3.1 INTRODUCTION

The aim of this chapter is to explain the materials used to manufacture the spacer fabric and the methodology adopted to analyse the properties of the fabrics. The specifications of yarn and fabric, production technique of spacer fabric, test procedures, and outline of the instrument used are discussed in this chapter.

3.2 MATERIAL

100% polyester multifilament and 100% polyester monofilament were used as raw materials for the manufacture of WKSF. The face and back layers of the spacer fabrics are formed with polyester multifilament and is connected by the middle layer made of monofilament. Details of the polyester filaments used in the spacer fabrics are given in the Table 3.1.

Table 3.1 Properties of Polyester multifilament and monofilament

<table>
<thead>
<tr>
<th>Particular</th>
<th>Multifilament</th>
<th>Monofilament</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filament denier</td>
<td>120 100 80 70 50 30</td>
<td>40 30 20</td>
</tr>
<tr>
<td>Number of filaments</td>
<td>36 36 36 24 24 24</td>
<td>1 1 1</td>
</tr>
<tr>
<td>Diameter (mm)</td>
<td>0.128 0.113 0.088 0.069 0.061 0.041</td>
<td>0.054 0.048 0.033</td>
</tr>
<tr>
<td>Tenacity (g/d)</td>
<td>4.63 4.6 4.4 4.3 4.1 3.9</td>
<td>3.94 3.38 3.15</td>
</tr>
<tr>
<td>Elongation (%)</td>
<td>26.3 23.8 25.2 24.7 25.3 26.1</td>
<td>25.9 23.4 21.6</td>
</tr>
</tbody>
</table>
For preparation of body armour, Kevlar 29 was used. Twill woven Kevlar fabrics with a pick ratio of 2:6 (Cotton: Kevlar) and 100% Kevlar in warp direction was used for the manufacturing of armour fabric. The fabrics were produced with 198g/m², 0.7mm thickness with an average thermal resistance of 0.075m²K/W and the air permeability of 27.4cc/sec/cm².

3.3 SPACER FABRIC PREPARATION

The fabric manufacturing technique and the different types of fabrics produced for the study are explained in this section.

3.3.1 Knitting Machine Specification

The WKSF was produced by Raschel double needle bed warp knitting machine (Karl Mayer RD 6) of 170 inches width.

![Schematic diagram of Rashchel warp knitting machine](image)

Figure 3.1 Schematic diagram of Rashchel warp knitting machine
The Raschel double needle bed warp knitting machine has six ground guide bars and a gauge of E22. In this machine, the needle bars are defined as GB1 and GB2 which constitute the front needle bars, GB5 and GB6 the back needle bars and GB3 and GB4 the stitch forming on both front and back needle bars. The schematic diagram of Raschel warp knitting machine is shown in Figure 3.1. By adjusting the two needle bars in the machine, the thickness (T) of spacer fabrics was maintained as constant and therefore the structures were modified by guide bars movements.

Figure 3.2 shows the side view of WKSF and the middle layer maintains the distance between two outer surface layers as constant.

### 3.3.2 Spacer Fabric Structure

Polyester WKSF samples were developed by varying their thickness and structure. The structure of the face surface layers was selected as locknit, rhombic mesh and hexagonal net and for the bottom surface layer the structure is maintained as plain knit structure. The structure of the WKSF surfaces is shown in Table 3.2 and stitch notations are given in Table 3.3.
### Table 3.2 Polyester WKSF

<table>
<thead>
<tr>
<th>Face surface layer</th>
<th>Middle spacer layer</th>
<th>Bottom surface layer</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Cross Wise" /></td>
<td><img src="image2.png" alt="Length Wise" /></td>
<td>![image3.png]</td>
</tr>
</tbody>
</table>

