PREDICTION OF FABRIC COMPRESSIVE PROPERTIES USING ARTIFICIAL NEURAL NETWORKS

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Abstract:

Data analysis relating to a fabric's compression properties can only be carried out when the limits of compression are known. The study of the compressibility of woven fabrics was initiated with Peirce, Kemp & Hamilton's approach to circular yarns and flattened yarns of a fabric under pressure. The fit of the pressure-thickness relationship is being improved using the exponential interpolation & extrapolation methods, as well as iterative methods such as the Marquardt algorithm for fitting the curves. Although there is a recent trend towards the automation of studying the structure-property relationship of textile fabrics, an objective and efficient method for predicting properties with a rapid prototype that outputs to sophisticated instruments such as the KES-FB3 is essential. This characterisation of data for fabric materials will help maintain companies' commercial experience and expertise. This established predicting model can provide guidance to fabric manufacturers, fashion designers and ?[makers-up] in fabric design, fabric selection and the proper use of fabrics. This approach will make online fabric sourcing more realistic. Fabric sourcing experts are now visiting supplier's websites for tracking fabrics. Overall, this approach provides an opportunity to generate a dynamic database of fabric properties, and hence may result in the development of new fabrics or the updating of existing fabrics to keep pace with fashion.

Key words:

compression energy, flattening factor, bulk density, specific volume

1. Introduction

Compressibility is one of the important properties of fabric, in addition to friction, bending, tension and shear. In garment automation, for instance, compressibility can be a crucial property for successfully separating plies from a stack. With the growing need for better material modelling for simulation purposes, objective measurements of fabric compression will become increasingly important, since static compression gives an indication of the mechanical 'springiness' of the material. The lateral compression of a fabric is defined as the intrinsic change in thickness with an appropriate increase in pressure when the fabric is subjected to a barely perceptible pressure, which is generally about 1% of the maximum pressure. Hence a lower volume is registered, which will decrease continually over 5 to 10 successive compression cycles.

In order to compare compression curves from different fabrics, Kawabata introduced four parameters as part of the KES-F (the Kawabata evaluation system for fabrics). The four parameters in the KES-FB3 test express the work of compression WC (WC' is the area under the release curve).

Linearity (LC), resilience of the fabric RC, and relative compressibility EMC, are all calculated as follows:

$$WC = \int_{To}^{Tm} \vec{P} dt \quad \text{and} \quad WC' = \int_{Tm}^{To} \overleftarrow{P} dt \qquad (1)$$

$$LC = \frac{WC}{(0.5(Pm(T_o - T_m))} \quad (2)$$

$$RC = \frac{WC'}{WC} \quad (3)$$

$$EMC = 1 - \left(\frac{T_m}{T_o} \right) \quad (4)$$

The applied pressure is expressed by **'P'** and the thickness by **'T'**, with **'To'** being the thickness at a minimum pressure of 0.5 gf/cm^2.

The compressional work per unit area, WC (CN/cm), varies depending on the type of fabric. A more compressible material gives larger values; for example, wool gives a larger value of WC when compared to other fabrics. The difference in the values may be attributed to the surface layer of the fabric, which makes a large contribution to the compressibility (springiness) of the material.

The second distinctive parameter for compression is the linearity of the compression 'LC'. If the thickness of the fabric decreases linearly with increasing pressure, the LC value would be 1. However all fabrics compress non-linearly, and have an LC value ranging between 0.14 to 0.47. The harder fabrics have a lower value of LC, which would result in a steeper rising compression. The third parameter 'RC' represents the hysteresis in the compression graph. Finally, the dimensionless EMC parameter expresses the compressibility of a fabric. The smaller the EMC value, the more incompressible the fabric.

van Wyk's equations are used to approximate the static low-load compression curves (maximum 10gf/cm^2) of both woven and knitted materials generally used in garment automation. The simple two-parameter approach, which excludes the volume in unloaded conditions, is first used as an estimate and gives the starting values for the more refined three-parameter model. All these models give only an approximate fit, considering the complexity of volume and pressure. Some of the constants used in these models are not defined, and there are significant differences between the model values. Therefore, the main problem is to optimise the compression pressure-thickness curve and predict the compression characteristics of woven fabrics by using rapid prototypes such as neural networks which can learn data and analyse the complexity of the relationship between variables,

The study of the compressibility of woven fabrics is initiated coupled with Peirce, Kemp & Hamilton's approach for circular yarns and flattened yarns of a fabric under pressure. The fit of Pressure-thickness relationship is being improved using exponential interpolation and extrapolation methods, as well as iterative methods like the Marquardt algorithm for fitting the curves to overcome the limitations of existing models. Although there is a recent trend towards the automation of studying the structure/property relationship of textile fabrics, an objective and efficient method for predicting properties with a rapid prototype that outputs to sophisticated instruments like the KES-FB3 is essential.

