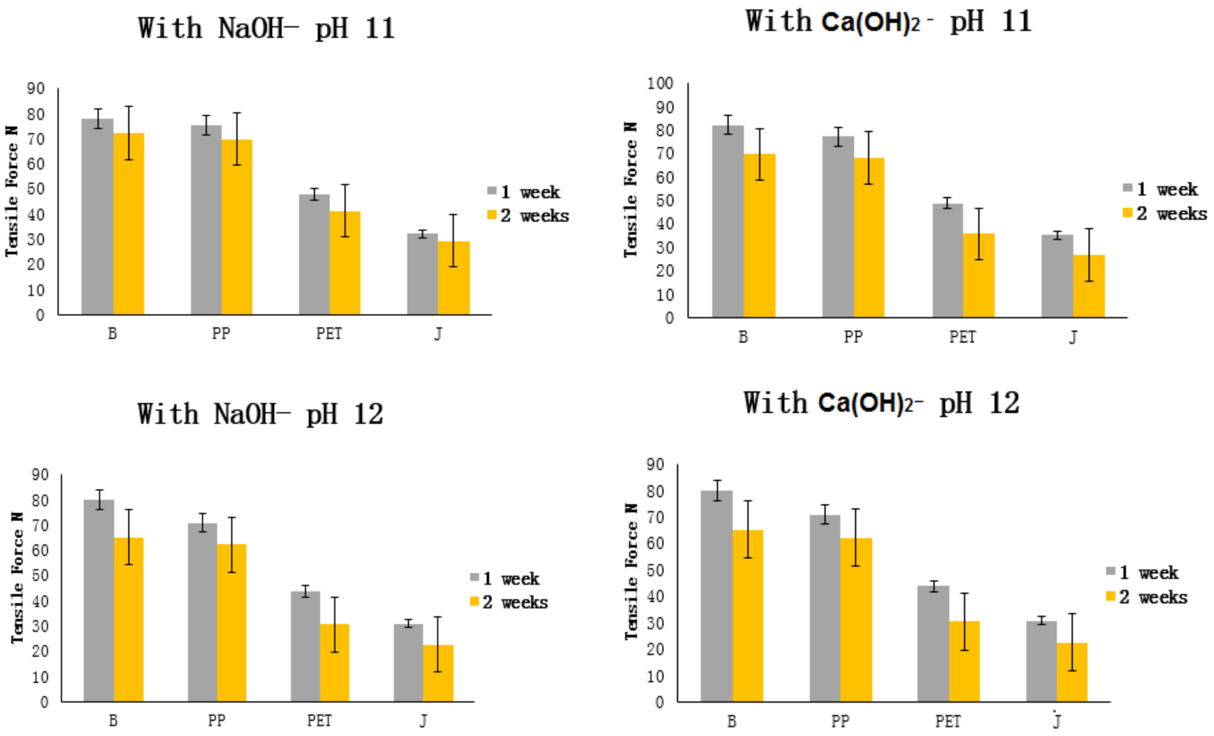



Figure 11: Effect of time on degradation of yarn after alkali treatment.

The tensile test results for the controlled samples are compared to the alkali treated samples in terms of applied maximum load versus elongation %. It can be noticed that ultimate tensile strain decreases in all the fiber types along with decrease in $F_{max}$. Reduction in mechanical properties in basalt yarn is minimum. The percentage reduction is maximum 30% after 14 days of accelerated ageing as compared to other yarns especially jute yarn where % reduction is more than 38 %.

**SEM morphology analysis**

The time-dependent degradation of fiber surface is additionally investigated using an electron-microscope.

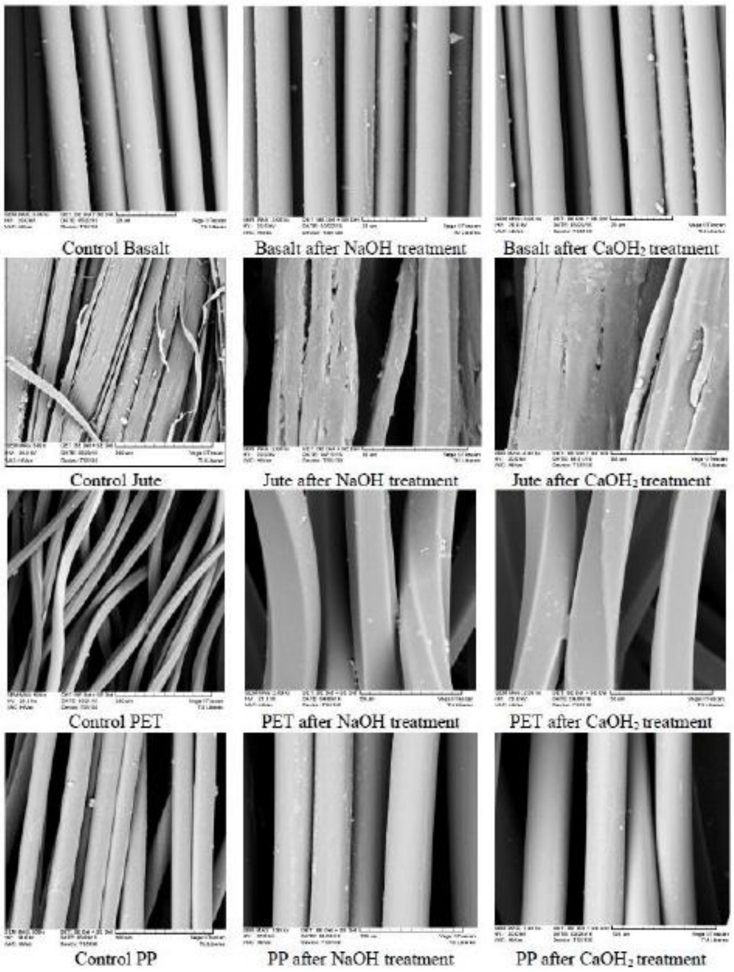



Figure 12: SEM images of fibers after alkali treatment.

## 5.4 Yarn pull out test from cement matrix

The interaction between the concrete matrix and reinforcement is characterized by the bond behavior. Bond strength may dominate the mechanical properties of fiber-reinforced concrete. Pull out test is most general test for this purpose. This tests is useful to get information about the load transfer behavior between matrix and reinforcement. The pull-out tests characterize both pull-out and rupture of the textile yarn as failure modes. The breaking point does not designate the definitive breaking point of the yarn in itself, but rather the location of crack initiation.

The force/displacement curves for all yarns are shown in Figure 13. From these curves, the average maximum force and the respective average crack-opening displacement, i.e. total slip, were calculated. The traditional way to characterize the quality of interfacial bonding is calculating the apparent interfacial shear strength (apparent IFSS, $\tau_{app}$), according to the definition.

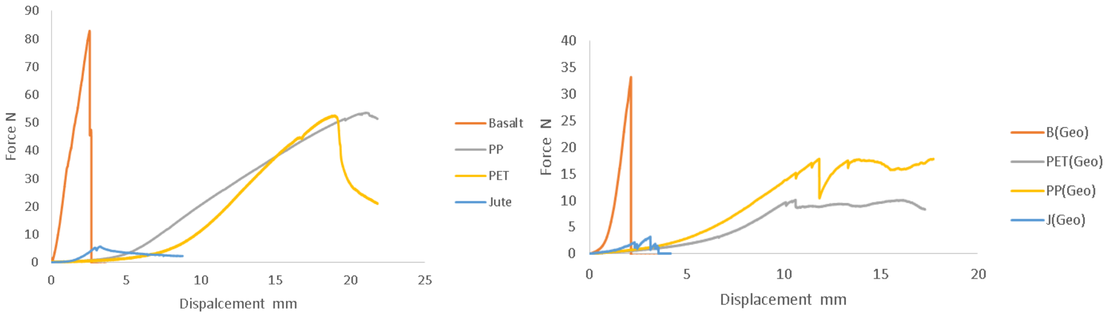
$$\tau_{app} = F_{max}/(\pi d l_e)\ \mathrm{n} \qquad (1)$$

where $d$ is the fiber diameter , $l_e$ is the embedded length and n is no. of filaments/fibers

The $\tau_{app}$ values calculated from Eq. 1 usually suffice to distinguish between ‘‘good’’ and ‘‘poor’’ bond strength and to estimate the efficiency of matrix and fiber surface interfacial bonding.

Table 6: Apparent interfacial shear strength ($r_{app}$) for different fibers in cement.

| **Reinforcement type** | **app $r_{app}$** | |
|---|---|---|
| | **OPC** | **GPC** |
| B | 1.769 | 0.709 |
| PP | 0.872 | 0.222 |
| PET | 0.663 | 0.169 |
| JUTE | 0.091 | 0.051 |




(a) (b)

Figure 13: Force vs displacement for yarns in Portland and Geopolymer cement.

In case of basalt, very small slippage (displacement) is observed as they have good adhesion with cement matrix. Maximum stress recorded as tensile stress of yarn is highest in case of basalt yarn. Similar situation is observed in case of jute yarn, but in this case Force recorded is much lower as jute yarn has overall lower strength value. In case of PP and PET, adhesion is not good and it can be viewed by high slippage/displacement/deformation. Such large displacement prior to material failure are crucial with regard to structural safety as well as energy dissipation, in particular in the case of dynamic loading. However, the fact that high strength levels can be only reached at high deformations means that for the service state, where only small deformations are acceptable, and the design load-bearing capacity of TRC must be considerably lower than its tensile strength. Moreover, relatively wide cracks observed at high deformations are undesirable.

It can be seen that performance of highly twisted yarn e.g. PP is higher than less twisted PET yarn. This can be explained on the basic of mechanical anchoring which is the result of waviness. Also if density of crimped yarn increased effect is more prominent. The experimental findings are given in Table 7.

Table 7: Experimental findings of the pull out study.

| **Reinforcement type** | **Max force (N)** | | **Crack opening displacement at max force (mm)** | | **Failure mechanism** |
|---|---|---|---|---|---|
| | **OPC** | **GPC** | **OPC** | **GPC** | |
| B | 82.90 | 33.24 | 2.56 | 1.46 | Telescopic |
| PP | 53.54 | 17.87 | 21.19 | 9.30 | Pull out |
| PET | 52.61 | 10.14 | 10.84 | 7.28 | Pull out |
| JUTE | 5.68 | 3.21 | 2.30 | 4.24 | Rupture |

The force is transmitted by adhesion and friction between the reinforcement and the concrete. The load transfer between the filaments enclosed in the yarn/roving will however occur either based on adhesion or friction depending on the quality of the bond. The bond quality differs across the depth of yarn/roving which causes a complex failure mechanism involving the partial rupture and pull-out of singular filaments. The failure mechanism denoted as *pull-out*, was often observed to be a telescopic failure (i.e. partial rupture and pull-out) a common failure phenomenon.

