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Comparative Study on the Frictional Sound Properties of Woven Fabrics

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Abstract
An innovative Frictional Sound Automatic Measuring System (FSAMS) was designed to collect and enable analysis of the frictional sound spectra of four natural fibre woven fabrics which included cotton, linen, silk, and wool. The Fast Fourier Transform (FFT) method was used to convert time-domain signals into frequency-domain signals to enable the maximum sound amplitude (MSA) and the level pressure of the total sound (LPTS) of the cotton, linen, silk, and wool fabrics to be calculated and analysed. Subsequently auto-regression formulae were used to calculate the fabric auto-regressive coefficients (ARC, ARF, and ARE); the correlations between fabric frictional sound in terms of LPTS and AR coefficients, and mechanical properties as measured by KES-FB were also evaluated. Stepwise regression was then used to identify the key frictional sound parameters for the four types of fabric. The results show that LPTS values for cotton, linen, silk, and wool fabrics increase with their ARC values. It was revealed that the key mechanical parameters affecting fabric frictional sound for the four natural fibre woven fabrics were not the same for each fabric type: the parameters that influenced LPTS values were the fabric weight and bending hysteresis for the cotton fabric, tensile energy for the linen, tensile resilience for the silk and shear hysteresis at a 5° shear angle for the wool fabric.

Key words: *KES-FB, Fast Fourier Transform, auto-regressive coefficients, LPTS.*

Introduction

Fabric frictional sound is generated when two pieces of fabric are rubbed against each other. These sounds are closely related to the fundamental structures and mechanical properties of the fabric. In 1996, Bishop et al. [1] considered that fabric sound amplitudes and frequencies were correlated to the physical and chemical properties of fabrics including friction, roughness, shear, and bending rigidity (B) [2-3]. In 1999, Cho and Casali [4] used FFT to record the frictional sounds of five knitted or woven fabric materials and calculate their LPTSs and autoregressive (AR) model to measure and compare AR coefficients (ARs), together with the Kawabata Evaluation System for Fabrics (KES-FB) to measure and compare mechanical properties. Linear trends in frequency with autoregressive errors were fitted to the amplitude, and three coefficients (ARF, ARE and ARC) of the functions were obtained. The level pressure of the total sound (LPTS) was calculated to evaluate sound loudness from specimens and the level range (ΔL) and frequency differences (Δf) were used to quantify sound spectra shapes. In 2000, Cho and Yi [5] conducted a study on fabric friction sounds using a sound generator together with the Fast Fourier Transform (FFT) method to convert fabric friction time domain signals to frequency domain signals to enable them to calculate the respective level pressure of the total sound (LPTS). Additionally they used the autoregressive (AR) model to evaluate fabric friction sounds and clustered the LPTS and AR model parameters.

Prior to the work of Cho and Yi [5], studies of frictional sound were focused mainly on the correlation between sound parameters and mechanical properties. In 2001, researchers began to focus on single fabric analyses using a measuring apparatus designed to determine fabric noise, and Cho and Yi [6] developed an integrated wool fabric evaluation system by combining FFT, the AR model and Zwicker's psychoacoustic models. In 2003, Choi and Cho [7] published their study on the influence of various silk fabric woven structures on frictional sound parameter variations. The same authors studied the influence of various fundamental fabric structures and fibre thicknesses on friction sound variations using seven sample fabrics, three fibre thicknesses, and various knitted structures to compare their psychoacoustic responses. In 2008, Cho and Kim [8] studied the friction of weft-knitted fabrics with the aim of investigating possible correlations between the frictional sound and mechanical properties of knitted fabrics, as well as the influence on frictional sound variations of various knitted structures (plain, ribbed, half-cardigan, and half-milano) and mechanical properties (as measured by the Kawabata Evaluation System). In 2012, Park and Cho [9] tested the fabric frictional sounds of knitted, woven, and vapour-permeable, water-repellent fabrics using another measuring apparatus for fabric noise.

In 2013, Jin and Cho [10] applied cluster analysis to the study of the individual sound-producing properties of three types of woven fabrics used in combat uniforms during the Korean War (1950-53), with the eventual objective of enabling control over the sounds produced by the friction of clothing worn during combat. Autonomic nervous system (ANS) and KES-FB mechanical property-related analyses were also undertaken to determine whether any correlations could be found between the two.

Whereas most of the earlier studies outlined the above-investigated single or composite fibre materials, for the work reported here, natural fibre woven fabrics were investigated using a specially developed automatic frictional sound testing arrangement to:
- determine the differences in frictional sounds and physical properties of four

commercially-available natural fibre woven fabric types (cotton, linen, silk, and wool), and
- investigate the correlation between frictional sound and the mechanical properties of the four fabric types.

The mechanical properties of the fabric samples were obtained by KES-FB, and stepwise regression was used to identify the key mechanical parameters influencing fabric frictional sounds.

Experimental methods

Experiment materials

A total of 124 samples were taken from four different types of natural-fibre woven fabrics, namely cotton, linen, silk and wool, of which 42 were cotton with a weight average of 140.2 g/m^2; 20 – linen with a weight average of 163.2 g/m^2, 16–silkwitha weightaverageof91.7 g/m^2, and 46 were wool fabric with a weight average of 192.6 g/m^2. A range of fabric weights and thickness were used for each fibre type, as summarised in ***Table 1***. Three distinct areas were taken as samples from each piece of fabric. The fabric for the experiment was trimmed to a 20 cm × 20 cm square to be measured by a KES-F instrument (Kyoto University, Japan) [11, 25]; and to 20 cm × 20 cm for the FSMA. To keep each piece of fabric in a natural state prior to the taking of measurements, all samples were conditioned for 24 hours at 20 ± 2 °C and 65 ± 2 % RH so as to minimise the effect of fabric finishing.

Experimental methods

FSAMS system

Test equipment included a personal computer, a programmable logic controller (PLC) ECMA-C20604FS (Delta Electronics, Inc., Taiwan), a human machine touch screen interface (DOP-B05S100), a fabric friction sliding device, an acoustic enclosure (950 mm 600 mm 940 mm), fixtures to hold one of the test fabric pieces stationary and flat, fixtures to support the second fabric piece and enable it to be moved in a controlled manner over the stationary fabric sample, an integrating-averaging sound level meter, and a spectrum analyser. An overall structural diagram for the device is shown in ***Figure 1***, and the experimental process flow diagram is shown in ***Figure 2*** [12-17].

