

# ANALYSIS AND COMPARISON OF THICKNESS AND BENDING MEASUREMENTS FROM FABRIC TOUCH TESTER (FTT) AND STANDARD METHODS

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## Abstract:

*Fabric Touch Tester (FTT) is a relatively new device from SDL Atlas to determine touch properties of fabrics. It simultaneously measures 13 touch-related fabric physical properties in four modules that include bending and thickness measurements. This study aims to comparatively analyze the thickness and bending measurements made by the FTT and the common standard methods used in the textile industry. The results obtained with the FTT for 11 different fabrics were compared with that of standard methods. Despite the different measurement principle, a good correlation was found between the two methods used for the assessment of thickness and bending. As FTT is a new tool for textile comfort measurement and no standard yet exists, these findings are essential to determine the reliability of the measurements and how they relate to the well-established standard methods.*

## Keywords:

*fabric touch tester, thickness, bending, standard method*

## 1. Introduction

Fabric comfort is a globally discussed issue as humans are dealing with fabrics every single day. Since everyone perceives comfort differently, the result is subjective and different for each individual. Hence, many attempts have been made in order to communicate about this subject objectively, so that everyone would understand the same common language of fabric comfort. The efforts involved research to understand the way comfort is perceived,[1–3] to develop equipment for the estimation of hand related features,[4–6] and to model the skin-textile interaction.[7–9] Skin-textile interaction is important as it forms the basis of how comfort is perceived by humans.[1, 10]

A number of devices were developed to be able to objectively measure textile comfort. Amongst many research studies conducted, *Kawabata* (KES-F)[11–13] and *Fabric Assurance by Simple Testing* (SiroFAST)[13, 14] are systems that are well accepted for this purpose. However, these systems require several different testing apparatuses to measure all touch modules, and also require much time and material for testing. Hence, recently SDL Atlas has developed a new device called the fabric touch tester (FTT) in collaboration with a team of researchers from The Hong Kong Polytechnic University, which is claimed to be able to measure 13 touch indices simultaneously in less than five minutes per sample (see Figure 1). The FTT has four modules which are integrated in one single equipment and operated at the same time: compression, thermal, bending and surface module. All the indices are then computed to yield the primary hand value, which consists of smoothness, softness and warmth, total hand and total touch. Table 1 lists the indices measured in FTT.



Figure 1. Fabric touch tester

There is limited work pertaining to the use of this device as it has been introduced relatively recent in the market. The study by Hu et al. from The Hong Kong Polytechnic University using the prototype version of the FTT found that this device can be used to evaluate fundamental fabric mechanical and thermal properties. It is also able to predict fabric-skin touch sensations under non-sweating conditions like smoothness, softness, prickliness, warmth and dampness.[15] It is further reported that the stiffness measurement of FTT is significantly correlated with subjective assessment and KES.[16] In 2014, the device was improved with some refinement in indices by Liao et al.[17] They investigated the effects of thermal perceptions on the tactile perceptions and found correlations between FTT results and subjective evaluation scores. A study by the same team about psychophysical relations between various conditions of fabric thermal-tactile properties and psychological

**Table 1.** FTT indices

Item	Fabric Property	Index	Description	Unit given by FTT software	SI unit	Usual interpretations
1	Bending	BAR	Bending Average Rigidity	gf mm rad <sup>-1</sup>	N m rad <sup>-1</sup>	Force needed to bend per radian
2		BW	Bending Work	gf mm rad	N m rad	Work needed to bend the specimen
3	Surface friction	SFC	Surface Friction Coefficient	-	-	Friction coefficient on surface with ribbed metal plate
4	Surface roughness	SRA	Surface Roughness Amplitude	μ m	m	Roughness irregular wave amplitude
5		SRW	Surface Roughness Wavelength	mm	m	Roughness irregular wave wavelength
6	Compression	CW	Compression Work	gf mm	N m	Work needed to compress the specimen
7		CRR	Compression Recovery Rate	-	-	Percentage of thickness changes after compressed
8		CAR	Compression Average Rigidity	gf mm <sup>-3</sup>	N m <sup>-3</sup>	Forces needed to compress per mm
9		RAR	Recovery Average Rigidity	gf mm <sup>-3</sup>	N m <sup>-3</sup>	Forces reflected when recovery per mm
10		T	Thickness	mm	m	Thickness of the materials
11	Thermal conductivity	TCC	Thermal Conductivity under Compression	10 <sup>-3</sup> W m <sup>-1</sup> °C <sup>-1</sup>	W m <sup>-1</sup> °C <sup>-1</sup>	Energy transmitted per degree per m per second when the specimen is under compression
12		TCR	Thermal Conductivity under Recovery	10 <sup>-3</sup> W m <sup>-1</sup> °C <sup>-1</sup>	W m <sup>-1</sup> °C <sup>-1</sup>	Energy transmitted per degree per m per second when the specimen recovers
13		Qmax	Thermal Maximum Flux	W mm <sup>-2</sup>	W m <sup>-2</sup>	Maximum energy transmitted during compression

touch perceptions utilized the FTT device to obtain physical data. The results imply that both thermal and tactile physical stimuli affect the touch sensation simultaneously.[18] An on-going project named Touché, funded by the European Commission, aims to develop a set of fast, cost-effective and reliable objective test methods and improve textile skin models for the assessment of Hand of Textiles (HoT) and Fabric Feel (FF). This research project employs FTT for the objective measurements.[19]