### Table 3.3 Stitch notation of polyester WKSF

#### Structure: Locknit

<table>
<thead>
<tr>
<th>Face Layer</th>
<th>Middle Layer</th>
<th>Bottom Layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bar1: 1-0 0-0</td>
<td>Bar3: 1-0-1-2/2-3-2-1</td>
<td>Bar5: 1-0 0-0</td>
</tr>
<tr>
<td>Bar2: 2-1 1-1</td>
<td>Bar4: 2-3-2-1/1-0-1-2</td>
<td>Bar6: 4-5-5-5</td>
</tr>
</tbody>
</table>

#### Structure: Rhombic mesh

<table>
<thead>
<tr>
<th>Face Layer</th>
<th>Middle Layer</th>
<th>Bottom Layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bar1: 1-0 0-0/1-2 2-2</td>
<td>Bar3: 1-0-1-2/2-3-2-1</td>
<td>Bar1: 1-0 0-0/ 1-2 2-2</td>
</tr>
<tr>
<td>Bar2: 2-3 3-3/2-1 1-1</td>
<td>Bar4: 2-3-2-1/1-0-1-2</td>
<td>Bar2: 4-5-5-5/1-0-0-0</td>
</tr>
</tbody>
</table>

![image4.png]  ![image5.png]  ![image6.png]
### Table 3.3 (Continued)

<table>
<thead>
<tr>
<th>Face Layer</th>
<th>Middle Layer</th>
<th>Bottom Layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bar1: 1-0-0-0/1-2-2-2/3-4-4-4/3-2-2-2/</td>
<td>Bar3: 1-0-1-2/2-3-2-1</td>
<td>Bar5: 1-0-0-0/1-2-2-2</td>
</tr>
<tr>
<td>Bar2: 3-2-2-2/3-4-4-4/1-2-2-2/1-0-0-0</td>
<td>Bar4: 2-3-2-1/1-0-1-2</td>
<td>Bar6: 4-5-5-5/1-0-0-0</td>
</tr>
</tbody>
</table>

#### 3.4 EXPERIMENTAL METHODOLOGY

The methodology followed for this study is expressed in the process flow chart as shown in Figure 3.3, which shows the particulars of various fabric parameters such as thickness, structure and filament linear density. The low stress mechanical properties, thermophysiological comfort and moisture management properties of polyester WKSF are examined, further the deformation behaviour of body armour was also studied.
Figure 3.3 Methodology flow chart for the present research work
3.5 TESTING METHODS

The various test methods and testing procedures used to test the geometrical characteristics and comfort properties of polyester WKSF are given below. All tests were carried out under standard atmospheric conditions of 25 ± 2°C temperature and 65 ± 2% relative humidity as recommended by ASTM D 1776.

3.5.1 Fabric Geometrical Characteristics

Fabric wales and courses per unit length (ASTM D 3887: 1996 (RA 2008)) and loop length (ASTM D 3887) were determined. The thickness (T) of the samples were measured using fabric thickness gauge (ASTM D 1777 - 96) at presser foot load of 100 g/sq.cm.

The angle of the spacer yarn can be calculated by using the formula (3.1) which will be useful to study the compression and resilience properties of spacer fabrics.

\[ \theta = \tan^{-1}\left(\frac{t}{W}\right) \]  

(3.1)

where W is segment width and t is fabric thickness. Figure 3.4 shows that the methods of taking the angle of spacer yarn of the spacer fabric.

![Figure 3.4 Angle of spacer yarn in WKSF](image)

Mass per unit area of the spacer fabrics was measured using a weighing balance (ASTM D 3776 - 07) and the areal density of the fabrics
calculated. Spacer fabric weight was calculated by using the following formula (3.2) and it is useful to estimate the theoretical weight of individual three layers of spacer fabric.

\[
\text{Areal Density (g/m}^2\text{)} = \frac{\text{WPcm} \times \text{CPcm} \times \text{SL} \times 39.37 \times 39.37 \times D}{1000 \times 9000}
\]

(3.2)

where WPcm is wales per centimeter, CPcm is coarse per centimeter, SL is stitch length and D is count in denier.