Fabric frictional sound parameters

LPTS value

The value of LPTS represents the loudness of the physical parameter within human audible frequencies. Thus the LPTS calculation range was set to be between 16-20 kHz [18].

$$LPTS = 10log^{10^{\frac{BL_1}{10}}+\dots+\frac{BL_n}{10}} \quad (1)$$

BL represents the broadband level.

MSA

The MSA value represents the corresponding frequency position of the maximum level of decibels on the spectrum. corresponding decibel values at the ±100 Hz positions of the MSA were also averaged.

Spectral-Shape Fitting by Using an Autoregressive (AR) Model

The spectral-estimation technique is generally regarded as the optimal statistical method for analysing the Fast Fourier Transform algorithm [19]. The method used in this work for spectral analysis was an AR model applied to obtain the parameters characterising the sound

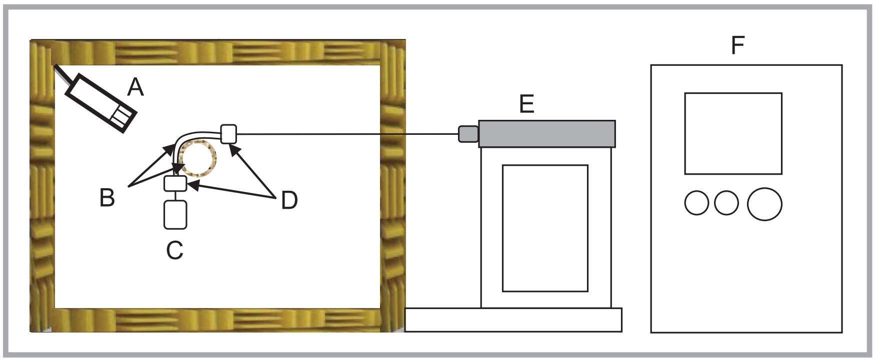

Figure 1. *A schematic diagram of the automatic friction sound test equipment for fabric noise; A: microphone, B: fabric, C: load, D: fixture, E: sliding device, F: programmable logic controller (PLC) [12-17].*

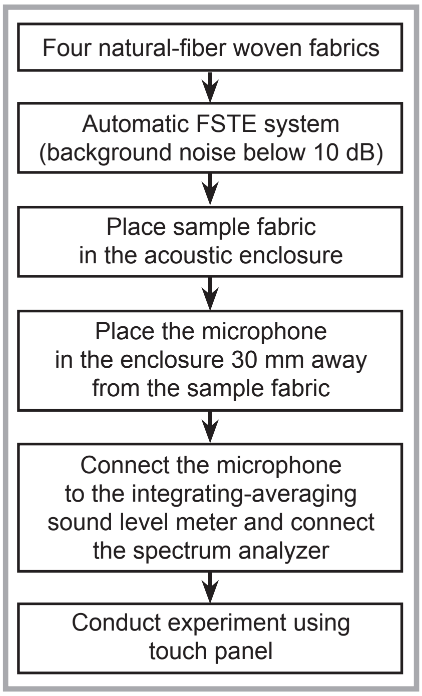

Figure 2. *Flow chart of the automatic FSTE system [12-17].*

Table 1. *Fabric specifications.* ***Note:*** ** Thickness measured under 0.5 cN/cm^2; MAX.: maximum value; MIN.: minimum value; MEAN: average; S.D.: standard deviation.*

Fabric		Warp density, ends/in	Weft density, picks/in	Thickness*, mm	Weight, g/m^2	MSA, dB	LPTS, dB
Cotton	MAX	172.00	104.00	0.68	186.9	69.40	46.53
	MIN	49.00	47.00	0.36	102.1	49.01	21.54
	MEAN	114.52	68.95	0.52	140.2	56.79	30.56
	S.D.	29.08	16.41	0.08	26.1	5.11	7.22
Linen	MAX	112.00	72.00	0.95	280.7	57.28	33.93
	MIN	24.00	32.00	0.40	101.5	50.92	24.06
	MEAN	64.35	54.00	0.62	163.2	54.92	30.09
	S.D.	20.19	10.34	0.14	47.4	1.82	2.89
Silk	MAX	174.00	152.00	0.72	180.7	63.40	40.90
	MIN	56.00	48.00	0.16	55.1	50.64	21.12
	MEAN	103.75	90.00	0.34	91.7	57.84	32.01
	S.D.	37.70	25.76	0.18	33.1	3.70	5.61
Wool	MAX	120.00	112.00	0.80	272.0	68.38	37.03
	MIN	48.00	44.00	0.42	152.6	59.50	26.19
	MEAN	84.65	80.46	0.53	192.6	63.58	30.93
	S.D.	16.30	14.49	0.10	27.8	2.53	2.70

Table 2. Means of physical properties for each cluster. ***Note:*** *tensile linearity (LT), tensile energy (WT), tensile resilience (RT), shear rigidity (G), shear hysteresis at = 0.5° (2HG), shear hysteresis at = 5° (2HG5), bending rigidity (B), bending hysteresis (2HB), compressional linearity (LC), compressional energy (WC), compressional resilience (RC), surface coefficient of friction (MIU), mean deviation of the MIU (MMD), geometrical roughness (SMD), fabric thickness (T_o), and fabric weight (W).*

