CHAPTER - 2

THEORY AND LITERATUER SURVEY

2.1 Introduction:

Man (Homo sapiens), an "unfinished being" needs a 'second skin' called clothing. Clothing is defined, in its broadest sense, as coverings for the torso and limbs as well as coverings for the hands (gloves), feet (socks, shoes, sandals, boots) and head (hats, caps). After food and shelter, clothing is considered as a basic need of mankind. People almost universally wear clothing, which is also known as dress, garments, attire, or apparel. People wear clothing for functional as well as for social reasons. Clothing protects the vulnerable nude human body from the extremes of weather.

According to archaeologists and anthropologists[1], the earliest clothing probably consisted of fur, leather, leaves or grass, draped, wrapped or tied about the body for protection from the elements. The invention of clothing may have coincided with the spread of modern Homo sapiens from the warm climate of Africa, thought to have begun between 50,000 and 100,000 years ago. Other cultures have supplemented or replaced leather and skins with cloth: woven, knitted, or twined from various animal and vegetable fibres. More recently man-made fibres have been used extensively for their low weight and high ratio of strength/weight. Although, making the fabrics that go into clothing is not easy. In the thousands of years that humans have spent constructing clothing, they have created an astonishing array of styles. Though the modern trends give fashion as the first priority for owning clothes but comfort value of the cloth can not be ignored.

2.2 Properties influencing comfort characteristics of woven fabric[42].

Fabric performance in relation to better fitting to the human body is an essential requirement of clothing material. Comfort is a wide term used to assign performance of fabric. It is a complex phenomenon involving physical interactions between the human body, the fabric, and the external environment.

The clothing comfort can be segregated into three groups.

1. Psychological comfort
2. Tactile comfort
3. Thermal comfort

Psychological comfort is related to the visual appeal which includes color and luster of fabric. Tactile and thermal comforts are mostly sensed through skin during fabric-skin interaction. Tactile comfort includes fabric surface characteristics and other low stress mechanical properties such as tensile, bending, shear etc. It is also referred to as "Handle of Cloth". Thermal comfort on the other hand involves the heat and moisture transfer characteristics of the cloth, the manner clothing facilitates to maintain balance of heat of the body during various activities.

Fibre material, the construction of fabric (weave structure) and the treatments of fabric finishing greatly influence the cloth comfort properties[66].

Physical properties of fibres such as fineness, stiffness, surface roughness, cross sectional shape and its mechanical properties viz. tensile, bending and compression properties directly reflect in corresponding yarn and therefore the fabric properties.

Linear density, twist, yarn structure as decided by the spinning system, hairiness, bending rigidity, tensile modulus are some of the important yarn properties which play vital role in determining fabric hand character. Coarser yarn increases the cover factor resulting in higher stiffness of fabric. The hard twist in the yarn increases the yarn packing density and so the fabric stiffness.

Fabric sett, cover factor or tightness factor and weave considerably change the performance of the fabric in respect to low stress mechanical properties. Fabric stiffness increases with cover factor. Plain weave fabric has the highest shear rigidity because of more yarn to yarn interlacing with smaller float. Plain weave also gives low thickness as compared to other weaves. Twill weave gives higher smoothness and compressibility than plain weave[2]. But the bending and shear rigidity of twill fabric is significantly lower than that of plain weave. A twill fabric gives better fullness. Fabric with higher crimp gives lower flexural rigidity. Fabric dimensional property such as fabric thickness and aerial density influence the bending, compression and shear properties.

Finishing techniques can altogether change fabric appearance and feel.

2.2.1. Fabric Constructional parameters[32,36,37,65]:

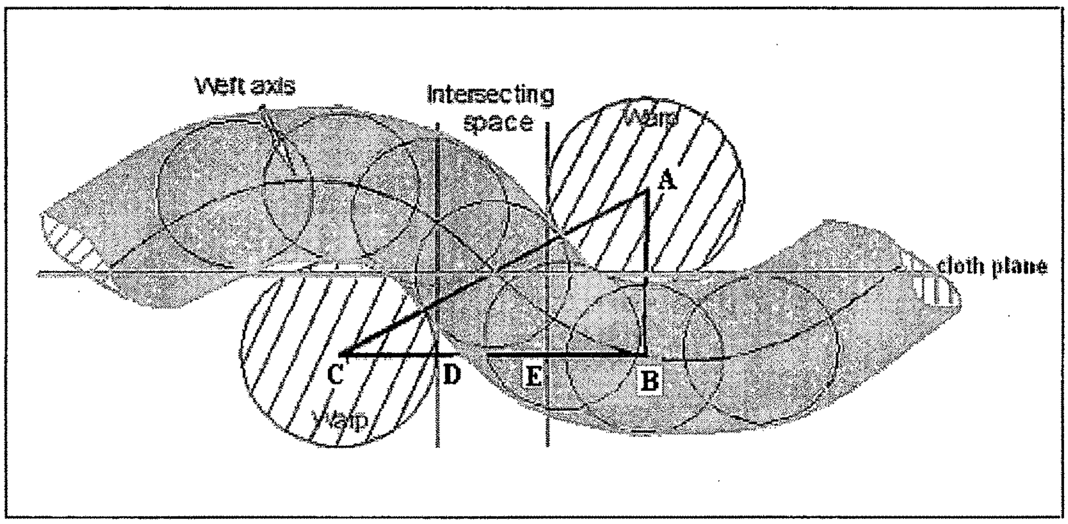


Figure 1. Fabric Cross section.

Fabric cross section in fig .1 shows weft thread interlacement with warp threads. It represents unit cell of a plain woven fabric.

Notations used for the fabric construction parameters are:

N_e – yarn count in English system; d – yarn diameter in inches

M – weave factor; n – Thread per inch

p – inter yarn spacing in inch = 1/n; C – construction factor;

c – crimp in fraction; E_r – ends per repeat of weave;

P_r – picks per repeat of weave; K – yarn cover factor;

I_r – intersections (of transverse thread) per repeat of weave;

e – yarn flattening factor; m – yarn bending rigidity;

t – fabric thickness in mils(1/1000th inch); h – crimp amplitude in mils;

(***Suffix 1 and 2 are for warp and weft respectively***)

Kc – cloth cover; β – yarn balance;

w – fabric weight in grams per sq. mt.

Assumptions considered in derivation of fabric parameters include:

1. Yarn is considered perfectly circular with diameter in inches, $d = \frac{1}{28\sqrt{Ne}}$

   and specific volume of 1.1 cu. cm / gm.
2. Yarn is perfectly elastic and isotropic in nature with has finite rigidity (m).
3. Both the yarns under go equal amount of bending with yarn axes make an angle α = 30° (in fig.1) with the plane of the cloth.

2.2.1.1 Fabric weaves and its appearence[3].

The fabric's integrity is maintained by the mechanical interlocking of the yarns. Woven fabrics are produced by the interlacing of warp and weft in a regular pattern called weave. Plain weave repeats on two ends and two picks and is firmest due to maximum number of interlacements. As the weave float increases the interlacement decreases which on the other hand accommodates more threads per inches. This gives heavier fabrics with higher cover.

Some of the commonly found weave styles used in suiting fabrics which gives desired appearance and properties are:

1. Plain weave: The fabric has symmetrical interlacement, with good stability. High level of yarn crimp imparts relatively low mechanical properties compared with the other weaves. It provides reasonable porosity but poor drape to fabric. With coarser yarn the weave gives excessive crimp therefore it is used in light weight fabrics.

2. Rib: It is extension of plain weave in either warp of weft direction to produce warp rib or weft rib effect. Extension may be on regular or irregular number of threads.

3. Hopsack, basket or matt weave: In which plain weave is extended both in warp and weft direction for equal or unequal number of threads and thus called regular or irregular Hopsack, basket or matt weave. Combining hopsack with warp and weft ribs produces fancy basket. Basket weave is flatter and stronger than a plain weave due to less crimp but it is less stable. It must be used on heavy weight fabrics made with coarser yarns to avoid excessive crimping.

4. Twill: It produces diagonal line on the fabric surface. With reduced crimp the fabric has a smoother surface and better mechanical properties. Regular Twills are produced in balanced (2/2 gaberdine, 3/3 twill etc) or unbalanced (3/1 twill or drill fabric, 1/3 twill etc). In either category ends and/or picks are arranged in

numerous patterns to give special effect for designing of fabric. In pointed twill, the twill line is reversed after half of the repeat while in curved twill any pattern of reversal and repetition of ends produces curved lines.

5. Satin/Sateen : By means of transposition or rearrangement of regular twill interlacement satin weaves are produced. It produces fabrics with a close 'tight' weave. Satin is warp faced re-arrangement while as sateen is weft faced re-arrangement. They are used in combination of other weaves and gives bright appearance and smooth feel.

6. Crepe weaves: Generally combining two different weaves like satin and twill or plain with twill, irregular weaves are produced to give rough surface. Further roughness can be increased by highly twisted crepe yarns too.

7. Bedford cord : It gives longitudinal warp line with fine sunken lines in between to produce stripe in solid colour. It is used in heavier suiting.

Similarly fabrics for other applications are produced with numerous other weaves which are not included in this report.

2.2.1.2 Fabric sett :

It refers to the threads per inch or cm as a measure of fabric density. It varies with yarn count and also with weave. Theoretical maximum sett can be expressed as

$$n_{1max} = \frac{M_1}{M_1 x d_1 + l_{s1} x d_2}.$$

where $M_1 = \frac{E_r}{l_r}$, is a constant of weave structure called weave factor.

Thus fabric sett varies with the weave type and also yarn diameters.

Geometrically intersecting space between adjacent warp in fig.1

$l_{s1} = (d_1+d_2)\cos\alpha - d_1$;

Similarly,

$$n_{2max} = \frac{M_2}{M_2 x d_2 \quad + \quad l_{s2} x d_1}$$

Where $M_1 = \frac{P_r}{l_r}$, and

l_{s2}(intersecting space between adjacent weft) = $(d_1+d_2)\cos\alpha - d_2$.

For square fabric intersecting space is 0.732 (for $\alpha = 30°$),

Hence $$n_{max} = \frac{M}{(M+0.732)xd} \qquad \text{.......(1)}$$

Brierley[32] found that the above theory does not differentiate between different weave types i.e. twill, satin/sateen, or basket weaves of same number of healds. He suggested an empirical formula for square worsted fabric.

$$n_{max} = \frac{M^m}{1.84 \times d} \qquad \text{.......(2)}$$

where m varies with weave.

Weave	M
Twill	0.39
Satin	0.42
Basket	0.45

2.2.1.3 Tightness of weave structure:

The maximum sett for a given yarn counts and weave obtained above is the theoretical value. This fabric is called reference fabric. Any deviation of fabric sett from maximum theoretical value can be compared by the Russell[67] construction factor defined as

$$C_1 = \frac{n_1}{n_{1max}}$$

$$C_2 = \frac{n_2}{n_{2max}}$$

$$C_f = \frac{n_1 + n_2}{n_{1max} + n_{2max}} \quad \text{.......................} \quad (3)$$

It refers to tightness of fabric structure. It affects fabric stiffness, shrinkage in laundering, air permeability etc. Thus depending on end use of cloth, designer can use this construction factor (fabric tightness) to construct similar fabrics from various cloth constructional parameters.

2.2.1.4 Cloth cover:

Pollitt[63] defined cover as a quantity which indicates the extent to which a fabric covers with its material out of the entire area within its outside boundary. It is the ratio of the area covered by the warp and weft threads to the outside area covered by the fabric boundary.

Various measures of cloth cover are

- Fractional yarn cover = d/p
- Yarn cover factor $K = n/\sqrt{Ne}$
- $\text{cloth cover} = \frac{K_1}{28} + \frac{K_2}{28} - \frac{K_1 \times K_2}{28^2}$ ....(4)

Cloth cover affects the passage of light, water and air to decide fabric hand property as well as thermal comfort.

2.2.1.5 Yarn crimp :

During interlacement the axial displacement of warp and weft threads perpendicular to the plane of the cloth causes excess length of thread in the fabric. It is called yarn crimp. Yarn crimp provides extensibility to the fabric and influences fabric mechanical properties. Crimp in the fabric is governed by weave and sett. Pollitt[63] derived an equation relating these parameters based on geometrical assumptions and yarn flattening as

$$\left(\frac{\sqrt{c1\%}}{n_2}+\frac{\sqrt{c2\%}}{n_1}\right)=0.28e\left(\frac{1}{\sqrt{N_1}}+\frac{1}{\sqrt{N_2}}\right)\quad\text{.............................(5)}$$

e = b/d is degree of flattening where b and d are yarn diameter perpendicular to cloth plane after and before flattening.

Determination of yarn flattening factor:

On flattening yarn becomes elliptical in shape with a and b as major and minor diameters respectively. If the area of yarn cross sections is assumed to remain the same before and after flattening then,

$$\frac{\pi}{4}Xd^2=\frac{\pi}{4}X\,a\,X\,b$$

$$\therefore d=\sqrt{a\,X\,b}$$

And Flattening factor $e = b/d$

$$=\sqrt{b/a}$$

Hemilton's method[64] under condition of thread tension and compression similar to those occurring during weaving determines the yarn major and minor diameters and flattening factor $e=\sqrt{b/a}$.

Cross section of any 2-fold yarn will give a value of b/a approaching 0.5 in which case e = 0.707.

Peirce[36] suggested that for a plane fabric of roughly square structure,

$$\sqrt{c_1} + \sqrt{c_2} = \frac{K1 + K2}{4} \quad \text{.........................} \quad \text{...} (6)$$

But it is truly geometrical method and yarn flexural rigidity (m) has not been considered. Balance of rigid resistance of the Elastic thread model by Peirce[36] gives the ratio of crimps

$$c_1/c_2 = \left(p_2/p_1\right)^4 x \left(m_2/m_1\right)^2 \quad \text{...} (7)$$

Thus yarn bending property and fabric forming parameters like weave, sett and the tension during weaving affects the final crimp balance in the fabric[43]. Crimp increase with the close setting of the yarns, but the degree of twist in the yarn affects the magnitude of the crimp. There is minimum crimp with soft twisted yarn which increases with harder twisted yarn.