## 5.5 Testing of fabric samples

### *5.5.1 Physical properties*

The areal density, thickness and other physical parameters have been measured. Volume porosity of the hybrid composition is calculated based on ratio of the component fibers. With regards to fabrics the inter-yarn, inter and intra-fiber spaces contribute to the total porosity in woven structures. Inter-yarn porosity (macro porosity) is more important but if fabrics are made of different fibers, inter- fiber space (micro porosity) also plays a major role.

### *5.5.2 Static mechanical properties*

**Tensile properties of yarns**

The tensile properties are very important in terms of making a decision about end use of the material. The tensile behavior of fabrics is closely related to the inter-fiber friction effect, the ease of crimp removal and load-extension properties of the yarns themselves. Thus tensile properties (i.e. tensile force and tensile elongation) of all yarns used were measured .It was established that Basalt yarn is the strongest and Jute has the lowest breaking tenacity among the yarns under investigation.

**Tensile properties of basalt hybrid fabrics**

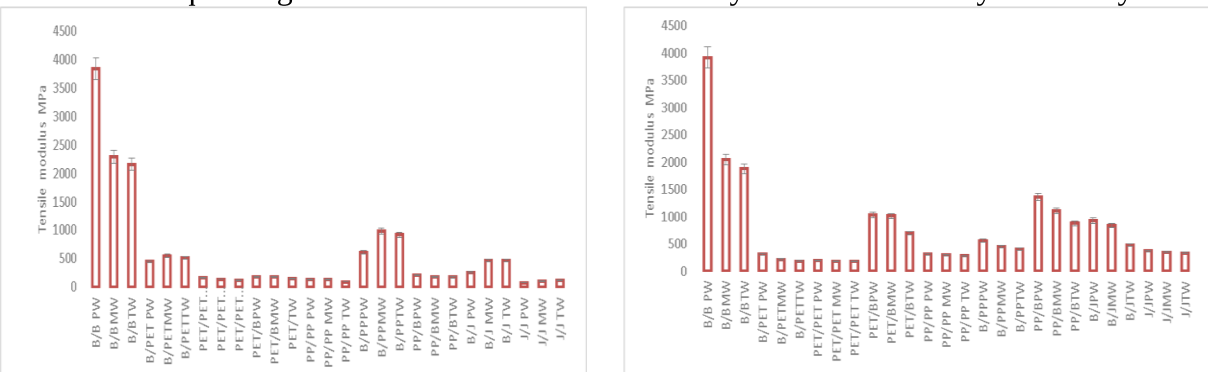
In this study, tensile properties of hybrid and non- hybrid woven fabrics were characterized by fabric breaking load and elongation. Tensile properties of all fabrics were measured in both warp and weft direction. Measurement of tensile stress–strain properties is the most common mechanical measurement on fabrics. It is used to determine the behavior of a sample while under an axial stretching load.

**Effect of fiber type on tensile properties of basalt hybrid fabrics**

In warp direction, B/B has highest tensile modulus as basalt is strongest yarn and jute has lowest. With the use of basalt in warp/weft, stress/strain behavior changes a lot. Tensile/Initial moduli of all fabrics increased with the hybridization with basalt. When basalt yarn is introduced, the tensile modulus of hybrid fabric sharply increases to 50 % for B/PP, 40% for B/PET and 70% for B/J respectively. In addition, strain decreases dramatically as basalt yarn is introduced, which suggests that the toughness of hybrid fabric began to decline. The hybridization of basalt in warp direction improves moduli more as compared to use of basalt in weft direction.

**Effect of weave structure on tensile properties of basalt hybrid fabrics**

It is also established that the type of weave has a great influence on the tensile modulus of fabrics in warp direction. It is obvious that in non- hybrid structures, plain weave has highest value followed by matt and twill. The highest level of stress and elastic modulus is observed in plain weave because of the maximum number of interlacing points in a given area and therefore the highest degree of crimp, resulting in higher friction between yarns. So they can absorb more energy. In jute fabrics twill has highest modulus followed by matt which have longer floats compared to plain weave. In hybrid fabrics when basalt is used in warp, the highest tensile modulus is obtained in matt weave (groups of yarns have woven together), due to its cohesiveness and because grouping of yarn pairs leads to increase in contact area which subsequently increases friction between warp and weft. Plain weave has lower modulus, as basalt is a brittle yarn and during weaving, a lot of weaving stresses acted on it causing fiber rapture. During tensile test, breaking elongation of warp yarn is lower as the yarn is already extended during weaving process. This results in lower residual strain. The differences in the same weave depend considerably on the material used in weft. When using basalt in weft direction, modulus is not affected much as compared to non-hybrid fabrics. Moduli of PP/B and PET/B is quite higher in weft direction due inherently lower extensibility of basalt yarns.

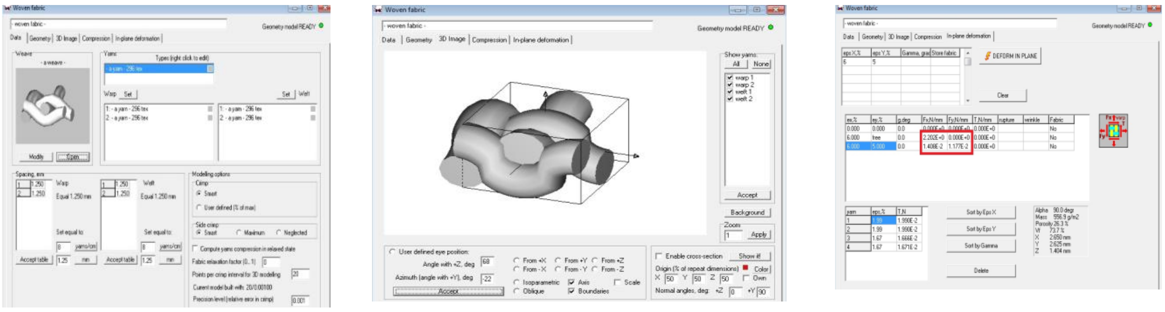



(a) Warp direction (b)Weft direction

Figure 14: Initial moduli of hybrid and non-hybrid fabrics.

**Prediction of tensile properties using Wisetex**

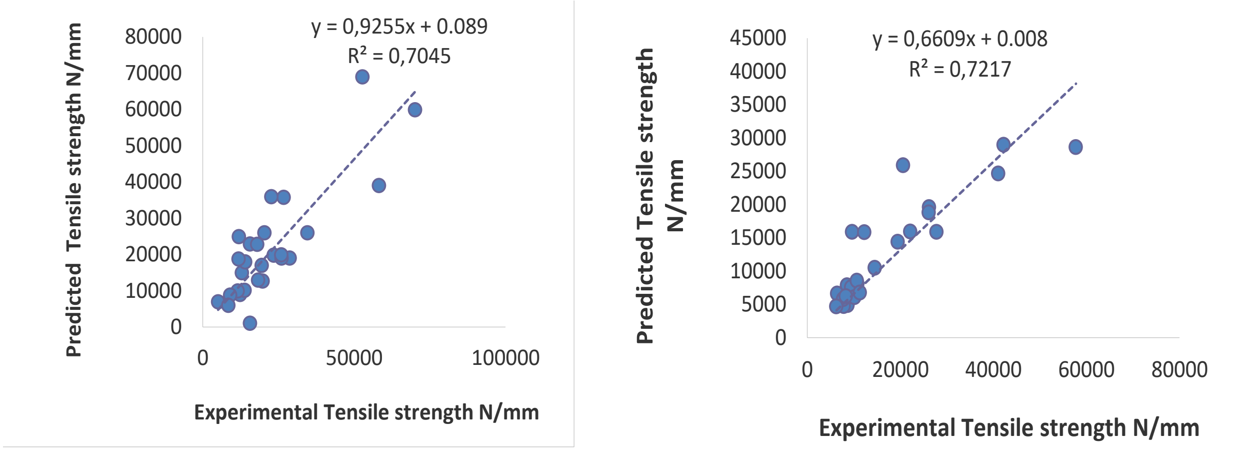
Calculations for uniaxial tension in warp direction and weft direction are done.



(a) Tightness of fabric (b) Yarn parameters (c ) Tensile properties

Figure 15: Prediction of tensile properties with WISETEX.

The calculated values are compared with the measured tensile properties. The results of the simulations have been compared with the experimental observations, resulting in a reasonable agreement between them. The comparison with experiments validates the models for fabric tensile properties. Its correlation is only 70% as new kind of material was used for development of hybrid fabrics in this work. The most important factors of the uncertainty of these data are (1) approximate nature of the model, which does not consider details of the contact between the yarns and (2) numerical difficulties of convergence for very low compression and tension stiffness of the yarns in the initial stage of deformation.




(a) warp

(b) weft

| Equation y = a + b*x | Value | t-test Significance "Yes" or "No" | Adj. R-Square | F-test Significance "Yes" or "No" |
|---|---|---|---|---|
| Intercept | **0.089** | Yes | **0.704** | Yes |
| Slope | **0.925** | Yes | | |

(a)

| Equation y = a + b*x | Value | t-test Significance "Yes" or "No" | Adj. R-Square | F-test Significance "Yes" or "No" |
|---|---|---|---|---|
| Intercept | **0.008** | Yes | **0.72** | Yes |
| Slope | **0.661** | Yes | | |

(b)

Figure 16: Correlation of tensile strength predicted by WISETEX and measured values.

