

## Review Article

# Structure-property relationship of fibre, yarn and fabric with special reference to low-stress mechanical properties and hand value of fabric

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An attempt has been made to review the work done so far in understanding the influence of wool fibre, yarn and fabric structures and their properties on low-stress mechanical properties and hand value of fabric. The role of finishing treatments and application of softeners on low-stress mechanical properties has also been reviewed. Finally, the need of establishing a vertical relationship between fibre and garment is suggested.

**Keywords:** Fabric structure, Fibre structure, Fabric handle, Low-stress mechanical properties, Wool, Yarn structure

### 1 Introduction

The comfort characteristics like fabric aesthetic property, thermal comfort and physical comfort like handle of clothing material are getting more priority in the quality evaluation of fabric. The fabric handle mainly depends on its low-stress mechanical properties<sup>1</sup>. The low-stress mechanical properties of fabric such as shear, bending and tensile together with compression and surface friction have, therefore, become essential facets of fabric and clothing objective measurement technology. The low-stress mechanical properties of the fabric mainly depend on fibre, yarn and fabric structures and their properties<sup>2-7</sup>. Yarn and fabric manufacturing as well as finishing conditions also significantly influence these properties<sup>8-16</sup>.

The measurement of low-stress mechanical properties of fabric on Kawabata Fabric Evaluation System (KES-F) has become popular among textile researchers for the evaluation of fabric hand value and assessing the suitability of fabric for the manufacture of clothing. The system is also expected to help in the development of newer products in future<sup>17-23</sup>. This paper presents a review of the work done and experience obtained so far in understanding the role of fibre, yarn and fabric structures and various other factors in determining the fabric hand.

### 2 Hand Value Evaluation

The term hand has been defined<sup>24</sup> as the subjective assessment of textile material obtained from the sense

of touch. Hand is thus a psychological phenomenon. It implies the ability of fingers to make a sensitive and discriminating assessment and of the mind to integrate and express the results in a single valued judgment. Kawabata<sup>17</sup>, from the visual and tactual judgment of the fabric by HESC experts, recognized three attributes as primary hand values and named them as *Koshi*, *Numeri* and *Fukurami*, which mean stiffness, smoothness and fullness respectively. Kawabata and associates, in an experiment with 500 samples of winter suit fabrics, asked the experts to rank these fabrics, in order, from 10 (with strongest feeling) to 0 (with no feeling). Total hand represents an assessment of the overall quality of the fabric and is a measure of its value in the market i.e. its selling appeal to the consumer. The fabric handle, which is concerned with the fabric quality, is the total hand and this was also graded by the experts in the same manner as the rating of primary hand. Each expert graded the fabric according to six grades and the ratings from 5 to 0 were given in order of quality level. The rating was named total hand value or THV<sup>17</sup>. Elaborate statistical correlation then led to equations relating (i) the total hand ranking to the three primary hand rankings, and (ii) the primary hand values to set of objective measurements from the KES system. Thus, this method provides an estimate of both features assessed in primary hand and market preference as denoted by total hand value. Subsequently, they extended the study to men's summer suiting, women's wear and knitted fabrics<sup>22, 23, 25</sup>.

Recently, two sets of instruments—KES and FAST systems—have become commercially available for measuring the fabric low-stress mechanical

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properties with satisfactory results. Kawabata Fabric Evaluation System (KES-F) consists of four instruments, which measure the tensile, shear, bending, compression and surface properties of the fabric. The KES-F system of measurement combined with calculation model developed by Niwa and Kawabata is used to obtain an objective evaluation of the hand of the fabrics<sup>20-23</sup>. The measured parameters are linked to the primary hand values. Fabric Assurance by Simple Testing (FAST) is a system involving four instruments developed by CSIRO in Australia to measure the properties of wool and wool blended fabrics that affect the tailoring performance of these fabrics and the appearance of the tailored garments in wear<sup>26</sup>. As such, it does not predict the subjective perception of fabric handle. It predicts some aspects of quality and can be used as an alternative to KES-F system in many applications, such as fabric development, optimization of finishing routes, evaluation of new technologies, etc.

Several attempts have been made to find out an alternative method for routine measurement as well as for application of those fabric objective properties, particularly relevant to industry, due to the high price and lengthy process of measurement as well as overlapping of the sixteen parameters of the Kawabata system<sup>26-35</sup>. A simple device attached to tensile testing machine measures the force generated while passing a fabric specimen through a ring<sup>27-29</sup>. In another approach, Loknadan<sup>30</sup> measured the percentage compression for a series of the fabrics by using a cloth thickness gauge at three different pressures. Fabric extraction method was developed to measure multiple fabric properties and was applied to handle measurement and evaluation<sup>31</sup>.

