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Analytical Approach for Simulating the Compression and Recovery Behaviour of Nonwoven Fabrics for Automotive Floor- -Covering Application under Static Loading

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Abstract

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In this study, viscoelastic model parameters are obtained to predict the compression and recovery behaviour of needle-punched nonwoven textiles which are customarily used in industrial applications such as automotive floor-coverings. To this end, two different models are used to explain the compression and recovery behaviour of non-woven textiles under brief, moderate static loading (BMSL) and prolonged, heavy static loading (PHSL) according to ISO 3415 and ISO 3416, respectively. The first model consists of a linear spring and damper set parallel to each other. This combination is placed in series with a linear damper. The second model, however, consists of a linear spring and damper set parallel to each other and placed in series with a nonlinear damper. The results obtained for the compression and recovery behaviour of the non-woven textiles under BMSL and PHSL are compared with experimental results. The results obtained indicated that the nonlinear model is more accurate in the prediction of the compression and recovery behaviour of needle-punched nonwoven *textiles under static loading than the linear model. The best result for the prediction of the compression and the recovery behaviour of nonwoven textiles under BMSL and PHSL occurs with the nonlinear model, in which the errors are 4.68% and 4.66%, respectively, when compared to the experimental results.*

Key words: *compression, recovery, nonwoven textile, non-linear Jeffrey's II model, static loading.*

nonwoven fabrics. As they observed, recovery from a deformed state increases with an increase in the relaxation time after the compression–recovery cycle. However, the time-dependent effect is insignificant in the case of heat-sealed nonwovens as much of the recovery is instantaneous. In another study, Khotari and Das [3] presented a theoretical analysis of the compressional behaviour of nonwoven fabrics based on their bending properties. They found that spun-bond heat-sealed fabrics are more compatible with the theoretical model as compared to spun-bond needle-punched fabrics. Debnath and Madhusoothanan [4] modelled the compression properties of needle-punched nonwoven fabrics produced from polyester and a blend of jute-polypropylene fibres of varying fabric weight, needle density and blend ratio of jute and polypropylene fibres. The initial thickness, compression percentage, percentage of thickness loss, and compression resilience were predicted using an artificial neural network. Debnath and Madhusoothanan [5] investigated the effects of fabric weight, fibre cross-sectional shapes, and reinforcing materials on the compression properties of polyester needle-punched industrial nonwoven fabrics. They showed that in fabrics with no reinforcing materials, the compression and thickness loss are higher than

those in fabrics with reinforcing materials, regardless of fibre cross-sections. They also showed that polyester fabrics made from hollow cross-sectioned fibres have the least rate of compression at every level of fabric weight. In another research, Debnath, and Madhusoothanan [6] investigated the effects of fabric weight, fibre cross-sectional shapes, and reinforcing materials on compression properties under dry and wet conditions of polyester needle-punched industrial nonwoven fabrics. The results showed that compression resilience is higher in round cross-sectional fabrics without reinforcing materials under wet conditions than in fabrics with reinforcing materials. It also emerged that when the fabric weight increases, the initial thickness increases, but the percentage of compression and thickness loss decreases. This is regardless of the fibre cross-sectional shape in either dry or wet conditions. In a subsequent study, Debnath and Madhusoothanan [7] examined the effects of parallel-laid and cross-laid webs of polypropylene needle-punched nonwoven fabrics on their compression properties under wet conditions. Their results showed that an increase in the needle density would lead to a reduction in the initial thickness, compression percentage, and thickness percentage under wet conditions, compared to dry condi-

Introduction

Nonwoven textiles have various applications in the industry, such as making household goods, automotive floor-coverings [1], filters and geotextiles. These textiles are subjected to different kinds of force and deformation. One of the important deformations is compression and recovery after the load removal. It has been shown that thickness loss in nonwoven textiles is highly affected by the compression behaviour of the textiles. In recent years, many researchers have taken an interest in the study of the compression and recovery of nonwoven textiles. Khotari and Das [2] studied the time-dependent compression of different fabrics. It was also found that the compression resilience would rise with an increase in the needle density under dry and wet conditions of parallel-laid webs. A linear viscoelastic model was presented by Jafari and Ghane [8] to evaluate the recovery behaviour of machine-made carpets after a brief and heavy static loading (BHSL). Different combinations of spring and damper systems were taken into consideration to model the mechanical behaviour of the carpets. According to the results, there was reasonably good agreement between the Jeffrey's model and experimental findings. It was also revealed that the linear standard model has poor regression for the recovery properties of cut pile carpets after static loading. Khavari and Ghane [9] used three different models to investigate the compression, decompression and recovery of cut pile carpets under BHSL and with a constant rate of compression. The Maxwell mechanical model as well as linear and nonlinear three-element models were used to simulate the compression and recovery behaviour of the carpet samples. The results showed that a three-element model consisting of a Maxwell body paralleled with a non-linear spring can describe compression and decompression more accurately than Maxwell and linear models. Tower and Carrillo [10] predicted the compression behaviour of nonwoven carpets by considering their fibre properties and doing discrete fibre finite element simulation through the Abaqus technique. Jafari and Ghane [11] studied the effect of UV radiation on the recovery behaviour of pile carpets after BHSL through analytical and viscoelastic modelling. The thickness loss and maximum compression both proved to be higher within longer UV exposure times. In their subsequent study in 2018 [12], Jafari and Ghane used the linear and nonlinear Jeffrey's models, as two different mechanical models, to investigate the recovery property of machine-made carpets. It was indicated that, in comparison to the linear model, the nonlinear Jeffrey's model has a lower speed of recovery at zero time.

Although various models are presented Γ
to simulate the compression and recover $\frac{1}{2}$ ery behaviour of nonwoven textiles, there $\frac{1}{2}$ in the I to simulate the compression and recovis little research regarding compression and recovery properties under BMSL and PHSL simultaneously. Also, those researches used curve fitting methods to adapt the experimental data to the theoretical models. Therefore, the purpose of

l model: a) Linear Jeffrey's model and b) Non<mark>-</mark> are the same same ϵ is obtained using ϵ $(0, 1)$ and $(0, 0)$ $(0, 1)$ $(0, 1)$ (1) *Figure 1. Mechanical model: a) Linear Jeffrey's model and b) Non-linear Jeffrey's model.*

this study is to obtain viscoelastic model parameters analytically to predict the compression and recovery properties of needle-punched non-woven textiles under BMSL and PHSL according to ISO3415 and ISO3416 simultaneously.

Mechanical model

Figure 2. ing of a Voigt-Kelvin body that is placed To investigate the compression and recovery behaviour of nonwoven fabrics under BMSL and PHSL, two different $c_0 \ddot{x} + k \dot{x} = \frac{kF}{\sqrt{2}}$ mechanical models based on massspring- dashpot are presented: a) a linear model consisting of a Voigt-Kelvin body that is placed in series with a linear damper and b) a nonlinear model consistin series with a nonlinear damper. It is known as Jeffrey's II model.

Schematic diagrams of the two models are presented in *Figure 1*.