**Shear properties of basalt hybrid woven fabrics**

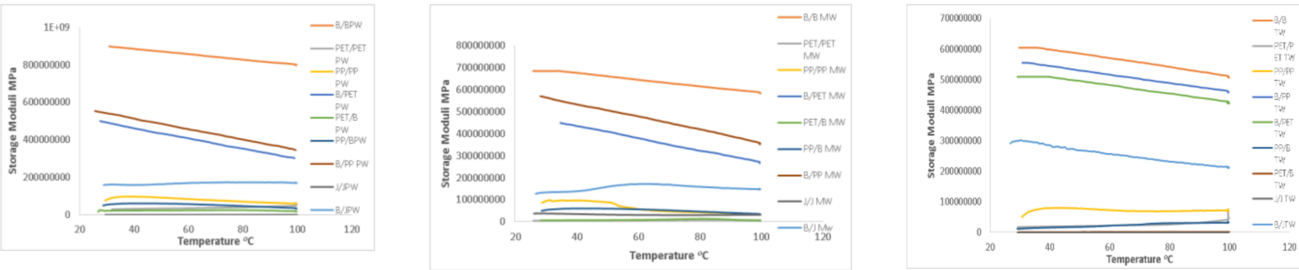
The picture frame test method is used for the fabrics under consideration. In the beginning, there is no shearing. Subsequently the shear deformation resistance is mainly from the friction between the yarns before reaching the limiting locking angle. B/B plain weave shows highest initial modulus as compared to matt and twill weave. In plain weave more interlacement between warp and weft yarns results in more friction, more resistant to slippage. Dissimilar yarn based fabrics have less cohesive forces. In matt weave, it has longer float on both sides so it exhibits more resistant to angular slippage in a biased direction. In B/PET, spacing between adjacent yarns is high, less chance of inter-yarn cohesion so less resistance to slippage. In matt weave, due to yarn floats on both faces of fabric, it is more resistant to slippage. Polyester yarn is bulky, relatively high specific surface friction and thus cohesion between weft yarns dominates the frictional resistance. In B/J, as jute is a spun yarn, there is surface hairiness and cohesion of yarn is enhanced. All these yarn surface behavior plays vital role in deciding the shear resistance and shear rigidity of basalt hybrid woven fabrics. Among structures where basalt is used in weft, plain weave has highest initial modulus and high shear resistance followed by matt and twill which is predominantly due to higher interlacement between warp and weft.

**Correlation between experimental and image analysis based results**

The shear angles are calculated by considering sample length and it is further used for calculation of shear force. The differences between image analysis and calculated shear angle using sample length at the chosen points are relatively small. Less than 8% CV was obtained in all measurements. It does not show any significant difference until pre-buckling (upto 20 mm displacement) but significant difference is observed after 20 mm displacement. It is also believed that during image processing in MATLAB, detection of X and Y coordinates on the image is not accurate due to wrinkling in the central zone of samples.

### *5.5.3 Dynamic mechanical properties*

Storage modulus, loss modulus, and tan δ are described as a function of temperature. All the hybrid fabrics exhibited higher storage modulus (higher stiffness) than the non- hybrid fabrics. Tensile strength of the fabrics showed the same behaviour. At each temperature, hybrid fabrics exhibit higher modulus than the non–hybrids. Storage modulus of hybrid fabrics increased significantly with the incorporation of basalt yarn especially when it is used in warp direction. This condition is primarily attributed to the increase in the stiffness of the structure due to the nature of basalt fiber that allows more stress to bear. B/B structures are least effected by the temperature as compared to other materials due to the stable property of basalt(inorganic) fiber over wide range of temperatures.




PW MW TW

Figure.17: Storage moduli of different weaves.

There was a decreasing trend in the loss tangent over the temperature range. This can be justified by the restriction of the motion of polymer chains resulting from the incorporation of rigid fibers. In this case, the incorporation of basalt fibers for hybrid fabrics, which act as barriers to the mobility of polymer chain, led to a lower degree of molecular motion and consequently lower damping characteristics. Matt weave structure shows lower value of tan δ showing fabrics have better impact resistance under elevated temperatures.

### *5.5.4 Thermal and transmission related properties*

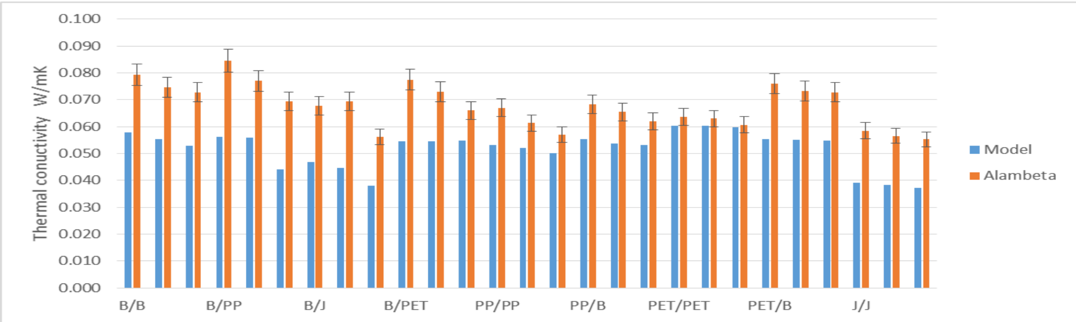
**Air permeability**

Among non-hybrid structures, B/B has highest value of air permeability, because of open structure resulting from smaller yarn diameter due to higher density of fibers. It is followed by J/J combination. J/J has lower permeability than B/B due to hairy structure of yarn which blocks the inter yarn spaces. Among all the non-hybrid structures, twill has highest porosity, followed by matt and plain respectively. Among non- hybrid fabrics, the bigger differences observed between the air permeability values of the plain and twill fabrics are due to differences in their characteristic covering properties. It is noted that most of the air flow takes place through the gaps between warps and wefts due to the nature of air, i.e air always finds its easiest way to flow.

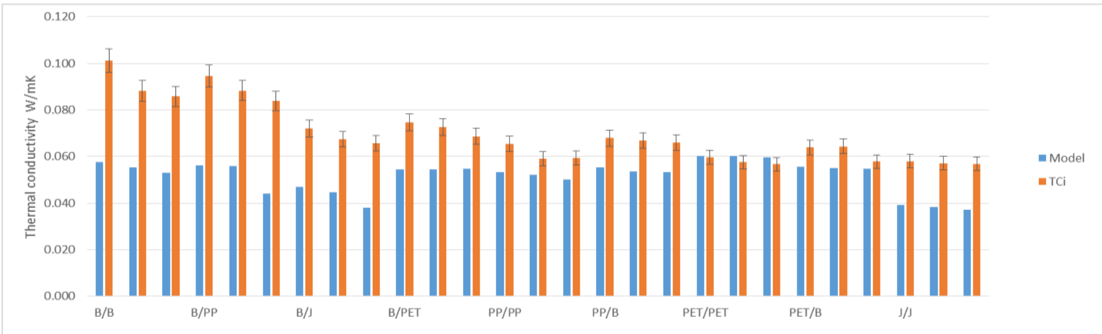
Among all hybrid structures, highest air permeability is observed in B/J structures that is because of higher yarn porosity in jute, while in other structures i.e B/PP, PP/B, B/PET and PET/B lower air permeability is observed because of compact structure in filament yarns. The PP and PET yarns are relatively bulkier and it results in a better cover of the fabric, therefore less permeable to air, which is also investigated by other researchers. From this analysis it was found that samples woven in twill weave have nearly 5- 25% higher air permeability compared to plain structures for the same sett (thread density) of the woven fabrics.

**Thermal properties**

In all structures fabric density has significant effect on thermal conductivity. As fabric density increases thermal conductivity also increases. The thermal conductivity was calculated using the theoretical model. The parallel/series structure gives a firsthand prediction and gives reasonable prediction accuracy for practical application due to its simplicity as shown in Figure. 4.24. From theoretically calculated indicators of thermal conductivity, it is clear that the measured values with device Alambeta are most similar to theoretical values of samples.




(a) Alambeta




(b) TCi

Figure 18: Theoretical model and measured thermal conductivity.

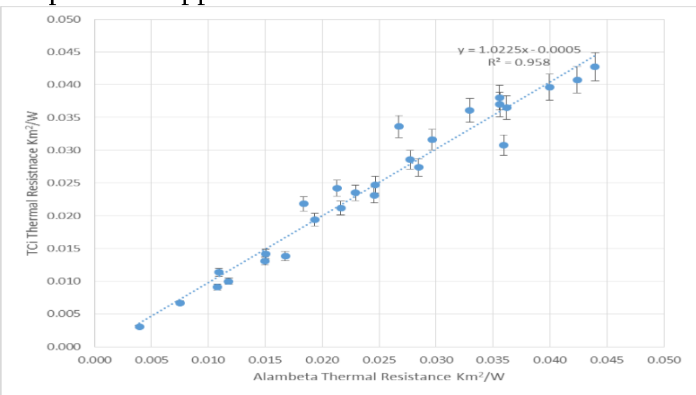
Among all structures, plain weave has highest thermal conductivity due to maximum interlacement and thus increase in fabric density. The fabric with a twill pattern has lower number of cross over points, longer yarn floats and, as a result, lower yarn crimps than the fabric with a plain pattern for the same warp and weft densities. This results in a looser and more open structure in twill fabrics. Consequently, as also mentioned in literature, the thermal conductivity values of the plain fabrics are higher than corresponding values of the twill fabrics. Among all structures, thermal conductivity of 100% basalt fabric is highest followed by structures having PP and PET yarns. Although basalt fiber has low value of thermal conductivity but in case of fibrous structures e.g. yarns and woven fabrics, thermal properties are greatly influenced by the porosity which is around 65-85%. Basalt yarn has a compact structure and thus less porosity than PET and PP structures. Between PET and PP structures, the later has higher packing density and thus higher thermal conductivity. Thermal conductivity of hybrid structures are increasing by adding basalt yarn due to the reason mentioned above.

**Thermal resistance**

Thermal insulation properties are mainly dependent on thermal resistance properties. Higher the thermal resistance value, lower will be the heat loss.

**Correlation of thermal resistance calculated from TCi and alambeta measurements**

The measurements from TCi and alambeta instrument are correlated based on thermal conductivity and thermal resistance. The correlation of the two instruments for thermal resistance is shown in Fig. 4.25. The thermal resistance of both the instruments are correlated well with $R^2$ =0.95. A relationship between theoretical calculations and actual measurements of thermal resistance by Almabeta and TCi is shown in Fig. 18(a&b). It has given reasonable prediction accuracy for practical applications.




| **Equation y = a + b*x** | **Value** | **t-test Significance "Yes" or "No"** | **Adj. R-Square** | **F-test Significance "Yes" or "No"** |
|---|---|---|---|---|
| Intercept | 0.0005 | Yes | 0.958 | Yes |
| Slope | 1.0225 | Yes | | |

Figure 19: Correlation of thermal resistance from TCi and Alambeta

Among all structures, jute based fabrics have higher thermal resistance values because of inter fiber micro pores and inter yarn (macro porosity). Physical clogging of air will lead to increase in thermal insulation. With the addition of basalt fiber, thermal resistance of hybrid fabrics decreased. In all hybrid structures using basalt in warp, B/J has highest thermal resistance. B/PET has second highest value of thermal resistance as the PET yarn is more bulky and has less twist so it has higher thermal resistance value than PP. Among all hybrid structures where basalt is used in warp, twill weaves have highest resistance followed by Matt and Plain respectively, although this effect is not significant in case of B/PP and B/PET. In matt structure, due to floating of yarn on both surfaces, clogging of air occurs. Among all weave structures, plain has minimum thermal resistance because of structural compactness and only one types of macro-pores in their structure. Plain woven fabrics also have more dense structure due to the highest number of interlacing points of warp and weft and that prevents yarns from grouping. The thermal resistance is also strongly correlated with thickness in the present study. A surface plot provides a three-dimensional view of how the factors affect the response. As it is obvious from one axis of graph, thickness has a direct relation with thermal resistance. As thickness increase, thermal resistance increase. As porosity increase, thermal resistance also increases. For the thermal resistance, the 3D surface plot shows that the highest thermal resistance values were found near an average thickness of 0.0025 m and average porosity of 0.80. For the thermal resistance data, the contour plot shows that the highest thermal resistance values were found near an average thickness of 0.0025 m and average porosity of 0.80.

