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Hybrid fabrics for composites reinforcement

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Abstract. In this study, experimental investigations are carried out to check the thermal and mechanical behavior of woven Basalt/PET and Basalt/PP fiber hybrid woven fabric epoxy composite laminates. Three types of weaves are used for all hybrid structures. Fabricated composite samples are subjected to mechanical and thermal characterization. Results are discussed in terms of fiber effect, weave geometry and the resin effect. The results reveal that the hybridization of basalt in different weaves leads to significant improvement in the static and dynamic mechanical properties of composites. Structure of weave, fiber type and resin properties have strong influence on mechanical properties of composites of basalt hybrid fabrics. The modulus is significantly increased in composites due to interfacial bonds between fibers and resin. Thermal behavior of fiber and composite was observed by Thermal Gravimetric Analysis and Differential Scanning Calorimetry. Thermal properties are also affected by hybridization. Thermal conductivity is strongly affected by resin properties. Fractography studies of the damaged surface are also demonstrated.

Introduction

The textiles are core ingredient of human life since ancient times. Use of fabrics ranges from clothing to industrial application based on the raw material for specific use. The development of different set of materials has spread its uses beyond expectations. Hi-tech composite reinforcing materials have become an integral part of many applications, e.g. IT, Electronics, Automotive, Sports, Health care, Energy generation, Energy storage etc. Fibers are used in different polymer matrices for enhancement of features like strength and rigidity. In aerospace and defense industries, there is a demand for materials with higher strength and lower weight. Thus fiber reinforced composites became an obvious choice. Recently, the composite products are increasingly used for sun-shading devices, plane wings, fuselages or any other beams and shells in modern applications [1,2]. As the demand for fiber reinforced composites increased for specific applications, a number of new fiber/resin systems were on offer for the designers. These composites exhibit brittle fracture and bear high cost but their extra ordinary properties like low density, high rigidity and high strength raise their demand for specialized solutions. Two or more types of fibers embedded in a matrix of reinforcing phase constitute a hybrid composite. Hybrid composites give the privilege to create a material bearing desirable properties among the combination of fibers, that is more cost effective and we 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 resistance behavior, reduced weight and/or cost, improved fatigue resistance, reduced notch sensitivity, improved fracture toughness and impact resistance [3-6].

The reinforcement fibers themselves are unmanageable and are therefore usually arranged into sheets which can be handled, oriented on a mould, shaped and cut. 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 fibers are bound in a variety of ways including weaving, stitching and knitting. Woven fabric composites particularly offer better dimensional stability when they are exposed to a large range of temperatures.

Woven structure is defined by orthogonal interlacement of at least two sets of yarns called warp and weft. 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 provides 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. Considering that the woven fabric reinforced composite materials are not entirely homogeneous, large resin rich areas are formed by the interlacing of undulating warp and fill yarns. In the high performance fiber-polymer matrix system, the difference of damping is much larger than that of the stiffness. Large resin rich areas act as the built-in damper elements. Their distribution, depending on the architectures of the weave, determines the damping of the composite structure.

Glass fiber-reinforced composites were widely used to fabricate various applications in recent times but the aim to produce more environment friendly composites is leading to reduction of glass fiber use [7,8]. Basalt fiber has evolved as a replacement of glass fiber due to its environment friendly natural origin. Basalt rock is known for its thermal properties, strength and durability since long time. Basalt is known to possess better tensile strength in comparison with E-glass fibers, they have greater failure strain than carbon fibers, they have very good resistance to chemical attacks and they produce less poisonous fumes [9]. The recycling of basalt fiber can be done in much better environment friendly way than glass fibers (Behera and Mishra, 2008). When a resin with basalt fibers is recycled, same material of basalt powder is obtained so it is classified under sustainable material category.

Conventional reinforced composites are always problematic at the end of their service life during recycling. Due to environmental and legal issues, recycling process has become an increasingly difficult issue. The solution to the issues related to recycling was answered by use of green matrix based renewable resource or green composite which are generally formulated by embedding the fibers into bed of bio-polymers that can integrate more readily into natural biodegradation cycles, for example by CO_2-neutral incineration, which includes recovery of energy, or by composting.

We have a twofold aim of our research which is, to enhance use of green composites by adding natural basalt fibers in biodegradable polymeric resins and, to develop hybrid composites with most commonly used fiber i.e. polyester and polypropylene. Basalt woven hybrid composites are developed. An investigative study is conducted about role of different reinforcing yarns in composites with their properties and capabilities. PET and PP yarns have been used in the hybrid composites besides basalt yarn, and the mechanical characteristics of the composites have been investigated as a function of weave and fiber composition. Further aim of the work is to study the thermal properties of these hybrid composites. In this study, geometry of hybrid textile fabric was the prime focus and effect of weave structure on the mechanical behavior in textile composites was investigated.

Experimental

Basalt is a fiber originated from rocks and having excellent thermal resistance. PET and PP are thermoplastic polymeric materials. The idea was to use these different polymeric fibers in the weft along with basalt warp so as to create hybrid woven structures and to further investigate the compatibility with epoxy resin in a composite manufacturing. The prepared composites were evaluated for mechanical and thermal characteristics. The polyester (PET) and polypropylene (PP) yarns used in this study were available commercially. The basalt yarn was received from company Kamenny Vek (KV). The details of yarns are given in Table 1. Green epoxy resin CHS-Epoxy G520 and hardener TELALIT 0600 were supplied by Spolek, Czech Republic. It is a low molecular weight basic liquid epoxy resin containing no modifiers, certified by International Environmental Product Declaration Consortium (IEC).

