Dokuz Eylül Üniversitesi Mühendislik Fakültesi Fen ve Mühendislik Dergisi
Dokuz Eylul University Faculty of Engineering Journal of Science and Engineering
Elektronik/Online ISSN: 2547-958X

RESEARCH ARTICLE / ARAŞTIRMA MAKALESI

Determining Deformation and Recovery Characteristics of Woven Fabrics Using A Novel Instrument

Dokuma Kumaşların Deformasyon ve Geri Dönüş Özelliklerinin Yeni Bir Cihaz Kullanılarak Belirlenmesi

Nazlı Üren

Dokuz Eylül Üniversity, Faculty of Engineering, Department of Textile Engineering, İzmir, TÜRKİYE
Corresponding Author / Sorumlu Yazar: nazli.uren@deu.edu.tr

Abstract

Deformation and recovery characteristics of fabrics are important factors to be considered when evaluating comfort and formability. In this study, deformation (D), elasticity (E), plasticity (P) and hysteresis (H) properties of nine woven fabrics made of cotton and its blends were measured by Tactile Sensation Analyzer (TSA), and the relations between obtained results and low-stress mechanical properties (compressibility, bending rigidity, extensibility, shear resistance), structural properties (mass per unit area, thread count) and formability were investigated. Parameters which indicate the magnitude of out-of-plane deformation (D and E) were found out to be strongly related to bending, shear and extension properties. Recovery characteristics of fabrics - plasticity and hysteresis - were observed to be highly related to bending length and extensibility recorded under 5 N/m load. Moreover, parameters P and H were noted to be moderatly related to mass per unit area, thread count and resistance to repeated shear deformation. In addition to these findings, formability of cotton blended woven fabrics was detected to be significantly corelated with deformation and elasticity parameters measured by TSA.

Keywords: *Tactile Sensation Analyzer, out-of-plane deformation, bending rigidity, shear deformation, tactile comfort, formability*

Öz

Kumaşların deformasyon ve geri dönüş özellikleri, konfor ve şekil alabilirliğin değerlendirilmesi esnasında dikkate alınması gereken önemli faktörlerdir. Bu çalışmada, pamuk ve karışımlarından elde edilmiş dokuz adet dokuma kumaşın deformasyon (D), elastisite (E), plastisite (P) ve histeresiz (H) özellikleri Tactile Sensation Analyzer (TSA) ile ölçülmüş ve elde edilen sonuçlar ile düşük-yük mekanik özellikler (sıkıştırılabilirlik, eğilme direnci, uzama yeteneği, kayma direnci), yapısal özellikler (birim alan kütlesi ve iplik sıklığı) ve şekil alabilirlik arasındaki ilişkiler incelenmiştir. Yüzey-dışı deformasyonun büyüklüğünü ifade eden parametrelerin (D ve E) eğilme, kayma ve uzama özellikleri ile kuvvetle ilişkili olduğu bulunmuştur. Kumaşların geri dönüş özelliklerinin - plastisite ve histeresiz - eğilme uzunluğu ve 5 N/m yük altında kaydedilen uzama yeteneği ile yüksek ilişkili olduğu gözlemlenmiştir. Ayrıca, P ve H parametrelerinin, birim alan kütlesi, iplik sıklığı ve tekrarlanan kayma deformasyonuna gösterilen direnç ile de orta derecede ilişkili olduğu kaydedilmiştir. Bu bulgularak ek olarak, pamuk karışımlı dokuma kumaşların şekil alabilirliğinin, TSA ile ölçülen deformasyon ve elastisite parametreleri ile anlamlı korelasyon gösterdiği saptanmıştır.

Anahtar Kelimeler: *Tactile Sensation Analyzer, yüzey-dışı deformasyon, eğilme direnci, kayma deformasyonu, dokunsal konfor, şekil alabilirlik*

1. Introduction

Fabrics are subjected to different types of deformations during garment production. Low-stress mechanical properties determine the formability of a fabric and affect the appearance and comfort of the end product. Formability is the ability of a fabric to be formed into a garment, whereas tactile comfort is the sensations of stiffness and roughness which are felt as the clothing contacts and interacts with the skin. Comfort of textiles plays a crucial role in the purchasing decision of individuals and formability determines the overall look and sewing performance of fabrics such as inclination to seam puckering, needle damage, distortion and overfeeding [1-3].

Formability and tactile comfort are both known to be related to low-stress mechanical properties which can be listed as bending rigidity, extensibility, shear rigidity and compressibility [3-8]. Kawabata Evaluation System (KES-F) and Fabric Assurance by Simple Testing (FAST) are measurement systems which are commonly used to determine the low-stress mechanical properties of woven fabrics [9-13]. Zhang et al. [14] proposed a device which measures the force needed to pull a fabric through parallel pins and stated that the results given by this device were significantly correlated with bending rigidity, thickness, formability and extensibility. Nozzle test is another method where the force required to pull a fabric sample through a ring is

DOI:10.21205/deufmd.2024267611
Atıf şekli / How to cite:
Uren, N. (2024). Determining deformation and recovery characteristics of woven fabrics using a novel instrument. DEUFMD, 26(76), 90-97.

Geliş Tarihi / Received: 30.12.2022
Kabul Tarihi / Accepted: 13.07.2023

recorded [15-17]. Uren and Okur [18] reported that the pulling forces recorded during nozzle test were related to bending rigidity, shear rigidity and extensibility. These properties can also be measured using standard test methods and equipment [19].