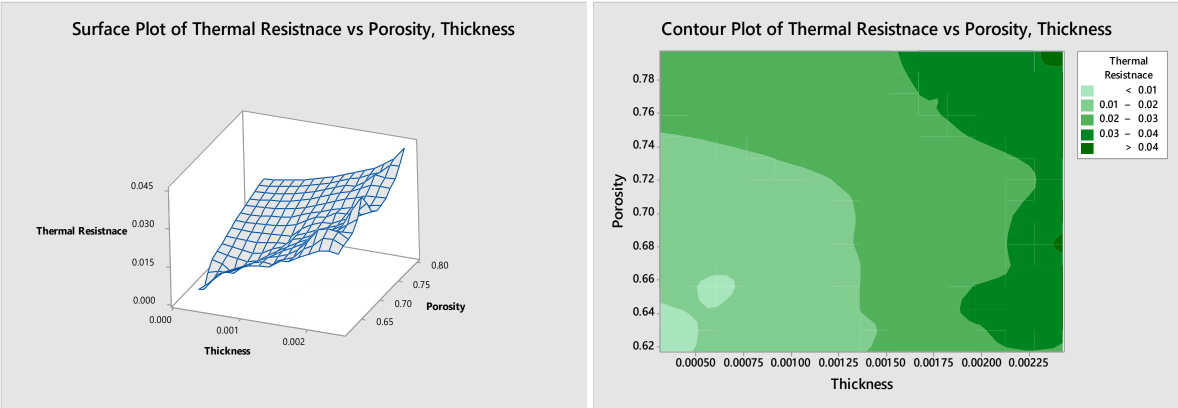



Figure 20: 3D mapping

### *5.5.5 Electrical properties*

Figure 21 shows overall electrical resistances (mean values and 95 % confidence intervals) of all samples under investigation. It is visible that the highest electrical resistance is shown by 100 % basalt samples with twill and matt structures. There is no statistically significant difference between electrical resistances of twill and matt weave of B/B samples. On the other hand, statistically significant difference can be observed between samples with different material composition having the same weave pattern.

The electrical resistance values of the fabrics are mainly determined by the presence of air in the interstices i.e between the binding points of woven fabric. Air is a bad conductor of elecricity showing resistivity at 20 °C ranging from 1.3E+16 to 3.3E+16. Plain and basket weaves belong to a group of similar weaves but the floating of yarns is different by direction: in plain weave – no floating takes place, in basket weave – two floating of each yarn in both directions and in twill woven samples there is floating over three consecutive yarns.

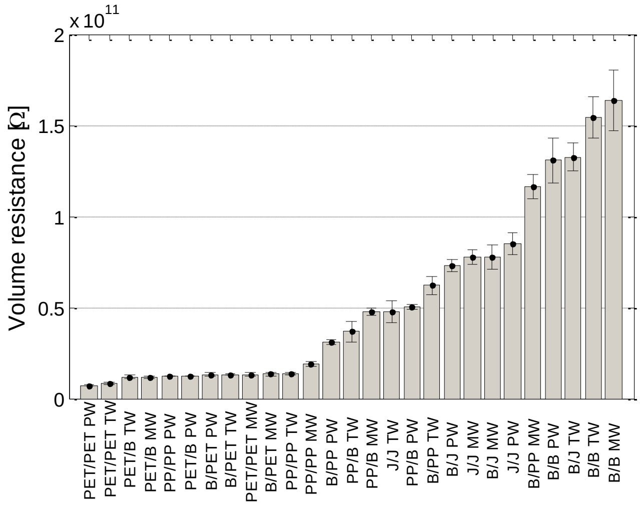


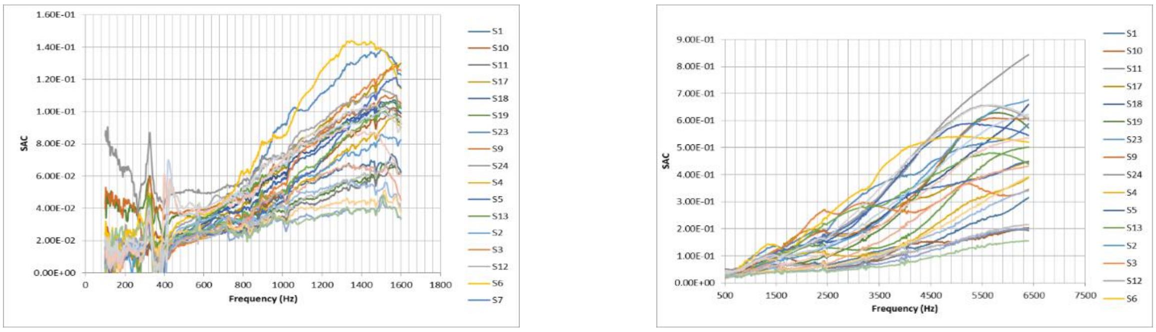

Figure 21: Volume resistance of all samples tested.

Based on exploratory data analysis it can be summarized that structure (weave pattern) has statistically significant effect on the resulting resistance especially for samples where one of the component is basalt and the second component is either basalt, polypropylene, polyester or jute. Plain woven structure has the lowest resistance.
It can also be observed that in all the hybrid structures, highest electrical resistance is in

B/Jute structures. Although jute material has lower electrical resistivity than polyester and polypropylene, the synthetic fibers (PET & PP) tend to generate static electricity and thus exhibit lower resistance. It is also observed that among non-hybrid structures, B/B composition has highest electrical resistance followed by Jute/Jute

### *5.5.6 Acoustic properties*

From Fig. 22, it can be observed that, with the increase of frequency, the sound absorption coefficient (SAC) of all the samples increases. As is known that with the increase of frequencies, larger is the sound energy which accelerates the air vibration inside fabrics and creates the opportunities of friction between air and pore walls. This process causes sound energies to be converted into heat energies and gradually diminishes the sound effect. This is indicated as an increase in SAC.




(a)At low frequency

(b) At high frequency

Figure 22: Sound absorption coefficient of all samples.

It can be seen that fabrics with polyester fiber have better SAC. The reason for better SAC of polyester fabrics may be finer fibers which results in higher number of fibers per unit weight of the material. This leads to higher total fiber surface area, and greater possibilities for a sound wave to interact with the fibers and ultimately dissipate inside the structure. 100% Jute and Basalt fabric shows lower SAC values in both frequency ranges. With the use of basalt fiber for hybrid structures SAC improves for all fabrics. Flow resistance has been used as an important parameter in theoretical estimations by many researchers. Static flow resistance could also measure acoustical performance.
The maximum sound absorption for all samples occurs at a frequency of 1000 Hz.

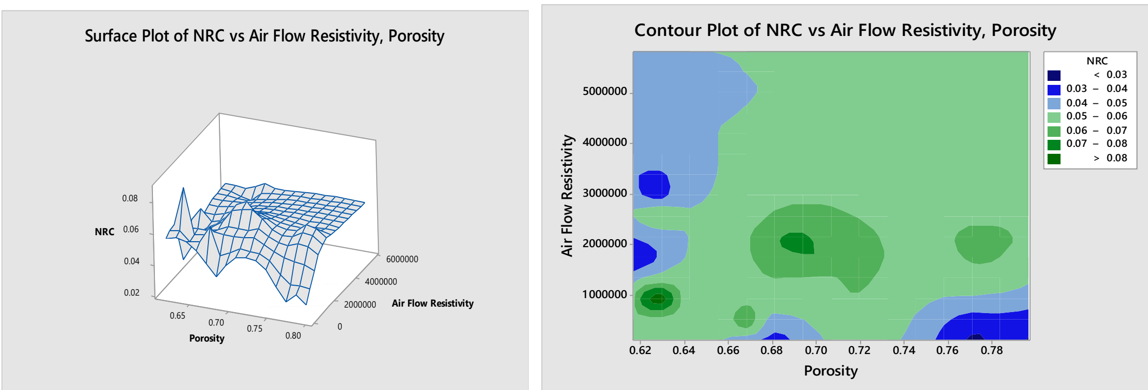
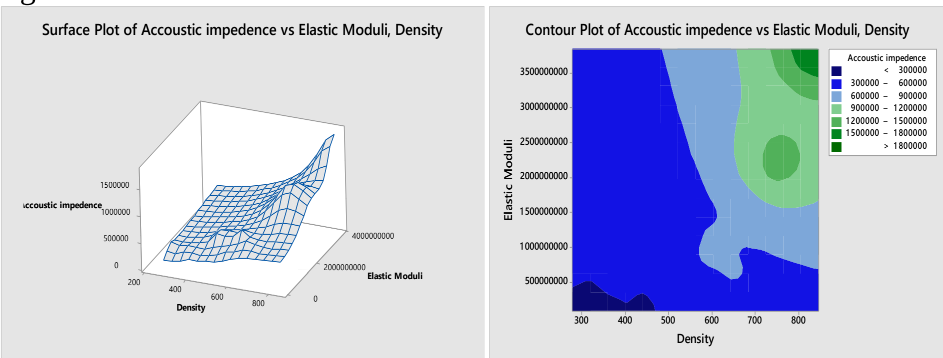
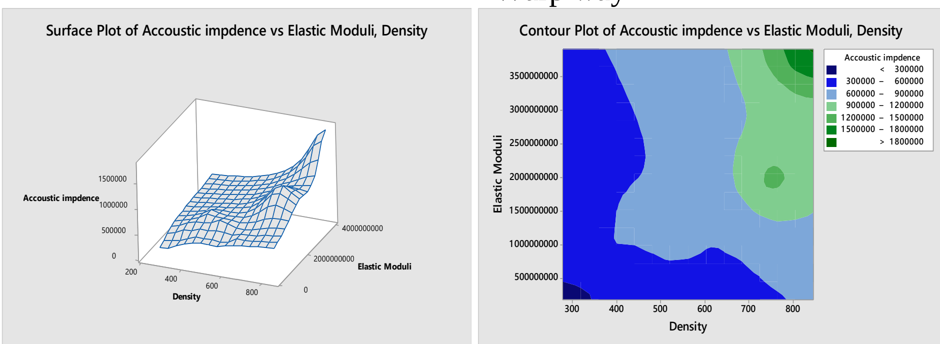