Table 1: Properties of fibers and yarn

Properties	Basalt	Polyester	Polypropylene
Diameter of fibers (micron)	12	22	34
No. of filaments	890	900	300
Linear density of yarn (Tex)	295	250	292
TPM (Twists/m)	20	24	30
Tensile strength (N)	92.75	88.91	57.44
Tensile elongation %	1.29	12.55	12.27
Tenacity (N/tex)	0.315	0.305	0.23
Modulus MPa	9,378	1069	721

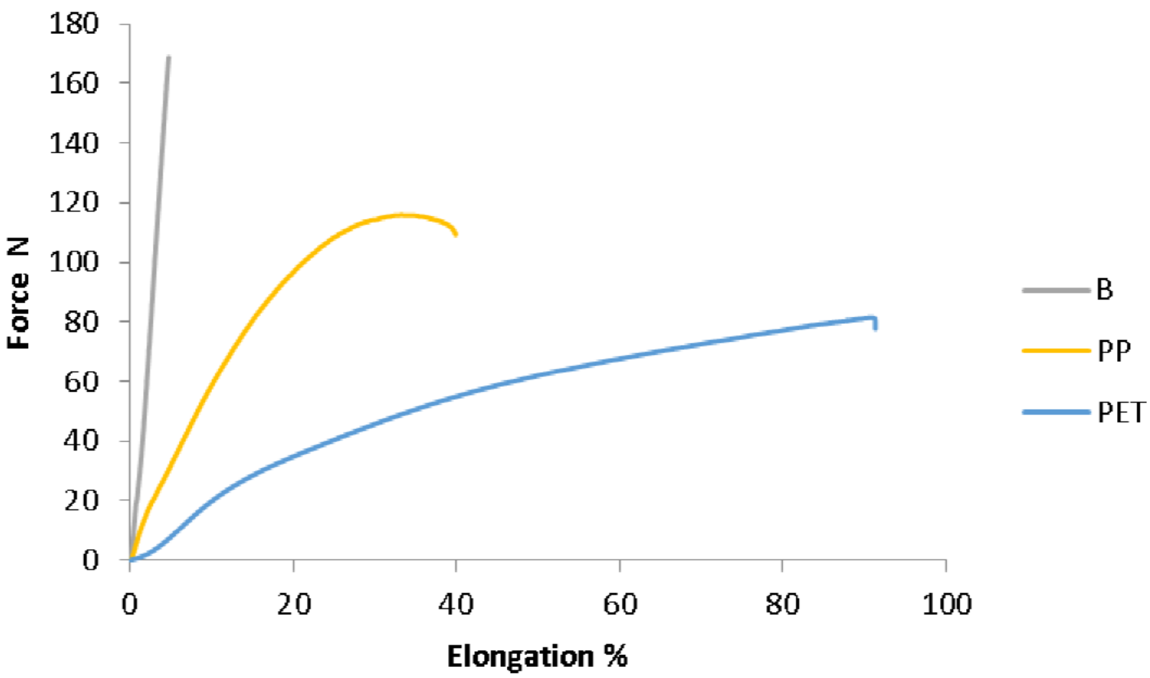


Fig. 1: Force & elongation curve for yarns

Methods. Hybrid fabric samples were developed with Plain, Matt, and Twill weaves from Basalt/PET and Basalt/PP yarns. Non-hybrid Basalt–Basalt fabrics were also developed. All fabrics were made on the CCI sample loom with the same thread density for all fabrics, 12 threads/cm in warp and 8 threads/cm in weft. All the fabric variants were measured, according to standard procedures. Yarn tensile properties were measured and shown in Fig. 1.

Preparation of composites. The Basalt hybrid (B/J) and non-hybrid (B/B) fabrics were reinforced in epoxy resin to prepare the composites with single ply of the reinforcing fabric. The Bio epoxy resin and corresponding hardener at weight ratio of 100:32 (by weight) according to manufacturer recommendations were mixed. The mix was stirred manually to disperse the resin and the hardener in the matrix. The mixing was done thoroughly before the fabrics were reinforced in the matrix body. The composite slabs were made by conventional hand-lay-up technique followed by light compression molding technique. A stainless steel mould having dimensions of 250 x 250 x 40 mm^3 was used as shown in Fig. 2. The prepared resin mixture was poured on fabric layers and spread out by a hand roller. The gentle rolling action of hand roller confirmed the wetting of fabrics and the excess resin was squeezed out of the panel layup by the roller. The composite layup along with Teflon sheets were sandwiched between a pair of steel plates and cured at 120°C for 1.0 h in mechanical convection oven with predetermined weight. The fiber volume fraction (Vf) of all composites was around 0.4.

Testing methods. The static and dynamic mechanical Properties of composites are characterized along with thermal stability characterization.

Impact test was performed according to standard EN ISO 527-5. The specimen size for tensile testing was 15 cm × 2 cm as per standard. Using aluminum tapes of 1 mm thickness to prevent gripping damage. Composites elastic modulus was quantified through measurements of samples for the tensile properties in warp and weft direction on a TIRATEST universal tensile tester at a crosshead speed of 2 mm/min at room temperature. For each type of sample, 5 tests were repeated.

Three points bending test is used to find the flexural strength and flexural modulus according to EN-ISO 14125 on TIRATEST universal testing machine. All tests were carried out with a span to thickness ratio of 32:1 and a cross-head speed of 2 mm/min. Load is applied at the midpoint of a beam until the specimen bends. The average values of 5 specimens for each sample in both warp and weft direction have been reported.

Impact tests are designed to measure the resistance to failure of a material to a suddenly applied force. The test measures the impact energy, or the energy absorbed prior to fracture. All impacted specimens were un-notched. Charpy impact test was conducted as per EN-ISO 14125 rectangular using CEAST RESIL 5.5 with a force of 22 J at a velocity of 2.9 m/s. The width and thickness of the specimen were measured and recorded. The work of fracture/impact strength values were calculated by dividing the energy in J recorded on the tester by the cross-sectional area of the specimen. The average values of 5 specimens for each sample in each direction have been reported.

Dynamic mechanical properties. Dynamic mechanical analysis was performed on a DMA 40XT RMI equipment. The samples were tested using three-point bending mode at a frequency of 1Hz in temperature scan mode. The DMA test was executed in the temperature range of 27 to 100 ºC at a heating rate of 3 ºC/min. This test was performed according to EN ISO 6721-1. For each sample, five measurements were done. 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. It allows the measurement of two different moduli of the materials, a storage modulus (E') which is related to the ability of the material to return or store mechanical energy and a loss modulus (E″) which is related to the ability of the material to dissipate energy as a function of temperature. Ratio of loss modulus to storage modulus is given by tan (delta).