2. Theory

2.1. Assumptions for studying the compressive behaviour of woven fabrics using a mathematical model

1. The yarns in the fabric are assumed to be elastic and isotropic, although there are some anisotropy and in-elastic properties.
2. The yarn is assumed to be a solid cylinder.
3. The geometry of the yarn surface is assumed to be smooth and uniform (which is in fact not smooth, because of the yarn twist and the protruded fibres present on yarn surface); the resistance of the fine hairs on the yarn surface is therefore ignored.
4. The difference caused by different fibres and fibre arrangements arising from different spinning technologies is assumed to have been captured in the material constant, and is not considered for modelling.

5. The fabric is assumed to be completely relaxed; this means that the fabric does not have any residual force within itself.
6. The response of the fabric to different machine settings (yarn tension, yarns per dent, beat up-force, etc., and post-weaving treatments (desizing, bleaching, softening, dyeing, reducing weight, etc.,) will not be taken into consideration.
7. Change in crimp crowns is assumed to occur in a transverse direction and is not taken into account when calculating geometric thickness; the longitudinal deformation due to lateral pressure is negligible.
8. Yarn rigidity, slippage between the fibres or filaments, crimp balance and crimp interchange effects in longitudinal directions is negligible under low pressure, and its effect is not considered.
9. The compressive force applied on the fabrics is at low pressure, ranging from 0.5 to 50 gf/cm^2.
10. On compression threads moving closer to attain equilibrium conditions following different cross section models and its phenomenon is not taken into consideration.

2.2 Peirce model for change in thickness

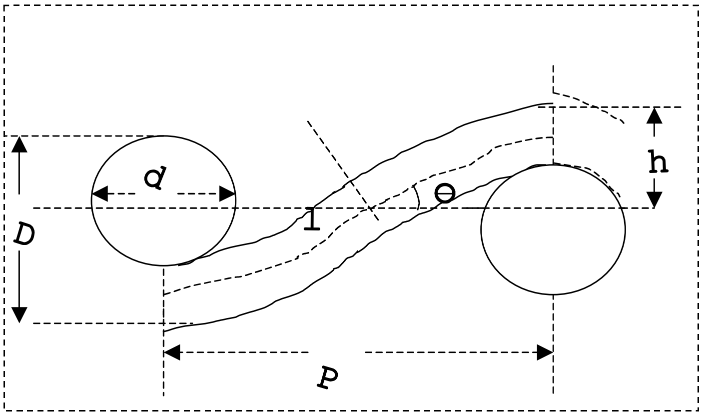

Figure 1 . Peirce unit cell model

From Pierce's geometry, the fabric thickness 't' is calculated, which is the sum of the crimp height and the diameter. Let the crimp height be *'h'* and the yarn diameter be *'d'*.

Fabric thickness *'t'* is given by

$$t = h_1 + d_1 \text{ or } h_2 + d_2 \quad (5)$$

Since the yarn diameters are assumed to be circular, we have

$$t = \max(t_1, t_2) \quad (6)$$

where:

N_1 and N_2 are warp and weft counts,
e is the flattening factor, and
t is the thickness of fabric.

In reality, cross sections are far from circular, and later models modified the cross section; the race-track (the rectangle with circular arcs at the sides) was widely adopted for mathematical tractability. The compressed thread may be considered to have the form of a flattened elliptical cross section, where the area of the ellipse is given by

$$\frac{ab\pi}{4} \quad (7)$$

where '*a*' and '*b*' are major and minor diameters. But this is not true; when pressure is applied, the threads spread unevenly, and can attain a configuration which can be assumed to lie somewhere between the ellipse and the rectangular with circular arcs. For ?structural reasons, the limit of compression where the crowns are flattened must be considered, and hence a flattening factor 'e' must be introduced.

By introducing the flattening factor 'e', which is a function of crimp of yarn, cloth setting, and count, the flattening factor 'e' is obtained by [12].

$$\frac{\sqrt{C_1\%}}{n_2}+\frac{\sqrt{C_2\%}}{n_1} = 0.28\, e \left(\frac{1}{\sqrt{N_1}}+\frac{1}{\sqrt{N_2}}\right) \tag{8}$$