Figure 23: Relationship between fabric porosity, airflow resistivity and NRC.
Matt weave structures have highest value of NRC due to more porosity. This phenomenon

can be justified by considering that, upon reaching the fabric surface depending on fabric characteristics, the incident sound wave is partially absorbed, transmitted or reflected. Yarn intersection points in the fabric act as frictional elements that resist sound wave propagation through the fabric. Fabric internal tortuosity causes sound wave amplitude to decrease. This in turn leads to conversion of sound energy into heat. Matt weave has more number of pores as compared to plain weave. Thus, the NRC of the fabric against sound waves is increased. Therefore, absorption occurs due to energy loss as the sound wave passes through the fabric and the frictional resistances offered by the fibers and entrapped air in the fabric is overcome. Dependence of specific acoustic impedance on elastic moduli and density of woven fabrics is shown in Figure 24.




Warp way




Weft way

Figure 24: Dependence of specific acoustic impedance on elastic moduli and density of woven fabrics.

### *5.5.7 Thermal Stability*

To evaluate the thermal stability of fabrics, the TGA analysis was carried out and pursed by presenting comparative analysis between different types of fabrics as shown in Fig. 25.

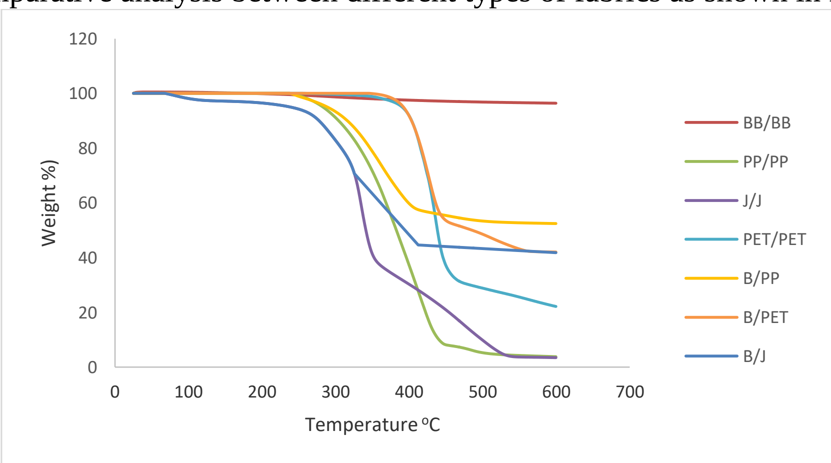
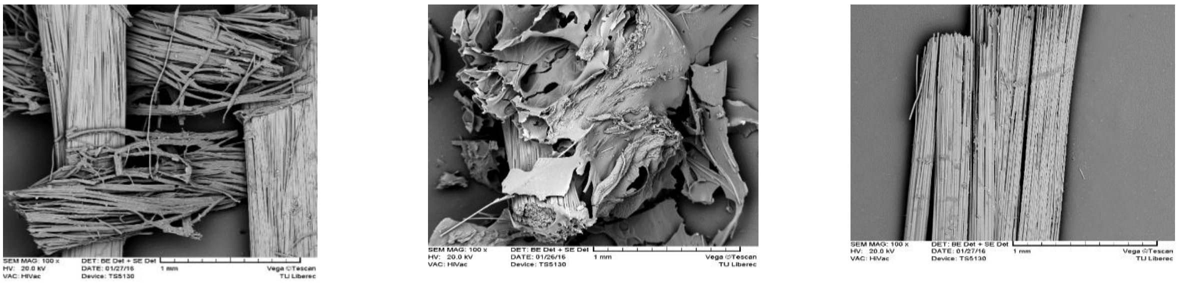



Figure 25: TGA curves for all hybrid and nonhybrid compositions.

For the 100 % basalt samples (B/B), it can be observed Basalt has excellent thermal stability during the TGA which implies that basalt fibers are almost flame resistant.



B/J B/PET B/PP

Figure 26: SEM images of hybrid fabrics after TGA.

It can be seen from the result that the rate of weight loss of the hybrid samples was less than non-hybrid fabrics. TGA analysis of hybrid samples show that residue left at 600°C is more than that for non-hybrid fabrics. The effectiveness of using basalt yarn in hybrid structures may be indicated by shifting of decomposition stages to higher temperature and leaving more amount of residue at maximum temperature as compared to the non-hybrid samples where residue is almost nil at 600°C.

## 6 Evaluation of results and new findings

In this research work, new kind of yarns were run on the weaving machine and set of parameters for efficient weavability was developed. Parameters for weaving of basalt hybrid fabrics were optimized. The knowledge of mechanical properties is very important for development of a fabric for specific end use.The results reveal that the hybridization of basalt with polypropylene and polyester in different weaves leads to significant improvement in the static and dynamic mechanical properties of fabrics. Structure of weave and fiber type have strong influence on static and dynamic mechanical properties of fabrics. Hybridization of basalt yarn in warp direction has more significant effect on mechanical properties.

The comparison of predicted tensile properties from computation with *Wisetex* correlates reasonablly with experimental data. Its correlation is only 70% as new kind of material was used for development of hybrid fabrics in this work. Shear properties i.e ability of fabric to deform within its plane, which is important for molding of TRC (Textile reinforced concretes) was evaluated using picture frame tester. It showed good correlation with image analysis based evaluation of shear angle till buckling occurs. The results reveal that the hybridization of basalt with polypropylene, polyester and jute in different weaves leads to significant improvement in thermal and transmission related characteristics. Structure of weave and fiber type have strong influence on conductivity. Plain weave has highest thermal conductivity and lowest thermal resistance values in all hybrid structures. Thermal conductivity of other structures can be improved by adding basalt fiber for application as heat sinks. Thermal resistance of basalt structures can be improved by adding other fiber especially jute fiber for application as thermal insulation. The hybridization with Jute and PET significantly increases the thermal resistance. It is clear from the measurement that there are considerable differences in the results of measurement with two instruments, although correlation exists. In this research, electrical behavior of different technical textile woven fabrics was analyzed according to fiber and weave type. Fabrics were evaluated according to their electrical resistance (volume and surface) with reference to structure (porosity).The highest resistance was observed in samples made of 100% basalt fiber regardless of weave type. It can be concluded that plain weave structures show lower electrical resistance compared to other non-

plain weave patterns. It can be seen that fabrics with polyester fiber have better Noise Reduction Coefficient. The reason for better NRC of polyester fabrics is attributed finer fibers which results in higher number of fibers per unit weight of the material. By hybridization with basalt, the noise reduction coefficient increases. Matt weave structures have highest value of NRC due to more porosity. Specific acoustic impendence depends on elastic moduli of materials with linear relationship between them. As elastic modulus of material increases, impedance value increases i. e material can be good sound reflector, but not good sound absorber. The thermal stability of the basalt fiber is excellent. When comparing TGA curves for hybrid samples it demonstrates that thermal stability of the samples containing basalt is much higher than the non-hybrid samples. Percentage weight loss is less in basalt hybrid samples as compared to non-hybrid samples. It is also confirmed from SEM images.
In accelerated ageing test ,the weight loss of basalt fiber is minimum as it is least affected by alkali followed by PP fiber in aging experiments. Reduction in mechanical properties in basalt yarn is minimum and maximum in Jute yarn and this is also verified by SEM images. Pull out test is most general test for checking the adhesion between the fiber and the cement matrix. In case of basalt, very small slippage (displacement) is observed as they have good adhesion with cement matrix. In case of PP and PET, adhesion is not good and it can be viewed by high slippage/displacement/deformation. So, overall hybrid basalt structures have promising application in TRC.

## 7 References


[1] Chaphalkar, P and Kelkar, A.D. “Classical laminate theory model for twill weave fabric composites”. *Composites Part A: Applied Science and Manufacturing*, vol. 32, No. 9, pp. 1281-1289, 2001.

[2] Razera, A.T. and Frollini, E. “Composites based on jute fibers and phenolic matrices: properties of fibers and composites”. *Journal of Applied Polymer Science*, vol. 91, No. 2, pp. 1077-1085, 2004.

[3] Dalinkevich, A.A. et al. “Modern basalt fibrous materials and basalt fibre-based polymeric composites”. J*ournal of Natural Fibers*, vol. 6, pp. 248-271, 2009.

[4] Barbero, E.J. Introduction to Composite Materials Design. 2nd Ed. Taylor and Francis Group, LLC. 2011.

[5] Kalaprasad, G. et al. “Hybrid effect in the mechanical properties of short sisal/glass hybrid fiber reinforced low density polyethylene composites”. *Journal of Reinforced Plastics and Composites*, vol. 15, pp. 48, 1996.

[6] Rabinovich, F.N et al. “Stability of basalt fiber in a medium of hydrating cement”. *Journal of Glass and Ceramics*, vol. 58, pp. 11-12, 2001.

[7] William, D.C and David, G.R. Materials Science and Engineering, an Introduction. 8th Ed. John Wiley & Sons, Inc. 2010

[8] Muthuvel, M. et al. “Characterization study of jute and glass fiber reinforced hybrid composite material”. *International Journal of Engineering Research & Technology*, vol. 2, pp. 335-344, 2013.

[9] Laroche, et al. "Forming of woven fabric composites.". *Journal of Material Composites*, vol. 28, pp. 1825-1839, 1994.

[10] Mohammed, U. et al. “Experimental studies and analysis of draping of woven fabrics”. *Composites Part A: Applied Science and Manufacturing*, vol. 31, pp. 1409-1420, 2000.

[11] Mishra, R. “Meso-scale finite element modeling of triaxial woven fabrics for composite inplane reinforcement properties”. *Textile Research Journal*, vol. 83, pp. 1836-1845, 2013.