(a)Tensile (b)Flexural (c)Impact

Fig. 2: Experimental set up for mechanical characterization of composites

Thermal properties. Thermal properties of materials indicate the physical response to the application of heat and resultant change in temperature in response to the applied heat. Physical impact of temperature on materials is reversible in case of short term application where as it is non reversible in long term application as it associates with the chemical changes. The long term effects at elevated temperature are aging/degradation resulting in affecting the mechanical, physical and chemical properties. There is a variety of standard testing methods for thermal properties. Various techniques include differential scanning calorimetry (DSC), thermo mechanical analysis (TMA), thermo gravimetric analysis (TGA) etc.

The Mettler Toledo TGA/SDTA851^e instrument was used to study the thermal gravimetric behavior (thermal stability and degradation) of the composites. Differential thermal and thermogravimetric analysis (DTG)/(TGA) was done. Thermo gravimetric analysis was performed under dynamic nitrogen atmosphere. The samples were heated from 25°C to 700°C at a heating rate of 10°C/min to yield the decomposition temperature, mass loss and maximum decomposition peak.

The Perkin Elmer Differential Scanning Calorimeter DSC6 was used. Samples weighing approximately 7±3 mg were placed in aluminum crucibles and sealed. The samples were heated at a constant rate of 15°C/min between temperature ranges of 25°C to 400°C and then cooled in nitrogen atmosphere with a flow rate of 20 ml/min.
Measurement of thermal conductivity by C-Therm TCi Thermal conductivity analyzer was performed. It allows determining accurate values for thermal conductivity of material without extensive sample preparation or damage to the sample. Measurement of the thermal conductivity of the composite samples was done with TCi Thermal conductivity analyzer by following EN 61326-2-4:2006 standard. To minimize the measurement error to 5%, each sample was repeatedly measured 10 times.

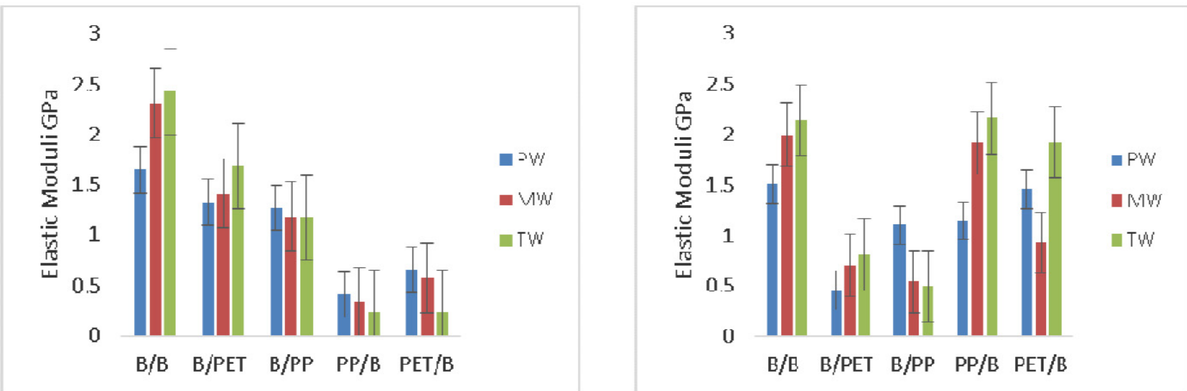
Morphology analysis was done by SEM and video macro scope (Navitar Macroscope) with CCD camera, software N/S-Elements. The SEM photographs of composite samples were taken using a scanning electron microscope TS5130-Tescan SEM at 20 kV accelerated voltage. The surfaces of the samples were coated with gold by means of a plasma sputtering apparatus prior to SEM investigation and were investigated at 2,000× magnification to observe the fiber matrix adhesion. Fractography studies of tensile and impact-damaged sample were carried out by scanning electron microscope. Prior to analysis, the fractured samples were also coated with gold and samples were examined with different magnification level for obtaining high resolution images. Broken laminates were also investigated by Macro scope.

Results and discussion

Mechanical properties describe the resistance of material against external forces. When evaluating the mechanical properties of hybrids, a general rule of mixtures approach may be utilized to quantify a material property with respect to the volume concentration of its constituents. Many researchers (Chou and Kelly, 1980) have however noted the existence of a hybrid effect in which the material property as predicted by the rule of mixtures differs to that observed in reality.

Measurement of tensile stress-strain properties is the most common mechanical measurement. It is used to determine the behavior of a sample while under an axial stretching load. The tensile properties of the composite material is dependent on tensile properties of fiber, matrix and interfacial bonding of resin and reinforcement material. Normally in fiber reinforced composites, the modulus of a composite material is dependent on the reinforcing fiber properties, whereas the tensile strength is a function of the matrix properties. During failure, initially the crack starts at interface (junction between fiber and resin) and then propagates to matrix. Cracking is followed by progressive failure of the fibers (Munikenche, Naidu, and Chhaya, 1999).

Tensile properties. It can be observed from Fig. 3, that non-hybrid basalt woven fabrics have highest tensile properties as basalt yarn has highest strength value, followed by hybrid structures with PET yarn. Tensile modulus indicates the stiffness of materials. Following 100% basalt based composites, Basalt/polyester based composites have high modulus followed by Basalt/PP composites. As polyester tows have higher number of filaments per crosssection, lower liner density and low twist, thus the warps come closer after relaxation and a higher level of crimp in warp direction is achieved which makes them more stiffer.