	Cluster	MSA, dB	LPTS, dB	ARE, –	AEF, –	ARC, –	LT, –	WT, cN.cm/cm²	RT, %	G, cN/cm.degree	2HG, cN/cm	2HG5, cN/cm
Cotton	Cluster 1	23.09	50.29	0.9988	-0.0004	15.99	0.681	11.234	42.022	0.856	1.128	2.466
	Cluster 2	26.55	54.09	0.9989	-0.0003	17.37	0.754	9.742	44.355	1.705	2.727	5.590
	Cluster 3	33.43	58.61	0.9991	-0.0001	19.33	0.693	10.084	43.491	1.198	2.436	4.039
	Cluster 4	41.09	64.81	0.9992	0.0000	22.12	0.713	11.208	41.854	1.646	3.238	4.982
Linen	Cluster 1	26.96	51.91	0.9991	-0.0006	19.20	0.680	10.390	44.610	0.280	0.177	1.900
	Cluster 2	28.73	53.60	0.9994	-0.0006	20.15	0.741	9.850	41.318	0.924	0.992	4.778
	Cluster 3	31.50	55.95	0.9993	-0.0005	20.71	0.654	12.654	37.528	0.349	0.357	1.848
	Cluster 4	31.28	57.02	0.9992	-0.0004	20.96	0.731	13.550	33.567	0.583	0.900	3.350
Silk	Cluster 1	25.30	51.89	0.9989	-0.0003	14.70	0.659	9.283	41.913	0.250	0.327	1.787
	Cluster 2	30.03	56.74	0.9989	-0.0007	18.90	0.721	5.750	62.893	0.233	0.080	1.598
	Cluster 3	34.90	59.57	0.9993	-0.0004	18.80	0.689	6.647	59.401	0.231	0.120	1.277
	Cluster 4	35.95	62.93	0.9990	-0.0003	20.55	0.691	4.910	60.080	0.455	0.430	2.250
Wool	Cluster 1	28.30	60.33	0.9989	-0.0002	24.18	0.661	13.773	60.330	0.484	0.335	0.840
	Cluster 2	29.11	61.91	0.9989	-0.0002	24.70	0.684	13.423	58.216	0.500	0.425	0.953
	Cluster 3	32.15	64.98	0.9989	-0.0001	26.20	0.688	13.322	61.049	0.593	0.414	1.145
	Cluster 4	34.69	67.35	0.9990	0.0000	27.37	0.661	12.328	63.638	0.645	0.519	1.544

	Cluster	B, cN.cm²/cm	2HB, cN.cm/cm	MIU, –	MMD, –	SMD, μm	LC, –	WC, cN.cm/cm²	RC, %	T, mm	W, g/m²
Cotton	Cluster 1	0.041	0.036	0.138	0.014	3.816	0.304	0.144	53.984	0.458	11.312
	Cluster 2	0.064	0.076	0.143	0.017	5.121	0.332	0.167	53.446	0.493	13.209
	Cluster 3	0.064	0.066	0.147	0.018	4.980	0.314	0.163	50.075	0.523	13.883
	Cluster 4	0.089	0.093	0.158	0.036	7.383	0.314	0.157	51.469	0.609	17.437
Linen	Cluster 1	0.090	0.053	0.165	0.044	10.133	0.346	0.166	55.373	0.553	13.507
	Cluster 2	0.190	0.137	0.139	0.031	8.982	0.279	0.184	55.806	0.598	14.738
	Cluster 3	0.139	0.063	0.169	0.028	9.733	0.330	0.209	54.836	0.666	17.989
	Cluster 4	0.143	0.080	0.147	0.036	9.363	0.314	0.187	50.523	0.600	16.750
Silk	Cluster 1	0.087	0.048	0.185	0.021	6.583	0.383	0.189	54.250	0.590	13.453
	Cluster 2	0.085	0.051	0.144	0.032	2.943	0.374	0.042	107.083	0.190	6.493
	Cluster 3	0.048	0.026	0.159	0.019	4.414	0.397	0.092	92.023	0.314	8.969
	Cluster 4	0.050	0.026	0.138	0.011	3.115	0.504	0.112	66.455	0.315	8.830
Wool	Cluster 1	0.071	0.020	0.131	0.013	3.396	0.328	0.124	72.370	0.520	18.135
	Cluster 2	0.080	0.024	0.140	0.014	3.233	0.349	0.141	72.574	0.567	19.153
	Cluster 3	0.072	0.036	0.134	0.015	3.805	0.320	0.112	74.118	0.493	18.616
	Cluster 4	0.081	0.026	0.134	0.015	2.853	0.316	0.131	71.944	0.558	21.809

specimens of each specimen. A function to fit each spectrum was developed, including error terms. The AR function was applied to frequencies in the range of 500-16,000 Hz. The AR functions used to describe the sound-spectra forms are expressed as follows:

$$\tilde{y}_t = \hat{y}_1,\ t = 1 \quad (2)$$

$$\tilde{y}_t = \hat{\alpha} + \hat{\beta}x1 + \hat{\varphi}_t - 1,\ t = 2,..., n \quad (3)$$

where:

$$\tilde{t} - 1 = yt - 1 - \hat{y}_t - 1,\ \hat{y}_t - 1 = \hat{\alpha} + \hat{\beta}x_t - 1 \quad (4)$$

In these equations, $\tilde{y}_t$ is the estimated value of y (amplitude), $\hat{y}_1$ the estimated value of y (amplitude) when $t = 1$; t represents the frequency order (when $t = 1$, the frequency value is 16 Hz, and when $t = 2$ the frequency value is 32 Hz); x_t denotes the value of t (when $t = 1$, the frequency is 16 Hz); $\hat{\alpha}$ is a constant called ARC; $\hat{\beta}$ is a coefficient of x_t called ARF, and $\hat{\varphi}$ is a coefficient of $t - 1$ (the error term) called ARE. With the ARC, ARF and ARE making the spectral shapes of fabric sounds, it was possible to investigate their relationships with mechanical properties.

Statistical analysis

Mechanical property-related analysis

Pearson correlation coefficients were determined in the correlation analysis of 16 fabric mechanical properties measured with the Kawabata Evaluation System for fabrics (KES-FB). The correlation coefficient represents the correlation between two variables (r value ranges between ±1). The plus and minus signs represent positive and negative correlations in the linear relationships, which reflect the degrees of linear relationships between two data groups. A correlation close to one indicates a high degree of correlation, and 2-tailed tests were used to determine the significance among variables. Correlation coefficients exhibiting significance levels of 0.05 and 0.01 were denoted using single and double asterisks (* and **), respectively [20-21].