[12] Wittek, T. and Tanimoto, T. “Mechanical properties and fire retardancy of bidirectional reinforced composite based on biodegradable starch resin and basalt fibers”. *EXPRESS Polymer Letters*, vol. 2, No.11, pp. 810-822, 2008.

[13] Woven fabric edited by Edited by Han-Yong Jeon, chapter 1. B. K. Behera, Jiri Militky, Rajesh Mishra and Dana Kremenakova, Modeling of Woven Fabrics Geometry and Properties ,2012.

[14] Behera, B.K. and Mishra R. “3-Dimensional weaving”. *Indian Journal of Fibre and Textile Research*, vol. 33, pp. 274-287, 2008.

[15] Jamshaid, H. and Mishra, R. “A green material from Rock: A basalt fiber”. *Journal of the Textile Institute*, vol.107,pp.923-937,2015.

[16] KamennyVek. (2009). Advanced basalt fiber.Basfiber. Internet: http://www.basfiber.com, Retrieved May9, 2012.

[17] Sim, J. et al. “Characteristics of basalt fiber as a strengthening material for concrete structures”. *Composites Part B: Engineering*, vol. 36, No. 6-7, pp. 504-512, 2005.

[18] Wang, Y. et al. “Concrete Reinforcement with Recycled Fibers”. *Journal of Materials In Civil Engineering*, vol. 12, pp. 314-319, 2000.

[19] Ochia, T.et al. “Development of recycled PET fiber and its application as concrete-reinforcing fiber”. *Cement and Concrete Composites*, vol. 29, No. 6, pp. 448-455, 2007.

[20] Karmaker, A.C. and Youngquist, J.A. “Injection Molding Of Polypropylene Reinforced With Short Jute Fibers”. *Journal of Applied Polymer Science*, vol. 68, No. 8, pp. 1147-1151, 1996.

[21] Chand, N. and Hashmi, S.A.R. “Mechanical Properties of Sisal Fiber at Elevated Temperature”. *Journal of Material Science*, vol. 28, pp. 6724-6728, 1993.

[22] Zastrau, B. et al. “The Analytical Solution of Pullout Phenomena in Textile Reinforced Concrete”. *Journal of Engineering Materials and Technology*, vol. 125, No. 1, pp. 38-43, 2003.

[23] Neville, A.M. “Properties of Concrete”. Pearson Education Asia Pvt. Ltd., London, 2000.

[24] Gartner, E. M.et.al , “Hydration Of Portland Cement Structure and Performance Of Cements”,Bensted, J. & Barnes, P. Eds. Spoon Press, London, 2002.

[25] Keller, T. “Use of Fiber Reinforced Polymers in Bridge Construction”. *International Association for Bridge and Structural Engineering*. Zurich, 2003.

## 8 List of Papers published by the author

### 8.1 Publication in journals

1. **Hafsa Jamshaid**, Rajesh Mishra and Jiri Militky, "Thermo-Mechanical Characteristics of Basalt Hybrid & Non-hybrid Woven Fabric Reinforced Composites, published online in **Polymer Composites,** 2015.(**Impact factor=1.6332**)
2. **Hafsa Jamshaid**, Rajesh Mishra, Jiri Militky and Veronika Safarova, "Investigation of electrical properties of basalt and its hybrid structures", published online in **Textile Research Journal,** 2016. (**Impact factor=1.599**)
3. **Hafsa Jamshaid**, Rajesh Mishra, Jiri Militky and Jan Novak, "End use performance characterization of novel fabrics", **Fibers and Polymers**, published 16 (11), pp. 2477-2490, 2015.**(Impact factor=0.881)**
4. **Hafsa Jamshaid**, Rajesh Mishra and Jiri Militky, "A green material from Rock : A basalt fiber", published in the **Journal of the Textile Institute**, 107(7),pp. 923-937,2016 .( **Impact factor=0.722)**
5. **Hafsa Jamshaid**, Rajesh Mishra, Jiří Militký "Thermal and mechanical characterization of novel basalt woven hybrid structures published in the **Journal of the Textile Institute.** 107 (4), pp. 462-471,2015 **(Impact factor=0.94).**
6. **Hafsa Jamshaid**, Rajesh Mishra "Photoilluminance of different woven structure published in **Fiber & Polymer** 15 (5), pp. 950-953,2014. **(Impact factor=0.881)**
7. **Hafsa Jamshaid**, Rajesh Mishra, Jiri Militky, Miroslava Pechociakova, Muhammad Tayyab Noman, "Mechanical, "Thermal and Interfacial Properties of Green Composites from Basalt and Hybrid Woven Fabrics" is accepted in Fibers & Polymers**.(Impact factor=0.881)**
8. **Hafsa Jamshaid**, Rajesh Mishra, Jiri Militky "Analysis of Mechanical Properties of Basalt hybrid woven fabrics" is accepted in **Journal of Fiber Bioengineering and Informatics** (**Impact factor=0.43**).
9. **Hafsa Jamshaid**, Rajesh Mishra, Jiří Militký "Characteristics of woven basalt and hybrid structures as composite reinforcement" is under review in **JTI**. (**Impact factor=0.94)**
10. **Hafsa Jamshaid**, Rajesh Mishra, Jakub Weiner, Jiri Militky "New generation of flame-resistant woven fabrics from green material" is submitted in Chemical Engineering Journal (**Impact factor** =**4.16**)
11. **Hafsa Jamshaid**, Rajesh Mishra, Lubos Hes, Jiri militky, Sajid Hussain " Sustainable textile materials for advanced thermal applications "is under review in Fibers & Polymers.(**Impact factor=0.881**)
12. **Hafsa Jamshaid,** Rajesh Mishra, Jiri Militky, Miroslava Pechociakova, Muhammad Tayyab Noman, "Usability of Textile Reinforced Concrete: Structural Performance and Durability" is under review in Journal of Textile institute textiles. (**Impact factor =0.94**)
13. **Hafsa Jamshaid,** Rajesh Mishra, Maros Tunak "Investigation of mechanical Properties of basalt woven fabrics by theoretical and image analysis methods" is submitted in **Journal of material science** (**Impact factor=2.302**).
14. Muhammad Tayyab NOMAN, Jakub WIENER, Jana SASKOVA, Muhammad Azeem ASHRAF & **Hafsa Jamshaid** Synthesis and Characterization of $TiO_2$ nanoparticles prepared from Ultrasonic Assisted Technique (UAT) is submitted in Ultrasonic (**Impact factor =1.94**)
15. Mohanapriya Venkataraman, **Hafsa Jamshaid**, Rajesh Mishra, Jiri Militky, Aerogel for high performance thermal insulation in textiles, **Textile progress, Vol. 48, No. 2,** 2016.

## 8.2 Contribution in conference proceedings

1. Hafsa Jamshaid, Rajesh Mishra" New material: Basalt fiber" in design & light workshop 2016.
2. Hafsa Jamshaid, Rajesh Mishra, , Jiří Militký "Characterization of Mechanical Properties of Basalt Hybrid Fabrics" in TBIS2016.
3. Hafsa Jamshaid, Rajesh Mishra, , Jiří Militký, "Mechanical & Functional Characterization of Basalt woven structures" in Fiber society, 25-27 May, 2016
4. Hafsa Jamshaid, Rajesh Mishra ,"Characteristics Of Woven Basalt Hybrid Composites" Textile institute conference -28april 2016
5. Hafsa Jamshaid, Rajesh Mishra, Jiří Militký "Investigation of Thermal Properties of Hybrid Structures ISERD conference 2016 ISBN 978-93-85973-41-3
6. Hafsa Jamshaid Seminar on "Advances in Material engineering" 1-2 December 2015, Technical University of Liberec, Czech Republic
7. R. Mishra, Hafsa Jamshaid, Performance utility of novel basalt woven hybrid fabrics, 6th international Technical Textile congress, Izmir, 14-16 October, 2015.
8. R. Mishra, Hafsa Jamshaid, Bio-based composite materials, Keynote lecture, International conference, CET, Bhubaneswar, 9th november, 2015.
9. R. Mishra, Hafsa Jamshaid, Basalt based hybrid woven stuctures and composites, Keynote lecture, INNOTEX-International conference, JNGEC, Sundernagar, Himachalpradesh, 7th November, 2015.
10. Hafsa Jamshaid, Rajesh Mishra, Thermal and Mechanical Characterization of Basalt Hybrid Structures in 15th AUTEX world Textile conference 2015 is presented. ISBN; 978-606-685-275-3
11. Hafsa Jamshaid, Rajesh Mishra, "Thermo-Mechanical Characteristics of Hybrid Woven Structures" in Clotech 2015 is presented. ISBN ;978-83-7283-665-6
12. Hafsa Jamshaid, Rajesh Mishra, "Mechanical & Functional Characterization Of Unconventail Knitted Fabrics" in 5 th SMARTEX , 2015. (Egypt)
13. Analysis if basalt fabrics: thermal and mechanical analysis, Svetlanka 2015 ,ISBN; 978-80-7494-229Hafsa Jamshaid, Rajesh Mishra,"Thermal and mechnical properties of woven Basalt fabric reinforced hybrid & non-hybrid composites" presented in 6th International Istanbul conference on Future Technical textiles (FTT2014) ,15-17 October 2014.ISBN:978-975-400-386-4.
14. Hafsa Jamshaid, Rajesh Mishra,"Thermal And Mechanical Properties Of Novel Basalt Woven Structures presented in 20th International conference STRUTEX 2014.
15. Hafsa Jamshaid, Rajesh Mishra, Thermo-Mechanical Characteristics of Hybrid Woven Structures in Clotech 2015 is presented.
16. Hafsa Jamshaid, Rajesh Mishra, Jan Novak, Jiri Militky, "Mechanical and functional characterization of unconventional knitted structures," SMARTEX, World textile conference, Egypt, November 2015.
17. Hafsa Jamshaid, Rajesh Mishra,"Thermal and mechanical properties of woven Basalt fabric reinforced hybrid & non-hybrid composites" presented in 6th International Istanbul conference on Future Technical textiles (FTT2014) ,15-17 October 2014. ISBN: 978-975-400-386-4.
18. Hafsa Jamshaid, Rajesh Mishra, "Thermal and Mechanical Properties of Novel Basalt Woven Structures presented in 20th International conference STRUTEX 2014.
19. Hafsa Jamshaid,Mohnapryia Venkataraman, Rajesh Mishra."Effect of temperature on mechanical properties of polymer fibers" Textile Science Conference 23-25 September 2013, Liberec, Czech Republic.