2.2.1.6 Fabric thickness :

It gives the third dimension to the fabric structure. Geometrically it is given in thousandths of an inch either by[57]

$$t = h_1 + \frac{36}{\sqrt{N_1}}; \quad \text{where} \quad h_1 = 136\frac{\sqrt{c1\%}}{n_2} \qquad \text{or}$$

$$t = h_2 + \frac{36}{\sqrt{N_2}}; \quad \text{where} \quad h_2 = 136\frac{\sqrt{c_1\%}}{n_1} \qquad \text{...................................} \quad (8)$$

which ever is greater.

Thus fabric thickness depends on yarn diameter, the weave & the yarn crimp. In practice it is determined by precise measurement of the distance between the pressure foot and anvil at two arbitrary pressures. Pressure foot must be lowered on the sample at slow rate of 2 /1000 in/sec.

Fabric thickness plays a critical role in fabric handle as well as its thermal properties. Increase in fabric thickness increases fabric stiffness which results in a reduction in the true fabric/skin area of contact. The air pockets between fabric and skin affect the rate of cooling from fabric.

2.2.1.7 Fabric weight (GSM):

The weight of a fabric is an important parameter. It makes graceful fall. Lighter fabrics with low-drape and low-shear (example: cotton organdy) often crumple in use. Large amounts of heavy fabric can be uncomfortable to wear.

Fabric weight is expressed as grams per square meter (ounces per square yard) or grams per running meter (ounces per running yard).

Analytically weight of fabric per running meter is calculated as

$$R = \text{weight of warp} + \text{weight of weft}$$

$$= \frac{\text{cloth width } X n_1 X (1+c_1) X 453.6}{840 X Ne_1 X 0.914} + \frac{\text{cloth width} X n2 X (1+c_2) X 453.6}{840 X Ne_2 X 0.914}$$

$$= 0.590 X \text{cloth width } x \left[\frac{n_1 X (1+c_1)}{Ne_1} + \frac{n2 x (1+c_2)}{Ne_2} \right] \quad \text{..................................(9)}$$

Neglecting the effect of selvedge, weight per unit area can be obtained from weight per unit length by

$w = 39 X R/ W$ ....(10)

where W is the fabric width in inches.

2.2.2 Fabric Mechanical Properties[80,81].

Handle reflects a mechanical interaction between human skin and fabric in which both the fabric surface and the material bulk are being spontaneously tested by exerting external body movement. The physical properties of fabric are affected by yarn and weave structure and also the warp and weft tension during weaving[4,5,6]. The mechanical properties of fabric longitudinal extension and compression, shear and bending have an important influence on the performance of fabrics during use. Fabric low stress mechanical properties and surface characteristics contributing to its handle include extensibility, stiffness, shear deformation, compression properties, surface smoothness etc[38,46].

Notation used for fabric Mechanical properties are

b = Bending length in cms; G = Flexural rigidity in gm-cm;

q = Bending modulus in kg per sq.cm;

S = Shear stiffness in gf per cm per degree.

E_a = Tensile modulus where a = 1, 2, & 45 for warp, weft and 45 degree bias direction respectively.

2.2.2.1 Fabric extensibility[43]:

Yarn crimps in the fabric correspond closely to the fabric extensibility which increases with the increase in sett. With open woven cloth the constant tension on the warp prevents any great amount of bending unless the weft is tensioned considerably. The extensibility decreases as the number of interlacement of the weave decreases from plain, to 2/2 twill and matt weaves.

Single thread strength of the yarn in the fabric exceeds the unwoven yarn strength. This shows the structure of fabric influences its strength. The mutual binding of warp and weft yarns at the interaction is governed by type of weave and tightness of structure i.e. fabric sett. Also compressibility of the thread when interlaced is affected by the amount of twist and this has an effect upon the mutual binding of the constituent yarns in the fabric. Comparing the twill and satin weaves, the frequency of interlacement is more with the satin than twill weave which gives more strength.

On uni-axial tensile tester of raveled fabric strip test[3], the load at 2% extension is converted into modulus by dividing load by the fabric cross section. Here fabric thickness at 10 gm per sq.cm is taken for fabric cross sectional area.

2.2.2.2 Fabric stiffness[60]:

Peirce[19] defined bending length as the length of a rectangular strip of fabric which bends under its own mass to an angle of 7.1°. It refers to the interaction between fabric weight and fabric stiffness. Heavier fabric will bend easily giving lesser value of bending length. But it may appear stiffer while bending through fingers while handling. Thus Flexural rigidity has been obtained from bending length to compare fabric of varying weight.

Flexural rigidity is a measure of stiffness where two equal and opposite forces are acting along parallel lines on either end of a strip of unit width bent into unit curvature in the absence of any tension. It affects the handle of fabric sensed by the fingers. The stiffer fabrics will have a higher bending length and the flexural rigidity value.

G in gm-cm x $10^{-4} = w \times b^3$..(11)

Bending modulus of cloth is obtained from Flexural rigidity

q in kg /$cm^2 = 12 \times G / t^3$..(12)

where t is fabric thickness in mm. It takes into account the fabric thickness.

Bending stiffness depends on fabric thickness, the thicker the fabric, stiffer it is if all other factors remain the same. The rigidity of cloth given by bending modulus governs the fabric puckering in application of stress say at cuffs and collar of a garment. During fabric bending, the outer layer of fabric stretches and inner layer contracts. If the fabric is unable to accommodate this change it puckers.

2.2.2.3 Fabric Shear deformation [8,68]:

Shearing forces are applied to the fabric while it is fitted onto a spatial surface. It enables fabric to conform to the shape of the body. Formability differentiates fabric from other thin sheet material such as paper or plastic film. It is defined as the maximum compression a fabric can take up before it buckles[8].

During fabric shearing complex stresses act on fabric which tend to cause extension along one diagonal and compression along the other. This causes slippage of warp and weft at the intersection. Slope of the shearing force v/s shearing deformation curve is called shearing rigidity. Thus shearing rigidity is highest in the beginning of shearing deformation which affect the stiffness of the fabric handle property. Total shearing force is the sum of the frictional resistance at all the intersecting points of warp and wefts which is affected by weave and sett. The yarn tension generates a pressure at intersecting points increasing the frictional force.

In the KES-FB1 Tensile-Shear Tester[8] opposite and parallel forces are applied to the fabric as in fig.2 until a maximum offset angle of 8° is reached.

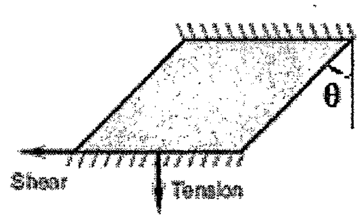


Figure 2. fabric shear on KESF tester

Assuming linear relationship between shear stress F and shear deformation tanθ, F = S tanθ where S is Shear stiffness (gf per cm per degree) is the ease with which the yarns slide against each other resulting in pliable structures. Lower values indicate less resistance to the shearing movement corresponding to a softer material having better drape. Hysteresis of shear force (gf/cm) at 0.5° & at 5° shear angle is measured to characterize fabric shear property.

Alternatively Young's modulus in bias direction (G) can be obtained as[7]

$$\frac{1}{S}=\frac{4}{E_{45}}-\frac{1-\sigma_2}{E_1}-\frac{1-\sigma_2}{E_2} \qquad (13)$$

Where σ1 and σ2 are poisson's ratios.

Generally warp and weft direction modulus are much larger as compared to modulus in bias direction so a rough approximation of $E_{45} \approx 4 \times S$.

Jurgita & Eugenija[8] detected the onset of specimen wrinkling as a measure of fabric shear. In uni-axial tensile test of the bias-cut specimen on an extensometer, the angle between warp and weft change. At the critical shear angle fabric buckles i.e. wrinkling is observed as in fig. 3.

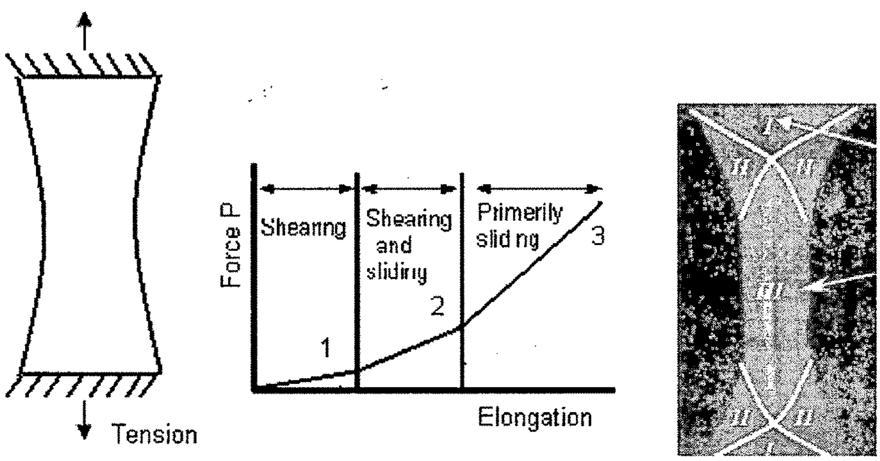


Figure 3. Fabric shear in bias extension

The load and elongation is a tri-linear relationship. The first part of the represents the initial shearing when the angle between threads changes in the central part (zone III) of the stretched fabric specimen. At the first point when the critical shearing angle is reached (point 1 in Figure 3), the threads in the specimen's central part are packed tightly. The increase in tension causes a lateral compression of the threads, so the buckling wave is formed. The second part represents thread shearing and sliding. Point 2 of the tension curve indicates the beginning of the third part of the curve, when the predominant mode of deformation becomes thread sliding.

The buckling of a specimen during shearing is associated with the level of compressive stresses, thickness and stiffness of a fabric and its structure.

2.2.2.4 Compression properties[59]:

During compression of cloth perpendicular to the plane of cloth, the fabric undergoes three stages of deformation. Firstly the fibres protruding from the surface are compressed. The resistance to compression in this region comes from bending of the fibres. Secondly inter yarn spaces between the fibre are compressed until fibres are all in contact with one another. The yarn is flattened and inter fibre friction provides the resistance to compression in this stage. In the third stage the resistance is provided by the lateral compression of the fibres themselves. The elastic deformation in the first and third stage of compression due to fibre bending and the fibre lateral compression cause the fabric to regain most of its original thickness. But the hysteresis i.e. difference in thickness between the loading and the unloading curves is due to the internal fibre friction in the second stage of the fabric deformation. It can be used as a measure of resilience. Fig.4 shows the change in thickness with pressure and recovery in thickness as the pressure is removed. The steep initial slope of the curve contains information about the handle of the fabric.

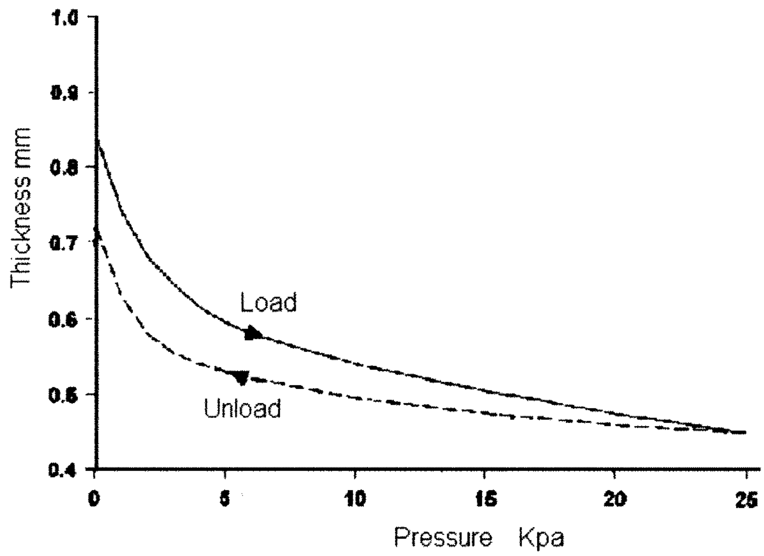


Figure 4. The change in thickness with pressure

Peirce[19] defined hardness and compression modulus as a measure of the compactness of the material. Hardness or Resistance to compression (H) in mgm/cm^3 is measured by determining thickness under different pressure. Numerically it is the ratio of the difference of pressure to the difference of thickness such as may be appreciated by pressing with a finger tip. Alternately, the ratio of stress (difference in pressure) to strain (the difference in thickness divided by the original thickness) gives a Young's modulus' for the material in a direction normal to the surface, called the compression modulus, 'h'. It is evaluated from the hardness H.

2.2.2.5 Surface smoothness:

Fabric friction during fabric/skin interaction due to body movements has a significant effect on the fabric tactile comfort[54,57]. High frictional forces resisting body movement can be a source of discomfort.

Fabric friction is defined[57] as the resistance to motion when a fabric is rubbed tactually between the finger and thumb. Subjectively it is expressed as rough or scratchy by assessing the cloth surface by the thumb or finger.

The frictional interaction depends on

- Fabric surface roughness: It is affected by the type of fibre, yarn structure and fabric weaves. For a fibre type and yarn structure increasing threads per inch, the fabric surface becomes smoother. Increasing yarn linear density (diameter) fabric surface roughness increases due to increased crown height or crimp amplitude.
- Fabric/skin contact area: Fabric surface exhibits many ridges and indentations by virtue of its structural composition. Human skin also has ridges and indentations as shown in Figures 5.

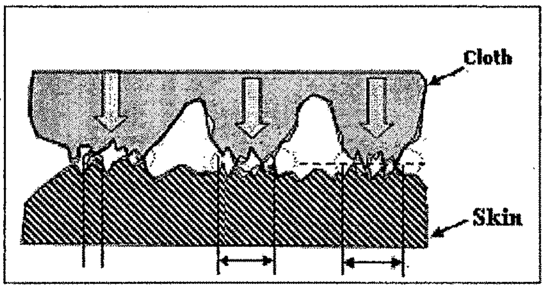


Figure 5. Fabric skin interaction[69]

The true area of contact between skin surface and fabric is a complex parameter affected by yarn and fabric structural parameters.

- The pressure applied on the skin by the fabric[69] : Pressure on the contact surface $P = KA^{\alpha}$ ....(14)

where A is the true area of contact, K is a stiffness factor, and α is a shape factor determined by the nature of deformation at the junctions of contact under pressure. The pressure exerted by fabric on skin ranges from 0 to 0.12 KPa (i.e. 0 to 0.83 PSI).

