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Basalt hybrid woven textile materials for advanced thermal applications

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The thermal properties of hybrid basalt-polypropylene (B/PP), basalt-polyester (B/PET) and basalt-jute (B/J) as well as non-hybrid structures have been studied. The fabric structures have been developed as plain weave (PW) for B/PP, B/PET & B/J; matt weave (MW) for B/PP, B/PET & B/ J; and 1/3 twill weave (TW) for basalt-PP, basalt-PET, and basalt–Jute along with the non-hybrid fabrics. The thermal properties of the fabrics, such as thermal conductivity and thermal resistance are studied along with the physiological behavior. Thermal properties are measured by Alambeta and TCi. Correlation between theoretical and experimental measurement of thermal conductivity are also studied. Air permeability is tested by air permeability tester. Based on the results, the influence of fabric structure on specific thermal insulation parameters are analyzed. The findings show that there is a significant impact on thermal properties of basalt hybrid woven structures by geometrical parameters of weave. Structure and fibre type have strong influence on thermal properties. Twill weave structures show higher air permeability and thermal resistance in all combinations.

Keywords: Basalt yarn, Hybrid structures, Industrial textiles, Thermal applications, Woven fabric

1 Introduction

A textile material is composed of fibres with entrapped air, which shows that the thermal conductivity of fabric is a combination of air thermal conductivity and fibre polymer. It is based on the thermal conductivity of fibres/yarns and on the fabric structure, that is interlacements. Morton and Hearle [6] observed that thermal conductivity of fabric depends majorly on the trapped air inside the pores in comparison to fibre conductivity, as thermal conductivity of air is about 0.025 Wm-1K-1 which is much lower than that of the fibre forming polymers[1-5, 7]. In addition, the immobilized air inside the structure of fabric can influence the thermal behavior of fabric significantly, as it behaves as an insulating medium in the absence of convection. Materials with low thermal conductivity are used as thermal insulator. Thermal conductivity of textile fibres generally depends on their chemical composition, porosity and moisture content.

Basalt, being an ecologically pure substance, has a wide spectrum of applications. Basalt fibres are non-hazardous as compared to the conventional asbestos/glass fibres. They are spun with a diameter higher than 6 μm. Basalt fibres also have heat insulating capability three times higher than that of asbestos. Abrasion of the only basalt produces thick fibre fragments that pose no respiratory hazard. Basalt fibre is non-reactive towards water and does not cause air pollution. They are ecofriendly, non-toxic, and green. They have been tested and proven to be non-carcinogenic and non-toxic. Basalt fibre can be classified as a sustainable material. This is because basalt fibres are made of natural material and during their production no chemical additives as well as solvents, pigments or other hazardous materials are added. Basalt fibres are environmental friendly and recycling of basalt is much more efficient than glass fibres. Basalt fibres & fabrics are labeled as safe according to both the USA (Protective clothing for mine workers, US Mines Authority, 2007) and the European occupational safety (Safety regulation norms for industrial workers EU-2009).

Thermal properties are very important for adequate manufacturing process of the composites. However, the study on the effect on thermal properties by the fabric structures, especially the hybrid woven, is scanty. Basalt hybrid woven fabrics can be used as possible reinforcing materials in polymer matrix composites as a replacement of glass fibre for their use in several applications. In some applications of

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composites where thermal capacity or insulation character of materials needs to be considered, they can be used. The thermal behavior of fabrics, made of two materials with different thermal properties is important especially when used in composites for applications like thermal protection, heat guides, heat shields, composite boards, etc.

The present study was therefore aimed at measuring the thermal conductivity/resistance as a function of material (fibre type) and construction parameters (porosity or packing density). In present study, thermal properties of hybrid basalt and the non-hybrid structures are studied .The thermal conductivity measurement is performed by the Alambeta apparatus and TCi. (C-Therm thermal conductivity analyzer). The concepts of methods are different. In the thermal conductivity analyzer (C-Therm TCi), an interfacial test method is employed which illustrates that the heat produced on sensor is detected by the sensor. In the hot plate method used in Alambeta, the heat generated on sensor is required to penetrate through sample and detection is done at the other side [2,8]. Air permeability is also measured to relate with thermal conductivity and thermal resistance.

2 Materials and Methods

2.1 Materials

The commercially available jute (J) and polyester (PET) yarns were used in this study. Polypropylene (PP) yarn was procured from Synthetic (Pakistan). The basalt(B) yarn was received from Kamenny Vek (KV) (Russia).