Shear rigidity can be determined by biaxial extension test or shear frame test. Shear frame can produce a near-uniform shear deformation state. Therefore, it is commonly preferred by researchers for characterizing in-plane shear behavior of fabrics [20,21].

Tissue Softness Analyzer is an instrument that simulates the sensory properties of the human hand when touching tissue paper products. The device measures micro-surface variations, macro-surface variations and stiffness of any kind of tissue paper [22-24]. Kim et al. [25] proposed a study in which macro and micro-surface variations (TS750 and TS7) of a large set of fabrics were measured by Tissue Softness Analyzer and the data was used for clustering and classification of textiles.

Tactile Sensation Analyzer (TSA) is a novel instrument developed to evaluate hand related properties of various textile products. The device has a working principle similar to Tissue Softness Analyzer. TSA determines surface variations, deformation behavior and recovery characteristics of textiles by two simple measurement steps which are carried out with a single desktop unit. The sound analysis provides information about macro and micro-surface variations (TS750 and TS7) of the fabric surface, while deformation (D), elasticity (E), hysteresis (H) and plasticity (P) properties are measured in the deformation test stage.

The aim of this study was to carry out an in-depth analysis of out-of-plane deformation behavior of cotton blended woven fabrics. For this purpose, deformation, elasticity, hysteresis and plasticity of the fabrics were measured by TSA and their relations with several structural and low-stress mechanical properties were investigated. To ensure a comprehensive evaluation, bending properties in diagonal directions, extensibility under five different loads and shear resistance of fresh and previously deformed samples at three different shear angles were determined. Relations between TSA results and fabric formability were also discussed.

2. Materials and Methods

2.1. Material

In the current study, nine woven fabrics made of cotton and its blends with polyester, lyocell, viscose and bamboo were procured. The fabrics within a comparable unit weight, thickness and raw material range were selected for the study (Table 1). Samples were white, undyed fabrics with no print or pattern. The samples were conditioned before measurements as prescribed in ASTM D1776/D1776M-20. All measurements were carried out at standard atmospheric conditions. No additional treatment was applied to the fabrics.

2.2. Method

Deformation and recovery properties of fabrics were determined by TSA and compressibility, extensibility, bending rigidity, and shear resistance of fabrics were measured by independent laboratory tests. Abbreviations used in the current study are given in Table 2.

2.2.1 Compressibility

Neutral thickness (T5) and compressed thickness (T50) of fabrics were measured under 5 gf/cm^2 and 50 gf/cm^2 pressures, respectively. For the measurements, James Heal R&B Cloth Thickness Tester, having a circular presser foot with 100 mm^2 size was used. Compressibility (C) of fabrics was calculated using equation 1. For each fabric type, five trials were done.

$$C = \frac{T5 - T50}{T5} \times 100\ (\%) \qquad (1)$$

2.2.2 Bending rigidity

Bending length (BL) and bending rigidity (BR) of samples were determined as prescribed in ASTM D1388-18 Option A, using a cantilever stiffness measurement equipment. In addition to the measurements realized in warp and weft directions, bending properties in diagonal directions (-45° and +45°) were determined as well (Figure 1). Four trials were done for each test direction.

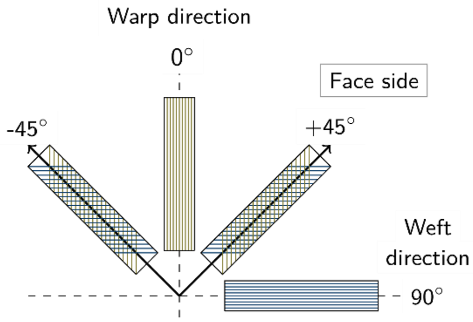

Figure 1. Sample orientation

2.2.3 Extensibility

Extensibility of fabrics was determined using Instron 4411 Universal Tensile Tester. For the measurements, rectangular samples (200 mm x 50 mm) were prepared in warp and weft directions. The distance between clamps was 100 mm and the test speed was 20 mm/min. No pre-tension was applied to the samples. Percent elongation values recorded under 5 N/m, 20 N/m, 50 N/m, 100 N/m and 400 N/m loads were presented as EU5, EU20, EU50, EU100 and EU400, respectively. Five measurements were realized for each test direction.

2.2.4 Resistance to shear

Shear frame test can produce a near-uniform shear deformation state. Therefore, it is proposed as the most standardized test method for characterizing in-plane shear behavior of fabrics [20,21]. In the current study, in-plane shear behavior of fabrics was determined using the shear frame apparatus designed by Uren et al. [21]. The frame and sample dimensions are given in Figure 2.

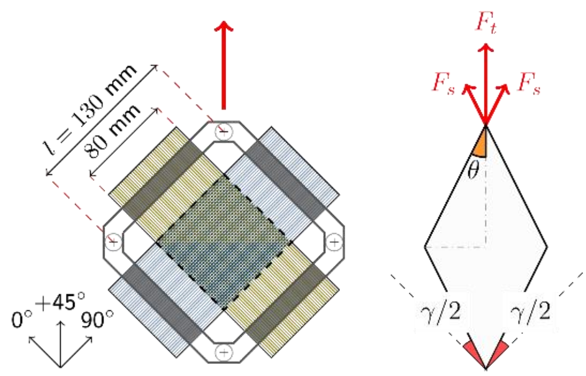

Figure 2. Graphical representation of shear frame, test sample and shear geometry

Table 1. Structural properties of fabrics.