Techniques have been employed to assess the fabric static and dynamic friction quantitatively as well as determine the factors that may affect it. The difference between static and kinetic frictional forces (F_s-F_k) has been reported to be strongly correlated with fabric handle. For a scroopy handle a higher magnitude of F_s-F_k is required. Relationship between subjective assessment and objective measurement of the properties has a linear function on a logarithmic scale[9].

Various measurement techniques used to measure fabric friction include

1. Flat bed method[70]:

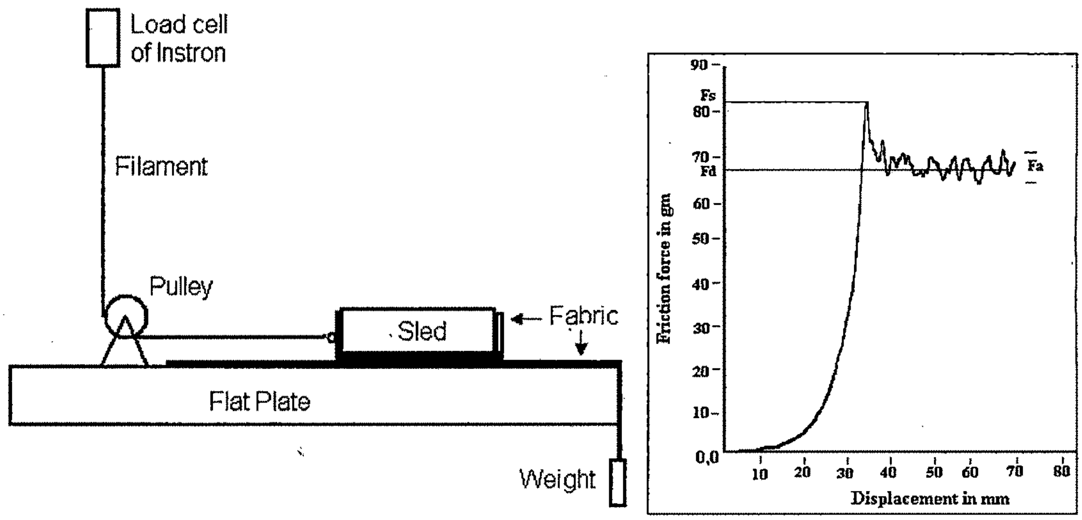


Figure 6. Sled test apparatus for fabric friction

The principle of measurement is based on the rectilinear motion of a wooden sled pulled over a rectangular fabric specimen mounted on horizontal platform. Static & kinetic frictional resistances were determined directly from the friction trace on Instron tester. The sled is pulled by the cross head at a constant speed by means of an inextensible towing yarn passing over a frictionless pulley as shown in fig.6. The highest peak at the commencement of motion was taken as the static frictional resistance (F_s) The mean of peaks & troughs (equivalent to drawing a straight line to the middle of the stick slip pulses) was taken as a dynamic frictional resistance (F_d) and height of pulses of the stick-slip traces was taken as the frictional amplitude(Fa).

2. Inclined plane method:

Shirley Fabric Friction Tester (SDL M264) works on inclined plane principle. It determines the frictional behavior of fabrics according to BS 3424 standards by measuring movement against a standard fabric when raised through an angle at a pre-determined rate.

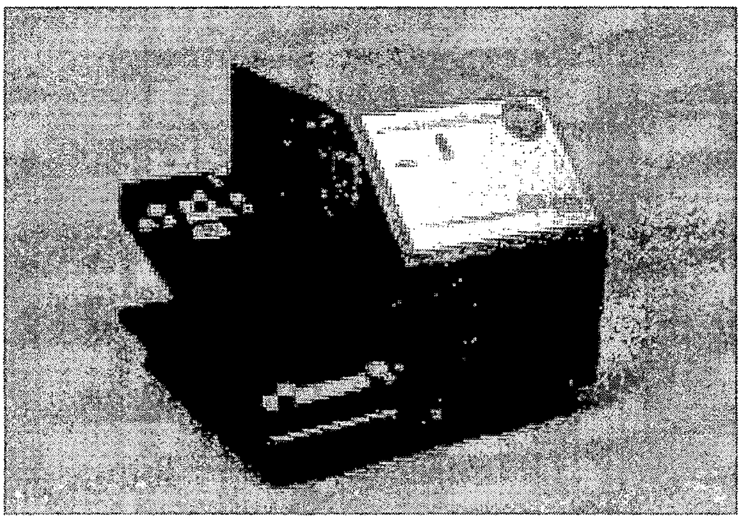


Figure 7. M264 - Shirley Fabric Friction Tester[85]

A sled on which fabric sample is mounted is placed on a level platform against a micro switch. The standard friction fabric covers the platform. The platform tilts at a uniform rate of 15 degrees per minute. When the sled slips off the platform and no longer contacts the micro switch the motor stops. The angle of surface drag can be read from the scale in degrees. Smoother fabric gives lesser angle of surface drag. The angle gives an indication of the fabric friction, but not the absolute value of the coefficient of friction.

3. KES-F SURFACE TESTER[10] (The Kawabata Evaluation System)

The KES-F surface tester instrument is designed to measure fabric friction and surface roughness.

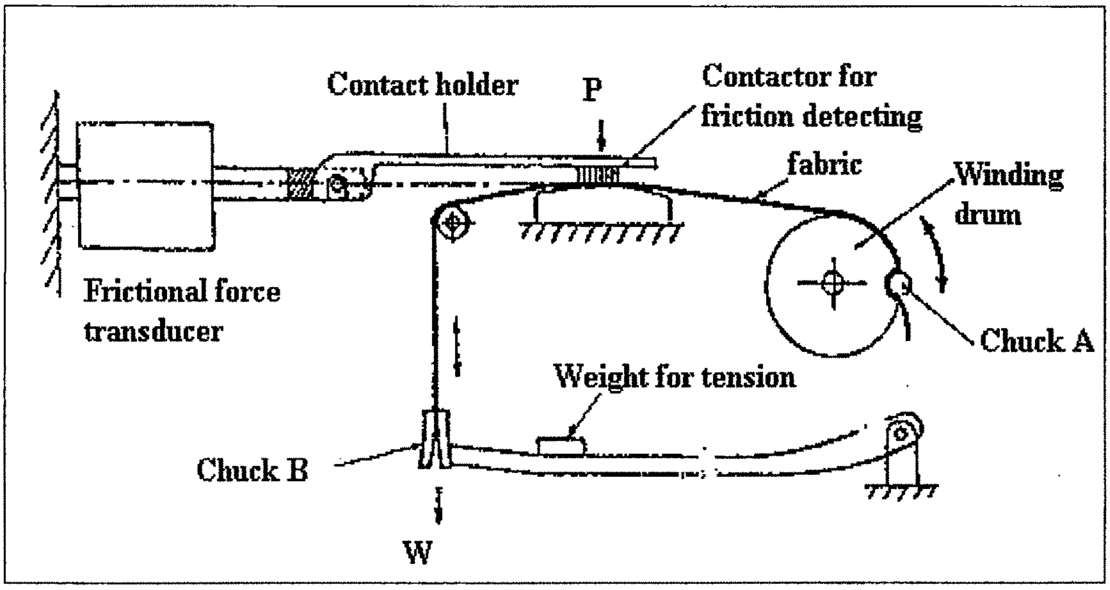
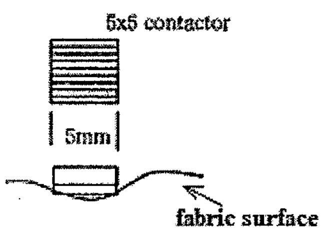


Figure 8. Kawabata Friction tester unit



For both surface and friction measurement, the specimen is moved horizontally for a distance of 2 cm over a period of 20 sec at a constant velocity of 0.1 cm/sec on a smooth steel plate. The tension of the specimen is kept at 20 gf/cm when the contactor is in its position. The transducer consists of 10 steel piano wires of 5mm each arranged side by side over 5 mm thus providing friction surface of 5mm x 5mm. Diameter of wire is 0.5 mm. The detector is connected by a free joint with the end of the transducer, which detects the frictional force picked up by the detector and simulate human finger. The friction force between the fabric surface and the metal detector measures surface property. Variation of friction coefficient of the fabric changes during the measurement, and the two parameters, MIU (mean friction coefficient) and MMD (mean deviation of friction coefficient) present the fabric friction property. Both the above two measurement data from KES tester are useful in the simulation of fabric surface characteristics but MMD is sensitive to fabric smoothness property.

Auburn Beard Test[11]:

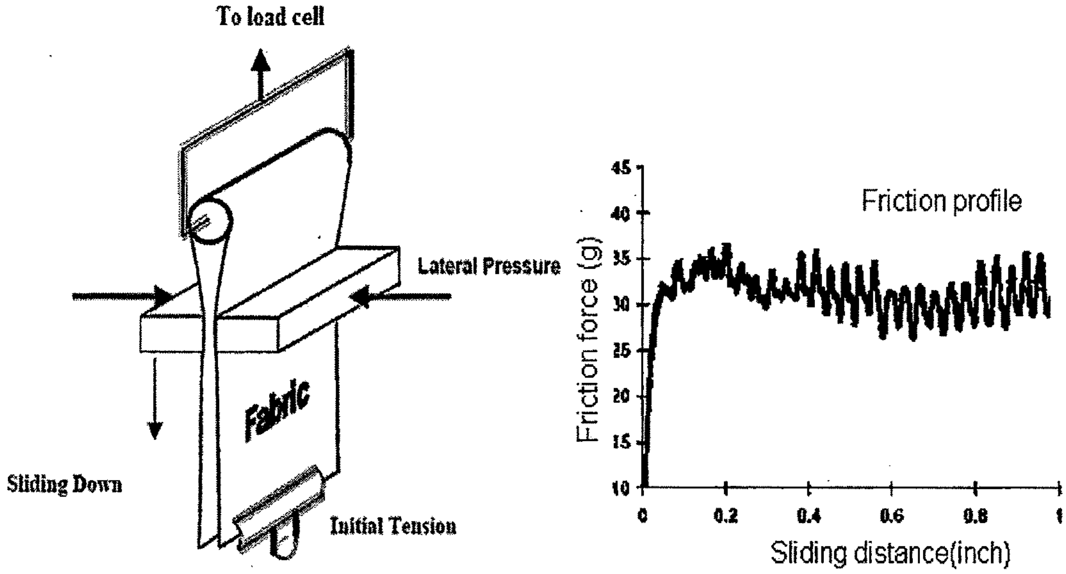


Figure 9. Auburn Beard Fabric Friction Testing Device.

The schematic diagram of the Auburn Beard Test to measure the friction force of textile fabric is shown in Figure 9. Fabric applied with initial tension has been rubbed by downward moving slides under certain lateral pressure. The force picked up by the load cell has been obtained in form of the friction profile to give friction force and also the stick-slip patterns obtained as shown in figure gives smoothness of fabrics.

4. FRICTORQ, FABRIC SURFACE FRICTION TESTER[71]:

The principle is based on measurement of torque between two flat rubbing surfaces - the upper one with a contact surface of an annular geometry, which is placed over a horizontal flat lower sample. The second one is forced to rotate

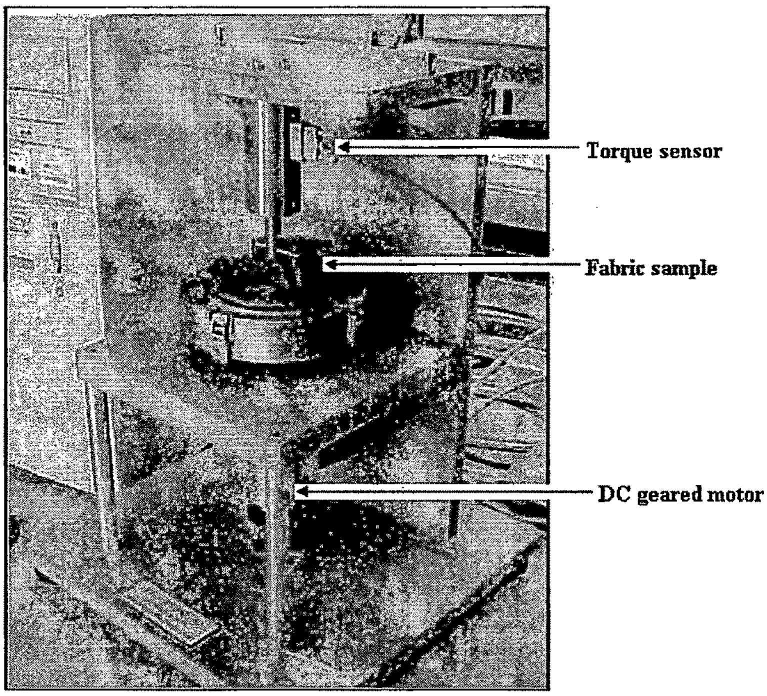


Figure 10. Frictorq friction tester

around a vertical axis at a constant angular velocity. Contact pressure between both samples is kept constant and is given by the ratio between the own weigh of the upper element and contact area. Friction coefficient is then proportional to the level of torque being measured by means of a high precision torque sensor. The signal from the torque sensor is digitalised through an electronic interface and fed into a PC where friction coefficient is worked out.

2.2.3. Fabric thermal comfort parameters.

The thermal properties are the most important factors contributing to (dis)comfort in hot weather. Improper clothing creates a barrier between the skin surface and surroundings influencing the heat exchange by convection, radiation and also the evaporation of excreted sweat. The influence of clothing on the heat exchange[33,49] between the human body and the surroundings is very complex. The human body is designed to maintain thermal equilibrium with its outside environment, so that the body heat produced by metabolism roughly equals the amount of body heat lost to ambient air. It depends on factors described by the general heat balance equation of human body[72] described as

Heat produced in the body = Heat loss at the skin + Heat loss due to respiration.

$$M - W = \{(C+R) + Em + Es\} + (Cres + Eres) \qquad (15)$$

where M = rate of internal or metabolic energy production.

W = rate of mechanical work.

C = rate of convective heat loss from the skin.

R = rate of radiation heat loss from the skin.

E_s = rate of evaporative heat loss from the skin through sweating.