The fabric mass density or fabric bulk density (g/m\(^3\)) depends on both fabric weight and fabric thickness. The bulk density of the fabric was calculated using the following formula (3.3):

\[
\text{Bulk density (g/m}^3\text{)} = \frac{\text{Areal Density (g/m}^2\text{)}}{\text{Thickness (m)}}
\]

(3.3)

Many theoretical models were developed and the standard equation for the fabric porosity is given below (3.4) (Das et al 2011; Delkumburewatte and Dias 2009). WKSF porosity was calculated by using the density of polyester filament (1.38g/m\(^3\)).

\[
\text{Porosity (\%)} = \left[1 - \frac{\text{Fabric Density (g/m}^3\text{)}}{\text{Filament Density (g/m}^3\text{)}}\right] \times 100
\]

(3.4)

The porosity can be expressed either as a fraction or as a percentage.

3.5.2 Air Permeability

The air permeability of WKSF was evaluated based on Bureau of Indian Standards (BIS) IS 11056:1984 at 10 cm water head. The unit of
measurement is cc/sec/cm², accuracy 3% of Full Scale Range (FSR) and test area of 4cm².

This instrument designed had two provisions, one for calculating the volume of air flowing through the test fabric, and another to determine the pressure drop between the faces of the fabric. The two round shaped grips hold the fabrics lined with rubber gaskets to avoid the air leakage through the edges. Vacuum needed was determined by drawing the air through the fabric by vacuum pump. The vacuum pressure in a defined water level (terms of mm) was maintained by the digital manometer (or manometer tube) and the airflow measured by the Rotameters.

3.5.3 Water Vapour Permeability

Water vapour permeability was measured on Permetest instrument that works on control dish method as stated in BS 7209 and ISO Standard 11092. An average of five readings was taken and Figure 3.5 shows the schematic diagram of water vapour permeability instrument.

The water vapour permeability is the amount of vapour transfer passed through unit area of a fabric of unit thickness in unit time and expressed as the ability of fabric to permit a water vapour to pass through it. The fabric sample size for the testing is 11 cm in square or diameter. The fabric was sealed over the open mouth of a disc containing water and placed in the open air.
The loss of mass calculated is the difference between the total weight at starting time \( W_o \) and the weight \( w_t \) after the specific time of testing. The relative water vapour permeability of the spacer fabrics is calculated through the equation (3.5).

\[
WVP \ (g/m^2/24h) = \frac{(24 \times M)}{(A \times t)} \quad (3.5)
\]

where M is the loss of mass in g; t is the time between weighing hours and A is the internal area of the dish in m².

3.5.4 Wicking

Wicking characteristics of the fabric decide how fast the fabric can transfer the moisture to another layer or to the other side of the fabric. The two main categories of wicking are vertical and horizontal or in-plane wicking testing.
3.5.4.1 Vertical wicking

The test was conducted using a vertical wicking tester according to the DIN 53924 method. Vertical strip wicking tests were carried out using the equipment shown in Figure 3.6.

![Diagram of vertical wicking apparatus](image)

Figure 3.6 Schematic diagram of vertical wicking apparatus (Fangueiro et al 2010, Bagherzadeh et al 2012)

WKSF was cut into 200mm × 25mm along the wale wise and course wise directions. Five specimens were prepared for each sample. The specimen was hung vertically from the stand with a 1 gram clip and was dipped in a reservoir of distilled water at a depth of 30 mm. 1% reactive dye (Procion blue) added in the reservoir for tracking the movement of water at a regular time interval. The wicking height was measured at a regular time of interval and recorded for a direct evaluation of the fabric wickability.
3.5.4.2 In-plane wicking

Gravimetric in-plane wicking apparatus was used to determine the transfer or in-plane wicking of spacer fabric and the tester was developed at the Indian Institute of Technology, Delhi, India. Fabric sample cut into 160mm×160mm size was placed on the horizontal base plate.