2.2 Methods

The idea for using these different polymeric fibres in the weft/warp along with basalt warp/weft is to create hybrid woven structures. The set of basalt hybrid and non-hybrid woven fabrics (total of 27 samples) with plain, matt and twill weave is used as experimental material. Thermo physiological properties of fabrics were studied using combination of basalt in warp and polypropylene, jute and basalt yarns in weft and vice versa. The structures in plain weave of hybrid B-PP, B-PET & B-Jute; matt weave of B-PP, B-PET & B-jute; and 1/3 twill weave of B-PP, B-PET & B–jute along with the non-hybrid fabrics were developed. The fabric samples were developed on the CCI Rapier sample loom (CCI Tech Inc.) with the same thread density (number of yarns per cm) , 12 threads/ cm in warp and 8 threads/ cm in weft **.**

All the samples were tested for the basic structural parameters, such as the real warp and weft thread density, mass per square meter, and fabric thickness, according to standardized procedures. All the samples were conditioned in standard atmospheric temperature of about 20° ± 2°C and relative humidity of 65 ± 2% for 24 h before subjecting to testing .The fabric thickness was obtained according to standard ASTM-D1777 method. Measurements were done at different positions; the probe with a disc delivered a pressure of 1 kPa over an area of 1000 mm^2, then the thickness was obtained in mm. Ten readings were obtained and an average was statistically computed.

The air permeability of the samples was analyzed by using FX 3300 air permeability tester 111 according to standard ISO 9237(1995) procedure. The measurement was performed at a constant drop of 200 Pa(20 cm^2 test area) in the standard atmosphere[9] .

Thermal insulation properties of the fabrics were measured by means of Alambeta according to ISO EN31092 standard. This method belongs to the ‘plate methods’, the acting principle of which relies on the convection of heat emitted by the hot upper plate in one direction through the sample being examined to the cold bottom plate adjoined to the sample. The instrument directly measures the stationary heat flow density (by measuring the electric power at the known area of the plates), the temperature difference between the upper and bottom fabric surface, and the fabric thickness. The device calculates the real thermal resistance for all fabric dimensions [10].

Measurement of thermal properties of fabrics was 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. A spiral-type heating source is located at the center of the sensor, and heat is generated at the center. The heat that has been generated enters the material through the sensor, due to which a voltage decrease occurs rapidly at the heating source, and the thermal conductivity is calculated through the voltage decrease data. The thermal properties of the sample material are inversely proportional to the rate of increase in the sensor voltage. The thermal conductivity was calculated through the voltage drop data [1,8]. The tests of thermal properties were repeated five times and that of air permeability were repeated 10 times. The mean and SD of data were calculated for all tests.

The parameters often used for describing porosity and its influence on permeability are the number of pores, diameter, volume and distribution of pores. Fractional porosity was calculated from physical densities of fabrics and fibres. The fractional porosity (P=volume porosity) was calculated by the following formula:

$$P = 1 - \frac{W}{t(thickness)\,\rho_{fiber}} = 1 - \frac{\left(D_{weft}T_{weft} + D_{warp}T_{warp}\right)}{\left(d_{weft} + d_{warp}\right)\rho_{fiber}} \quad ...(2)$$

where W is the areal density of fabric (kg/m^2); t, the thickness of fabric (m); D_{warp} and D_{weft}, the sett of warp and weft respectively (m^{-1}); T_{warp} and T_{weft}, the fineness of warp and weft yarns respectively (tex); and d_{warp} and d_{weft}, the diameters of warp and weft yarns respectively (m).

The average density of a hybrid composition was calculated, based on the ratio of the component fibres. The inter-yarn, inter and intra-fibre spaces in fabrics contribute to the total porosity in woven structures. Inter-yarn porosity (macro porosity) is more important but if fabrics are made of different fibres, inter- fibre space (micro porosity) also plays a major role [11] .

Volume porosity can be calculated from fabric and fibre densities respectively, but the weaves influence the shape and dimension of pores. The weave determines the interlacement pattern which ultimately affects the nature of pores and fabric volume porosity [12] classified the pore structure into four basic categories as shown in Fig. 1, assuming that the planes are perpendicular to the fabric surface and the bisection of any two adjacent warp and filling yarns are used to form a unit cell. For Type 1, the four yarns of a unit cell alternate from top to bottom surface of the cloth and vice versa. One warp and one filling alternate for Type 2. No alteration of yarns is visible for Type 3. For Type 4, either two warp yarns or two filling yarns alternate from top to bottom surface and vice versa [13] .

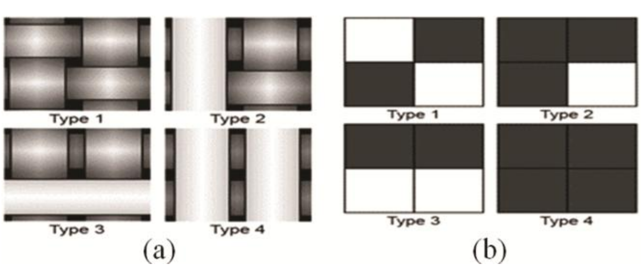

Fig. 1 — Four types of pores in woven fabric (a) planar way and (b) on the graph paper

At least two or three types of pores will be there in most of fabric constructions. The fabrics having the plain weave construction consist entirely of Type 1 pore structure. Pore volume and shape of two fabrics woven with identical yarn diameter and yarn spacing will vary depending on the manner of interlacing of the threads. The pore walls are not flat and their cross-section changes with the fabric thickness with respect to the type of pores, type of yarns and their characteristics [14, 15].