The compressive force F is applied to every model. As shown in *Figure 1*, *k* is the linear spring constant (N/m) , and c_1 ing from **Equation (6)**: and c_2 are the damper constants (N·s/m). In the first model, c_1 is a linear damper, while in the second method, c_1 (N·s/m²) $x = -\frac{Rz_2c}{k} + \frac{1}{c_1}t + B$ (7) is a nonlinear damper. The governing $\frac{1}{\sqrt{N}}$, and are the first model, $\frac{1}{\sqrt{N}}$. differential equations for the linear and nonlinear models are presented in the second method, is a nonlinear models are presented in the second method, is a nonfollowing section. dels are presented in the **Determining the response of the system** tion.

Linear Jeffrey's II model *Compression*

 ϵ_1 and in the voigt-kei-
vin element are the same. Thus, the com-In the Linear Jeffrey's II model, the forc-**Linear Jeffrey's II model** es in the dashpot c_1 and in the Voigt-kelpressive force is obtained using *Equa-* $\begin{bmatrix} a_1 \\ b_2 \end{bmatrix}$ $\begin{bmatrix} a_1 \\ b_2 \end{bmatrix}$ (0) *tions (1)* and *(2)* [13];

$$
F = ky + c_2 \dot{y} \tag{1}
$$

$$
F = c_1(\dot{x} - \dot{y}) \tag{2}
$$

Equation (3) can be obtained from $Equations (1)$ and (2) as: and (2) as: $\mathbf{1}$ can be obtained from Equations (1) and (2) and (2) associated from Equations (1) as:

$$
\dot{F}\left(1 + \frac{c_2}{c_1}\right) + \frac{kF}{c_1} - (k\dot{x} + c_2\ddot{x}) = 0 \quad (3)
$$

force F is constant, its derivative is zero, and *Equation* (3) can be α Because the force F is constant, its deexpressed as follows:

$$
c_2 \ddot{x} + k \dot{x} = \frac{kF}{c_1} \tag{4}
$$

Considering $\dot{x} = u$, *Equation (4)* can be $\overline{ }$ written as: C^{c} , C^{c} can be written as: \overline{C} , \overline{C} as \overline{C} can be written as \overline{C} can be written as \overline{C} can be written as:

$$
\dot{u} + \frac{k}{c_2} u = \frac{kF}{c_1 c_2} \tag{5}
$$

differential *I* can be obtained as follows: collows: $\ddot{}$ rameter u can be obtained as follows: Solving the differential *Equation (5)*, pa c_2 c_1c_2
ferential *Equati* $S₁$ Equation (5), parameter (v, v) Solving the differential Equation (5), parameter *u* can be obtained as follows: S^{c}_{c} Equation (5), parameter σ

 $\overline{1}$

$$
u = Ae^{\frac{-kt}{c_2}} + \frac{F}{c_1} \tag{6}
$$

Where, \hat{A} is a constant coefficient. Where, A is a constant coefficient. where, *a* is a constant coefficient. constant coefficient.

x can be obtained by integrating from *Equation* (6): Parameter x can be obtained by integrat-

$$
x = -\frac{Ac_2e^{\frac{-kt}{c_2}}}{k} + \frac{F}{c_1}t + B \qquad (7)
$$

 $\ddot{}$ Where, *B* is a constant coefficient. Where, *B* is a constant coefficient. s a constant coefficient. Where, B is a constant coefficient. Where, *B* is a constant coefficient. istant coefficient. html between **B** is a coefficient.

from *Equation* (7) needs two initial cont = 0, $x = 0$ and $u = 0$ into **Equations (6)** $t = 0, x = 0$ and $u = 0$ into *Equations* (*o*)
and (7), constants A and B can be ob- P and P a Determining the response of the system $\frac{1}{11}$ tained as follows: International conditions *as* follows: I interval intervals **the initial conditions** constants *A* and *B* can be obtained as follows: stants *A* and *B* can be ob-

$$
A = -\frac{F}{c_1} \tag{8}
$$

(2) [13];
\n
$$
F = ky + c_2 y
$$
 (1) $B = \frac{Ac_2}{k}$ (9)

Recovery

Since the start point in the recovery is the sar equivalent to the end point of the com-
 pression, the initial conditions for this case are:
case are: $(x = x^*)$ case are:

$$
x(t_1) = x^*
$$
 (10) recovery can be calculated as: **Non-linear Jett**

$$
u(t_1) = R_r \tag{11}
$$

Where, t_1 is the recovery time.

moved, the recovery (or stress relaxation) time are changed in *Equation (7)*. In order to calculate the constant coeffi-After the constant load applied is reequations can be calculated. Consider ing $F = 0$ and substituting it into **Equa-** $\hat{B} = \frac{z}{k} (\hat{A} - A) + \frac{1}{C_1} T + B$ like indicate a compro- $\lim_{k \to \infty} r - \sigma$ and substituting it into *Equa-*
 $\lim_{k \to \infty} \frac{c_1}{c_1}$ as follow in which the constant parameters and $F = ky + c_2y$ the arc changed in *Equation (7)*. In order to calculate the constant coeffi-

Equation (30) can be calculated by the order of the constant coeffi- $\mathcal{L}(18)$, Equation (12) can be achieved, the recovery can can expect relaxation (18)

$$
x^* = x(t_1) = -\frac{\hat{A}c_2e^{\frac{-kt_1}{c_2}}}{k} + \hat{B}
$$
 (12) (21) (22) is solved analyt-
ically, and parameters and are calculated as follows:

$$
R_r = u(t_1) = \hat{A}e^{\frac{-kt_1}{c_2}}
$$
 (13)
$$
x = -\frac{Ac_2e^{\frac{-kT}{c_2}}}{k} + \frac{F}{T} + B
$$
 (19) differential Equation (29) as:

agram at the first point. $u = Ae^{\frac{-\kappa t_1}{c_2}}$ Where, R_r is the slope of the recovery di-
 $\frac{-kt_1}{r}$ F \int at the the first point.

compression, and x_∞ is the last displace-itial position in the compress As shown in *Figure 2*, x_p is the maximum In $T = 7200$, $x = x_p$ and the s maximun

$$
\frac{-\hat{A}c_2}{k}e^{\frac{-kt_1}{c_2}} = x_p - x_\infty
$$
 (14) of thickness variation against time is linear
and the value of $Ae^{\frac{-kt_1}{c_2}}$ is ignorable, then: *Equation (33)*

 $=\widehat{B}$,

$$
\frac{R_r c_2}{k} = x_\infty - x_p \tag{15}
$$

Equation (14) can be rewritten as follows: $-bt$, $\mathbf{I} \leftarrow \mathbf{I} + \mathbf{I} + \mathbf{I} + \mathbf{I} + \mathbf{I}$ lows:

$$
\frac{c_2}{k} = \frac{x_{\infty} - x_p}{R_r} = c_2 k
$$
 (16)
\n
$$
\ln T = 7200 \text{ s. the slope is equal to that of}
$$
 (35) can be

The recovery behaviour under BMSL

hour and 24 hours after load removal on $= -\hat{A} \frac{c_2}{k} e^{\frac{c_2}{c_2}} + \hat{B}$ (26) $\frac{1}{1}$ is the samples, respectively. Also, the dis- $(x_p = x^*)$. Therefore, the initial point of $\sum_{n=1}^{\infty}$ local to the end point of $\sum_{n=1}^{\infty}$ local to the initial point of $f(x_p = x^*)$. Therefore, the initial point of underlies $\begin{array}{ccc} k & c & c_1 \\ c_2 & c_2 & c_1 \end{array}$

removal.

