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Knitted Spacer Fabrics for Multi-Functional Applications

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SUMMARY OF THE THESIS

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Abstract

The objective of this thesis was to examine multi-functional properties of both warp and weft knitted 3-dimensional spacer fabrics which could be used to replace the existing cushion materials in the mattress, pillows, in-sole, car seat and back supports. It presents an experimental and analytical investigation on intra-ply shear properties of 3D knitted spacer fabrics conducted using picture frame shear fixture. The nonlinear behavior of shear stress versus shear angle and the deformation mechanism were analyzed. The curves for shear stress versus shear angle and position of buckling for in-plane shear test are recorded by considering two different frame lengths in order to compare with each other. Load–displacement curves of inter-ply shear tests are also analyzed. In addition to this, a program was developed in MATLAB using Hough transform to analyze the shear angle in the real-time image taken during displacement of specimen at various positions. The results of image analysis were compared with the actual experimental results. Also, the shear stress was predicted using finite element model and compared with experimental results.

This study also determines the influence of different structural characteristics of knitted a spacer fabric on the compressive behavior and energy absorption capability. The potential compression mechanism of the fabric was identified with support of the compression stress-strain curve, work done and efficiency at different compression stages. Third order polynomial regression model was used to establish the elastic deformation properties used to obtain the compression results.
Spacer textile fabrics have superior thermal and acoustic characteristics compared to conventional woven/knitted structures, foams or nonwovens due to their wonderful 3D sandwich pattern and porous nature. Hence this research work also investigates the influence of different structural parameters of spacer fabrics e.g. areal density, porosity, thickness, stitch density etc. on thermo-physiological and acoustic performance. The sound absorption coefficient (SAC) was evaluated using two microphone impedance tube. Moreover, tortuosity of the spacer fabrics was calculated analytically and compared with experimental results. This study also discusses the influence of material parameters and structural characteristics on acoustic properties of 3D spacer knitted fabrics.

Advanced statistical evaluation and two-way analysis of variance are used to analyze the significance of various factors such as thickness, type of spacer yarn, surface structures and raw materials on specific properties. These findings are important requirements for designing knitted spacer fabrics which could be used as suitable cushioning material in the applications such as car mattress, seats, shoe insole, pillows, back supports etc.

Keywords: - 3D Spacer fabrics; in-plane shear; compression stress; energy absorption; efficiency; thermo-physiology; sound absorption

Abstrakt

Cílem této práce bylo prověřit multifunkční vlastnosti osnov a útků 3D distančních pletených textilií, které by mohly být použity jako náhrada existujících vycpávkových materiálů v matracích, polštářích, vložkách do bot, autosedačkách a podpěrách zad. To představuje experimentální a analytické šetření vlastností na vnitřních vrstvách 3D distančních textilií smykem prováděných pomocí upnutí ve fixačním rámečku (The Picture-frame shear test). Bylo analyzováno nelineární chování smykového napětí oproti úhlu smyku a deformačnímu mechanismu. Křivky smykového napětí vůči úhlu smyku a pozici vzpěry pro zkoušku smyku v rovině jsou zaznamenány pro dvé různé délky rámu pro účely dalšího porovnávání s ostatními. Jsou analyzovány zátěžové-posunuté křivky smykového testu ve vnitřních vrstvách. Kromě toho byl v prostředí MATLAB vytvořen program s využitím Houghovy transformace pro analýzu snímání obrazu smykového úhlu v reálném čase při posunutí vzorku v různých polohách. Výsledky obrazové analýzy byly porovnány se skutečnými experimentálními výsledky. Rovněž i smykové napětí bylo predikováno s použitím modelu konečných prvků a porovnáno s experimentálními výsledky.

Tato práce se také zabývá určením vlivu různých strukturních charakteristik pletených distančních textilií na chování tlaku a absorpční schopnosti energie. Potenciál tlakového mechanismu textilie byl identifikován s podporou kompresní křivky napětí/deformace, práce a účinnosti při různých stupních komprese. Třetí stupeň polynomické regrese byl použit pro stanovení vlastností pružné deformace k získání výsledků komprese.

Distanční textilie mají vynikající tepelné a akustické vlastnosti ve srovnání s konvenčními tkanými či pletenými strukturami, pěnami nebo netkanými textiliemi oproti jejich nádherné 3D struktuře sendviče a porézní povaze. Proto tato práce rovněž zkoumá vliv různých strukturních parametrů distančních pletenin,jako jsou plošná hustota, porozita, tloušťka, hustota očekatd. na termo-fyziologické a akustické vlastnosti. Absorpční koeficient zvuku (SAC) byl hodnocen pomocí dvou mikrofonové impedanční trubice. Kromě toho, křivolakost textilie byla vypočítána analyticky a porovnána s experimentálními výsledky. Tato práce také popisuje vliv materiálových parametrů a strukturních charakteristik na akustické vlastnosti 3D distančních textilií.

Pokročilé statistické vyhodnocení a dvoufaktorová analýza rozptylu jsou použity k analýze významu různých faktorů, jako je tloušťka, typ distanční nitě, povrchové struktury a surovin, na specifické vlastnosti.Tyto poznatky jsou důležitými požadavky pro navrhování pletených distančních textilií, které by mohly být použity jako vhodný fixační materiál v aplikacích pro automobilový průmysl, matrace, sedačky, vložky do bot, polštáře, podpěry zad atd.

Klíčová slova: 3D distanční textilie, smyk ve vnitřní vrstvě, komprese-napětí, absorpce energie, účinnost, termo-fyziologie, zvuková pohltivost

Summary

1 Introduction

This research work discusses the potential contribution of spacer fabrics to the field of multifunctional light weight material for car seats, mattress, shoe insole, golf hitting mats, compressive bandage etc. Spacer fabrics can be defined as fabrics which have two outer surfaces connected to each other with spacer yarns. Since the middle layer comprised of monofilaments or multifilament yarns, the fabrics possess special characteristics. There are two types of knitted spacer fabrics: warp-knitted spacer fabrics and weft-knitted spacer fabrics. The first type can be produced on rib Rachel machine having two needle bars [1], while the second type can be produced on double jersey circular knitting machine having a rotatable needle cylinder. It can be produced by flat knitting too [2]. It has excellent compression resilience and breathability is the greatest advantages of spacer fabric [3]. Admirable compressibility indicated that, crush resistant property and bending performance are excellent. Spacer fabric possesses excellent cushioning and shock absorbing properties [4]. It is because spacer fabric is able to absorb and dissipate kinetic mechanical energy when it is subjected to compression at regular stress over a large extent of displacement [5]. In spacer fabric construction, the two separate outer fabric layers are kept apart by spacer yarns through the thickness direction. A through-thickness property is developed in this 3D textile materials. The spacer yarns act as linear springs, yarn loops are deformed under impact loading and hence created a high damage tolerance characteristic [6]. Besides, the hollow structure created by the spacer yarns between two outer layers resulted in outstanding moisture transmission property since moisture vapor is allowed to transmit freely. The major application areas such as automotive textiles, medical textiles, geotextiles, protective textiles, sportswear and composites. Further promising application of these spacer fabrics using favorable materials include the protective textiles as “Active Protection System (APS)” [7]. Nevertheless, because of the extreme elasticity and deformability due to applied forces along with limited reinforcing possibilities, these pile yarns connected conventional spacer fabrics are not considered as load-adapted 3D spacer fabric for high performance lightweight applications. Hence, the lack of comprehensive studies on the functional characteristics especially on mechanical , thermo-physiological and acoustic properties of knitted 3D spacer fabrics are sound basis for this research.

2 Purpose and the aim of the thesis

The goal of the current study was to characterize the 3-Dimensional knitted spacer fabrics for the multi-functional application. This research mainly involves investigating the effect of various structural and material characteristics on multi-functional properties of both warp and weft knitted spacer fabrics. The major sub-objectives of this research work are as follows:

2.1 To study the effect of structural parameters on advanced characteristics of spacer fabrics

The aim of this work was to investigate various structural parameters of 3D knitted spacer fabrics such as knit structure, thickness, type of spacer yarn, stitch density, porosity and volume density on mechanical and functional properties. This study specially focuses on spacer fabric behavior such as in-plane shear deformation, compressibility, air and water flow, thermal behavior and acoustic properties due to their structural variations. Due to the advanced characteristics of spacer fabrics such as bulkiness, lower density and air layer in the middle part, spacer fabric might be a proper selection for various applications according to its suitability.

2.2 Theoretical and experimental analysis of in-plane shear behavior of 3D spacer knitted fabrics

The objective of this study was to study the shear behavior of 3D spacer knitted fabrics by using a picture frame fixture. Three different methods were used to find the shear angle during loading rate of 10mm/min. All the tests were recorded by a CCD monochrome camera. The images acquired during loading process were used for analysis in order to obtain the full-field displacement and shear angles at chosen points on the surface of test specimen. To determine its suitability for measuring intra-ply shear properties of 3D knitted spacer fabrics, an experimental and analytical investigation of picture frame shear fixture was conducted. In this work, a fixture was designed to analyze the in-plane shear behavior of these fabrics. The nonlinear behavior of shear force versus shear angle and the deformation mechanism were analyzed. The curves for shear force versus shear angle and position of buckling for in-plane shear test were recorded by considering two different frame lengths in order to compare with each other. Load–displacement curves of intra-ply shear tests were also analyzed. In addition, a MATLAB program was developed using Hough transform to analyze the shear angle in the real-time image taken during displacement of specimen at various positions. The image analysis results were compared with the actual experimental results.

2.3 Study of compressibility and related behavior of 3D spacer fabrics

The aim of this study was to determine the influence of different structural characteristics of knitted spacer fabrics on the compressive behavior and energy absorption capability. The potential compression mechanism of the fabric was identified with support of the compression stress-strain curve, work done and efficiency at different compression stages. Third order polynomial regression model was used to establish the elastic deformation properties used to obtain the compression results. Advance statistical evaluation and two-way analysis of variance was used to analyze the significance of various factors such as thickness, spacer yarn diameter and surface structures on energy absorption at maximum compression load and deformation. These findings are important requirements for designing warp and weft knitted spacer fabrics for cushioning applications.

2.4 Thermo-physiological characteristics of knitted 3D spacer fabrics

In recent years, mattress, shoe-insole, automobile interiors etc. play an important role in improving thermal comfort. This research was to evaluate the thermal comfort properties of 3-Dimensional knitted spacer fabrics which could be used to replace the existing polyurethane foams in the functional applications. This study was to determine the influence of different characteristics of spacer fabrics like structure, areal density, thickness, density on thermo-physiological performance. The potential thermal behavior was identified with the support of the thermal conductivity and resistance evaluation. The air and water vapour permeability were measured and analyzed in order to study the breathability performance of spacer fabrics. Advanced statistical evaluation and two-way analysis of variance was used to analyze the significance of various factors on desired properties. These findings are important requirements for designing the cushioning materials with required thermal comfort properties using 3D spacer fabrics.

2.5 Study of acoustic behavior of 3D knitted spacer fabrics with respect to permeability

This study also focussed on finding the suitability of 3D porous spacer fabrics for the interior applications by improving acoustic performance. Hence, an experimental investigation on the sound absorption behavior of 3D knitted spacer fabrics was conducted. The sound absorption coefficient (SAC) was measured using two microphone impedance tube. Moreover, tortuosity of the spacer fabrics was calculated analytically and compared with experimental results. This study deeply discusses the influence of material parameters and characteristics on acoustic properties of 3D spacer knitted fabrics.

3 Overview of the current state of the problem

The customer requirement for applicationa such as car seats, mattress, shoe insole, golf hitting mats, compressive bandage are depends on various factors, mainly shearing, excellent cushioning and conditioned air and heat (breathability) etc. There are a number of materials and structures with the above mentioned features for those applications. Airbags, bubble films, rubberized fibre cushioning, and polymer-based foams are just a few typical examples. The use of foamed materials results in a significant improvement in the passive safety, owing to their excellent energy dissipation properties. In addition, they have low apparent density and are relatively cheap; allow great design flexibility as they can be easily modeled in complex geometric parts. However, despite their promising applications, these materials are not suitable for many critical applications due to inferior comfort properties and environmental hazards both in terms of production and recycling. Hence, in order to overcome all these drawbacks in car interior application, 3-dimensional spacer fabrics has attracted attention of researchers in recent times. Spacer fabrics are a class of material with unique properties and applications. Hence, the current study relies entirely on objective measures of 3D spacer fabrics for evaluating the multi-functional properties like in-plane shear, compressibility, thermal comfort, also in addition to that acoustic performance for the replacement of foam for cushioning applications. This research aims to provide a new material and design strategy for the replacement of existing cushioning materials with 3D spacer fabrics. For better performance, different materials and methods were used to aid in the determination of the best material parameters for the improvement of functional properties. A thorough study of the properties of the processed materials was performed.

4. Methods used, studied material

4.1 Materials

Twelve different spacer fabrics made up of polyester filament yarn were knitted using Raschel warp knitting machine with gauge of E22 and 6 guide bars. The surface layer of spacer fabrics were produced with polyester multifilament yarn with same linear density, the spacer layer (connecting) was knitted using polyester monofilament with different diameters and linear densities. By adjusting guide bar movements, the fabrics were produced with two different surface structures. The samples classification is clearly presented in Table 1. The structure and knit pattern of both lock knit and hexagonal net warp knit structures are given in Figure 1. The loop length of the all twelve warp knit spacer fabrics were kept at 2.12 mm.

Six different types of spacer fabrics were developed using computerized Mayer & Cie, OVJA 1.6 E 3 WT knitting machine with 5 feeders and 14 gauge. The six spacer fabric samples were classified into two groups for convenient analysis of results, the first group has been developed using Polyester/Polypropylene blend with three different proportions and second group with Polyester/Polypropylene/Lycra blend having another 3 different compositions. The samples classification is and characteristics are clearly presented in Table 2. Ther structure and knit pattern of the spacer fabric is shown in Figure 1. The loop length of the fabric without lycra (WES 1) was 2.46 mm and samples

(WES 2 and WES 3) were 2.78. The loop length weft knit spacer fabrics with Lycra on the surface (WES 4) was 1. 28 mm and for samples (WES 5 and WES 6) were 1.52 mm.

Table 1 Description of warp knitted spacer fabrics

S.No.	Structure	Fibre Composition (%)	Face Layer (dtex)	Middle Layer (Spacer) (dtex)	Back Layer (dtex)	Spacer Yarn Dia (mm)
WAS 1	Lock knit	100% Polyester	83f36 (linear density – 83 dtex, number of filaments – 36)	33f1	83f36 (linear density – 83 dtex, number of filaments – 36)	0.055
WAS 2						
WAS 3						
WAS 4				108f1		0.1
WAS 5						
WAS 6						
WAS 7	Hexagonal net			33f1		0.055
WAS 8						
WAS 9						
WAS 10				108f1		0.1
WAS 11						
WAS 12						

Table 2. Description of weft knitted spacer fabrics

Fabric sample No.	Fabric layers	Technical face	Spacer yarn	Technical back	Fiber composition (%)
Group 1 - Without Lycra					
WES 1	Type of yarns and linear density	Polypropylene (PP) - 14.5 tex	Polyester monofilament (PES) - 88 dtex	Polypropylene (PP) -14.5 tex	58% PP, 42% PES monofilament
WES 2		Polypropylene (PP)- 14.5 tex	Polyester (PES) - 14.5 tex	Polypropylene (PP) -14.5 tex	45% PP, 55% PES
WES 3		Polypropylene (PP) - 14.5 tex	Polyester (PES) - 167 dtex	Polypropylene (PP) -14.5 tex	41%PP, 59% PES
Group 2- With Lycra					
WES 4	Type of yarns and linear density	Polypropylene (PP)- 14.5 tex Lycra - 44dtex	Polyester monofilament (PES) - 88 dtex	Polypropylene (PP) -14.5 tex	55%PP, 39%PES monofilament, 6% Lycra
WES 5		Polypropylene (PP)- 14.5 tex Lycra - 44dtex	Polyester (PES) - 14.5 tex	Polypropylene (PP) -14.5 tex	42% PP, 52% PES, 6% Lycra
WES 6		Polypropylene (PP)- 14.5 tex and Lycra - 44dtex	Polyester (PES) - 167 dtex	Polypropylene (PP) -14.5 tex	39% PP, 55% PES, 6% Lycra

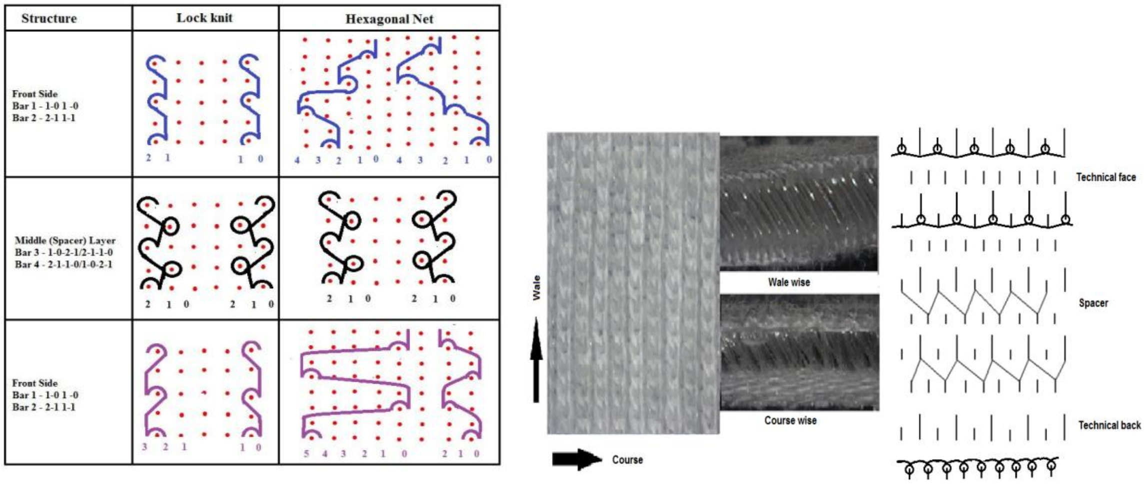


Figure 1. Structure and knit pattern of warp and weft knit spacer fabrics

4.2 Methods

The Structural properties including the yarn linear density and fabric weights per unit area were determined according to ASTM D1059 standard using electronic weighing scales. The thickness of the fabrics was measured according to ASTM D1777-96 standard with the SDL digital thickness gauge at a pressure of 200Pa. Air flow resistance of spacer fabric was calculated from air permeability value obtained from Textest FX-3300 air permeability tester. The Stitch density was calculated from wales per centimeter (WPC) and course per centimeter (CPC) with the help of optical microscope. Porosity, H, was calculated with bulk density of spacer fabrics and weighted average absolute density of fibres in the spacer fabric, expressed in kg/m^3. These results are shown in Table 3 & 4.

Table 3. Structural characteristics of warp knitted spacer fabrics

Warp Spacer Samples	Stitch Density (Stitches/cm^2)				GSM (g.m^{-2})				Thickness (mm)				Density (Kg.m^{-3})	Porosity (%)
	Mean	ME	LL	UL	Mean	ME	LL	UL	Mean	ME	LL	UL		
WAS 1	120.4	1.1	119.30	121.50	87.33	0.72	261.62	263.06	1.50	0.03	1.47	1.53	174.89	87.33
WAS 2	121	1.4	119.60	122.40	89.73	0.77	353.55	355.09	2.50	0.04	2.46	2.54	141.73	89.73
WAS 3	120.3	1.3	119.00	121.60	90.77	3.10	442.88	449.08	3.50	0.03	3.47	3.53	127.42	90.77
WAS 4	119	1.2	117.80	120.20	72.31	0.68	572.41	573.77	1.50	0.02	1.48	1.52	382.06	72.31
WAS 5	120	1.1	118.90	121.10	74.73	0.62	871.30	872.54	2.50	0.01	2.49	2.51	348.77	74.73
WAS 6	120.5	0.9	119.60	121.40	75.69	0.69	1173.44	1174.82	3.50	0.01	3.49	3.51	335.47	75.69
WAS 7	119	1.6	117.40	120.60	87.27	2.87	260.572	266.31	1.50	0.03	1.47	1.53	175.63	87.27
WAS 8	120	0.9	119.10	120.90	89.76	0.62	352.50	353.74	2.50	0.03	2.47	2.53	141.25	89.76
WAS 9	119.1	1.2	117.90	120.30	90.74	0.85	446.27	447.97	3.50	0.02	3.48	3.52	127.75	90.74
WAS 10	121	1.3	119.70	122.30	72.35	1.39	570.93	573.71	1.50	0.02	1.48	1.52	381.55	72.35
WAS 11	119.6	1.1	118.50	120.70	74.71	1.00	871.45	873.45	2.50	0.01	2.49	2.51	348.98	74.71
WAS 12	119.5	1.4	118.10	120.90	75.71	1.39	1171.93	1174.71	3.50	0.03	3.47	3.53	335.23	75.71

Table 4. Structural characteristics of weft knitted spacer fabrics

Weft Spacer Samples	Stitch Density (Stitches/cm^2)				Thickness (mm)				Density (kg.m^{-3})	Stitch Density (Stitches/cm^2)				Porosity (%)
	Mean	ME	LL	UL	Mean	ME	LL	UL		Mean	ME	LL	UL	
WES 1	493	0.16	492.84	493.16	4.4	0.88	3.52	5.28	112	200	0.1	199.9	200.1	90.12
WES 2	443	0.12	442.88	443.12	2.62	1.1	1.52	3.72	169.1	150	0.04	149.96	150.04	86.21
WES 3	477	0.2	476.8	477.2	2.74	0.61	2.13	3.35	174.1	150	0.12	149.88	150.12	85.06
WES 4	632	0.1	631.9	632.1	4.4	0.55	3.85	4.95	144.8	350	0.06	349.94	350.06	87.15
WES 5	657	0.12	656.88	657.12	3.5	0.86	2.64	4.36	187.7	280	0.1	279.9	280.1	84.09
WES 6	695	0.22	694.78	695.22	3.4	0.45	2.95	3.85	205.4	280	0.1	279.9	280.1	83.11

4.2.1 In–plane shear behavior

The picture frame test is preferred by many researchers for shear testing since it generates pure state of strain which can be imposed on the test specimen. Shearing is induced by restraining the textile reinforcement in a rhomboid deformation frame with fibers constrained to move parallel to the frame edges. The frame is extended at diagonally opposing corners using simple tensile testing equipment. The 3D spacer fabrics for shear tests were prepared according to the size of the picture frame and the characteristics of samples are described in the Figure 2 & 3.

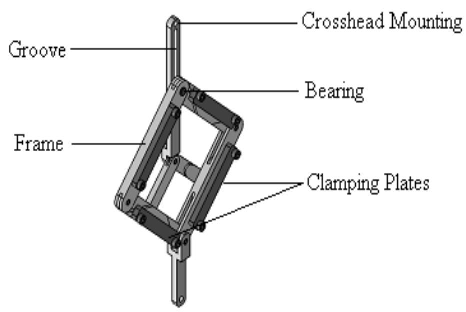
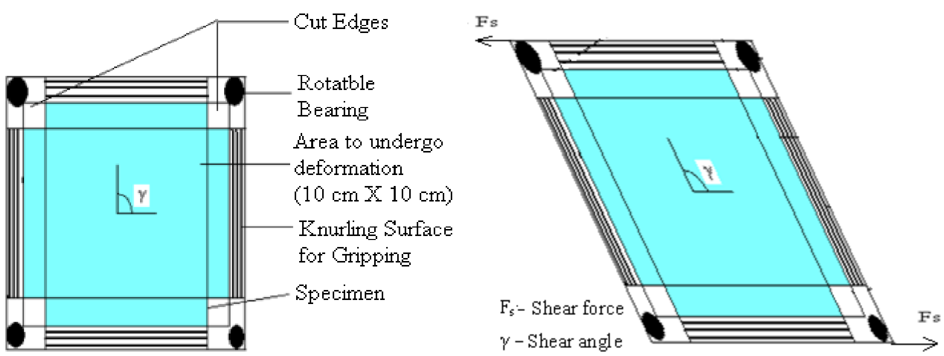


Figure 2. Picture frame fixture design



a. Before deformation **b.** After deformation

Figure 3. Shear deformation of frame and specimen

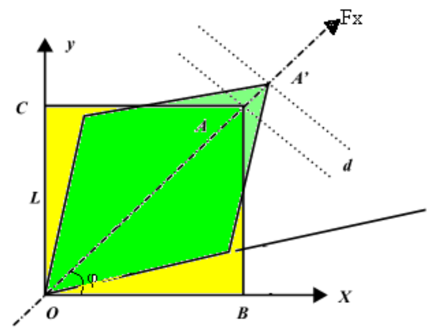


Figure 4. Deformation kinematics of picture frame.

A tensile force is applied at the crosshead mounting. The rig is jointed at each corner such that its sides can rotate and the interior angle between adjacent sides can change. The initially square frame thus becomes of rhomboid (or diamond) shape as shown in Figure 3. Material inside the rig is subjected to pure shear deformation kinematics (Figure 4). The force required to deform the material is recorded at the crosshead mounting as a function of crosshead displacement [8, 9]. Direct measurement of axial load and shear angle is possible through this following relationship in eqn. 1 [10, 11].

$$F_S = \frac{F_x}{2\cos\varphi} \qquad (1)$$

Shear force (F_s) is determined by the axial force (F_x) frame rig length (L) and the frame angle (φ). Meanwhile frame angle can be determined directly from cross head displacement (d). Shear angle (γ) can be obtained from frame angle by using the following equations 2 and 3 [9].

$$\varphi = \cos^{-1}\left(\frac{L\sqrt{2}+d}{2L}\right) \quad (2)$$

$$\gamma = \frac{\pi}{2} - 2\varphi \quad (3)$$

4.2.1.1 Image analysis using MATLAB

Image analysis can aid in the determination of the shear angle and displacement at any particular point on the surface of fabric specimen. The complete displacement of the specimens during loading process was obtained by image analysis methods. The images were captured at certain regular interval of time using digital camera. A special program is developed in MATLAB 7.10 (R 2010a) using Hough's transform to find the angle between the lines on the specimens. The results of experimental methods and image analysis were compared with each other.