E_m = rate of evaporative heat loss from the skin through moisture diffusion.

C_{res} = rate of convective heat loss from respiration.

E_{res} = rate of evaporative heat loss from respiration.

All terms in the equation are in watt per sq. meter. .

The primary role of clothing in the process of heat balance is to act as an adjusting media between the human body and its environment. It modifies the heat loss from the skin surface. At the same time it has the secondary effect of altering the moisture loss from the skin. When the operative temperature drops to lower values, the dry heat exchange is increased and the evaporative heat loss is mainly respired vapour loss. The skin temperature and the temperature of superficial and deep tissues drop, resulting in negative heat storage.

When the operative temperature exceeds 29°C, the rate of evaporative heat loss is significantly increased in order to counterbalance the reduction of dry heat exchange to maintain the thermal equilibrium. If the evaporative heat loss is inadequate, the body sweats. Typical activity levels of people in summer causes skin surface wet with 20% of the sweat. There exists a positive rate of heat storage and body temperature tends to rise. Body temperature above 43 °C may cause death.

The exchange of heat and moisture in the dermisphere i.e. the air space between the skin and the clothing depends on the choice of a fabric. At normal metabolic rate of 1 met (58.2 W/m^2), there is neither body cooling nor body heating at an operative temperature of about 25.5 °C for light clothed person and 31 °C for nude person.

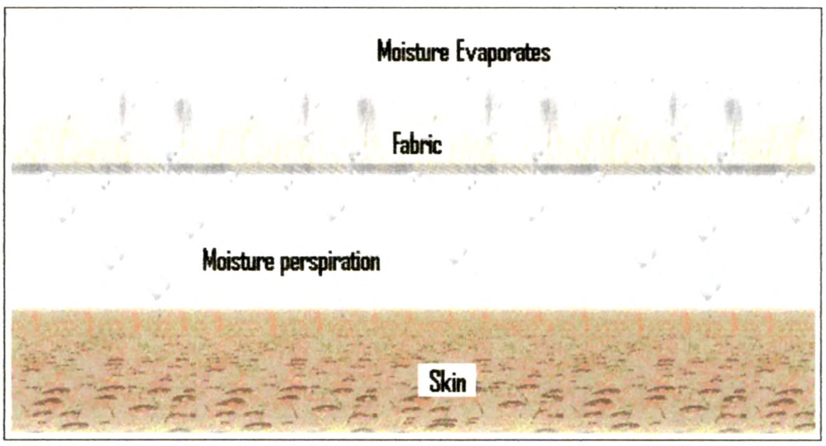


Figure 11 Moisture exchange in the dermisphere

Micro pores in the fabric enable the heat and water vapour from skin to escape to the atmosphere simultaneously allowing outside fresh air to enter. This keeps the skin dry and comfortable. If the fabric is not effective at transporting moisture it causes uncomfortable feeling of damp dermisphere.

The type of fibers and construction of the fabric directly affect the climate in the dermisphere and determine how comfortable, or uncomfortable, you are regardless of the air temperature or activity in which you are engaged. Air Temperature, Relative Humidity and Air Velocity are important factors influencing Thermal Comfort. The accumulation of moisture is mostly a drawback. Moisture absorbed by the fabric reduces clothing thermal insulation by increasing thermal conductivity of fabric. This causes sudden cooling of skin called after-chill.

Summer clothing should ensure appropriate heat transfer between the human body and the environment. Physical characteristics of fabric like fabric weight, its thickness, weave, cover etc affect thermal comfort character.

Thermo-physiological comfort of cloth are measured by fabric properties such as

2.2.3.1. Air Permeability:

Air permeability describes the characteristic of fabric to allow air to pass through. It is the rate of air flow passing perpendicular through a known area under a prescribed air pressure differential between the two surfaces of the material.

It is defined[3] as the volume of air in milliliter which is passed in one second through 100 mm^2 of fabric at a pressure difference of 10 mm head of water. SI unit is $cm^3/sec/cm^2$ and in inch-pound is $ft^3/min/ft^2$.

$$\text{Air permeability } A = \frac{V}{F \times t \times \Delta p} \qquad \text{.......(16)}$$

Where V - capacity of the flowing medium,

F - the area through which the medium is flowing,

t - time of flow, &

Δp - drop in pressure of the medium.

ASTM D-737 standard is used to measure air permeability of Textile fabrics. Air permeability depends on fabric porosity, which means the number of canals in the fabric, its cross section and shape. Fabric construction and finishing techniques can have an effect on air permeability by causing a change in air flow paths through the fabrics.

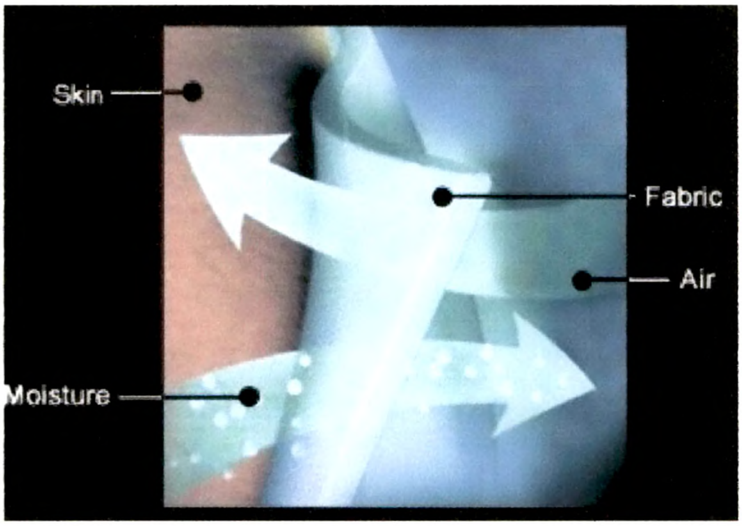


Figure 12. Air & moisture permeability through garment

Air permeability is a hygienic property which influences the flow of gases from the human body to the environment and the flow of fresh air to the body. A fabric that is permeable to air is in general, likely to be permeable to water as well, either in the vapour or the liquid phase. Thus, the moisture-vapour permeability and the liquid-moisture transmission are normally closed related to air permeability. Thus thermal properties are essentially influenced by air permeability.

Fabric thickness and cover factor affect its permeability. Increase in yarn twist increases the circularity and reducing the yarn diameter. This results in decreasing cover factor hence increasing the air permeability. Yarn crimp and weave permit yarn to extend easily increasing the air permeability. Considering the influence of weave, the highest value is observed for twill and the lowest for plain weave. Hot calendaring flattens the fabric, thus reducing air permeability. Fabric with different surface textures on either side can have different air permeability depending upon the air flow.

2.2.3.2. Thermal insulation:

It is an important measure of clothing functional design and suitability of clothing for intended end uses. It determines

- heat stress of a clothed person in a hot environment in terms of sweat rate and skin wetness and
- cold stress in a cold condition in terms of the required insulation.

The heat flow through a fabric is due to combine effect of conduction and radiation, convection within the fabric being negligible. Although large air gap between the layers of clothing and also between body and garment (loose fit) ensures sufficient air movement leading to heat loss by convection.

Thermal conductivity, k, is the property of a material that indicates its ability to conduct heat.

In physics, heat conduction $H = \frac{\Delta Q}{\Delta t} = k \times A \times \frac{\Delta T}{x}$ ....(17)

where $\frac{\Delta Q}{\Delta t}$ is the rate of heat flow, k is the thermal conductivity, *A* is the total cross sectional area of conducting surface, ΔT is temperature difference, and *x* is the thickness of conducting surface. Thus conduction loss is determined by the thickness(t) of the fabric and the thermal conductivity.

Thus thermal conductivity $k = \frac{\Delta Q}{\Delta t} x \frac{1}{A} x \frac{x}{\Delta T}$. Its SI unit is watt/(m -° K). Thermal conductivity of fabric is the combination of the conductivity of the air k_a and that of the fibres k_f and has been given by

$k = (1\text{-}f)\ k_a + k_f$,..(18)

where f is the fraction by volume of the fabric taken up by fibre. The conductivity of air is 0.025 watt/m- ° K and that of fibres is 0.01 watt/m- ° K.

Thus hairy and bulky structure of fabric entraps more air within it and also increases the air gap between the skin and the fabric hampering the heat flow. Radiation heat transfer between the body and the external environment is indirect and depends on the absorption and emission property of the fibres. Dense fabric from finer fibres reduces the radiation heat flow[56].

Thus fabric thickness and number of layers, drape, fibre type, yarn hairiness etc are of critical importance to thermal insulation of the fabric. Fabric thermal resistance increases with increase in thickness, decreasing of heat losses for the space insulated by the textile.

Fabric thermal insulation is measured by its thermal resistance value(r). It is reciprocal of thermal conductance and hence has SI unit as m^2 °K per watt. Cloth thermal resistance is measured in two different units of clo or tog value.

1. Clo is an American unit. It is the resistance necessary to keep resting person (producing heat at rate of 56 watt / m^2) comfortable at 21°C and at an air movement of 0.1 m/s.

'Clo' Values for Clothing

Clothing combination	Clo	M^2K/watt
Naked	0	0
Shorts	0.1	0.018
Typical tropic clothing outfit	0.3	0.047
Light summer clothing	0.5	0.078
Working cloths	0.8	0.124
Typical indoor winter clothing combination	1.0	0.155
Heavy traditional European business suit	1.5	0.233

Guarded hot plate device is used to measure thermal conductivity of cloth.

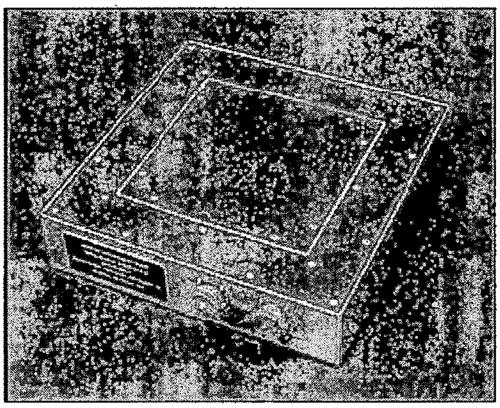


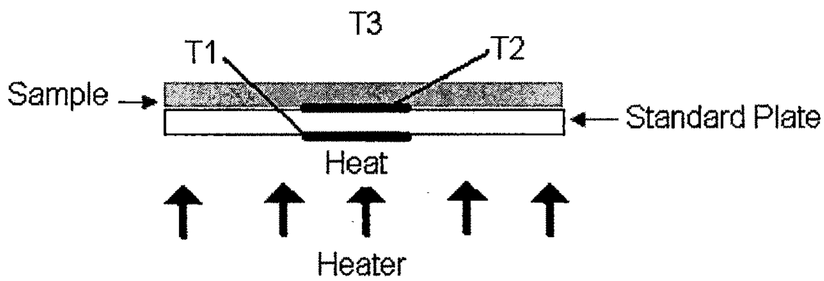
Figure 13. Guarded hot plate device by Measurement Technology Northwest

It consist of a 8" or 10 "square copper thermo test plate with lateral and lower thermal guards. A stable resistance wire heating generates uniform heat flux to maintain 35 °C to simulate skin surface temperature. Fabric samples placed on the test plate and heat transfer from the plate through the material into the ambient test environment of 21°C & 65% RH is measured to determine fabrics' conductance value (watts/m^2 °C) and the conductivity (watts/m °C) value i.e. normalization of conduction on a per thickness basis for material comparisons. Higher values indicate there is greater heat loss.

2. Tog is British unit proposed by Shirley Institute for thermal resistance. Fabric has thermal resistance of one tog when temperature difference between two surfaces of 0.1 °C produces a heat flow equal to one Watt/ m^2.

Thus 1 tog = 0.1 m^2 °C / w and 1 Clo = 1.55 tog = 0.155 m^2 °C /watt.

Tog meter measures thermal resistance of the test fabric by comparing the temperature drop across it with the temperature drop across the standard material of known thermal resistance. Shirley tog meter[73] in figure 14 has a heater controlled by a digital temperature controller housed in a special cabinet in which air flow can be regulated.



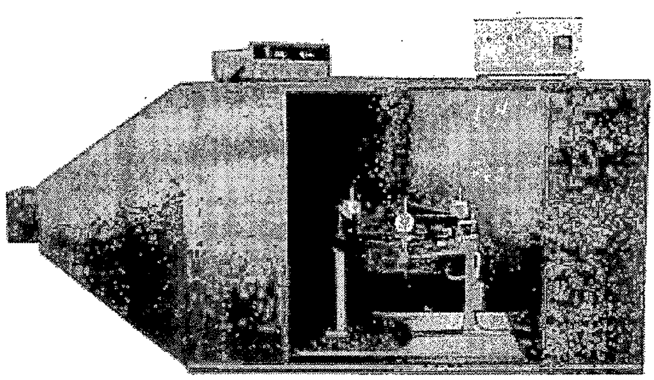


Figure 14. Single plate togmeter

The air above the specimen has a considerable thermal resistance which is first measured without sample being placed.

$$R_{air} = R_{standard} \times \frac{T2-T3}{T1-T2} \quad \text{.......(19)}$$

where T_1, T_2 and T_3 are the temperatures of the heater, the standard plate and air temperature respectively.

Then the temperatures are noted with sample placed on the standard plate.

The thermal resistance of sample

$$R_{sample} = R_{standard} \times \frac{T2-T3}{T1-T2} - R_{air} \quad \text{.......(20)}$$

- **KAWABATA 's THERMO-LABO[75] :**

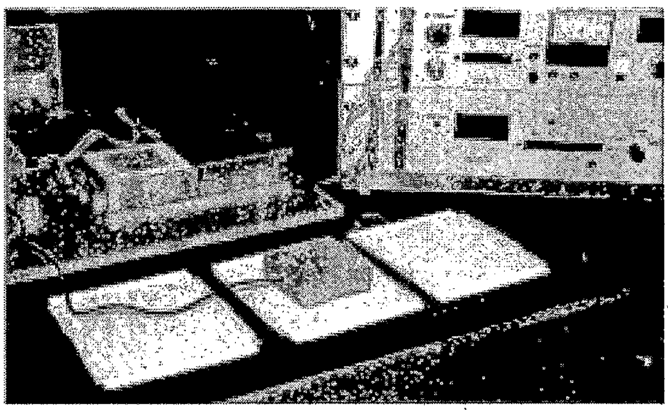


Figure 15. Thermolabo apparatus by Kawabata

The Thermolabo instrument consists of three main elements:

T-Box – It consists of a thin copper plate of 3 cm x 3 cm attached to a block of an insulating material. The change in temperature of the copper plate is measured by a temperature sensor of high response speed attached to the back side of the copper plate.