 r_i *<i>sion* and recovery

$$
u(t_1) = R_r
$$
\n
$$
u(t_1) = R_r
$$
\n
$$
x_p = -\frac{Ac_2e^{\frac{-kT}{c_2}}}{k} + \frac{F}{c_1}T + B =
$$
\n
$$
= -\hat{A}\frac{c_2}{k}e^{\frac{-kT}{c_2}} + \hat{B}
$$
\n
$$
= -\hat{A}\frac{c_2}{k}e^{\frac{-kT}{c_2}} + \hat{B}
$$
\n
$$
= -\hat{A}\frac{c_1}{k}e^{-\frac{kT}{c_1}} + \hat{C} = C_1(\hat{x} - \hat{y})(x - y)
$$
\n
$$
= C_1(\hat{x} - \hat{y})(x - y)
$$
\n
$$
= C_1(\hat{x} - \hat{y})(x - y)
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= C_1(\hat{x} - \hat{y})(x - y)
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= C_1(\hat{x} - \hat{y})(x - y)
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= C_1(\hat{x} - \hat{y})(x - y)
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= C_1(\hat{x} - \hat{y})(x - y)
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= C_1(\hat{x} - \hat{y})(x - y)
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= C_1(\hat{x} - \hat{y})(x - \hat{y})
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= C_1(\hat{x} - \hat{y})(x - \hat{y})
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= C_1(\hat{x} - \hat{y})(x - \hat{y})
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= C_1(\hat{x} - \hat{y})(x - \hat{y})
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= C_1(\hat{x} - \hat{y})(x - \hat{y})
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$$
= C_1(\hat{x} - \hat{y})(x - \hat{y})
$$
\n
$$
= C_1(\hat{x} - \hat{y})(x - \hat{y})
$$
\nAccording to Figure 1, the governing differentiable in the non-linear, as presented in Equation (28):

$$
\hat{B} = \frac{c_2 e^{\frac{-kT}{c_2}}}{k} (\hat{A} - A) + \frac{F}{c_1} T + B
$$
\ndifferential equation for the linear part of the model under a compressive force is
as follows:

$$
(18)
$$
\n
$$
F = ky + c_2 \hat{y}
$$
\n(29)

 $\frac{e^{-\overline{c_2}}}{k}$ + \hat{B} (12) (k, c_1, c_2) , *Equation (12)* is solved analytically, and parameters and are calculated $-\kappa t_1$ cients (A, B, \hat{A}, \hat{B}) and model parameters grating *Equation* $x(t_1) = -\frac{\hat{A}c_2e^{-\frac{-kt_1}{c_2}}}{L} + \hat{B}$ (12) is solved analytically and parameters and are calculated
 $x(t_1) = -\frac{\hat{A}c_2e^{-\frac{-kt_1}{c_2}}}{L} + \hat{B}$ (12) is solved analytically and parameters and are calculated $x = \frac{2(F.t - A)}{$ α as follows: *quation (7)*. In order to calculate the constant coeffi-
cients (A, B, \hat{A}, \hat{B}) and model parameters $\begin{array}{ccc}\n\lambda & - & \sqrt{c_1} & \lambda \\
\hline\n\end{array}$ (50) \mathcal{V} is solved analytically, and parameters and parameters and parameters are calculated as follows:

as follows:
\n
$$
\hat{A}e^{\frac{-kt_1}{c_2}}
$$
\n
$$
= \hat{A}e^{\frac{-kt_1}{c_2}}
$$
\n(13)\n
$$
x = -\frac{Ac_2e^{\frac{-kT}{c_2}}}{k} + \frac{F}{c_1}T + B
$$
\n(19)\n
$$
\text{differential } \text{Equation (29) as:}
$$
\n
$$
x = \frac{F}{k} + \frac{F}{c_1}T + B
$$

here,
$$
R_r
$$
 is the slope of the recovery d1-
ram at the first point. $u = Ae^{\frac{-kt_1}{c_2}} + \frac{F}{c_1}$ (31)
 $u = Ae^{\frac{-kt_2}{c_2}} + \frac{F}{c_1}$ (31)
Equation (32) can be obtained by substi-

 x_∞ are substituted into *Equation (12)*: diagram. If it is assumed to $\frac{1}{2}$ compression, and x_{∞} is the last displace-
ment in the recovery section. Now, x_p and is equal to the slope of the experimental ubstituted into *Equation (12)*: diagram. If it is assumed that the diagram $x = Be^{-\frac{k}{c_2}t} + \frac{F}{k} - \sqrt{\frac{2(F.t - A)}{c_2}}$ (32) when $\text{Figure 2}, x_p$ is the maximum In $T = 7200$, $x = x_p$ and the slope of the into Equation (12): $x = Be^{-c_2} + \frac{1}{k} \sqrt{\frac{c_1}{c_1}}$ (32)
of thickness variation against time is linear ection. Now, x_p and is equal to the slope of the experimental
Equation (12) ssion, and x_{∞} is the last displace-
the recovery section. Now x, and in the displacement in the compression diagram as follows: recovery section. Now, and are substituted into Equation (12): (14) (21) the last displace-
the strength of the method of the method of the method of the strength of the strength of the strength of the
as follows:
as follows: $x_p - x_\infty$ (14) and the value of $Ae^{\frac{-kt_1}{c_2}}$ is ignorable, then: *Equatio* derivatio

Since
$$
x_{\infty} = \hat{B}
$$
, hence:
\n
$$
\frac{F}{c_1} = \frac{x_p}{T}
$$
 (21)

 $\frac{u}{k} = x_{\infty} - x_p$ (15)
Equation (22) is derived from the first $u = \dot{x} = -\frac{\dot{x}}{c_2}$ $n(14)$ can be rewritten as fol-
derivation of **Equation (12)** as follows:

$$
x_2 \quad x_{\infty} - x_p \qquad \text{introduction}
$$
\n
$$
\dot{u} = \hat{A}e^{\frac{-kt_1}{c_2}} \qquad (22) \qquad \text{Introducing}
$$

 $k = R_r$ $-22k$ (16)
In $T = 7200$ s, the slope is equal to that of (35) can be obtained as: and PHSL is taken into consideration and which is defined as:
 $B = (-$ The recovery behaviour under BMSL the loading diagram at the first point (R_r) ,
 $B - (-\frac{2A}{r})^{0.5} + \frac{F}{l} = 0$ (34) point is uncertainty consideration and the which is defined as. had a removal on the samples removal on the start of displacement at the start of α h_{tot} after load removal on the samples of the start r_{tot} . $T_{\rm D}$ is taken into consideration and $V_{\rm H}$ which is defined as. o consideration an which is defined as: $\begin{array}{ccc} a_1 & b_1 \\ b_2 & c_1 \end{array}$ $\begin{array}{ccc} a_1 & b_1 \\ b_2 & c_1 \end{array}$ α is taken the consideration and which is defined as.