(a) Warp (b) Weft

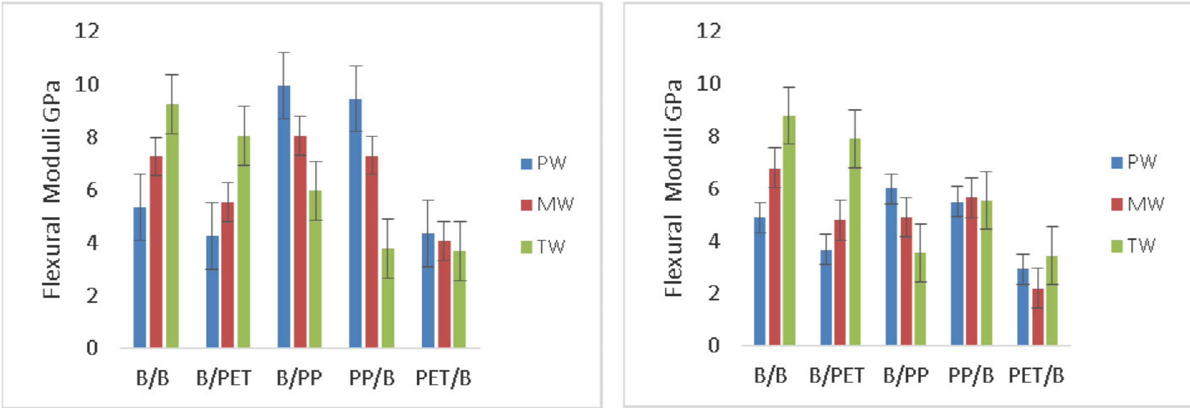
Fig. 3: Elastic moduli of composites

The amount of crimp in a plain woven fabric is more than any other existing weave due to the presence of huge no of intersections. For such high amount of crimp, the yarn orientation is very poor resulting in to weaker in-plane tensile strength. Tensile strength of plain weave is less than twill, probably due to lesser orientation of yarns in the direction of the applied force in non- hybrid basalt as well as B/PET woven structures.

In case of B/PP this condition is reversed i.e plain woven composites have maximum strength. It may be due to weaker interfacial bonding between PP and bio epoxy resin. As PP yarn has compact structure due to higher amount of twist and slightly higher linear density. This leads to less porosity of yarn, decrease interfacial bonding between fiber and resin, so load is transferred to fabric, which follows the same trend of fabric although, effect is not very significant.

In structures where basalt is used in weft, it follows the same trend as fabric due to weaker interfacial bonding with the thermoplastic filament yarns having lower porosity which prevents efficient impregnation of resin into core of the tows. During weaving process of fabric, level of stresses on warp yarn is more which leads to decrimping, elongation and compactness of yarn causes contraction. This causes the floating adjacent yarns which are free from interlacement to join together to form jammed structure. The jammed structure has great influence on the properties of the fabric such as the porosity and it adversely affects resin penetration between fibers. Load is transferred to fabric directly from the resin. Also it can be seen that by using basalt in weft direction, the increase of moduli is not significant. In the fabric composite formation, there is a mechanical interlocking between the fibers and the resin due to frictional forces. Friction force is highly dependent on the area of contact between the resin and the fibers. In case of twill, contact area between resin and fiber is higher, bonding between fiber and matrix is high, thus higher modulus is observed. The plain weave (under almost the same condition of fabric weight/area) is less stiff than twill (due to higher amount of crimp). This is due to the fact that the resin transmits and distributes the applied stress to the yarns resulting in higher modulus. When load is applied to textile reinforced composites, resin transfers the stress to the reinforced fibers. Effective transfer of stress and load distribution throughout the interface is possible when strong adhesion exists at the interfaces. The reinforcing woven fabrics contain more number of yarns in warp direction than in weft direction. Due to higher thread density along warp direction, composites show contrast in mechanical behavior compared to weft direction. When basalt is used in weft direction moduli improvement in weft direction is prominent because of dominance of basalt yarn properties. The mechanical properties of basalt yarn are superior as compared to basalt in warp as the later gets abraded and strained to a higher extent during flexing action of shedding and during beat up action on the loom.

Flexural properties. The flexural modulus is a measure of the resistance to deformation of the composite under bending loads. Under the flexural loading, the surfaces of the specimen are subjected to greater strains than the specimen centre. Composite samples face compressive and tensile fracture during flexural test. Surface layer of composites face tensile fracture while the compressive mode works on the bottom layer [10-12].



(a) Warp (b) Weft

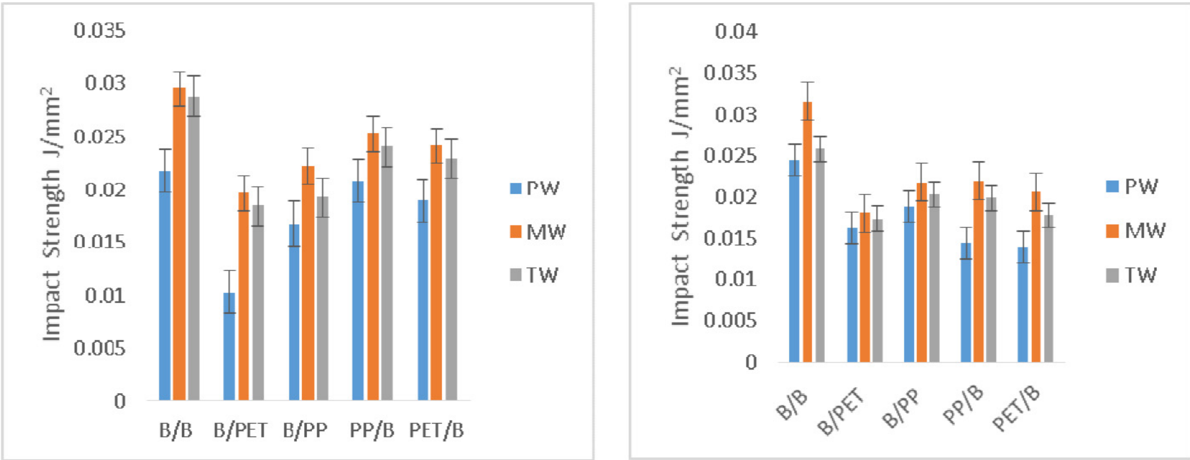
Fig. 4: Flexural moduli of composites

It can be seen from Fig. 4 that, B/B composites have higher bending properties as it also dependent on fiber properties and it follows the same trend as tensile properties. The twill woven fabrics have higher interfacial bonding thus higher bending strength and modulus except B/PP, PP/B and PET/B, where interfacial bonding is not so strong. The resistance to bending is best for composites reinforced with twill fabric as they are stiffer than plain.