The first property studied in this paper is thickness. It is a common physical property evaluated in many fields including textiles. In textiles, thickness can influence the comfort sensation, as it is related to heat dissipation and air permeability through fabrics.[20, 21] On the other hand, bending behavior that is the second property for this study, reflects the stiffness property of the textiles, which also influences the smoothness sensation, thus would also contribute to the overall comfort perceived by humans. It is one of the basic parameters which are decisive for sensorial comfort along with compression, elongation, dimensional stability, etc.[22,23]

This paper uses the FTT, but focuses only on thickness measurement and the bending module. We compared results

obtained from the FTT with the existing techniques as described in standard methods. The findings from this study serve as an indicator to check for the reliability and comparability of this equipment as it would determine how far the singular FTT results can be used to replace the current standard techniques to draw conclusions for thickness and bending properties.

## 2. Materials and methods

A total of 11 fabrics were prepared to be tested using FTT and standard methods. The fabrics have different fiber compositions and some of them are imparted with water and oil repellent finish. Table 2 shows the details of the fabrics.

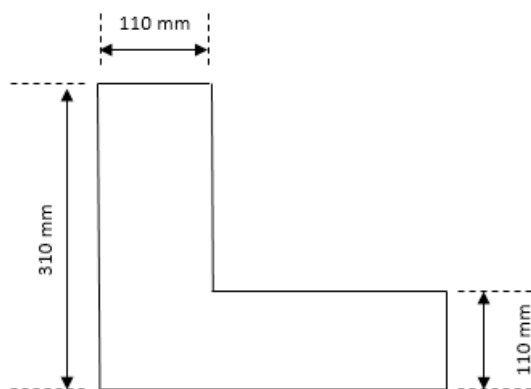
For FTT, each fabric was cut in an L shape (31x31 cm) (see Figure 2) as per guidelines provided by the machine manufacturer.[24] The sample was placed on the bottom plate of the FTT instrument with two legs of the L shape placed on adjacent platforms within the device. The upper plate was set-up with 10°C higher temperature than the bottom plate to mimic the temperature difference between skin and textiles. When the test starts, the upper plate moves gradually downward

**Table 2.** Fabrics characteristics

Fabric	Fiber composition	Weight (g/m <sup>2</sup> )	Warp linear density (tex)	Weft linear density (tex)	Fabric density (per cm)	Fabric construction	Finishes
A	50% Nomex, 50% viscose	269.18	22/2	22/2	32 x 22	Twill 2/1	Water and oil repellent
B	50% Kermel, 50% viscose	253.44	22/2	22/2	32 x 22	Twill 2/1	Water and oil repellent
C	70% Kermel, 30% viscose	228.74	20/2	19/2	32 x 22	Twill 2/1	Water and oil repellent
D	50% Nomex, 50% viscose	253.56	22/2	22/2	32 x 22	Twill 2/1	-
E	69% Nomex, 31% wool	242.72	17/2	18/2, 13/4	32 x 22	Combination twills	-
F	50% M-Aramid, 50% Lenzing FR (flame retardant)	268.64	24/2	24/2	32 x 22	Twill 2/1	-
G	50% M-Aramid, 48% Lenzing FR (flame retardant), 2% carbon-based fibers	262.82	23/2	23/2	32 x 22	Twill 2/1	-
H	70% M-Aramid dope dyed, 30% viscose	220.08	20/2	20/2	32 x 22	Twill 2/1	Water and oil repellent
I	100% polyester	293.86	50/2	20/1	36 x 25	Twill 4/1	-
J	100% cotton	281.88	50/2	20/1	36 x 25	Twill 1/4	-
K	50% cotton, 50% polyester	202.72	30/1	30/1	12 x 16	Knitted – single jersey	-

and touches the fabric. The fabric is brought further downward by both plates and after several seconds, they go back to the initial position (see Figure 3). As the test was running, the compression and bending sensors, concurrently with other sensors, were fed with the input from the tested fabrics, and the readings were computed through the FTT software provided by the manufacturer. This is done for the inside and outside of the fabric in warp and weft directions. Ten specimens were tested for each of the 11 fabrics.

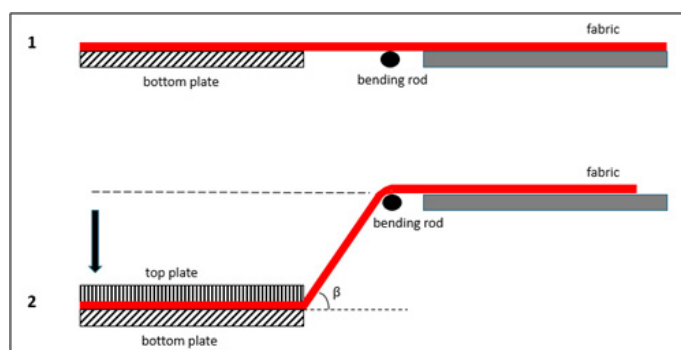
By using a thickness gauge, the thickness of the fabrics was measured according to the ISO 5084:1996 (E), standard



**Figure 2.** Fabric sample dimension

method for determination of thickness of textiles.[25] Following the standard, the fabrics were placed in between the circular presser foot and the reference plate of the thickness tester. The area of the presser foot is approximately 2000 mm<sup>2</sup> with 1 kPa pressure. Then, the gauge reading was taken after 30 seconds at different areas on the samples for at least five times. After that, the mean was calculated to be used in the analysis.