## 8.3 Contribution in books

1. Hafsa Jamshaid, Rajesh Mishra, Jiří Militký, "Analysis of Electrical Properties of Basalt and its Hybrid Structures" in Recent Developments In Fibrous Material Science, ISBN 978-80-87269-45-9, 2015
2. Hafsa Jamshaid, Rajesh Mishra, Jiří Militký, "Thermal Properties of Basalt Hybrid Woven Fabrics" in Recent Developments in Fibrous Material Science, ISBN 978-80-87269-45-9. 2015
3. Hafsa Jamshaid, Rajesh Mishra, Jiří Militký, "Thermal Properties of Electrospun Nanofibres Embedded with Aerogel" in Recent Developments in Fibrous Material Science, ISBN 978-80-87269-45-9. 2015
4. Hafsa Jamshaid, Rajesh Mishra, Jiří Militký, "Acoustic Properties of Aerogel Embedded Nonwoven Fabrics" in Recent Developments in Fibrous Material Science, ISBN 978-80-87269-45-9. 2015
5. Hafsa Jamshaid, Rajesh Mishra, Jiří Militký "Effect of Washing Treatments and Blend Ratio on Comfort Properties of Denim Fabrics" in Recent Developments In Fibrous Material Science, ISBN 978-80-87269-45-9. 2015
6. Hafsa Jamshaid, Rajesh Mishra, Jiří Militký, Miroslava Maršálková and Rudolf Šrámek, "Baslat hybrid and non-hybrid fabric reinforced composites", Progress in fibrous material science, ISBN 978-80-87269-40-4, 2014.
7. Hafsa Jamshaid, Mohanapriya Venkataraman, Rajesh Mishra et. Al, "Photoilluminance of Different Woven Structures By Treatment With Phosphorescent Pigment, Selected Properties Of Functional Materials," ISBN 978-80-87269-28-2, 2013.
8. Hafsa Jamshaid, Mohanapriya Venkataraman, Rajesh Mishra, Jiri Militky, "Aerogels: Novel Materials For Insulative Textiles, Selected Properties Of Functional Materials", ISBN 978-80-87269-28-2, 2013.
9. Hafsa Jamshaid, Mohanapriya Venkataraman, Rajesh Mishra, Jiri Militky, Aerogel Based Insulation Materials: Characterization of Thermal, Electrical and Electromagnetic Behavior, Selected Properties Of Functional Materials, ISBN 978-80-87269-28-2, 2013.

**Curriculum Vitae**

**Engr. Hafsa Jamshaid /Riaz**
**Department of Fabric Manufacturing, National Textile University, Faisalabad**

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***Qualification:***

**PhD,** Technical University of Liberec,Czeck Republic (in Progress)

**MSc**, Engineering Management, University of Engineering and Technology, Lahore, Pakistan 2009.

**BSc**, Textile Engineering, University of Engineering and Technology, Lahore, Pakistan, 2003.

**B.Com**, Commerce, University of the Punjab, Faisalabad, Pakistan, 2000.

***Employment History:***

- Educational Experience:

**Assistant Professor/Chairperson** 2009-December 2013

Department of Fabric Manufacturing,

National Textile University, Pakistan

*As teaching is main concern, other duties are conducting research projects and involve in management decisions. I also conduct fabric testing & supervise.*

**Lecturer** 2003-2009

Department of Fabric Manufacturing,

National Textile University, Pakistan

*Teaching courses on weaving, Knitting Technology Textile Testing & Quality control, Fabric Technology, Introduction to Fabric Formation, Fabric structure & design, Human resource management & researching, Plant design, project management.*

**Visiting Lecturer** 2010

Department of Industrial Management,

GC,University,Faisalabad.

- Industrial Experience:

- Training for circular knitting machine by Mayer & Cie.
- 40 Days Training in Crescent Textile Ltd. Faisalabad.
- 30 days Training for the Denim Preparation in Crescent Bahuman Ltd.
- 30 days Training for the machine setting of Sulzer Weaving Machines in Nishat Textile Ltd. Faisalabad
- Training for dobby and tappet by Staubli (French Company) representative.
- Working Experience and knowledge of designing based software **SCOT** weave that includes the color and weave effect, design combinations and complex designs, fabric appearance in three dimensional views by scanning.

***Academic Achievements:***

- Coordinator of SCI (sustainable and cleaner production in the manufacturing sector of Pakistan) a project funded by European Commission.
- Awarded with Scholarship by **VDMA (**German machinery manufacturers organization) for **40 days** training in Germany. That training comprised of visits, seminars, practical workshops of Weaving and knitting machinery manufacturers in Germany, collection of samples and representation of Pakistan textile sector.
- Paper setter of Punjab Board of Technical Education,
- Awarded scholarship throughout my BSc. Engineering

***Membership in Professional Societies:***

**Pakistan Engineering Council** (PEC No. TEXTILE/105)
**Institute of Engineers** (M16385-61)
**TWOWS** (Third World Organization for Women in Science)
(Membership Number:3920)
**Textile Institute UK**(Lahore Section)928626.

**Record of the state doctoral exam**

TECHNICKÁ UNIVERZITA V LIBERCI
Fakulta textilní

# ZÁPIS O VYKONÁNÍ STÁTNÍ DOKTORSKÉ ZKOUŠKY (SDZ)

*Jméno a příjmení doktorandky:* **Hafsa Jamshaid, M.Sc.**

*Datum narození:* **30. 6. 1979**

*Doktorský studijní program:* **Textilní inženýrství**

*Studijní obor:* **Textile Technics and Materials Engineering**

*Termín konání SDZ:* **3. 2. 2016**

**prospěla** ~~**neprospěla**~~

*Komise pro SDZ:*

| | | Podpis |
|---|---|---|
| Předseda: | prof. Ing. Jiří Militký, CSc. | [signature] |
| Místopředseda: | prof. RNDr. Oldřich Jirsák, CSc. | [signature] |
| Členové: | prof. RNDr. Jan Picek, CSc. | [signature] |
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| | doc. RNDr. Jiří Vaníček, CSc. | [signature] |
| | Ing. Blanka Tomková, Ph.D. | Tomková |

V Liberci dne 3. 2. 2016

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**Reccomedation of the supervizor**

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## Supervisor’s opinion on PhD thesis of Hafsa Jamshaid,M.Sc.

**Date: 04.10.2016**

**Thesis title: Hybrid woven structures**

**Doctoral candidate: Hafsa Jamshaid, M.Sc.**

The thesis titled “Hybrid woven structures” submitted by Hafsa Jamshaid, M.Sc., fulfills the objectives outlined in her thesis. The work is comprehensive and shows the analytical ability of Ms Jamshaid in evaluating results obtained. Her rich publication record further demonstrates the ability to explain complex scientific problem in objective terms.

The work includes weavability study of Basalt and other yarns on CCI loom followed by an industrial production on commercial machines. As the study involves some unconventional materials being processed on standard weaving machines the outcomes are not usual. Basalt is a relatively new material for the weaving industry. There is no established setting available to run such a yarn. It is also relatively stronger as compared to other materials used in this work, and thus it is difficult to handle weft insertion. The production of such hybrid woven structures is a commendable work.
The focus of the study is on evaluation of performance properties in a concrete matrix, thermo-mechanical properties and degradation under strong alkaline conditions. It is demonstrated that basalt hybrid woven structures can prove to be suitable candidates in combining properties of this unconventional material with polymeric fibers e.g. PET, PP and Jute. Results reveal that the hybridization of basalt with polypropylene, polyester and jute in different weaves leads to significant improvement in thermal and transmission related characteristics. Structural parameters have strong influence on thermal properties. Structure of weave and fiber type have strong influence on thermal as well as electrical conductivity. The thesis also explains the acoustic performance of such hybrid woven fabrics to be used in building construction.

The thesis is written in clear English and the quality of figures and tables are very good. The overall quality of thesis is very good and I recommend it for the defense.

**doc. Rajesh Mishra, PhD**
**Supervisor**

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## Opponents' reviews

**Technical University in Liberec**

**Opponents review for the degree of Doctor of Philosophy defence**

**Candidate:** Hafsa Jamshaid, M.Sc.

**Thesis title:** Hybrid woven structures

**Thesis tutor:** Doc. Rajesh Mishra, Ph.D.

**Study subject:** Textile Engineering/Textile Technics and Materials Engineering

This opponent´s review was written based on request of Ing. Jana Drašarová, Ph.D. – dean of the Faculty of textile, ref. no. TUL-16/4814/029198 of August 8, 2016.

**General information:** Thesis is composed from 5 chapters and 2 appendices, total volume of 160 A4 pages. Thesis structure is based on commented individual chapters dealing with the introduction, definition of the objectives, state of the art of the matter under study, experimental, results and discussion, summary and conclusions. Totally there was cited 139 references. Thesis were written in English language.

1. **The nature and the scope of the investigation:** The thesis presented deals with interesting scientific and technical problem of application and processing and manufacturing of basalt hybrid fabrics for technical application in the construction industry. The thesis presented is of applied materials engineering nature. The main objectives of the study were to analyse the weavability of the basalt hybrid fibres, to predict structural and mechanical properties of the fabrics manufactured by means of geometrical/computational tools, to characterize the effect of weave and fibre composition on mechanical, thermal and functional properties of the studied hybrid basalt textiles, study thermomechanical characteristics of the latter systems, their acoustic performance as well as their resistance against accelerated ageing conditions. Finally the compatibility study of the latter systems with the cement compositions were performed as well.
2. **The contribution made to the subject field, including the extent to which the thesis contains original, publishable work or merit:** Obtained results are the original contribution to the studied problem of novel type of composite structure preparation and manufacturing and their material characterization. Author in her thesis has vigorously analysed and compared wide range of physico-chemical and material characteristics and their mutual dependences. Thesis represent complex experimental study with excellent theoretical data evaluation and analysis. Results obtained by the applicant´s study brought a new valuable knowledge to the applied materials science and engineering study field. Student has published majority of the results in prestigious scientific journals of the materials engineering/ materials science and textiles materials scientific orientation, to name a few such as J Textile Institute (2 publications, Q1), Fibers and Polymers (2 publications, Q2, Q3), Polymer Composites (1 publication, Q2) which were already published in international scientific journals. Two manuscripts are under review consideration. Applicant has attended many scientific conferences were she has presented her results in 17 contributions, 9 book chapters. Majority of the papers has successfully passed through vigorous review process in the journals, where the papers were published.