As like tensile properties, flexural moduli of composites are found to be higher in the warp direction than weft direction. Less number of yarns in weft direction of composites limits their tensile stress dispersion. Therefore, as the tensile stress tries to propagate upwards, delamination failure occurrs and thus reducing its flexural strength.

Moreover, this research work found that fiber orientation has maximum impact on flexural properties compared to the tensile properties. It is also evident that the hybrid material follows theory and experiment that has been reported by others. A main reason for the higher flexural strength of laminates is that the volume of material subjected to the maximum stress is smaller for three point bending test than the tensile test. So, the presence of the critical defects is much lower than in the tensile test. It may attribute the observed higher flexural strength to laminates [13, 14].

Impact strength. Impact Strength of textile reinforced composites is a measure of the ability of the composites to resist the fracture failure under stress applied at high speed and is directly related to the toughness of the composites. This is one of the ways to measure the relative toughness value of reinforced composites, but it will not reflect the overall toughness value of the composite material. Impact strength is a measure of the impact energy required to fracture a specimen. It is generally accepted that the toughness of a fiber reinforced composite is mainly dependent on the stress–strain behaviour of fiber. Strong fibers with high failure strain impart high work of fracture on the composites. Fibers play an important role in the impact resistance of composites as they interact with the crack formation and act as stress-transferring medium. Next to fiber, another important factor that influences the impact energy is the fiber-matrix interfacial shear strength. It can vary depending on the adhesion between fiber and matrix [15-17].



(a) warp (b) weft

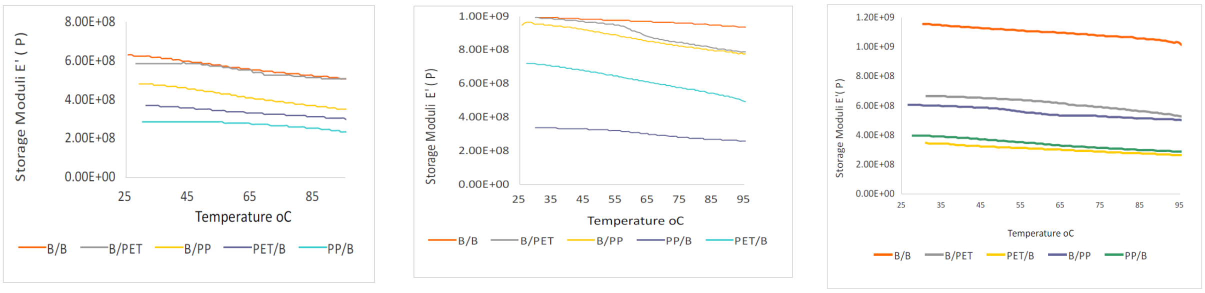
Fig. 5: Impact energy of composites

Unnotched specimens were not broken during Charpy tests. It can be observed from fig. 5, that non-hybrid basalt structures have higher impact strength followed by PP/B structures. The increase in the impact strength with the basalt fibers content can be attributed to the higher energy dissipation at the fiber/matrix interface required to detach the fibers from the matrix. It can be observed that PP yarn decreases the stiffness and rigidity of the composite, thus causing an increase of impact resistance.

Matt weave based structures have highest impact strength in all composites. During an impact situation, radial distribution of forces in all axes is desired, which is more probable in balanced weaves like the matt weave where groups of floats exist in both warp and weft. Containing higher amount of aligned fibers in warp direction, the composite produces higher resistance to impact stress.

Dynamic mechanical properties. The dynamic mechanical properties of the composite materials have been the objective of many investigators. In order to assess the performance of structural applications, the dynamic mechanical properties help in material evaluation with repect to temperature, time and frequency. In designing of the composite materials with desired dynamic properties, storage modulus and damping are the important features. The developed composite samples from Basalt hybrid and non-hybrid fabrics were subjected to a range of temperatures in order to predict and control composite processing behavior. The results are shown in Fig.s 6-7. Fig. 6 shows the *E'* of each sample in the warp direction. It is found that the values of *E'(storage modulus)* have decreased in varying degrees with the increasing temperature, indicating that the visco-elasticity of composite varies significantly from the fabric structures [18].

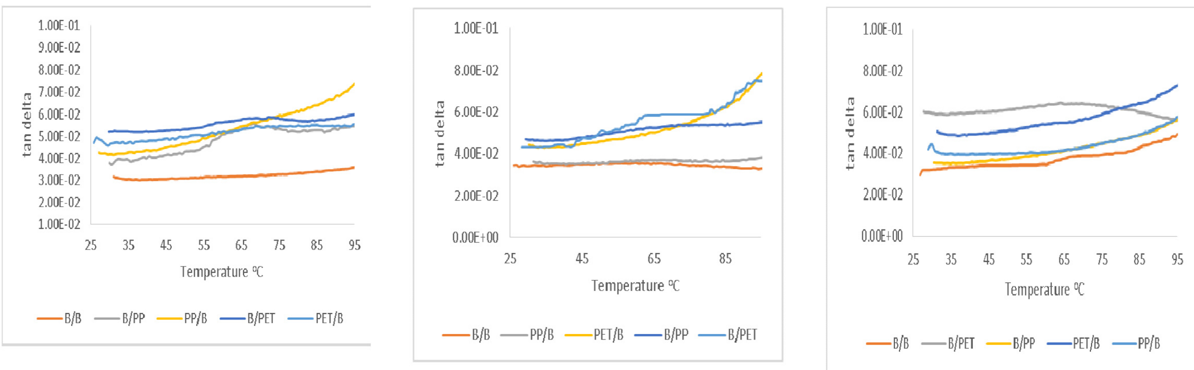
Storage modulus (*E'*) is related to elastic response of material and is the reflection of stiffness. It is related to its load bearing capacity. Since the epoxy resin exhibits temperature dependencies of visco-elastic properties, increased temperature results in the decrease of *E'*. It can be seen that there is a gradual fall in the storage modulus of all composites when the temperature is increased.