Bending measurement was performed based on BS 3356-1990 standard.[26] For this test, rectangular samples measuring 2.5 X 20 cm were prepared so that the length is parallel to the direction to be tested. Five warp and five weft pieces were tested for each type of fabric in this experiment. The samples were glided on the fixed-angle flexometer, which is based on the cantilever principle. According to Pierce,[27] bending length C is the length of rectangular strip of material that will bend under



**Figure 3.** Schematic diagram of bending motion in FTT

its own mass to an angle of 7.1°. For ease of measurement, this method uses the cantilever length corresponding to the angular deflection  $\theta = 41.5^\circ$ , so that the bending length is half of the cantilever length, as shown in the following equation. Hence, the bending length was read from the ruler when the tip of the sample touched the red line of 41.5° on the apparatus (see Figure 4). The higher the bending length, the stiffer the fabric is.

Bending length C is given by the calculation (1):

$$C = l \left( \frac{\cos(\theta/2)}{8 \tan \theta} \right)^{1/3} = l/2, \tag{1}$$

where we used  $\theta = 41.5^\circ$ , and  $l$  is the sample overhanging length at that angle.

By using the appropriate mean value, the flexural rigidity  $G$  of the fabrics is determined in the standard using formula (2):

$$G = 0.10 M C^3 \text{ (mg cm)} \tag{2}$$

where  $C$  is the bending length (cm), and  $M$  is the fabric mass (g/m<sup>2</sup>). In the standard method, the unit is not given in a standard unit (SI). With SI units, the flexural rigidity of a plate is the force couple (Nm) required per width (m) to bend the plate in one unit of curvature (1/m), and hence, has the general unit for a plate of Nm.

In FTT, thickness is part of the compression module, where the value is recorded together with the pressure exerted when the fabric is sandwiched between upper and lower plates. The compression sensor measured the compression forces and at the same time, the laser distance sensor recorded the distance

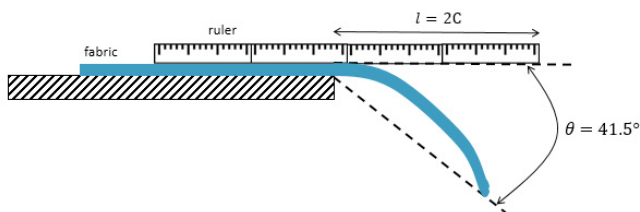


Figure 4. Schematic diagram of bending test according to BS 3356-1990 standard method

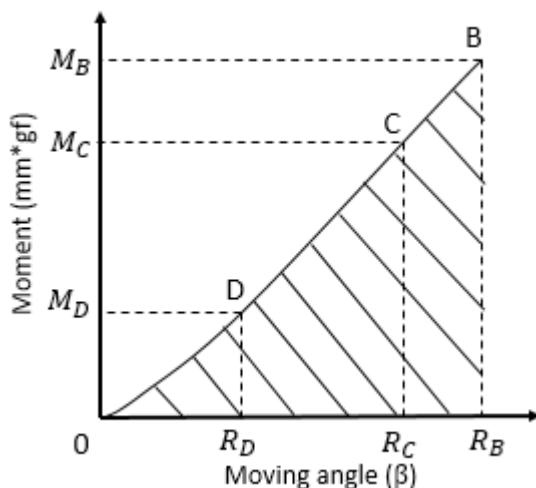


Figure 5. Calculation diagram of BAR and BW indices

between the two plates, which were then converted to sample thickness. The reading for thickness is given when the pressure is at 4.018 kPa[15], whereas ISO 5084: 1996 (E) applies a specified pressure of  $1.0 \pm 0.01$  kPa when compressing the samples, and thus, the thickness value is read from the thickness gauge when that pressure is reached.[25]

Bending in the FTT is expressed as bending work (BW) and bending average rigidity (BAR), which are both categorized with bending module. The bending rods in FTT are placed at the same level as the lower plate and can be pushed downwards to exert a bending force during the test (see Figure 3). Force sensors are positioned under the bending rods to record the dynamic bending forces, which are then converted into a bending moment. A graph of the moving bending angle of the sample (which has maximum value of 1.05 radian) versus bending moment (gf mm) is obtained (see Figure 5), and the integral of this curve over all angles is reported as the BW parameter, while the slope of this curve for the center 60% of the bending moment is reported as the BAR parameter.[17] The main interface of the FTT software is as shown in Figure 6. This instrument takes angle dependent bending into account, while the standard method BS 3356-1990 only measures bending at 41.5° or 0.724 rad in one direction of bending, which means the fabric bends under its own weight. The formulae for BAR (unit gf mm /rad) and BW (unit gf mm rad) are as follow (3);

$$\text{BAR} = \frac{M(R_C) - M(R_D)}{R_C - R_D}, \tag{3}$$

$$\text{BW} = \int_0^{R_B} M(\beta) d\beta,$$

where  $M(\beta)$  is the measured bending moment at angle  $\beta$  for the sample of 11 cm width, and  $R_D$  to  $R_C$  are the angle values at 20% and 80% of maximum bending moment  $M_B$  obtained at maximum angle  $R_B=1.05$  radian.