Key parameters selection

Based on the KES-FB system, correlation coefficient analysis was used to determine the relationship among frictional sound parameters and among the sixteen physical properties measured by KES-FB. ANOVA analysis was used to compare the differences among the four natural-fibre fabrics with regard to their physical properties. *t*-test analysis

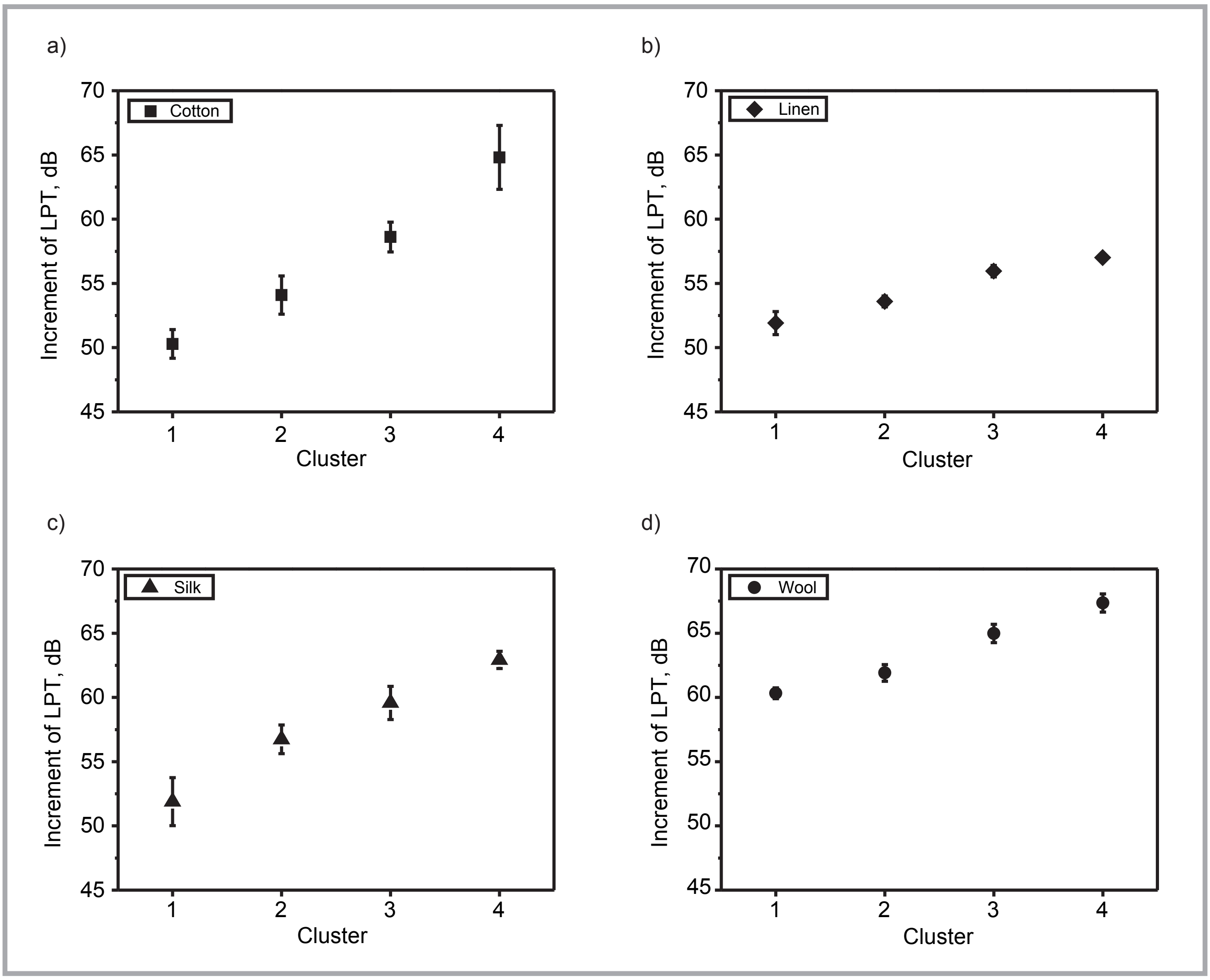

Figure 3. *Confidence intervals for LPTS among four clusters from each of the four natural-fibre fabrics: a) cotton, b) linen, c) silk, d) wool.*

was performed to evaluate the difference between the physical properties of two fabrics. Based on the sixteen physical properties, the key parameters of fabric frictional sound were selected by using the stepwise regression method [20-21]. The relative contribution of the selected parameters was evaluated by using the partial F-test criterion method. The ANOVA analysis was accomplished using SPSS 18, while the t-test and correlation coefficient analysis was made by multiple stepwise regressions [22-24].

Results and discussion

Effectiveness analysis of the four classifications of natural fibre woven fabrics

To provide a means for clearly clustering friction sound data through FSTE systems, we used the mean and standard deviations (SD) of LPTSs as bases for distinguishing between the fabrics. The data were divided based on fabric type: cotton, linen, silk and wool (***Table 2***). Clusters 1-4 represented groups of the smallest to the largest LPTSs, respectively. Analysis of variance was used to verify the correctness of the LPTS values of cotton, linen, silk and wool-fabric with regard to the level pressure of the total sound (LPTS) friction sounds. An F-test was conducted and the cotton, linen, silk and wool fabrics yielded values of 115.144, 76.951, 34.813 and 210.174, respectively, whereas the corresponding P values are all 0.000, showing that the frictional sounds between the cotton, linen, silk and wool fabric classifications exhibited significant differences. Applying Duncan's multiple range test, as shown in ***Figure 3***, the 95% confidence intervals (CIs) of cotton fabric's first, second, third and fourth classifications were (49.306, 51.270), (53.435, 54.738), (57.809, 59.416), and (63.185, 66.435), respectively; because no overlap was observed, this indicated that the fabric frictional sounds can all be effectively classified. Similarly no overlap was observed in the respective 95% CIs of the first, second, third and fourth classifications for linen (50.893, 52.934), (53.220, 53.972), (55.662, 56.247) and (56.741, 57.292); silk (49.768, 54.006), (55.640, 57.830), (58.620, 60.526) and (61.994, 63.856); and wool (60.028, 60.622), (61.583, 62.240), (64.618, 65.345) and (66.857, 67.846), where the lack of overlap once again indicates that the fabric frictional sounds can all be effectively classified. ***Table 2*** shows the 21 average physical parameters for each classification of natural fibre woven fabrics. The ARCs for the first to the fourth classifications of the cotton, linen, silk and wool fabrics were respectively 15.99,17.37,19.33, and 22.12; 19.20, 20.15, 20.71 and 20.96; 14.70, 18.90, 18.80 and 20.55; and 24.18, 24.70, 26.20 and 27.37, showing that the