4.2.1.2 Finite Element Analysis of shear behavior

The spacer fabric geometry was created using solidworks and was imported into ANSYS platform for finite element analysis of shear stress. SOLID45 is used for the 3-D modelling of spacer structures. The element is defined by eight nodes having three degrees of freedom at each node: translations in the nodal x, y, and z directions. The element has plasticity, creep, swelling, stress stiffening, large deflection, and large strain capabilities. The mesh size and number of nodes were determined in order to minimize processing time and yet have accurate results.

4.2.2 Compression behavior

All the compression tests were carried out on a universal testing machine (TIRA) fitted with 5kN load cell. The speed of compression was chosen at 12mm/min in accordance to the ASTM d 575 (Test methods for rubber properties). The compression test was performed on the machine equipped with 2 strictly parallel plates having diameter of 150mm and a smooth surface. The samples were cut with dimensions of 100 mm x 100 mm. All the spacer fabric specimens are compressed up to 80 % of the initial thickness in an atmospheric condition of 20oC and 65% relative humidity. Five tests were carried out for each sample under each testing condition and the average compression stress-strain curves are presented.

4.2.2.1 Energy absorption during in-plane shear of spacer fabrics

It is necessary to evaluate and analyze the spacer fabrics energy absorbing ability during shear and compression. It would be more useful to get a better understanding about the applicability of spacer fabric for cushion materials. The shear and compression curve suggests that all spacer fabric samples may potentially be good energy-absorbing materials. The area under the load-displacement curve represents the total energy absorbed and it can be calculated by multiplying the area under the stress-strain curve by the volume of the sample. The energy absorption capacity per unit volume, *W*, can be calculated by integrating the stress-strain curve, as given by equation 4 [12]:.

$$W = \int_0^{\varepsilon} \sigma(\varepsilon) d\varepsilon \quad (4)$$

Where, σ is the shear or compressive stress, $\mathscr{E}$ is the shear or compression strain at the end/beginning of densification stage. In order to better understand the energy-absorption capacity of a spacer fabric, the energy-absorption efficiency E can be used to analyze its energy-absorption process. The efficiency E is expressed by Equation (5)

$$E = \frac{Ah\int_0^{\varepsilon} \sigma(\varepsilon) d\varepsilon}{Ah\sigma} \quad (5)$$

Where A – area, h – thickness, σ – shear or compressive stress at the strain $\mathscr{E}$. The energy-absorption and efficiency of all the spacer fabrics are compared and analyzed to find the suitable material for hi-end applications.

4.2.3 Thermo-physiological properties

Air permeability tests were performed according to standard ISO 9237 using a Textest FX-3300 air permeability tester. The water vapor permeability of the samples has been measured using the PERMETEST. PERMETEST characterizes the capability of the fabric to transfer water vapor, by measuring the relative water vapor permeability. Thermal conductivity measurements were performed using C-Therm Thermal Conductivity Analyzer Tci. The standard test method EN 61326-2-4:2006 was used for this testing using TCi. This test was performed under room temperature. The results are reported in Table 5 & 6.

4.2.4 Determination of tortuosity

The tortuosity is a fundamental parameter which describes complexity of the path of sound wave propagating within a porous material. The analytical model considers these pores to be inclined at an angle (*θ*) normal to the surface of the fabric. Also angle *θ* can be determined using the spacing between loops on alternate wales/corse on the front and back face of the fabric (*d*) and its thickness (*t*). So tortuosity (K_s) of the fabric and angle of inclination *θ* can be determined using the equations (6,7);

$$K_s = \frac{1}{\cos^2\theta} \text{(6)} \quad \theta = \tan^{-1}\left(\frac{d}{t}\right) \text{(7)}$$

The spacing *d*can be determined from the number of wales/corse per cm (*W*) of the knitted face of a particular fabric and the number of needle positions between the two alternate wales (*p*) using equation (8).

$$d = (p+1) + \frac{10}{(W-1)} \text{(8)}$$

Thus, with the use of equations (6 - 8), the tortuosity of the spacer fabrics can be calculated approximately [13].

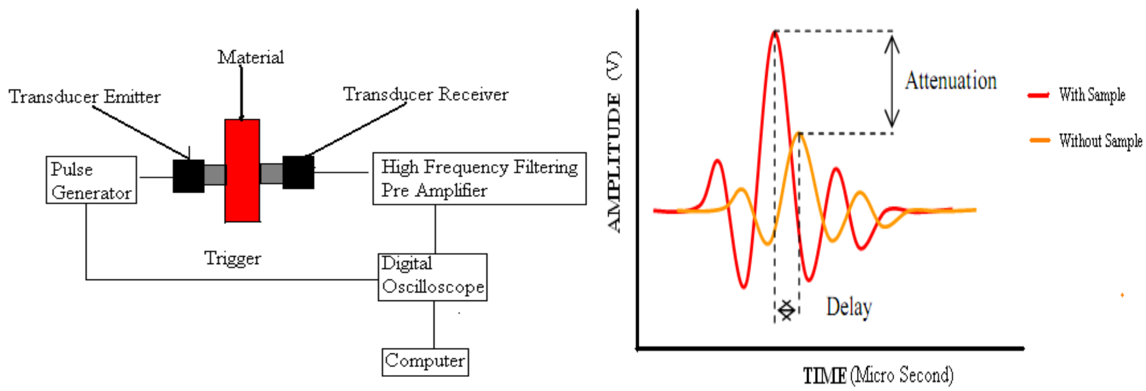


Figure 5. Experimental set up to measure tortuosity using ultrasonic method.

The experiment is performed with the sample positioned between two transducers and then compared with reference signal (without sample) to extract the relative time delay and amplitude attenuation [Figure 5]. From the time delay (τ) and attenuation ratio amplitude (T) with/without sample of signal time, it is possible to calculate tortuosity using the equation (9) given below [14],

$$\text{Tortuosity, } K_S = \left[\left(\frac{|\ln(T)|c_o}{d\omega}\right) - \sqrt{\left(\frac{|\ln(T)|c_o}{d\omega}\right)^2 + \left(1 + \frac{c_0\tau}{d}\right)}\right]^2 \quad (9)$$

Where,K_S– Tortuosity (no unit), *T* – Attenuation ratio amplitude ($|\ln(T)| = a*d$), a - Attenuation per unit length, *d* – thickness of Material, *ω* – Ultrasound Frequency (40 KHz), C_0– Speed of sound in free air (343 m/s), *τ* - Time delay in (micro sec)

4.2.5 Measurement of sound absorption coefficient (Impedance Tube Method)

In this research, the impedance tube method was used to determine the normal incident sound absorption coefficient, SAC (α). A minimum of three specimens for each sample were tested according to ASTM E 1050-07. Standard test method for impedance and absorption of acoustic materials using a tube with two microphones and a digital frequency analysis system was used. The "Noise Reduction Coefficient" (NRC) is a measure of how much sound is absorbed by a particular material, and is derived from the measured Sound Absorption Coefficients [15]. The NRC was determined using the following formula (eqn. 10).

$$NRC = \frac{\alpha_{250} + \alpha_{500} + \alpha_{1000} + \alpha_{1500} + \alpha_{2000} + \alpha_{3000} + \alpha_{4000} + \alpha_{5000} + \alpha_{6000} + \alpha_{6400}}{10} \quad (10)$$

4.2.6 Statistical analysis

Statistical analysis software, QC Expert - Trilobyte was used to conduct all the statistical tests mentioned in this work. Advance statistical evaluation and two-way analysis of variance was used to analyze the significance of various factors on required properties of warp as well as weft knitted spacer fabrics. Also, differences in means between various groups were examined for statistical significance using one-way and two-way ANOVA followed by pair comparison using Scheffe's method. For all the statistical tests, differences were considered significant at $P < 0.05$. Data were reported as mean ± standard error of mean, unless otherwise stated.

5. Summary of the results achieved

5.1 In-plane shear behavior of 3D spacer fabrics

The picture frame test method was verified for the 3D spacer fabrics under consideration. Figure 6 shows the array of images for a 3D spacer fabric specimen captured during the loading process at each 5mm displacement for every 30 sec.

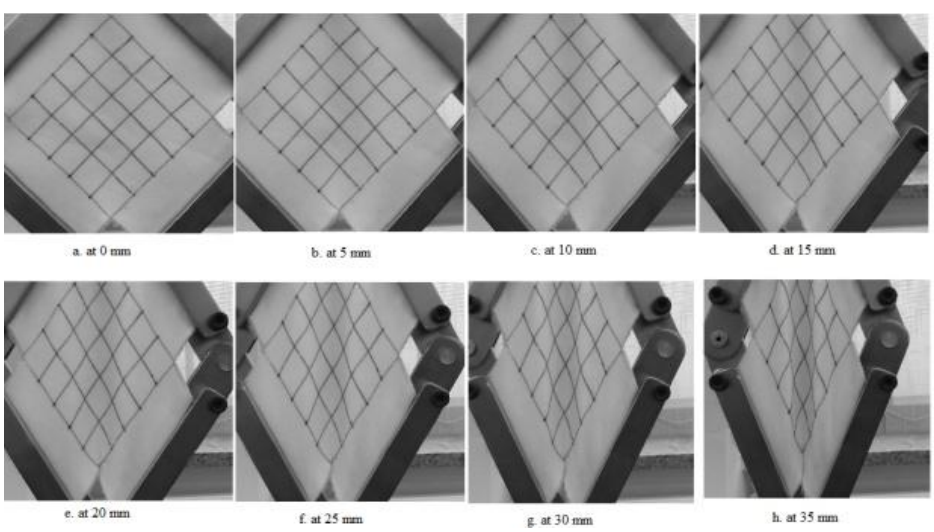


Figure 6. Shear deformation of specimen at different displacement levels

Table 5. Thermo-physiological properties of 3D warp knitted spacer fabrics

Fabric Samples	Air Permeability ($l/m^2.s$)				Thermal Conductivity ($W.m^{-1}k^{-1}$ X 10^{-3}) (λ)				Thermal Resistance (km^2W^{-1} X 10^{-3}) (r)				RWVP (%)				Evoporative Resistance ($Pa.m^2kW^{-1}$) (R_{et})			
	Mean	**ME**	**LL**	**UL**	**Mean**	**ME**	**LL**	**UL**	**Mean**	**ME**	**LL**	**UL**	**Mean**	**ME**	**LL**	**UL**	**Mean**	**ME**	**LL**	**UL**
WAS 1	3082	6.36	3075.64	3308.41	47.94	0.4	47.54	48.34	64.92	0.67	64.25	65.6	51.12	0.89	50.23	52.01	7.32	0.4	6.92	7.72
WAS 2	3216	9.64	3206.36	3460.05	46.82	0.27	46.55	47.09	66.16	0.24	65.92	66.4	49.62	0.53	49.09	50.15	8.14	1.05	7.09	9.19
WAS 3	3348	15.92	3332.08	3595.17	45.61	0.78	44.83	46.39	68.42	0.39	68.03	68.8	48.7	1.3	47.4	50	8.86	0.9	7.96	9.76
WAS 4	2032	22.79	2009.21	2228.86	53.48	0.51	52.97	53.99	53.98	0.32	53.66	54.3	28.56	1.14	27.42	29.7	18.35	1	17.35	19.35
WAS 5	2134	17.28	2280.72	2373.42	52.27	0.29	51.98	52.56	56.16	0.56	55.6	56.7	27.1	1.11	25.99	28.21	20.12	1.05	19.07	21.17
WAS 6	2298	27.17	2106.83	2555.00	51.96	0.31	51.65	52.27	59.44	0.33	59.11	59.8	25.92	0.33	25.59	26.25	21.98	1.22	20.76	23.2
WAS 7	3290	18.41	3271.59	3088.36	46.78	0.86	45.92	47.64	71.34	1.02	70.32	72.4	61.28	1.64	59.64	62.92	4.92	1.09	3.83	6.01
WAS 8	3432	28.05	3403.95	3225.64	45.64	0.7	44.94	46.34	77.56	0.72	76.84	78.3	58.38	0.42	57.96	58.8	6.04	0.77	5.27	6.81
WAS 9	3568	27.17	3540.83	3363.92	44.38	0.75	43.63	45.13	82.12	0.9	81.22	83	57.16	0.6	56.56	57.76	6.6	0.89	5.71	7.49
WAS 10	2212	16.86	2195.14	2054.79	51.19	0.28	50.91	51.47	60.71	0.32	60.39	61	39.48	0.47	39.01	39.95	12.58	0.96	11.62	13.54
WAS 11	2348	25.42	2322.58	2315.28	50.45	0.2	50.25	50.65	61.13	0.81	60.32	61.9	37.88	0.76	37.12	38.64	14.4	0.74	13.66	15.14
WAS 12	2536	19.00	2517.00	2161.17	49.78	0.38	49.4	50.16	63.45	0.49	62.96	63.9	36.61	0.53	36.08	37.14	15.9	1.1	14.8	17

Table 6. Thermo-physiological properties of 3D weft knitted spacer fabrics

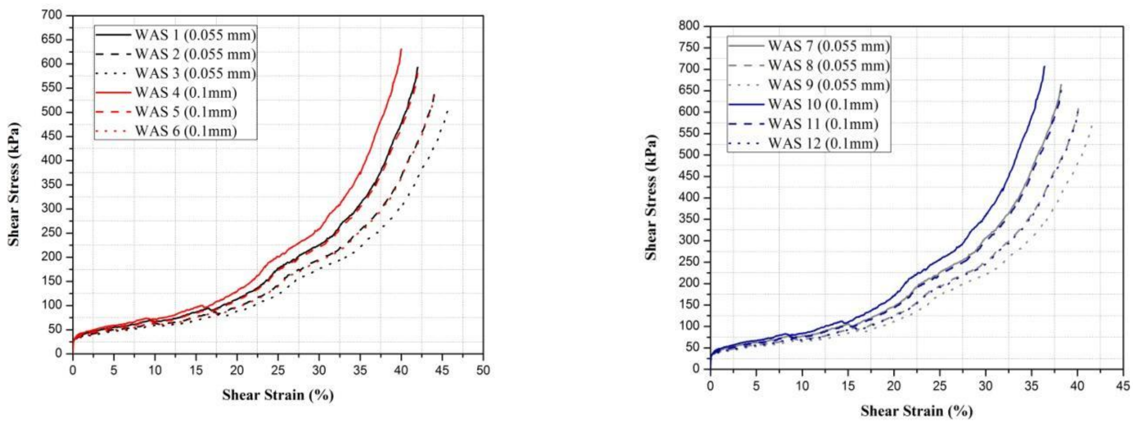
Sampl e Nos.	Air Permeability ($l/m^2/s$)				Thermal Conductivity ($W.m^{-1}k^{-1}$ X 10^{-3}) (λ)				Thermal Resistance (km^2W^{-1} X 10^{-3}) (r)				RWVP (%)				Evaporative Resistance ($Pa.m^2kW^{-1}$) (R_{et})			
	Mean	**ME**	**LL**	**UL**	**Mean**	**ME**	**LL**	**UL**	**Mean**	**ME**	**LL**	**UL**	**Mean**	**ME**	**LL**	**UL**	**Mean**	**ME**	**LL**	**UL**
WES 1	1806.4	12.6	1793.8	1819	59.98	0.86	59.12	60.84	71.7	1.02	70.63	72.67	47.3	2.48	44.8	49.7	18.61	1.17	17.4	19.78
WES 2	621.8	8	613.8	629.8	61.24	0.7	60.54	61.94	64.4	0.72	63.71	65.15	26.3	1.18	25.1	27.5	7.58	0.31	7.27	7.89
WES 3	545.2	14	531.2	559.2	66.56	0.75	65.81	67.31	61.7	0.9	60.77	62.57	24.2	0.98	23.2	25.2	6.34	1.12	5.22	7.46
WES 4	946.6	13	933.6	959.6	53.42	0.28	53.14	53.70	77.6	0.32	77.23	77.87	37.1	2.74	34.4	39.9	18.45	1.4	17.1	19.85
WES 5	318.8	6.9	311.9	325.7	56.31	0.2	56.11	56.51	69.2	0.81	68.35	69.97	25.8	1.76	24.0	27.5	11.7	2.14	9.56	13.84
WES 6	305.8	7.2	298.6	313	61.72	0.38	61.34	62.10	65.1	0.49	64.60	65.58	24.0	1.2	22.8	25.2	10.31	1.26	9.04	11.57

***ME-Margin of Error, UL – Upper Limit, LL – Lower Limit**

Grid pattern was applied on the specimen surface before the test and used as the reference points of image analysis. Around 16 points (25 square cells ($4cm^2$ each) with 90^o angle at 4 points) can be chosen on a 100 mm x 100 mm specimen for image analysis to determine the displacements and shear angles at the chosen points. This distance and angle indicate the line which bisects the points being tested after each 5 mm displacement at every 30 sec interval. The bucking starts at 20 mm displacement and having maximum buckling at 35 mm. The determination of shear angle for both warp and weft knitted spacer fabrics using image analysis are discussed and presented clearly in the following section.

5.1.1 Experimental evaluation of in-plane shear behavior of warp knitted spacer fabrics

As shown in Figs. 7a & b, the stress-strain curve reveals that the shear resistance decreases with increase in thickness. It can be seen that, the samples have almost similar behavior as they behave linearly in surface extension stage due to same surface structure and density. It was also observed that the thicker fabric has ability to undergo larger deformation in both shear and compression conditions. It was found that the hexagonal net structure fabrics (WAS 7 - WAS 12) show similar trend as the lock knit structures . The angles between spacer yarn and surface layer can be varied by means of needle under lapping. In this study, spacer yarn angles (84^o – 86^o) of different samples have been maintained. From the Figures 7, it is observed that, the shear stress is high for the fabrics with coarser spacer yarn for both types of structures. In surface elongation and compression (1^{st} stage), a higher shear force was observed in the fabrics with coarser spacer yarn as compared to the fabrics made up of finer spacer yarns. It might be the fact that the large diameter and linear density of the coarse spacer yarns have higher ability to resist compressive stress than the fabrics made up of finer spacer yarn. In stage 2, the pre–buckling was observed after 20% of shear strain because the surface layers come in contact with each other leading to a locking effect. The fabrics have almost identical stress-strain curves with same thickness for both lock knit and hexagonal spacers in stage 1 region. However, a significant difference in the shear stress-strain behavior was obtained in the densification stage. It was due to the fact that the internal surface and spacer layer experience a closer compaction which depends on the thickness, the surface structure and spacer yarn properties.



(a) **(b)**

Figure 7. Influence of spacer yarn linear density on shear behavior of warp knit spacer fabrics (a) Lock Knit, (b) Hexagonal Net

The shear stress-strain behavior for both the structures (Lock knit and Hexagonal net) exhibits almost same load and deformation in stage 1. In stage 2, it is found that the Hexagonal-mesh fabric offers higher shear resistance than that of lock knit structures. All the samples have almost close value in the surface elongation region and the differences could be observed when the fabric undergoes lateral compression in stage 2. It might be due to those insignificant differences in the stitch density in surface deformation stage and thickness and spacer yarn properties influences in compression stage. In stage 3, the lock knit fabrics (WAS 1 – WAS 6) undergo large shear deformation for the same shear stress.

5.1.2 In-plane shear work done of warp knit spacer fabrics

Overall, the work done values were higher for the fabrics made up of hexagonal net structure on face side than that of lock knit fabrics. Also, it can be seen that fabrics with finer spacer yarn have low work done when compared to other fabrics; it might be due to finer spacer yarn offers low resistance towards compression [Figure 8 & 9]

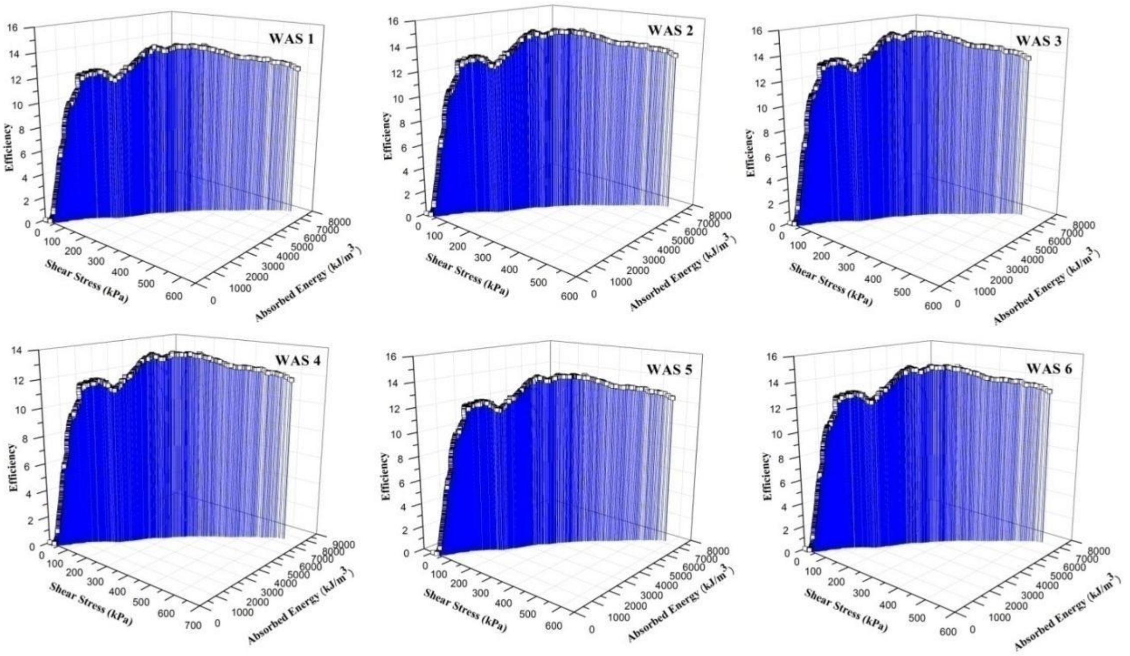


Figure 8. In-plane shear energy absorption and efficiency of lock knit spacer fabrics

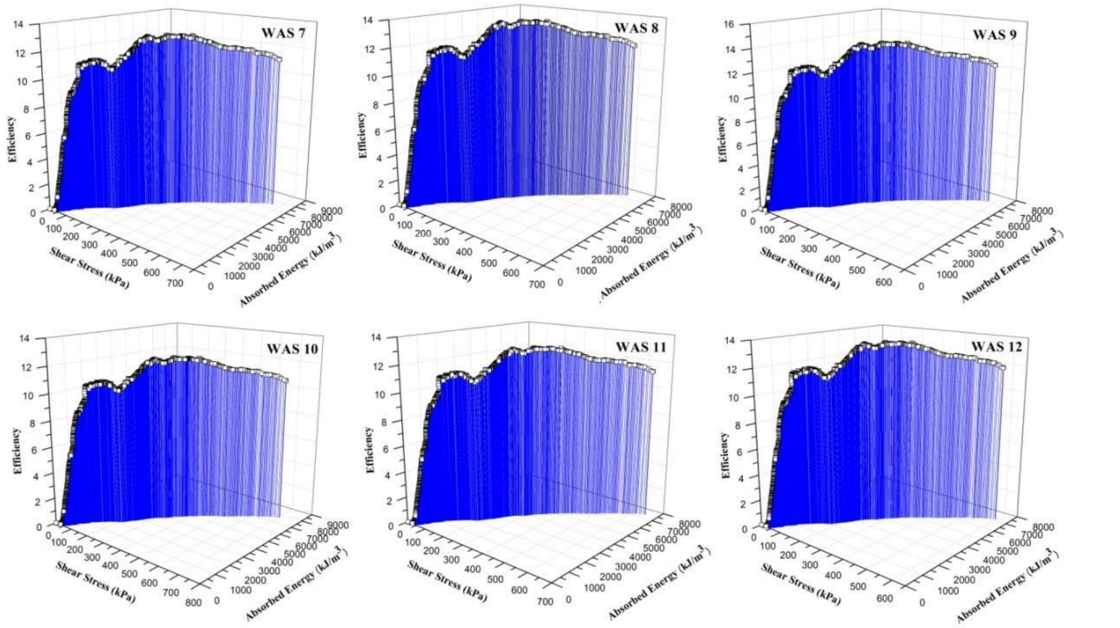


Figure 9. In-plane shear energy absorption and efficiency of hexagonal net spacer fabrics

Figure 8 and Figure 9 present the graphical analysis of shear stress versus absorbed energy versus efficiency. The shear work done of lock knit spacer fabrics (WAS 1 – WAS 6) linearly increases with the stress in the surface extension and compression stage. The marginal differences in work done between the samples can be seen when the shear stress reaches towards the stage 2 for both the structures. At the start of densification stage, the rapid increases in stress results in small deformation and work done. From the energy absorption graph, it is easy to find the stress associated with the required amount of energy to be absorbed. So, it is more convenient to select the suitable spacer fabrics for cushion application with optimum in-plane shear performance. The maximum energy-absorption efficiency is obtained at the end of the densification stage. The point at the maximum energy-absorption efficiency can be considered a critical point in the densification zone. Overall, it was observed that the shear work done and efficiency is higher for the thin fabrics with low density. Also, it was found that fabrics with finer spacer yarns undergoes large amount of work done as well as high efficiency during shearing mechanism.