It is important to note that all the samples were conditioned at  $20^\circ\text{C} \pm 2^\circ\text{C}$  and relative humidity of  $65\% \pm 4\%$  for at least 24 hours prior testing. The results obtained from the thickness and bending test were then compared and analyzed with FTT results.

### 3. Results and discussion

FTT software computes the results for 13 indices (as displayed in Table 1) simultaneously, plus the handle value of the fabrics. However, for this study, only the indices related to thickness and bending were emphasized. FTT gives thickness results in millimeter (mm). Similarly, the standard method yields the value in the same unit although the measurement methods were different. On the other hand, the two FTT indices related to bending; BAR and BW, have the units of Nm rad<sup>-1</sup> and Nm rad respectively, in contrast with the unit given by the standard method, which is in centimeter (cm) for bending length  $C$  and mg cm for flexural rigidity  $G$ . Table 3 shows the results from FTT and the thickness and bending test from standard methods as well.

FTT measures the outside and inside of the sample and gives two distinct readings for thickness even for the same piece of fabric sample. However, statistical analysis confirms that there are no significant differences for both sides thickness reading of a specific fabric type ( $p$ -value > 0.05). Hence, the values for inside and outside are averaged out for the correlation analysis. A t-test is conducted to examine whether the measurements are different between both methods and it shows significant differences ( $p$ -value < 0.05) between the thickness measured by FTT and the standard method. Correlation analysis of the measurements also yields the result that they are however correlated to each other (Pearson's correlation coefficient = 0.97).

In Figure 7, the thickness measurement of FTT and standard method are displayed in a scatter diagram with a regression

line drawn on it. It shows that both measurements are highly positively correlated in linear relationship and the line fits most of the data ( $R^2=0.95$ ). The differences in readings for FTT and standard method ISO 5084: 1996 (E) can be the results of the different pressure used over a different contact area. The pressure is 1 kPa for the standard method and 4.018 kPa in FTT, which interacts differently with the compression rigidity of the fabrics. Due to the higher pressure on the sample and the bigger surface area during compression in FTT, the readings given are consistently lower than that of the standard method. However, the intercept at  $y = -0.2341$  is unexpected. Although the FTT does not export the full measurement, it is possible in the interface to consult this data. Hence, we investigated the measurement data for compression as given in Figure 8, which shows a measurement of sample K (FTT thickness 0.67, BS thickness 0.84). From the figure, it can be clearly seen how the