Figure 2. Compression, and is the slope of the slope of the slope of the slope of the recovery displacement in the slope of the slope of the slope of the first point. The slope of the slope of the first point. The first $R_r =$ Ξ c_2 (23) (23)

ven textiles during Considering Equation (15), Equation (23) loading and after its seen be required as \parallel *loading and after its* $\frac{1}{2}$ can be rewritten as: val. considering *Equation* can be rewritten as: \mathbf{r} 5),

$$
\frac{c_2}{k} = \frac{x_p - x_\infty}{-R_r} = c_2 k \tag{24}
$$

Constants $A \propto B$ and x_p can be obtained
as follows: Constants $\hat{A} \& \hat{B}$ and x_p can be obtained as follows: \sqrt{S} . $\cos \theta$ and $\sin \theta$ be obtained as follows: Γ and can be obtained as follows: δ constants δ and can be obtained as follows: Constants & and can be obtained as follows: $\overline{\text{OWS}}$: \hat{A} & \hat{B} and x_p can be obtained $\sum_{i=1}^{n}$ \mathcal{L} nstants \hat{A} & \hat{B} and x_p can be obtained

$$
\hat{A} = R_r e^{\frac{-kT}{c_2}}
$$
 (25)

$$
x_p = \frac{-Ac_2e^{\frac{-kT}{c_2}}}{k} + \frac{F}{c_1}T + B =
$$

rs after load removal on
$$
= -\hat{A}\frac{c_2}{k}e^{\frac{-kT}{c_2}} + \hat{B}
$$
 (26)

to the end point of the com-
ne initial conditions for this

$$
(x_p = x^*)
$$
. Therefore, the initial point of
 $(x_p = x^*)$. Therefore, the initial point of

In the non-linear, damper is considered to be non-linear, as presented to be non-**Non-linear Jeffrey's II model Non-linear Jeffrey's II model Non-linear Jeffrey's II model** Eq. (28): **Non-linear Jeffrey's II model Non-linear Jeffrey's II model Non-linear Jeffrey's II model** I_{model}

 \overline{a}

 $u(t_1) = R_r$ (11) $A c_2 e^{\frac{-kT}{c_2}} F T + R$ damper c_1 is considered to be nonlinear, $\frac{F}{c_1}T + B = \text{ as presented in Equation (28):}$ **Non-linear Jeffrey's II model** $\frac{1}{2}$ In the non-linear Jeffrey's Π model $\frac{1}{2}$ in the non-linear, defined to be non-linear, as presented to be non-linear, as presented in the non-linear, as $\frac{1}{2}$ In the non-linear Jeffrey's II model, as presented in *Equation (28)*: \mathcal{E} in *Equation* (20). -linear Jeffrey's II model, If the non-linear Jeffrey's II model, $\frac{1}{2}$

$$
F = c_1(\dot{x} - \dot{y})(x - y)
$$
 (28)

 $\begin{array}{r}\n (17) \\
 \text{According to Figure 1, the governing}\n \end{array}$ the model under a compressive force is differential equation for the linear part of
differential equation for the linear part of $+B$ are follower and a compressive force is al equation for the finear part of
1 under a compressive force is $V.S.$ $\frac{1}{2}$ covering pressive force is $\frac{1}{2}$ the model under a compressive force is as follows: the model under a compressive force is According to Figure 1, the governing differential equation for the model of the $F = c_1(x - y)(x - y)$ (28)
According to *Figure 1*, the governing According to Figure 1, the governing differential equation for the linear part of the model $\mathbf{v}_\mathbf{S}$: \sim 29. \sim $\sum_{i=1}^{n}$ \mathbf{r} (29) \mathbf{r} $\overline{}$ S: e model under a compressive force is μ , the governing μ \overline{a}

(18)
$$
F = ky + c_2 \dot{y} \qquad (29)
$$

ting *Equation (29)* as: Four be calculated by integration (30) as: constant coeffi-
 Equation (30) can be calculated by inte-

<u>nodel</u> parameters $\ddot{}$ $\frac{E_q}{\text{equation (29)}}$ as: α inte- ω can be calculated by inte- (29) (29) (29) (29) (29) (29) (29) (29) (29) (29) (29) (29) (29)

$$
x = -\sqrt{\frac{2(F.t - A)}{c_1}} + y \tag{30}
$$

 \mathfrak{m} be $\mathop{\text{rad}}$ \blacksquare $\frac{1}{1}$ rential Equ y can be determined from the ordinary
differential **Equation (29)** as: $\ddot{}$ acternation 129 differential *Equation (29)* as: $\frac{dy}{dx}$

$$
\frac{F}{c_1}
$$
 (20) $y = Be^{-\frac{k}{c_2}t} + \frac{F}{k}$ (31)

(32) (32) (32) (32) (32) (32) (32) (32)

am at the first point.

shown in *Figure 2*, x_p is the maximum In $T = 7200$, $x = x_p$ and the slope of the in-
 $u = Ae^{-c_2} + \frac{c_1}{c_1}$ (20) k
 Equation (32) can be obtained by substi-

tuting *Equation (30)* into *Equ* c_1
 $\text{Equation (32) can be obtained by substit-}$ $(0.00, x = x_p$ and the slope of the in-
tuting *Equation (30)* into *Equation (31)*
tion in the compression diagram \mathbf{v}_s . E can be obtained by substituting Equation (31) δ by substituting Equation (32) into δ \mathfrak{a} $E₂ = 32$ can be obtained by substituting Equation (31) into $E₁$ as follows: **Equation (32)** can be obtained by substias follows: \mathbf{S} . Equation (32) can be obtained by substituting *Equation (30)* into *Equation (31)* δ follows:

s slope of the experimental
s assumed that the diagram
riation against time is linear

$$
x = Be^{-\frac{k}{c_2}t} + \frac{F}{k} - \sqrt{\frac{2(F.t - A)}{c_1}}
$$
(32)

and the value of $Ae^{-\epsilon_2}$ is ignorable, then: $Equation (33)$ is derived from the first derivation of $Equation (32)$ as follows: *Equation (33)* is derived from the first $\frac{1}{2}$ derivation of *Equation* (32) as follows: $\sum_{i=1}^{n}$ is derivatived from the first derivation of Equation (32) as follows:

$$
\frac{R_r c_2}{k} = x_{\infty} - x_p
$$
\n(15)\nEquation (22) is derived from the first\n
$$
u = \dot{x} = -\frac{k}{c_2} B e^{-\frac{k}{c_2}t} - \frac{F}{c_1} \sqrt{\frac{2(F.t - A)}{c_1}}
$$
\n(14) can be rewritten as fol-
\nderivation of *Equation (12)* as follows:

 x_2 $x_{\infty} - x_p$ $\dot{u} = Ae^{c_2}$ (22) $t = 0$, and $\dot{x} = R_{c0}$, Equal $=\frac{1}{2}$ (16)
In $T = 7200$ s the slope is equal to that of (35) can be obtained as: $\dot{u} = \hat{A}e^{\frac{-kt_1}{c_2}}$ (22) Introducing the initial conditions $x = 0$, $I = 0$, and $\chi = K_{c0}$, Eq at the slope is equal to the slope is the first point (), which is the first point (), which is the first point of In $T = 7200$ s, the slope is equal to that of (35) can be obtained as: $\dot{u} = \hat{A}e^{\overline{c_2}}$ (22) $t = 0$, and $\dot{x} = R_{c0}$, **Equations (34)** and Introducing the initial conditions $x = 0$,

\n The equation is given by:\n
$$
B = \left(-\frac{2A}{c_1} \right)^{0.5} + \frac{F}{k} = 0
$$
\n (34)\n

Figure 3. Static loading device \overline{a} **re 3.** Static loading device.