Table 3. Correlation coefficient analysis of the friction sound parameters of four natural-fibre fabrics; ***Note:*** ** p-value < 0.05, ** p-value < 0.01, maximum sound amplitude (MSA), the level pressure of the total sound (LPTS), auto-regressive coefficients (ARC, ARF and ARE).*

		MSA	LPTS	ARE	ARF	ARC
Cotton	MSA	1				
	LPTS	0.920**	1			
	ARE	0.652**	0.471**	1		
	ARF	0.621**	0.792**	0.066	1	
	ARC	0.771**	0.891**	0.433**	0.536**	1
Linen	MSA	1				
	LPTS	0.649**	1			
	ARE	0.619**	0.053	1		
	ARF	0.006	0.674**	-0.488*	1	
	ARC	0.150	0.335	0.238	-0.072	1
Silk	MSA	1				
	LPTS	0.757**	1			
	ARE	0.707**	0.253	1		
	ARF	-0.414	0.006	-0.639**	1	
	ARC	0.330	0.720**	-0.090	-0.091	1
Wool	MSA	1				
	LPTS	0.892**	1			
	ARE	0.225	0.172	1		
	ARF	0.425**	0.510**	-0.571**	1	
	ARC	0.628**	0.685**	0.626**	-0.233	1

Table 4. Correlation coefficient analysis of the friction sound parameters and physical properties of four natural-fibre fabrics; ***Note:*** ** p-value < 0.05, ** p-value < 0.01.*

	Cotton	Linen	Silk	Wool
* p-value < 0.05	MSA-B(0.315*) MSA-MIU(0.390*) LPTS-B(0.388*) ARE-MMD(0.318*) ARF-WC(0.343*) ARC-SMD(0.308*)	MSA-G(-0.536*) MSA-2HG(-0.498*) MSA-2HG5(-0.554*) ARE-G(-0.543*) ARE-2HG(-0.559*) ARE-2HG5(-0.542*) ARC-MIU(-0.461*) ARC-MMD(-0.477*)	LPTS-RT(0.585*) LPTS-MIU(-0.537*) LPTS-T(-0.509*) ARF-SMD(0.604*) ARC-SMD(-0.518*) ARC-RC(0.590*)	MSA-RT(0.350*) LPTS-RT(0.306*) LPTS-W(0.309*) ARE-2HG(0.306*) ARE-SMD(-0.358*) ARE-T(0.339*) ARF-T(-0.328*) ARC-B(0.336*)
** p-value < 0.01	MSA-MMD(0.570**) MSA-SMD(0.479**) MSA-T(0.515**) MSA-W(0.620**) LPTS-MIU(0.508**) LPTS-MMD(0.636**) LPTS-SMD(0.464**) LPTS-T(0.657**) LPTS-W(0.765**) ARE-LC(-0.404**) ARE-WC(-0.509**) ARF-B(0.411**) ARF-2HG(0.433**) ARF-MIU(0.518**) ARF-MMD(0.481**) ARF-SMD(0.456**) ARF-RC(-0.444**) ARF-T(0.766**) ARF-W(0.779**) ARC-MIU(0.444**) ARC-MMD(0.559**) ARC-T(0.484**) ARC-W(0.617**)	ARE-RT(-0.603**) ARE-LC(-0.563**) ARC-RT(-0.564**)	ARC-RT(0.749**) ARC-WC(-0.629**) ARC-T(-0.718**) ARC-W(-0.665**)	MSA-2HG5(0.381**) LPTS-G(0.452**) LPTS-2HG(0.380**) LPTS-2HG5(0.495**) ARE-B(0.441**) ARE-2HG5(0.444**) ARE-W(0.629**) ARF-RT(0.439**) ARF-B(-0.392**) ARC-G(0.394**) ARC-2HG(0.430**) ARC-2HG5(0.475**) ARC-W(0.508**)

Table 5. Parameter selection process, criteria, pout: 0.1, pin: 0.05.

Categories	Parameter	Signif.–F	*R*
Cotton LPTS	W	0.00	0.77
	W、2HB	0.00	0.79
Linen LPTS	WT	0.03	0.46
Silk LPTS	RT	0.02	0.59
Wool LPTS	2HG5	0.00	0.50

ARC values for each fabric increased as LPTS values increased.

Correlation analysis of the 16 fabric KES-FB mechanical properties

Before the selection of LPTS and mechanical parameters, correlation coefficient analysis of the 16 mechanical parameters was performed. To facilitate the following descriptions, the mechanical parameters have been abbreviated as follows: tensile linearity (LT), tensile energy (WT), tensile resilience (RT), shear rigidity (G), shear hysteresis at $\varphi = 0.5°$ (2HG), shear hysteresis at $\varphi = 5°$ (2HG5), bending rigidity (B), bending hysteresis (2HB), compressional linearity (LC), compressional energy (WC), compressional resilience (RC), the surface coefficient of friction (MIU), the mean deviation of the MIU (MMD), geometrical roughness (SMD), fabric thickness (T_o), and fabric weight (W).

For the cotton fabric 2HB-B (0.775), G-LT (0.650), 2HG-2HB (0.788), 2HG5-LT (0.758), SMD-MMD (0.706), WC-LC (0.766), T-MMD (0.646), T-SMD (0.632), W-B (0.606), W-MMD (0.692), and W-SMD (0.623) exhibited very good correlations (i.e., between 0.6 and 0.8), whereas G-2HB (0.878), 2HG-G (0.855), 2HG5-2HB (0.823), 2HG5-G (0.866), 2HG5-2HG (0.824) and W-T (0.804) presented excellent correlations (i.e., 0.8-1.0).

For the linen fabric: RT-WT (-0.664), 2HB-LT (0.692), G-LT (0.766), G-2HB (0.640), 2HG-LT (0.783), 2HG-2HB (0.608), 2HG5-2HB (0.663), LC-MIU (0.756), RC-WC (-0.620), T-RC (-0.613) and W-T (0.707) exhibited very good correlations, whereas: 2HB-B (0.824), 2HG-G (0.986), 2HG5-LT (0.807), 2HG5-G (0.994), 2HG5-2HG (0.988), and T-WC (0.893) presented excellent correlations.