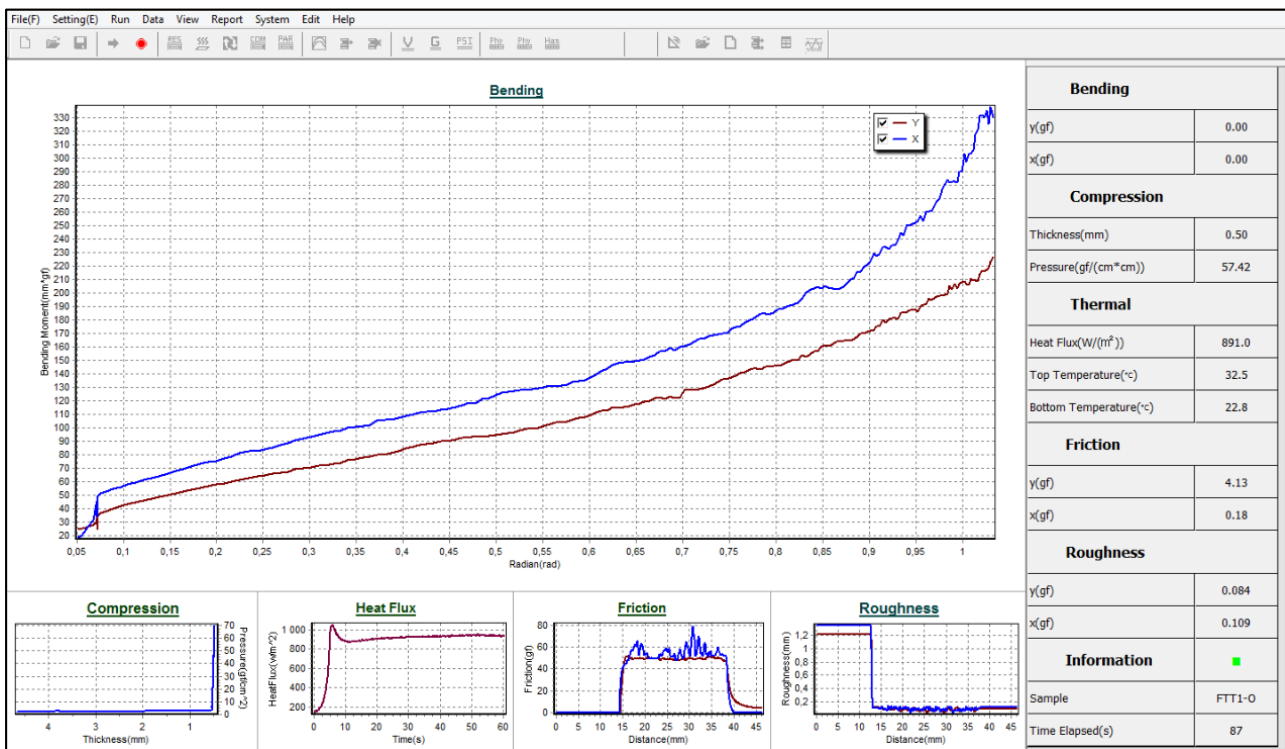


Figure 6. An example of FTT main interface during measurement

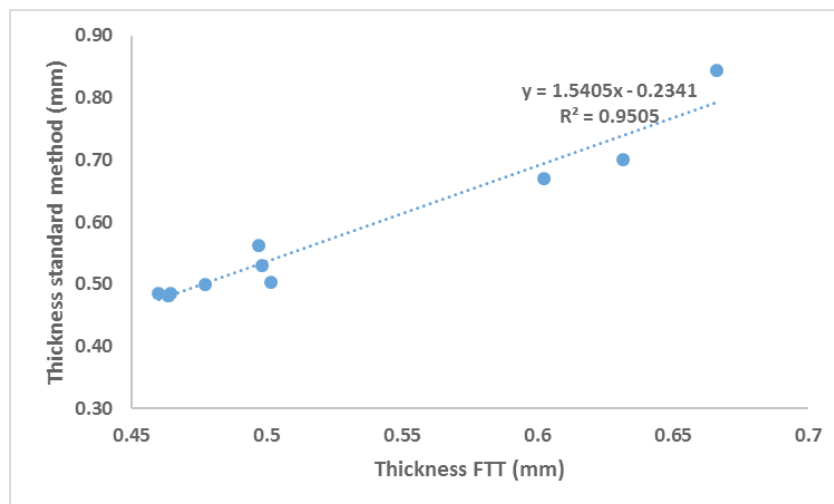


Figure 7. Correlation between thickness FTT and thickness standard method

thickness value reduces under increasing pressure. Focusing on the lower pressure, it is observed that the compression pressure starts to increase around 0.85, consistent with the standard method value. Hence, careful analysis of the data should allow us to obtain thickness values closer to the 1 kPa (about 10 gf/cm<sup>2</sup>) of the standard. However, it is impossible to obtain this dataset from the FTT software; hence, the thickness data of the lower pressure is not accessible for further exploration. The graphical data does show that when there is no contact yet with the fabric, the compression pressure is already over 0.25 kPa, indicating that the sensor used has an accuracy around 0.25 kPa which might explain why 4.018 kPa is used to set the FTT thickness.

Since the FTT is not provided with a zero-point thickness calibration, an investigation is done to determine whether there is any shift in the zero-point of the FTT. First, the FTT was run without any sample on it in order to see what are the values it picks up. Next, we measured several rigid bodies for which FTT is expected to give consistent values. Results from this showed that the FTT picks up 0 mm thickness when no sample was present and a very small deviation of 0.01 mm was observed for a 1 mm thick rigid plate. This is as expected, as for a rigid plate, no thickness changes are expected at 1 kPa versus 4.018 kPa. Although the deviation is very small, textiles cannot be expected to behave the same way as the factors like hairiness, and surface contour would give different impact to the measurement. Hence, we conclude that there is no zero shift in the FTT, provided the operator regularly performs a thickness calibration with rigid bodies, as we did here. In our experience, deviations in thickness measurement > 0.02 mm on rigid bodies with the FTT can be resolved by extensive cleaning of the lower and upper FTT plates.

However, despite the differences in the measurement methods, a very good correlation is found for the selected samples.

Although the found regression line will not be universal for all fabrics, it will instead depend on the compression rigidity. Hence, for fabrics outside the tested range of approximately 0.45 – 0.85 mm thickness or with different compression rigidity, a new regression curve is needed before solely depending on the FTT for thickness measurements and correcting for the higher pressure applied.

The bending module in FTT computes the input for bending average rigidity (BAR) and bending work (BW) indices in warp and weft directions, also from outside and inside of the fabric. These two indices were compared with the bending length C and flexural rigidity G obtained from the standard method measurement, as well as the MC and MCC value. The MC index is obtained by multiplying the fabric mass M with the bending length C, and for the MCC index, the mass is multiplied by its squared bending length. These two indices, MC and MCC are derivatives from G (= 0.1 MC<sup>3</sup>), included to test any other possible relationship that could be linked to bending.

The Pearson correlation or the r value indicates the strength of the interaction between the analyzed indices. As can be seen in Table 4, the r values ranged from 0.77 to nearly 1 for all the indices compared. It is no doubt that BAR is highly correlated with BW, where a high BAR would make a high BW in a linear way relationship. Looking at the measurement principle of both FTT and standard methods, huge differences can be seen where FTT measures the moment or work needed to bend one radian of sample, which means the more work or moment needed to bend the sample, the stiffer the fabric is. Instead, flexural rigidity G, in the standard method, measures the force needed to bend the sample in one unit curvature and C or bending length is half the overhanging length of the sample, when it bends down under its own mass during the experiment. In the FTT, the sample bends over a thin rod, while the angle of bending increases as the FTT plates go down, while the