3 Results and Discussion

The results of the air permeability and thermal properties with both types of instruments are presented in Table 1.

3.1 Air Permeability

Figure 2 shows the air permeability of both non-hybrid and hybrid structure. In non hybrid structure [Fig. 2(a)], B/B has highest value of air permeability, because of open structure resulting from smaller yarn diameter due to higher density of fibres. 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.

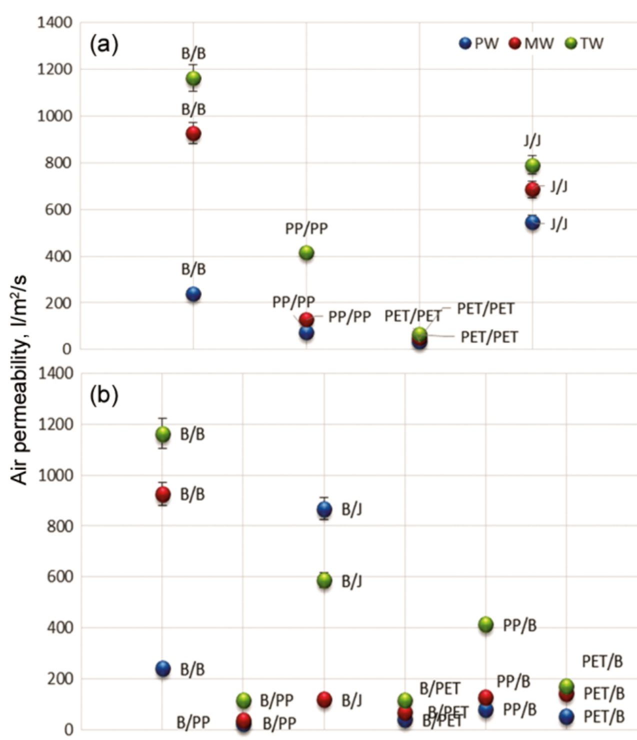

Fig. 2 — Air permeability of (a) non hybrid and (b) hybrid woven fabrics

Table 1— Thermal and transmission properties of hybrid and non-hybrid fabrics

Fabric code	Structure	Air permeability $l/m^2/s$	Thermal conductivity, W/mK		Thermal resistance, km^2/W	
			Alambeta	TCi	Alambeta	TCi
S1	B/B PW	208.00	0.079	0.101	0.004	0.003
S2	B/B BW	851.13	0.075	0.088	0.011	0.009
S3	B/B TW	878.89	0.073	0.086	0.012	0.010
S4	PP/PP PW	74.76	0.067	0.065	0.023	0.024
S5	PP/PP BW	128.00	0.061	0.059	0.036	0.037
S6	PP/PP TW	414.22	0.057	0.059	0.042	0.041
S7	PET/PET PW	34.59	0.064	0.060	0.030	0.032
S8	PET/PET BW	49.36	0.063	0.057	0.033	0.036
S9	PET/PET/TW	64.94	0.061	0.057	0.036	0.038
S10	Jute/Jute PW	546.44	0.059	0.058	0.036	0.037
S11	Jute/Jute BW	685.44	0.057	0.057	0.040	0.040
S12	Jute/Jute TW	789.80	0.055	0.057	0.044	0.043
S13	B/PP PW	57.99	0.084	0.095	0.008	0.007
S14	B/PP BW	89.82	0.077	0.088	0.015	0.013
S15	B/PP TW	118.13	0.069	0.084	0.017	0.014
S16	B/PET PW	40.53	0.078	0.075	0.011	0.011
S17	B/PET BW	69.84	0.073	0.073	0.025	0.025
S18	B/PET TW	116.00	0.066	0.069	0.028	0.027
S19	B/Jute PW	867.22	0.068	0.072	0.015	0.014
S20	B/Jute BW	320.80	0.069	0.067	0.028	0.029
S21	B/Jute TW	586.00	0.056	0.066	0.036	0.031
S22	PP/B PW	82.28	0.068	0.068	0.019	0.019
S23	PP/B BW	128.00	0.066	0.067	0.022	0.021
S24	PP/B TW	414.22	0.062	0.066	0.025	0.023
S25	PET/B PW	54.22	0.076	0.064	0.018	0.022
S26	PET/B BW	145.75	0.073	0.064	0.021	0.024
S27	PET/B TW	172.55	0.073	0.058	0.027	0.034

In non- hybrid fabrics, the bigger differences observed between the air permeability values of plain and twill fabrics are due to differences in their characteristics. For equivalent weaving parameters, twill fabric has a lower fabric density and thus higher porosity, resulting in a looser construction because of lower number of yarn intersections as compared to the plain fabrics. The twill fabrics exhibit much more air permeability as compared to plain fabrics.

Among most hybrid woven structures, fabrics woven with 1/3 twill weave show highest air permeability with the exception of B/J twill fabric due to the higher cohesiveness of yarns resulting from surface hairiness. Twill weave has lower number of cross over points and longer yarn floats as compared to other weaves. It is noticeable that majority of air flow, due to nature of air, takes place between gaps of weft and warp yarns as air follows the easiest path for flow.

