Compressional and recovery behaviour of highloft nonwovens

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The compressional and recovery behaviour of highloft nonwovens has been studied with a view to know how the fibre materials used and manufacturing technologies employed drive and dictate this behaviour. The results show significant effects of physical and mechanical properties of fibres on the compressional and recovery behaviour of highlofts. It is also observed that highlofts produced by different bonding technologies show significantly different compressional and recovery behaviour. The experimental results are found in satisfactory agreement with the theoretical results.

Keywords: Compressional behavior, Recovery behavior, Highloft, Nonwoven

1 Introduction

Highlofts are defined as a low-density fibrous structure characterized by a high ratio of thickness to mass per unit area. This is accomplished by bonding or interlocking of fibres, or both using mechanical, chemical, thermal, or solvent means or combination thereof. Ideally, highlofts should be soft, bulky, permeable and at the same time, they should have sufficient resistance to mechanical actions. Typical usage of highlofts can be found in the areas of geotextiles, home upholstery, building insulation, etc. in making a range of products, such as furniture, bedspreads, quilts, mattresses, pillows, sleeping bags, apparel insulation pads, roofing and building insulation pads, fibrous filters, etc. In application, the fibres are often compressed to create a necessary number of contacts among themselves so as to withstand the mechanical load, and when the load is removed, the fibres are recovered to their original arrangement, thus the fibrous structure stays soft, stable, bulky and permeable. It is anticipated that this behaviour will be influenced by the fibre materials used and the manufacturing technologies employed to create such structures. In this work, an attempt has been made to examine the role of fibre properties and fibre bonding technologies on the compressional and recovery properties of highlofts. This will further develop a deeper understanding to relate the physical and mechanical properties of fibres and that how the fibres are arranged in a highloft structure resulting from the influence of a manufacturing technology to its compressional and recovery behaviour. Applications of this study include development of new products by combining the positive contributions of fibre properties and manufacturing technology to the compressional and recovery behaviour of highlofts.

Some earlier research studies were dealt with the influence of different fibres and different fibre properties on the compressional and recovery characteristics of loose fibrous masses, fibrous webs and highlofts. Dunlop 2,3 studied the compressional characteristics of loose fibrous masses composed of wool, polyester, acrylic and viscose fibres and found that all these loose fibrous masses show remarkably different behaviour under compression. Parikh et al. 4 studied the compressional and recovery behaviour of cotton-polyester blended highlofts and observed that the cotton-rich highlofts are less elastic and less resilient than the polyester-rich highlofts. Study by Verma and Meredith 5 showed that fibre length and fibre fineness are not important in determining the recovery behaviour of loose fibrous masses, however, the fibre crimp, to a lesser extent, and fibre friction are found important for high recovery. Beil and Roberts 6,7 showed how the compressional behaviour of a fibrous assembly could be predicted from the properties of its constituent fibres. They found that the fibre crimp plays a very vital role in determining the compressional behaviour of a fibrous assembly.

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Schoppee\textsuperscript{8} simulated the effects of fibre fineness and fibre transverse compression modulus on the compressional behaviour of fibrous webs, and found that fibres of higher fineness and modulus would not pack as well when compressed as similar webs composed of fibres of lower fineness and modulus, therefore, the former experiences more compressive stress than the latter. However, no attempt has been made to verify the simulated results with the experimental results. Kothari and Das\textsuperscript{9} studied the compressional and recovery behaviour of nonwoven geotextiles, but they did not examine the role of fibre properties on compressional behaviour. Recently, Icchaporia \textit{et al.}\textsuperscript{10} studied the effect of fibre properties on the compressional and recovery behaviour of highlofts. They concluded that fibre cross-sectional shape and fibre bending rigidity influence the compressional behaviour at low as well as high pressure, but fibre crimp influences the recovery behaviour at low pressure only.

The effect of highloft formation technology on the compressional behaviour has not been extensively studied so far. Krcma and Jirsak\textsuperscript{11} claimed that the highlofts made by perpendicular-laid technology (vertical lapping) show superior compressional and recovery behaviour to those made by using the cross-laid technology. This observation was in line with that made by Parikh \textit{et al.}\textsuperscript{12} and Jirsak \textit{et al.}\textsuperscript{13}. Very recently, Kang \textit{et al.}\textsuperscript{14} studied the effect of compression on highlofts made by perpendicular-laid technology using two types of fibrous web formation techniques, namely air folding technique and mechanical folding technique. They found that the perpendicular-laid highlofts made by air folding technique show higher compressional energy with higher web density, but the perpendicular-laid highlofts made by mechanical folding technique show lower compressional energy with higher web density. The reason of this distinct behaviour is however scientifically not yet known. Furthermore, no attempt has been made to study the effect of fibre-to-fibre bonding technology on the compressional and recovery behaviour of highlofts.