BT-Box - The BT-Box is an insulated hot plate capable of being controlled from room temperature to up to 60°C.

Water-Box or Styrofoam plates - The water-Box is a constant temperature plate through which water at a constant temperature flows to act as a heat capacitor having infinite capacity. Styrofoam plates are used instead of the Water-Box during "Qmax" test on thin fabrics and when room temperature and humidity are controlled.

It measures fabric thermal properties in terms of

1. Q_{max} value which indicates the instantaneous warm/cool feeling sensed when there is initial contact of fabric with the skin surface. A higher value of q_{max} denotes that there is more rapid movement of heat from the body to the fabric surface resulting in a cooler feeling fabric.
2. Ratio of maximum and stationary heat flow density. With time the heat flow stabilizes itself at determined level qs, which is called the stationary heat flow density.

The room temperature is first sensed by placing the "T-Box" with the copper plate facing upwards. The BT-Box is then set to a temperature of 10°C higher than the T-Box. The guard heater on the BT-Box is also set to the same temperature. When the temperature of the BT-Box and BT guard reach the set temperature, the T-Box is placed face down on the BT-Box until its temperature reaches the BT-Box temperature. The fabric sample is then placed on the Styrofoam plates or the water box. For Qmax measurement, the T-Box is removed from the BT-Box and immediately placed on the room temperature equilibrated sample. The peak in transient heat loss from T-Box to the fabric is Qmax and is measured from the temperature of the T-Box which is converted to Qmax by analog circuits.

Alambeta device[74]:

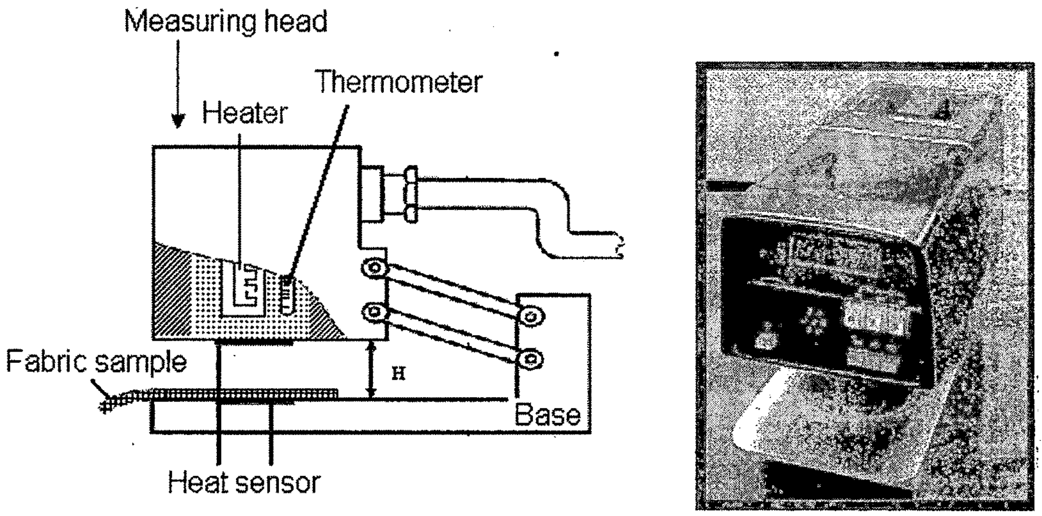


Figure 16. Alambeta device

It is constructed by Hes (Czech Republic) which measures transient and steady-state thermo-physical properties of cloth. Six parameters related to thermal insulation of cloth can be obtained in less than 5 min.

1. Thermal conductivity $\lambda = \dfrac{Q}{F\tau\dfrac{\Delta T}{\sigma}}$ watt - m $^{-1}$K $^{-1}$, ...(21)

where Q - amount of conducted heat ; F - area through which the heat is conducted; τ - time of heat conducting; ΔT - drop of temperature; σ - fabric thickness. It is normalization of conduction value on a per thickness basis.

2. Thermal diffusion $a = \dfrac{\lambda}{\rho\, c}$ m^2s^{-1} ....(22)

where ρ - fabric density & c - specific heat of fabric.

It is related to the heat flow through the fabric structure

3. Thermal absorption $b = \sqrt{\lambda \rho c}$ $Ws^{1/2}m^{-2}K^{-1}$ ....(23)

It is a surface property that allows assessment of the fabric's character in the aspect of its 'cool-warm" feeling. Fabrics with a low value of thermal absorption give us a "warm" feeling. The finishing processes can change thermal absorption.

4. Thermal resistance $r = \frac{\sigma}{\lambda}$ m^2KW^{-1} ....(24)

It is a very important parameter from the point of view of thermal insulation.

5. Stationary heat flow density $q_s = \frac{Q}{F\tau}$ $W\,m^{-2}$ ....(25)

It acts at the contact point when fabric comes in contact with a cold body.

6. The ratio of maximal to stationary heat flow density v: The maximum heat flow density (i.e. qmax) from the skin to the fabric appears at the moment of contact of the cold fabric with human skin. With time the heat flow stabilizes itself at determined level q_s, which is called the stationary heat flow density. The maximum heat flow is one of the parameters which characterise fabric thermal insulation, and similar to thermal absorption, is a surface property.

2.2.3.3. Moisture Vapour permeability[34,77,78,83]:

Moisture transfer through fabric occurs due

1. moisture vapour permeability through fabric pores and
2. absorption of moisture by fabric.

Fabric made from hygroscopic fibres absorbs vapour and bring it on the surface of cloth from where it evaporates into atmosphere. This keeps the dermisphere free from sweat. Non-hygroscopic clothing poses a risk of sweat accumulation.

Skin remains wet and the cause discomfort. The absorption capacity (called regain) is expressed as the amount of water vapour that is absorbed by 100 gm of dry fibre at the relative humidity of 65%. Accordingly fibres are classified as:

· low absorption-acrylic, polyester (1 to 2 g per 100 g)

· intermediate absorption-nylon, cotton, acetate (6 to 9 g per 100 g)

· high absorption-silk, flax, hemp, rayon, jute, wool (11 to 15 g per 100 g).

Moisture vapour permeability also called breath ability of clothing is another important parameter which ensures escape of the evaporative heat loss from skin to the atmosphere and hence regulates the latent heat of body. It is affected by the pore size decided by the structure of fabric. Permeation efficiency factor (Fpcl) is the measure of moisture vapour transfer from skin, the value of which ranges from 0 for total impermeable cloth to 1 for no cloth. Impermeable clothing captures the moisture between skin and clothing. This causes hindrance to the heat dissipation and the body temperature tends to rise. As a consequence, heat and moisture starts building up, body produces sweat. Wet skin due to perspiration causes rashes due to skin abrasion and thus discomfort.

The mechanism of water vapour transfer from the surface of the human skin to the external environment is governed by three distinct parts in clothing assembly.

1. Air gap between the surface of the skin and inner side of the fabric,
2. Structure of the fabric, and
3. Existence of a boundary layer caused by forced convection.

According to Fick's equation

$$U = \frac{Q}{t \times A \times \Delta P} \qquad \text{.......(26)}$$

where U = water vapour transmission,

Q = mass of water vapour,

t = time,

A = area and

ΔP = pressure difference across the fabric.

Higher vapour pressure difference across the fabric increases the water vapour transfer. Increasing wind speed the air pressure above the fabric is reduced. This reduces the vapour pressure above the fabric and hence increases the difference in vapour pressure between the air above and below the fabric, increasing water vapour transfer. With increase in temperature, the air pressure of environment increases and water vapour transfer rate falls regardless of the wind speed. MVTR is affected by fabric thickness, Porosity, Air permeability and Bulk density. Moisture Vapor Transmission Rate (MVTR) through a fabric under controlled conditions is a measurement of the moisture vapor permeability. Standard test methods used[35] for measurement of water vapour transmission rate (WVTR) are

1. ASTM E 96 upright cup tests with water(turl disc method):

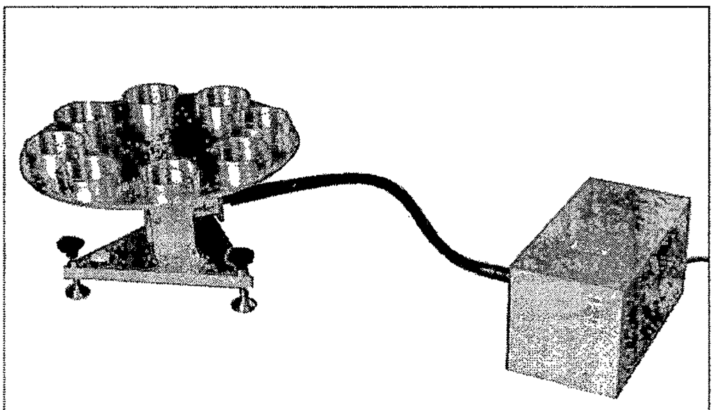


Figure 17. Shirley Turl dish water vapour permeability tester

Shirley water vapour permeability tester consists of eight dishes of 83 mm inside diameter and 20 mm height filled with 46 cu.cm of water. A circular sample covers each dish to give a 10mm deep layer of air between the surface of the water and underside of the specimen. The dishes are placed inside a climate-controlled chamber and rotated gently to ensure that a saturated air layer above the fabric did not impede evaporation. The loss in weight of water after 24 hours is used to calculate the water vapour transfer from cups in gm / sq. m / day and the water vapour permeability index is the water vapour transfer (WAT) of fabric expressed as a percentage of WAT of a reference fabric which is tested alongside the test fabric.

2. ASTM F 2298 standard using the dynamic moisture permeation cell (DMPC).
3. Sweating guarded hot plate:

It determines evaporative Resistance of Clothing as an indirect measurement of cloth comfort. It is also referred to as the "skin model" gives measurements for both the thermal insulation values R_{ct} & moisture transmission values R_{et} (vapor permeability) of textile samples in accordance with ISO 11092 and ASTM F1868.

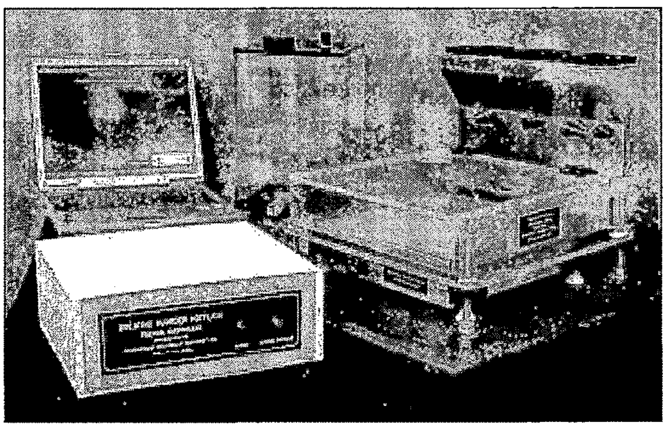


Figure 18. Sweating Guarded hot plate.

A plate is heated to the skin temperature and supplied with water to simulate sweating. It includes a unique porous wicking assembly on the surface of the test plate and its outer guard ring, gravity-fed fluid supply system, hotplate, ambient temperature and humidity sensors, and variable speed airflow hood. ThermDAC control and data logging system makes testing easy.

2.2.3.4 Wicking property[29,30,55,79,84]:

Any accumulated sweat (water) on the fabric surface tends to block the holes preventing the breathing effect to carry away water vapor. The garments must therefore transport moisture away to the outer layer from where it can easily evaporate in the atmosphere. Evaporation cools down the temperature in the dermisphere and reduces perspire and dehydration of body. This phenomenon of spreading water well sideways along capillaries in fabric is known as wicking. Thus, wicking helps to regulate the body's temperature by cooling the body core temperature.

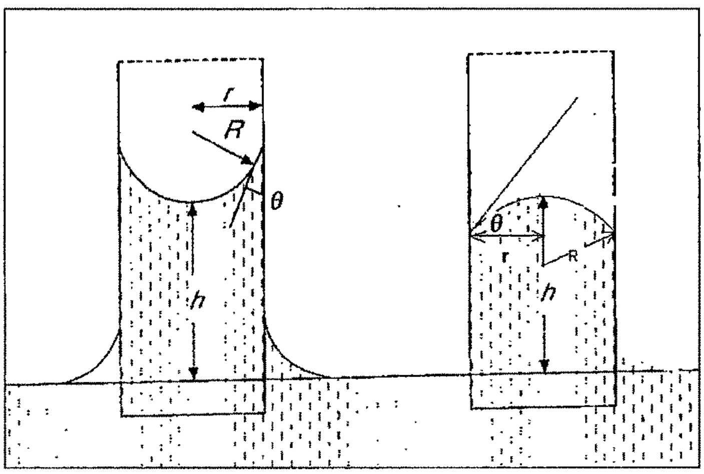
The phenomenon of liquid transport in fabrics is related to – wettability and wickability. In the absence of any external forces the ability of fabric to transport water is called Wickability. Fabric is a bundle of capillaries. Due to capillary action in capillaries formed from the fibers in the yarns and also by the inter yarn spaces, water is pulled in all directions. These capillary forces arise from the wetting of the fabric surface. Thus wicking is a result of spontaneous wetting in a capillary system[13]. Hence, they are coupled and one cannot occur in the absence of the other. Since the capillary action is a weak force if the fibre content has strong affinity for the water it soaks up water quickly and holds on to it. Absorption of water by fibres in the fabrics holds it near skin for longer time. The fabric cling wet to the skin due to increased coefficient of friction and causes rashes on the skin. Clothing thermal insulation reduces on wetting which causes the wearers feel "after chill" effect. These cause discomfort.