In B/J fabrics, plain weave has highest permeability due to highest fractional porosity % , this porosity is attributed to jute which is a staple yarn. It has more irregularities in fibre structure as well as yarn structure leading to higher inter–fibre and inter-yarn porosity. Twill has higher value of air permeability compared to matt weave due to less interlacement and more number of pores in its weave structure.

Among all hybrid woven structures, highest air permeability is observed in B/J structures due to higher porosity in jute yarn, while in other structures (B/PP, PP/B, B/PET and PET/B) lower air permeability is observed because of compact filamant yarns which leads to lower yarn diameter . The PP yarn is relatively bulkier among the filament yarns which provides fabric with better cover and less air permeability, which is also investigated by Kullman *et al.*[16].

It is evident from the analysis that twill fabrics have nearly 5- 25% higher value of air permeability compared to plain structures for the same sett (thread density) of the woven fabrics. As the pores in plain weave (pore type No.1) are the least influenced by denting, the fabric results in lowest value of air permeability. The highest number of interlacements between warp and weft results in most stable structure, leading to prevention of gapping in yarns.

Matt weaves have equal yarn floats on both sides of fabric which helps in grouping of yarns and ultimately results in moderate size of pores. Twill weaves have a lower number of interlacing points and longer yarn floats, which tend to group together resulting in a bigger size pore between groups of adhering yarn floats and consequently in a higher air permeability.

3.2 Thermal Properties

In general, thermal properties of textiles including thermal conductivity and thermal resistance are influenced by fabric structure and density, properties of fibres, surface treatments, air permeability, temperature and humidity. In all structures developed, the fabric density has significant effect on thermal conductivity. It is also observed that as the fabric density increases, the thermal conductivity also increases.

3.3 Theoretical Calculation of Thermal Conductivity

The fabric structure consists of the air spaces and binding points. If the fabric porosity is known, thermal conductivity of all fibres and air can be calculated to obtain the thermal conductivity of fabric. The calculation of thermal conductivity has been done on the basis of two phase model of porous systems [17].

The thermal conductivity of parallel arrangement λ_{hP} (higher limit) is:

$$\lambda_{hP} = P\ \lambda_a + (1-P)\ \lambda_f \quad \ldots (3)$$

For serial arrangements, thermal conductivity λ_{hS} (lower limit) is:

$$\lambda_{hs} = \frac{\lambda_a\ \lambda_f}{P\ \lambda_f + (1-P)\ \lambda_a} \quad \ldots (4)$$

The presentation of actual composition of fibres and air phases can be presented by linear combination of parallel and series structures. The average conductivity λ_h is calculated for fibrous structure which is arithmetic mean between upper and lower limit, as shown below:

$$\lambda_h = \frac{\lambda_{hP} + \lambda_{hS}}{2} \quad \ldots (5)$$

where λ is the thermal conductivity, and P, the porosity.

Among all the woven structures (Fig. 3), plain weave has highest thermal conductivity due to maximum interlacement and 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 [5, 6], the thermal conductivity values of the plain fabrics are higher than the corresponding values of the twill fabrics. Among all structures investigated, thermal conductivity of 100 % basalt fabric is highest followed by structures having PP and PET yarns. Although basalt fibre has low value of thermal conductivity but in case of its fibrous structures (yarns and woven fabrics) the 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 PP has higher packing density and thus higher thermal conductivity. Thermal conductivity of hybrid structures are found to increase by adding basalt yarn due to the reason mentioned above.

The parallel/series structure, due to its simple nature, provides a first-hand prediction and gives reasonable prediction accuracy for practical application as shown in Figs 3 and 4. 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.

3.4 Correlation of Results obtained by TCI and Alambeta

Thermal resistance(R) is the opposition to flow of heat energy. Thermal resistance is defined as the difference of the temperature across a unit area of the material of unit thickness (t) when a unit of heat energy flows through it in a unit of time:

$$R = t/\lambda \quad \ldots (6)$$

Thermal resistance is directly proportional to the thickness (t) and inversely proportional to the thermal conductivity (λ). The thermal resistance and conductivity results from TCi and Alambeta instrument are correlated. Figure 5 expresses the correlation of the two instruments for thermal resistance. The thermal resistance of both the instruments are correlated well with the value of around R^2 =0.95. A relationship between theoretical calculations and actual measurements of thermal resistance by Almabeta and TCi is shown in Figs 6(a)and (b). It has given reasonable prediction accuracy for practical applications.