Fabric code	Material	Weave pattern	Warp setting	Weft setting	Warp linear density	Weft linear density	Unit weight
	(%)		*(cm-1)*	*(cm-1)*	*(tex)*	*(tex)*	*(g/m2)*
C1	Cotton	Plain	33.0	24.0	20	18	118
C2	Cotton	Plain	33.0	21.0	19	19	112
C3	Cotton	Plain	41.5	32.0	15	15	117
CL1	Cotton / Lyocell (85/15)	Plain	45.0	33.0	15	16	130
CL2	Cotton / Lyocell (60/40)	Sateen	78.0	47.0	10	10	128
CV	Cotton / Viscose (50/50)	Twill	27.0	36.5	22	19	140
CB	Cotton / Bamboo (30/70)	Plain	36.0	28.5	20	22	148
CP1	Cotton / Polyester (48/52)	Plain	24.0	15.0	20	30	97
CP2	Cotton / Polyester (63/37)	Plain	30.5	23.0	12	28	105

Table 2. Abbreviations used for the studied parameters.

Abbreviation	Unit	Description	Test direction*
W	g/m2	Mass per unit area - ASTM D3776/D3776M-20	.
TC	Inch-2	Thread count - ASTM D3775-17e1	.
T5	mm	Thickness under 5 gf/cm2 pressure	.
T50	mm	Thickness under 50 gf/cm2 pressure	.
C	%	Compressibility (Equation 1)	.
EU5	%	Extensibility under 5 N/m load	0, 90
EU20	%	Extensibility under 20 N/m load	0, 90
EU50	%	Extensibility under 50 N/m load	0, 90
EU100	%	Extensibility under 100 N/m load	0, 90
EU400	%	Extensibility under 400 N/m load	0, 90
S.A6	cN	Shear force at 6.4° shear angle, fresh sample (Equations 2 and 3)	-45, +45
S.A13	cN	Shear force at 13.3° shear angle, fresh sample (Equations 2 and 3)	-45, +45
S.A21	cN	Shear force at 20.7° shear angle, fresh sample (Equations 2 and 3)	-45, +45
S2.A6	cN	Shear force at 6.4° shear angle, deformed sample (Equations 2 and 3)	-45, +45
S2.A13	cN	Shear force at 13.3° shear angle, deformed sample (Equations 2 and 3)	-45, +45
S2.A21	cN	Shear force at 20.7° shear angle, deformed sample (Equations 2 and 3)	-45, +45
BL	mm	Bending length - ASTM D1388-18	0, 90, -45, +45
BR	µJ/m	Bending rigidity - ASTM D1388-18	0, 90, -45, +45
D	mm/N	Deformation (measured by TSA)	.
E	mm/N	Elasticity (measured by TSA)	.
P	µm	Plasticity (measured by TSA) (absolute values)	.
H	J	Hysteresis (measured by TSA)	.
F	µJ/m.%	Formability (Equation 4)	.

*Warp (0°), weft (90°) and diagonal (-45° and +45°) directions.

Shear angle (γ) was calculated using equation 2, where d is the displacement recorded by the tensile testing machine, and l is the length of one dimension of the shear frame.

$$\gamma = \frac{\pi}{2} - 2\cos^{-1}\left(\frac{1}{\sqrt{2}} + \frac{d}{2l}\right) \tag{2}$$

Shear force (F_s) was calculated using equation 3, where F_t is the load recorded by the tensile testing machine during shear deformation (Figure 2).

$$F_s = \frac{F_t}{2\cos\left(\frac{\pi}{4} - \frac{\gamma}{2}\right)} \tag{3}$$

For the measurements, the sample was fixed to the frame and deformed until a maximum shear angle of 69.5° was reached (Figure 3). The shear forces required to create 6.4°, 13.3° and 20.7° shear angles on a fresh test sample were recorded and given as S.A6, S.A13 and S.A21 respectively. When the first cycle of shear deformation was completed, the frame and the sample were returned to their initial position and the test was repeated with the deformed sample. The shear force required to re-deform the previously deformed sample was recorded for 6.4°, 13.3° and 20.7° shear angles (S2.A6, S2.A13 and S2.A21 respectively). Five shear frame samples were tested for each direction (-45° and +45°). Pre-tension was equal to zero and the test speed was 20 mm/min.

2.2.5 Formability

Fabric formability depends on bending and extension properties in case of small loads [26]. In this regard, formability can be calculated by equation 4, which was previously proposed by Lindberg et al. [27].

$$F = BR \times \frac{EU20 - EU5}{14.7} \tag{4}$$

In the current study, formability (F) values of fabrics were calculated using equation 4, based on average of bending rigidity values measured in warp, weft and diagonal directions (BR) and average extensibilities recorded under 5 N/m and 20 N/m loads (EU5 and EU20).

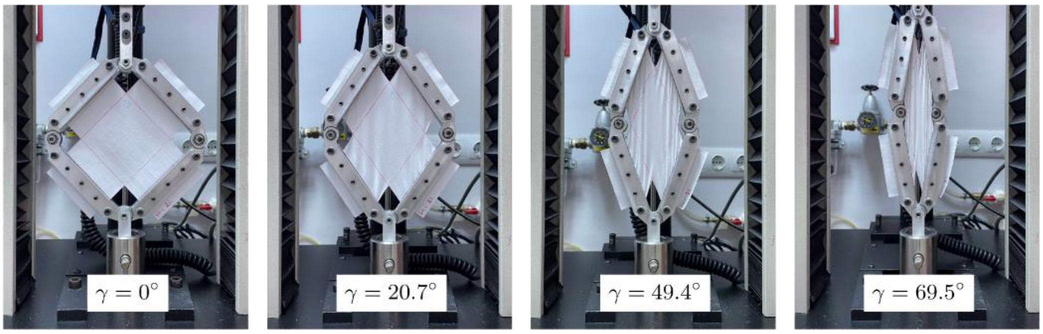

Figure 3. Shear deformations observed on the test sample at different shear angles (γ)

2.2.6 Tactile Sensation Analyzer

Tactile Sensation Analyzer (TSA) is a multifunctional measuring instrument developed by the German company emtec Electronic GmbH (Figure 4). The device can determine surface variations and several mechanical properties of textiles.