(a) Plain weave (b) Matt weave (c) Twill weave

Fig. 6: Storage moduli for composites of all weaves

Storage modulus of basalt fiber epoxy composite is attributed to the strength of fibers and also the fiber morphology, which aided the fiber to matrix adhesion thereby reducing the mobility of the polymer chains. It is clear that Twill structures have better stiffness than other structures at 1 Hz. Higher storage modulus means stiffer material. Storage modulus of the matrix affects the mechanical properties of the composite material. Hence, improvement in storage modulus also gives improvement in mechanical properties of the composite system, specifically the tensile properties. The results for storage modulus explain the highest gain in tensile modulus of the Twill weave based composites. Trends of graphs obtained for storage modulus and tensile modulus are similar.



(a) Plain weave (b) Matt weave (c) Twill weave

Fig. 7: Loss factor of all woven composites

Damping factor is the ratio of the loss modulus (E″) to the storage modulus (E′). It is the ratio of the energy dissipated to the energy stored during a dynamic loading cycle. It is also known as loss factor (tan delta). Material with higher tan delta suggests that more heat was produced and more deformation could not recover when extgernal force was removed i.e., the elastic behavior decreases. In nature, tan delta is the response of internal friction forces. The mechanical damping factor can be utilized to show the impact resistance of the material. When a composite material consisting of fibers (essentially elastic), polymer matrix (viscoelastic) and fiber/matrix interfaces is subjected to deformation, the deformation energy is dissipated mainly in the matrix and at the interface (Mishra, 2014).

If one material has lower tan delta than other, it means better impact resistance and the lower tanδ value is shown in B/B exhibiting a better adhesion between basalt fibers and green epoxy matrix possible as compared to hybrid composites. This can be justified by the restriction of the motion of polymer chains resulting from the incorporation of rigid fibres. B/B have lower value of tan delta, and it indicates that more deformation for B/B composites could recover when external force is removed. 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.

Thermogravimetric analysis. Thermogravimetric/Differential thermogravimetric (TG/ DTG) analysis and differential heat flow (DHF) were performed to study the thermal properties of hybrid and non-hybrid composites.

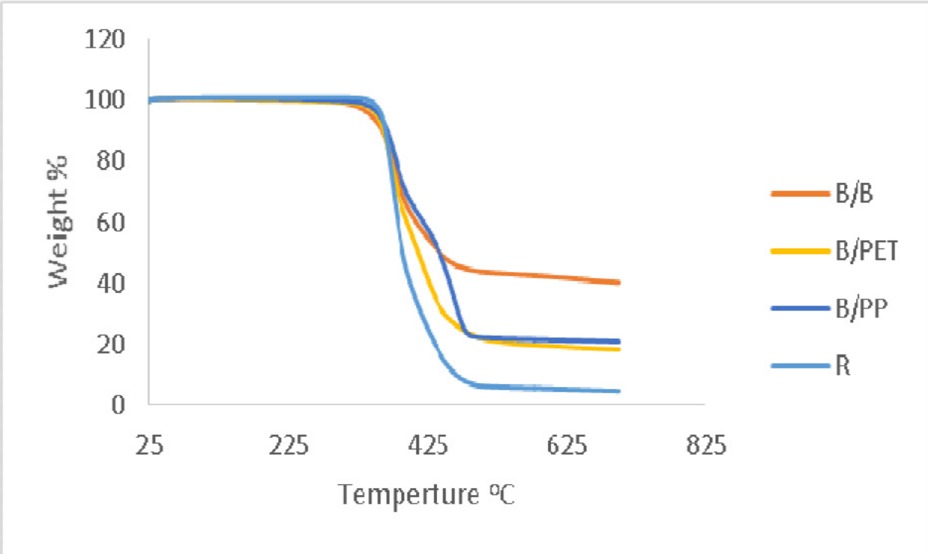


Fig. 8: TGA of composites

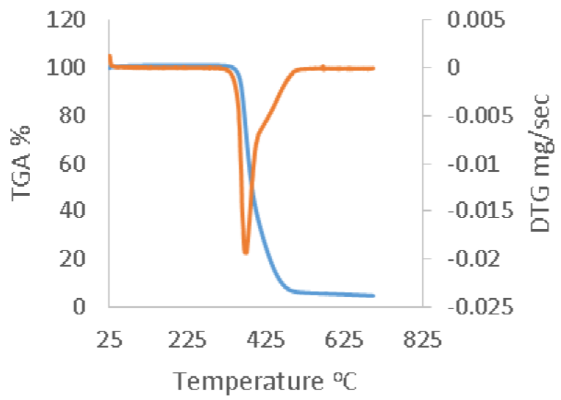
TGA is a useful technique for studying thermal behavior of composite materials. Thermal stability of the polymer and reinforcing materials is an important parameter because manufacturing of composites in most cases requires curing; therefore the degradation behavior of the reinforcing fibers helps in selecting the processing temperature and also the working temperature of the developed composite materials. The derivative results of TGA can be plotted to view clear picture of those events which occur at very close interval with each other. The point of greatest rate of change on mass loss in TGA curves i.e. the inflection point is indicated by peak on DTG curve that helps in getting identification of events easier and extraction of data becomes easier as well.

It can be seen from Fig. 8 that no degradation takes place until 325ºC. The Thermogram of the neat green epoxy resin shows a gradual weight loss with increasing temperature which started around 320ºC. From DTG thermogram it is observed that a broad single peak starts around 330ºC with a maximum degradation at 375ºC. The curves presented in Fig. 8 indicate the existence of only one main mass-loss region, always located between 330ºC and 375ºC. This region can be attributed to the thermal decomposition of the polymer matrix. From the thermograms TGA, it can be observed that, in fiber reinforced composites, two stage degradations occur: one stage is responsible for epoxy and other stage is for fiber. It can be viewed that B/B and B/PET composites degradation starts around 363ºC and for B/PP at 330ºC. The slightly lower onset of degradation is attributed to the decomposition of the fibers in the fabric microstructure.