2.3. Change in thickness for non-circular yarns

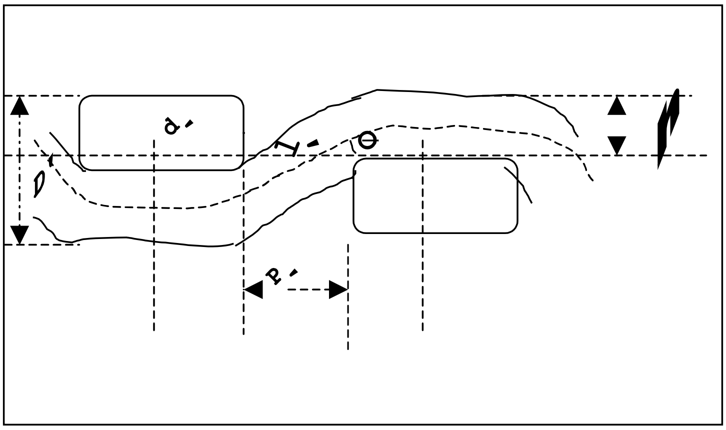

Figure 2. Kemp's race-track geometry cross-section

In the case of industrial fabrics like canvas and tarpaulins subjected to large deformation by compressive force, would result in jamming of either warp or weft. In large deformations, one has to consider different assumptions for the analysis, introduce change into the structural elements and then infer the thickness. It would be appropriate to fix the limits of compression using Kemp's racetrack model for flattened yarns [3] with changes in pick spacing, diameter of yarns, crimp height etc.

This new shape, which is termed the race-track section, is rectangular with semi-circular ends, and is used as the basis for an extension of Peirce's theory to the more general case of non-circular threads.

The horizontal and vertical diameters of the threads are denoted by *'a'* and *'b'* respectively. The scale unit *'D'* is equal to the sum of the vertical diameters:

$$D = b_1 + b_2 = h_1 + h_2 \tag{9}$$

Peirce's formulae and tables of functions may be used for part of this section, the variables being $p_1', p_2', l_1', l_2', c_1', c_2'$

The relationships between these variables and the structural particulars $p_1, p_2, l_1, l_2, c_1, c_2$ are as follows:

$$\begin{aligned} p_2' &= p_2 - (a_2 - b_2) \\ l_1' &= l_1 - (a_2 - b_2) \end{aligned} \tag{10}$$

and $$c_1' = (l'_1 - p_2')/p_2' = c_1 p_2 / [p_2 - (a_2 - b_2)] \tag{11}$$

similarly, for p_1', l_2' and c_2'.

Thus, if the term $(a_2 - b_2)$ is known,

p_2', l_1', c_1' can be easily calculated from the structural particulars, $p_2, l_1,$ and c_1. Similarly, a knowledge of $(a_1 - b_1)$ is required for the calculation of p_1', l_2' and c_2'

From the circular thread theory, assuming 'θ', the angle of crimp, to be small, and $p_2^{'}$ and $l_1^{'}$ large, the following relation holds as a useful approximation:

$$h_1 = \frac{4}{3} p_2^{'} \sqrt{c_1^{'}} * \qquad (12)$$

Hence, from equations (11) &, (12), the following relation is obtained:

$$b_1 + b_2 = \frac{4}{3}\sqrt{c_1 p_2 [p_2 - (a_2 - b_2)]} + \frac{4}{3}\sqrt{c_2 p_1 [p_1 - (a_1 - b_1)]} \qquad (13)$$

If the thread flattening coefficient 'e' is defined by

$$e = \frac{b}{a} \qquad (14)$$

and *'d'* is the diameter of the circular thread of equal area, then it can be easily shown that

$$b = d\sqrt{\frac{1}{\left[1 + \frac{4}{\pi}\left(\frac{1-e}{e}\right)\right]}} \qquad (15)$$

and $$(a-b) = d\sqrt{\frac{[(1-e)/e]}{[e/(1-e) + \frac{4}{\pi}]}} = df(e) \text{ , say} \qquad (16)$$

hence

$$b_1 + b_2 = \frac{4}{3}\sqrt{c_1 p_2 [p_2 - d_2 f(e_2)]} + \frac{4}{3}\sqrt{c_2 p_1 [p_1 - d_1 f(e_1)]} \qquad (17)$$

$$\frac{4}{3}\sqrt{c_1 p_2 [p_2 - d_2 f(e_2)]} + \frac{4}{3}\sqrt{c_2 p_1 [p_1 - d_1 f(e_1)]}1 = d_1\sqrt{\frac{1}{[1 + \frac{4}{\pi}\left(\frac{1-e_1}{e_1}\right)]}} + d_2\sqrt{\frac{1}{[1 + \frac{4}{\pi}\left(\frac{1-e_2}{e_2}\right)]}} \qquad (18)$$

This equation contains the unknowns d_1, d_2, e_1 and e_2. Assuming that d_1 and d_2 can be accurately estimated from the count of the warp and weft yarns, then if a further relation is evolved between e_1 and e_2 (for example, in special cases it may be valid to assume $e_1 = e_2 = 1$, the two variables e_1 and e_2 can be reduced to one 'e'.

In such cases, a graphical method of solving the equation may be conveniently be adopted, that is, by plotting both sides of the final equation against 'e', the intersection of two curves giving the required value 'e'.