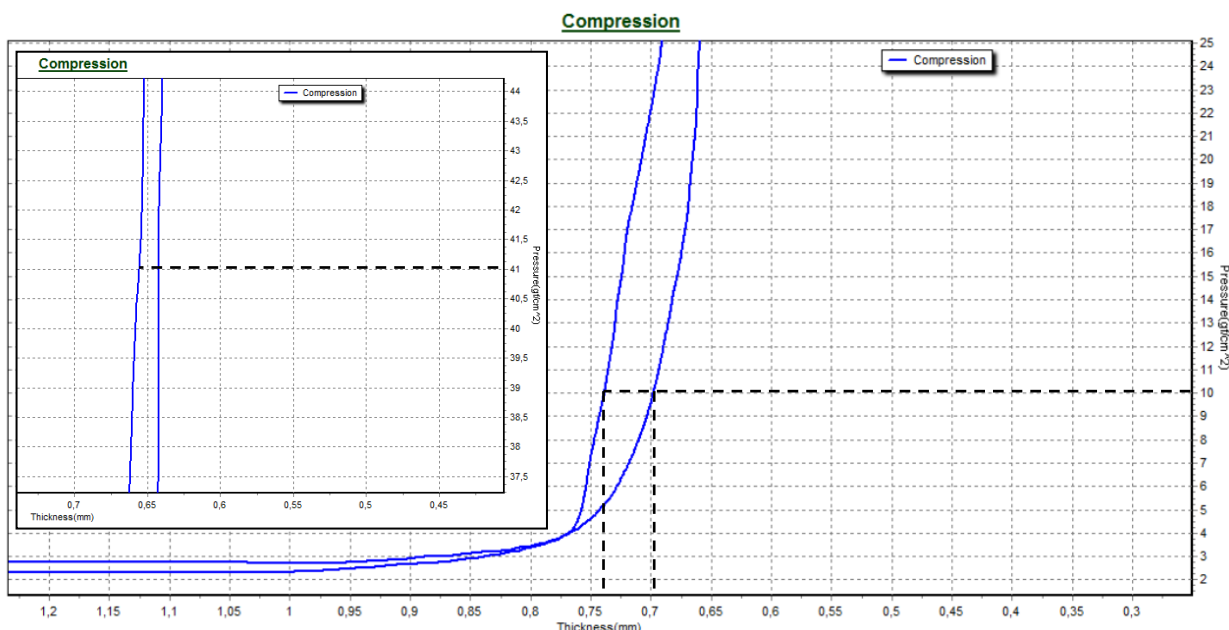


Figure 8. Measurement data of compression for sample K (screenshot from FTT software)