A new measure for total handle of fabric has been suggested by Pan *et al.*<sup>32</sup> in place of Kawabata's handle value. They used Weighed Euclidean Distance (WD) value to define total hand and reported that WD value is more logical and rational mathematical process, possibly feasible for total handle evaluation because of its simplicity and suitability for different textile materials and fabrics. Recently, the neural network system has also been used for fabric categorization<sup>33-35</sup>. Self-organizing neural network is a systematic and dynamic method of storing the knowledge of human expert assessors of fabric quality<sup>34,35</sup>. The actual industrial application of this system is yet to be exploited by conducting large-scale trials under controlled conditions.

### 3 Factors Affecting Hand Value of Fabric

The low-stress mechanical properties of a fabric mainly depend on the fibre type, shape and structure as well as on fibre mix used in manufacturing the fabric<sup>2-7</sup>. The spinning system and the conditions used for manufacturing the yarn also significantly influence yarn structure and its properties, which, in turn, affect the fabric handle<sup>36-40</sup>. The other factors which contribute to fabric handle are fabric construction parameters (weave structure, fabric sett and areal density) and wet processing conditions used during the finishing of the fabric<sup>8-11, 40</sup>.

#### 3.1 Fibre Structure and Properties

Fibre is considered as the unit cell of textile material. Fineness, diameter, crimp, surface roughness and all mechanical properties of fibre contribute to fabric mechanical property. Wool being a natural fibre, the variation of diameter significantly influences the fabric properties. The fibre diameter has main effect on fabric stiffness and handle<sup>2,3</sup>. Hunter *et al.*<sup>2</sup> reported that an increase in mean fibre diameter increased the *Koshi* (stiffness), *Hari* (anti-drape stiffness) and *Shari* (crispness) but decreased the *Fukurami* (fullness and softness) of the fabric. It has also been reported that the coefficient of friction of the fabric decreased with an increase in mean fibre diameter whereas the mean deviation of the coefficient of friction of fabric surface (MMD) increased. Among the various compressional characteristics, the resiliency of compression (RC) increased with an increase in fibre diameter. The fine wool imparts distinctively higher smoothness, fullness and softness, which result in higher THV of the fabric<sup>12</sup>. Fabric handle is considered to rely on and be determined by the cross-sectional shape of fibres<sup>6,7</sup>. The fabric becomes soft and deformable with an increase in the space ratio in the fibre cross-section; however, it does become inelastic and unrecoverable<sup>7</sup>. It is further reported that *Fukurami* and *Shinayakasa* (flexibility with soft feel) of fabric are increased with increase in space ratio, whereas *Koshi* and *Hari* are decreased.

Fibre crimp and fabric quality are highly correlated<sup>2,4</sup>. An increase in fibre crimp results in increase in fabric thickness and weaves crimp, which, in turn, affect *Fukurami*, *Numeri* and total hand value<sup>2</sup>. The fibre crimp also influences the fabric shear rigidity and shear hysteresis. These properties are increased with increase in the fibre crimp whereas the fabric surface properties, such as MIU (coefficient

of friction) and MMD (mean deviation of MIU), are decreased<sup>2</sup>. A good correlation between fibre crimp and primary hand is reported by Matsudaira *et al.*<sup>4</sup>. They observed that *Numeri* and *Fukurami* are strongly related with fibre crimp.

Fibre mechanical properties, such as tensile, bending and compressional properties, are directly reflected in their corresponding yarn and fabric properties. Among all these properties, bending and extensibility largely influence low-stress mechanical property and hence the hand behaviour of the fabric<sup>2</sup>.

### 3.2 Yarn Structure and Spinning System

The low-stress mechanical properties of fabric are directly related to the structure and properties of yarn from which it is made<sup>36-39</sup>. These are significantly influenced by yarn linear density, twist and other process parameters. The effect of yarn linear density on the hand value was reported by Dhingra *et al.*<sup>36</sup>. They reported that both *Numeri* and *Fukurami* are increased considerably by spinning the same fibres into a finer count. Coarser yarns increased the cover factor, resulting in higher stiffness of the fabrics. The hard twist in the yarn increases the yarn packing density and hence the fabric stiffness significantly<sup>36</sup>. Fibre mix in the blends also significantly influenced the low-stress mechanical properties of the woven fabrics. Fabrics produced from pure wool fibre gave higher THV than wool-polyester blended winter fabrics of similar construction<sup>36</sup>. Yarns produced on different spinning systems have different structures, especially fibre arrangement and twist distribution in the yarn<sup>37-48</sup>. Due to change in yarn structure, the properties of yarn are varied significantly. Fibre assembly in the yarn prominently affects the physical and mechanical properties of fabric<sup>37-41</sup>. Therefore, mule-spun yarn has always been considered as being superior to ring-spun yarn<sup>37</sup>. The properties quoted as being superior are the evenness of the yarn and its handle. The influence of ring and rotor spinning systems has been studied by Subramaniam and Amarvati<sup>5</sup>. They reported that the fabrics woven from open-end spun yarn have greater thickness than the fabrics woven from ring-spun yarn. The value of compressional energy (WC) is therefore higher for the fabrics woven from open-end spun yarn. It has been further reported that the coefficient of friction of fabric (MIU) increases significantly in the case of fabric woven from open-end spun yarns. Most of the primary hand values, except the *Fukurami*, are higher for the fabrics woven from open-end spun yarns