2.4. Change in the cover factor of the fabric

Hamilton[13] defines the fabric tightness which could be used for comparison of fabrics at different configurations as the ratio of the sum of the fabric cover factors to the sum of the cover factors of the maximum-set fabric with the same ratio of cover factors. This is simply expressed as:

$$T = \frac{(K_1 + K_2)_{actual}}{(K_1 + K_2)_{\lim it}} \qquad (19)$$

Here, the warp cover factor $K_1 = \frac{d_1}{p_1}$ where d_1 is the warp yarn diameter and p_1 the thread spacing, and the weft cover factor $K_2 = \frac{d_2}{p_2}$ where d_2 and p_2 are the weft yarn diameters and thread spacing respectively. The term '$(K_1 + K_2)_{actual}$ refers to the actual values of a specific fabric, the value $(K_1 + K_2)_{\lim it}$ is determined graphically from graphs from Hamilton's paper.

Hamilton and others were concerned that yarns in fabrics are not circular in the cross-section, and they therefore used modified equations to allow for yarn flattening. This procedure is no doubt essential for calculating a wide range of properties and dimensions. The Peirce equations assume a circular cross-section, rather than an elliptical or race-track shape, such as may occur in a more open fabric. Hence we need to use yarn diameter rather than arbitrary or measured major & minor diameters.

2.5. Specific volume of fabric

Bulk density is defined as the density of bulk materials. Bulk density is a material property, and is given by the following equation:

$$Fabricbulkdensity(gms/cm^3) = \frac{fabricweight(gm/cm^2)}{Thickness(cm)} \quad (20)$$

Then

$$Fabricspecificvolume(cm^3/gm) = \frac{Thickness(cm)}{Fabricareaweight(gms/cm^2)} \quad (21)$$

3. Experimental

3.1 Materials

Table 1. Characteristics of woven fabric

Sl no	Fabric no	Variety	Warp count(Ne)	Weft count(Ne)	EPI	PPI	C1%	C2%	Geometric thickness(mm)
1	3	Cotton	48	37	92	80	5	5	0.2431
2	4	Cotton	42	40	100	92	5	3	0.2159
3	5	Cotton	40	36	92	80	7	7	0.2616
4	6	Cotton	40	12	100	48	10	7	0.4496
5	7	Cotton	40	40	112	84	7	7	0.2489
6	16	Cotton	40	40	122	88	5	7	0.2464
7	19	Cotton	40	14	120	50	13	4	0.3759
8	21	Cotton	40	20	136	84	6	12	0.287
10	24	Cotton	45	40	132	92	7	7	0.2413

3.2. Compression testers

In order to arrive at the compressive property of woven fabrics, an Essdial thickness tester is used for interpolation problems, and limits of change in thickness are measured using an ASTM D695M-91 manual tester-presser for testing lateral compressive properties of woven fabrics, with foot diameter set at 2 cm, and load in gf/cm^2 = 20, 50, 100, 200.

The KES-FB3 DC is one of the most reliable instruments available for testing low stress compressive property for woven fabrics, coupled with both mechanical measuring devices and electronic devices. The instrument's sensory device is encapsulated in an environment where the movement of hairs on the surface of the fabric due to external disturbances are prevented, and hence more reliable results are obtained.

1. Compressive deformation rate: 0.1mm/sec (max)
2. Compressing plate type: circular, with 2 cm^2 compression area.

3. Dimensions of sample: 2 cm × 2 cm
4. Testing conditions: low stress compressive property, sensitivity: 2 × 5

3.3. Exponential Interpolation method

The exponential method of interpolation is used for approximating an exponential curve for two points, where x_1 and x_2 are known and a point x between them is to be found. Suppose the points (x_1, y_1) and (x_2, y_2) lie on the curve of the form $Y = ke^{mX}$, where *'k'* and *'m'* are constants. Solving '*k*' and '*m*' by using

$$m = \frac{\ln(\frac{Y_2}{Y_1})}{x_2 - x_1} \text{ and } k = Y_1 e^{-mx_1} \quad (22)$$

many pairs of values are obtained.

3.4. Curve fitting

Using lab fit curve fitting software [11], a curve is fitted for the compressive and decompressive behaviours of woven fabrics. The independent variable is plotted along the horizontal axis. Most linear equations are functions (i, e, for every value of '*x*', there is only one corresponding value of '*y*'). here assigning a value to the independent variable '*x*', and hence computing the value of the dependent variable '*y*'. Plotting the points named by each (*x,y*) pair on a coordinate grid yields an exponential curve which is non-linear with *'P'* as a dependent variable plotted on the *Y*-axis and *'X'* the thickness (mm), an independent variable on the X-axis. Normally the curves relating to pressure-thickness relationships are plotted considering pressure on the *Y*-axis. The relationship between pressure and thickness is defined by an exponential curve.