5.1.3 Relation between shear angle versus shear force of warp knit spacer fabrics

It is observed from the graph that the thin hexagonal net spacer fabric with coarser spacer yarn (WAS 10) offers more resistance towards shear deformation than that of other fabrics. The thick lock knit fabrics with low linear density spacer yarn (WAS 3) have ability to undergoes high shear angle with low shear stress. Linear relationship between two variables x and y is a common concept, in which effective and easy assumptions helps to deduct relationship between them [Figure 10].

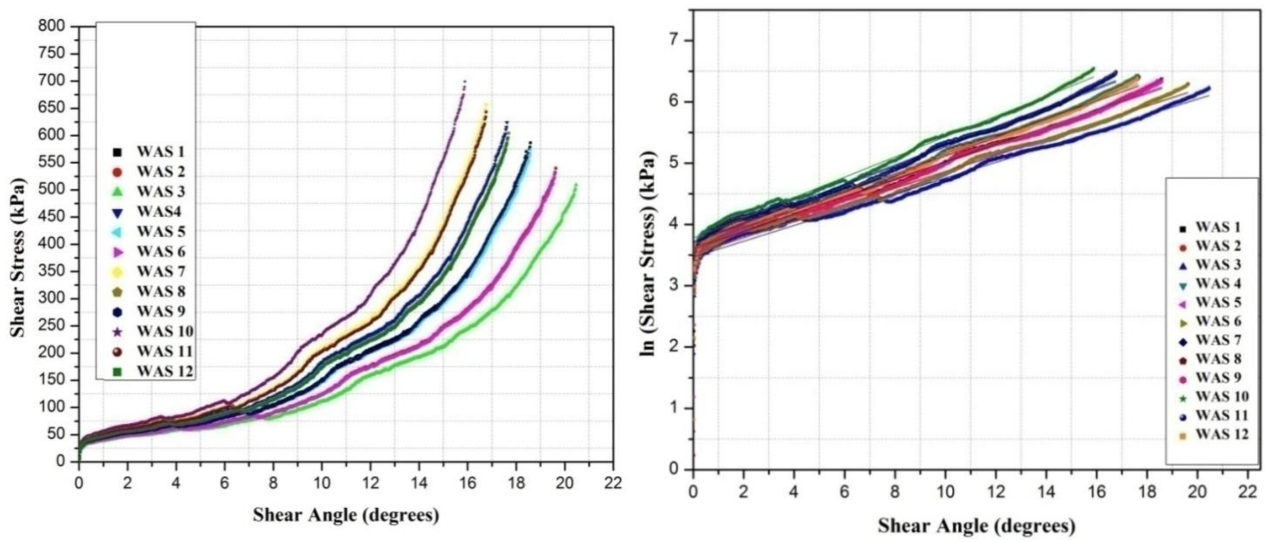


Figure 10. Experimental determination of shear angle vs shear force and linear regression fit of warp knit spacer fabrics

The average of in-plane stress responses against shear angle obtained for each spacer fabrics samples was fitted in the general form of linear fit (Figure 10). To obtain highly fitted linear equation and R^2 value, the dependent variable values (shear stress) were transformed using log-transformation. Response fit analyses, regression coefficient estimations and model significance evaluations were conducted. The estimated coefficient of determination and fitted linear regression equation are given in Table 7. The adequacy of the models was tested using residuals sum of squares and adjusted coefficient of determination (R^2).

5.1.4 Statistical evaluation – in-plane shear behavior of warp knit spacer fabrics

The selected value of significance for all statistical tests in the study is 0.05 levels. Analysis of different combination of factors on shear work done is presented in Table 8. The factors mainly considered were thickness, spacer yarn diameter and structure which strongly influence the shear behavior and energy absorption of the three-dimensional spacer fabrics. The critical quantile ($F_{critical}$) values were obtained for factor A - 18.51, Factor B – 19.00 and Interaction – 161.45 with respect to degrees of freedom. The value of $F_{critical} < F_{statistic}$ proved that the changes in the thickness and surface layer structure of warp-knitted spacer fabric has significant influence on the above-mentioned fabric shear properties. Even the minor changes in the fabric thickness resulted in significant impact on the shear behavior. Interaction factors thickness – spacer yarn diameter with in both lock knit and hexagonal net structure doesn't have significant influence ($p > 0.05$) on shear behavior.

Table 7. Prediction of experimental shear strength of warp knit spacer fabrics using linear regression model

Equation			y = a + b*x				
DF			Model - 1, Error - 926, Total - 926 - 927				
Weight			No Weighting				
Sample Nos.			Value	Standard Error	Residual Sum of Squares	F Value	Prob>F
ln(Shear Strength)	**WAS 1**	Intercept	3.611	0.007			
		Slope	0.141	0.001	11.837	41678.774	0.000
	WAS 2	Intercept	3.529	0.007			
		Slope	0.134	0.001	13.309	37124.890	0.000
	WAS 3	Intercept	3.470	0.008			
		Slope	0.129	0.001	16.564	29911.002	0.000
	WAS 4	Intercept	3.671	0.007			
		Slope	0.149	0.001	12.088	40814.370	0.000
	WAS 5	Intercept	3.588	0.008			
		Slope	0.141	0.001	13.950	35438.801	0.000
	WAS 6	Intercept	3.510	0.008			
		Slope	0.134	0.001	15.042	32910.134	0.000
	WAS 7	Intercept	3.719	0.008			
		Slope	0.157	0.001	15.121	32725.172	0.000
	WAS 8	Intercept	3.635	0.009			
		Slope	0.149	0.001	18.338	27052.690	0.000
	WAS 9	Intercept	3.584	0.007			
		Slope	0.142	0.001	11.382	43314.790	0.000
	WAS 10	Intercept	3.778	0.008			
		Slope	0.165	0.001	15.815	31309.158	0.000
	WAS 11	Intercept	3.695	0.008			
		Slope	0.157	0.001	16.971	29212.851	0.000
	WAS 12	Intercept	3.620	0.008			
		Slope	0.149	0.001	14.202	34815.729	0.000

5.1.5 Determination of shear angle of warp knit spacers using image analysis method

In both the cases (lock knit and hexagonal structures), the spacer fabric samples (WAS 1 – WAS 12) have smooth and linear increases in shear angle till 25mm displacement. The irregular trend in shear angle observed after 25 mm displacement may be due to the fact that spacer fabric undergoes compaction which leads to buckling. The image analysis shear angle is plotted against the shear strain for both the structures such as lock knit (WAS 1 – WAS 6) and hexagonal net (WAS 7 – WAS 12) as given in the Figure 11. Also, the linear model fit was presented in figures with shear strain as independent variable and shear angle as dependent variable .

Table 8. Statistical evaluation for in-plane shear behavior of warp knit spacer fabrics

Source of variability	*Sum of squares*	*Mean square*	*Degrees of freedom*	*Standard deviation*	*F-statistic*	*Critical quantile*	*Conclusion*	*p-value*
Influence of spacer yarn diameter and thickness on shear work done - lock knit								
Thickness	199036.55	99518.27	2.00	315.47	83.16	19.00	Significant	0.011882
Spacer Yarn Diameter	6868.82	6868.82	1.00	82.88	5.74	18.51	Insignificant	0.13884
Interaction	1695.60	1695.60	1.00	48.92	2.43	161.45	Insignificant	0.3631136
Residuals	697.78	697.78	1.00	26.42				
Total	208298.75	41659.75	5.00	204.11				
Influence of spacer yarn dia and thickness on shear work done - Hexogonal net								
Thickness	206704.21	103352.11	2.00	321.48	83.12	19.00	Significant	0.0118881
Spacer Yarn Diameter	7132.91	7132.91	1.00	84.46	5.74	18.51	Insignificant	0.138906
Interaction	1761.48	1761.48	1.00	49.87	2.43	161.45	Insignificant	3.63E-01
Residuals	725.40	725.40	1.00	26.93				
Total	216324.00	43264.80	5.00	208.00				
Influence of structure and thickness on shear work done for spacer yarn dia (0.055 mm)								
Structure	28576.03	28576.03	1.00	169.04	3818.59	18.51	Significant	0.0002618
Thickness	167843.18	83921.59	2.00	289.69	11214.38	19.00	Significant	8.92E-05
Interaction	14.97	14.97	1.00	3.87	35386.51	161.45	Significant	3.38E-03
Residuals	0.000	0.000	1.000	0.021				
Total	196434.17	39286.83	5.00	198.21				
Influence of structure and thickness on shear work done for spacer yarn dia (0.1 mm)								
Structure	29112.10	29112.10	1.00	170.62	2681.85	18.51	Significant	0.0003727
Thickness	242741.17	121370.58	2.00	348.38	11180.82	19.00	Significant	8.94E-05
Interaction	21.71	21.71	1.00	4.66	228306.94	161.45	Significant	0.0013324
Residuals	0.000	0.000	1.000	0.010				
Total	271874.98	54375.00	5.00	233.18				

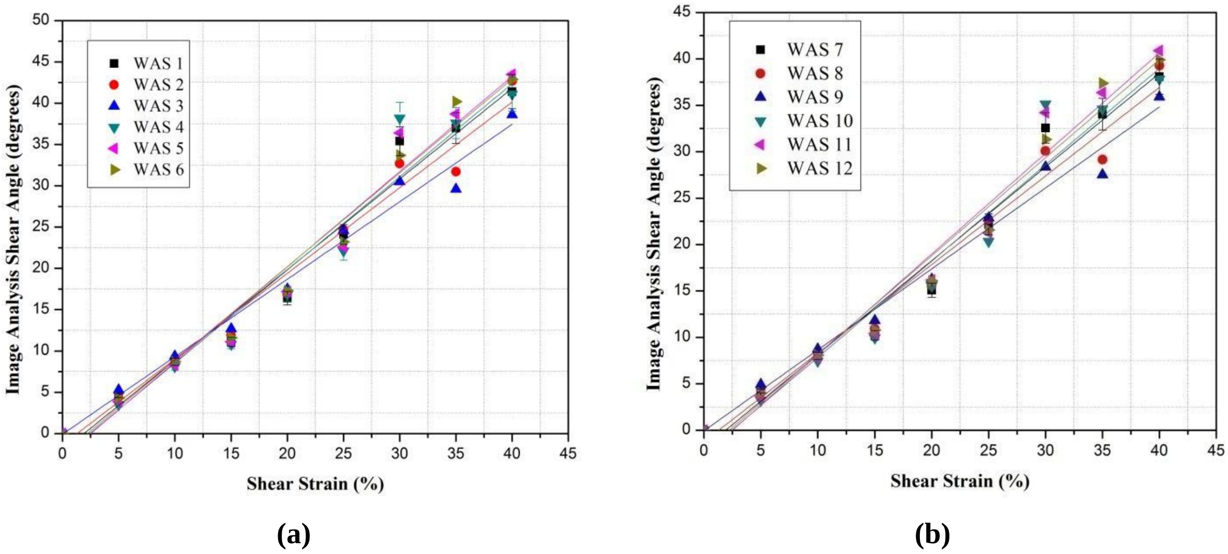
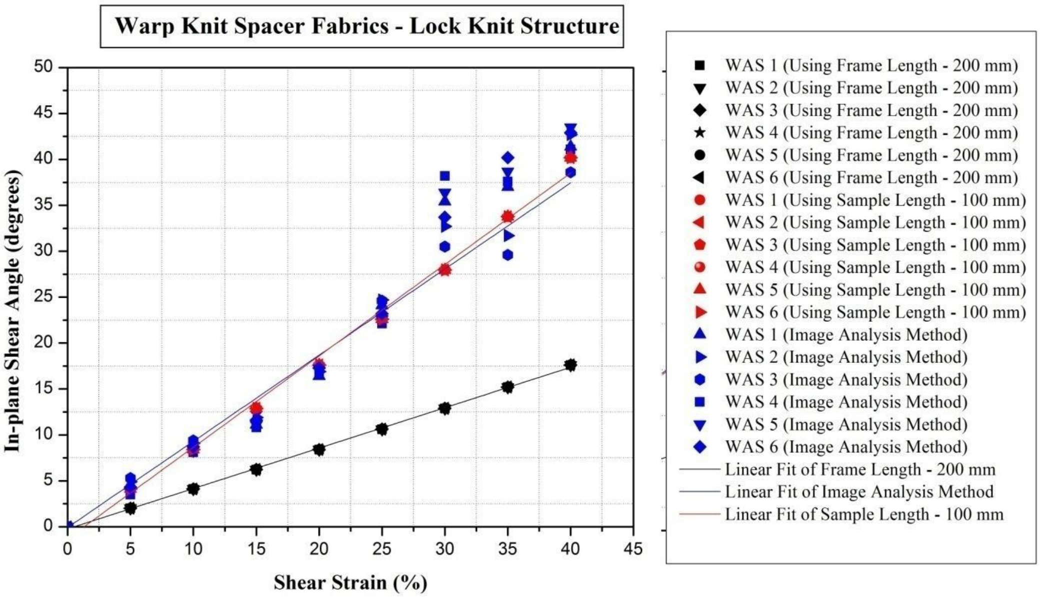


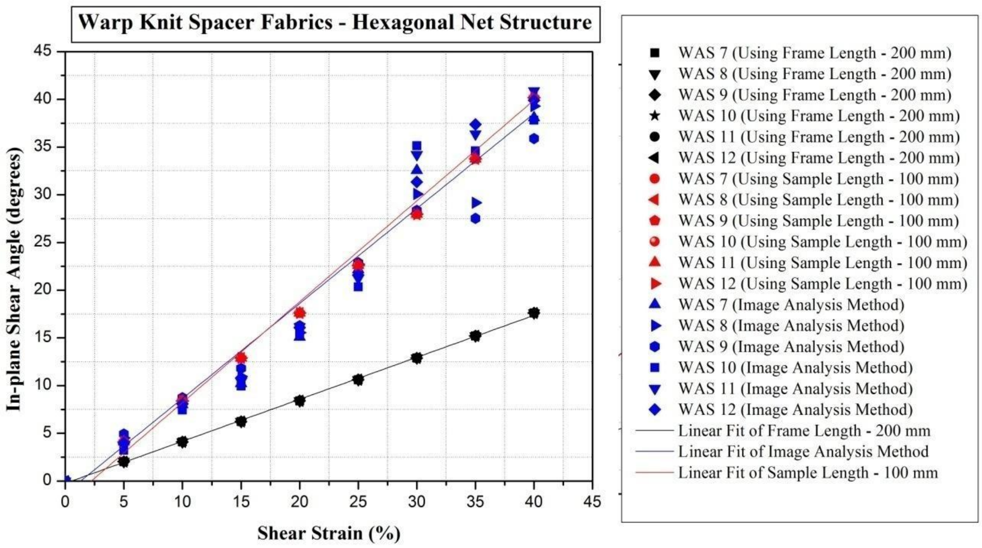
Figure 11. Linear regression fit of shear angle using image analysis as a function of strain of warp knit spacer fabrics (a) Lock knit structure (b) hexagonal net structure

5.1.6 Comparative discussion of shear behavior of warp knitted spacer fabrics using different methods

The shear angles are calculated by considering sample length as a substitute for L in Equation 2 and it is further used for calculation of shear force. Figure 12 shows the comparison of shear angles between image analysis and both experimental measurements for all 12 specimens. It was noted that dimension of the frame rig length can cause big difference in shear angle as shown in Figure 12. Further study is required on the effect of different frame rig length and ratio of frame length to specimen size on in-plane shear behavior of 3D warp spacer fabrics. The comparative linear regression is given in the Table 9 as a function of shear strain.



(a)



(b)

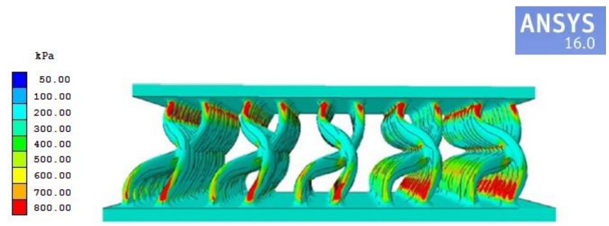
Figure 12. Comparison of shear behavior of warp knit spacer fabrics using different test methods (a) Lock knit structure (b) Hexagonal net structure

Table 9. Prediction of shear stress of warp knit spacer as a function of shear strain using different methods

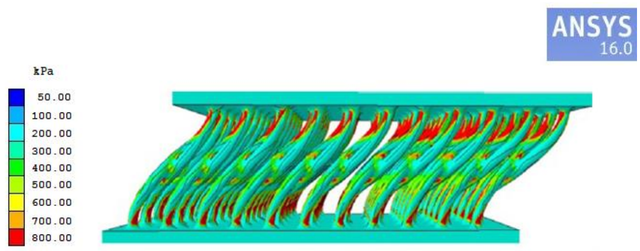
Warp Knit Spacer Fabrics - Lock Knit Structure						
Equation	y = a + b*x					
DF	**Model - 1 , Error - 7, Total - 8**					
Methods		**Value**	**Standard Error**	**Residual Sum of Squares**	**F Value**	**Prob>F**
Using Frame Length	**Intercept**	-0.236	0.101	0.188	10820.581	2.00E-12
	Slope	0.440	0.004			
Using Sample Length	**Intercept**	-1.297	0.641	7.607	1367.847	2.75E-09
	Slope	0.046	0.027			
Image Analysis Method	**Intercept**	-0.071	1.097	22.283	414.594	1.73E-07
	Slope	0.046	0.046			
Warp Knit Spacer Fabrics - Hexagonal Net Structure						
Using Frame Length	**Intercept**	-0.236	0.101	0.188	10820.581	2.00E-12
	Slope	0.440	0.004			
Using Sample Length	**Intercept**	-1.297	0.641	7.607	1367.847	2.75E-09
	Slope	0.995	0.027			
Image Analysis Method	**Intercept**	-2.339	1.451	39.032	300.433	5.23E-07
	Slope	1.057	0.061			

5.1.7 Prediction of shear stress using Finite Element Method

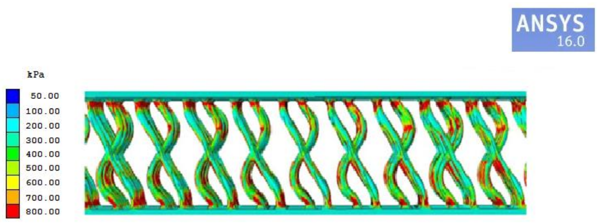
The spacer structures were made using solidworks45 and were imported into ANSYS platform for mesh generation. The number of nodes in unit cell was 2130. Material properties e.g. tensile modulus, tensile strength, strain rate, Poisson's ratio etc. were used. Shear stress at various displacements were simulated. The results are shown in figure 13 and 14.



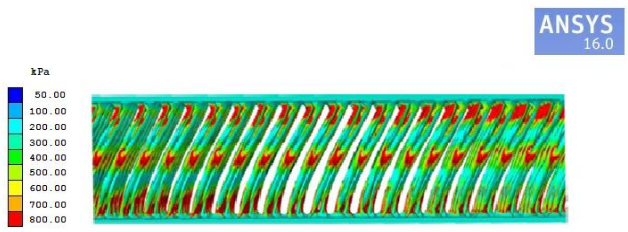
(a)



(b)



(c)



(d)

Figure 13 (a) Lock knit spacer before shear, (b) Lock knit spacer after shear, (c) Hexagonal net spacer before shear and (d) Hexagonal net spacer after shear

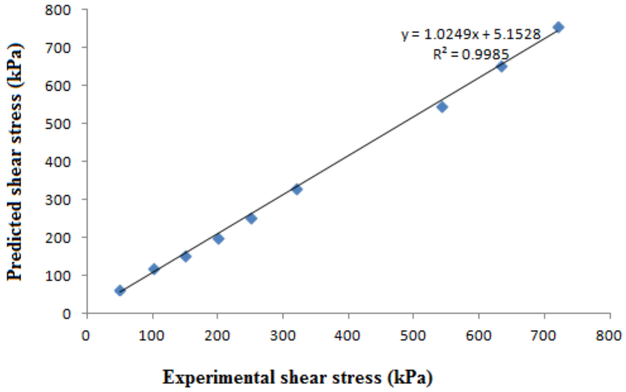
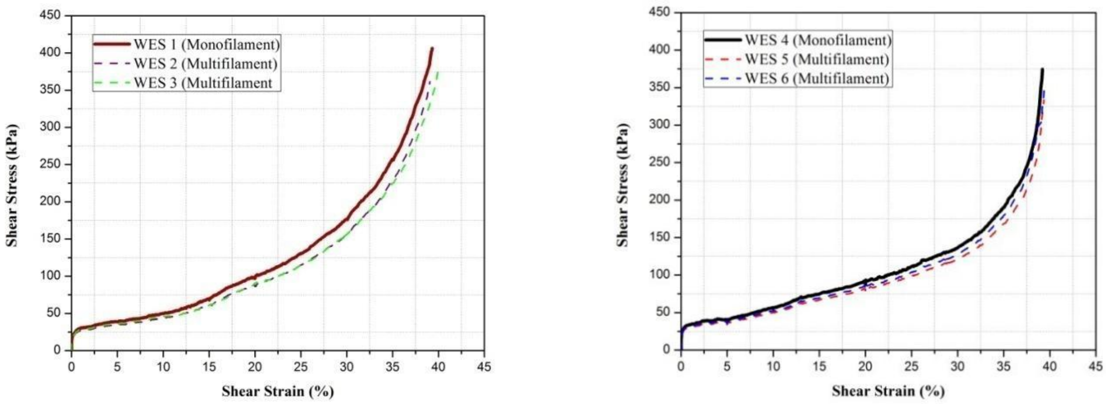


Figure 14 Correlation of simulated and experimental shear stress

The predicted shear stress was well correlated with experimental values obtained.

5.1.8 Experimental evaluation of in-plane shear behavior of weft knitted spacer fabrics

There is no shearing in the beginning of axial displacement of frame. Subsequently, the shear deformation resistance was mainly from the friction between the wale and course direction loops before reaching the limiting locking angle. The limiting locking angle is the ultimate shear deformation observed by means of local wrinkling. A vertical displacement of 40 mm, which corresponds to a shear angle of around 50^o was found to be the maximum displacement but the pre-buckling occurs after 20 mm displacement with shear angle range of 20-30^o. The local buckling is calculated using image analysis software. The effect of thickness and types of spacer yarn on in-plane shear behavior of weft knitted spacer fabrics have been carefully evaluated and analyzed with respect to different structural parameters. As shown in Figure 15, the fabric samples (WES 1 and WES 2) offers higher resistance to shear than that of other fabrics. Also, the stress-strain curve reveals that the shear deformation is high is high for the fabric samples WES 4 to WES 6. It might be due to the two reasons that, fabrics (WES 4 – WES 6) made up of 6% lycra yarn on the surface layer which results large deformation during initial surface elongation. Also the sample with monofilament spacer yarn (WES 1 & WES 4) offers more resistance to compressive force results high shear resistance during the lateral compression stage.



(a) (b)

Figure 15. Influence of fabric characteristic on shear behavior of weft knit spacer fabrics

There was no marginal differences in shear stress between the samples in stage 1 (surface extension and lateral compression), but significant differences was seen immediately before pre-buckling and stage 3 (densification). From this observation, it is suggested that the fabrics with different thicknesses have ability to undergo different shear stress. The thickness of the fabric should be selected according to the amount of the energy to be absorbed and the allowed stress level.

5.1.9 In-plane shear work done of weft knit spacer fabrics

The figure reveal that fabrics WES 1 and WES 4 have higher work done than that of other fabrics when it undergoes in-plane shear. Over all work done values are higher for the fabrics made up of monofilament spacer yarn and without lycra on the face side than that of other fabrics. Figure 16 presents the graphical analysis of shear stress versus absorbed energy versus efficiency. The maximum energy-absorption and efficiency are obtained at the end of the densification stage. The point at the maximum energy-absorption efficiency can also be considered a critical point in the densification zone. Overall it is observed that the shear work done and efficiency is higher for the thick fabrics made up of monofilament spacer yarn with low density. Also it is found that fabrics with multifilament yarns undergoes large amount of shear deformation during shearing mechanism. From the energy absorption graph, it is easy to find the stress associated with the required amount of energy to be absorbed.

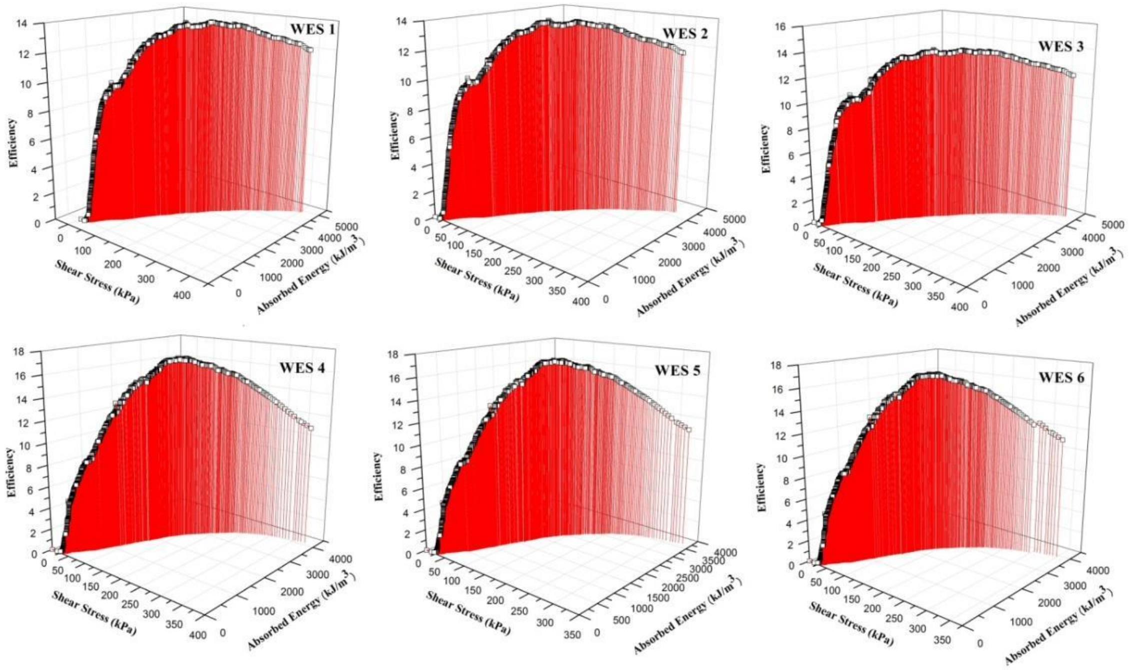


Figure 16. In-plane shear energy absorption and efficiency of weft knit spacer fabrics

5.1.10 Relation between shear angle versus shear force of weft knit spacer fabrics

It was observed from the graph that the spacer fabric without lycra on the surface with monofilament spacer yarn (WES 1) offers more shear resistance than that of other fabrics. The thick spacer fabric with lycra on surface with multifilament spacer yarn (WES 5) have ability to undergoes high shear angle with low shear stress. The average of in-plane stress responses against shear angle obtained for each spacer fabrics samples was fitted in the general form of linear fit (Figure 17) [Table 10].