For the silk fabric: RT-WT (-0.783), 2HG-G (0.777), 2HG5-G (0.740), 2HG5-2HG (0.764), MIU-WT (0.704), MIU-RT (0.629), MMD-B (0.694), MMD-2HB (0.689), SMD-WT (0.686), WC-RT (-0.786), WC-MIU (0.624), RC-RT (0.791), T-WT (0.667), T-MIU (0.684), T-SMD (0.741), T-RC (-0.782), W-MIU (0.686), W-SMD (0.775), W-WC (0.748), and W-RC (-0.642) exhibited very good correlations, whereas: 2HB-B (0.959), RC-WC (-0.832), T-RT (-0.856), T-WC (0.950), W-WT (0.807), W-RT (-0.829), and W-T (0.882) presented excellent correlations.

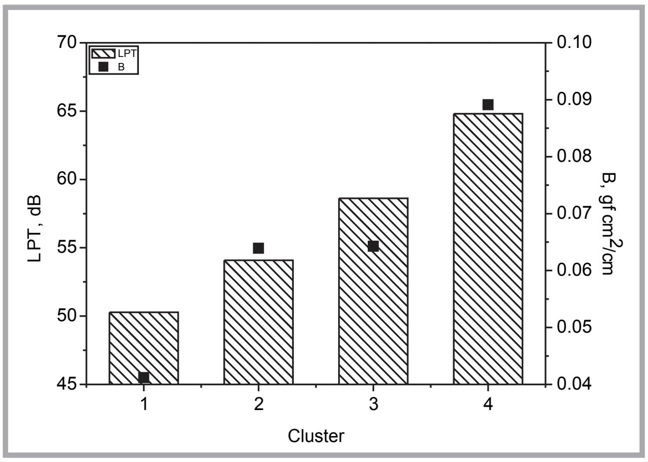

Figure 4. *Comparison of bending rigidity (B) and LPTS of cotton fabric in four clusters.*

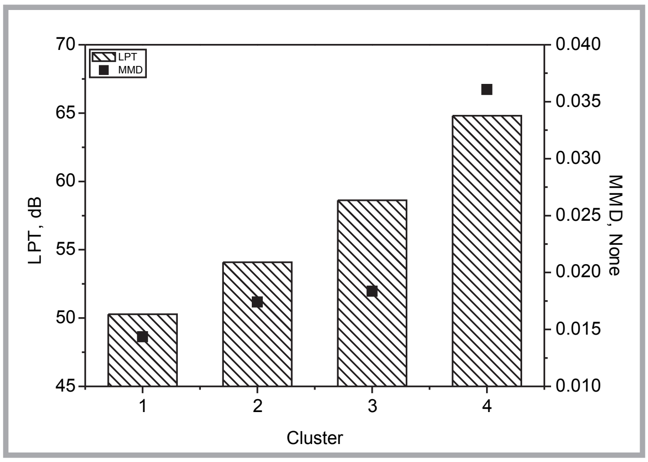

Figure 5. *Comparison of mean deviation of MIU (MMD) and LPTS of cotton fabric in four clusters.*

For the wool fabric RT-LT (-0.623), 2HG5-2HG (0.665), SMD-MMD (0.690), WC-B (0.635), WC-MIU (0.707), RC-MIU (-0.709), RC-WC (-0.645), T-MIU (0.699), T-RC (-0.710), W-B (-0.761), and W-T (0.706) exhibited very good correlations, whereas T-B (0.813) and T-WC (0.916) showed excellent correlations.

The aforementioned analysis shows that the shear properties (G, 2HG and 2HG 5) of the cotton fabrics exhibited excellent correlations. The bending property (2HB) exhibited excellent correlations with shear properties (G, 2HG5). In addition, the weight (W) exhibited an excellent correlation with thickness (T). For the linen fabrics, bending (B, 2HB) and shear (G, 2HG, 2HG5) properties exhibited excellent correlations, respectively. The shear property (2HG5) exhibited an excellent correlation with the tensile property (LT). Thickness (T) exhibited an excellent correlation with the compressional property (WC). For the silk fabrics, bending (B, 2HB) and compressional (WC, RC) properties exhibited excellent correlations, respectively. Thickness (T) exhibited an excellent correlation with the tensile property (RT) and weight (W). Weight (W) exhibited an excellent correlation with tensile properties (WT, RT) and thickness (T). For the wool fabrics, the thickness (T) with the bending property (B) and weight (W) also presented excellent correlations. The mechanical properties correlated with and influenced the frictional sound of the four natural-fibre fabrics and the key mechanical parameter selection process.

Correlation analysis of sound and mechanical parameters

In ***Table 3***, the correlation analysis of the sound parameters of the four types of natural fibre woven fabrics shows that for cotton fabric the maximum sound amplitudes (MSA)-ARE (0.652), MSA-ARF (0.621), MSA-ARC (0.771) and LPTS-ARF (0.792) exhibited very good correlations, whereas MSA-LPTS (0.920) and LPTS-ARC (0.891) presented excellent correlations. For the linen fabric MSA-LPTS (0.649), MSA-ARE (0.619) and LPTS-ARF (0.674) exhibited excellent correlations. For the silk fabric MSA-LPTS (0.757), MSA-ARE (0.707), LPTS-ARC (0.720) and ARF-ARE (-0.639) exhibited very good correlations. For the wool fabric MSA-ARC (0.628), LPTS-ARC (0.685) and ARC-ARE (0.626) exhibited very good correlations, whereas MSA-LPTS (0.892) presented a high-level correlation.

The relative influence of LPTS and the 16 mechanical and sound parameters of the four types of natural fibre woven fabrics showed the following (***Table 4***): For the cotton fabric very good correlations were observed for MSA-W (0.620), LPTS-MMD (0.636), ARF-T (0.766), ARF-W (0.779) and ARC-T (0.484). For the linen fabric a medium-to-high-level correlation was observed for ARE-RT (-0.603). For the silk fabric very good correlations were observed for ARC-WC (-0.629), ARC-T (-0.718) ARC-W (-0.665). For the wool fabric, a medium-to-high-level correlation was observed for ARE-W (0.629).

These results reflected strong correlations between AR coefficients, LPTS and MSA because the AR coefficients are parameters generated from the autoregression of LPTS. In the subsequent stepwise regression analysis, therefore, only the selection of LPTS and key mechanical parameters are discussed.