Ξ

$$
-\frac{k}{c_2}B - \frac{F}{c_1}\left(-\frac{2A}{c_1}\right)^{-0.5} = R_{c0} \quad (35) \qquad x_p
$$

 $\prod_{i=1}^{n}$ **Equation (36)** can be calculated from (43) *Equation (36)* can be calculated from Equations (34) and (35) as follows: The displacement of the f $from$

$$
-\frac{k}{c_2}\left(-\frac{2A}{c_1}\right)^{0.5} - \frac{F}{c_1}\left(-\frac{2A}{c_1}\right)^{-0.5} + \frac{F}{c_2} = \begin{array}{c} \text{recovery curve is equal to that of the last point in the compression curve as fol-} \\ \text{point in the compression curve as fol-} \\ \text{lows:} \end{array}
$$

= R_{c0} (36) $x_p = \hat{B}e^{-\frac{k}{c_2}T} + \left(-\frac{2\hat{A}}{c}\right)^{0.5}$ (44)

 are introduced as follows: For simplification, parameters a and X
The slope of the first point ation, parameters a and λ $\overline{1}$

$$
a = -\frac{2A}{c_1}
$$
 (37)
\n
$$
X = a^{0.5}
$$
 (38)
\nThe slope of the last point in the com-

Farameter *X* can be calculated by solving Equation (36) as follows: $\frac{k}{R} - \frac{k}{T}$. Parameter X can be calculated by solving pression curve can be obtained as: as follows:

$$
X = \frac{(\frac{F}{c_2} - R_{c0}) + \sqrt{(\frac{F}{c_2} - R_{c0})^2 - \frac{4kF}{c_1 c_2}}}{2\frac{k}{c_2}}
$$
Con

rorce, *Lym*
rewritten as: Considering that there is no recovery $\begin{array}{ccc} & k & F & \boxed{2(F + - 4)} \\ & & 2(F + - 4) & & 2(F + - 4) \end{array}$ that there is no recover Ĩ Ĩ.

$$
x = \hat{B}e^{-\frac{k}{c_2}t} + \left(\frac{-2\hat{A}}{c_1}\right)^{0.5}
$$
 (40)

$$
R_r = -\frac{k}{c_2}\hat{B}e^{\frac{-k}{c_2}r}
$$
 (41)

Equation (42) can be o $\frac{1}{E}$ $\sum_{i=1}^n$ $\frac{1}{3}$ (37) and *Equation (34)* $\frac{1}{2}$ mon-woven samples. To produce nee- PHSL. In order to measure the thickness not (34) $E_{\rm c}$ can be obtained by substituting Equations (37) and (38) into Equations (37) and (38) into Equation (34) into Equation (34) into Equation (37) into Equation (34) into Equation (34) in the Equation (34) into Equati

$$
B = X - \frac{F}{k}
$$
 (42) Table 1. Needing parameters.

$$
\begin{array}{|c|c|}\n\hline\n\text{Displacement} \\
\hline\nx_0\n\end{array}
$$

(34)

 \overline{a} Figure 4. Schematic diagram of thickness measurement. t_{square} A Schamatic digaram of thickness magnitude and t_{old} C_{α} , the value of parameter (i.e. the displacement of the displacement of the last point in the last point in $C = \frac{1}{2}$, the value of parameter (i.e. the displacement of the displacement of the last point in the last poin **the comparison computer** current current current assumed as (42)

Ξ

 $\begin{array}{cc} \text{can be calculated from} \end{array}$ (43) $\begin{array}{cc} \text{(winc)} \\ \text{trial} \end{array}$ (36) can be calculated from (43) and (43) and (5) and (5) and (6) and (7) and (8) and (8) and (8) and (9) and (10) and (20) and (35) and (36) and (37) and (38) and (38) and (39) and $x_p = Be^{-\frac{K}{C_2}T} + (2(\frac{F}{\cdot}))$ $\left(\frac{B}{c_1}\right)$)^{0.5} + $\frac{F}{k}$ *Be* c_2 ¹ + $(2\left(-\frac{c_1}{c_1}\right))^{0.5}$ + $\frac{1}{k}$ (43) $t_p = Be^{-c_2t} + (2\left(\frac{1}{c_1}\right))^{0.5} + \frac{1}{k}$ $)^{0.5}$ + $-\frac{k}{2}T$ (ϵ_0 $(FT-A)_{3.05}$) c_{1} $\angle FT = 4$ $\frac{1}{2}$ $-\frac{k}{r}$ $\frac{1}{r}$ $T - A$

Equations (34) and (35) as follows:

The displacement of the first p $\frac{F}{C_1}$ $\left(-\frac{2A}{C_2}\right)^{-0.5}$ + $\frac{F}{C_2}$ point in the compression curve as fol-
lows: lows: Ï

$$
= R_{c0}
$$
 (36)
$$
x_p = \hat{B}e^{-\frac{k}{c_2}T} + (-\frac{2\hat{A}}{c_1})^{0.5}
$$
 (44) feed a lattice of the horizontal cross-lap-
per and cross-laid webs produced.

According to the more can be obtained as:
 $\begin{array}{ccc}\n\text{at } & \text{if } \\
\text{at } & \text{if } \\
\text{if } & \text{if } \\
\text$ the slope of the first point in the com-
as follows: The slope of the first point in the com-
a pair mst pon ed as follows:

2A pression force can be obtained as:

$$
a = -\frac{2A}{c_1}
$$
 (37)
\n
$$
R_{co} = -\frac{k}{c_2}B + \frac{F}{c_1}\left(-\frac{2A}{c_1}\right)^{-0.5}
$$
 (45)
\n
$$
\text{Groz-Bec}
$$

Parameter *X* can be calculated by solving Equation (36) person curve can be obt

ation (36) as follows:
\n
$$
R_{cp} = \dot{x} = -\frac{k}{c_2}Be^{-\frac{k}{c_2}T} + \text{ {}•"Fehrer".} \text{ Table 1 shows the mass of the\nrameters.\n
$$
R_{cp} = \dot{x} = -\frac{k}{c_2}Be^{-\frac{k}{c_2}T} + \text{ {}•"Fehrer".} \text{ Table 1 shows the mass of the\nrameters.\n
$$
+ \frac{F}{c_1} \left(\left(\frac{FT - A}{c_1} \right) \right)^{-0.5} + \text{ {}•} \left(\frac{FT - A}{c_1} \right)
$$
\n
$$
= \frac{k}{c_2}Be^{-\frac{k}{c_2}T} + \text{ {}•} \left(\frac{FT - A}{c_1} \right)
$$
\n
$$
= \frac{k}{c_2}Be^{-\frac{k}{c_2}T} + \text{ {}•} \left(\frac{FT - A}{c_1} \right)
$$
\n
$$
= \frac{k}{c_2}Be^{-\frac{k}{c_2}T} + \text{ {}•} \left(\frac{FT - A}{c_1} \right)
$$
\n
$$
= \frac{k}{c_2}Be^{-\frac{k}{c_2}T} + \text{ {}•} \left(\frac{FT - A}{c_1} \right)
$$
\n
$$
= \frac{k}{c_2}Be^{-\frac{k}{c_2}T} + \text{ {}•} \left(\frac{FT - A}{c_1} \right)
$$
\n
$$
= \frac{k}{c_2}Be^{-\frac{k}{c_2}T} + \text{ {}•} \left(\frac{FT - A}{c_1} \right)
$$
$$
$$