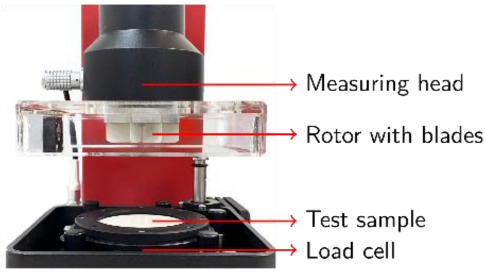

Figure 4. Tactile Sensation Analyzer

Deformation (D), elasticity (E), plasticity (P) and hysteresis (H) can be measured by TSA in deformation test stage. For the measurements, the test sample is fixed to a circular frame. When the deformation test starts, the measuring head moves down, and the blades contact with the sample surface with a load of 100 mN. As the measuring head moves further down, the load applied to the sample increases from 100 mN to 600 mN. This vertical motion of the measuring head causes the out-of-plane deformation (D) (Figure 5).

When the measuring head moves up, the recovery parameters are measured. One of these parameters is hysteresis (H) which indicates the energy generated during recovery. The other parameter related with recovery characteristics is plasticity (P). Plasticity is the magnitude of permanent deformation recorded when the load applied to the sample decreases from 600 mN to 100 mN. P represents the ability of a material to undergo a non-reversible change of shape in response to an applied force. Therefore, a P value closer to zero indicates a very good recovery, thus a very poor plasticity. It must be noted that in the current study, absolute values of P were used.

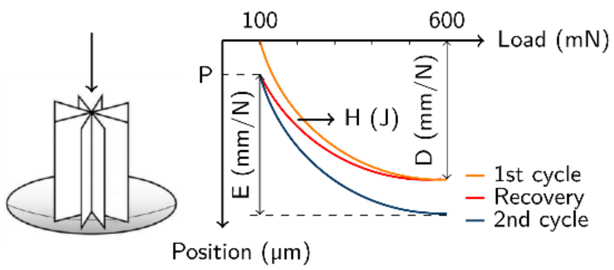

Figure 5. Graphical representation of deformation and recovery parameters measured by Tactile Sensation Analyzer; deformation (D), elasticity (E), plasticity (P) and hysteresis (H)

In the final stage of deformation test, a load of 600 mN is applied to the previously deformed sample, and the displacement of measuring head is recorded as elasticity (E). The measurement process of parameter E is identical with parameter D. The only difference is that E is measured with the deformed sample.

In this study, five samples (120 mm x 120 mm) were measured with TSA for each fabric type. The specimen was placed on the frame face side up.

2.3 Statistical analysis

Correlation relations were investigated by Spearman's rank-order correlation analysis, using SPSS 25.0 statistical software. The significant relations observed at 90%, 95% and 99% confidence levels were reported.

3. Results

3.1. Deformation

Deformation (D) parameter measured by TSA indicates the magnitude of out-of-plane deformation of a fresh sample under a certain load. Deformation (D) values of fabrics measured in the current study were between 1.6 and 2.4 mm/N (Figure 6). Results pointed that cotton/viscose and cotton/bamboo blend samples (CV and CB) have higher D values. On the contrary, lower D values were recorded for cotton/polyester blend samples (CP1 and CP2).

D was found out to be inversely proportional to bending length (BL) and bending rigidity (BR) in general (Table 3). In fact, the correlation relation calculated between parameter D and average bending length (average of warp and weft directions) was the highest among all relations calculated for that parameter. D values were more related to BL rather than BR. This finding was attributed to the direct proportional relation observed between D and mass per unit area (W) (Figure 6).

The second strongest correlation relation recorded for parameter D was with resistance to repeated shear. Results of correlation analysis indicated that parameter D was strongly related to shear resistance of previously deformed samples recorded at 13.3° shear angle (S2.A13) (Figure 7). Meanwhile, no significant relation was detected for shear properties recorded at 6.4° and 20.7° shear angles.

The magnitude of out-of-plane deformation (D) of a fresh sample was observed to be strongly correlated with and directly proportional to extensibility, where the highest correlation coefficients were calculated for average extensibilities recorded under 20 N/m and 100 N/m loads (Table 3).

Formability of investigated fabrics was found to be significantly correlated with and directly proportional to deformation results (Figure 6).

Table 3. Spearman's correlation coefficients (r_s) calculated between parameters measured by TSA (deformation, elasticity, plasticity, hysteresis) and fabrics' structural properties, low-stress mechanical properties and formability.