![In-plane wicking apparatus](image)

Figure 3.7 In-plane wicking apparatus (Fangueiro et al 2010; Das et al 2013)

It is connected to a liquid reservoir by means of a siphon tube as shown in Figure 3.7. By using a cover plate, the fabric samples were covered to ensure a closer contact between the fabric and the base plate. The reservoir is adjustable to provide a good contact between the bottom surfaces of the fabric samples with the water in the siphon tube. The reservoir was placed on an electronic balance and the water level is maintained. The rate of water uptake is the weight of water absorbed by the fabric in a particular interval of time and can be measured in the form of reduced weight of water in the reservoir and the differences in the two consecutive readings.
3.5.5 Thermal Conductivity

Thermal conductivity is a property of materials that articulates the heat flow through the material and it was calculated using Lee's disk instrument (ASTM-D570).

To measure the thermal conductivity, a number of methods are available. A suitable type depends on the range of materials, the thermal properties and the medium temperature.

Figure 3.8 shows Lee’s Disc, which is used to determine the thermal conductivity of spacer fabrics. The WKSF (D) is positioned in between a brass base (B) and a brass disc (C). The entire arrangement is balanced through a string that is attached to hooks in C. To record the temperature of B and C, the thermometers T1 and T2 are inserted into the holes in B and C. A steam is passed into the chamber (A). The temperatures of disc C and B were noted at intervals of 5 minutes. Based on the above particulars, the following formula (3.6) was used to derive the thermal conductivity of spacer fabrics.

\[
\text{Thermal conductivity (} \lambda \text{) Wm}^{-1}\text{K}^{-1} = \frac{\text{MSR} \cdot \text{d} \cdot (2h+r)}{\text{A} \cdot (T1-T2) \cdot (2h+2r)}
\]

where,
- M = Mass of brass disc (C) in kgs
- S = Specific heat of the material of the disc (370 J Kg\(^{-1}\) K\(^{-1}\))
- R = Rate of fall of temperature (dT/dt)
- h = Thickness of brass disc in mm
- r = Radius of the brass disc in mm
- d = Thickness of the specimen in mm
- A = Area of cross section of the specimen in mm\(^2\)
3.5.6 Thermal resistance

Thermal resistance was also measured by using Permetest instrument working on similar skin model principle according to both BS 7209 and ISO Standard 11092.

Thermal resistance articulates the thermal insulation of fabrics and is inversely proportional to thermal conductivity. The connection between thermal conductivity and thermal resistance is defined as the amount of heat flow across a unit area of the material of unit thickness in a unit of time. The following formula (3.7) was used:

\[
\text{Thermal resistance (r) m}^2.\text{K/W} = \frac{T}{\lambda}
\]  
(3.7)

where:

T = Fabric thickness,
\( \lambda \) = Thermal conductivity.
3.5.7 Low Stress Mechanical Properties

The low stress mechanical properties of polyester WKSF were tested by the Kawabata evaluation system (KES-FB). Table 3.4 clearly indicates the test parameters of the fabric properties evaluated through KES.