The estimated regression coefficients of the fitted linear regression equation as well as the correlation coefficients for each model are given in Table 4.5. The adequacy of the models was tested using residuals sum of squares, probability and adjusted coefficient of determination (R^2).

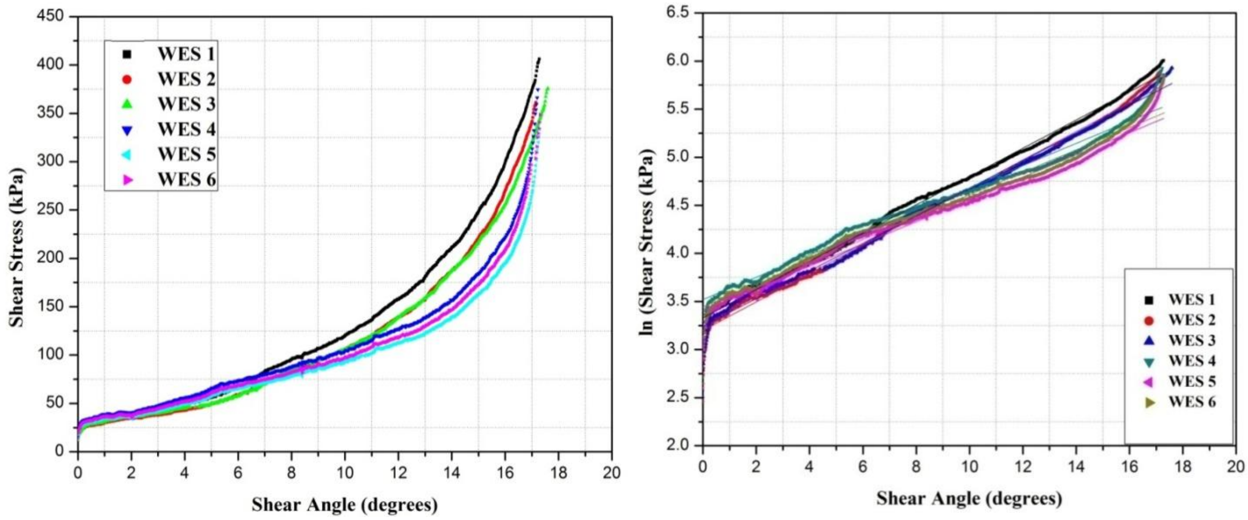


Figure 17. Experimental determination of shear angle vs shear force and linear regression fit of weft knit spacer fabrics

Table 10. Prediction of experimental shear strength of weft knit spacer fabrics using linear regression model

Equation	**y = a + b*x**						
DF	**Model - 1 , Error - 910, Total - 911**						
Weight	**No Weighting**						
Sample Nos.			**Value**	**Standard Error**	**Residual Sum of Squares**	**F Value**	**Prob>F**
ln (Shear Stress)	**WES 1**	**Intercept**	3.330	0.003			
		Slope	0.147	0.000	2.615	169893.047	0.000
	WES 2	**Intercept**	3.201	0.003			
		Slope	0.148	0.000	2.847	155905.056	0.000
	WES 3	**Intercept**	3.244	0.004			
		Slope	0.143	0.000	2.990	147895.851	0.000
	WES 4	**Intercept**	3.520	0.005			
		Slope	0.116	0.001	5.544	49779.348	0.000
	WES 5	**Intercept**	3.405	0.005			
		Slope	0.116	0.001	5.566	49599.977	0.000
	WES 6	**Intercept**	3.445	0.005			
		Slope	0.117	0.001	5.396	51150.606	0.000

5.1.11 Statistical evaluation – in-plane shear behavior of weft knit spacer fabrics

The above-mentioned results are confirmed by analysis of variance (ANOVA), and the result is significant influence of the surface structure, types of spacer yarn and thickness on fabric properties. In this section, one-way ANOVA is described and the selected value of significance for all statistical tests in the study is α = 0.05 levels. The degree of freedom is 1, 8, the $F_{critical}$ is 5.318, and degree of freedom 3, 16, the $F_{critical}$ is 3.239.. The results of the ANOVA are listed in Table 11, which analyses the effect of groups of thickness and surface characteristics and types of spacer yarn of spacer fabric samples with in-plane shear stress. The value of $F_{critical} < F_{actual}$ proves that the changes in the thickness, types of spacer yarn and surface layer structure (stitch density) of warp-knitted spacer fabric results is highly significant on the above-mentioned fabric in-plane shear stress.

Table 11. Statistical evaluation for in-plane shear behavior of weft knit spacer fabrics

		F_{cri}	F_{cal}	Prob.	Conclusion	Z-score (95% interval)	Pairwise comparison (Scheffé's method): Compared Pair	Prob.	Significance
One Way Anova - Influence of various factors on shear stress of weft knit spacer fabrics									
Test of factor influence : Influence of monofilament spacer yarn between both the groups									
a	**Without Lycra**	5.318	25.205	0.0010	Significant	1.255	a-b	1.03E-03	Significant
b	**With Lycra**					-1.255			
Test of factor influence : Influence of multifilament spacer yarn between both the groups									
a	**Without Lycra (Thickness - 2.62mm)**	3.239	19.803	2.03E-08	Significant	4.577	a-b	1.34E-01	Insignificant
							a-c	0.001959	Significant
b	**Without Lycra (Thickness - 2.74mm)**					4.761	a-d	2.21E-01	Insignificant
c	**With Lycra (Thickness - 3.5mm)**					-4.226	b-c	2.1E-05	Significant
							b-d	0.002302	Significant
d	**With Lycra (Thickness - 3.4mm)**					-4.416	c-d	1.16E-01	Insignificant
Test of factor influence : Influence of types of spacer yarn within the group - Without Lycra									
a	**Monofilament Spacer Yarn (Thickness - 4.4 mm)**	5.318	52.654	8.75E-05	Significant	5.883	a-b	8.75E-05	Significant
b	**Multifilament Spacer Yarn (Thickness - 2.62 mm)**					-5.231			
Test of factor influence : Influence of types of spacer yarn within the group - With Lycra									
a	**Monofilament Spacer Yarn (Thickness - 4.4 mm)**	5.318	19.902	2.11E-03	Significant	5.591346	a-b	0.002108	Significant
b	**Multifilament Spacer Yarn (Thickness - 3.4 mm)**					-5.20286			

The pair comparison result shows that the insignificant differences in shear stress within group for the samples made up of multifilament space yarn with same surface yarn with different thickness. But the quite significant values are obtained for the samples with multifilament yarn between the groups.

5.1.12 Determination of shear angle of weft knit spacers using image analysis method

The shear angle of weft knitted spacer fabrics was determined using image analysis method at different displacement levels and presented in the Figure 18. The spacer fabric samples (WES1 – WES 6) have smooth and linear increases in shear angle till 20mm displacement. The image analysis shear angle is plotted against the shear strain all weft knit spacer samples (WES 1 – WES 6) are given in the Figure 18.

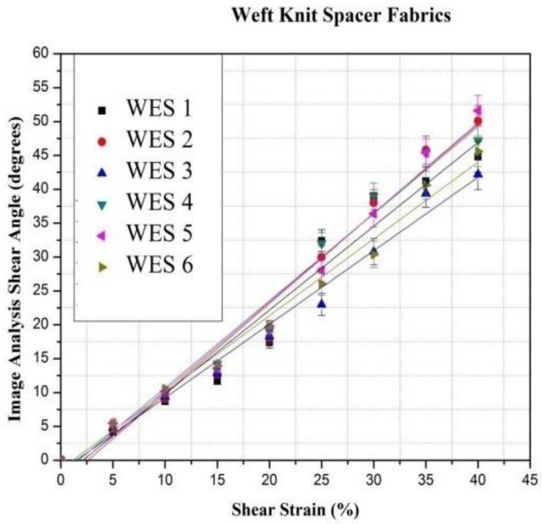


Figure 18. Linear regression fit of shear angle using image analysis as a function of strain of weft knit spacer fabrics

Table 12. Prediction of shear angle using image analysis as a function of shear strain of weft knit spacers

Equation	**y = a + b*x**					
DF	**Model - 1 , Error - 7, Total - 8**					
Sample Nos.		**Value**	**Standard Error**	**Residual Sum of Squares**	**F Value**	**Prob>F**
WES 1	**Intercept**	-2.593	2.196	89.350	180.101	2.99E-06
	Slope	1.238	0.092			
WES 2	**Intercept**	-3.451	1.862	64.220	289.352	5.95E-07
	Slope	1.330	0.078			
WES 3	**Intercept**	-1.611	1.176	25.630	482.255	1.03E-07
	Slope	1.085	0.049			
WES 4	**Intercept**	-2.162	1.744	56.330	307.898	4.81E-07
	Slope	1.285	0.073			
WES 5	**Intercept**	-2.816	1.618	48.490	371.373	2.52E-07
	Slope	1.310	0.068			
WES 6	**Intercept**	-1.304	1.101	22.460	599.889	4.82E-08
	Slope	1.133	0.046			

Also, the linear model fit was presented in figures with shear strain as independent variable and shear angle as dependent variable. The regression equation for all the samples are given in the Table 12. with the correlation coefficient (R^2) to find the degree of linear fit.

5.1.13 Comparative discussion of shear behavior of weft knitted spacer fabrics using different methods

The differences between image analysis and calculated shear angle using sample length at the chosen points are relatively small. It did not show any significant difference until pre-buckling occurs but significant difference occurs after 20 mm displacement [Figure 19]. The regression equation for all the samples are given in the Table 13. with the correlation coefficient (R^2) to find the degree of linear fit.

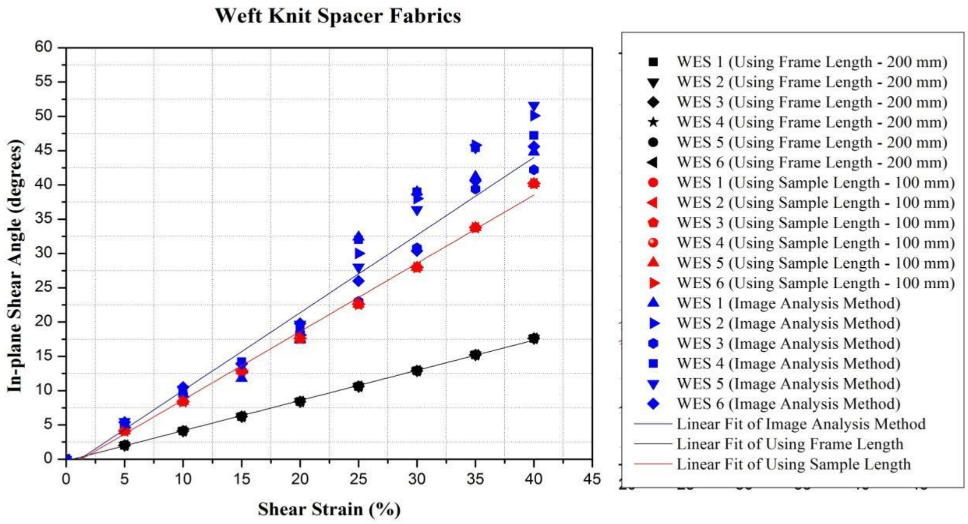


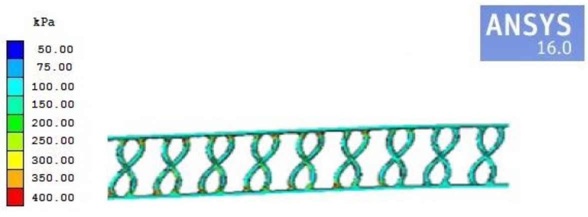
Figure 19. Comparison of shear behavior of weft knit spacer fabrics using different test methods

Table 13. Prediction of shear stress of weft knit spacer as a function of shear strain using different methods

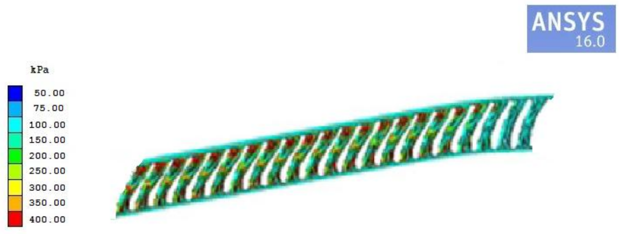
Equation	y = a + b*x					
DF	**Model - 1 , Error - 7, Total - 8**					
Sample Nos.		**Value**	**Standard Error**	**Residual Sum of Squares**	**F Value**	**Prob>F**
Using Frame Length	**Intercept**	-0.236	0.101	0.188	10820.581	2.00E-12
	Slope	0.440	0.004			
Using Sample Length	**Intercept**	-1.297	0.641	7.607	1367.847	2.75E-09
	Slope	0.995	0.027			
Image Analysis Method	**Intercept**	-1.304	1.101	22.469	599.889	4.82E-08
	Slope	1.133	0.046			

5.1.14 *Prediction of shear stress using Finite Element Method*

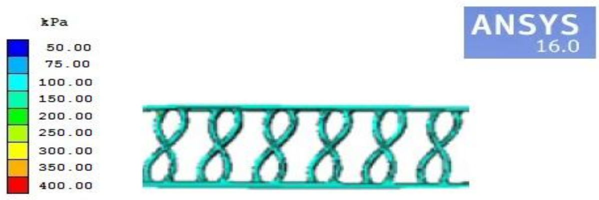
The FEM analysis was also employed for predicting shear stress for both categories of weft knitted spacer fabrics. Results are shown in figures 20 and 21.



(a)



(b)



(c)

(d)

Figure 20. Weft knitted spacer (a) without Lycra before shear (b) without Lycra after shear (c) with Lycra before shear and (d) with Lycra after shear

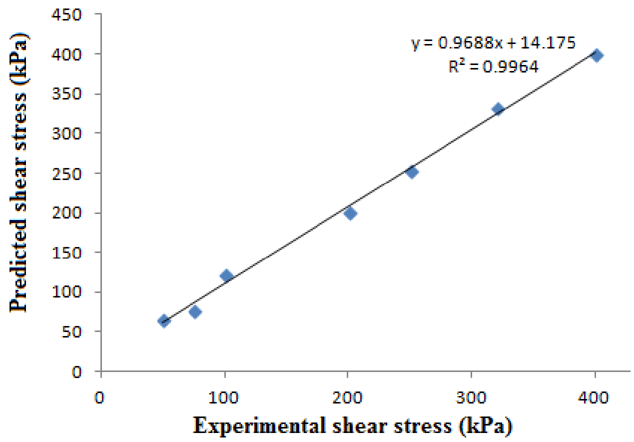
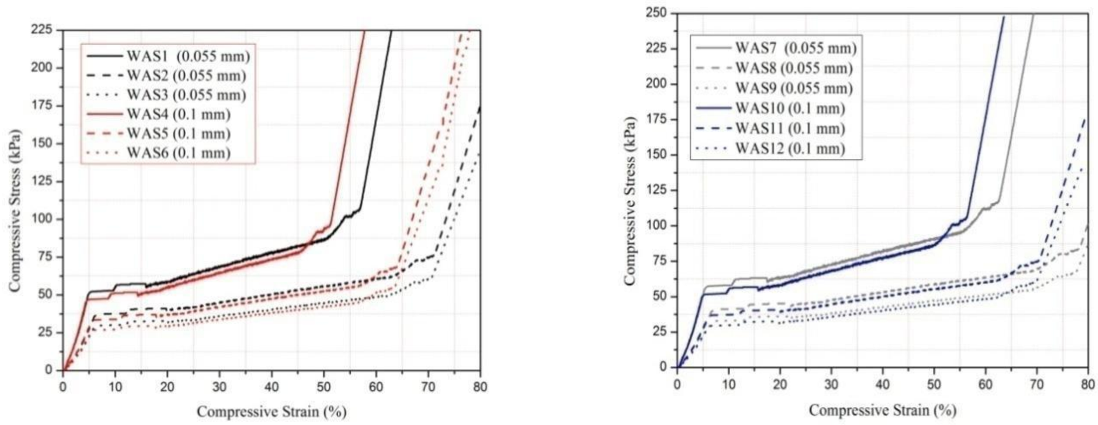


Figure 21. Correlation of shear stress predicted vs experimental

5.2 Compression behavior of spacer fabrics

5.2.1 Influence of fabrics characteristics on compression behavior of warp knit spacer fabrics

The stress-strain curve reveals that the compressive resistance decreases with increase in thickness [Figure 22 & 23]. It can be seen that, the samples have almost same at linear stage due to same surface structure and density. In stage two (elastic), the compressive stress of all fabrics was directly proportional to the strain. It was also observed that the thicker fabric had the ability to undergo larger deformation under low loading condition. In both sets of spacer fabrics (lock knit and hexagonal net), two types of spacer yarn with different linear density (33 & 108 dtex) and diameter (0.055 & 0.1 mm) were used for convenient analysis of its effect on compression. The spacer yarns act as a linear spring which offers more resistance towards compression as compared to other type of materials in cushioning applications. It is observed that, the compressive resistance is high for the fabrics with coarser spacer yarn for both the structures. In plateau region (3^{rd} stage), the fabrics have almost identical stress-strain behavior with same thickness for both lock knit and hexagonal spacers. But in stage 4, the lower deformation was observed in the fabrics with coarser spacer yarn than the fabrics made up of finer spacer yarn. The compression stress-strain behavior for both the structures (Lock knit and Hexagonal net) exhibits same load and deformation in initial stage. In linear elastic stage, it was found that the Hexagonal-mesh fabric offers lowest compression resistance than that of lock knit structures. All the samples had almost close value in the plateau region irrespective of other structural parameters such as thickness and spacer yarn properties. Also, it might be due to insignificant differences in stitch density. In stage 4, the Hexagonal net fabrics (WAS 7 – WAS 12) undergo large deformation for the same compression stress.



(a) **(b)**

Figure 22. Influence of thickness and spacer yarn on compressive behavior of warp knit spacer fabrics

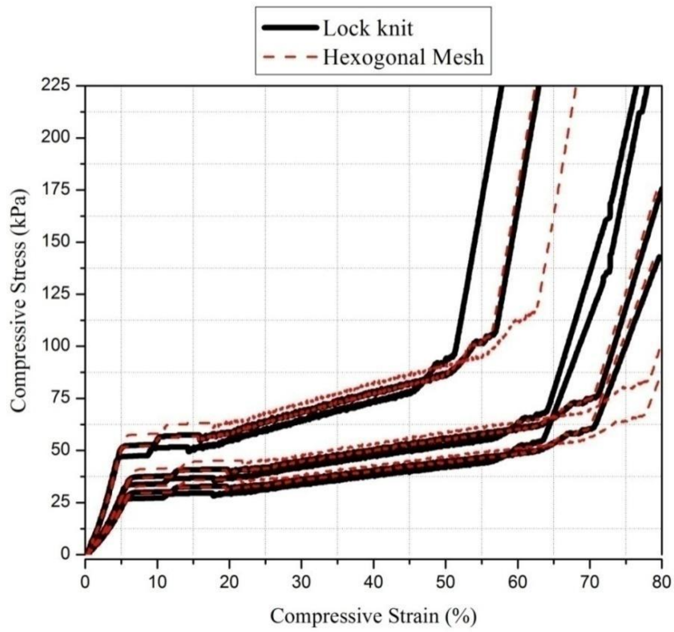


Figure 23. Influence of surface structure on compressive behavior of warp knit spacer fabrics

5.2.2 Compressive energy absorption of warp knit spacer fabrics

From the Figure, the absorbed energy of lock knit spacer fabrics (WAS 1 – WAS 6) linearly increases with the stress in the initial stage of compression. The marginal differences in energy absorption between the samples can be seen when the compressive stress reaches towards the third stage for both the structures. At the start of densification stage, the rapid increases in stress results in small deformation and energy absorption. From the energy absorption graph, it is easy to find the stress associated with the required amount of energy to be absorbed. So, it is more convenient to select the suitable spacer fabrics for cushioning application with optimum compressive performance [Figure 24].

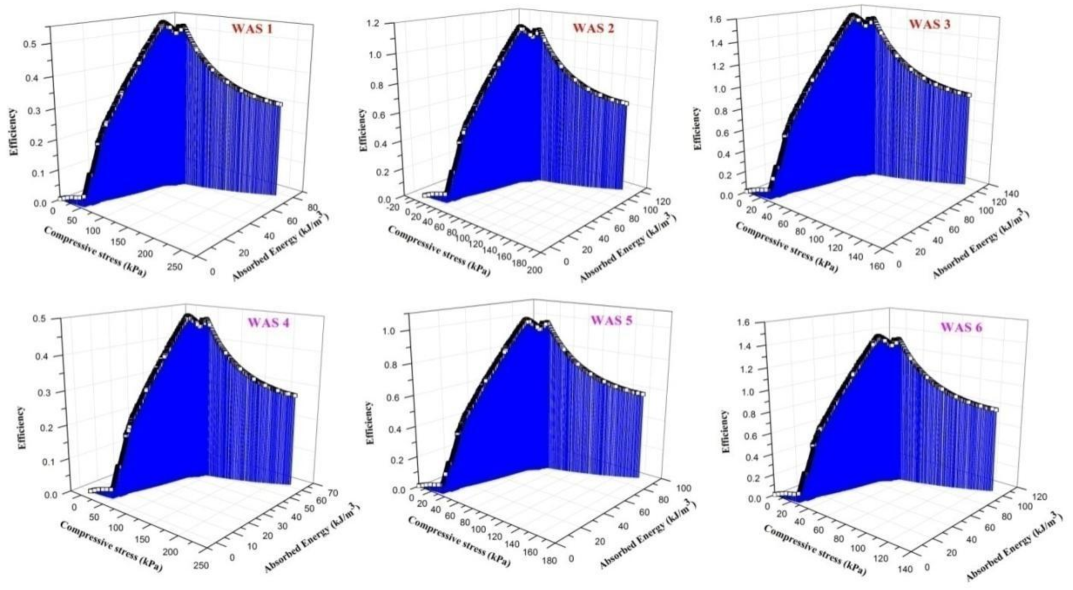


Figure 24. Energy absorption and efficiency of lock knit spacer fabrics

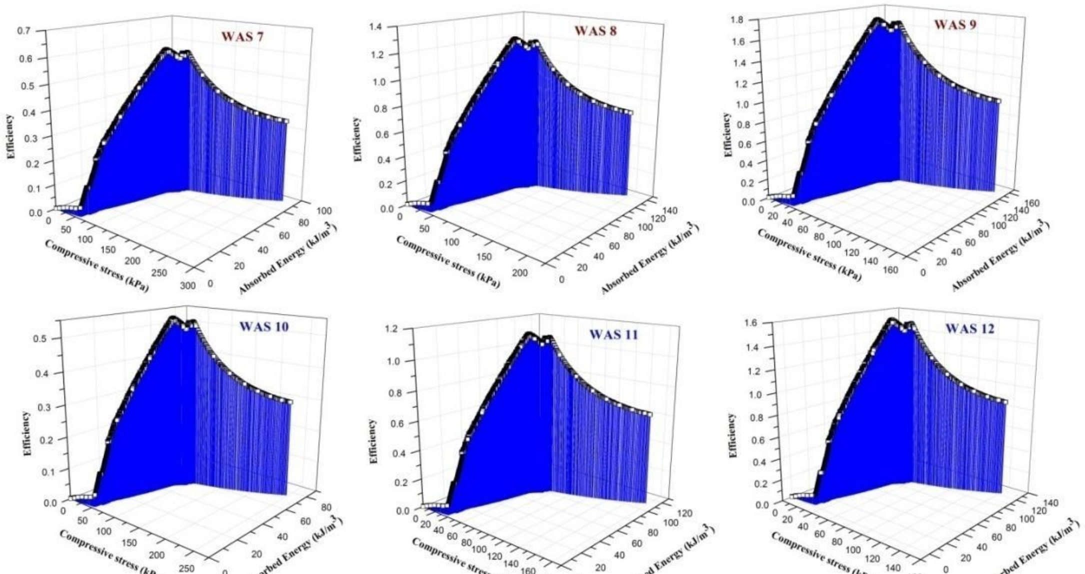


Figure 25. Energy absorption and efficiency of hexagonal net spacer fabrics

As observed in Figure 25., the fabric with hexagonal net structure also shows the same tendency in energy absorption and efficiency with the effect of thickness and spacer yarn. Similar tendency was observed for the efficiency- stress curve until the densification stage starts as like energy absorbed for the spacer samples. The maximum energy-absorption efficiency was obtained at the end of the plateau stage. Efficiency decreases with rapid increase in stress level in the densification stage. It was also due to dramatic increase in volume density of the spacer fabrics. The point at the maximum energy-absorption efficiency can also be considered a critical point between the plateau zone and the densification zone. Overall it was observed that the compressive energy and efficiency is higher for the thicker fabrics with low density.