Fabric properties	Symbol	Test direction	TSA Parameters			
			Deformation (D)	Elasticity (E)	Plasticity (P)	Hysteresis (H)
Deformation	D	.	1	0.950***	-0.633*	-0.717**
Elasticity	E	.	0.950***	1	-0.750**	-0.867***
Hysteresis	H	.	-0.717**	-0.867***	0.950***	1
Plasticity	P	.	-0.633*	-0.750**	1	0.950***
Mass per unit area	W	.	0.683**	0.750**	-0.683**	-0.717**
Thread count	TC	.	.	.	-0.617*	-0.683**
Formability	F		0.800***	0.650**	.	.
Bending length	BL	*warp*	-0.833***	-0.833***	.	.
	BL	*weft*	.	-0.583*	0.833***	0.767**
	BL	*average*^{w}	-0.967***	-0.950***	0.650*	0.750**
	BL	*-45*	-0.883***	-0.950***	0.667**	0.833***
	BL	*+45*	-0.828***	-0.937***	0.669**	0.837***
	BL	*average*^{d}	-0.850***	-0.950***	0.717**	0.867***
	BL	*average*^{a}	-0.900***	-0.983***	0.817***	0.917***
Bending rigidity	BR	*warp*	-0.733**	-0.650*	.	.
	BR	*weft*	.	.	0.600*	.
	BR	*average*^{w}	-0.767**	-0.767**	.	.
	BR	*-45*	-0.850***	-0.867***	0.683**	0.783**
	BR	*+45*	-0.700**	-0.817***	.	0.683**
	BR	*average*^{d}	-0.717**	-0.833***	.	0.717**
	BR	*average*^{a}	-0.800***	-0.817***	.	0.583*
Shear force	S2.A6	*-45*	.	.	.	.
	S2.A6	*+45*	.	.	0.650*	0.650*
	S2.A6	*average*	.	.	.	.
	S2.A13	*-45*	.	-0.610*	0.865***	0.763**
	S2.A13	*+45*	-0.917***	-0.933***	0.600*	0.750**
	S2.A13	*average*	-0.950***	-0.950***	0.667**	0.783**
	S2.A21	*-45*	.	.	.	0.600*
	S2.A21	*+45*	.	.	.	.
	S2.A21	*average*	.	.	.	.
Extensibility	EU5	*warp*	.	.	.	.
	EU5	*weft*	0.583*	0.633*	-0.817***	-0.750**
	EU5	*average*	0.850***	0.900***	-0.833***	-0.867***
	EU20	*warp*	0.767**	0.650*	.	.
	EU20	*weft*	0.717**	0.667**	-0.750**	-0.667**
	EU20	*average*	0.933***	0.850***	-0.617*	-0.650*
	EU50	*warp*	0.767**	0.650*	.	.
	EU50	*weft*	0.683**	0.600*	-0.633*	.
	EU50	*average*	0.917***	0.800***	.	.
	EU100	*warp*	0.733**	0.633*	.	.
	EU100	*weft*	0.683**	0.600*	-0.633*	.
	EU100	*average*	0.933***	0.817***	.	.
	EU400	*warp*	0.733**	0.633*	.	.
	EU400	*weft*	.	.	-0.817***	-0.700**
	EU400	*average*	0.867***	0.783**	.	.

Correlation is significant at the 0.10 level (*), 0.05 level (**) and 0.01 level (***), (2-tailed).
Shear forces recorded with deformed samples at 6.4° (S2.A6), 13.3° (S2.A13) and 20.7° (S2.A21) shear angles.
Extensions recorded under 5 N/m (EU5), 20 N/m (EU20), 50 N/m (EU50), 100 N/m (EU100) and 400 N/m (EU400) loads.
Average values calculated for warp and weft directions (^{w}), diagonal directions (^{d}) and all test directions (^{a}).

3.2. Elasticity

Elasticity (E) parameter given by TSA describes the magnitude of out-of-plane deformation of a previously deformed sample. The differences between out-of-plane deformations recorded with fresh and deformed samples (D and E) were lower than 8% - except polyester blended samples (Figures 6 and 7).

E values were observed to be significantly correlated with bending length and rigidity and the highest correlation coefficient calculated for E was with bending length. Magnitude of out-of-plane deformation of previously deformed samples (E) was strongly related to average BL measured in multiple test directions (warp, weft, and diagonal) whereas results of fresh samples (D) were more related to average BL measured in warp and weft directions.

The relation between E and shear properties was almost identical to parameter D, where E was found out to be significantly correlated with resistance to repeated shear deformation, recorded at 13.3° shear angle (Table 3). No correlation relation was detected for 6.4° and 20.7° shear angles.

Elasticity (E) was found to be significantly correlated with extensibility results measured under various loads (Table 3). It was observed that parameter E was more related to extensibility under 5 N/m load. On the other hand, D was more related to extensibilities recorded under 20, 50 and 100 N/m loads.

Results of the study indicated that E was directly proportional to mass per unit area and formability, yet the relation between formability and E was less significant when compared to D.

3.3. Plasticity

Plasticity (P) defines the magnitude of permanent deformation. Plasticity of cotton blended woven fabrics investigated in the current study was found out to be between 69.7 and 181.2 µm (Figure 8), where P was highly correlated with bending length and extensibility under low loads (Table 3).