The present study focuses on fundamentals of compressional and recovery behaviour of highlofts with a view to know how the fibre materials used and manufacturing technologies employed drive and dictate this behaviour.

\textbf{2 Theoretical Considerations}

The most referred theoretical work on the compressional behaviour of a fibrous assembly is due to Van Wyk\textsuperscript{15}. He idealized a fibrous assembly consisting of many straight and cylindrical fibres of equal length and diameter that are oriented randomly. Let the length, breadth, and thickness of the assembly be $x$, $y$, and $z_0$ respectively. Then, the volume $V_0$ of the assembly can be expressed as $V_0 = xyz_0$. Let the volume of fibres in the assembly be $V_f$. Then, the fibre volume fraction $\mu_0$ in the assembly can be written as $\mu_0 = V_f / V_0 = V_f / xyz_0$. Now consider that a pressure is applied onto this assembly and as a result, it gets compressed to thickness $z$ (one-dimensional deformation). Thus, the volume of the assembly changes to $V_c = xyz$. Accordingly, the fibre volume fraction changes to $\mu = V_f / V_c = V_f / xyz$. This change in fibre volume fraction can be described in term of the change in thickness of the assembly and also in term of the compressive strain $\varepsilon$ experienced by the assembly as follows $\varepsilon = (z - z_0) / z_0 = (\mu_0 / \mu)$. Here it is evident that $\varepsilon < 0$. Further, Van Wyk\textsuperscript{15} imagined that the fibres just touch one another under compression, as shown in Fig. 1(a). He then derived the following theoretical relationship between compressive pressure $p$ and fibre volume fraction $\mu$:

$$p = k_p \mu^3$$ \hfill (1)

where $k_p$ is a parameter characteristic to the fibre material used and the manufacturing technology employed for the production of the fibrous assembly. As it is evident from the aforesaid relationship that the pressure $p$ is not equal to zero at fibre volume fraction $\mu = \mu_0$. Van Wyk suggested an empirical correction to the aforesaid relation as stated below:

$$p = k_p \left( \mu^3 - \mu_0^3 \right)$$ \hfill (2)

There is a great controversy whether Van Wyk\textsuperscript{5} model can explain the compressional behaviour of a real fibrous assembly. It is found that this model corresponds well to the experimental results for relatively low values of fibre volume fraction, but not for relatively high values of fibre volume fraction\textsuperscript{2,3,16,17}. Moreover, Eq. (2) suggests that the fibrous assembly can have fibre volume fraction more than one at a very high pressure. That is, when $p > k_p$, one can obtain $\mu > 1$. But, a real fibrous assembly can never have fibre volume fraction greater than one. This discrepancy was explained by Necka\textsuperscript{5}. According to him, Van Wyk\textsuperscript{5} idea of fibres just
touching each other (Fig. 1a) is not probably real; instead fibres press each other and occupy a significant volume around the contact place (Fig. 1b). When the pressure is low, the fibres are pressed slightly; therefore, the contact volume is relatively small. On the other hand, when the pressure is high the fibres are pressed greatly and therefore, the contact volume is relatively high. Based on this imagination, Neckář derived the following relationship between compressive pressure and fibre volume fraction:

\[ p = k_p \left( \mu^3 - \mu_0^3 \right) \left( 1 - \mu^3 \right)^{-3} \left( 1 - \mu_0^3 \right)^{-3} \]  

\( \mu \leq \mu_0 \)

Equation (3) is also compared with Eq. (2) in the light of experimental results obtained on loose fibrous masses by Balyasov. This comparison is shown in Fig. 2. Neckář's model appears to explain the compressional behaviour of loose fibrous masses better than that does by Van Wyk model. Here, attempts have been made to examine if Neckář's model can also explain the compressional behaviour of highlofts produced by using different fibre materials and employing different manufacturing technologies.