Table 2. Measured thickness of woven fabrics using manual essdial thickness tester

Sample no.	Fabric no.	Compress	(mm)	Decompress	(mm)
		20 gf	50 gf	20 gf	50 gf
1	3	0.30	0.27	0.275	0.27
2	4	0.35	0.31	0.320	0.31
3	5	0.29	0.27	0.285	0.27
4	6	0.35	0.33	0.335	0.33
5	9	0.285	0.26	0.265	0.26
6	16	0.31	0.275	0.290	0.275
7	19	0.37	0.340	0.350	0.340
8	21	0.32	0.280	0.30	0.280
10	24	0.310	0.280	0.290	0.280

Table 3. Interpolated and extrapolated values of thickness for different pressures
Compression cycle $\rightarrow pressure$

Sample no.	Fabric no.	Geometric thickness (mm)	5 gf	10 gf	15 gf	20 gf	25 gf	30 gf	35 gf	40 gf	45 gf	50 gf
1	3	0.2431	0.3454	0.3237	0.3104	0.30	0.2927	0.2867	0.2817	0.2773	0.2735	0.27
2	4	0.2159	0.4105	0.3802	0.3625	0.35	0.3402	0.3323	0.3256	0.3200	0.3146	0.31
3	5	0.2616	0.3203	0.3052	0.2963	0.29	0.2852	0.2812	0.2779	0.2749	0.2723	0.27
4	6	0.4496	0.3804	0.3653	0.3564	0.35	0.3453	0.3413	0.3380	0.3350	0.3325	0.33
5	7	0.2489	0.3228	0.3039	0.2929	0.285	0.2789	0.2740	0.2697	0.2661	0.2629	0.26
6	16	0.2464	0.3629	0.3364	0.3209	0.31	0.3014	0.2945	0.2886	0.2835	0.2790	0.275
7	19	0.3759	0.4154	0.3927	0.3794	0.37	0.3627	0.3567	0.3517	0.3473	0.3435	0.340
8	21	0.287	0.3811	0.3508	0.3331	0.32	0.3108	0.3029	0.2961	0.2903	0.2852	0.280
10	24	0.2413	0.3554	0.3327	0.3195	0.310	0.3027	0.2968	0.2917	0.2873	0.2835	0.280

Table 4. Decompression cycle

Sample no.	Fabric no.	Geometric thickness	5 gf	10 gf	15 gf	20 gf	25 gf	30 gf	35 gf	40 gf	45 gf	50 gf
1	3	0.2431	0.2826	0.2788	0.2766	0.275	0.2738	0.2728	0.2719	0.2712	0.2706	0.27
2	4	0.2159	0.3352	0.3276	0.3232	0.320	0.3176	0.3156	0.3139	0.3125	0.3112	0.31
3	5	0.2616	0.3078	0.2964	0.2898	0.285	0.2814	0.2784	0.2759	0.2737	0.2718	0.27
4	6	0.4496	0.3426	0.3388	0.3366	0.335	0.3337	0.3328	0.3320	0.3312	0.3306	0.33
5	7	0.2489	0.2725	0.2687	0.2665	0.265	0.2637	0.2627	0.2619	0.2612	0.2605	0.26
6	16	0.2464	0.3126	0.3012	0.2946	0.290	0.2862	0.2832	0.2807	0.2785	0.2766	0.275
7	19	0.3759	0.3651	0.3576	0.3531	0.350	0.3476	0.3456	0.3439	0.3424	0.3411	0.340
8	21	0.287	0.3303	0.3151	0.3063	0.30	0.2951	0.2912	0.2878	0.2849	0.2823	0.280
10	24	0.2413	0.3051	0.2976	0.2932	0.29	0.2876	0.2856	0.2839	0.2825	0.2812	0.280

$Y = ke^{mX}$, where *'k'* and *'m'* are constants. Solving *'k'* and *'m'* using

$$m = \frac{\ln(\frac{Y_2}{Y_1})}{x_2 - x_1} \text{ and } k = Y_1 e^{-mx_1} \qquad (23)$$