Table 14. Prediction of compressive stress of warp knit spacer fabrics using polynomial regression model

Model	Polynomial						
Equation	$y = Intercept + B1x + B2x^2 + B3x^3$						
	Warp Knit Spacer Sample Nos.		Value	Standard Error	Residual Sum of Squares	F Value	Prob>F
Compressive Stress	WAS 1	Intercept	4.576	0.936	291173.900	10909.738	0
		B1	7.579	0.125			
		B2	-0.289	0.004			
		B3	0.003	0.000			
	WAS 2	Intercept	3.269	0.669	148558.100	10910.738	0
		B1	4.331	0.071			
		B2	-0.132	0.002			
		B3	0.001	0.000			
	WAS 3	Intercept	2.615	0.535	95077.180	10911.738	0
		B1	3.493	0.058			
		B2	-0.108	0.002			
		B3	0.001	0.000			
	WAS 4	Intercept	4.119	0.843	235850.800	10912.738	0
		B1	7.579	0.125			
		B2	-0.322	0.005			
		B3	0.004	0.000			
	WAS 5	Intercept	-3.036	0.736	202133.900	17542.797	0
		B1	5.488	0.082			
		B2	-0.193	0.002			
		B3	0.002	0.000			
	WAS 6	Intercept	-5.978	0.718	199599.900	17012.842	0
		B1	5.100	0.079			
		B2	-0.183	0.002			
		B3	0.002	0.000			
	WAS 7	Intercept	5.034	1.030	352320.400	10912.738	0
		B1	7.579	0.125			
		B2	-0.263	0.004			
		B3	0.003	0.000			
	WAS 8	Intercept	3.596	0.736	179755.300	10913.738	0
		B1	4.331	0.071			
		B2	-0.120	0.002			
		B3	0.001	0.000			
	WAS 9	Intercept	2.876	0.589	115043.400	10914.738	0
		B1	3.493	0.058			
		B2	-0.098	0.002			
		B3	0.001	0.000			
	WAS 10	Intercept	4.530	0.927	285379.500	10915.738	0
		B1	7.579	0.125			
		B2	-0.292	0.005			
		B3	0.004	0.000			
	WAS 11	Intercept	3.236	0.662	145601.800	10916.738	0
		B1	4.331	0.071			
		B2	-0.134	0.002			
		B3	0.001	0.000			
	WAS 12	Intercept	2.589	0.530	93185.140	10917.738	0
		B1	3.493	0.058			
		B2	-0.109	0.002			
		B3	0.001	0.000			

Also it was found that fabrics with finer spacer yarns undergoes large amount of work done as well as high efficiency during compression mechanism. The true relationship between two variables is more complex than that, and this is when polynomial regression comes in to help. The Polynomial curves can be used as a sort of replacement for transformations of x. The average of compressive stress responses against strain obtained for each spacer fabrics samples was fitted in the general form of third order polynomial (Figure 26). Response fit analyses, regression coefficient estimations and model significance evaluations were conducted. The estimated regression coefficients of the fitted polynomial equation as well as the correlation coefficients for each model are given in Table 14. The adequacy of the models was tested using residuals sum of squares and adjusted coefficient of determination (R^2).

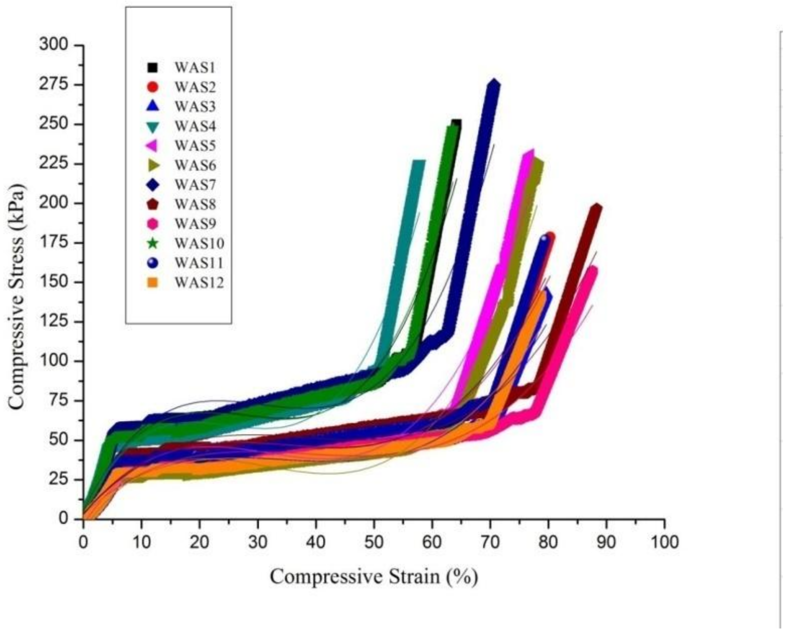


Figure 26. Third order polynomial regression fit for compressibility of warp knit spacer fabrics

5.2.3 Statistical evaluation for compressive behavior response of warp knit spacer fabrics

In this section, two-way ANOVA is analyzed and the selected value of significance for all statistical tests in the study is 0.05 levels. Analysis of different combination of factors on compressive work done is presented in Table 15. The factors mainly considered are thickness, spacer yarn diameter and structure which strongly influence the compressive behavior and energy absorption of the three-dimensional spacer fabrics.The critical quantile ($F_{critical}$) values obtained for factor A-18.51, 19, Factor B–19 and Interaction–161.45 with respect to degrees of freedom. The value of $F_{critical} < F_{statistic}$ proves that the changes in the thickness, spacer yarn linear density and surface layer structure of warp-knitted spacer fabric significantly influences the above-mentioned fabric compression properties. Even a minor change in the fabric thickness results in significant impact on the compression behavior. Interaction factors structure–thickness with spacer yarn diameter (0.1mm) and spacer yarn diameter–thickness in lock- knit structure don't have significant influence ($p > 0.05$) on compression behavior.

Table 15. Statistical evaluation for compression behavior of weft knit spacer fabrics

ANOVA Table

Source of variability	Sum of squares	Mean square	Degrees of freedom	Std deviation	F-statistic	Critical quantile	Conclusion	p-value
Influence of spacer yarn dia and thickness on energy absorption - lock knit								
Spacer Yarn Diameter	289.94	289.94	1	17.028	399.858	18.513	Significant	0.0024916
Thickness	2743.96	1371.98	2	37.04	1892.078	19	Significant	0.0005282
Interaction	0.1	0.1	1	1.204	0.077	161.448	Insignificant	0.8275701
Residuals	1.35	1.35	1	1.16				
Total	3035.35	607.07	5	24.639				
Influence of spacer yarn dia and thickness on energy absorption - Hexogonal net								
Spacer Yarn Diameter	887.57	887.57	1	29.79	49.54	18.51	Significant	0.0195932
Thickness	3251.63	1625.82	2	40.32	90.75	19	Significant	0.0108991
Interaction	35.83	35.83	1	5.99	5.54141E+13	161.45	Significant	8.55E-08
Residuals	0	0	1	0				
Total	4175.04	835.01	5	28.9				
Influence of structure and thickness on energy absorption for spacer yarn dia (0.055 mm)								
Structure	740.68	740.68	1	27.22	49.61	18.51	Significant	0.0195683
Thickness	3311.36	1655.68	2	40.69	110.89	19	Significant	0.0089373
Interaction	29.86	29.86	1	5.46	93824837.28	161.45	Significant	6.57E-05
Residuals	0	0	1	0				
Total	4081.9	816.38	5	28.57				
Influence of structure and thickness on energy absorption for spacer yarn dia (0.1 mm)								
Structure	208.77	208.77	1	14.45	206.12	18.51	Significant	0.0048165
Thickness	2689.96	1344.98	2	36.67	1327.91	19	Significant	0.0007525
Interaction	0.71	0.71	1	1.42	0.54	161.45	Insignificant	0.5978509
Residuals	1.32	1.32	1	1.15				
Total	2900.75	580.15	5	24.09				

5.2.4 Effect of fabric characteristics on compression behavior of weft knit spacer fabrics

As shown in Figure 26, the compressive stress-strain curve reveals that the compressive resistance of spacer fabric without lycra made up of monofilament yarn is low in linear and elastic stage, but sudden increase in compressive stress observed in plateau and densification stage. From Figure 27, spacer fabrics with lycra made up of monofilament spacer yarn constantly offers high compression resistance in all four stages. It was observed that the denser fabrics require higher compressive stress to undergo same compressive deformation than the fabric with low density. It was also observed that the thicker fabric has ability to undergo larger deformation under low loading condition. It has also been found that the outer layer structures could affects the stitch density of the fabrics. The stitch density on the surface layer directly affects the compressive strength of the spacer fabrics. The compressive resistance increases with increase in stitch density. The lower stitch density on the surface of the fabric results in large surface deformation. In stage 4, the lower deformation was observed in the fabrics with monofilament spacer yarn than the fabrics made up of multifilament spacer yarn. It might be the fact that the spacer yarns have comes in to contact with each other and also makes locking effect with surface structure as quick as possible.

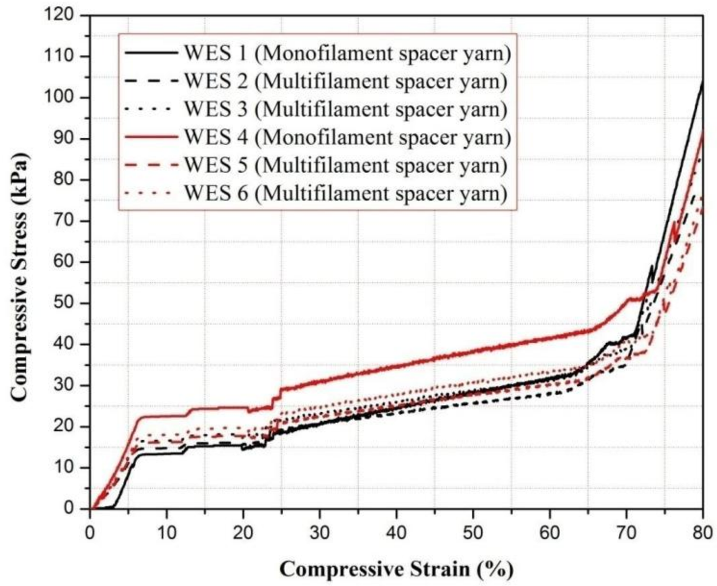


Figure 27. Influence of fabric characteristics on compressive behavior of weft knit spacer fabrics

5.3.5 Compressive energy absorption of weft knit spacer fabrics

It is observed from the figure that the absorbed energy of weft knit spacer fabrics (WES 1 –WES 6) linearly increases with the stress in the initial stage of compression. The marginal differences in energy absorption between the samples can be seen when the compressive stress reaches towards the third stage for both the groups [Figure 28].

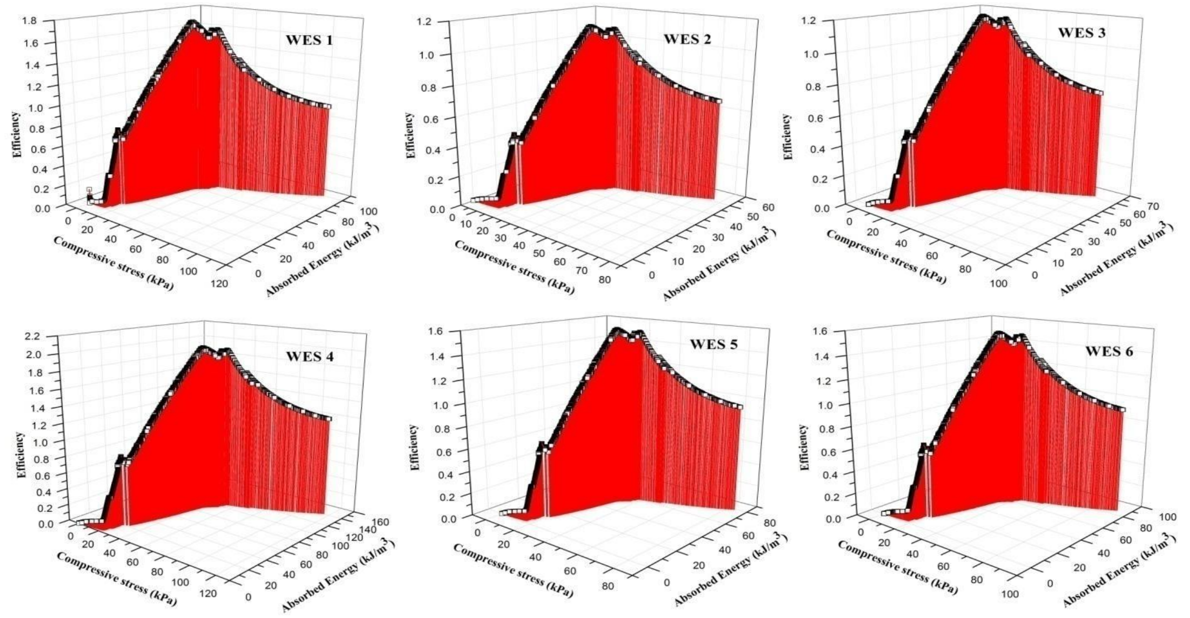


Figure 28. Energy absorption and efficiency of weft knit spacer fabrics

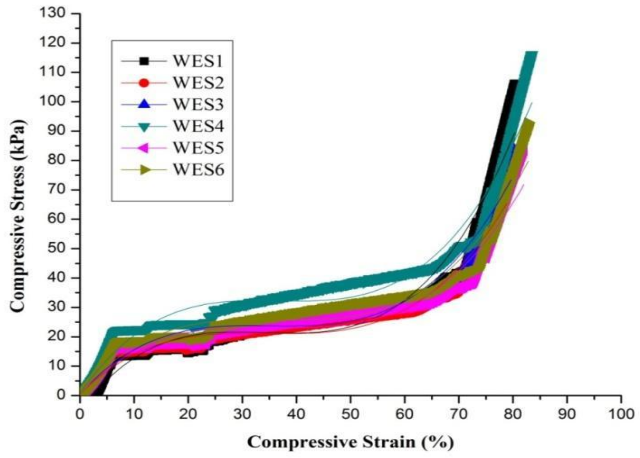


Figure 29. Third order polynomial regression fit for compressibility of weft knit spacers

Table 16. Prediction of compressive stress of weft knit spacer fabrics using polynomial regression model

Model			**Polynomial**				
Equation			y = Intercept + B1x + B2x^2 + B3x^3				
Weight			**No Weighting**				
	Sample Nos.		**Value**	**Standard Error**	**Residual Sum of Squares**	**F Value**	**Prob>F**
Compressive Stress	**WES 1**	**Intercept**	-5.123	0.413	56756.200	12126.867	0.000
		B1	2.450	0.044			
		B2	-0.073	0.001			
		B3	0.001	0.000			
	WES 2	**Intercept**	0.473	0.270	24157.850	12940.484	0.000
		B1	1.835	0.029			
		B2	-0.054	0.001			
		B3	0.001	0.000			
	WES 3	**Intercept**	0.531	0.303	30483.590	12940.484	0.000
		B1	2.040	0.033			
		B2	-0.059	0.001			
		B3	0.001	0.000			
	WES 4	**Intercept**	0.722	0.412	56274.350	12940.484	0.000
		B1	2.644	0.042			
		B2	-0.073	0.001			
		B3	0.001	0.000			
	WES 5	**Intercept**	0.520	0.296	29172.620	12940.484	0.000
		B1	1.939	0.031			
		B2	-0.055	0.001			
		B3	0.001	0.000			
	WES 6	**Intercept**	0.578	0.329	36015.580	12940.484	0.000
		B1	2.132	0.034			
		B2	-0.059	0.001			
		B3	0.001	0.000			

At the start of densification stage, the rapid increases in stress results in small deformation and energy absorption. From the energy absorption graph, it is easy to find the stress associated with the required amount of energy to be absorbed. As noticed from the Figure 28, in the densification stage, efficiency decreases with rapid increase in stress level. It is also because of dramatic increase in volume density of the spacer fabrics. The point at the maximum energy-absorption efficiency can also be considered a critical point between the plateau zone and the densification zone. The average of compressive stress responses against strain obtained for each spacer fabrics samples was fitted in the general form of third order polynomial (Figure 29). The estimated regression coefficients of the fitted polynomial equation as well as the correlation coefficients for each model are given in Table 16.

5.2.6 Statistical evaluation for compressive behavior response of weft knit spacer fabrics

The degree of freedom is 1, 8, the F_{critic}al is 5.318, and degree of freedom 3, 16, the $F_{critical}$ is 3.239. The insignificant difference in compressive stress is obtained between the pair, sample made up of multifilament spacer yarn without lycra on surface and with lycra. But the quite significant values are obtained in compressive stress between the other samples with multifilament spacer yarn [Table 17].

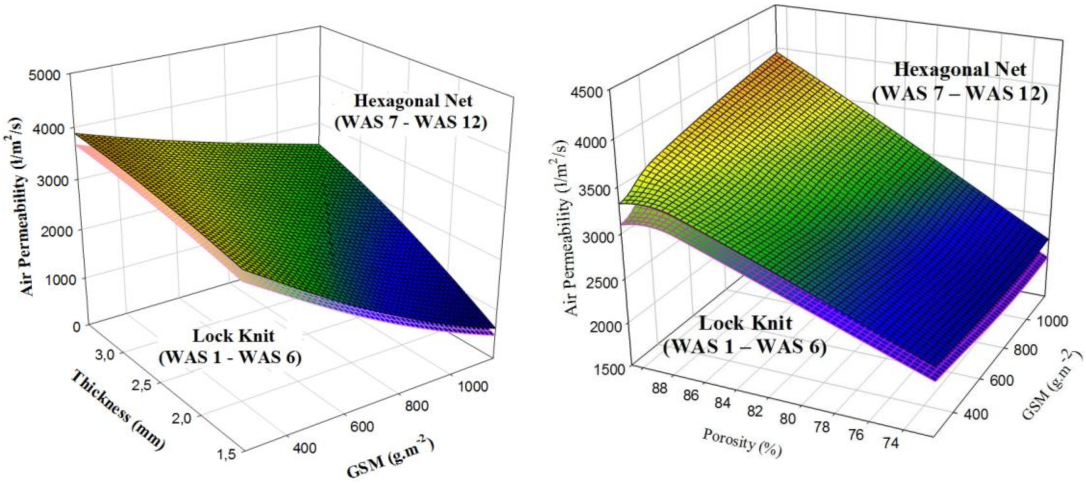
Table 17. Statistical evaluation for compressive behavior of weft knit spacer fabrics

One Way Anova - Influence of various factors on compression stress of weft knit spacer fabrics									
Test of factor influence : Influence of monofilament spacer yarn between both the groups									
							Pairwise comparison (Scheffé's method)		
		F_{cri}	**F_{cal}**	**Prob.**	**Conclusion**	**Z-score (95% interval)**	**Compared Pair**	**Prob.**	**Significance**
a	**Without Lycra**	5.318	30.520	0.0006	Significant	-2.859	a-b	5.57E-04	Significant
b	**With Lycra**					3.126			
Test of factor influence : Influence of multifilament spacer yarn between both the groups									
a	**Without Lycra (Thickness - 2.62mm)**	3.239	92.238	2.03E-08	Significant	-1.974	a-b	4.98E-05	Significant
b	**Without Lycra (Thickness - 2.74mm)**					2.217	a-c a-d	0.000561 2.22E-08	Significant Significant
c	**With Lycra (Thickness - 3.5mm)**					-2.169	b-c	0.614266	Insignificant
d	**With Lycra (Thickness - 3.4mm)**					2.410	b-d c-d	0.000637 5.59E-05	Significant Significant
Test of factor influence : Influence of types of spacer yarn within the group - Without Lycra									
a	**Monofilament Spacer Yarn (Thickness - 4.4 mm)**	5.318	409.016	3.73E-08	Significant	3.138	a-b	3.73E-08	Significant
b	**Multifilament Spacer Yarn (Thickness - 2.62 mm)**					-2.248			
Test of factor influence : Influence of types of spacer yarn within the group - With Lycra									
a	**Monofilament Spacer Yarn (Thickness - 4.4 mm)**	5.318	187.617	7.78E-07	Significant	3.215	a-b	7.78E-07	Significant
b	**Multifilament Spacer Yarn (Thickness - 3.4 mm)**					-2.572			

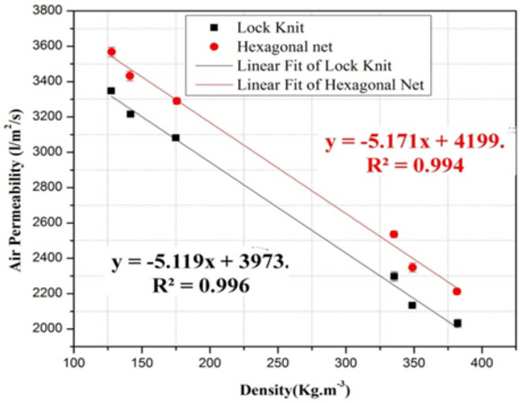
5.3 Thermo-physiological behavior of spacer fabrics

5.3.1 Effect of structural characteristics on air permeability of warp knit spacer fabrics

The results show that fabric thickness has a significant effect on the air permeability values of the spacer fabric, as air permeability tended to increase as thickness decreased, irrespective of yarn linear density and stitch density. As shown in Figure 30, the lower thickness and mass per square meter also facilitate the passage of air through the fabric. It is also noticed from the graph, the denser fabrics offers more resistant towards air to pass from one surface to other. Also it is observed, porous with lower areal density fabrics offers more permeable to air. Lock knit fabrics (WAS 1 – WAS 6) have tighter surface structure because it inter-loops the filament very close to each other, So, it is resistant to air flow. Comparison between all the samples show the hexagonal net fabrics have more air permeability than lock knit fabrics with respect to thickness and areal density. Hexagonal knit fabrics (WAS 7 – WAS 12) produces more open structure on surface, it produce more gaps which results in highly permeable to air. All these factors contribute towards the higher air permeability.



(a) (b)



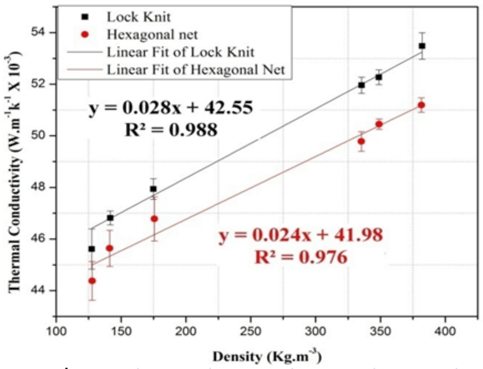
	ANOVA	DF	Sum of Squares	Mean Square	F Value	Prob > F
Lock Knit	Model	1	1.75E+06	1.75E+06	1056.4929	5.34E-06
	Error	4	6634.3417	1658.5854		
	Total	5	1.76E+06			
Hexagonal	Model	1	1.78E+06	1.78E+06	747.54169	1.06E-05
	Error	4	9536.979	2384.2448		
	Total	5	1.79E+06			

(c)

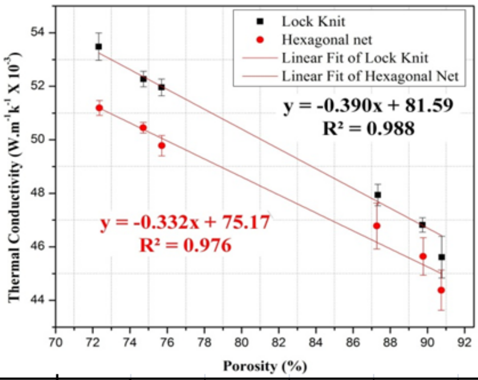
Figure 30. Influence of structural parameters on air permeability of warp knit spacer fabrics

5.3.2 Influence of structural characteristics on thermal properties of warp knit spacer fabrics

It is reported that the thermal conductivity decreases with increase in thickness and areal density for both the structures. The major factors influencing the thermal behavior of fabrics are density, porosity and air permeability. As shown in Figure 31 a & c, the thermal conductivity of spacer fabrics significantly increased with increase in density and decrease in air permeability. Also it is observed that, hexagonal net fabrics (WAS 7- WAS 12) have ability to resist more heat than the fabrics with lock knit structure on the surface (WAS 1 – WAS 6).