The relationship between porosity and thermal resistance is shown in Fig. 7. Correlation between measurements of Alambeta and TCi with porosity is

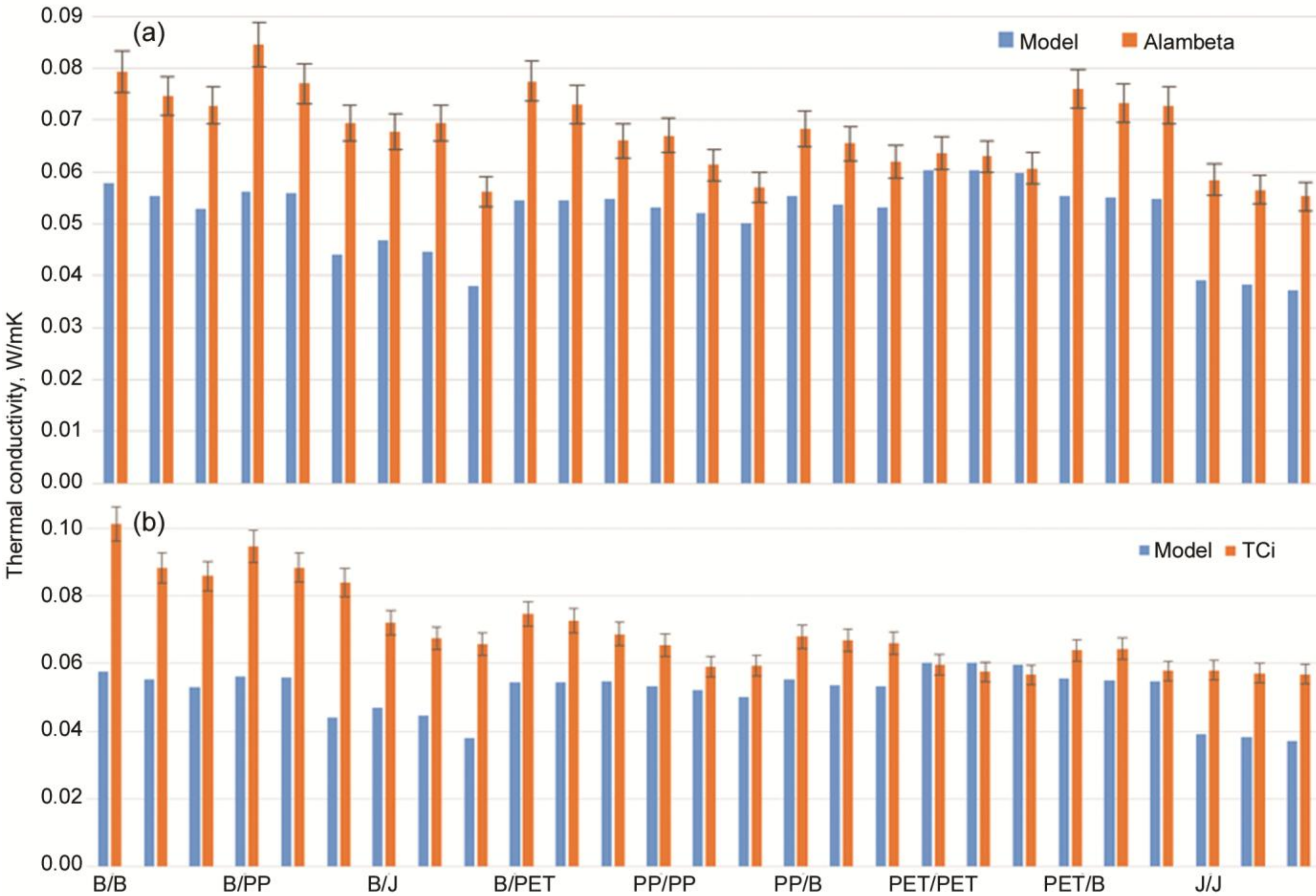

Fig. 3 — Theoretical model and measured thermal conductivity by (a)Alambeta and (b) TCi

significant. Among all structures, jute based fabrics have highest thermal resistance values because of interfibre micro pores and inter yarn (macro porosity). Jute fibre has empty lumens in the cells; this hollow nature may increase intra fibre porosity. Also natural fibres have smaller diameter, thus the no. of fibres increases for same linear density of yarn which increases the total volume of air pockets within the yarn and fabric structure. Secondly, as it is a staple yarn, it has prominent hairiness on the surface and hence increases content of air pores in the fabric. Physical clogging of air will result in an increase in thermal insulation. With the addition of basalt fibre, thermal resistance of hybrid fabrics decreases. In all hybrid structures using basalt in warp, B/J has highest thermal resistance due to the reason explained above. There is a similarity in results when an increase of jute % happens in knitted structure[7] . A prominent and higher number of hairiness results in more physical clogging of air which leads to increased thermal insulation. B/PET has second high value of thermal resistance as polyester yarn is more bulky and has less twist. Therefore, it has higher thermal resistance value than PP. In 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. Twill weaves contain less points of interlacement and longer float lengths, which tend to group together. There is lower yarn crimp, so more bulky structure leading to clogging of higher volume of air. The overall thickness of fabric is also higher for twill fabric consequently giving higher thermal resistance. Matt weaves have two equal floats in both warp and weft directions of fabric which help in yarn grouping, resulting in moderate size of pores. In matt structure, due to floating of yarn in both directions, clogging of pores occurrs. 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 are compact in structure due to highest number of interlacement