Table 3. Results from FTT and standard methods

Fabric	Side	FTT						ISO 5084:1996 (E) (thickness, mm)	BS 3356-1190 (bending)			
		Thickness (mm)	BAR (warp) ( $10^{-4}$ Nm rad <sup>-1</sup> )	BAR (weft) ( $10^{-4}$ Nm rad <sup>-1</sup> )	BW (warp) ( $10^{-4}$ Nm rad)	BW (weft) ( $10^{-4}$ Nm rad)	C (warp) (cm)		C (weft) (cm)	G (warp) (mg cm)	G (weft) (mg cm)	
A	Inside	0.48 ± 0.03	22.72 ± 1.29	23.94 ± 1.77	182.56 ± 6.73	198.97 ± 4.06	0.50 ± 0.01	3.14 ± 0.06	2.82 ± 0.11	833.36 ± 0.01	605.26 ± 0.04	
	Outside	0.47 ± 0.02	23.89 ± 1.42	26.11 ± 3.01	187.49 ± 9.73	212.73 ± 15.20		2.28 ± 0.09	2.91 ± 0.07	319.04 ± 0.02	665.03 ± 0.01	
B	Inside	0.50 ± 0.03	24.33 ± 1.86	21.09 ± 2.18	212.76 ± 14.41	175.28 ± 9.55	0.50 ± 0.01	3.14 ± 0.08	2.68 ± 0.12	784.63 ± 0.01	487.84 ± 0.04	
	Outside	0.50 ± 0.03	23.67 ± 2.01	23.23 ± 2.22	194.18 ± 13.44	188.94 ± 8.87		2.68 ± 0.07	2.70 ± 0.06	487.84 ± 0.01	498.85 ± 0.01	
C	Inside	0.47 ± 0.02	44.72 ± 5.81	27.49 ± 1.73	359.69 ± 28.02	236.65 ± 17.33	0.49 ± 0.01	4.09 ± 0.10	3.31 ± 0.07	1564.99 ± 0.02	825.77 ± 0.01	
	Outside	0.46 ± 0.02	39.98 ± 3.38	27.83 ± 2.22	313.89 ± 28.84	238.11 ± 17.15		3.59 ± 0.14	3.46 ± 0.08	1058.34 ± 0.06	947.48 ± 0.01	
D	Inside	0.47 ± 0.02	18.38 ± 1.84	19.77 ± 1.78	130.40 ± 6.05	136.73 ± 2.63	0.48 ± 0.00	2.38 ± 0.05	2.18 ± 0.04	341.83 ± 0.00	263.60 ± 0.00	
	Outside	0.46 ± 0.02	18.77 ± 1.45	17.35 ± 2.19	140.94 ± 5.15	127.47 ± 7.17		2.07 ± 0.08	2.17 ± 0.08	224.90 ± 0.01	258.20 ± 0.01	
E	Inside	0.46 ± 0.02	19.01 ± 0.68	16.25 ± 1.51	117.14 ± 6.32	109.24 ± 6.26	0.48 ± 0.01	1.86 ± 0.03	2.07 ± 0.04	156.19 ± 0.00	213.73 ± 0.00	
	Outside	0.47 ± 0.02	14.73 ± 1.33	17.74 ± 1.23	94.46 ± 4.15	120.78 ± 4.03		1.98 ± 0.03	2.02 ± 0.03	188.41 ± 0.00	200.06 ± 0.00	
F	Inside	0.60 ± 0.03	21.36 ± 1.51	22.20 ± 2.10	152.09 ± 7.00	145.90 ± 10.08	0.67 ± 0.00	2.62 ± 0.03	2.43 ± 0.05	483.14 ± 0.00	384.28 ± 0.00	
	Outside	0.60 ± 0.03	21.41 ± 3.94	25.27 ± 1.66	135.40 ± 6.89	165.10 ± 8.38		1.97 ± 0.05	2.45 ± 0.02	205.39 ± 0.00	395.07 ± 0.00	
G	Inside	0.49 ± 0.02	23.39 ± 1.77	23.37 ± 1.13	174.59 ± 6.47	173.70 ± 10.21	0.53 ± 0.01	2.96 ± 0.07	2.66 ± 0.07	681.61 ± 0.01	493.26 ± 0.01	
	Outside	0.50 ± 0.02	22.03 ± 1.41	25.19 ± 1.51	158.84 ± 7.97	188.72 ± 4.36		2.23 ± 0.09	2.75 ± 0.07	291.46 ± 0.02	543.61 ± 0.01	
H	Inside	0.45 ± 0.03	21.15 ± 2.10	17.27 ± 1.44	177.14 ± 12.21	136.71 ± 9.93	0.49 ± 0.01	2.88 ± 0.11	2.63 ± 0.02	525.72 ± 0.03	401.50 ± 0.00	
	Outside	0.46 ± 0.03	20.56 ± 1.22	18.23 ± 1.09	164.27 ± 11.47	141.76 ± 7.43		3.18 ± 0.09	2.58 ± 0.07	707.72 ± 0.02	375.76 ± 0.01	
I	Inside	0.50 ± 0.01	25.06 ± 1.87	20.74 ± 1.67	163.37 ± 5.50	168.91 ± 10.52	0.56 ± 0.01	1.95 ± 0.02	2.32 ± 0.10	217.89 ± 0.00	366.95 ± 0.03	
	Outside	0.49 ± 0.01	18.72 ± 2.71	24.29 ± 3.72	129.69 ± 7.75	190.54 ± 10.86		2.12 ± 0.06	2.18 ± 0.12	279.99 ± 0.01	304.45 ± 0.05	
J	Inside	0.64 ± 0.01	25.12 ± 1.38	19.29 ± 1.04	185.61 ± 9.64	131.34 ± 4.83	0.70 ± 0.01	2.57 ± 0.07	1.67 ± 0.04	478.48 ± 0.01	131.28 ± 0.00	
	Outside	0.63 ± 0.01	23.11 ± 1.41	24.64 ± 1.38	178.76 ± 5.48	144.96 ± 6.00		1.90 ± 0.04	2.01 ± 0.06	193.34 ± 0.00	228.05 ± 0.01	
K	Inside	0.67 ± 0.02	10.24 ± 1.81	8.78 ± 1.10	55.96 ± 3.08	41.11 ± 1.71	0.84 ± 0.02	1.00 ± 0.04	1.19 ± 0.05	20.27 ± 0.00	33.73 ± 0.00	
	Outside	0.66 ± 0.02	9.56 ± 1.77	10.34 ± 2.03	52.94 ± 3.25	47.39 ± 3.30		1.61 ± 0.06	0.73 ± 0.06	84.60 ± 0.00	7.81 ± 0.00	

amount of material being bent is constant. This allows to obtain the BW as an integration of the forces, and the BAR as a slope of the measured forces. Comparing the correlations calculated between the indices from FTT and standard method, it can be observed that BW has a better correlation than BAR with the parameters obtained from the standard method. However, as highlighted in Table 4, BW correlates best with MC (mass of the fabric multiplied by its bending length) in two cases, while it correlates best with MCC (mass of the fabric multiplied by its squared bending length) in one case (and twice close to the MC result), and also once with G. Nevertheless, if the overall data is considered, BW is best correlated with MCC. We conclude that BW correlates best with the standard measurement, and specifically with the MCC value.