3.5. Plotting the compression and decompression cycles using Lab-Fit software [11]

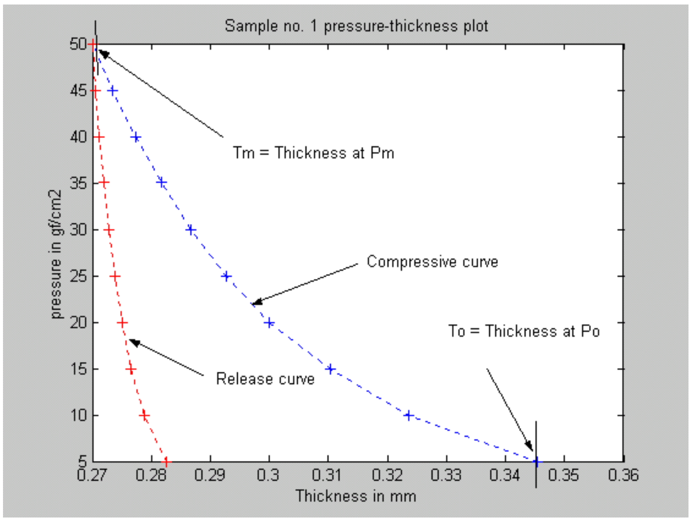

Figure 3. Pressure-thickness plot of compression curve

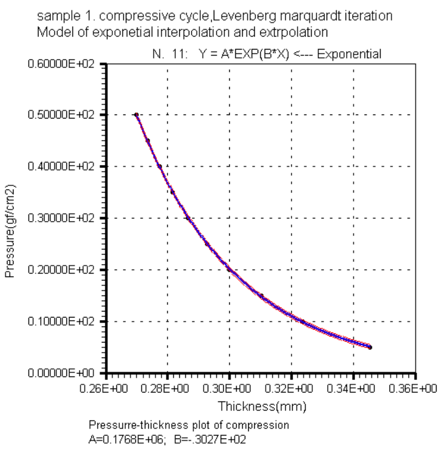

Figure 4. Compressive cycle

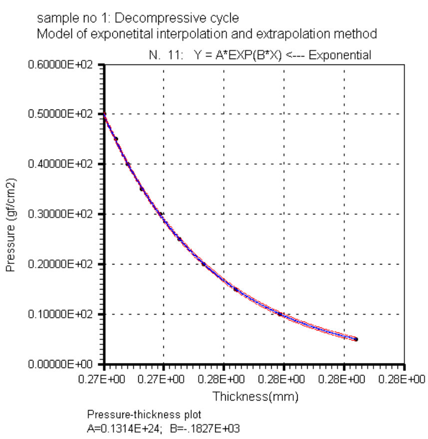

Figure 5. Decompressive cycle

3.6. Evaluation of compression properties

Table 5. Method of interpolation and extrapolation

Sample no.	Fabric no.	T_0	T_m	WC
1	3	0.3454	0.27	0.377
2	4	0.4105	0.31	0.5025
3	5	0.3203	0.27	0.2500
4	6	0.3804	0.33	0.2500
5	7	0.3228	0.26	0.3140
6	16	0.3629	0.275	0.4395
7	19	0.4154	0.340	0.377
8	21	0.3811	0.280	0.5055
10	24	0.3554	0.280	0.3770

Table 6. Experimental values (measured using the KES-FB3 DC compression tester)

Sample no.	Fabric no.	T_0	T_m	LC	WC	RC	EMC
1	3	1.22	0.41	0.2725	0.552	47.46	66.39
2	4	0.718	0.346	0.4075	0.379	49.34	51.81
3	5	0.474	0.254	0.2965	0.163	40.49	46.41
4	6	0.498	0.322	0.2885	0.127	25.2	35.34
5	7	0.484	0.268	0.352	0.19	38.95	44.63
6	16	0.538	0.274	0.226	0.149	9.4	49.1
7	19	0.616	0.342	0.213	0.146	13.7	44.48
8	21	0.43	0.264	0.3665	0.152	25.66	38.64
10	24	0.464	0.298	0.436	0.181	50.28	35.78

3.7. Comparison of theoretical and experimental values

Comparing the compressive property of theoretical and experimental results using the average value of the residual absolute, which is defined by

average value of residual absolute (%) =

$$\frac{(|\text{Theoretical value - Experimental value}|)}{\text{Total number of samples}} \text{ x } 100 \quad (24)$$

Table 7. Comparison of theoretical and experimental results

Sample no.	Fabric no.	WC (theoretical)	WC (experimental)	Average value of residual absolute
1	3	0.377	0.552	0.175
2	4	0.5025	0.379	0.1235
3	5	0.2500	0.163	0.087
4	6	0.2500	0.127	0.123
5	7	0.3140	0.19	0.124
6	16	0.4395	0.149	0.2905
7	19	0.377	0.146	0.231
8	21	0.5055	0.152	0.3535
10	24	0.3770	0.181	0.196
		Average value of residual absolute (%)		18.93%

8.93% of absolute difference in error exists between the two methods discussed. This is attributed to the changes in model assumptions which were used to make the model output deterministic.

4. Neural networks

Although there is a recent trend in automation towards studying the structure-property relationship of textile fabrics, an objective, correct and efficient method for studying the effects has become an important indicator in yielding rapid prototypes that output to sophisticated instruments such as the KES-FB3. Neural networks are normally applied to automatic control and operating systems for solving problems related to the prediction of nonlinear systems, where artificial neural networks show powerful learning, fault tolerance and response capabilities

4.1. Structure of artificial neural network

The multi-layer perceptron (MLP) artificial neural network applied in this study is a kind of learning by updating errors called the back-propagation algorithm. The structure of the MLP can be divided into three layers, including the input layer, the hidden layer and the output layer. By applying an artificial neural network, a prediction model for studying the compressive properties of woven fabrics is developed.