compared to those for woven from ring-spun yarns. Fabrics produced from ring-spun yarns exhibit better handle than those produced from open-end spun yarns. They further reported that the use of carded cotton with polyester fibre enhances the handle of the fabrics<sup>5</sup>.

Behera *et al.*<sup>40</sup> compared the fabrics produced from ring-, rotor- and friction-spun cotton yarns. They reported that the fabric produced from ring yarn gives lower bending, shear rigidity and hysteresis as compared to the fabrics produced from rotor and friction yarns. The fabric from ring yarn also shows better compressional behaviour than the fabrics from rotor and friction yarns and hence the best hand. It has also been reported that the fabric from friction yarn shows the highest hysteresis loss, which indicates poor dimensional stability of the fabric.

The influence of sheath and core in covered yarn has been reported by Sawhney *et al.*<sup>41-46,48</sup> and Harper and Ruppeniker<sup>47</sup>. They reported that two identically constructed cotton-polyester fabrics—one from polyester staple-core cotton covered yarn and other from a random blended yarn—showed significant difference in low-stress mechanical and surface properties<sup>45,46</sup>. Difference in fabric properties mostly reflected the difference in the physical properties of the yarn. Fabric made from polyester-core cotton covered yarn was most resilient to tensile and compressive deformation and had higher bending rigidity, lower tensile elongation and shear modulus. This fabric also gave higher values for all the four primary hand qualities and higher total hand values associated with men's summer suit application. The same fabric also gave higher values for five out of six primary hand qualities for women's thin dress application. It is further reported that same fabric also offered a cooler contact sensation and much less variation in contact sensation along its length compared to fabric from random blended yarns. The fabric made of cotton-covered yarn had better thermal comfort value for cold and dry (winter) as well as hot and humid (summer) weather conditions. Radhakrishnaiah *et al.*<sup>45</sup> reported that the core-sheath yarn showed lower values for bending rigidity, bending hysteresis, compressive resilience and tensile elongation. The same yarn also showed higher values for compressive softness and tensile modulus. The lower tensile elongation and higher tensile modulus of core-sheath yarn is reflected in lower elongation and higher modulus of corresponding fabric. However, the bending and compressional properties of core-sheath

yarn are inversely related to bending and compression properties of corresponding fabrics. Cotton-polyester core yarn fabrics have cotton feel and appearance and luxurious full hand<sup>46</sup>.

Core-wrap composite yarn produced by air-jet spinning system is relatively weak and extremely harsh in handle<sup>39</sup>. The air-jet/friction spun composite core yarn is less hairy and bulky than the ring spun, attributable to major basic difference in their structures. The fabric made from this composite yarn has a harsher handle than that of 100% ring-spun cotton fabric<sup>39</sup>. A very preliminary subjective evaluation of finished fabric, however, revealed a satisfactory appearance<sup>49</sup>.

### 3.3 Fabric Structure

The fabric construction parameters, such as fabric sett, cover factor and weave, considerably change the performance of the fabric, particularly in respect of low-stress mechanical properties. Fabric stiffness increases considerably if the cover factor of the fabric is increased, which, in turn, changes the THV of the fabric. Plain weave fabrics have higher shear rigidity compared to other weave fabrics because of more yarn-to-yarn interlacing in the fabric with smaller float<sup>50</sup>. The fabric produced with plain weave gives more compact structure, resulting in lower thickness, as compared to other weave structures<sup>50</sup>. Behera *et al.*<sup>40</sup> reported that twill weave provides higher extensibility, smoothness and compressibility than plain weave. They also reported that the bending and shear rigidity of twill fabric is significantly lower than that of plain fabric. A twill fabric gives higher *Fukurami* and THV<sup>40</sup>. The level of weave crimp influences the bending property; fabrics with high crimp give lower flexural rigidity and vice versa. The twill weave fabric behaves differently to the plain weave fabrics because of less interference between warp and weft threads. Fabric dimensional properties, such as fabric thickness and areal density, play important role in deciding fabric hand, because bending, compression and shear properties are influenced by these two parameters. Wool, being a bulkier fibre, exhibits high compressibility and softer/fuller feel adding to the fabric hand.