Selection and comparative analysis of LPTS and key mechanical parameters

The fabric frictional sounds and 16 mechanical parameters exhibited varying degrees of correlation. Thus stepwise regression was adopted to identify the most significant and independent key mechanical parameters that influence fabric frictional sounds for each of the cotton, linen, silk and wool fabrics. Each parameter was selected based on the procedure shown in ***Table 5***.

The parameters selected were as follows: cotton – W and 2HB (R = 0.794), linen – WT (R = 0.456), silk – RT (R = 0.585) and wool – 2HG5 (R = 0.495). The mechanical parameter correlations derived using a matrix diagram and stepwise regression were then analysed. W and 2HB were selected for the stepwise regression of the cotton fabric. W and B (0.606) and MMD (0.692) both exhibited very good correlations and T (0.804) presented a high-level correlation. This showed that the cotton fabric's LPTS and B, MMD, T, and W were correlated. ***Figures 4-12*** show a bar diagram of the key mechanical and sound parameters drawn using the aforementioned physical parameters based on the four MSA classifications. W and 2HB were selected for the cotton fabric during stepwise regression; W-B (0.606), 2HB-B (0.775), and W-MMD (0.692) exhibited very good correlations, whereas W-T (0.804) presented a high-level correlation.

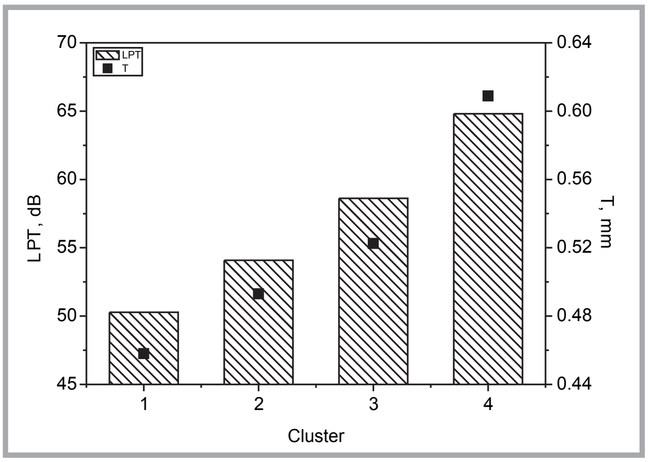

__Figure 6.__ Comparison of thickness (T) and LPTS of cotton fabric in four clusters.

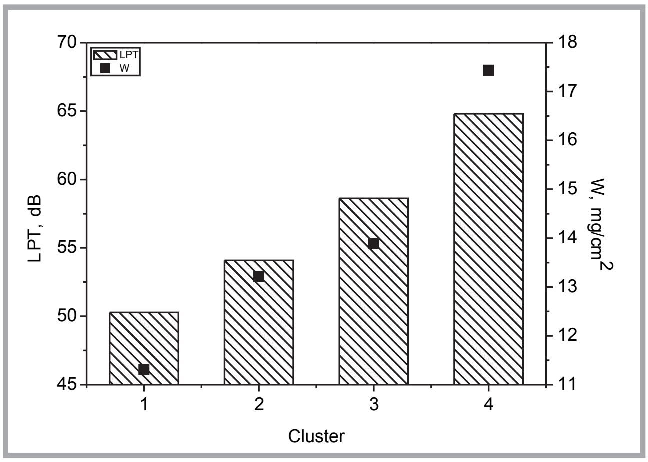

__Figure 7.__ Comparison of weight (W) and LPTS of cotton fabric in four clusters.

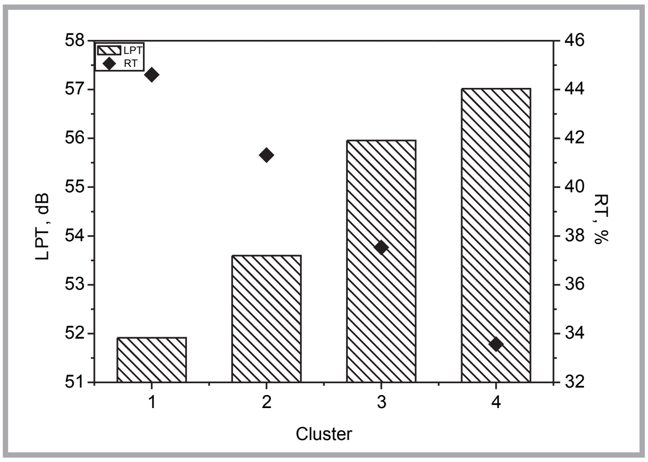

__Figure 8.__ Comparison of tensile resilience (RT) and LPTS of linen fabric in four clusters.

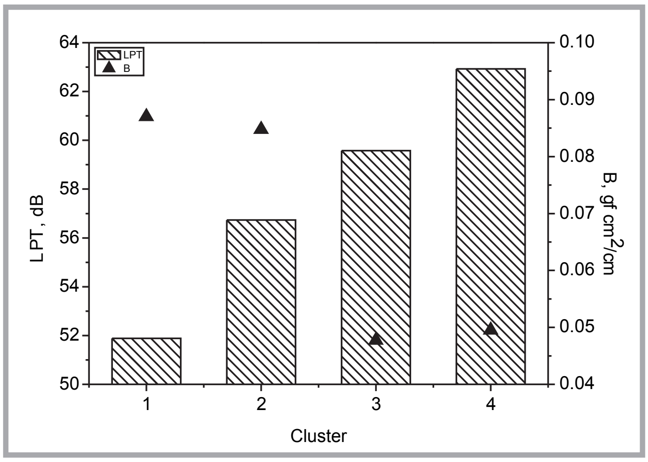

__Figure 9.__ Comparison of bending rigidity (B) and LPTS of silk fabric in four clusters.

The average values of B, MMD, T and W for the cotton fabric from the first to the fourth classifications were 0.041, 0.064, 0.064 and 0.089 (***Figure 4***); 0.014, 0.017, 0.018 and 0.036 ***(Figure 5***); 0.458, 0.493 0.523, and 0.609 (***Figure 6***); and 11.312, 13.209, 13.883 and 17.437 (***Figure 7***), respectively. This showed that the B, MMD, T, and W values for the cotton fabric increased as the fabric's LPTS increased.

For the linen fabric, WT was selected during stepwise regression and WT-RT (-0.664) exhibited a medium-to-high-level correlation. The average values of RT for the linen fabric from the first to the fourth classifications were 44.610, 41.318, 37.528 and 33.567, respectively (***Figure 8***). This showed that RT values for the linen fabric decreased as the fabric's LPTS increased.