The best correlation of BW with MCC can be explained as follows. The formula for G is  $0.1 \times M \times C^3$ , so MCC is actually reducing the power of C from 3 to 2. Since bending moment B is also regarded as flexural rigidity G times the curvature ( $B = G k$ ), where k is the curvature given by  $1/R$ , with R being the radius of the circle from where the bending curvature is formed. In a first order approximation, R can be considered proportional with C, so  $R \approx a C$ , and hence  $B \approx G / (a C)$ . The bending work BW in the FTT, on the other hand, is the average bending moment over all radians sampled by the FTT. As a consequence, the good correlation between BW and MCC is not unexpected. Figure 9 shows a scatter plot and the regression model of relationship between the overall BW and MCC. Coefficient of determination  $R^2 = 0.83$  demonstrates a strong fitting of the data towards the model and from that, yields 0.91 as Pearson correlation value, which proves a very good correlation between BW and MCC. The regression model  $MCC = 1.1194 BW - 266.1$  has an intercept at MCC at -266.1, which might have contributed to the given device tolerance of  $\pm 10\%$  for the FTT. We conclude that three closely related indices, MC, MCC and G, have a good relationship with BAR and BW, with just small Pearson's correlation r-value differences between them. Amongst all, MCC gives the best correlation for the overall data set with BW.

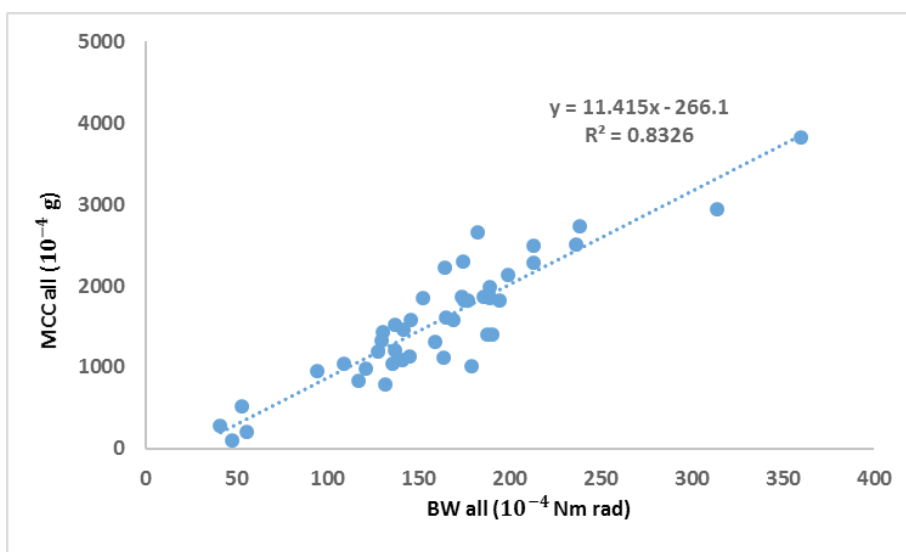
On a side note, the BAR derivation in the reference from the manufacturer is mathematically not so well defined. Although

it still gives a very strong correlation with other indices, this is because of the strong correlation with BW, which reduces the usefulness of BAR as a separate FTT parameter. It should however relate to the speed to which the bending moment

**Table 4.** The Pearson's correlation values for outside and inside warp and weft bending parameters of the tested fabrics

Outside warp						
	BAR	BW	C	MC	MCC	G
BAR	X	0.99	0.78	0.86	0.84	0.82
BW	-	X	0.82	0.89	0.87	0.84
C	-	-	X	X	X	0.99
Inside warp						
	BAR	BW	C	MC	MCC	G
BAR	X	0.98	0.82	0.77	0.85	0.88
BW	-	X	0.91	0.84	0.92	0.94
C	-	-	X	X	X	0.94
Outside weft						
	BAR	BW	C	MC	MCC	G
BAR	X	0.93	0.82	0.92	0.86	0.77
BW	-	X	0.93	0.96	0.96	0.90
C	-	-	X	X	X	0.93
Inside weft						
	BAR	BW	C	MC	MCC	G
BAR	X	0.96	0.87	0.93	0.91	0.86
BW	-	X	0.92	0.95	0.96	0.93
C	-	-	X	X	X	0.97

\*X: non-relevant correlation \*\* - correlation is already stated in other cells



**Figure 9.** Correlation between the overall BW and MCC



increases, as the sample bends more. Therefore, as a suggestion, it might be useful to have an automated bending tester that can measure the bending length in terms of the angle as an extension to the BS 3356-1990 standard. The speed of the bending length change should then in turn relate to the rigidity of the samples against bending. Thus, it would be possible to draw a better conclusion from the phenomenon underlying the principle of BAR.

#### 4. Conclusions

A new equipment from SDL Atlas, the FTT, offers a new way of computing hand and touch sensations of fabrics. The bending module and thickness measurement were analyzed and compared with the standard methods that are commonly used in the textile industry, in order to gain a better understanding on how they relate and if the FTT can be used as an alternative. This will reduce the testing and computing time for the companies having an FTT in their lab. 11 fabrics with different fiber composition and construction type were tested using FTT and standard methods for thickness and bending. Despite having differences in the principle of measurement, it is found that FTT demonstrates a significant correlation with the standard methods. The Pearson's correlation,  $r$  gives 0.97 for thickness while for bending, in overall, BW shows the highest correlation with MCC, which is at 0.91 for the overall value from warp and weft samples. The correlation analysis indicates a very strong correlation between FTT and standard methods for thickness and bending. The findings are significant as to estimate the reliability and comparability of the FTT towards the standard measurements, within the said scope and limitation. For the thickness measurement, although the correlation is high, FTT should not be used as an alternative measure at the moment. A standard calibration method of the FTT would be required, and the compression measurement at 1 kPa should be used instead of the value at 4.018 kPa.

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