Liquid in the capillary flows in response to capillary pressure[12]. Moisture flows from a region of low capillary pressure to a region of high capillary pressure. The magnitude of capillary pressure Pc can be expressed by Young-LaPlace equation

$$P_c = \frac{2\gamma\cos\theta}{R} \quad \text{.....(27)}$$

where γ is the liquid surface tension, θ is the contact angle of the liquid with the fibre surface. In hydrophilic fibres the forces of adhesion between the liquid and the fibre surface are greater than the forces of cohesion between the molecules of the liquid which makes concave surface of meniscus ($\theta \le \frac{\pi}{2}$). Lower value of θ increases the value of Pc which assists wicking. Since γ & θ remain constant for a liquid and the surface

$$Pc \propto 1/R$$



θ < 90 θ > 90

Figure 19. Wicking in a capillary

The capillary pressure is higher for narrow capillary. This causes moisture front to move from the larger pores to the smaller pores. The moisture can travel only up to certain heights in the larger pores where it then migrates to the smaller pores. With increases in wicking length moisture held in the fabric decreases. Thus wicking characteristics of a fabric can be quantified by

1. Fluid filling fraction (f) = V_{fluid} / V_{total}, ...(28)

   where V_{fluid} is the volume of the liquid present in the fabric and V_{total} is the total volume of the fabric through which the fluid travels. It indicates the amount of liquid fabric can hold.

2. Wicking coefficient: It is given by the slope of the wicking length and the wicking time plot. It gives rate of wicking i.e the extent of rise of water column with time.

Yarn and fabric construction as well as fiber type affect moisture flow.

Fibre properties:

- Contact angle of the liquid on the fibre surface:

Wicking depends on the surface energy of the fibres. Table gives the surface energy in mJ/m^2 of various fibers used in apparel fabric.

polyethylene	22	polyester	43
Marino	29	Acrylic	44
polypropylene	29	Polyamide(nylon)	46
Aramid	30	cellulose/cotton	200

Too high value of surface energy makes poor wicking and highly absorbent fabric. Cellulosic fibres such as cotton, linen and flax etc have high surface energy. These fibres will retain moisture and require over an hour to dry. A wicking under layer is important but an absorbent under layer must be avoided. Polyester and nylon fabrics pull perspiration away from the body to keep the body cooler, dryer and more comfortable. While as cotton, Polypropylene etc has a great affinity for water keeping moisture near your skin.

- Irregular and rough c/s of natural fibres forms irregular capillary which slow down fluid movement while as polyester and nylon gives uniform capillary surface assist wicking.
- Cotton fibres swells on absorption of moisture which blocks the capillary and inhibit fluid flow.

Factors of weave structure:

- Physical size of the capillaries : Larger capillary holds more water but water does not travel through long distance. In smaller capillaries the water spread through more area in the fabric.
- The weave intersection at cross over acts as reservoirs that feed the remaining branches equally increases the wicking height.

Types of Wicking Tests[81]:

1. Finite (limited) reservoir :

It is also called e.g. spot test. It include placing a drop of water onto the fabric and measuring the drop absorbency time or the spreading rate of the liquid within the fabric[12]. As fabrics are not isotropic the spreading liquid does not usually form a circle with a well-defined radius. The capillary penetration of a drop indicates several important properties of a textile fabric, including repellency, absorbency, sorption of stain, and stain resistance[13].

2. Infinite (unlimited) reservoir :

a) Canvas disc-wetting test:

Wicking during immersion occurs when the fabric is completely immersed in a liquid and the liquid enters the fabric from all directions[13]. A liquid wicking into an immersed yarn or fabric displaces most of the air in the fibrous assembly and causes it to sink. The canvas disc-wetting test measures the sinking time of a disc submerged in a liquid. Though this type of test is no longer used.

b) Trans planar or transverse wicking:

In a Gravimetric Absorbency Testing System (GATS) developed by NTSU T-PACC (North Carolina State University's Textile protective and comfort center), transmission of a liquid through the thickness of the fabric i.e. perpendicular to the plane of the fabric is measured using Plate tests.

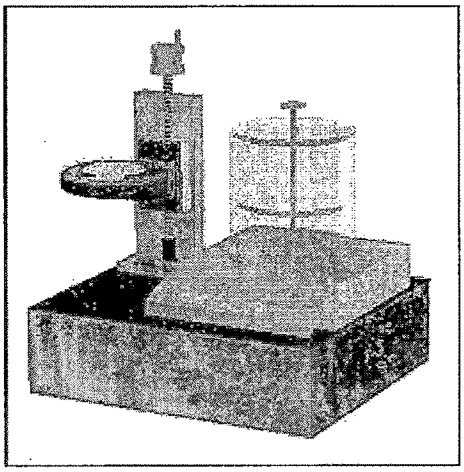


Figure 20. Absorbency Testing System (GATS) by NTSU T-PACC

The apparatus consists of a horizontal sintered glass plate kept moist by a water supply whose height can be adjusted so as to keep the water level at the upper surface of the plate. The specimen is placed onto the porous glass plate, and the uptake of water is measured by timing the movement of the meniscus along the long horizontal capillary tube. These tests have been used as simulation of a sweating skin surface.

c) Longitudinal wicking :

Longitudinal wicking from an infinite reservoir occurs when the fabric is partially immersed in a large volume of liquid that can wet the fabric[13]. If the liquid does not wet the surface it will not wick into the fibrous assembly.

Three types of longitudinal wicking tests include

i) Vertical (upward) :

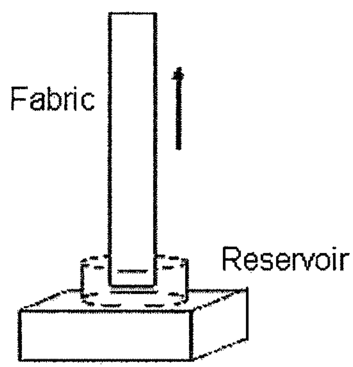


Figure 21 Vertical upward wicking test

In BS 3424, the test specimen (150 mm x 50 mm) and hung from a glass rod to lower the surface of the fabric 50 mm from one end vertically into a liquid in a reservoir for twenty-four hours after which the length of the fluid path is measured to the nearest millimeter with reference to the indelible marked line. This distance that the liquid travels is what is designated as the extent of wicking.

The capillary pressure Pc which derives the wicking process is opposed by a continuously increasing hydrostatic head Ph = Lc ρ g.

At wicking height L_c when Pc = Ph , the net driving force becomes zero.

Thus $\frac{2\gamma\cos\theta}{R} = L_c\, \rho\, g$ ....(29)

Though $L_c \propto 1/R$ for γ, θ & ρ remaining constant for a given fibre type and liquid, it is affected by g which changes with height. Thus upward wicking tests do not produce a constant flow rate or fluid filling fraction during the entire test due to

1. Gravity opposes the fluid flow to slow down and eventually stop
2. Frictional drag increases with increases in the length of the liquid column.

ii) Downward wicking:

Bernard Miller of TRI Princeton[14] proposed downward wicking tests to minimize the negative affects of gravity. His approach is based on the physics of a siphon, where the fabric is used like a tube to transport water because of a pressure gradient.

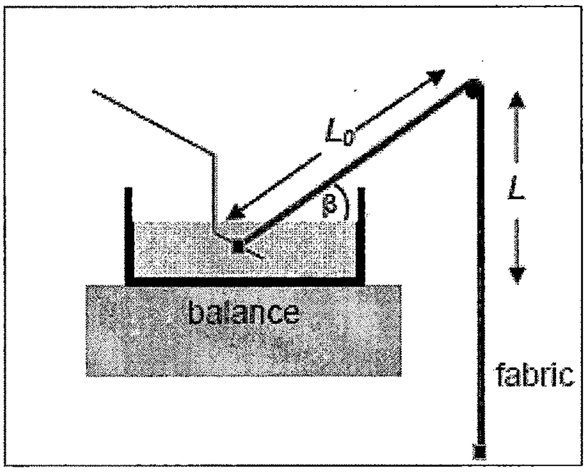


Figure 22. Miller downward wicking tests

In Fig.22 once the moisture front reaches the bar and begins its descent, the flow rate becomes essentially constant. Downward wicking tests cannot be run without some initial upward wicking phase, after an initial deceleration, the rate of wicking becomes essentially constant. The time is recorded after the liquid moves over the bar and downward wicking begins. Since the downward wicking flow rate is at a steady state, the length L becomes arbitrary. Volume can be calculated by multiplying length L by the cross sectional area A normal to the direction of flow. The downward wicking test produces a constant flow rate and fluid filling fraction throughout the fabric test.

iii) Horizontal – downward :

Fabric capillary systems involve wicking in a substantially horizontal plane in which the flow under capillary pressure in horizontal capillaries can be modeled by the Lucas-Washburn[15,16,17,18] equation

$$L^2 = \frac{\gamma R \cos\theta}{2\eta} t \qquad (30)$$

where L is the liquid front position or wicking length, γ and η are the surface tension and viscosity of liquid and θ is the apparent contact angle of the moving front, R is the effective hydraulic radius of the capillaries (voids), and t is time.

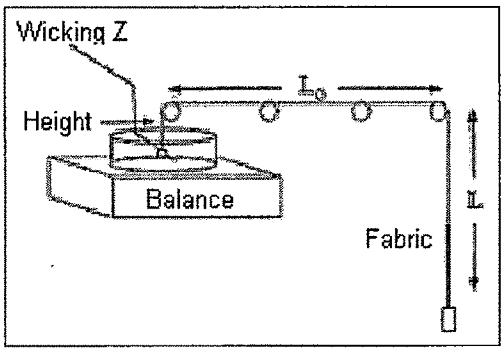


Figure 23. Horizontal wicking setup

According to Equation 30, a plot of L versus $t^{1/2}$ should be linear for a given system assuming that the radius of the tube or the equivalent radius of the nontubular system is substantially constant. The slope of the plot L versus $t^{1/2}$ is called the wicking coefficient Wc or the rate constant.

2.3 Fabric processing and its effect on fabric properties.[86,87,88]

The finishing treatment like application of steam, heat, tension, pressure, chemicals, etc influence the mechanical interaction between interlacing yarns in the finished fabrics, which in turn, determines the fabric hand and make-up quality. Mechanical finishing results into improvement of elastic recovery and surface hand feeling. The application of softners considerably improves the quality.

Processing sequence for P/V blended fabrics includes:

For piece dyed cloth	**For fibre dyed cloth**
Grey checking	Grey checking
Heat setting on stenter	Heat setting on stenter
Polyester dyeing in Jet dyeing m/c.	Singeing
Stretching/resetting on stenter	Scouring in Jigger or JT-10
Singeing	Drying on stenter
Viscose dyeing in Jigger	Finishing
Drying on stenter	Open decatising or keir decatising
Finishing	
Open decatising or kier decatising	

Heat setting: This is done to give the fabric dimensional stability especially for synthetic fibers. Temp ranges from 175 to 210 °C and speed 25-50 mt/min. Over feed and under feed are given according to requirement. Bow and skew in weft occurring due to loose construction and improper feeding of fabric are straightened on stenter.

Stretching: It is also called resetting. It is done only for piece dying. It is performed after jet dying to make the fabric in its original dimension. Because in jet dying fabric entangles so stretching is done to make fabric suitable for next Jigger dyeing (viscose dyeing).

Singeing: Surface fibers form small balls or pills on the cloth after being washed several times. Singeing burns protruding fibres from the fabric surface smoothening it and thus improves the feel of the fabric. Both sides of the fabric are given two to three rounds of singeing at 100 ± 10 mts/min speed with flame height of 2.2 inches either straight or inclined according to the quality of fabric.

Scouring: It is typically performed in an alkaline solution and high temperature to remove natural impurities by saponification at high pH. Scouring reduces rigidity.

Drying: Fabric is dried at a temp lower than that of heat setting at speed varies according to fabric and the moisture regain. Drying range consists of 12 cylinders 54 inches diameter and steam is supplied to maintain temp about 100 °C. It also imparts lustre to the fabric.

Finishing: Finishing is done at about 180°C and at 25-40 mt/min speed to enhance the appearance of the fabric. They impart luster, anti-creasing and softness in the fabric hence improving the quality of fabric. Fabric softener treatment has a significant influence on the thermal comfort (i.e., water vapor transmission and air permeability).

Finishing chemicals include

- cross-linking agents such as KVA gives anti-crease finish to the cloth.
- silicon emulsion works as softener as well as imparts lustre to the cloth.
- Polyvinyl acetate works as stiffeners.
- PE emulsion is a softener.
- cationic softener
- acrylic emulsion
- CH_3COOH
- body giving agents

Open decatising: It imparts lustre, gives final shrinkage to the fabric and also presses it. The m/c consist of big cylinder on which blankets is wrapped. At a time one cylinder is loaded and other is unloaded. Fabric is wrapped around the blanket. After loading the cylinder, steam is supplied through perforated cylinder for 6 minutes, then cooling is done for 4 min and fabric is unloaded. Decatizing makes modification in the behavior of fabric subjected to low stress tensile, compressive, shearing, bending and buckling.

The specific challenge for the finisher is to use fabric objective measurement to understand the operations in the finishing and to use the most appropriate options for each fabric quality. For this purpose it is required to correlate the structure and properties of fibres, yarn and fabric with the finishing techniques.

2.4 Fabric evaluation for comfort[40,82]:

Comfort and satisfaction with clothing are influenced by both extrinsic and intrinsic attributes, as well as by attitudinal and cognitive factors of the wearer. Extrinsic factors include brand labels and the price etc. The Intrinsic attributes include the physical characteristics of the cloth including its sensory (tactile) characteristics. The intrinsic quality of fabric is of critical importance determining the quality and performance of fabric. e.g. smooth fabric surface has a large area of contact with the skin and thus it may feel cool to skin because a thermal insulation air layer is absent. Though assessment of fabric intrinsic qualities by wearer is purely subjective in nature, objective methods of quantifying the fabric physical properties form the basis for its comfort character. Thus Fabric Objective Measurement (FOM) techniques facilitate prediction of the comfort character from the measured fabric properties.

2.4.1. Peirce approach to "The Handle of Cloth"[19]

Dr. F.T.Peirce[19] tried to describe this problem in 1930. He gave theoretical basis for work on fabric handle. He judged Handle as

a) bending properties i.e. stiffness and hardness and

b) surface characteristic i.e frictional properties like roughness or smoothness.

To initiate comparison, physical tests are devised to obtain several measurable character related to handle. They express facts that could be appreciated in handling the cloths. These are derived from vide varieties of fabrics without special selection.