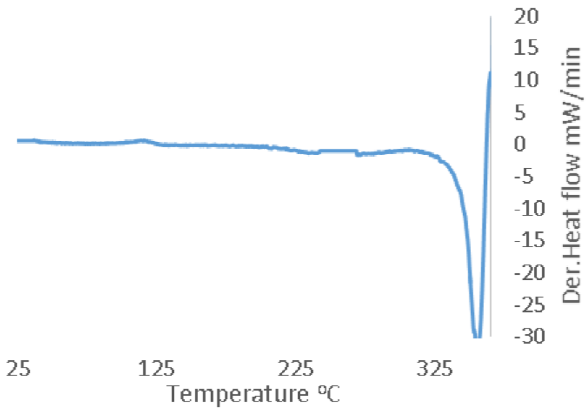
Fig. 9 shows different thermograms from DTG where it is observed that, B/PP decomposition is a two-stage process characterized by a first step in the temperature range 330ºC–380ºC which may be attributed to degradation of resin, followed by second weight loss at 478ºC and almost completely depleted. PP has branch points on alternative carbon atoms. The availability of reactive tertiary H atoms initiates its thermal degradation. Polypropylene is liable to chain degradation from exposure to heat. Oxidation usually occurs at the tertiary carbon atom present in every repeat unit. A free radical is formed here, and then reacts further with oxygen, followed by chain scission to yield aldehydes and carboxylic acids. Melting temperature of PP is around 168ºC, which is observed by the peak of DHF.

It can be noticed from Fig. 8 that the polyester degradation follows a two-step reaction scheme characterized by a first step in the temperature range of 340ºC–370ºC followed by a second decomposition step located in the range 410ºC–600ºC. This behavior is determined by random scission of the polyester backbone (ester linkage) and to the oxidation and the breakage of the secondary bonds. Melting temperature of PET is around 258ºC, which is observed by DHF in DSC.

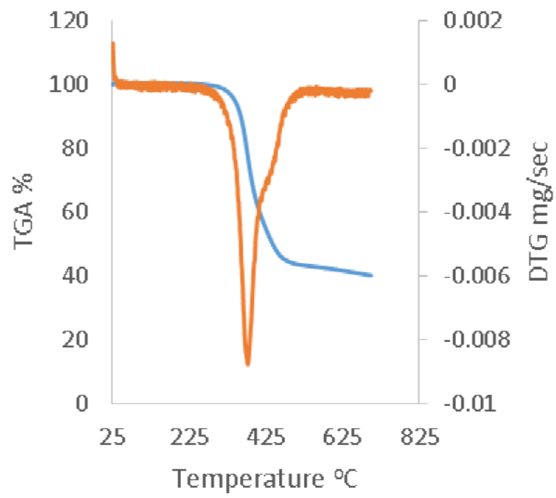
The thermal analysis has illustrated that hybrid composites are stable until 325 ºC. From the thermogram TGA, it can be viewed that the maximum degradation temperature T_{max} has significantly improved for B/PET fabrics and the thermal stability of the composites have been improved, which justifies the development of strong fiber-matrix interface in basalt hybrid woven composites.