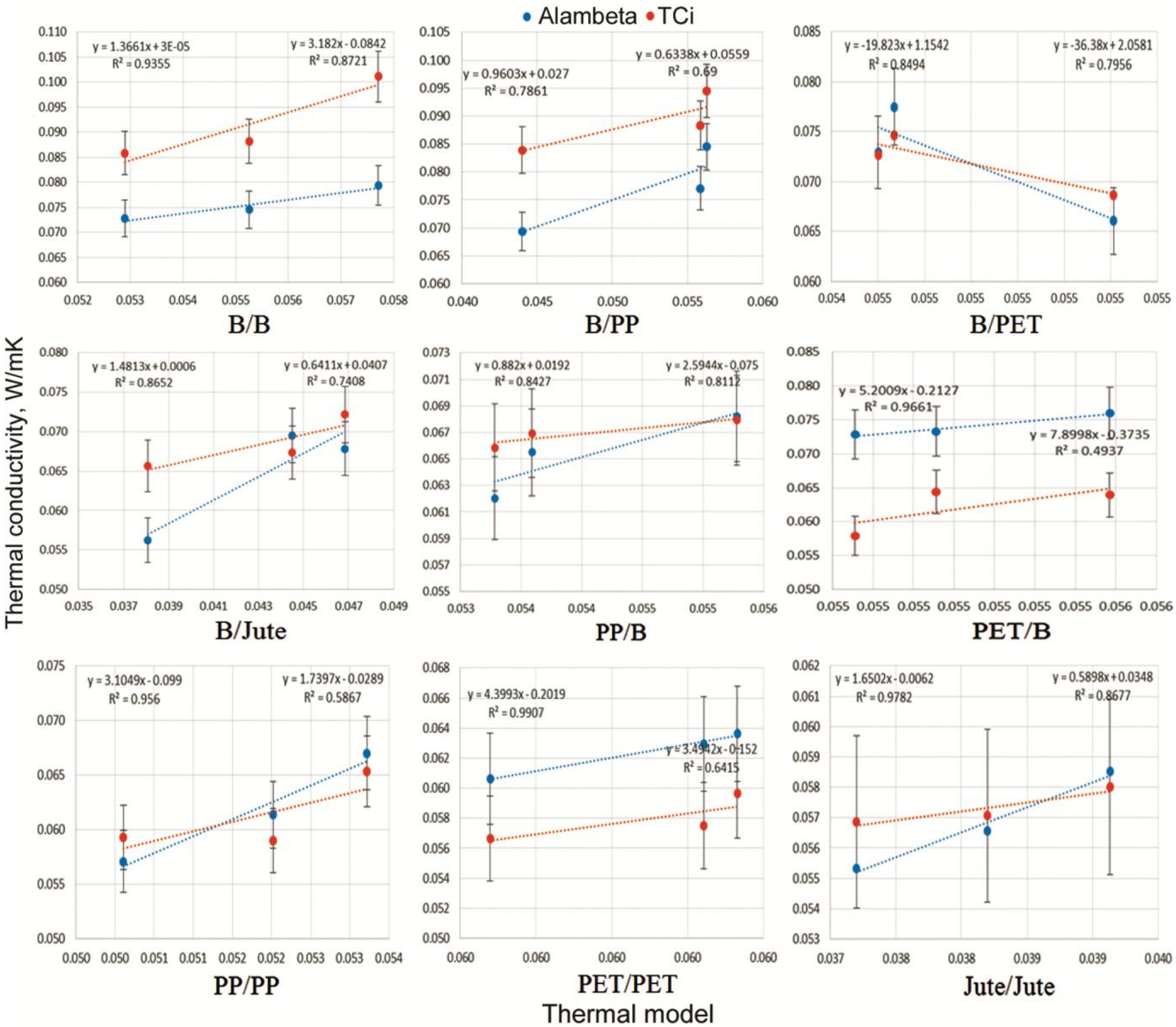

Fig. 4 — Correlation of thermal conductivity from Alambeta, TCi and theoretical model

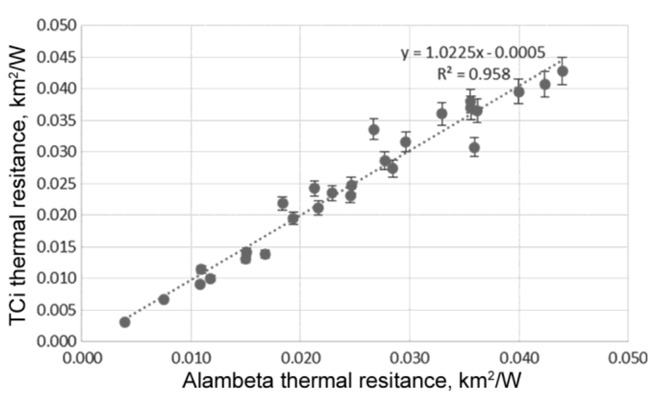

Fig. 5 — Correlation of thermal resistance from TCi and Alambeta

points among warp and weft and it is helpful in prevention of yarn from grouping. It is described by many research workers that thermal resistance of fabric is dependent on its thickness. They have done measurement of conductivity by application of different level of pressures. In case of fabrics made with same fibres, the thermal resistance is directly proportional and dependent upon fabric thickness. The fabrics investigated are characterized on the basis of fibre composition and weave in different thicknesses. The thermal resistance is also strongly correlated with thickness in the present study.