3. **The quality of the submission and, where appropriate, of the investigative work described:** Presented Ph.D. thesis is of usual quality standard both in content as well as in form of presentation and data analysis and interpretation. I have found several formal stylistic and graphical errors such as too small axes legends and numbers in many figures in the text, wrong averaging of the obtained data as using too many valid digits etc. However this is not lowering an overall high standard of the thesis. That is why I am fully supporting submission of this thesis as a base for final examination. Ph.D. thesis presented fulfils usual quality requirements for PhD thesis.

**Signed:** Prof. Ing. Lubomír Lapčík, PhD. **Date:** September 2, 2016

# <u>Opponent's review of the PhD thesis</u>

**PhD student: Hafsa Jamshaid, M.Sc.**

**Title: Hybrid woven structures**

The submitted PhD thesis in the range of 160 pages of text is rich in content, formally clearly arranged and carefully prepared with high graphical level. Also factual formulations and technical expressions contribute to the level of the work. Furthermore, a purposeful arrangement into 5 chapters that logically follow each other is the positives of the work.

**The subject of the thesis** is examination and design of hybrid woven fabrics intended for the production of composite materials. These are, in this case, concrete matrices with textile reinforcement. It is assumed that the basic component of the textile reinforcement will consist of basalt fibers or fibrous bundles and the hybridizing component of PP, PET fibers and jute.

**The aim of the thesis** is to describe the influence of hybridization and fabric structure on the physical and chemical properties of the composite reinforcement. It is studied and assessed with the help of experiments and the results are confronted with computer models in some cases.

In initial chapters, there is carried out an extensive and careful **research of state of the art**, importance of hybrid components, their structures and properties. The chemical, physical, mechanical static, mechanical dynamic, electric, thermal and acoustic parameters determining the properties of composites are depicted in detail. Furthermore, the available means for modeling the properties and measurements of particular parameters of the composite reinforcement are presented.

**The executive part of the thesis** starts with the choice of samples of the reinforcement for experimental analysis. As a manufacturing process, it is determined weaving, plain, matt and twill fabric structure, basalt as a material of the reinforcement, alternatively combined with PP, PES and jute. The arguments supporting just this selection along with the prediction of the expected changes in the properties and effect of the product could be defined in a more explicit form. When comparing with the extensive array and number of tests, the number of samples, particularly in terms of changes and combinations of thread parameters, is somewhat insufficient to obtain convincing results (thread fineness 250-280, thread densities not shown).

**Experiments and their results:**

The tests of weavability have been carried out on the CCI (sampling laboratory equipment) and on a weaving machine. The protocols show that the final outcome of those tests is the coefficient of efficiency (KTE). From the perspective of the CCI at the speed in an order of tens of $min^{-1}$, the evaluation of KTE is illusory. From the viewpoint of the weaving machine, the values of KTE in the range of 40-70% are unacceptable for the practice. A fortiori that this is a net KTE, involving only downtimes liquidating weft, warp and machine failures and by the fact that the fabric quality was not assessed simultaneously. In the description of the weaving tests, I have not found any mention of particular weft and warp densities.

The parts Characterization of fiber and cement raw, Accelerated aging in alkaline solution and Yarn pull out test from cement matrix, are processed in accordance with the procedures from the cited sources.

Another part of the work deals with the testing of fabric samples. Physical properties, i.e. real densities, basis weight, thickness and porosity are evaluated on the basis of standardized procedures. The tests of static mechanical parameters, tension (stress), elongation, pressure, and shear are complemented by predicting values of tension using simulation in SW Wisetex. The object of investigating the dynamic properties of the samples is essentially damping whose significance in the hybrid reinforcements is greater in polymer materials than in basalt. Damping coefficients are evaluated for all the samples depending on temperature.

Thermal and transmission related properties are evaluated by measuring on an Alambeta apparatus, acoustic properties are characterized by the SAC coefficient (sound absorption) and the NRC (noise reduction). The NRC has been associated with air flow resistivity and fabric porosity.

All experiments are carefully documented and evaluated. Laboratory equipment and technological processes as well.

The evaluations of the work results and the conclusions are relatively brief. Their validity and importance will be usually only applied within the study of individual parameters. With regard to a wide definition of goals of the work and to examining a considerable number of mutually different parameters selected from several disciplines, an expectation of generalized results and a definition of directions for innovations is difficult. The only, but expected, generalized result is an increase in the strength and rigidity of the composite with basalt fibers and vice versa, a decrease in the strength and an increase of elongation using PP and PET fibers.

**Comments on the work:**

1/The coefficient of technical efficiency of the weaving machine is very low. Explain the causes and suggest measures for its increase.

2/The set of the evaluated parameters is so diverse and extensive that it can be difficult to analyze it and to determine which combination of input parameters can provide, if not optimal, at least a rational solution of the quality of the composite product. Would it not be more effective to choose to study a smaller number of dominant and interrelated parameters?

**Conclusion**

The PhD thesis fulfills the set goal and contributes to solving the current and important problems in the development of hybrid reinforcements for concrete matrices.

The PhD thesis corresponds to the generally recognized requirements for granting the academic title of Ph.D.

I recommend this work for defense without reservation.

Prof. Ing. Miroslav Václavík, CSc.

VÚTS, a.s., Liberec

Liberec, 6.9.2016

**Opponent's Assessment of the Doctoral Dissertation**

**Doctoral Candidate: Hafsa Jamshaid, M.Sc.**

**Dissertation Title: Hybrid woven structures**

On the basis of appointment by Ing. Jana Drašarová, Ph.D., Dean of the Textiles Faculty of Liberec TU, I prepared this opponent's assessment of the doctoral dissertation.

The submitted dissertation contains the total of 155 pages. Of this text, the actual text comprises 133 pages. The dissertation is divided into five connected chapters, including the introduction and conclusion. The chapters are further broken down into sub-chapters. The dissertation has been prepared responsibly and without any significant terminological errors. The written text is supplemented with 31 tables and 66 images.

The structure of the dissertation is as follows: The current status is stated in the introductory part of the dissertation. The student when processing this part exploited scientific papers, professional books, collections of conference papers, publications from prestigious international scientific magazines. The information is corroborated by suitable references stated in the bibliography. The next part of the dissertation discusses the contribution of the doctoral student. The third chapter deals with the preparation of material for measurement and its realisation. It describes the methods applied to prepare the material samples. It further states the methods applied to the measurement of the selected textile structure parameters. The fourth chapter focuses on analysis of the measurement results and their discussion. The fifth chapter summarises the results of the author's dissertation. The conclusion is followed by the bibliography showing the list of the author's publications related to the research task and the list of publications, which were used during the research task.

**Overview of Doctoral Dissertation Objectives**

The objective of the dissertation is already clearly defined by its title. The selected dissertation topic fully corresponds to the scientific branch and field of study, in which the dissertation is submitted. The objectives are stated immediately in the dissertation introduction and are summarised into seven areas:

- To analyze the weavability problém during production of basalt hybrid fabrics.
- To predict structural parameters and mechanical properties by using suitable geometrical/computational tools and verify the predictability.
- To investigate the effect of weave and fiber composition on mechanical, thermal and functional properties in basalt based hybrid woven structures.
- Study of thermo-mechanical characteristics of basalt hybrid fabrics.
- Study of acoustic properties of basalt hybrid fabrics.
- Study of durability under accelerated aging conditions.
- Compatibility study of basalt and other yarns with cement.

In my opinion, all the objectives are not balanced in terms of their importance and their fulfilment for the main objective's successful completion.

**Opinion on the Up-to-Date Character of the Dissertation**

The development of new material structures, which can become full-fledged material for industrial applications and fulfil the ever-increasing requirements for physical mechanical properties, are a worldwide trend. This research work is based on an interdisciplinary approach, which combines knowledge of physics, chemistry, material research, etc.

The dissertation is set in the framework of the current thinking of engineers on materials for industrial applications. On one hand is the application of conventional materials where emphasis is placed on precision processing, and on the other hand, on conventional materials whose properties can be modified by completely different technological procedures other than those applied to conventional materials. The common objective of both are new technical solutions that bring new utility parameters. The interpretation of the procedures, which lead to the design and optimisation of construction from a hybrid material structure, must be classified into the area of non-conventional materials. This makes the topic really current. Besides this, it is necessary to highlight the current character of the research methods applied in this dissertation.

**Opinion on the Solution Procedure and Applied Methods**

For solution of the issues stated in the doctoral dissertation, the methods applied have been selected correctly. The solution procedure is logical and systematic. In the introduction, the author formulates the objectives of her dissertation, which she gradually fulfils in subsequent chapters. The applied procedures and methods completely meet the requirements, although they are inadequately specified at several points.

**Achievement of the Results and Objectives of the Dissertation**

I see the dissertation author's actual contribution mainly in the dissertation's practical part. It mainly concerns the preparation of samples for measurement, and its performance and evaluation. All these activities brought new knowledge and procedures. The above-stated conclusions of the presented dissertation's individual chapters prove that the main and partial objectives set forth in the dissertation were achieved.

**The Dissertation's Formal Processing**

The dissertation is also a success in terms of the formal aspect. The text is comprehensible. Many professional resources are used in the dissertation, to which references are made in the text. The images, graphs, and diagrams are demonstrative and properly legible. The opening part of the dissertation that provides information about the current position is unnecessarily extensive. It often features information that is generally known, which does not give any added value to dissertation's quality.

**Suggestions and Problematic Areas**

I do not have any major suggestions regarding the presented dissertation, but during the defence of the dissertation, the student should express her opinion regarding the following areas:

- To which type of a loom do the setting parameters expressed in the dissertation apply (Section 4.1.1)? What is the probability of application of the parameters you have set here for another type of a loom?
- Have you considered how recycling of material made in this way shall be done?
- Explain your reasons for stating the production efficiency of the material sample production used in the measurement at the CCI machine (Table 3.2)? Does stating the efficiency make sense in this case?

**Conclusion**

The doctoral student has proven that she mastered the scientific work methods and possesses corresponding knowledge in the researched area. According to the bibliography, it is clear that during her studies, she continuously published the results of her research work both at scientific conferences, as well as in the form of magazine articles. She published a significant part of her scientific works in foreign magazines listed in the WoS or Scopus databases. It is necessary to emphasise that part of the articles were published in magazines with an impact factor. This fact proves the student's capability to formulate and present achieved results to the scientific and professional community. From the submitted dissertation, it is clear that the published materials have the character of original solutions.

**I recommend acceptance of the doctoral dissertation titled Hybrid Woven Structures for defence and in the event of successful defence, I recommend awarding of the Ph.D. academic title.**

**Liberec 21.9.2016**

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