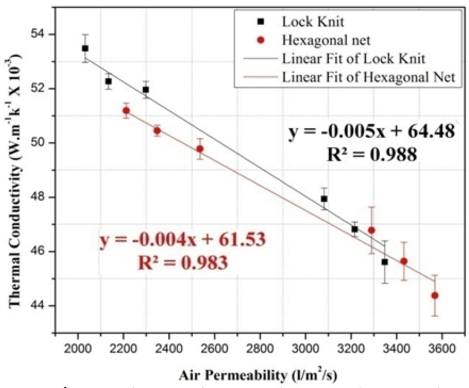


	ANOVA	DF	Sum of Squares	Mean Square	F Value	Prob > F
Lock Knit	Model	1	5.35E+01	5.35E+01	355.27414	4.67E-05
	Error	4	0.60253	0.15063		
	Total	5	5.41E+01			
Hexagonal	Model	1	3.86E+01	3.86E+01	166.06597	2.09E-04
	Error	4	0.92908	0.23227		
	Total	5	3.95E+01			



	ANOVA	DF	Sum of Squares	Mean Square	F Value	Prob > F
Lock Knit	Model	1	5.35E+01	5.35E+01	355.27414	4.67E-05
	Error	4	0.60253	0.15063		
	Total	5	5.41E+01			
Hexagonal	Model	1	3.86E+01	3.86E+01	166.06597	2.09E-04
	Error	4	0.92908	0.23227		
	Total	5	3.95E+01			

(a)(b)

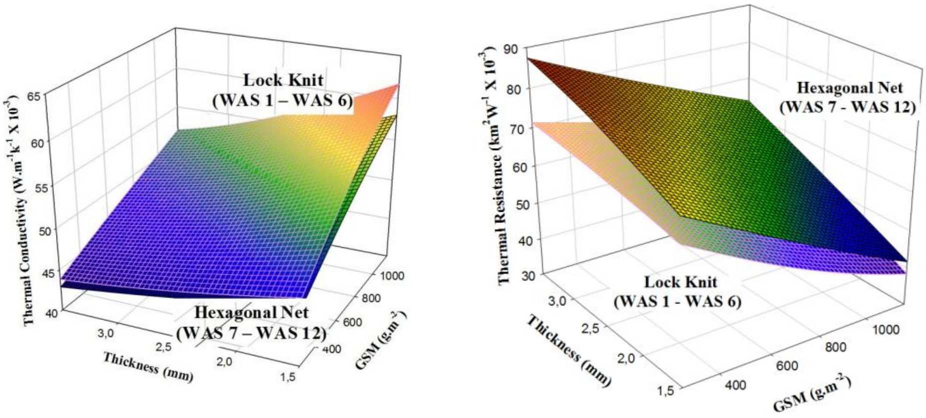


	ANOVA	DF	Sum of Squares	Mean Square	F Value	Prob > F
Lock Knit	Model	1	5.35E+01	5.35E+01	334.33428	5.26E-05
	Error	4	0.63982	0.15996		
	Total	5	5.41E+01			
Hexagonal	Model	1	3.89E+01	3.89E+01	240.412	1.01E-04
	Error	4	0.64647	0.16162		
	Total	5	3.95E+01			

(c)

Figure 31. Effect of structural characteristics and linear regression model for thermal conductivity of warp knit spacer fabrics

Because, the open surface pores in hexagonal fabrics results in higher air permeability makes thermally resistant materials comparatively. It is also proved from Figure 31 b, spacer fabrics with low porosity results in high thermal conductivity, due to fabrics act s a barrier for air permeability. Overall results give in the way that comparatively higher fabric thickness of a spacer fabric entraps more air within the middle layer and therefore cause higher thermal resistance with lower thermal conductivity. The amount of air entrapped in denser fabrics (WAS 4 –WAS 6 & WAS 10 – WAS 12) is high and it allows conduction of heat causing higher thermal conductivity. Figure 32 also presents the regression model for thermal conductivity with the effect of density and air permeability. The thermal conductivity of warp knitted spacer fabric has positive linear correlation with density and negative correlation with porosity and air permeability with the coefficient of determinant of more than 0.9. Figure 32a & b demonstrates the influence of thickness and areal density on thermal properties of all the samples. It is reported that the thermal conductivity decreases with increase in thickness and areal density for both the structures. The major factors influencing the thermal behavior of fabrics are density, porosity and air permeability.

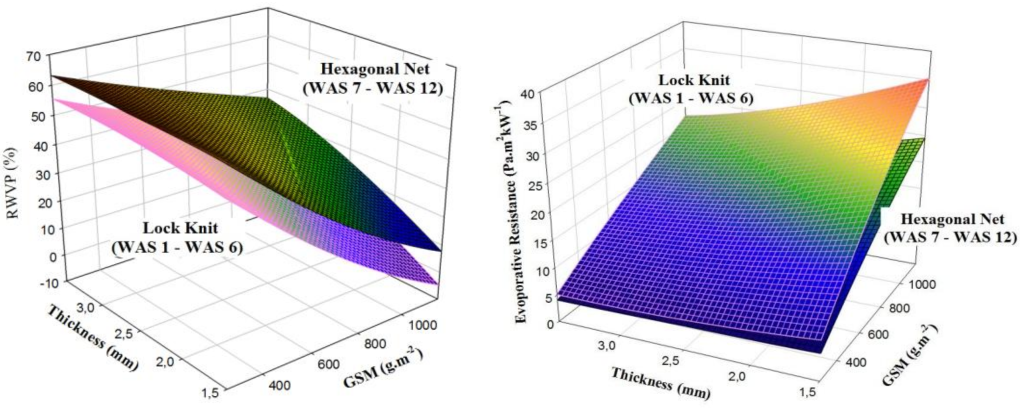


(a) (b)

Figure 32. Effect of gsm and thickness on thermal properties of warp knit spacer fabrics

5.3.3 Effect of structural parameters on water vapour permeability

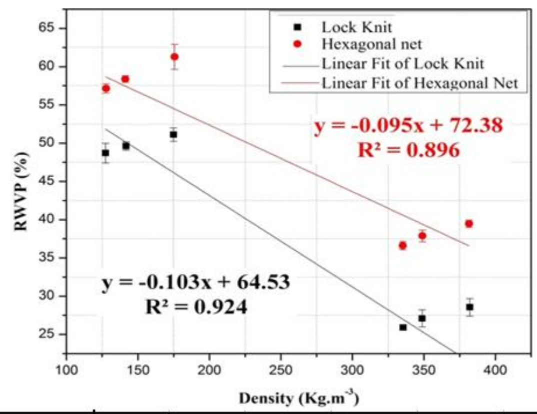
As shown in Figure 33(a) & (b), the evaporative resistance is lower for the porous spacer fabrics with high air permeability. It is also proved that, spacer fabrics with low density results in higher water vapour permeability. Overall it is observed from that the evaporative resistance decreases with increase in porosity and decrease in thickness, density and areal density of spacer fabrics. It was also noticed that, hexagonal net fabrics (WAS 7- WAS 12) have ability to pass more water vapour than the fabrics with lock knit structure on the surface (WAS 1 – WAS 6). Because, the open surface pores in hexagonal fabrics results in porous nature makes material with higher water vapour permeability.



(a) (b)

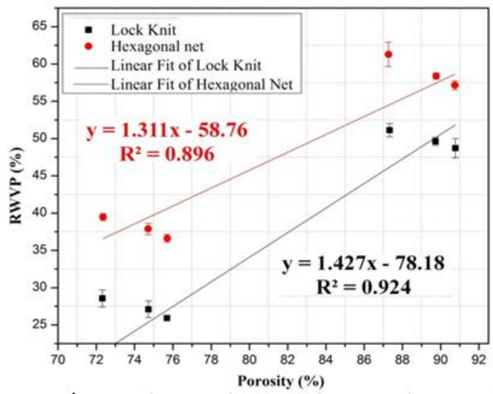
Figure 33. Effect of thickness and areal density on water vapour permeability

The results obtained shows that, the thick spacer fabric with high density have higher evaporative resistance (Figure 34a & b). The increase in thickness of middle (spacer) layer has ability to entrap more air therefore cause higher evaporative resistance with lower water vapour permeability. The spacer fabrics (WAS 1 – WAS 3 & WAS 7 – WAS 9) show relatively lower density and higher porosity; therefore allow water vapour to pass through easily. It is observed from the figure 34c, the water vapour permeability depends not only air permeability, it depends surface structure structural pores, thickness and density.



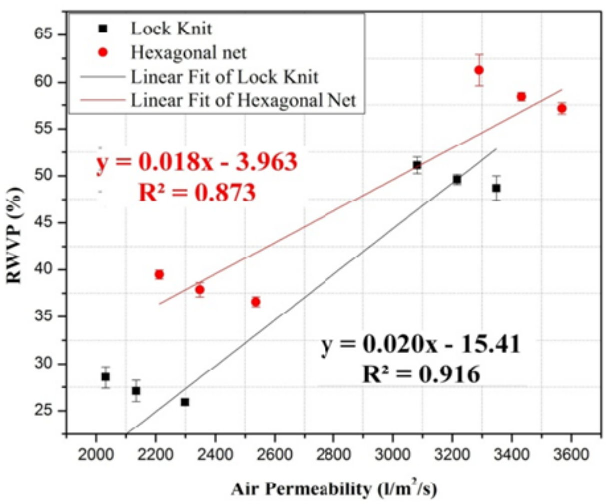
	ANOVA	DF	Sum of Squares	Mean Square	F Value	Prob > F
Lock Knit	Model	1	7.15E+02	7.15E+02	48.73043	2.21E-03
	Error	4	58.71211	14.67803		
	Total	5	7.74E+02			
Hexagonal	Model	1	6.02E+02	6.02E+02	34.67824	4.16E-03
	Error	4	69.43936	17.35984		
	Total	5	6.71E+02			

(a)



	ANOVA	DF	Sum of Squares	Mean Square	F Value	Prob > F
Lock Knit	Model	1	7.15E+02	7.15E+02	48.73043	2.21E-03
	Error	4	58.71211	14.67803		
	Total	5	7.74E+02			
Hexagonal	Model	1	6.02E+02	6.02E+02	34.67824	4.16E-03
	Error	4	69.43936	17.35984		
	Total	5	6.71E+02			

(b)



	ANOVA	DF	Sum of Squares	Mean Square	F Value	Prob > F
Lock Knit	Model	1	7.09E+02	7.09E+02	43.76966	2.70E-03
	Error	4	64.80923	16.20231		
	Total	5	7.74E+02			
Hexagonal	Model	1	5.87E+02	5.87E+02	27.65371	6.26E-03
	Error	4	84.8492	21.2123		
	Total	5	6.71E+02			

(c)

Figure 34. Linear regression model for water vapour permeability

5.3.4 Statistical evaluation for thermo-physiological behavior of warp knit spacer fabrics.

The test results were evaluated using the advanced statistical software QC EXPERT.

Statistical analysis also indicates that the structure and thickness of warp knit spacer fabrics are significantly influence on air permeability, thermal conductivity and evaporative resistance with $F_{critical} < F_{static}$. But the insignificant differences are observed in the interaction on fabric properties [Table 18].

Table 18. Statistical evaluation for thermo-physiology properties of warp knit spacer fabrics

TWO WAY ANOVA

Source of variability	Sum of squares	Mean square	Degrees of freedom	Std deviation	F-statistic	Critical quantile	Conclusion	p-value
Effect of Structure and Thickness on Air permeability								
Structure	69122.7	69122.7	1	262.9119	3703	18.5128	Significant	0.00027
Thickness	73989.3	36994.7	2	192.34	1981.86	19	Significant	0.0005
Interaction	36.1151	36.1151	1	6.110101	29.6465	161.448	Insignificant	0.11563
Residuals	1.21819	1.21819	1	1.103718				
Total	143149	28629.9	5	169.2036				
Effect of Structure and Thickness on Thermal Conductivity								
Structure	2.12415	2.12415	1	1.457446	3267.92	18.5128	Significant	0.00031
Thickness	5.5969	2.79845	2	1.672857	4305.31	19	Significant	0.00023
Interaction	0.00124	0.00124	1	0.036056	20.5853	161.448	Insignificant	0.13811
Residuals	6.02E-05	6.02E-05	1	0.007761				
Total	7.72235	1.54447	5	1.242767				
Effect of Structure and Thickness on Thermal Resistance								
Structure	165.585	165.585	1	12.86799	23.9144	18.5128	Significant	0.03936
Thickness	51.0137	25.5069	2	5.050432	3.6838	19	Insignificant	0.2135
Interaction	13.3868	13.3868	1	3.721308	29.0159	161.448	Insignificant	0.11685
Residuals	0.46136	0.46136	1	0.679235				
Total	230.447	46.0894	5	6.788916				
Effect of Structure and Thickness on Relative Water Vapour Permeability								
Structure	124.944	124.944	1	11.17784	303.508	18.5128	Significant	0.00328
Thickness	11.1185	5.55927	2	2.35781	13.5043	19	Insignificant	0.06895
Interaction	0.80228	0.80228	1	0.907377	38.1072	161.448	Insignificant	0.10224
Residuals	0.02105	0.02105	1	0.145097				
Total	136.886	27.3772	5	5.232321				
Effect of Structure and Thickness on Evaporative Resistance								
Structure	7.61627	7.61627	1	2.759758	676	18.5128	Significant	0.00148
Thickness	2.6284	1.3142	2	1.146386	116.645	19	Significant	0.0085
Interaction	0.00725	0.00725	1	0.150111	0.47394	161.448	Insignificant	0.61617
Residuals	0.01529	0.01529	1	0.123644				
Total	10.2672	2.05344	5	1.432983				

Statistical analysis also indicates that the structure and thickness of warp knit spacer fabrics are significantly influence on air permeability, thermal conductivity and evaporative resistance with $F_{critical} < F_{static}$. But the insignificant differences are observed in the interaction on fabric properties [Table 18].

5.3.5 Influence of structural parameters on air permeability

Figure 35 shows that fabric thickness has a significant effect on the air permeability values of the spacer fabric, as air permeability tended to increase as thickness decreased, irrespective of yarn linear density and stitch density. The areal density has high influences on air permeability, higher air permeability observed with low areal density of weft knit spacer fabrics. The lower thickness and mass per square meter also facilitate the passage of air through the fabric. As observed in Figure 36(a & b), in both groups of spacer fabrics, the lower air permeability values were obtained with samples WES 3 in group 1 and WES 6 in group 2 because of higher fabric density. As it can be observed in Figure 36 and was confirmed by ANOVA analysis, there is a significant influence of the density on air permeability and also linear correlation coefficient (0.947) with regression equation is given. The porosity of both groups has no significant differences, but the significant differences in air-permeability were observed due to its different surface characteristics (Figure 36b). The increase in porosity can result in a significant increase in air permeability. The porosity has direct positive correlation with air permeability with R^2 value of 0.964 and also regression relation equation presented in it.

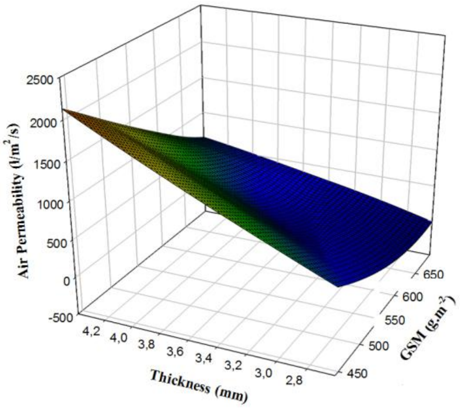
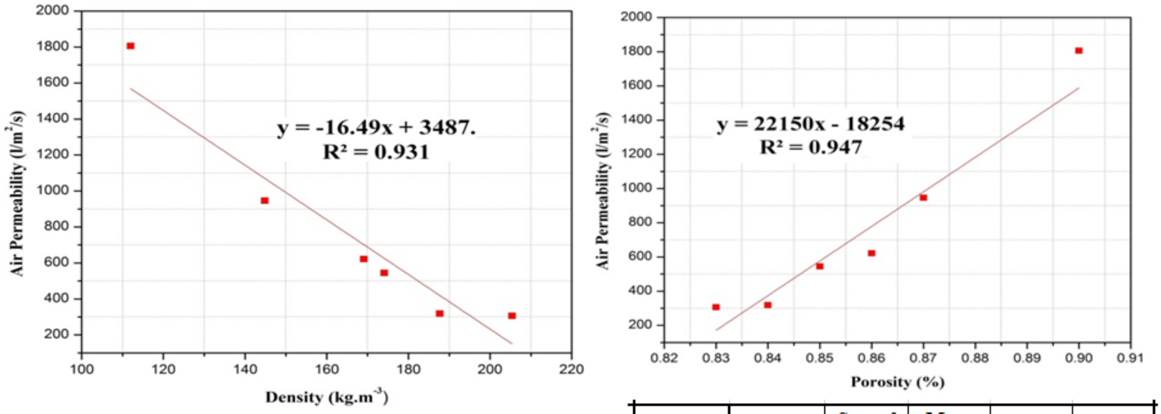


Figure 35. Influence of structural parameters on air permeability of weft knit spacer fabrics



ANOVA	DF	Sum of Squares	Mean Square	F Value	Prob > F
Model	1	1.49E+06	1.49E+06	54.26128	1.81E-03
Error	4	109570.3	27392.57		
Total	5	1.60E+06			

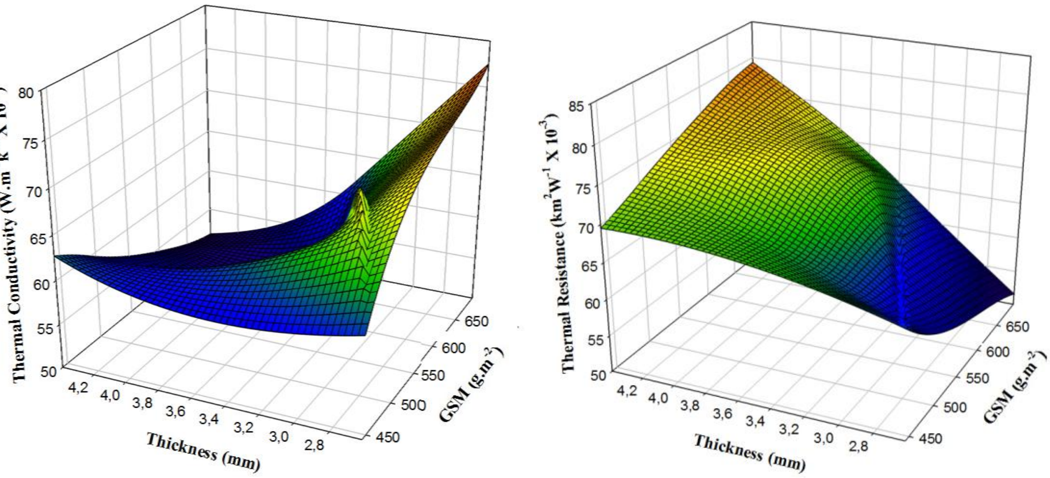
ANOVA	DF	Sum of Squares	Mean Square	F Value	Prob > F
Model	1	3.07E+01	3.07E+01	222.6534	1.17E-04
Error	4	0.55086	0.13771		
Total	5	3.12E+01			

(a) **(b)**

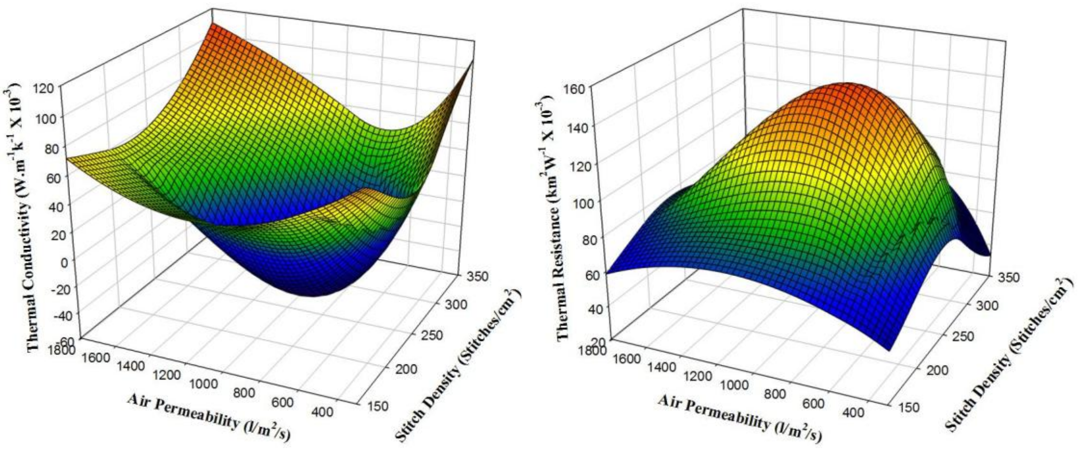
Figure 36. Effect of structural characteristics and linear regression model for air permeability of warp knit spacer fabrics

5.3.6 Influence of fabric characteristics on thermal properties

Figure 37a & b shows that, the spacer fabrics with more space to trap air inside the structure have relatively lower thermal conductivity value (0.053 – 0.066 W/mK). Since a lower value of thermal conductivity indicates a lower heat transfer from the skin to the fabric surface, this is usually associated with a warm feeling. The thickness is also a significant factor which influences the thermal resistance of spacer fabrics, higher thickness leads to higher thermal resistance. Also it is observed that, thick spacer fabric with low areal density leads the fabric to resist the heat to conduct. This study also found that, the thick fabrics with low density and higher air permeability exhibit relatively lower thermal conductivity for both the group of samples (Figure 37c &d). Also denser fabric has better thermal conductivity. It is also found that the spacer fabrics composed of monofilament spacer yarn (WES 1 & WES 4) have higher capacity to resist conduction of heat as compared to fabrics with multifilament spacer yarn (WES 2, WES 3 & WES 5, WES 6). It is mainly because monofilament spacer yarns make the fabric more bulky with lower density which offers more space to entrap air between the face and back layer. A remarkable difference between the heat transfer rates of group 1 and 2 fabrics are also justified here. It is also observed that fabrics made up of 6% of lycra yarn in the face layers (WES 4, WES 5 & WES 6) have lower thermal conductivity value than group 1 samples without lycra (WES 1, WES 2 & WES 3).



(a) **(b)**



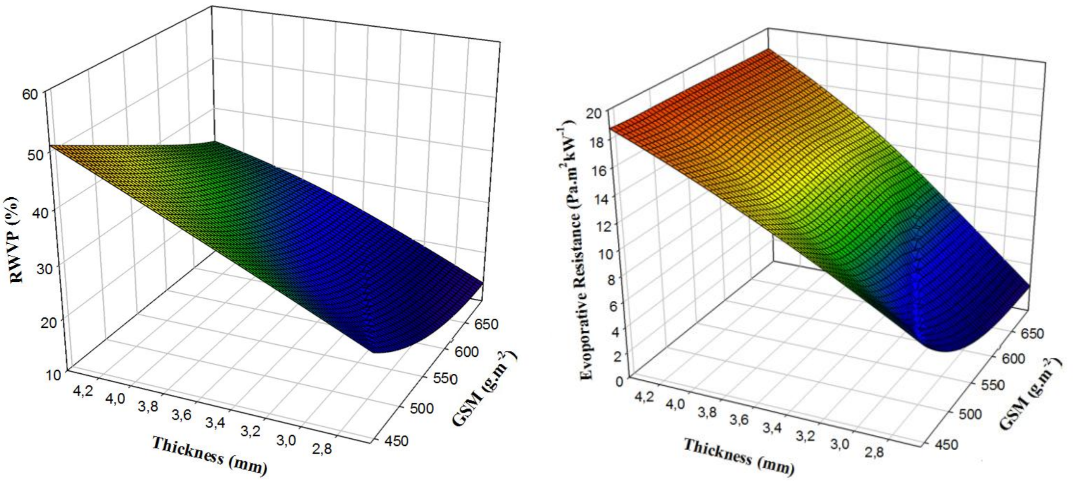
(c) (d)

Figure 37. Influence of structural parameters on thermal properties of weft knit spacer fabrics

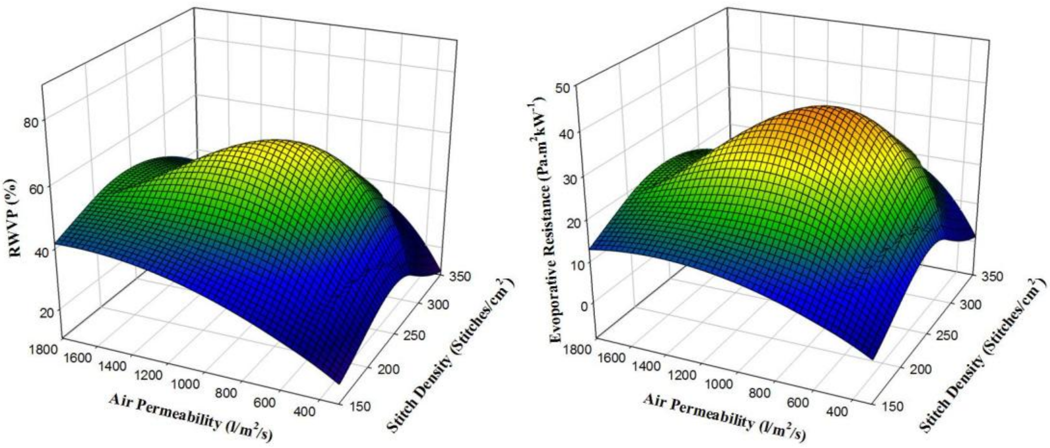
The air trapped within the fabric structure starts to circulate and that's why the heat transfer rate of Group 2 is lower than that of Group 1. Due to higher stitch density and lycra based filament yarns on the surface layers, these spacer fabrics have lower air permeability value and consequently a lower thermal conductivity. Thermal resistance is a very important parameter from the point of view of thermal insulation; it is directly proportional to the fabric density and inversely proportional to air permeability (Figure 37c). Due to increase in density between the samples WES 1 to WES 3 and WES 4 to WES 6, one can observe the increase in thermal conductivity and decrease in resistance value.

5.3.7 Effect of fabric characteristics on water vapour permeability

The water vapour permeability of fabric depends upon a number of factors including thickness and density of fabrics, wetting and wicking behavior of yarns, and the relative humidity and temperature of the atmosphere. Figure 38 a & b demonstrates the influence of thickness and areal density on physiological properties of all the samples. It is reported that the relative water vapour permeability decreases with increase in thickness and areal density for all the fabrics with multifilament spacer yarn. The thick spacer fabric made up of monofilament spacer yarn has ability to transfer high amount of water vapour from one surface to another (Figure 38 c &d).