For the silk fabric, the average values of B and LC from the first to the fourth classifications were 0.087, 0.085, 0.048 and 0.050 (***Figure 9***), and 0.383, 0.374, 0.397 and 0.504 (***Figure 10***), respectively. This showed that the B and LC values for the silk fabric increased as fabric LPTS increased.

For the wool fabric, 2HG5 was selected during stepwise regression and 2HG5-2HG (0.665) exhibited a medium-to-high-level correlation. The average values of G and 2HG5 for the wool fabric from the first to the fourth classifications were 0.484, 0.500, 0.593 and 0.645 (***Figure 11***), and 0.840, 0.953, 1.145 and 1.544 (***Figure 12***), respectively. This showed that the G and 2HG5 values of the wool fabric both decreased as the fabric's LPTS increased.

The key mechanical parameters selected for the cotton fabric were W and bending properties, which directly correlated to LPTS. Thus it can be said that the frictional sound of the cotton fabric was correlated to its bending properties.

For the linen fabric, the key mechanical parameters selected were the tensile properties, which decreased as the linen fabric's LPTS increased, confirming the correlation between tensile properties and linen fabric frictional sound. In the case of the silk fabric, bending and compressional properties were correlated with its frictional sound, whereas for the wool fabric, the key mechanical parameters selected were shear properties, which increased as the fabric's LPTS increased, confirming correlation between its shear properties and its frictional sound.

The correlations found between frictional sound and mechanical properties for the different fabrics can therefore be summarised as follows: cotton – frictional sound was correlated to its bending

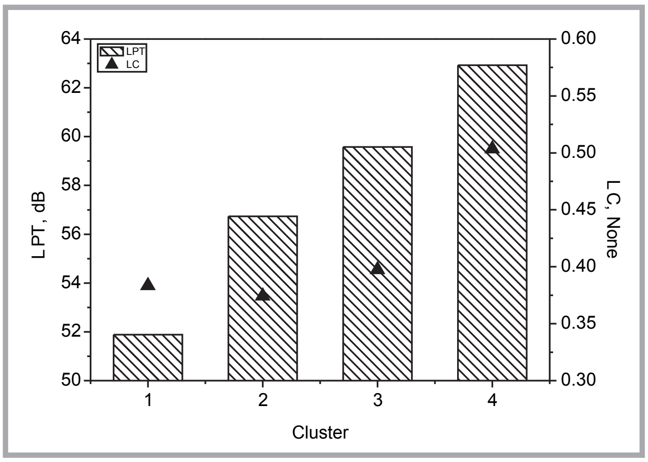

Figure 10. *Comparison of compressional linearity (LC) and LPTS of silk fabric in four clusters.*

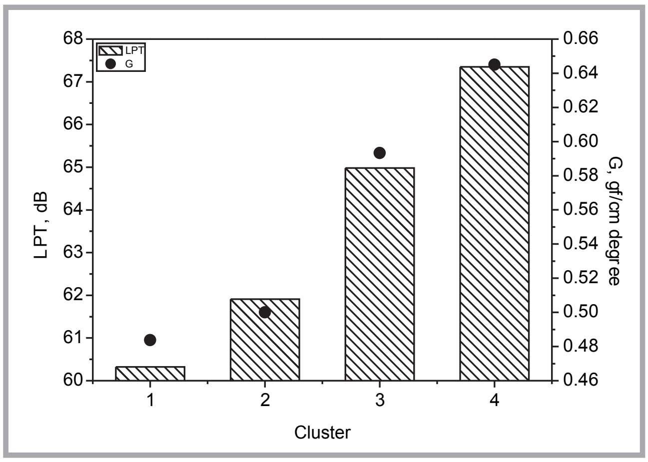

Figure 11. *Comparison of shear rigidity (G) and LPTS of wool fabric in four clusters.*

properties, linen – frictional sound was correlated to its tensile properties, silk – frictional sound was correlated to bending and compressional properties, wool – frictional sound was correlated to shear properties

Conclusions

This paper mainly describes the frictional sound generated by various composite materials and synthetic fibres. Four types of commercially available natural fibre woven fabrics were chosen for this study.

1. A newly-designed fabric frictional sound testing device and analysis system was used enabling the capture of frictional sound spectra and their analysis to determine LPTS and AR values for each fabric type.
2. The key mechanical parameters affecting fabric frictional sound for the four natural fibre woven fabrics were not the same for each fabric type; the parameters that influenced LPTS values for the fabrics were as follows: cotton – fabric weight and bending hysteresis (W and 2HB), linen – tensile energy (WT), silk – tensile resilience (RT), and wool – shear hysteresis at a 5° shear angle (2HG5).
3. The ARC values of the four types of fabric increased as the fabric's LPTS increased. The fabric's LPTS increased as the B and W properties of the cotton fabric increased. While, in the case of the linen fabric as the LT decreased, as the B and LC properties of the silk fabric decreased and increased respectively whereas for the wool fabric, as the G properties decreased.

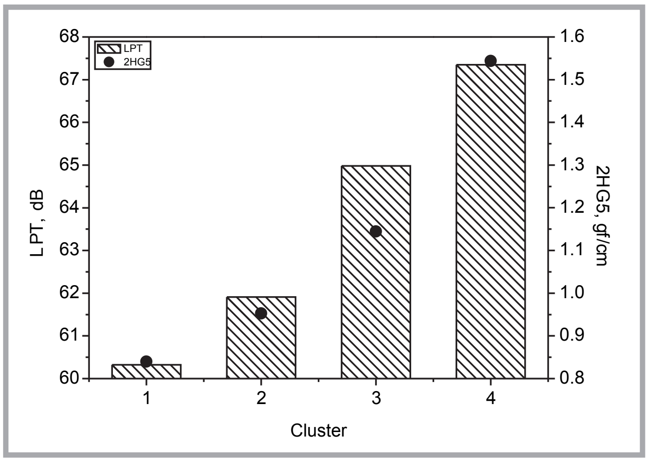

Figure 12. *Comparison of shear hysteresis at ø =5° (2HG5) and LPTS of wool fabric in four clusters.*

4. Frictional sound properties of woven fabrics can be used to analyse counterfeit goods and can also be applied in music used.

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