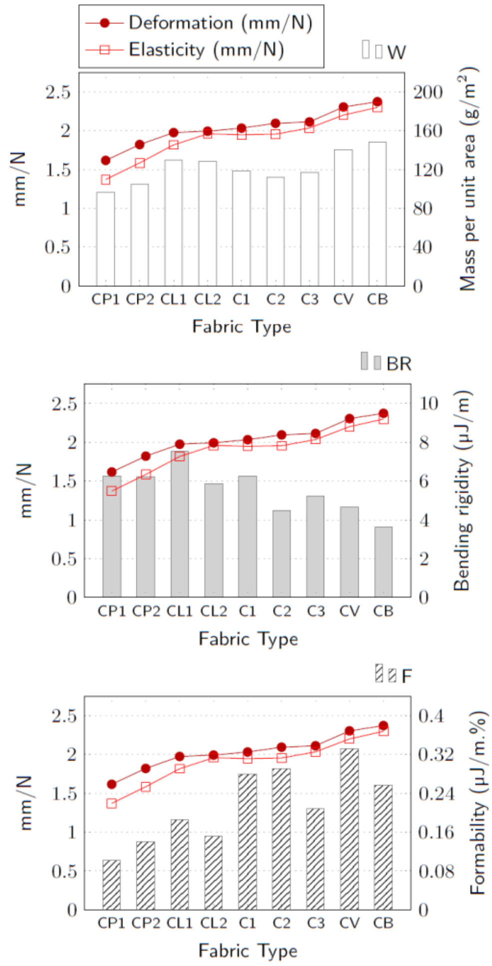

Figure 6. Deformation (D) and elasticity (E) results of investigated fabrics and their relations with mass per unit area (W), average bending rigidity (warp, weft, and diagonal directions) (BR) and formability (F)

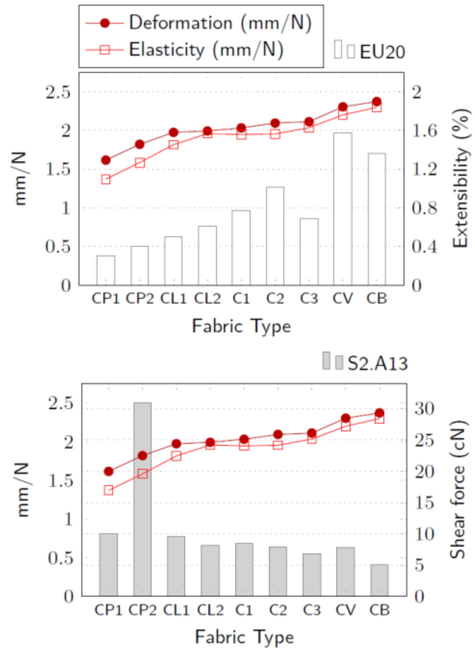

Figure 7. Deformation (D) and elasticity (E) results of investigated fabrics and their relations with average extensibility measured under 20 N/m load (EU20) and average shear force measured with deformed samples at 13.3° shear angle (S2.A13)

Magnitude of permanent deformation was moderately related to resistance to repeated shear recorded at 13.3° shear angle (S2.A13). However, a strong correlation relation was detected for -45° test direction (Table 3). It was observed that sample CP2, which exhibited the highest resistance to repeated shear, has the largest permanent deformation result (Figure 8).

It was observed that polyester blended cotton fabrics (CP1 and CP2) have a higher plasticity. Meanwhile, the sample with the highest thread count (CL2) and the samples with cotton/viscose

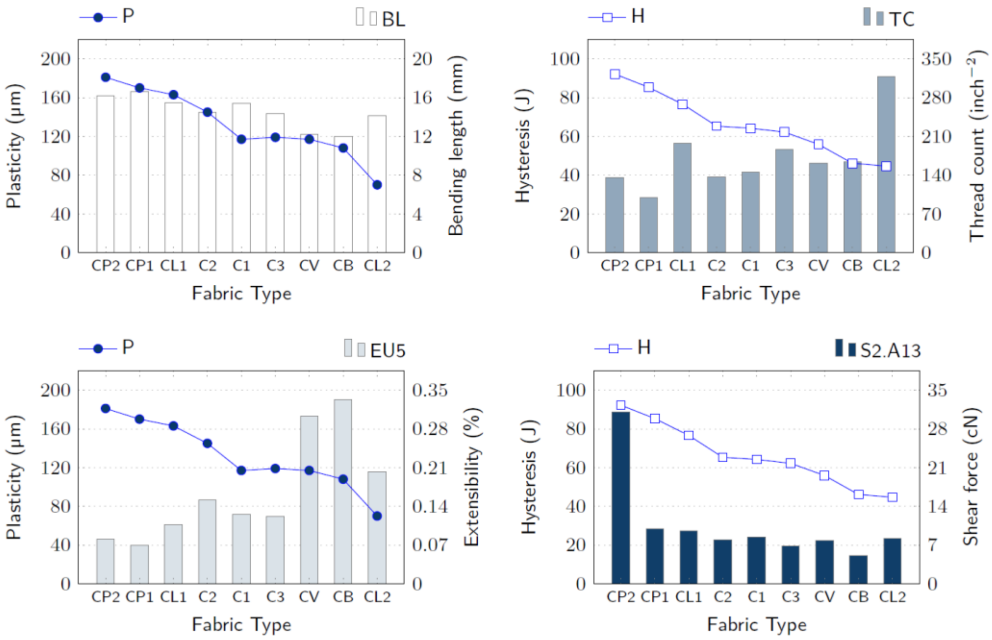

Figure 8. Plasticity (P) and hysteresis (H) results of investigated fabrics and their relations with average bending length (warp, weft, and diagonal directions) (BL), average extensibility measured under 5 N/m load (EU5), thread count (TC) and average shear force measured with deformed samples at 13.3° shear angle (S2.A13)

and cotton/bamboo blends (CV and CB) - which have the highest unit weights - occurred to have lower plasticity values (Figure 8). Statistical calculations verified that plasticity of investigated fabrics was inversely proportional to mass per unit area and thread count (Table 3).

3.4. Hysteresis

Hysteresis (H) is a parameter measured by TSA, which represents the energy generated during recovery. Hysteresis values of investigated fabrics were between 44.7 and 92.2 J (Figure 8). It was observed that polyester blended samples CP1 and CP2 have higher recovery energies and larger magnitudes of permanent deformation.