As it is obvious from one axis of graph, thickness has a direct relation with thermal resistance. As

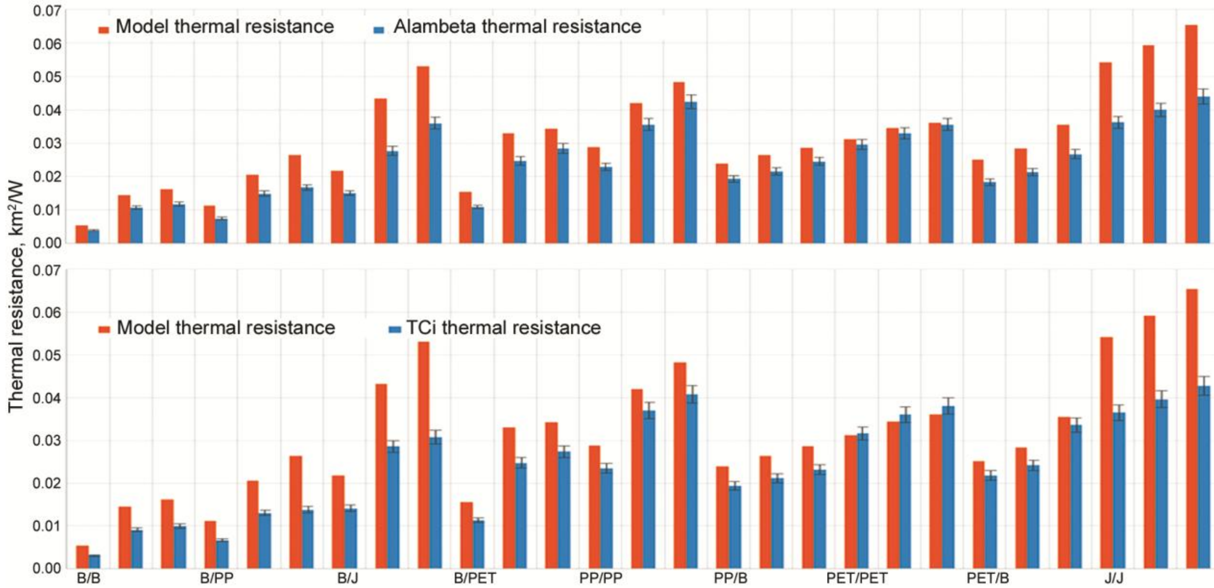

Fig. 6 — Thermal resistance from theoretical model and measured values by (a) Alambeta and (b) TCi