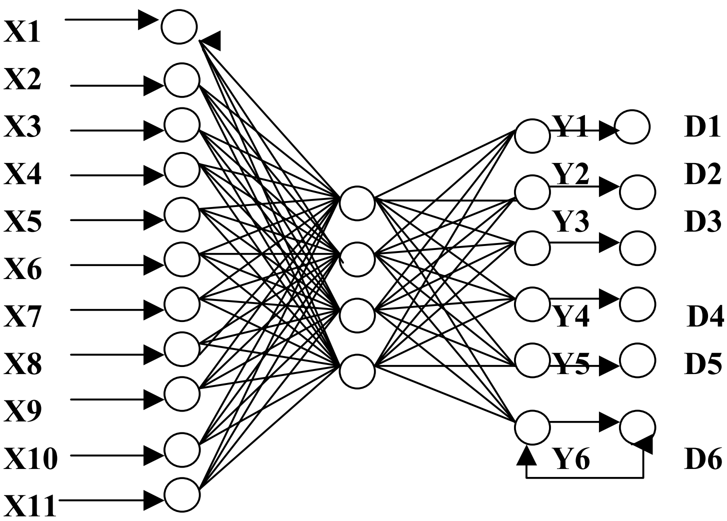

Figure 6. Structure of a study model for a neural network

4.2. Training network

This study utilises Mathworks neural network software to establish a prediction model. For non-linear transformation, the sigmoid function $f(x) = \frac{1}{1+e^{-x}}$ was used, with a range of inputs being (0,1). The learning network was designed to reduce the margin between the target value and prediction output. The quality of learning was evaluated using the energy function (E),

$E = \frac{1}{2}\sum\left(D_j - Y_j\right)^2$, where Dj is the output layer target value and Yj is the output layer prediction value. In order to minimise the value of the energy function, the gradient descent method was employed.

4.3. Input and output for neural networks

Table 8. Input variables

Network input variables	Input code
1.Warp yarn count (Ne)	X_1
2.Weft yarn count (Ne)	X_2
3.Ends per inch or ends per cm	X_3
4.Picks per inch or picks per cm	X_4
5. Warp crimp (%)	X_5
6.Weft crimp (%)	X_6
7.Fabric cover (Kc)	X_7
8.Fabric weight (g/cm^2)	X_8
9.Thickness (mm)	X_9
10.Fabric bulk density (g/cm^3)	X_{10}
11.Yarn tTwist (twist per cm)	X_{11}

4.4. Desired and network output variables

Table 9. Output variables

1. Linearity compression (LC)	D_1 and Y_1
2. Compressional energy (gf.cm/cm2)	D_2 and Y_2
3. Recovery compression (RC) (%)	D_3 and Y_3
4. To (mm)	D_4 and Y_4
5. Tm (mm)	D_5 and Y_5
6. EMC (relative compressibility) (%)	D_6 and Y_6

4.5. Training parameter of artificial neural network

Table 10. Training parameter

Elements of neural network	Definition	Parameter
Input layer	Normalisation	standard
	Number of units	11
Hidden layer	Transfer function	sigmoid
	Number of unit	3
Output layer	Normalisation	standard
	Number of unit	7
Learning rule	Algorithm	Back-propagation gradient descent
	Learning co-efficient	0.5
	Momentum co-efficient	0.3
	Maximum updates	90,000
Stop when	MSE error - Training % Correct - Training	0.001 95.0

RESULTS	LC	WC	RC	To	Tm	EMC
cumulative sum =	1.4714	0.8453	1.1584	1.1967	0.9257	1.3193
Sample size	41	41	41	41	41	41
Absolute residual error%	3.588	2.06	2.83	2.92	2.26	3.22