Various quantities that may be used as a measure of the stiffness of a fabric are:

1.Bending length ,b :

It is defined as the length of fabric that will bend under its own weight to a definite extent on an instrument called Flexometer. It is a measure of draping quality of a fabric. The fabric drape depends on its stiffness (resistance to bending) and on its weight. The stiffer the fabric the longer is the bending length.

A woven fabric has different properties in the warp and weft direction; the thread generally differ in count, twist, number and crimp, so there is no reason to expect a relation between the bending lengths measured in the two directions. And two measurements are separately significant in describing the stiffness.

The stiffness of a fabric in a direction oblique to warp and weft depends on the values obtained in these two directions. For practical purposes it is sufficient to multiply together the separate figures for the warp and weft directions, c_1 and c_2, and take the square root of the result. The mean value of bending length

$$b = \sqrt{b_1 \times b_2} \times \frac{1}{2}\left(K + \frac{1}{K}\right); K = \left(\frac{b_1}{b_2}\right)^{3/4}$$

$$b = \sqrt{b_1 \times b_2} \text{ (approximately)} \quad \ldots\ldots (31)$$

2. Flexural rigidity (G) :

It is the measure of resistance to bending or the stiffness that would be appreciated by the fingers. It is the couple on either end of a strip of unit width bent into unit curvature. Thus two fabrics may bend to the same extent under their own weight, but the heavier of the two will exert more resistance to bending say, by fingers, and so feel stiffer. When b is expressed in cms and w is the weight of fabric in milligrams per sq.cm., then F.R.

$$G \text{ (in mgm-cm)} = w \times b^3 \quad \ldots\ldots (32)$$

3. The thickness(t):

Thickness is sensed when the fabric is grasped but the sensation combines with hardness also. Thickness is measured in microns ($1/1000^{th}$ of a millimeter) by a micrometer dial-gauge. Three circular plane end pedals of diameter 0.1,0.25 and 1 inch are used. Thickness is very sensitive to pressure. It affects the fabric stiffness. Doubling thickness increases the F.R. eight fold.

4. Hardness(H):

Hardness or Resistance to compression (H) in mgm/cm^3 is measured by determining thickness under different pressure. Numerically it is the ratio of the difference of pressure to the difference of thickness such as may be appreciated by pressing with a finger tip.

5. Bending modulus(q):

F.R. does not take account of thickness. The intrinsic stiffness of the material of the fabric can be expressed by the modulus

$$q = 12G/t^3.10^6, \text{ in } kg/cm^3, \qquad (33)$$

where t is the thickness in microns. It compares stiffness of material of different thickness. It reflects the degree of compactness i.e. the adhesion between fibre and the threads and thus describes a fuller handle or thin and papery feel. Thus two fabrics if compared their draping quality as judged by the bending length may be same but the heavier fabric is stiffer to the fingers and that lighter fabric is more papery.

6. The compression modulus (h):

Compression is expressed as a strain, that is, the difference in thickness divided by the original thickness. The ratio of stress (difference in pressure) to strain gives a Young's modulus' for the material in a direction normal to the surface is called the compression modulus, 'h'. It is evaluated from the hardness H. Bending modulus is obtained in the direction parallel to the surface of the fabric while as compression modulus is in the direction normal to the fabric surface. This also measures the compactness of the material.

7. Density(ρ):

The density is obtained by dividing the weight in grams per sq. cm. by the thickness in cm. It is also a measure of compactness but is more influenced by the proportion of space left between the threads while as bending modulus is a measure of the degree to which the fibres and threads are welded together mechanically.

8.The extensibility(q'):

In mechanics the ratio of tensile stress to strain is termed Young's Modulus. But autographic strip test of the cloth yields a curve between load and extension that is usually far from straight, the strip being more extensible at the beginning of tension. So to compare fabric handle, the extensibility i.e. the resistance to extension of the cloth is expressed as the Young's modulus calculated from the load at 1% extension.

From the tabulated values of the above parameters he concluded the following facts.

- Other things being the same, the flexural rigidity varies with the third power of thickness.
- There is close correlation between the compression modulus, h and the density, ρ.

- The quantity, q is the best to consider when it is desired to estimate the effect of the structural factor.
- The density and stiffness are influenced at many of the earlier stages of production such as the counts and twist of yarn, the no. of picks and ends etc.
- Greater warp tension results into lower crimp and thus extensibility and gives stiffer fabric.
- A high correlation was found between the tensile and the bending moduli, and between both and thickness.

2.4.2. Objective Evaluation of Fabric comfort by NCSU's T-PACC centre[7,75,23].

Comfort is related to complex interactions between fabric, climatic, physiological and psychological variables. Comfort performance is evaluated objectively at North Carolina State University-NCSU's T-PACC centre (Textile protective and comfort center) in three different laboratories.

1. Fabric hand Lab tests fabric for low stress properties to predict the aesthetic quality perceived by human touch.
2. In Micro climate analysis lab heat and moisture transfer properties of fabric are tested.
3. Absorbency Lab is meant for water transport rate through fabric.

2.4.2.1. Fabric Hand Lab:

Prof. Sueo Kawabata developed Kawabata Evaluation System for Fabric (KESF) to predict the aesthetic qualities perceived by human touch by judgment of bending, shearing, tensile compressive stiffness, smoothness and frictional properties of a fabric surface. 214 winter suiting and 156 summer suiting fabrics are tested for 16 low stress properties using six tests from instruments:

1.KES-FB1- tensile and shear tester:

Following tensile properties are measured by plotting the force extension curve for a maximum force of 500 gf/cm.

- WT is the area under the load extension curve.
- LT – linearity of load – extension curve = $\frac{\text{WT}}{\text{area of triangle OAB}}$.
- RT - tensile resilience percent , indicates the recovery of deformation from stretching when the applied force is removed. Higher values indicate greater recovery from having been stretched.

$$\text{RT} = \frac{\text{area under recovery curve}}{\text{WT}}$$

- EMT - extensibility, percent strain at maximum applied force. It is 100% for completely elastic to 0% completely inelastic fabrics. Higher values indicate a stretcher material.

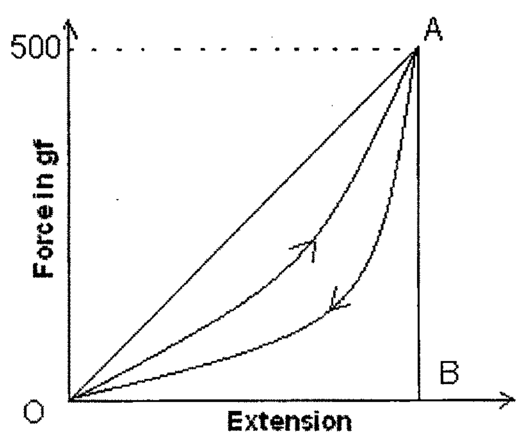


Figure 24. Tensile Load extension curve for KESF

In shear testing, opposing, parallel forces are applied to the fabric sample of 5x20 cm, until a maximum offset angle of 8° is reached. A pretension load of 10 gf/cm is applied to the specimen. Following properties are calculated from the shear curve as in fig 25.

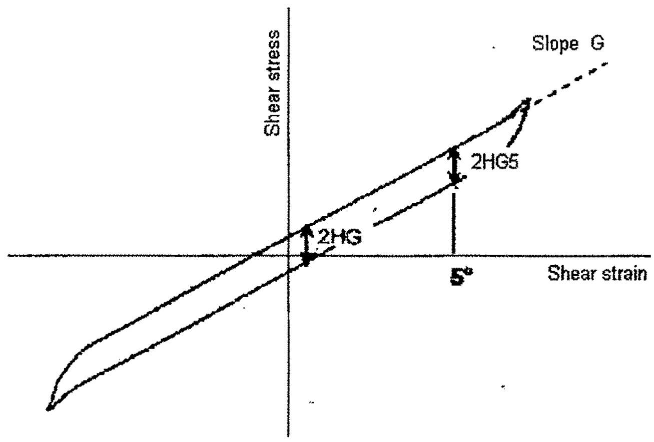


Figure 25. Shear curve for KESF

- G - shear stiffness, gf/cm. degree, is the slope of the shear force – shear strain curve. It is the ease with which the yarns slide against each other resulting in soft/ pliable to stiff/ rigid structures. Lower values indicate less resistance to the shearing movement corresponding to a softer material having better drape.
- 2HG - Hysteresis of shear force at 0.5deg shear angle. It is measured as the width of the hysterysis curve at 0.5°.
- 2HG5 - Hysteresis of shear force at 5deg shear angle. It is the width of the hysterysis curve at 5°.

2.KES-FB2- pure bending tester :

It measures the bending properties the fabric between the curvature -2.5 and 2.5 cm^{-1} (approximately 150°) to get the curve of bending moment- curvature curve as in fig 26.

- Bending rigidity (B) per unit fabric width, gf.cm^2/cm. is the slope of the curve.

Higher B value indicates greater stiffness/ resistance to bending.

- Moment of hysteresis (2HB) is the width of the hysteresis curve.

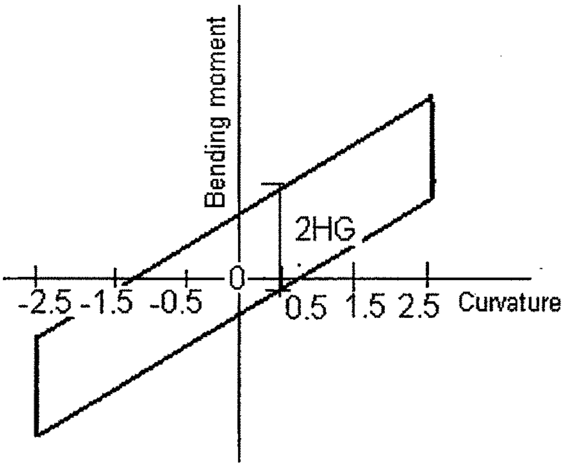


Figure 26. Plot of bending moment against curvature

3.KEF-FB3- compression tester:

Compressional properties WC, LC & RC are calculated in the same way as tensile from the force – compression curve of a 2 sq. cm area measured with the KES-FB3 Compression Tester at 0 to 50 gf/cm^2.

RC - compressional resilience, percent ,is the extent of recovery, or the regain in thickness, when the force is removed. Higher RC values indicates a high percent recovery from being compressed.

EMC – compressibility at maximum applied force, is the difference in thickness expressed as percent of initial thickness. A higher value indicates greater compressibility.

Thickness in millimeters is measured on a 2 sq. cm area at 0.5 gf/cm^2.

4. KES-FB4- surface tester:

It measures the surface properties of friction (resistance/drag) and surface contour (roughness) of the sample applied to a tension load of 20 gf/cm. A steel wire of 0.5 mm diameter is pulled with contact force of 10 gf on the fabric surface, the plot of height variation against distance is shown in fig

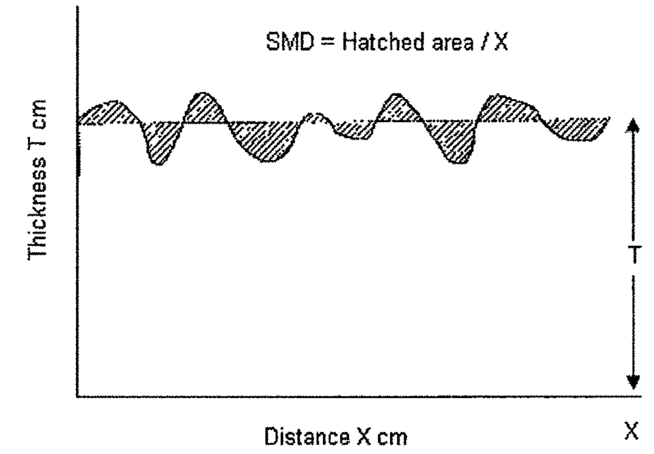


Figure 27. Surface thickness variation

SMD - geometric roughness, micron is the mean deviation of surface roughness. Higher SMD corresponds to geometrically rougher surface.

Similarly a contactor made of 10 such steel wires pulled through the fabric surface at contact pressure of 50 gf to measure force required to pull the fabric as in fig.28.

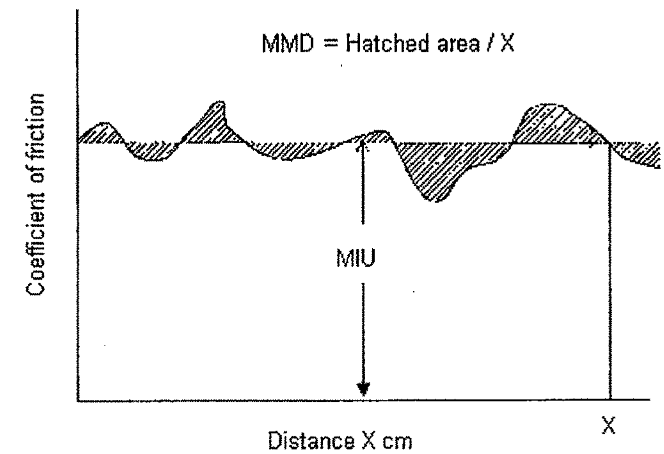


Figure 28. Surface friction variation

MIU – mean value of coefficient of friction which ranges from 0 to 1 value. Higher MIU value corresponds to greater friction or resistance and drag.

$$\text{MMD – mean deviation of coefficient of friction} = \frac{\text{hatched area}}{X}$$

5. Weight tester :

Three 20x20 cm specimens are weighed on an analytical balance and the weight is calculated in mass per unit area(oz per sq.yd).