Table 3.4 Test Parameters of Kawabata evolution system

<table>
<thead>
<tr>
<th>Property</th>
<th>Symbol</th>
<th>Parameter</th>
<th>Unit</th>
<th>Sample Area</th>
<th>Rate of deformation</th>
<th>Max &amp; Min Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compression (FB 3)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>T₀</td>
<td>Thickness at 0.5gf/cm² pressure</td>
<td>mm</td>
<td>2cm²</td>
<td>0.2 mm/sec.</td>
<td>0.5gf/cm² to 50gf/cm²</td>
</tr>
<tr>
<td></td>
<td>Tₘ</td>
<td>Thickness at 50gf/cm² pressure</td>
<td>mm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>LC</td>
<td>Compression linearity</td>
<td>---</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>WC</td>
<td>Compression energy</td>
<td>gf.cm/cm²</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>RC</td>
<td>Compression resilience</td>
<td>%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bending (FB 2)</td>
<td>B</td>
<td>Bending rigidity</td>
<td>gf·cm²/cm</td>
<td>20cm × 1cm</td>
<td>0.02 mm/sec.</td>
<td>+2.5cm⁻¹ &amp; -2.5cm⁻¹</td>
</tr>
<tr>
<td></td>
<td>2HB</td>
<td>Bending hysteresis</td>
<td>gf·cm²/cm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tensile (FB 1)</td>
<td>LT</td>
<td>Linearity of extension curve</td>
<td>---</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>WT</td>
<td>Tensile energy</td>
<td>gf·cm²/cm²</td>
<td>5cm × 1cm</td>
<td>0.2 mm/sec.</td>
<td>Max. Load 500gf/cm</td>
</tr>
<tr>
<td></td>
<td>RT</td>
<td>Tensile resilience</td>
<td>%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>EMT</td>
<td>Extension at 500gf/cm Load</td>
<td>%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shear (FB 1)</td>
<td>G</td>
<td>Shear stiffness</td>
<td>gf/cm. deg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2HG</td>
<td>Shear Hysteresis (0.5 °)</td>
<td>gf/cm</td>
<td>5cm × 1cm</td>
<td>Shear angle of ± 8°</td>
<td>Tensile force 10gf/cm</td>
</tr>
<tr>
<td></td>
<td>2HG 5</td>
<td>Shear Hysteresis (5 °)</td>
<td>gf/cm</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
3.5.8 Ballistic impact

The modeling backing material used for ballistic evaluation can be either mineral or polymeric clay. Roma Plastilina No1 is oil based modeling clay and it is designated as a backing material for the testing of ballistic vests. To build the backing material, 40kg of clay were taken at a constant temperature of 35°C for a few hours to make it pliable. A wooden block in the dimensions of 610mm×610mm ×140mm was prepared and then the clay was filled into the backing material fixture. The clay was worked upon using the hands and the air pockets were removed to ensure uniformity and density throughout the block.

Ballistic tests were conducted to determine the ballistic impact limit of polyester WKSF. Figure 3.9 shows the arrangement of Kevlar fabric, spacer fabric, backing model and rifle. The test was conducted in accordance with NIJ standard 0101.06. A standard fragment simulation projectile (FSP) was used in a Universal Test Gun system at the Madurai Rifle Club, Madurai. The target sample was clamped in all the four sides and positioned at 50 meters away from target gun. The 0.22mm rifle was used to test the samples. The weight of the projectile was 30gms and fired at a velocity of 1.5km/Sec. The force acted on the body armour by the bullet was 675 Newton and it can be calculated by using the following equation (3.8).

\[ F = m \times a \] (3.8)

where ‘F’ is force in Newton, ‘m’ is the mass in kilogram and the ‘a’ represent the acceleration in m/sec².
The samples were tested in two ways, one without spacer fabric and another with spacer fabric, to find out the impact caused the depth and diameter of impact caused by projectile on the clay.

3.6 DATA ANALYSIS

Three factorial Box and Behnken experimental designs were used to analyse the significance of polyester WKSF layer polyester denier on porosity, air permeability, water vapour permeability and thermal properties. Response surface method (RSM), and corresponding contour plots were used for optimisation of each response by using design-expert software version 8.0. The different properties of Polyester WKSF results were statistically analysed through ANOVA and both F and P values were employed to prove the influence of variables with the responses. One-way ANOVA and two way ANOVA were used and the selected value of significance level for all statistical tests in the study was 0.05. To confirm the significance of ANOVA, Tukey’s HSD test was also used. Tukey’s HSD test was used to determine the significant difference among all the groups.