4.6. Evaluation of network learning results

Convergence graphs

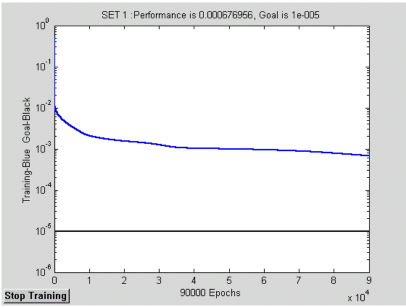

Figure 5. Set 1 Learning curve

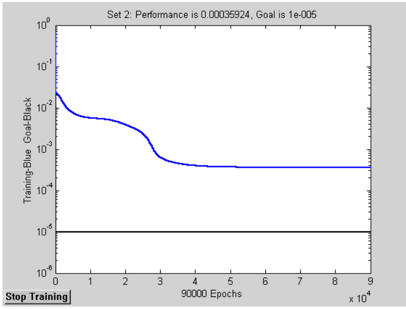

Figure 6. Set 2 Learning curve

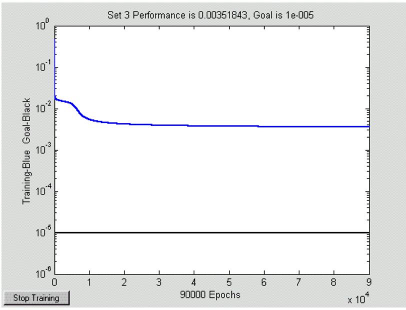

Figure 7. SET 3 Learning curve

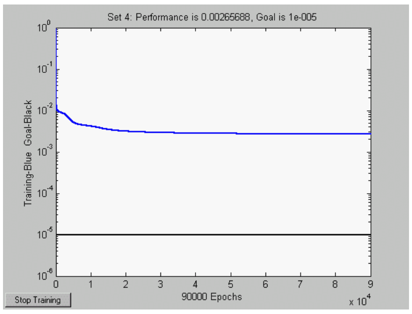

Figure 8. SET 4. Learning curve

Four test sets containing samples equally distributed for training, with a total sample size of 41 numbers, was scaled and fed into the neural network. Looking at the learning curve observations on the data input indicates the network has learned to the required standards.

4.7. Co-efficient of correlation

If the correlation coefficient between the predicted network value and actual test values is high, and all the scatter points are distributed on the diagonal, the residual should be small; that is, the model ability of fitting should be high.

4.8. MSE

In the learning network, the degree of convergence can be expressed in an MSE.

$MSE = \left[\frac{1}{n} \sum \left(T_j - Y_j \right)^2 \right]$ where ‘n’ is the number of units processed by the output layer. The value of MSE lies within the range of 0-1.0. If the MSE converges to less than 0.001, a good convergence effect is obtained, and the network learning is satisfactory.

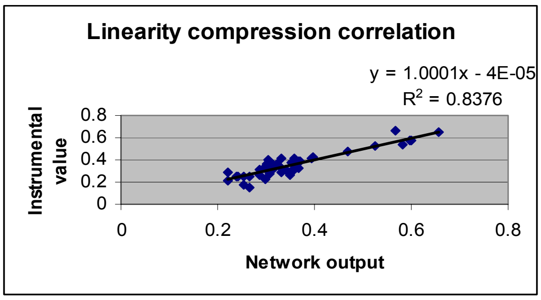

Figure 9. Correlation of linearity compression

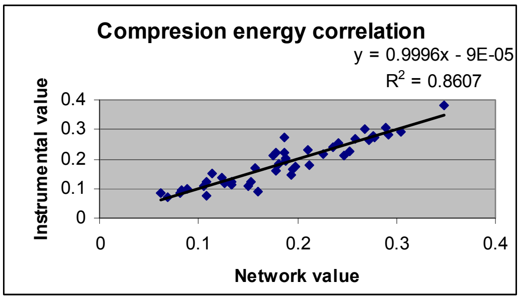

Figure 10. Correlation of compressional energy

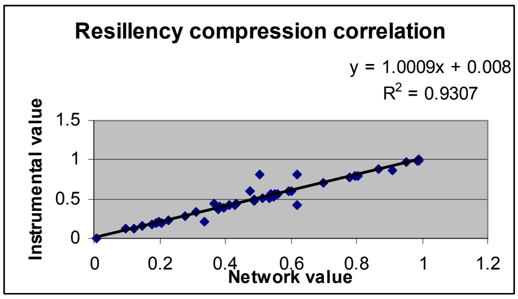

Figure 11. Correlation of resiliency compression

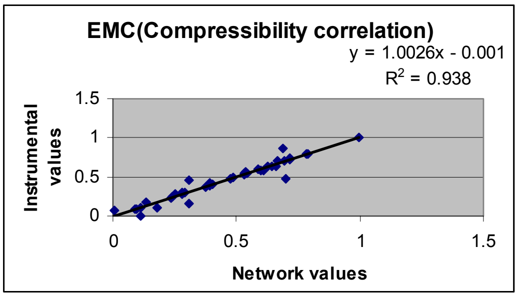

Figure 12. Correlation of compressibility

5. Conclusion

The difference between the mathematical methods and empirical machine-learning methods used to study the compressive behaviour of woven fabrics is significant. When a neural network is designed to perform the prediction problem which a mathematical model does, the results are encouraging. The correlation coefficient of the prediction models established in this study are within the range of 0.85-0.95, indicating that the model has good fitting ability. The absolute difference in outputs of artificial neural network and instrumental value is about 3%, and needs to be taken into account for model validity.

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