Considering that there is no recovery force, ***Equations*** (32) and (33) can be
$$
\hat{A} = -\frac{c_1}{2}(Be^{-\frac{k}{c_2}t} + \frac{F}{k} - \sqrt{\frac{2(F \cdot t - A)}{c_1}}
$$

\n1. $x = Be^{-\frac{k}{c_2}t} + \left(-\frac{2\hat{A}}{c_1}\right)^{0.5}$

\n2. (39) Constant \hat{A} can be obtained as follows:

\n3. $\hat{A} = -\frac{c_1}{2}(Be^{-\frac{k}{c_2}t} + \frac{F}{k} - \sqrt{\frac{2(F \cdot t - A)}{c_1}}$

\n4. $\hat{A} = -\frac{c_1}{2}(Be^{-\frac{k}{c_2}t} + \frac{F}{k} - \sqrt{\frac{2(F \cdot t - A)}{c_1}}$

\n5. $x = Be^{-\frac{k}{c_2}t} + \left(-\frac{2\hat{A}}{c_1}\right)^{0.5}$

\n5. $x = Be^{-\frac{k}{c_2}t} + \left(-\frac{2\hat{A}}{c_1}\right)^{0.5}$

\n6. $x = Be^{-\frac{k}{c_2}t} + \left(-\frac{2\hat{A}}{c_1}\right)^{0.5}$

\n7. $x = Be^{-\frac{k}{c_2}t} + \left(-\frac{2\hat{A}}{c_1}\right)^{0.5}$

\n8. $x = Be^{-\frac{k}{c_2}t} + \left(-\frac{2\hat{A}}{c_1}\right)^{0.5}$

\n9. $x = Be^{-\frac{k}{c_2}t} + \left(-\frac{2\hat{A}}{c_1}\right)^{0.5}$

\n10. $x = Be^{-\frac{k}{c_2}t} + \left(-\frac{2\hat{A}}{c_1}\right)^{0.5}$

\n21. $x = Be^{-\frac{k}{c_2}t} + \left(-\frac{2\hat{A}}{c_1}\right)^{0.5}$

\n3.

were used to prepare needle-punched samples was measured under BMSL and \sinh To $\mu_{\rm bb}$ ness of 12 denier and length of 70-90 mm The thickness reduction of the nonwoven stituting *Equations (37)* and (38) into were used to prepare needle-punched samples was m
non-woven samples To produce pee- PHSL In order (41) *Equation (42)* can be obtained by sub-

were used to general needle number and a semi- $R_r = -\frac{1}{c_2} \beta e^{c_2}$ (41) In this study, polyester fibres with a finethe measured under BMS of 12 definer and length of 70-50 hmm The directors reduction of the hortworch ness of 12 denier and length of 70-90 mm The thickness reduction of the nonwoven

(which is customarily used in indused nonwoven f 24.^{0.5} F (24.^{-0.5} F) $\left(24.24\right)^{-0.5}$ F a conventional carding. The fibrous web *Gaughtions* (34) and (35) as follows:
The displacement of the first point in the floor-coverings [1] and geotextiles),
 100% polyester fibres were processed on $\left(\frac{3}{2}\right)^{10} + \frac{F}{c_2} =$ point in the compression curve as fol-
coming out from the card was then fed to 1011S, S
---- $\frac{k}{\epsilon} = \frac{k}{\epsilon}$ ($\epsilon \geq (FT - A)$), $\epsilon \geq K$ dle–punched nonwoven fabrics with an The displacement of the first point in the floor-coverings [1] and geotextiles), The displacement of the first point in the $\frac{1001 - \text{overings}}{100\%}$ polyester fibres were processed on om (43) (which is customarily used in muus-
trial applications, such as automotive The displacement of the first processes of the recovery curve is equal to that of the last a conventional carding. The fibrous web WESTER STROUGHT ASSESSED ASSESSED FOR THE COMPRESSION FORCE COMPRESSION FORCE COMPRESSION FORCE CAN BE ONLY 2009. the second candidate of the first point in the compression curve as fol-

a conventional carding. The fibrous web

coming out from the card was then fed to ϵ_2 lows:
 ϵ_3 feed a lattice of the horizontal cross-lap-
 ϵ_4 ϵ_5 ϵ_6 ϵ_7 ϵ_8 ϵ_7 ϵ_8 ϵ_9 $\int -\frac{1}{c_1}(-\frac{1}{c_1}) + \frac{1}{c_2} = \lim_{\text{low }s_1}$ bound in the compression curve as following out from the card was then fed to the last point in the complexion of the last point in the complexion of the last point in the c $+(2\left(\frac{m}{c_4}\right))^{0.5}+\frac{1}{k}$ average mass per unit area of 600 g/m²

(34)

 \overline{a}

a pair of needle looms, needling s *a* and *X*
The slope of the first point in the com-
The 8 folded layers were fed to ly. Both looms were equipped with $X = a^{0.5}$ (38) The slope of the last point in the com-
 $X = a^{0.5}$ The slope of the last point in the com-
 $X = a^{0.5}$ Coded as $15*18*38*3R222G3067$ and $B + \frac{1}{c_1}$ (45) (45) Groz-Beckert [14] barbed needles, ession force can be obtained as:
from the top and bottom, respective- $R_{cn} = \dot{x} = -\frac{k}{B} e^{-\frac{k}{c_2}T} +$ "Fehrer". Table 1 shows the needling palast point in the com-
 $\frac{\text{coded}}{\text{as}}$ 15*18*38*3R222G3067 and $\frac{1}{6}$ $15*18*32*3R333G3007$. The repression curve can be obtained as:
was done at a machine company ϵ and ϵ The slope of the first point in the com-
a pair of needle looms needling rameters. pression curve can be obtained as:
 $w = k$ was done at a machine company called μ and μ (45) 15*18*32*3R333G3007. The needling