Hysteresis was found out to be inversely proportional to extensibility, mass per unit area and thread count, and directly proportional to bending rigidity and resistance to repeated shear deformation (Table3).

Recovery parameters P and H were strongly related to extensibility under 5 N/m load (EU5) and moderately related to extensibility under 20 N/m load (EU20). P and H were prominently correlated with bending length and less related to bending rigidity. The relations between shear behavior and recovery parameters were also slightly lower when compared to deformation parameters D and E.

4. Conclusions

Deformation and recovery properties of textiles are important parameters, which determine several qualities including formability and tactile comfort. In this study, deformation (D), elasticity (E), plasticity (P) and hysteresis (H) properties of cotton blended woven fabrics were measured by Tactile Sensation Analyzer (TSA) which is a novel instrument.

The parameters which represent out-of-plane deformation (D and E) were highly correlated with bending properties. It was observed that deformation (D) and elasticity (E) were more related to bending length than bending rigidity.

The second most related fabric property with parameters D and E was shear behavior. D and E were found to be specifically correlated with shear resistance recorded with deformed samples at 13.3° shear angle (S2.A13). No other significant relation was detected between these parameters and shear properties.

Extensibility was determined to be the 3rd most related property to parameters D and E. While out-of-plane deformation of fresh samples (D) was more related to extension values recorded under 20, 50 and 100 N/m loads, results of previously deformed samples (E) were observed to be more related to extensibility recorded under 5 N/m load.

Recovery properties - plasticity (P) and hysteresis (H) - of investigated fabrics were found out to be strongly related to bending length and extensibility recorded under 5 N/m load. Plasticity and hysteresis were also related to shear resistance, but this relation was less significant when compared to D and E.

Results indicated that bending properties calculated as average of warp, weft and diagonal directions represents deformation and recovery properties more successfully. In this respect, it was concluded that including diagonal samples in bending measurements can provide a better understanding of out-of-plane deformation characteristics.

It was observed that two diagonal directions (-45° and +45°) of the same fabric may exhibit different deformation behaviors - especially during shear. Therefore, it was suggested to include both diagonal directions in the measurements to obtain more accurate results.

Findings of the study pointed that production parameters of fabrics may define deformation and recovery characteristics. It was found out that parameters D, E, P and H were significantly correlated with mass per unit area, meanwhile recovery properties (P and H) were also moderately correlated with thread count.

Formability is an important parameter that determines the performance of the sewing process, as well as the appearance and quality of the final product. The findings obtained in the study revealed that parameters D and E were significantly related to formability.

In the current study, a novel test instrument was introduced, and the components of deformation and recovery properties of cotton blended woven fabrics recorded under out-of-plane deformation conditions were discussed. Statistical findings indicated that out-of-plane deformation of textiles is a complex phenomenon, where a series of fabric properties are effective on different levels. It is believed that the test results presented in the study could provide valuable data for future studies, and the established correlation relations would be a useful guide for understanding the nature of out-of-plane deformation of fabrics.

Ethics committee approval and conflict of interest statement

This article does not require ethics committee approval. This article has no conflicts of interest with any individual or institution.

Acknowledgment

The authors would like to thank to emtec Electronic GmbH for their cooperation in this study. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

[1] Hui, C-L., Ng, S-F. 2005. A New Approach for Prediction of Sewing Performance of Fabrics in Apparel Manufacturing Using Artificial Neural Networks, The Journal of the Textile Institute, Volume. 96, Issue. 6, 401-405. DOI: 10.1533/joti.2005.0101

[2] Giorgio Minazio, P. 1998. The Fabric Pressing Performance and its Role in Predicting the Appearance of Men's Wool Suit Jackets, International Journal of Clothing Science and Technology, Volume. 10, Issue. 3/4, 182-190. DOI: 10.1108/09556229810693609

[3] Mousazadegan, F., Ezazshahabi, N., Latifi, M., Saharkhiz, S. 2013. Formability Analysis of Worsted Woven Fabrics Considering Fabric Direction, Fibers and Polymers, Volume. 14, Issue. 11, 1933–1942. DOI: 10.1007/s12221-013-1933-2

[4] Liao, X., Hu, J., Li, Y., Li, Q., Wu, X. 2011. A Review on Fabric Smoothness-Roughness Sensation Studies, Journal of Fiber Bioengineering and Informatics, Volume. 4, Issue. 2, 105–114. DOI: 10.3993/jfbi06201101

[5] Ciesielska-Wróbel, I. L., van Langenhove, L. 2012. The Hand of Textiles – Definitions, Achievements, Perspectives – A Review, Textile Research Journal, Volume. 82, Issue. 14, 1457–1468. DOI: 10.1177/0040517512438126

[6] Sztandera, L. M., Cardello, A. V., Winterhalter, C., Schutz, H. 2013. Identification of The Most Significant Comfort Factors for Textiles From Processing Mechanical, Handfeel, Fabric Construction, and Perceived Tactile Comfort Data, Textile Research Journal, Volume. 83, Issue. 1, 34–43. DOI: 10.1177/0040517512438121

[7] Mahar, T., Wang, H., Postle, R. 2013. A Review of Fabric Tactile Properties and Their Subjective Assessment for Next-To-Skin Knitted Fabrics, Journal of the Textile Institute, Volume. 104, Issue. 6, 572–589. DOI: 10.1080/00405000.2013.774947

[8] Mahar, T.J., Dhingra, R.C. Postle, R. 1989. Fabric Mechanical and Physical Properties Relevant to Clothing Manufacture - Part 1: Fabric Overfeed, Formability, Shear and Hygral Expansion During Tailoring, International Journal of Clothing Science and Technology, Volume. 1, Issue. 1, 12-20. DOI: 10.1108/eb002941

[9] Kawabata, S. 1980. The Standardization and Analysis of Hand Evaluation. 2nd edition. The Textile Machinery Society of Japan, Osaka, Japan.