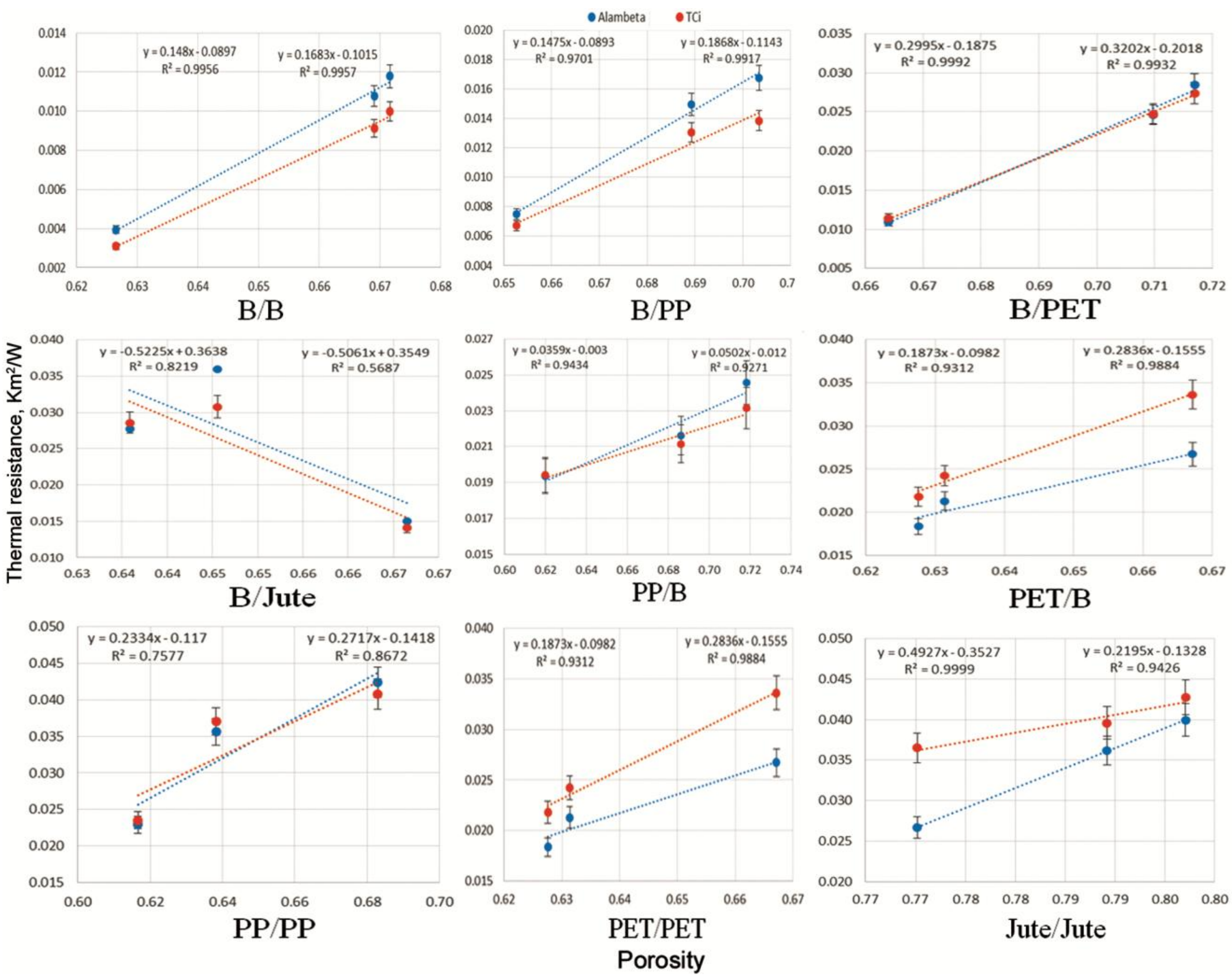

Fig. 7 — Correlation of thermal resistance from Alambeta and TCi *vs* porosity

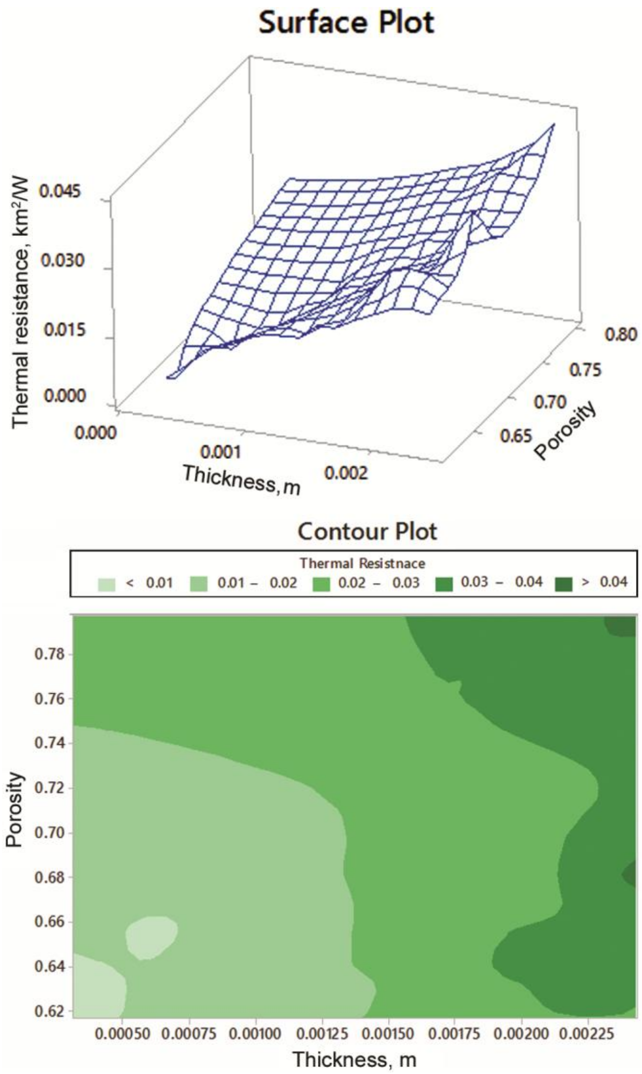

Fig. 8 — Dependence of thermal resistance on thickness and porosity

thickness and porosity increase, the thermal resistance also increases. For the thermal resistance, the 3D surface plot in Fig. 8 shows that the highest thermal resistance values are 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 are found near an average thickness of 0.0025 m and average porosity of 0.80.

4 Conclusion

The results reveal that the impact of hybridization of basalt with polyester, jute and polypropylene in different weave combinations lead to significantly improved thermo physiological characteristics. There is strong influence of structural parameters on thermal properties. Structure of weave and fibre type has strong influence on conductivity. Plain weave has highest thermal conductivity and lowest thermal resistance values in all structures. Twill weave has high air permeability and thermal resistance values overall. Thermal conductivity of other structures can be improved by adding basalt fibre for application as heat sinks. Thermal resistance of basalt structures can be improved by adding other fibre especially jute fibre for application as thermal insulation. The hybridization with Jute and PET significantly increases the thermal resistance. It is evident that measured values of different methods are different yet they have a high correlation.

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