(a) **(b)**



(c) **(d)**

Figure 38. Influence of structural parameters on thermal properties of weft knit spacer fabrics

It is also observed from Figure 38c and Table 6 that the water vapour permeability increases as the stitch density of the spacer fabric increases in both the group of samples. But the trend is reversed in the case of evaporative resistance as shown in Figure 38d. Also, From the Figure 38, the fabrics made up of multifilament as spacer yarn offers more resistant towards permeability of water vapour. It might be due to the fabrics with multifilament spacer yarn has higher density. It is greatly reduced by the presence of 6% of lycra in group 2 samples as shown in Figure 38. Variation in the fibre composition ratio between polypropylene and polyester shows significant effect in both water vapour permeability and evaporative Resistance. It is also seen that with the increasing density of samples in a dry state, the relative water vapour permeability increases in all samples. The research also showed that with a reduction in the percentage of polyester fibre content, the ability to transmit water vapour decreases. But the trend is reversed in the case of evaporative Resistance. So, the results demonstrate the apparent influence of fibre composition and density on the water vapour permeability of spacer knitted fabrics.

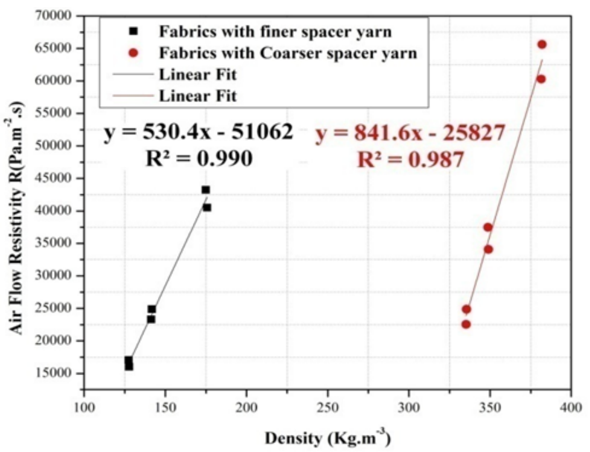
5.3.8 Statistical evaluation for thermo-physiological behavior of weft knit spacer fabrics.

The above-mentioned results are confirmed by analysis of variance (ANOVA), and the result is significant influence of the surface structure, types of spacer yarn and thickness on fabric thermo-physiological properties.

5.4 Acoustic properties of spacer fabrics

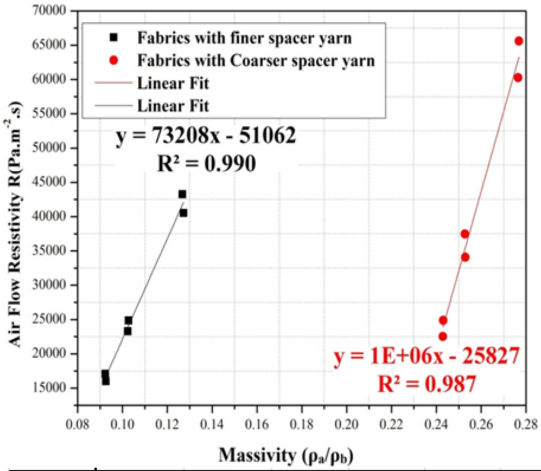
5.4.1 Effect of structural characteristics on air flow resistivity of warp knit spacer fabrics

The flow resistivity of material is majorly decides by the characteristics such as density, massivity or porosity and tortuosity.



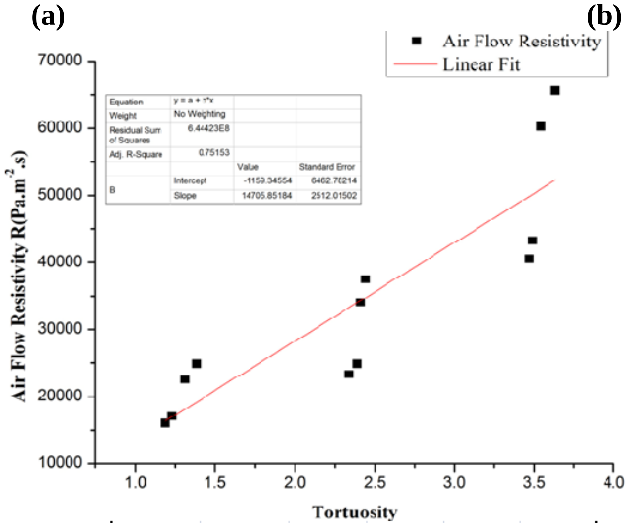
	ANOVA	DF	Sum of Squares	Mean Square	F Value	Prob > F
Finer spacer yarn	Model	1	6.77E+08	6.77E+08	415.0868	3.43E-05
	Error	4	6.52E+06	1.63E+06		
	Total	5	6.83E+08			
Coarser spacer yarn	Model	1	1.62E+09	1.62E+09	303.3484	6.38E-05
	Error	4	2.13E+07	5.33E+06		
	Total	5	1.64E+09			

(a)



	ANOVA	DF	Sum of Squares	Mean Square	F Value	Prob > F
Finer spacer yarn	Model	1	6.77E+08	6.77E+08	415.0868	3.43E-05
	Error	4	6.52E+06	1.63E+06		
	Total	5	6.83E+08			
Coarser spacer yarn	Model	1	1.62E+09	1.62E+09	303.3484	6.38E-05
	Error	4	2.13E+07	5.33E+06		
	Total	5	1.64E+09			

(b)



ANOVA	DF	Sum of Squares	Mean Square	F Value	Prob > F
Model	1	2.21E+09	2.21E+09	34.27172	1.61E-04
Error	10	6.44E+08	6.44E+07		
Total	11	2.85E+09			

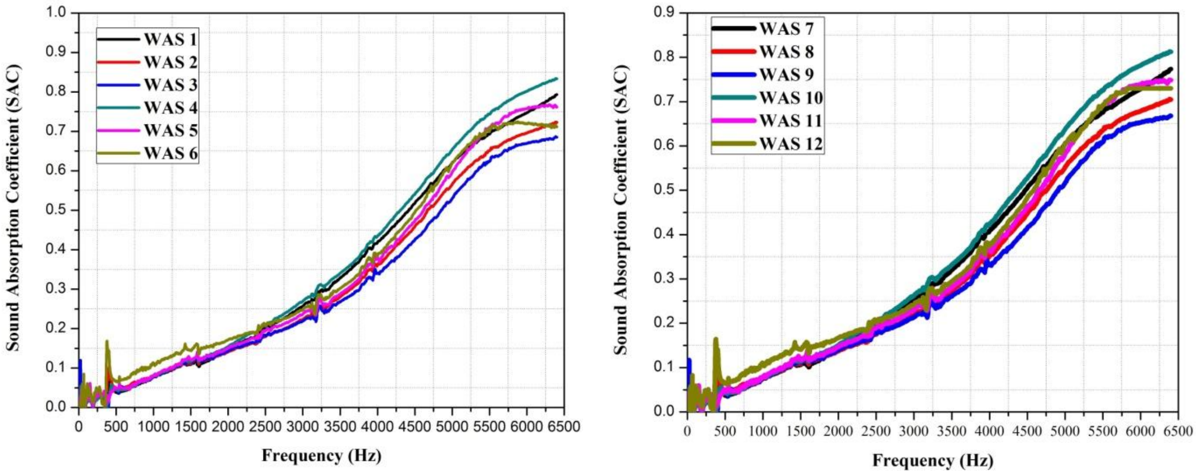
(c)

Figure 39. Effect of structural characteristics and linear regression model for air flow resistivity of warp knit spacer fabrics

The results show that fabric density has a significant effect on the air flow resistivity values of the spacer fabric, as air flow resistivity tended to increase as density increased, irrespective of yarn linear density and stitch density. As shown in Figure 39, the denser fabrics offer more resistant towards air to pass from one surface to other. Also it was observed from the Figure 39b, porous with lower massivity of fabrics offers more permeable to air. It was also noticed that the spacer fabrics with finer spacer yarn offers lower resistance to air due to lower density. As shown in Figure 39c, the torturous (high tortuosity) fabrics results high air flow resistivity because it is obvious that, when the material has more tortuous path, it resists the fluid to flow freely. Comparison between all the samples shows the lock knit fabrics have higher flow resistance than the hexagonal net fabrics. Hexagonal fabrics (WAS 7 – WAS 12) produces more open structure on surface, it produce more gaps which results in highly permeable to air.

5.4.2 Influence of structural properties on sound absorption of warp knit spacer fabrics

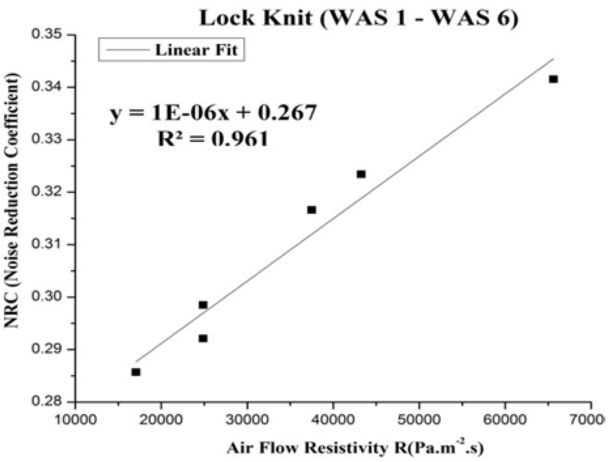
For the range of considered porosity, the influence on the sound absorption is complicated. As shown in Figure 40 a & b, porosity increases from 72 to 90 % for both the structures (lock knit and hexagonal net) warp knit spacer fabrics, the changes on sound absorption is insignificant for low frequency range (50 Hz to 2000 Hz). In middle frequency range, 2000 -4500 Hz, the absorption coefficient increases drastically when the porosity decreases because of increases in air-flow resistivity. For frequency range above 4500Hz (high frequency), the significant differences in sound absorption value between the samples can be observed clearly from the Figure 40, it might be due to the variation in flow resistivity and the thickness.

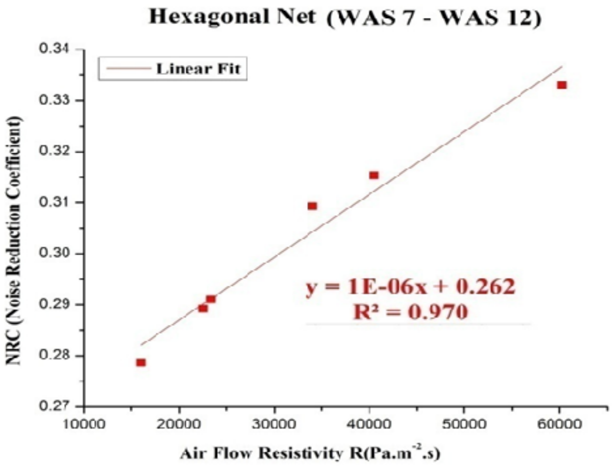


(a) **(b)**

Figure 40. Effect of structural properties on sound absorption behavior of warp knit spacer fabrics

The increase in torturous path of middle (spacer) layer has ability to entrap more air therefore cause higher flow resistance with more sound absorption. The spacer fabrics (WAS 4 –WAS 6 & WAS 10 – WAS 12) are relative shows higher density and lower porosity; allows sound waves to attenuate easily. In case of spacer fabric samples with hexagonal net (WAS 7 – WAS 12), the sound absorption is comparatively lower than samples with lock knit (WAS 1 and WAS 6) because of surface pore characteristics. This is mainly because of surface roughness and stitch density of the spacer fabrics which causes sound waves to reflect more on the surface itself. Variations of porosity in the range of 10 or 15 % have major influence on the acoustic behavior of spacer fabrics. Figure 41 indicate that the noise reduction coefficient of the spacer fabrics increase with the increase of airflow resistivity. Moreover, an increase in airflow resistivity gives rise to a reduction in porosity; thus, the sound absorbency of the fabric increases with the reduction in its porosity. The effect of airflow resistivity has a greater effect on the sound absorbency of the warp knit spacer fabric than its thickness.





	ANOVA	DF	Sum of Squares	Mean Square	F Value	Prob > F
Lock Knit	Model	1	2.17E-03	2.17E-03	99.56072	5.67E-04
	Error	4	8.74E-05	2.18E-05		
	Total	5	2.26E-03			
Hexagonal	Model	1	1.96E-03	1.96E-03	130.9826	3.33E-04
	Error	4	5.99E-05	1.50E-05		
	Total	5	2.02E-03			

Figure 41. Influence of air flow resistivity on noise reduction coefficient and its linear regression model of warp knit spacer fabrics

5.4.3 Statistical evaluation for sound-absorption behavior of warp knit spacer fabrics.

The critical quantile ($F_{critical}$) values obtained for factor A – 6.60, 19, Factor B – 5.05 and Interaction – 7.70 with respect to degrees of freedom. The value of $F_{critica}$l < $F_{statistic}$ proves that the changes in the density and surface layer structure of warp-knitted spacer fabric results is highly significant on the above-mentioned fabric sound absorption properties. But the insignificant differences are observed in the NRC for the interaction with p > 0.05 [Table 19].

Table 19 Statistical evaluation for acoustic properties of warp knit spacer fabrics

Two Way ANOVA Table

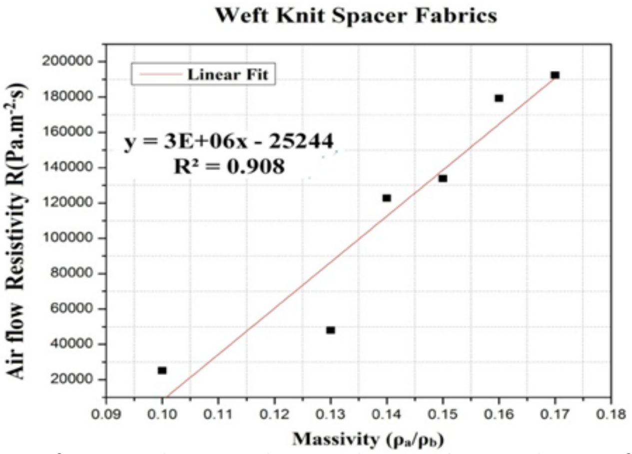
Source of variability	Sum of squares	Mean square	Degrees of freedom	Std deviation	F-statistic	Critical quantile	Conclusion	p-value
Influence of Structure and Density on Air Flow Resistivity								
Structure	22531048	22531048	1	4746.6881	19.410204	6.607891	Significant	0.0069846
Density	2.825E+09	564927223	5	23768.198	486.67742	5.0503291	Significant	1.03E-06
Interaction	5243226.3	5243226.3	1	2409.1323	37.405376	7.7086474	Significant	0.003619
Residuals	560692.27	140173.07	4	374.39694				
Total	**2.853E+09**	**259361007**	**11**	**16104.689**				
Influence of Structure and Density on NRC								
Structure	0.0001944	0.0001944	1	0.0139419	396.23513	6.607891	Significant	5.91E-06
Density	3.80E-03	7.60E-04	5	0.0275615	1548.5042	5.0503291	Significant	5.74E-08
Interaction	9.05E-07	9.05E-07	1	0.0015661	2.3407916	7.7086474	Insignificant	0.200767
Residuals	1.55E-06	3.87E-07	4	0.000622				
Total	**3.99E-03**	**3.63E-04**	**11**	**1.91E-02**				

5.4.4 Influence of structural parameters on air flow resistivityof weft knit spacer fabrics

Figure 42 shows the flow resistivity values for different samples (WES 1 – WES 6) with respect to density, massivity and tortuosity. I twas observed in both the group of samples (group 1 and group 2), it is because of the samples (WES 1 & WES 4) fabrics made up of monofilament spacer yarns have more open structure as compared to samples (WES 2, WES 3 & WES 5, WES 6 respectively). Also, it was observed that group 2 samples have significantly higher flow resistance than group 1 samples because of closeness of structure (higher stitch density) of the samples on the outer surface to resist air to move inside the material. As shown in Figure 42b, the density of the material has a strong influence on the air flow inside the material. It is obvious that the increase in density leads to increase in flow resistance.

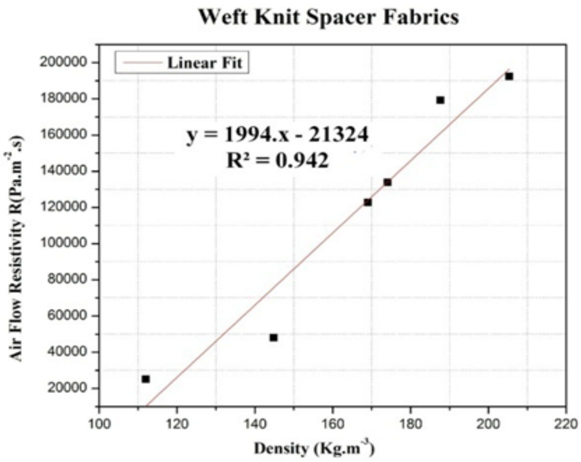
5.4.5 Influence of fabric properties on sound absorption properties of weft knit spacer fabrics

Variations of porosity in the range of 2 or 3 % have minor influence on the acoustic behavior of spacer fabrics (Figure 43). The effect of tortuosity on sound absorption coefficient can be seen, sound absorption coefficient increases with increase in the tortuosity values for both the group of samples (WES 1 to WES 6) for middle and high frequency ranges. At low and mid frequencies, variations of flow resistivity between samples have no noticeable effect on the absorption coefficient. In contrast, there is significant difference in high frequency ranges. It has also been observed that the variation in flow resistivity with respect to thickness and tortuosity for sample with monofilament spacer yarn WES 4 is higher as compared to sample WES 1.



ANOVA	DF	Sum of Squares	Mean Square	F Value	Prob > F
Model	1	2.10E+10	2.10E+10	39.80997	3.23E-03
Error	4	2.11E+09	5.26E+08		
Total	5	2.31E+10			

(a)



ANOVA	DF	Sum of Squares	Mean Square	F Value	Prob > F
Model	1	2.17E+10	2.17E+10	65.33096	1.27E-03
Error	4	1.33E+09	3.33E+08		
Total	5	2.31E+10			

(b)

Figure 42. Effect of structural characteristics and linear regression model for air flow resistivity of weft knit spacer fabrics

This variation might be due to stitch density (surface friction), anisotropic and in-homogeneous nature of spacer fabrics. Figure 44 also presents the regression model for noise reduction coefficient with the effect of air flow resistivity. The noise reduction coefficient (NRC) of weft knitted spacer fabric has positive linear correlation with flow resistivity with the coefficient of determinant of about 0.975. Overall it is observed that, at higher frequencies, spacer fabrics have ability to absorb around 40-60% of sound due to its 3-dimensional bulk structure. But it has less absorption in both mid and low frequencies.

5.4.6 Statistical evaluation for acoustic behavior of weft knit spacer fabrics

The above-mentioned results are confirmed by analysis of variance (ANOVA), and the result is significant influence of the surface structure, density and thickness on fabric sound absorption properties.

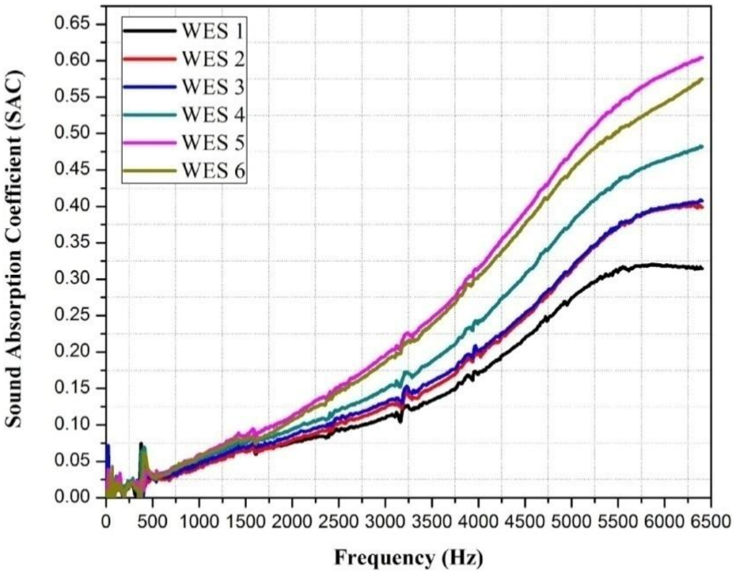
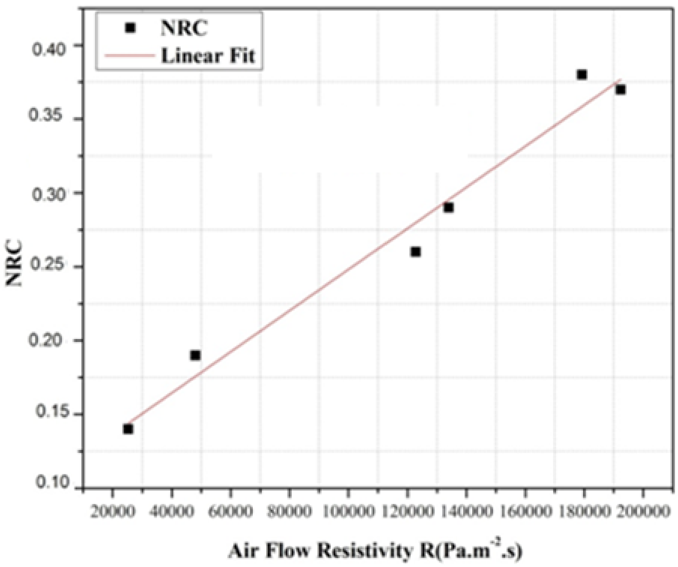


Figure 43. Effect of structural characteristics on sound absorption behavior of weft knit spacer fabrics



ANOVA	DF	Sum of Squares	Mean Square	F Value	Prob > F	Intercept	Slope
Model	1	4.47E-02	4.47E-02				
Error	4	1.15E-03	2.87E-04	155.7713	2.37E-04	3.09E-01	1.39E-06
Total	5	4.59E-02					

Figure 44. Influence of air flow resistivity on noise reduction coefficient and its linear regression model for weft knit spacer fabrics

6 *Evaluation of results and new finding*

This chapter summarizes the research that was carried out in this thesis. In this study, the in-plane shear, compressibility, thermo-physiology and acoustic properties of both warp and weft knitted spacer fabrics were evaluated. The shear behavior of 3D spacer fabrics was investigated by using a picture frame fixture. Three different methods were used to find the shear angle during loading rate of 10mm/min. All the tests were recorded by a CCD monochrome camera. The image analysis procedure can provide much detailed information about the shear behavior of the fabric than stroke measurement.

The in-plane shear behavior of spacer fabrics are greatly influenced by their surface structures, type of spacer yarn and the fabric stitch density. The outer layer structure affects the monofilament yarn inclination, binding condition with surface, distribution and multifilament stitches in surface layers. Overall, work done was higher for the fabrics made up of hexagonal net structure on face side than that of lock knit fabrics and weft spacers. It was also found that spacer fabrics with multifilament spacer yarn have lower work done when compared to other fabrics. Shear stress was higher for the fabrics with coarser spacer yarns among all the fabrics samples. The 3D spacer fabrics were more resilient towards compression stress. Indeed, this structure enables a vertical alignment of spacer yarn; this z axis yarn has the ability to provide maximum compression recovery to the fabric. On the other hand, it has been shown that the spacer fabrics dissipate sufficient energy in compression. Overall it was observed that the compressive energy and efficiency is higher for the thicker spacer fabrics with low density. Also it is found that fabrics with finer spacer yarns show large amount of work done as well as high efficiency during compression mechanism. The spacer fabric with large compressive deformation, high efficiency and energy absorption until plateau stage is the suitable solution for the materials especially for cushions. The porosity of both structures (lock knit and hexagonal) is almost similar, but significant differences in air-permeability were observed due to its different surface structure. The spacer fabric offers lower thermal conductivity due to the characteristics such as bulkiness, lower density and air layer in the middle part. Also, due to porous and highly permeable nature, the warp knit spacer fabrics have lower thermal conductivity and consequently a lower water evaporative resistance than the weft knitted spacer fabrics. It is also noticed that, hexagonal net fabrics have ability to pass more water vapour than the fabrics with lock knit structure on the surface. The spacer fabrics have too much air in the pores, hence, sound energy dissipation may weaken when the porosity is nearly 0.9. The air flow resistivity is inversely proportional to the porosity of the spacer fabrics; therefore, the sound absorption can increase with decrease in porosity and increases with air flow resistivity. The weft knit spacer fabrics have more tortuous path but still lower sound absorption because incident sound energy may get reflected away from the top layer and does not penetrate in to the fabric. The thickness of the porous material layer has also a great influence on the position of the peak value in the frequency spectrum. But the effect of density and flow resistivity is more predominant in terms of sound absorbency as compared to effect of thickness and tortuosity in case of both warp and weft knit spacer fabrics.These findings are important requirements for designing knitted spacer fabrics as an innovative cushion material in the applications such as mattress, car seats, pillows insole, back supports etc.

6.1 Scope for Future Work

The ideas, experiments and data generated as part of this research, have added to the knowledge base that could be useful to define the future direction and provide insightful references to researchers. The potential of this research can be realized by pursuing further studies into areas given below:

- The developed FEM model can be extended to other types of spacer fabrics and other properties such as compression, thermo-physiology and acoustic behavior.
- Conduct compression creep study for various spacer fabrics.
- Comparatives study of in-plane shear and compression behavior of both knitted and woven spacer fabrics.
- Develop analytical model to predict compression and shear properties of knitted spacer fabrics, by taking in to account of spacer yarn properties.
- Performing a series of tests with the human subjects in multiple test sessions.
- The image analysis of shear behavior of spacer fabrics can be further improved with suitable function to identify the perfect shear angle after wrinkling.