3 Materials and Methods

3.1 Fibre Materials

Polyester (PES) homocomponent fibre and copolyethylene-polypropylene (CoPE/PP) sheath-core bicomponent fibres were used. Their physical and mechanical properties are presented in Table 1. The staple length \( l \) and density \( \rho \) values of these fibres were obtained from fibre suppliers. The fibre fineness \( t \) was measured by Textechno Favimat fibre tester at a speed of 25 mm/min. The tenacity \( \sigma \) and breaking elongation \( \xi \) of these fibres were observed by using the same instrument under 10 mm gauge length at a speed of 20 mm/min. The fibre diameter \( d \) was calculated from the formula:

\[ d = \frac{\sqrt{4t}}{\pi \rho} \]

and the fibre flexural rigidity \( \eta \) from the formula:

\[ \eta = \frac{4t^2}{4\pi \rho} \]

where \( \gamma \) denotes Young's modulus of fibres. This was estimated from the stress-strain diagram of the fibres.

3.2 Preparation of Highloft Samples

The fibres were opened and carded to make thin fibrous webs. For this, a bale opener and a roller card were used respectively. The webs were then stacked one over the other by a cross-lapper to form a thick and voluminous fibrous web. In order to create bonds among the fibres in the web, three different technologies were used. In majority of the webs, the fibres were bonded mechanically by needling at 176 punches per cm² of the web. In one web, the fibres were bonded chemically by spraying 20 g acrylate binder onto one square meter of the web. In another web, the fibres were bonded thermally by passing the web through a hot air chamber at a temperature of...
110°C. Thus, in total, six highloft samples were prepared. The samples are described in Table 2.

### 3.3 Testing of Highloft Samples

The samples were tested for their basis weight \( W \) and thickness \( T \) following ASTM standards. Then, the density \( \rho^* \) of these samples was calculated from the formula \( \rho^* = W/T \). The fibre volume fraction \( \mu_0 \) in these samples was calculated from the formula: 
\[
\mu_0 = \rho^*/\rho.
\]
The results are presented in Table 2. The samples were tested for their compressional and recovery behaviour using Instron tensile tester at a constant rate of extension. The compression was conducted for one cycle and the recovery was allowed immediately. The cross-head speed was kept at 5 mm/min.

### 4 Results and Discussion

#### 4.1 Characterization of Compressional and Recovery Behaviour

The compressional and recovery behaviour of the prepared highlofts is characterized by the five parameters, namely compressibility \( c \), recoverability \( r \), compressional energy \( E_c \), recovery energy \( E_r \), and loss of energy \( \zeta \). They are defined below with reference to a typical load \( F \) - thickness \( z \) profile of a highloft (Fig. 3):

\[
c = \frac{z_0 - z_c}{z_0} \quad \text{é (4)}
\]

\[
r = \frac{z_c - z_0}{z_0 - z_c} \quad \text{é (5)}
\]

\[
E_c = \int_{z_i}^{z} F \, dz \quad \text{é (6)}
\]

\[
E_r = \int_{z_i}^{z} F \, dz \quad \text{é (7)}
\]

\[
\zeta = \frac{E_c - E_r}{E_c} \quad \text{é (8)}
\]
A simple computer program was developed to numerically calculate these parameters from the load-thickness profile of the tested samples. Table 3 shows that the highloft (S1) made up of bicomponent fibres experiences higher compressibility, higher recoverability, and less loss of energy as compared to the highloft (S6) made up of homocomponent fibre. The highloft (S4) made from coarser fibres shows higher compressibility, higher recoverability, and less loss of energy than the highloft (S6) made from finer fibres. The thermo-bonded highloft (S3) demonstrates remarkably higher compressibility and recoverability than the needle-bonded highloft (S1), which, in turn, shows higher compressibility and recoverability than the adhesive-bonded highloft (S2). Among all the samples tested, the thermo-bonded highloft (S3) experiences maximum loss of energy and the needle-bonded highloft (S4) shows minimum loss of energy.

### 4.2 Effect of Fibre Type on Compressional and Recovery Behaviour

The compressional and recovery behaviour of highlofts made from two different fibre types is shown in Fig. 4. The highloft made from homocomponent fibre experiences less compressive stress than the highloft made from bicomponent fibre. In other words, if we need to compress the two highlofts equally then we need to apply higher compressive pressure onto the bicomponent highloft as compared to the homocomponent one. This can be ascribed due to the fact that the bicomponent fibres, being more rigid, require higher compressive pressure to bending than the homocomponent fibres.

### 4.3 Effect of Fibre Fineness on Compressional and Recovery Behaviour

Figure 5 shows the compressional and recovery behaviour of highlofts made from polyester fibres of different fineness (14.9 den, S4; 5.53 den, S5; and 1.50 den, S6).