 $\begin{pmatrix} c_1 \\ c_2 \end{pmatrix}$ der a static pressure of (20.2) kpa was determined as follows: Experimental tions of 222 $^{\circ}$ C and 652% RH [16]. $\frac{2}{c_2}$ Considering *Equation* (42) and (43) measured using a digital thickness to (39) Constant \hat{A} can be obtained as follows: er according to ISO 1765 [15] (with $\begin{pmatrix} 4 \\ 2 \end{pmatrix}$ (47) sams were recorded oased on the average
of the measurements. All the experiments considering *Equation (42)* and *(43)* der a static pressure of (20.2) kpa was

measured using a digital thickness test- $\frac{368}{15}$ er according to ISO 1765 [15] (with an $\overline{9}$ $\frac{1}{2\sqrt{1-\frac{1}{2}}\sqrt{1-\frac{1}{2}}}}$ accuracy of 0.01 mm). Based on the measured using a digital thickness test- $\left(\frac{FT-A}{c_1}\right)$ (46) The initial thickness of the sample un- (47) (47) In this study, polyester fibres with a fineness of 12 denier and length of 70-90 mm were used (46) were prepared for each test, and the re $k \in \frac{-k}{k}$ **Experimental** were performed under standard condi-
 $k \in \frac{-k}{k}$ α accuracy of 0.01 mm). Based on the standard method, the sample was cut to $\frac{d}{dx}$ **Experimental** were performed under standard condif, cre recorded by were prepared for each test, and the re-
 (47) sults were recorded based on the average total metal performed direct samples conditions. The performed non-word non- $\mathcal{A}(\mathcal{A})=\mathcal{A}(\mathcal{A})=\mathcal{A}(\mathcal{A})=\mathcal{A}(\mathcal{A})=\mathcal{A}(\mathcal{A})=\mathcal{A}(\mathcal{A})=\mathcal{A}(\mathcal{A})=\mathcal{A}(\mathcal{A})=\mathcal{A}(\mathcal{A})=\mathcal{A}(\mathcal{A})=\mathcal{A}(\mathcal{A})=\mathcal{A}(\mathcal{A})=\mathcal{A}(\mathcal{A})=\mathcal{A}(\mathcal{A})=\mathcal{A}(\mathcal{A})=\mathcal{A}(\mathcal{A})=\mathcal{A}(\mathcal{A})=\mathcal{A}(\mathcal{A})=\mathcal{$ tions of 222 °C and 652% RH [16]. $\frac{Z(F \cdot F - A)}{2}$ standard method, the sample was cut to The initial thickness of the sample un-

> oven samples. To produce nee-
PHSL. In order to measure the thickness industrial applications, such as automotive floor-coverings (1) and geotextiles), 100% (1)

fabrics with an average mass per unit area of 600 g/ (which is customarily used in the 600 g/ (whic

Considering <i>Equation (32)</i> , the value of parameter x_n (i.e. the displacement of the last point in the compression curve) is obtained as:	Needling stage	Number of strokes. stroke/min	Penetration. mm	Input speed, m/min	Output speed, m/min
	Input board, top	520	13.5	2.5	3.4
	Output board, bottom	770	9.0	3.4	3.4

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Table 2. Thickness reduction of the nonwoven samples under BMSL.

Time, min	Thickness reduction, mm	Time, min	Thickness reduction, mm	
$\mathbf{0}$	0.00	70	1.37	
10	0.48	80	1.41	
20	0.96	90	1.44	
30	1.10	100	1.47	
40	1.25	110	1.49	
50	1.29	120	1.51	
60	1.34			

Table 3. Thickness recovery of nonwoven samples after the removal of BMSL.

Time, min	Thickness recovery, mm	Time, min	Thickness recovery, mm	
	1.51	40	1.15	
10	1.35	50	1.10	
20	1.28	60	1.02	
30	1 22			

Table 4. Thickness reduction of nonwoven samples under PHSL.

Time. min	Compression value, mm	Time, min	Compression value, mm	Time. min	Compression value, mm
0	0.00	540	1.69	1080	2.10
60	1.00	600	1.75	1140	2.15
120	1.18	660	1.80	1200	2.19
180	1.29	720	1.85	1260	2.22
240	1.37	780	1.90	1320	2.25
300	1.45	840	1.94	1380	2.26
360	1.51	900	1.99	1440	2.26
420	1.57	960	2.03		
480	1.63	1020	2.07		

Table 5. Thickness recovery of nonwoven samples after the removal of PHSL.

Time. min	Compression value, mm	Time, min	Compression value, mm	Time. min	Compression value, mm
$\mathbf 0$	2.26	540	1.69	1080	1.53
60	2.03	600	1.66	1140	1.53
120	1.95	660	1.64	1200	1.53
180	1.9	720	1.63	1260	1.52
240	1.85	780	1.61	1320	1.52
300	1.80	840	1.59	1380	1.52
360	1.77	900	1.58	1440	1.52
420	1.74	960	1.57		
480	1.72	1020	1.54		

Table 6. Linear Jeffrey's II model parameters.

Model	c ₁ N.s/m	С ₂ К, s	Α, m/s	В, m	m/s	В, m
Linear Jeffrey's model BMSL	6.864×10 ⁸	2.61×10^3	-3.2×10^{-7}	-8.3×10^{-4}	-3.93×10^{-6}	8.6×10^{-4}
Linear Jeffrey's model PHSL	1.75×10^{10}	3.09×10^{4}	-3.9×10^{-8}	-1.2×10^{-3}	-4.32×10^{-7}	1.4×10^{-3}

Table 7. Nonlinear Jeffrey's II model parameters.

reduction rate under BMSL and PHSL, the samples were placed under static loading in accordance with ISO 3415 and ISO3416 [17-18]. A laboratory static loading device was used to simulate the application of the static loading, shown in *Figure 3*. In this case, the samples were placed under a pressure of 220 kpa for two hours, and the thickness loss was measured every 10 minutes. After the load was removed, the thickness of the samples was measured at 10-minute intervals up to an hour. It should be mentioned that there were five samples to test, and the results were recorded based on the average of the measurements, illustrated in *Tables 2* and *3*.

Figure 4 shows a schematic of the compression value of the nonwoven fabric under static loading. As shown, is the initial thickness, and refers to the thickness of the nonwoven after the compressive force is applied to the sample surface. The displacement is defined as $(x_0 - x_1)$. An increase in the number of impacts led to an increase in the displacement.

In order to measure the thickness reduction rate under PHSL, the samples were placed under static loading in accordance with ISO 3416 [14]. They were subjected to a pressure of 700 kpa for 24 hours, and their thickness was measured during the pressure. After the load was removed, the thickness of the samples was measured up to 24 hours. Five samples were tested, and the results were recorded based on the average of the measurements, illustrated in *Tables 4* and *5*.

ш **Results and discussion**

In this study, the compression and recovery properties of needle-punched non-woven textiles were investigated under static loading. Also, the parameters of linear and nonlinear Jeffrey's models under BMSL and PHSL were obtained through analytical processes, listed in *Tables 6* and *7*.

Figure 5 shows the experimental data and results obtained from the linear Jeffrey's II model for the compression *Equation (7)* and recovery behaviour

Figure 5. Comparison of experimental data and results obtained from the linear Jeffrey's model for the compression and recovery *behaviour of nonwoven textiles under BMSL.*

Figure 7. Comparison of the experimental data and results obtained **Figure 6.** *from the nonlinear Jeffrey's model for the compression and recovery behaviour of nonwoven textiles under BMSL.*

Figure 6. Comparison of the experimental data and results obtained from the linear Jeffrey's model for the compression and recovery behaviour of nonwoven textiles under PHSL.

Figure 8. Comparison of the experimental data and results obtained f_{row} **the nonlinear** *Ieffrey's II model for the compression and recovery from the nonlinear Jeffrey's II model for the compression and recovery behaviour of nonwoven textiles under PHSL.*

Equation (12) of the non-woven sample after applying static loading for 120 minutes and an hour after the load removal.