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8 List of papers published by the author related to the thesis

List of publications in journals

1. **Veerakumar Arumugam,** Rajesh Mishra, Jiri Militky, Maros Tunak, In-plane shear behavior of 3D knitted spacer fabrics, **Journal of Industrial Textile**, Vol-46, Issue-3, p. 868-886, 2016 . **IF- 1.120. WoS and SCOPUS**
2. **Veerakumar Arumugam,** R Mishra, Jiri Militky and Jan Novak Thermo - acoustic Behavior of 3D Knitted Spacer Fabrics, **Fibres and Polymers**, 2015, Vol.16, No.11, 2467-2476. DOI 10.1007/s12221-015-5602-5. **IF- 1.022. WoS and SCOPUS**
3. **Veerakumar Arumugam**, R Mishra, Jiri Militky and Jana Salcova Investigation on Thermo-physiological and Compression Characteristics of Weft Knitted Spacer Fabrics, **Journal of the Textile Institute**, Epub ahead of print 12 August 2016. DOI: 10.1080/00405000.2016.1220035. **IF- 1.128. WoS and Scopus**
4. **V. Arumugam**, R Mishra & J. Militky: Thermo-physiological comfort properties of 3D spacer knitted fabrics, **International Journal of Clothing Science and Technology**, Vol- 28, No. 3, pp-328-339, 2016. **IF- 0.418. WoS**
5. **Veerakumar Arumugam**, Rajesh Mishra, Maros Tunak, Jiri Militky, Dana Kremenakova &

Mohanapriya Venkatraman. Investigation on Intra-Ply Shear Properties of 3d Weft Knitted Spacer Fabrics by Image Analysis, **Journal of Fibre Bioengineering and Informatics,** accepted September 2016. **in SCOPUS**

6. **Veerakumar Arumugam**, Rajesh Mishra, Jiri Militky, Louise Davies & Simon Slater. Thermal and Water vapour Transmission through Porous Warp Knitted 3D Spacer Fabrics for Car Upholstery Applications, **Journal of the Textile Institute,**Under Review.
7. **Veerakumar Arumugam**, Rajesh Mishra, Jiri Militky, Dana Kremenakova Jana Salacova, Mohanapriya Venkatraman & V. B. Raminisanthi Subramanian. Effect of 3-Dimensional Knitted Spacer Fabrics Characteristics on Its Thermal and Compression Properties,**Vlakna Textil**, published June 2016. **SCOPUS**
8. **Veerakumar Arumugam,** Rajesh Mishra, Jana Salacova, Mohanapriya Venkatraman, Dana Kremenakova, Hafsa Jamshaid, Tao Yang, Xiaoman Xiong, Kasthuri Venkatesh, Jiri Militky, Functional characteristic evaluation of 3-dimensional knitted spacer fabrics, **Vlakna Textil**, published 2017. **SCOPUS**
9. **Veerakumar Arumugam**, Rajesh Mishra, Jiri Militky, Jana Salacova, Effect of 3-Dimensional Knitted Spacer Fabrics Characteristics on Its Thermal and Compression Properties, **International Journal of Industrial and Manufacturing Engineering**Vol:3, No:3, 2016, **International Science Indexed.**
10. **Veerakumar Arumugam,** Rajesh Mishra, Jiri Militky, Dana Kremenakova, Jana Salacova, Mohanapriya Venkatraman. Compression behavior and energy absorption of three-dimensional spacer fabrics for automobile upholstery applications, **Journal of Industrial Textiles**, Under Review.
11. **Veerakumar Arumugam**, Rajesh Mishra, Jiri Militky, Dana Kremenakova, Jana Salacova, Mohanapriya Venkatraman. Study of heat and moisture transfer within 3-Dimensional spacer fabrics for car seat application**, International Journal of Thermal Sciences**, Under Review.
12. **Veerakumar Arumugam**, Rajesh Mishra, Jiri Militky, Maros Tunak, In-plane shear behavior and energy absorption of warp knitted spacer fabrics for car seat applications, **Journal of Industrial Textiles**, Under Review.
13. **Veerakumar Arumugam**, Rajesh Mishra, Jiri Militky, Structural evaluation and its effect on acoustic behavior of warp knitted spacer fabrics, **Fibres and Polymers**, Under Review
14. **Veerakumar A** and Selvakumar N, "A Preliminary Investigation on Kapok/Polypropylene Nonwoven Composite for Sound Absorption", **Indian Journal of fibre and Textile Research**, Vol. 37, pp. 385 – 388, December 2012. **WoS and SCOPUS.**

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1. **Veerakumar Arumugam**, Rajesh Mishra, Jiri Militky, Dana Kremenakova & Mohanapriya Venkataraman, Compression Behavior and Energy Absorption of 3d Weft Knitted Spacer Fabrics, TBIS, May 2017, Wuhan, China
2. **Veerakumar Arumugam**, Rajesh Mishra, Jiri Militky, Mohanapriya Venkatraman, Louise Davies and Simon Slater, Investigation of moisture management properties of 3-dimensional warp knitted spacer fabrics, TRS-IIT, December 2016, New Delhi, India
3. **Veerakumar Arumugam**, Rajesh Mishra, Jana Salacova, Mohanapriya Venkatraman, Dana Kremenakova, Hafsa Jamshaid, Tao Yang, Xiaoman Xiong, Kasthuri Venkatesh, Jiri Militky, Functional characteristic evaluation of 3-dimensional knitted spacer fabrics, STRUTEX December 2016, Liberec, Czech Republic
4. **Veerakumar Arumugam**, Rajesh Mishra, Jiri Militky, Louise Davies and Simon Slater: An analysis on the moisture and thermal protective performance of 3-dimensional knitted spacer fabrics, 3D Fabrics and their Applications, September 8-9, ENSAIT, Roubaix, France, 2016.
5. **Veerakumar Arumugam**, Rajesh Mishra, Vignesh Balaji Ramanisanthi Subramanian, Hafsa Jamshaid and Jiri Militky: Bio-composites Reinforced with Flax, Jute and Glass Fabric: Comparative

Study of Static, Dynamic-mechanical and Thermal Properties, 3D Fabrics and their Applications, September 8-9, ENSAIT, Roubaix, France, 2016.

6. **Veerakumar Arumugam**, Rajesh Mishra, Jiri Militky, Dana Kremenakova, Jana Salacova & Mohanapriya Venkataraman and V. B. Ramanisanthi Subramanian,: Effect of 3-Dimensional Knitted Spacer Fabrics Characteristics on its Thermal and Compression Properties, IFATCC XXIV International Congress, June 13-16,Pardubice, Czech Republic, 2016.
7. **Veerakumar Arumugam**, Rajesh Mishra, Maros Tunak, Jiri Militky, Dana Kremenakova, Mohanapriya Venkataraman and V. B. Ramanisanthi Subramanian,:Investigation on Intra-Ply Shear Properties of 3d Weft Knitted Spacer Fabrics by Image Analysis**,** TBIS-APCC, July 12-15, Melborne, Australia 2016
8. Rajesh Mishra, **Veerakumar Arumugam**, Dana Kremenakova & Jiri Militky,: 3D spacer knitted fabrics with advanced characteristics, 8^{th} International Textile, Clothing & Design Conference – Magic World of Textiles October 02^{-} 05^{th} 2016, Dubrovnik, Croatia
9. **Veerakumar Arumugam**, Rajesh Mishra, Jiri Militky, Dana Kremenakova, Jana Salacova & Mohanapriya Venkataraman : Experimental and analytical investigation on thermal and acoustic behavior of 3d spacer knitted fabrics, 90^{th} Textile Institute Conference, April 25-28, Poznan, Poland, 2016
10. **V. Arumugam**, R Mishra & J. Militky: Effect of material parameters on thermo-physiological comfort properties of 3D spacer knitted fabrics, ITTC 2015, October 14-16, Izmir/Turkey, 2015, ISBN 978-975-441-448-6.
11. **Veerakumar Arumugam**, Rajesh Mishra, Jiri Militky & Mohanapriya Venkatraman: Evaluation of thermo - physiological comfort characteristics of 3-dimensional spacer fabrics, CLOTECH 2015, University of Lodz Poland, ISBN 978-83-7283-671-7.
12. **V. Arumugam**, R Mishra, Analysis of air and water vapour transmission through knitted spacer fabrics, STRUTEX 2014, Decemeber 1-2, Liberec, 2014.
13. **Veerakumar Arumugam**: Thermo-acoustic behavior of 3D knitted spacer fabrics, Workshop Světlanka 2015, 22^{nd}-25^{th}September 2015, Rokytnice nad Jizerou, Czech Republic.
14. **Veerakumar Arumugam**, Rajesh Mishra, Jiri Militky, Jana Salacova: Effect of 3-Dimensional Knitted Spacer Fabrics Characteristics on Its Thermal and Compression Properties, 18th International Conference on Textiles and Fashion, Singapore, SG, March 03-04, 2016.
15. **Veerakumar Arumugam**: Experimental analyses of in-plane shear behavior of 3d spacer fabrics using picture frame fixture, Workshop Světlanka, 16^{th}-19^{th} September 2014, Rokytnice nad Jizerou, Czech Republic.
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17. **Veerakumar Arumugam**, R Mishra, V Saravanan and Jiri Militky, Braided composites from glass-polypropylene, ICIC 2014, Coimbatore, 29-30 April 2014, ISBN: 9788192375243.

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1. **Veerakumar Arumugam**, Rajesh Mishra, Dana Křemenáková, Jirí Militký, Mohanapriya Venkatraman and Ludmila Koukolíková, 3D warp knitted spacer fabrics for multifunctional applications, Progress in fibrous material science, ISBN 978-80-87269-40-4, 2014.
2. **Veerakumar Arumugam**[*], Rajesh Mishra, Jana Salcova, Jiri Militky, Dana Kremenakova, Mohanapriya Venkatraman & Vignesh Balaji Ramanisanthi Subramanian: Assessment of the sound absorptive performance of 3-dimensional knitted spacer fabrics, Recent Developments in Fibrous Material Science,ISBN 978-80-87269-45-9.
3. **Veerakumar Arumugam**[*], Rajesh Mishra, Jana Salcova, Jiri Militky, Dana Kremenakova,

Mohanapriya Venkatraman & Vignesh Balaji Ramanisanthi Subramanian: A study on thermo-physiological comfort behavior of 3-dimensional spacer knitted fabrics, Recent Developments in Fibrous Material Science,ISBN 978-80-87269-45-9.

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5. **Veerakumar Arumugam**, Rajesh Mishra, Maros Tunak, Jana Salcova, Jiri Militky, Dana Kremenakova, Mohanapriya Venkatraman & Vignesh Balaji Ramanisanthi Subramanian: Investigation on intra-ply shear properties of 3d knitted spacer fabrics by image analysis, In Press.

List of co-authored publications

1. Rajesh Mishra, Jiri Militky, Mohanapriya Venkataraman and **Veerakumar Arumugam** Functional advantages of 3D woven glass nanocomposites, Vlakna a textil, ISSN 1335-0617, Vol:3, 2014.
2. Mohanapriya Venkataraman, Rajesh Mishra, Jiri Militky, **Veerakumar Arumugam**& Srabani Misra, Thermal properties of high performance nonwoven padding fabrics at sub zero temperatures, Vlakna a textil, ISSN 1335-0617, Vol:3, 2014.
3. Mohanapriya Venkataraman, Rajesh Mishra, Jakub Weiner, Adnan Mazari, Jiri Militky, **Veerakumar Arumugam**, Innovative Techniques for Characterization of Nonwoven Insulation Materials Embedded with Aerogel International Journal of Chemical, Nuclear, Metallurgical and Materials Engineering Vol:8 No:9, 2014.
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5. Rajesh Mishra, Mohanapriya Venkatyaraman, **Veerakumar Arumugam**, Jiri Militky and Srabani Misra, Novel techniques to analyze thermal properties of nonwoven padding fabrics at subzero temperatures, TEXCO International conference, Ruzomberok, Slovakia, ISBN 978-80-8075-660-42, 7-28 August 2014.
6. Mohanapriya Venkataraman, Rajesh Mishra, **Veerakumar Arumugam** and Jiri Militky, Thermal analysis of aerogel treated non woven fabrics, fibre society spring conference, May 21-23, 2014.
7. Rajesh Mishra, B K Behera, Mohanapriya Venkataraman, **Veerakumar Arumugam**, Vijay Baheti and Jiri Militky, Green composites from textile waste: Thermo-mechanical characterization, fibre society spring conference, May 21-23, 2014.
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10. Mohanapriya Venkataraman, Rajesh Mishra, Jakub Wiener, Marie Štěpánková, **Veerakumar Arumugam**, Jiri Militky, Impact of Laser Thermal Irradiation on Kevlar Embedded with Aerogel Particles, STRUTEX 2014, Decemeber 1-2, Liberec, 2014.
11. Mishra Rajesh, Venkataraman Mohanapriya, Kremenakova Dana, Militky jiri, **Veerakumar Arumugam**, Thermal Properties of High Performance Nonwoven Padding Fabrics at Subzero Temperatures, , 7th International Textile, Clothing & Design Conference (ITC&DC) Conference Procedings with citation Index (CPCI-S), Tekstil, ISBN:978-953-7105-54-9, ISSN 1847-7275.
12. Venkataraman Mohanapriya, Mishra Rajesh, Kremenakova Dana, Militky Jiri, **Veerakumar Arumugam**, Thermodynamical characterization of Aerogel Treated Nonwoven Fabrics, 7th International Textile , Clothing & Design Conference (ITC&DC) Conference Procedings with citation Index (CPCI-S), Tekstil, ISBN:978-953-7105-54-9, ISSN 1847-7275.

Curriculum Vitae

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CAREER PROFILE	Seeking a challenging position as a scientific textile Person person to enhance my skills and knowledge in a renowned organization
PERSONAL INFORMATION	
Date of birth	06/10/1986
Nationality / Residence	Indian /Czech Republic
Secondary e-mail	arumugam.veerakumar@tul.cz
EDUCATION AND TRAINING	
Dates	March 2017 (Expected)
Name and type of institution providing education and training	Doctoral studies (Ph. D) Faculty of Textile Engineering, Technical University of Liberec, Czech Republic
Principal subjects	Specialization: Textile Technics and Materials Engineering
Dates	May 2011
Name and type of institution providing education and training	Post Graduation (M. Tech) Department of Textile Technology, Anna University, Chennai, Tamil Nadu, India.
Principal subjects	Specialization: Textile Technology
Dates	May 2008
Name and type of institution providing education and training	Graduation (B. Tech) Department of Textile Technology, Anna University, Chennai, Tamil Nadu, India.
Principal subjects	Specialization: Textile Technology

PRESENT POSITION AND RESEARCH ACHIEVEMENTS

- Since 11.9.2013 – Research Scholar at Faculty of Textile Engineering, Technical University of Liberec, Czech Republic
- **Research activities** – Design and Development of 3-Dimensional Textile Materials for Thermo-acoustic, Thermo-Physiology and Thermo-mechanical Applications.
- **Publications -** 12 research papers in peer-reviewed journals, 5 book chapters and nearly 20 international conferences happened in various countries.
- **Co-operation** – Research Co-operation with various industries and institutions

EXPERIENCE AND SKILLS

Professional Experience

- Assistant Professor - From June, 2011 – June, 2013, Bannari Amman Institute of Technology, Sathyamangalam, India.
- Teaching Assistant - June 2010 to May 2011, Anna University, Chennai, India
- Production Executive - From June, 2008 – June 2009, Go Go International, Bangalore, India.
- Research Scholar – September, 2013, Technical University of Liberec, Czech Republic.

Organizational Experience

- Board of Studies (BOS) member in Bannari Amman Institute of Technology, India.
- Department level All India Council for Technical Education Documentation In charge.
- Joint National Board Accreditation for College coordinator in India.
- Served as the Join Secretary for the Textile Department's Association

Projects Involved

- Development of Commingled Yarn (Glass/Polypropylene) Braided Thermoplastic composite
- Development of Natural Fibre Reinforced Circular Braided Composite Tubes
- Designing of Lab Model Injection Molding Setup and Produce Circular Braided
- Development of a Novel Electro-spinning Apparatus
- Utilization of Knitted Garment Waste for the Development of Composites as an Acoustic Panel.
- Development of apparatus for measuring Thermal Insulation Value of the fabrics.

Professional Strengths

- Good knowledge of project management and process improvement
- Ability to read, analyze and interpret technical, scientific and legal documents
- Ability to respond to common complaints/inquiries from colleagues and customer
- Possess excellent organizational and management skills
- Possess excellent communication skills
- Proven ability to handle different projects
- Extensive knowledge of setting and managing budgets within limits
- Goal-oriented and ability to work under skills
- Possess excellent monitoring and supervisory skills

Technical Skills and Competences

Familiar with FEM, Image J, Origin Lab, Mini TAB, MATLAB, Sigma plot, QC Expert, MS Project, MS Windows, MS Office, MS Outlook

Personal Interests

Reading, Playing Cricket, Hiking, Travelling and Volunteer work.

Record of the state doctoral exam

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Jméno a příjmení doktoranda: **Veerakumar Arumugam, M.Tech.**

Datum narození: **6. 10. 1986**

Doktorský studijní program: **Textilní inženýrství**

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

Termín konání SDZ: **6. 10. 2016**

prospěl ~~**neprospěl**~~

Komise pro SDZ:

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Předseda:	prof. Ing. Jiří Militký, CSc.	[signature]
Místopředseda:	doc. Ing. Maroš Tunák, Ph.D.	[signature]
Členové:	prof. Ing. Miroslav Václavík, CSc.	[signature]
	doc. Ing. Antonín Havelka, CSc.	[signature]
	doc. Dr. Ing. Dana Křemenáková	[signature]
	Ing. Irena Lenfeldová, Ph.D.	[signature]
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Recommendation of the supervizor

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Supervisor's opinion on PhD thesis of Veerakumar Arumugam, M.Tech.

Thesis title: **Knitted Spacer Fabrics for Multi-Functional Applications**

Mr. Veerakumar Arumugam, M.Tech., has worked for his PhD thesis under my supervision since 2013. His research is focused on extensive characterization of knitted spacer fabrics for various functional applications in automotive, mattresses, shoe insoles, back support etc. He has elaborately investigated the in-plane shear, compression, thermo-physiology and acoustic performance of knitted spacer fabrics. The results are presented in accurate manner supported with theoretical predictions in relevant cases.

Advanced statistical evaluation has been carried out for influence of various factors such as thickness, type of spacer yarn, surface structures and raw materials on specific properties. These findings are important requirements for designing knitted spacer fabrics which could be used for functional applications.

The candidate has shown adequate ability to analytically explain various complex scientific problems relating to such unique fabric structures. His ability to solve the technical problems of evaluation and characterization is reflected in the thesis. He has been able to demonstrate expertise in explaining the structural complexity of spacer fabrics in relation to performance requirements.

The results obtained and explained in the thesis are of great importance for the scientific community to design and develop suitable spacer fabrics for automotive industry, upholstery as well as applications in the military sector.

His publication activities are in very good level. He has published 12 papers in international journals with impact factor. A few more are under review and expected to be published soon. He has presented more than 30 papers individually or jointly at international conferences. 5 chapters are published in reputed books. These achievements are strong reasons for his thesis as a comprehensive work of independent research.

I therefore recommend the thesis for defence.

doc. Rajesh Mishra, PhD
Supervisor

Opponents's reviews

Opponent testimony - Dissertation

Author :	**Veerakumar Arumugam, M.Tech.**
Study programme :	P3106 – Textile Engineering
Study branch :	3106V015 - Textile Technics and Materials Engineering
Topic name :	

Knitted Spacer Fabrics for Multi-Functional Applications

In this Dissertation, properties of warp and weft 3-dimensional knitted spacer fabrics were studied and evaluated. These materials could be used to replace existing materials in many different applications. Furthermore, the influence of various fabric settings such as utilised yarns, material characteristics, fabric structures, etc. on multi-functional properties was tested. Specific goals and objectives are clearly specified in Chapter 1.

This Dissertation contains a theoretical part (Literature review – chapter 2), applied methodology (chapter 3), highly compelling results and discussions (chapter 4), clear summary and conclusions (chapter 5), references and all necessary appendices (List of Figures, Tables, Publications, Book Chapters, etc) . The work is clearly structured and well-oriented.

In Literature review, regularly used Cushioning materials and their properties important for comfort are described. Disadvantages of PU foam (toxic gases) during production and recycling are mentioned, as well as an opportunity for 3D spacer fabrics to replace them. The possible use of 3D textiles in particular areas and fields such as automotive, medical and health care, industry, sports and security is also demonstrated clearly. Also included is an overview of warp and weft spacer fabrics and their properties - mechanical, impact properties, shear properties, compressibility, sound absorption and many others.

The entire theoretical part is elaborated very carefully and transparently, including the respective references, lists of figures and tables. I appreciate the fact that the author quotes also very up-to-date sources and studies.

In chapter 3, the tested materials are described – 12 different warp knitted spacer fabrics in two structures (Lock knit and Hexagonal net) and also 6 weft knitted fabrics divided into 2 groups (with and without Lycra yarn). Structural characteristics of these samples such as stitch density, square weight, thickness, density and porosity were measured and calculated.

In sufficient detail, used testing methods and measuing equipment are specified – picture frame test for in-plane shear behavior, Hough transformation and MATLAB (analysis), compression behaviour, thermo-physiological properties (air permeability tester Testex, Alambeta, Permetest), acoustic properties (impedance tube method).

The results and discussions follow in chapter 4. I greatly appreciate the detailed description and results of the tests. In a clear overview, they give a comprehensive view of the tested materials and the possibilities of their use. Dependencies and correlations between the variables examined (different regression models, etc.) are summarized in foreground tables and graphs and clearly commented. Detailed and very precise statistical evaluations (perhaps a little too detailed for readers from non-academic sphere) are also performed.

I also highly regard the innovative and wide-ranging selection of testing methods and evaluation for individual experiments, including the drawing of clear and practical conclusions. It is apparent from the work that the author has acquired the subject fully and that he works actively and purposefully in this field. The author actively contributed to the development of this field, which is also apparent from the summary and conclusions in chapter 5.

Rich publishing activities of the author are also listed in the appendix, including publications in professional journals (WoS and SCOPUS), books and worldwide conference proceedings (China, India, France, Poland, Czech Republic, etc).

I have only a few formal comments to this work - perhaps made by a mistake. For example :

- *page 3 ..... Table of Contents ... there is used knit spacer fabrics x knitted spacer fabrics (select just one description);*
- *page 25 .... Figure 2.14 – it should be Figure 2.12;*

- *page 1 – Name of the Dissertation – „Pletené distanční tkaniny ...“. I would prefer „Pletené distační textilie ...“ but presumably it is not a fault of the author*

My questions to the author to be discussed:

- In which field do you see the best potential to use 3D knitted spacer fabrics instead of PU foam or another current materials ?
- In your opinion, what material is the best option for the face side of knitted fabric ?

Result :

I agree with all author‘s conclusions and I highly appreciate his work on this Dissertation. I consider the dissertation work as a whole to be significantly innovative and beneficial both theoretically and practically. The objectives set out in the dissertation thesis were fully met. The results of the dissertation will positively affect the theoretical area. I further appreciate numerous publications in professional books, magazines and conferences.

I recommend the dissertation work for the defense.

In Ústí nad Orlicí 22.9.2017

Ing. Jiří Procházka

Evaluation report

The thesis of Mr. Arumugan, named "Knitted Spacer Fabrics for Multi-Functional Applications" consists of 126 pages, distributed in 5 chapters. Chapter 1 provide the motivation of the thesis and its research objectives. Chapter 2 presents the state-of-the-art. Chapter 3 describes the methodology for the testing. Chapter 4 describes detailed analysis of the experiments and chapter 5 consists of the summary and conclusions.

A. Importance of the PhD Thesis

The main object of the investigation are warp knitted and weft knitted spacer structures. Both groups of fabrics are increasing their application areas during the last years, but there are less public available investigations about their properties. The better understanding of the in-plane shear, compression, thermo-physiological and acoustic properties of these structures can provide good engineering basis in the development of end products based on these structures. In this meaning the selected topic and aims are of high importance.

B. Evaluation of the procedure of problem solving, method and the fulfilment of the set aim

Mr. Arumugam performs large number of detailed experimental investigations of the 12 warp knitted and 6 weft knitted structures with different materials and pattern. The results are obtained using modern tools and techniques, like image processing, signal processing, ANOVA and other statistical methods with the check of the significance of the different influences. The obtained data is visualized suitable using different types of diagrams and charts. For few cases, he perform as well FEM simulation and receive very good correlation between the experimentally and simulation based computed parameters.

All these methods and procedures are very well selected and applied and he succeed to fulfil the aim of the thesis. What would make the methods more advanced, is the traditional for the Faculty of Textiles at Technical University of Liberec Level of deep theoretical understanding about the mechanics resp. physics of the processes. It would be better to reduce the number of the types of the tests or properties, but to extend the explanation about the connection between the pattern and yarn parameters and the experimental results, based on the mechanics of the beams, air motion etc. This is not simple task, as it require more mechanics, acoustics, mathematics and programming, and more time. So it is considered here not as critic, but as "it would be nice to have it" and as recommendation for the future development of Mr. Arumugam.

C. Evaluation of the results of the PhD. Thesis and the importance of the author's contribution

The author succeed to identify which parameters of the fabrics have significant influence over the investigated properties and which less. In the term of the large spectrum of the investigated properties, this is a serious contribution. At the current state in the thesis the several single results are distributed around the thesis, or explained with plain text at the end and remains not well visible. It would be good, if the author learn to summarize the important influences and present these more clear graphically in future publications.

D. Other statements about methodicalness, clarity of structure, layout and the language level

Language, structure and layout are fine.

E. Evaluation of the student's publications

The student has a large list of publications in peer review journals, conferences and book chapters as first author, which demonstrates her ability to perform research at the PhD level and to publish it in the suitable way.

F. Recommendation

Based on my evaluation I can highly recommend the thesis to be approved for defence and wish a lot of success of Mr. Arumugam

Mit freundlichen Grüßen

Prof. Dr. Ing. Math. Yordan Kyosev, CText FTI

Mönchengladbach, den 11.09.2017