### 3.4 Finishing Treatment

After weaving, the wool fabric tends to have a hard and stiff handle due to the residual tension in the fabric, which gives rise to high level of pressure between the yarns. The pressure between the fibres / yarns opposes their free movement. This is reflected

in high values of bending and shear hysteresis. The hysteresis is caused mainly due to the loss of frictional energy during deformation. The finishing treatments i.e. application of steam, water, heat, tension, pressure, chemical, etc influence the mechanical interaction between interlacing yarns in the finished fabric, which, in turn, determines the fabric handle and making-up quality<sup>8-16</sup>. The overall changes in the mechanical/surface properties due to finishing result in a progressive improvement of elastic recovery properties, surface hand feeling and desirable fabric aesthetic attributes. A significant reduction in both rigidity and hysteresis in shear and bending properties of wool fabrics has been reported after scouring<sup>8</sup>. During finishing, the pressure and steam decatizing and dry cleaning are the most critical steps in determining the final handle of woollen fabrics, especially with regard to shear rigidity and hysteresis losses. Finimore<sup>10,12</sup> reported the change in shear, tensile and bending properties after wet processing of wool fabric and observed that the shear rigidity is decreased after scouring but, in some cases, it is increased again after decatizing. The decrease in shear stiffness after setting is also reported by Kopke<sup>9</sup>. He also reported that the shear stiffness is increased with longer cooling time after decatizing. Dhingra *et al.*<sup>11</sup> reported a significant reduction in both rigidity and hysteresis in shear and bending properties of wool fabric after scouring. They further reported that these effects are almost equally divided between scouring and heat-setting of wool/polyester blended fabrics<sup>11</sup>.

Solvent scouring of loom state fabric imparts worst handle to wool fabric<sup>13</sup>. Solvent scouring reduces the stiffness whereas the steam press controls the smoothness, fullness and softness. It was also observed<sup>13</sup> that perchloroethylene treatment at an elevated temperature or in combination with a swelling agent only marginally affects the mechanical properties as compared to normal perchloroethylene treatment. The soap scouring produces fabric of best hand feeling with desirable aesthetic attributes.

During finishing, decatizing is most critical step in determining the final handle of the fabric<sup>11-14</sup>. Decatizing makes a large modification in the behaviour of the fabric subjected to low tensile, compressive, shearing, bending and buckling stresses<sup>11</sup>. Steam pressing of wool causes an increase in *Koshi* and decrease in *Fukurami* and *Numeri*<sup>12</sup>. The steam pressing results in increase in hysteresis and rigidity in shear and bending due to greater contact of warp and weft threads in the fabric. Whereas Shiomi

*et al.*<sup>14</sup> observed that steam pressing produced a fabric with lower *Koshi* value and higher *Numeri* and *Fukurami* values.

Dry cleaning improves fabric handle, with *Koshi* decreasing and *Fukurami* and *Numeri* increasing<sup>15</sup>. Dry cleaning causes stress relaxation within the fabric, leading to reduction in hysteresis and, to a lesser extent, in rigidity in shear and bending. When chemical setting is applied to wool fabric during finishing, it tends to give the fabric a greater rigidity as compared to the continuous wet setting process. The THV of chemically-set fabric is found to be slightly lower than that of wet-set fabric<sup>16</sup>. Wet setting process tends to relax the fabric to a greater extent when compared with chemical setting and the values for shear and bending stress are also lower than those for the chemically-set fabrics. The application of softeners considerably improves the quality of textile materials by modification of fibre surface<sup>51-53</sup>. The cationic and amino-silicon softeners are most commonly used on wool products<sup>52</sup>. Finimore<sup>12</sup> reported that the application of cationic softeners to Hercoset treated wool fabric results in a decrease in shear and bending rigidity. The cationic and amino-silicon softeners increase the tensile resiliency, tensile work (WT) and compressional energy (WC) and lower bending and shear rigidity and their hysteresis. They also reduce the coefficient of friction<sup>51-53</sup>.

#### 4 Remarks

With the change of life style and taste of consumers, it has now become very essential that product should be designed according to their need. The objective measurement of the low-stress mechanical properties of fabric by KES system is a basic tool for engineering the product to fulfil the consumers need. Using the objective measurement system for different end products could also optimize the fibre mix, process parameters and finishing treatments. To achieve a desired hand value in finished product, analysis of basic raw material characteristics and their impact on fabric hand value should be clearly understood before taking a product mix and design decision. For this purpose, detailed studies are required to correlate the structure and properties of fibre, yarn and fabric. Such studies would not only help in developing new products but also provide necessary feedback to processors in taking early actions. The present approach is being used by the authors to engineer the suiting fabric using Indian wool with different fibre mix, process

parameters and finishing treatments. Efforts are being made to gather suitable feedback from fabric hand study to enable spinners and breeders of wool fibres to contribute their best in developing value-added products.

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