<table>
<thead>
<tr>
<th>Sample code</th>
<th>c, %</th>
<th>r, %</th>
<th>$E_c$, joule</th>
<th>$E_r$, joule</th>
<th>$\zeta$, %</th>
<th>$k_p$, MPa</th>
</tr>
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<tbody>
<tr>
<td>S1</td>
<td>45.74</td>
<td>61.48</td>
<td>0.0759</td>
<td>0.0465</td>
<td>38.73</td>
<td>3.67</td>
</tr>
<tr>
<td>S2</td>
<td>32.66</td>
<td>57.72</td>
<td>0.0636</td>
<td>0.0367</td>
<td>42.29</td>
<td>6.68</td>
</tr>
<tr>
<td>S3</td>
<td>66.31</td>
<td>68.32</td>
<td>1.8423</td>
<td>1.2460</td>
<td>59.63</td>
<td>20.12</td>
</tr>
<tr>
<td>S4</td>
<td>47.63</td>
<td>69.78</td>
<td>1.7389</td>
<td>1.2032</td>
<td>30.81</td>
<td>168.20</td>
</tr>
<tr>
<td>S5</td>
<td>41.64</td>
<td>58.08</td>
<td>0.1950</td>
<td>0.1124</td>
<td>42.36</td>
<td>54.15</td>
</tr>
<tr>
<td>S6</td>
<td>38.11</td>
<td>49.11</td>
<td>0.0323</td>
<td>0.0157</td>
<td>51.39</td>
<td>15.10</td>
</tr>
</tbody>
</table>

$c$ Compressibility of highloft, $r$ Recoverability of highloft, $E_c$, $E_r$ Compressional energy of highloft, $\zeta$ Loss of energy of highloft, and $k_p$ Structural parameter of highloft related to compression.
three different fineness. It is observed that the highloft made from the coarser fibres experiences higher compressive stress than that made from the finer fibres. This indicates that higher compressive pressure needs to be applied to compress a coarser fibre highloft as compared to a finer fibre highloft. This observation is in-line with the computer simulation results obtained by Schoppee. As known, the coarser fibres, being more rigid, require more compressive pressure to bending than the finer ones.

4.4 Effect of Fibre Bonding Technology on Compressional and Recovery Behaviour

The effect of fibre bonding technology on compressional and recovery behaviour of highlofts is shown in Fig. 6. The thermo-bonded highloft shows remarkably different compression-recovery behaviour than the adhesive-bonded and needle-bonded highlofts. As shown, the thermo-bonded highloft experiences highest compressive stress and strain among the three highlofts tested. At a given strain, the adhesive-bonded highloft developes higher compressive stress than the needle-bonded highloft, but the latter experiences higher amount of strain than the former. The bonds formed between every contacting fibre in the thermo-bonded highloft result in significant increase in its structural integrity which, in turn, leads to develop significantly high compressive stress in the thermo-bonded structure. Of course, this is not the case with the needle-bonded highlofts where the fibre-to-fibre bonding is known to depend on the level of friction and entanglement between fibres. The integrity of fibre-to-fibre bonding in the case of needle-bonded highloft is perhaps lower than that in the case of chemically-bonded highloft, which leads to develop lower compressive stress in the needle-bonded highloft.

4.5 Theory versus Experiment

The real compressional behaviour of all the highlofts was compared with the theoretical compressional behaviour using Neckář's model [Eq. (3)]. This comparison for the needle-bonded highloft made up of 2.10 denier CoPE-PP sheath-core bicomponent fibres (S1) is shown in Fig. 7. As shown, there was a
satisfactory agreement between the experimental results and the Neckář model. A similar behaviour was obtained with the other highlofts produced and used in this work. The values for the parameter $k_p$ have also been found for all the highlofts studied in this work by using the standard non-linear regression technique. Table 3 shows different values for the parameter $k_p$ of different highlofts. Needless to say, these values can be used in Eq. (3) in order to predict the compressional behaviour of these highlofts under their real-world applications. It can be noted that different bonding technologies brought out different values for $k_p$, depending on the resistance to compression offered by different structures. It can also be noted that different fibres result in different values of $k_p$ and the value of $k_p$ increases with the increase in fibre flexural rigidity (Fig. 8).

5 Conclusions

It is observed that the compressional behaviour of highlofts can be explained by Neckář model. The effect of fibre-to-fibre bending on the compressional behaviour of highlofts is found to be very dominant. Highlofts made up of fibres of different types and different fineness show distinctly different compressional and recovery behaviour. Also, the way these highlofts are produced by using different bonding technologies has a remarkable effect on their compressional and recovery behaviour.

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