[10] Xue, Z., Zeng, X., Koehl, L. 2018. An Intelligent Method for The Evaluation and Prediction of Fabric Formability for Men's Suits, Textile Research Journal, Volume. 88, Issue. 4, 438-452. DOI: 10.1177/0040517516681956

[11] Kim, HA., Kim, SJ. 2011. Seam Pucker and Formability of the Worsted Fabrics, Fibers and Polymers, Volume. 12, Issue. 8, pp. 1099-1105. DOI: 10.1007/s12221-011-1099-8

[12] Fan, J., Ng, YN. 2001. Objective Evaluation of the Hand of Nonwoven Fusible Interlining, Textile Research Journal, Volume. 71, Issue. 8, 661-666. DOI: 10.1177/004051750107100802

[13] Tadesse, MG., Nagy, L., Nierstrasz, V., Loghin, C., Chen, Y., Wang, L. 2018. Low-Stress Mechanical Property Study of Various Functional Fabrics for Tactile Property Evaluation, Materials, Volume. 11, Issue. 12, 2466. DOI: 10.3390ma11122466

[14] Zhang, P., Liu, X., Wang, L., Wang, X. 2006. An experimental study on fabric softness evaluation. International Journal of Clothing Science and Technology, Volume. 18, Issue. 2, 83-95. DOI: 10.1108/09556220610645748

[15] Kim, J. O., Slaten, B. L. 1999. Objective Evaluation of Fabric Hand. Textile Research Journal, Volume. 69, Issue. 1, 59-67. DOI: 10.1177/004051759906900110

[16] El Mogahzy, Y.E., Kilinc, F. S., Hassan, M. 2005. Developments in Measurement and Evaluation of Fabric Hand, In Effect of Mechanical and Physical Properties on Fabric Hand, Woodhead Publishing, Cambridge, UK.

[17] Strazdiene, E., Martisi[ubar]te, G., Gutauskas, M., Papreckiene, L. 2003. Textile Hand: A New Method for Textile Objective Evaluation, Journal of the Textile Institute, Volume. 94, Issue. 3–4, 245–255. DOI: 10.1080/00405000308630613

[18] Uren, N., Okur, A. 2019. Analysis and Improvement of Tactile Comfort and Low-Stress Mechanical Properties of Denim Fabrics, Textile Research Journal, Volume. 89, Issue. 23–24, 4842-4857. DOI: 10.1177/0040517519840634

[19] Hu, J. Y., Li, Y. I., Yeung, K. W. 2006. Mechanical Tactile Properties, In Clothing Biosensory Engineering, Woodhead Publishing, Boca Raton, FL, USA. DOI: 10.1533/9781845691462.261

[20] El Abed, B., Msahli, S., Bel Hadj Salah, H., Sakli, F. 2011. Study of Woven Fabric Shear Behaviour, Journal of the Textile Institute, Volume. 102, Issue. 4, 322-331. DOI: 10.1080/00405001003771226

[21] Uren, N., Oner, E., Okur, A. 2016. A Novel Approach for Precise Determination of In-Plane Shear Behavior of Woven Fabrics, Textile Research Journal, Volume. 87, Issue. 11, 1335–1348. DOI: 10.1177/0040517516652346

[22] Hoefer, D., Handel, M., Müller, K.M., Hammer, T.R. 2016. Electroencephalographic Study Showing That Tactile Stimulation by Fabrics of Different Qualities Elicit Graded Event-Related Potentials. Skin Research and Technology, Volume. 22, Issue. 4, 470-478. DOI: 10.1111/srt.12288

[23] Wang, Y., De Assis, T., Zambrano, F., Pal, L., Venditti, R. A., Dasmohapatra, S., Pawlak, J., Gonzalez, R. 2019. Relationship Between Human Perception of Softness and Instrument Measurements. BioResources, Volume. 14, Issue. 1, 780-795.

[24] Wang, Y., Venditti, R.A., Gonzalez, R., Pawlak, J.J. 2020. Sheet Structural and Mechanical Properties and Their Relationship to Tissue Softness. Progress in Paper Physics Seminar, September 1-3, Jyvaskyl, Finland, 257-262.

[25] Kim, H.J., Youn, S., Choi, J., Kim, H., Shim, M., Yun, C. 2021. Indexing Surface Smoothness and Fiber Softness by Sound Frequency Analysis for Textile Clustering and Classification. Textile Research Journal, Volume. 91, Issue. 1-2, 200-218. DOI: 10.1177/0040517520935211

[26] Ezazshahabi, N., Mousazadegan, F., Saharkhiz, S., Latifi, M. 2015. Determining Formability Function of Worsted Woven Fabrics in Terms of Fabric Direction, Journal of Engineered Fibers and Fabrics, Volume. 10, Issue. 2, 1-10. DOI: 10.1177/155892501501000201

[27] Lindberg, J., Waesterberg, L., Svenson, R. 1960. Wool Fabrics as Garment Construction Materials, Journal of the Textile Institute Transactions, Volume. 51, Issue. 12, T1475-T1493. DOI: 10.1080/19447026008662578