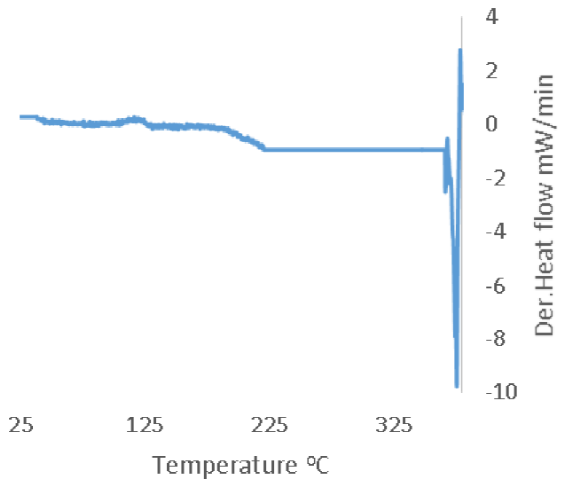
(a) Resin TGA & DTG



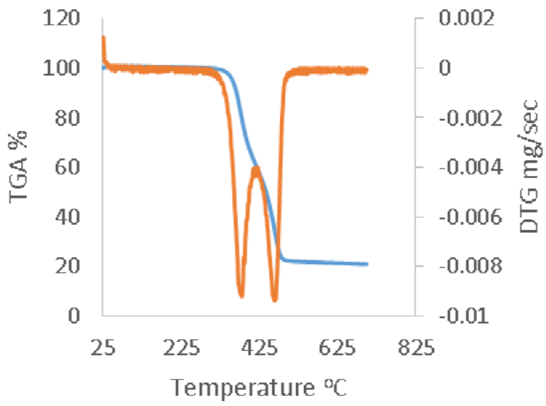
(b) Resin DHF



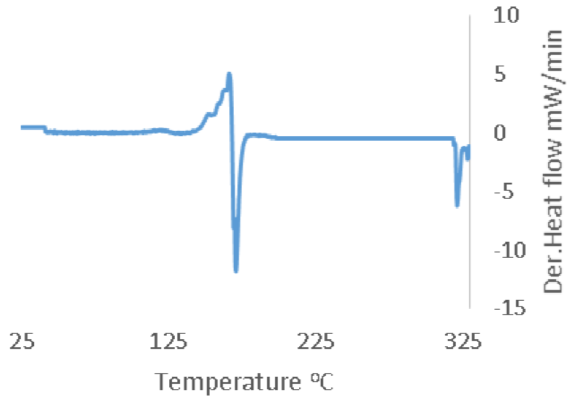
(c) B/B TGA & DTG



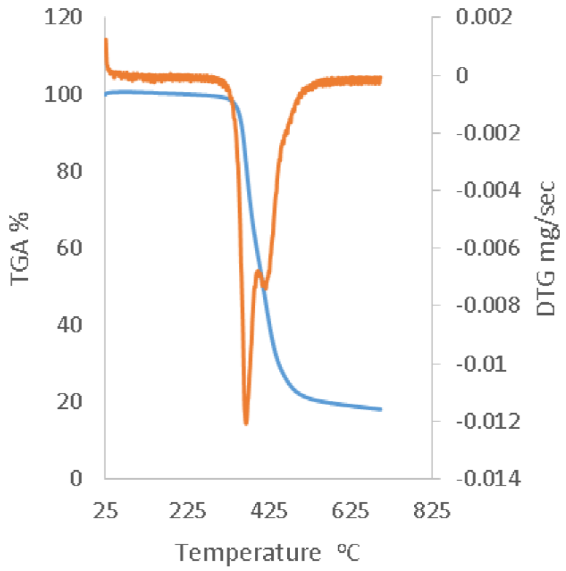
(d) B/B DHF



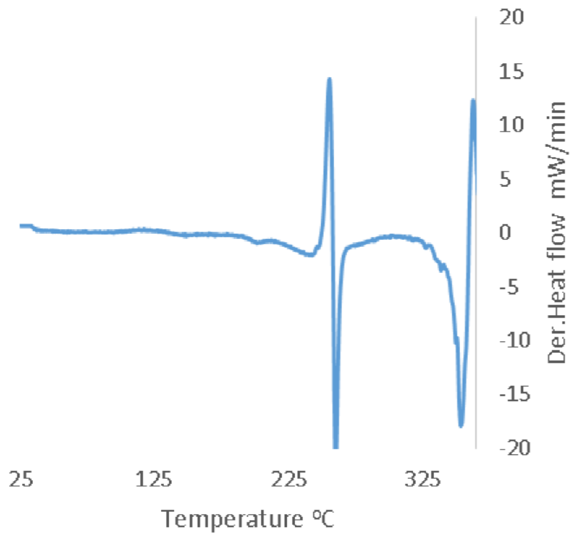
(e) B/PP TGA & DTG



(f) B/PP DHF



(g) B/PET TGA & DTG



(h) B/PET DHF

Fig. 9: TGA, DTG and DHF of specimens

Morphology/interfacial properties of composites. To find out the fiber matrix adhesion inside the composites, SEM studies were carried out. SEM images of the tensile fractured surfaces of the composites are presented in Fig. 10. It is clearly indicated for PP and PET based composites that fiber-matrix interface is not so strong and the bonding between fiber and matrix is not good. Small gaps are evident in the matrix near to the fibers However, for Basalt based composites, the interface suggested better fiber matrix adhesion which is supported by the SEM images. The data presented above for the mechanical properties of composites, also supported the SEM observation.

It shows excellent interfacial strength, which means that fracture occurs rather in the body of the matrix and not at the interface. Even though photography image shows less adhesion between fiber and matrix, microscopy image could not find any fiber slippage in damaged samples. It confirms that the interface bonding of fiber and matrix are good for basalt pure and hybrid fabric composites.

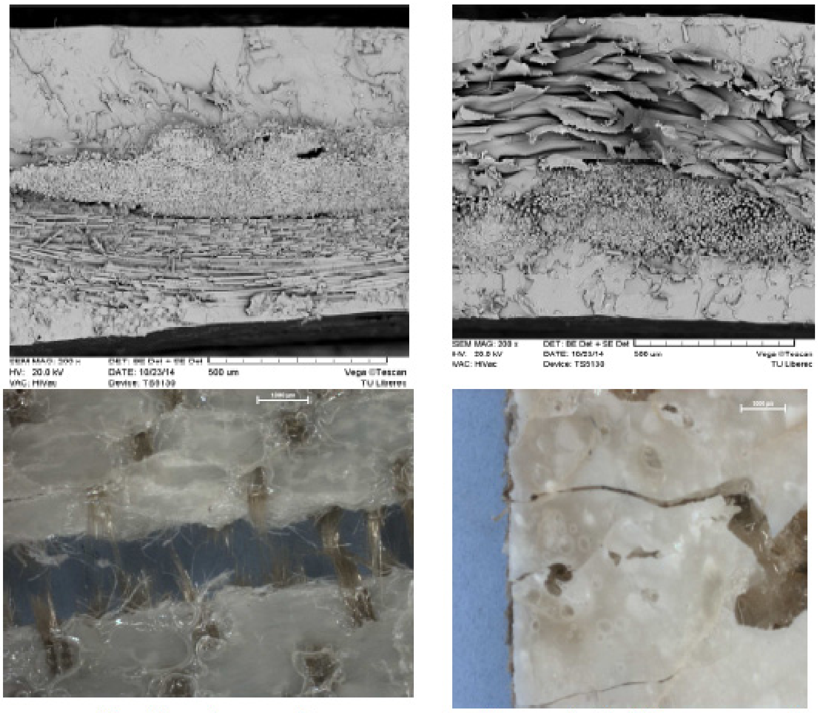


Fig. 10: SEM and macroscopic images

Conclusions

In the present work, the effect of weave and hybridization of basalt fiber on the mechanical and thermal behavior of woven fabric/green epoxy composites was investigated. Tensile, flexural and impact properties of composites were enhanced. It can be seen that 1/3 twill fabric composites have higher tensile and flexural moduli. Use of PET in weft direction increases tensile strength for all weaves. Use of PP in weft direction increases impact properties. Structure of weave, fiber type and resin properties have strong influence on mechanical properties of composites of basalt hybrid fabrics. It is concluded that, fiber type has strong influence on thermal properties of composites. The thermal conductivity of the composite depends on thermal conductivity of fiber and epoxy resin which is used for the matrix. The concept of hybrid polymer composites from basalt and synthetic fibers thus seems to be having promising application areas.

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