Figure 6 shows the experimental data and results obtained from the linear Jeffrey's model for the compression **Equa***tion (7)* and recovery behavior *Equation (12)* of the nonwoven sample after applying 24-hour static loading and 24 hours after the load removal.

As can be seen in *Figures 5* and *6*, there is a good correlation between the theory and experimental data for the linear a model to predict the recovery behaviour of nonwoven samples under BMSL and PHSL. However, as the results presented in these figures revealed, there is a poor correlation between the theory and experimental data for the linear Jef-

frey's model to predict the compression behaviour of nonwoven samples under BMSL and PHSL. In other words, the linear Jeffrey's model is more accurate in predicting the recovery properties under no BMSL and PHSL than in predicting the compression properties.

Figures 7 shows the experimental data and results obtained from the nonlinear Jeffrey's model for the compression *Equation (32)* and recovery behaviour *Equation (40)* of the nonwoven sample after applying 120-min static loading and an hour after the load removal.

Figure 8 shows the experimental data and results obtained from the nonlinear Jeffrey's model for the compression *Equation (32)* and recovery behaviour *Equation (40)* of the nonwoven sample after applying 24-hour static loading and after apprying 24-nour static load
24 hours after the load removal.

As can be seen in *Figures 7* and *8*, the nonlinear Jeffrey's II model is capable enough of predicting the compression and recovery behaviour of nonwoven samples under BMSL and PHSL.

> *Table 8* presents the mean absolute errors obtained from the linear and nonlinear Jeffrey's models under BMSL and PHSL for compression and recovery behaviour.

> The results showed that the mean absolute errors were 14.18% and 12.17% for the compression and recovery behaviour in the linear Jeffrey's II model and 4.68% and 4.66% in the nonlinear Jeffrey's II model under BMSL and PHSL, respectively. Thus, the compression and

Table 8. Mean absolute errors for the linear and nonlinear Jeffrey's models

Mechanical model	loading	Compression error value, %	Recovery error value, %	Average error value, %
	BMSL	25.34	3.02	14.18
linear Jeffrey's II model	PHSL	18.48	5.87	12.17
	BMSL	7.3	2.07	4.68
Non-linear Jeffrey's II model	PHSL	5.96	3.37	4.66

recovery behaviour can be predicted in the nonlinear Jeffrey's II models under BMSL and PHSL better than in the linear Jeffrey's II model.

In the prediction of the compression and recovery behavior for the nonlinear Jeffrey's II model under BMSL and PHSL; the mean absolute errors were 7.3%, 2.07%, 5.96% and 3.37%, respectively.

In the prediction of the recovery behaviour for the linear Jeffrey's II model under BMSL and PHSL the mean absolute errors were 3.02% and 5.87%, respectively. The magnitude of compression errors in the linear Jeffrey's II model under BMSL and PHSL were significant, which can be due to the extreme deformation of the samples at the start of the loading and the lack of ability of the model recommended to predict this change at the same speed.

Table 9 shows a comparison of various investigations with the methods developed in this study with respect to simulation of the compression and recovery behaviour of textiles.

Conclusions

In this study, two different mechanical models based on mass-spring-dashpot including linear and nonlinear Jeffrey's II models were developed to predict the compression and recovery behaviour of needle-punched non-woven textiles for automotive floor-covering application under brief, moderate static loading (BMSL) and prolonged, heavy static loading (PHSL) according to ISO 3415 and ISO 3416, respectively. Through solving the governing equation of the model to obtain the model parameters analytically, thickness loss of the nonwoven textiles within a certain time was achieved. The results obtained from the two models were compared with experimental results in four cases including the linear and nonlinear Jeffrey's II model under BMSL and PHSL. It was shown that the nonlinear Jeffrey's model is sufficiently able to predict the compression and recovery behaviour of nonwoven textiles under BMSL and PHSL. However, the linear Jeffrey's II model can predict recovery properties under BMSL and PHSL more accurately than compression properties.

 \Box

References

- 1. Atakan R, Sezer S, Karakas H. Development of Nonwoven Automotive Carpets Made of Recycled PET Fibers with Improved Abrasion Resistance. *J Ind Text*. 2018; 48: 1-23.
- 2. Kothari VK, Das A. Time-Dependent Behavior of Compression Properties of Nonwoven Fabrics. *Indain J Fibre Text Res*. 1994; 19: 58-60.
- 3. Kothari VK, Das A. An Approach to the Theory of Compression of Nonwoven Fabrics. *Indain J Fibre Text Res*. 1996; 21: 235-243.
- 4. Debnath S, Madhusoothanan M. Modeling of Compression Properties of Needle-punched Nonwoven Fabrics Using Artificial Neural Nwtwork *2008;* 33: 392-399.
- 5. Debnath S, Madhusoothanan M. Compression Properties of Polyester Needle-Punched Fabric. *J Eng Fibers Fabr 2009;* 4: 14-19.
- 6. Debnath S, Madhusoothanan M. Studies on Compression Properties of Polyester Needle-punched Nonwoven Fabrics under Dry and Wet Conditions. *J Ind Text* 2011; 41: 292-308.
- 7. Debnath S, Madhusoothanan M. Studies on Compression Properties of Polyester

Needle-punched Nonwoven Fabrics under Wet Conditions. *Fiber Polym* 2013; 14(5): 854-859.

- 8. Jafari S, Ghane M. An Analytical Approach for the Recovery Behavior of Cut Pile Carpet after Static Loading by Mechanical Models. *Fiber Polym 2016;* 17: 651-655.
- 9. Khavari S, Ghane M, Aanalytical Approach for the Compression and Recovery Behavior of Cut Pile Carpets under Constant Rate of Compression by Mechanical Models. *Fiber Polym 2017;* 18: 190-195.
- 10. Tower TT, Carrillo A. *Science in the Age Experience 2017; may 15-18, Chicago:* 296-305.
- 11. Jafari S, Ghane M. Analysis of the Effect of UV Radiation on the Recovery Properties of Pile Carpet after Static Loading through Analytical and Viscoelastic Modeling. *J Text I* 2017; 108: 1905-1909.
- 12. Jafari S, Ghane M, Viscoelastic Modeling of the Recovery Behavior of Cut Pile Carpet after Static Loading: A Comparison between Linear and Nonlinear Models. *J Text Poly* 2018; 6(1): 9-14.
- 13. Daniel D. Joseph .*Fluid Dynamics of Viscoelastic Liquids*.1st edition, 1990.
- 14. Groz-Beckert. Needles: general catalogue. Germany: Groz-Beckert, 2009.
- 15. International Standard. ISO 1765. Machine Made Textile Floor Coverings-Determination of Thickness. 1986.
- 16. ISO 139:2005. Textiles-Standard Atmospheres for Conditioning and Testing.
- 17. International Standard. ISO 3415. Textile Floor Covering – Determination of Thickness Loss After Brief, Moderate Static Loading. 1986.
- 18. International Standard. ISO 3416. Textile Floor Covering – Determination of Thickness Loss After Polonged, Heavy Static Loading. 1986.