16 low stress mechanical parameters from six tests are :

Parameters		Description	Unit
(1)Tensile test:	LT	Linearity of load-extension curve	None
	WT	Tensile energy	gf cm/cm^2
	RT	Tensile resilience	%
(2) Shear test:	G	Shear stiffness	gf cm/deg
	2HG	Hysteresis of shear force at 0.5degree	gf/cm
	2HG5	Hysteresis of shear force at 5 degree	gf/cm
(3)Bending test:	B	Bending rigidity	gf cm^2/cm
	2HB	Hysteresis of bending moment	gf cm/cm
(4)Compression test:	LC	Linearity of compression / thickness curve	None
	WC	Compression energy	gf cm/cm^2
	RC	Compressional resilience	%
(5)Surface characteristic	MIU	Coefficient of friction	None
	MMD	Mean deviation of MIU	None
	SMD	Geometrical roughness	µm
(6)Fabric construction	T	Fabric thickness	mm
	W	Fabric weight	mg/cm^2

Subjective Analysis for handle:

A hand evaluation and standardization committee (HESC) was organized by Kawabata under Textile machinery society of Japan. 12 experts mainly from finishing mills dealing with worsted fabric judged the fabric by touching for quality of fabric with respect to fitting to human body, the feel of the surface and the comfort in wearing and also by visual appearance such as the surface character. Fabric bending properties and surface characteristic are summarized in following hand characters:

Japanese terms	English synonyms	Feel character
Koshi	Stiffness	a feeling related mainly to bending stiffness.
Numeri	Smoothness	a mixed feeling coming from smooth and soft feel.
Fukurami	Fullness and smoothness	a feeling coming from a combination of bulky, rich and well formed impressions.
Shari	Crispness	a feeling coming from crisp and ridged (rough) fabric surface. It gives cool feeling.
Hari	Anti-drape stiffness	The word means spread. It is opposite of Limp conformability.

Kawabata called each of these a "primary hand" of fabric. To judge the Primary Hand value (HV's) every expert divided all the samples into three groups - strong, medium and weak. Each of the three groups are further divided into three sub groups. The fabrics are now separated into nine grades. Finally the fabric which had either an extremely strong feeling or an extremely weak feeling were separated from the strongest and the weakest group respectively to give a total of eleven grades which can be ranked numerically.

This rating was termed the 'hand value' (HV).The primary hand had thus been standardized. Thus each primary hand represents an assessment by experts of a characteristic feature of fabric , such as stiff to limp, rough to smooth and so on.

Thus primary hand values aim at universal validity as a way of characterizing fabric handle.

Hand value of the primary hand:

Hand value	feeling grade
10	the strongest
.	.
.	.
5	Medium
.	.
.	.
1	Weakest
0	No feeling

After their judgment of the primary hand value, experts then evaluate the final and over all impression and indicate whether the fabric handle is regarded as good or poor. This over all fabric handle was called the "total hand". The total hand, which is the fabric handle aspect of the assessment of fabric quality, was also graded in the same manner. But the grading of the quality levels were limited to the range from 5 to 0.

Grade	Total hand value (THV)
Excellent	5
Good	4
Average	3
Fair	2
Poor	1
Not useful	0

The grading number was termed the 'total hand value' (THV).

Total hand represents an assessment of the over all quality of the fabric, which in fact is a measure of its value in the market, namely, its selling appeal to the costumer. Its ranking will therefore reflect cultural difference, climate, tradition and fashion. Thus THV include both the mobility and also the universality.

Objective evaluation system for fabric handle:

On the basis of the standardization of fabric primary hands and total hand, a completely objective system for evaluating fabric handle has been developed.

A two stage translation method has been suggested by Kawabata for translation of fabric mechanical properties to fabric handle.

$$\begin{bmatrix} \text{Fabric mechanical} \\ \& \\ \text{surface properties} \end{bmatrix} \underset{\text{conversion eq.I}}{\Rightarrow} \begin{bmatrix} \text{Primery Hand value} \\ \text{(HV's)} \end{bmatrix} \underset{\text{conversion eq.II}}{\Rightarrow} \begin{bmatrix} \text{Total Hand Value} \\ \text{(THV)} \end{bmatrix}$$

First stage set of equations to translate parameters from the mechanical test to HVs as obtained from the subjective evaluation by 12 experts are derived and in second stage THV is obtained from these HV's.

Stage I: Development of equations translating the mechanical data into hand value.

The average of each of the primary hand values assigned by judges were denoted by Y_{pk}, where suffix p indicates the fabric sample (p=1...N) and suffix k indicates the primary hand (k=1...3,for winter suiting and k=1...4 for summer suiting). The measured value of mechanical parameters were denoted X_{pj}, where the suffix j indicates the particular parameter (j=1...16) .

The mechanical parameters are grouped in six block: tensile, bending, shear, compression, surface and constructional.

- A multivariable linear regression equations are formulated between Y_{pk} and the set of parameters in each of the blocks to find which block gives the best prediction Y^{*}_{pk}. This gives the first regression equation.
- Secondly the prediction error $E_{pk}=Y_{pk} - Y^{*}_{pk}$ are regressed with the sets of parameters in the remaining blocks in order to seek the block that is regressed with the highest accuracy.
- The first and the second eq. are then summed to obtain a single eq. that includes the parameters of these two blocks. This gives the second prediction Y^{**}_{pk}
- The error $E_{pk}=Y_{pk} - Y^{**}_{pk}$ are again regressed with parameters in the remaining blocks in the same manner and this procedure is continued until all the blocks are included.

The complete regression eq. is linear and can be expressed in the form

$$Y_k = C_0 + \sum_{i=1}^{16} C_i X_i \quad \text{..........(34)}$$

where C_0 and C_i are constants and $X_i = \frac{X_i - M_i}{\sigma_i}$. Here X_i=absolute value of the parameter, M_i=mean value of X_i for the population of N fabrics and σ_i = standard deviation of X_i , suffix i is the order in which the parameters have been placed in order of their importance in the final regression equation for a particular primary hand value Y_k. It is different from j earlier taken in the analysis.

Thus the block regression gives

1). clustering of parameters in a block

2) minimum influence of the correlation between the parameters belonging to different blocks on the final regression equation.

3) relative influence of each block on the primary hand value

Stage II : Prediction of THV

Equations predicting the total hand value, THV were constructed on the basis of the subjective evaluation of THV and HV by the experts from 214 winter and 156 summer suiting fabric samples. The variables of these eq. are the primary hand values and the eq. consists of linear and squared terms of these variables.

$THV = C_0 + \sum_{k=1}^{n} Z_k$, n is the number of primary hands viz. 3 – for winter and 4 – for the summer suiting.

$$Z_k = f(Y_k, Y_k^2)$$

$$Z_k = C_{k1}\frac{Y_k - M_{k1}}{\sigma_{k1}} + C_{k2}\frac{Y_k^2 - M_{k2}}{\sigma_{k2}} \quad \text{.........(35)}$$

where Y_k = value of k^{th} primary hand value;

M_{k1} = mean value of Y_k for the population of N fabric:

σ_1 = standard deviarion of Y_k ;

M_{k2} = mean value of Y_k^2;

σ_2 =standard deviation of Y_k^2 and

C_{k1} & C_{k2} are constant coefficient

The relationship between physical properties and HVs of expert assessment can be directly represented in mathematical forms. But no HV can be related to any single mechanical or physical test. There are certain major physical parameters closely related to each HV.

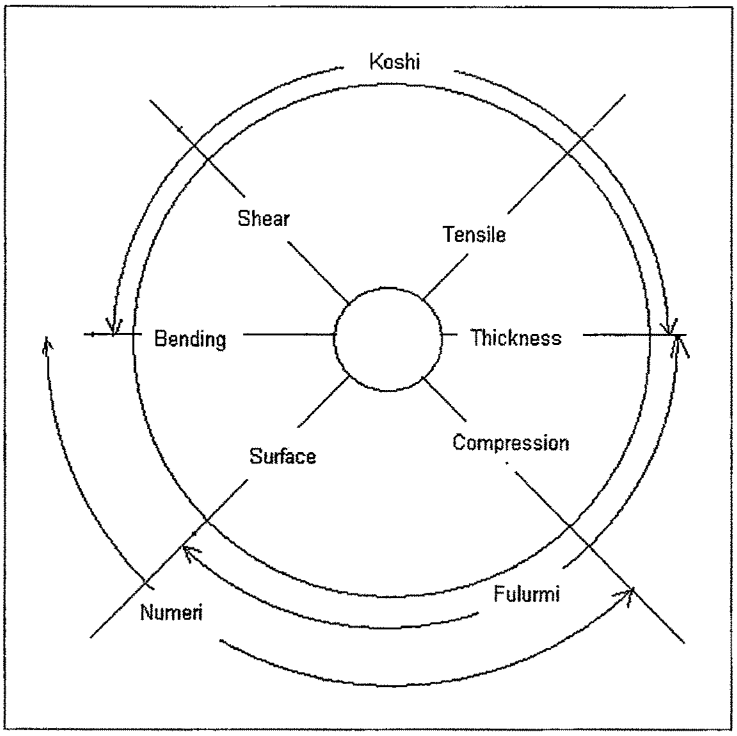


Fig. 29. Relationship between physical properties and HVs.

Total Hand value (THV) meets the need of judges for a clear end use. For different end uses, cultures, geographical area, the relationship between HVs and THV may be quite different and so THV is not stable.

Typical result for a summer fabric are shown by a snake chart after normalizing the values as $x = \frac{(X - \bar{X})}{\sigma}$ where $\bar{X}$ = mean and σ = Standard deviation so that results can be plotted on the same scale.

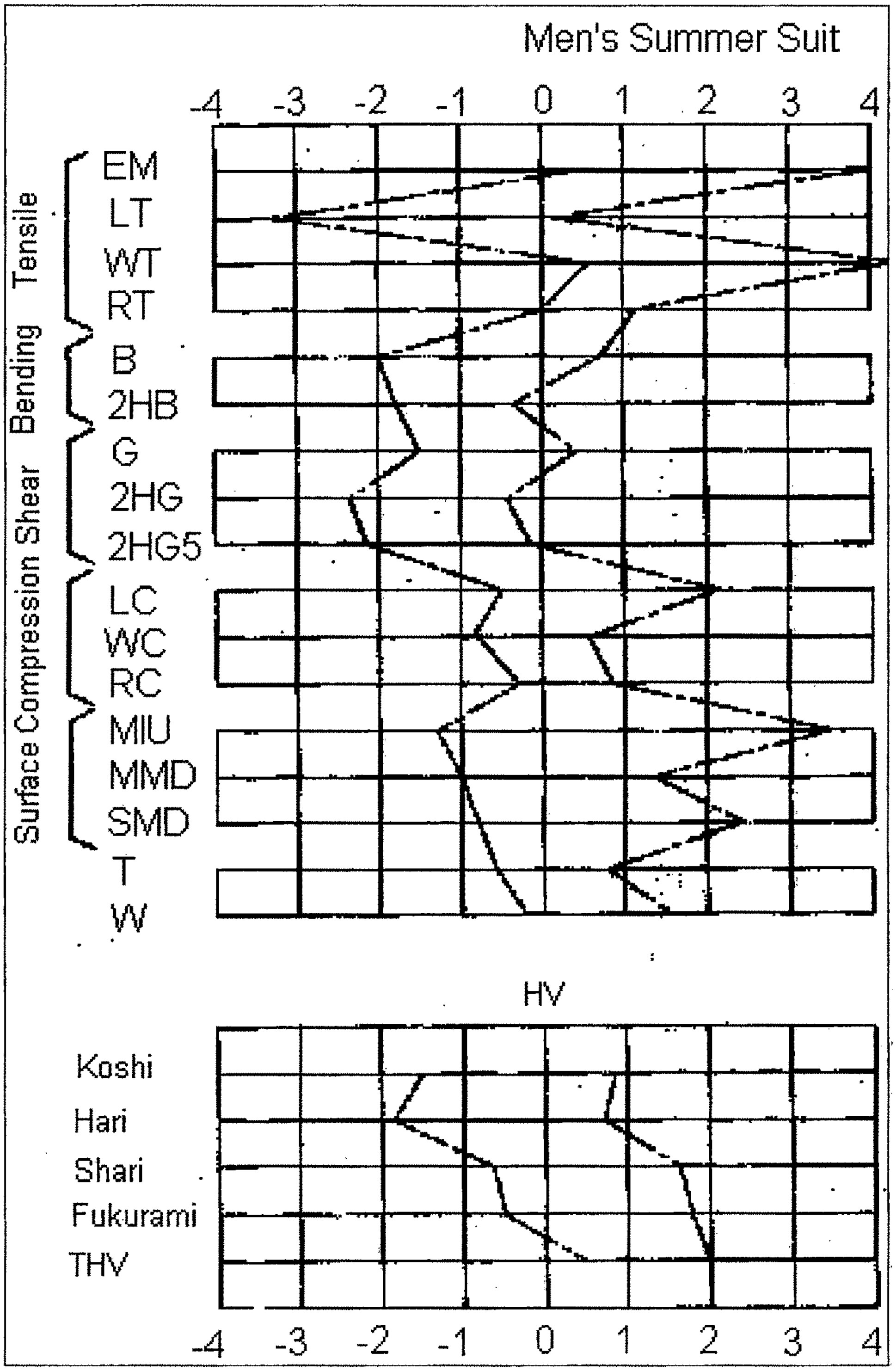


Figure 30. HESC data chart

Guidelines can be drawn from the snake chart for the high quality of fabric falling in the good zone in the chart.

2.4.2.2. Micro climate analysis lab:

Research instruments, which measure the heat and moisture transfer properties of fabrics related to thermal comfort are located in the Micro Climate Analysis Laboratory. The conductivity, thermal insulation, and moisture vapor transmission rate of fabrics are measured.

1. Sweating hot plate:

It is heated to a skin surface temperature of 35°C and housed in an environmental chamber in which temperature, humidity, and wind speed are controlled to create climatic conditions to simulate the heat loss from sweating skin. It measures the thermal insulation in Clo unit and the Permeability index (i_m value) as the moisture-heat permeability through the material on a scale of 0 (totally impermeable) to 1 (totally permeable) which indicates the effect of skin moisture on heat loss of a sweating skin condition.

2. Large hot plate instrument:

It measures

a. Intrinsic Thermal Resistance (R_{cf}) in °C-m^2/ watt as an indicator of heat transfer from a dry, heated test plate through a fabric into the test environment.

b. Apparent Intrinsic Evaporative Resistance ($R_{re}{}^A$), (DkPa)(m^2)/ watt, as an indicator of the resistance of a fabric to transport heat and moisture while in contact with a wet, heated plate surface.

c. Total Heat Loss (Q_t), watts/ m^2, is an indicator of the heat transferred through the test material by the combined dry and evaporative heat loss, from a fully sweating test plate surface into the test environment. Total heat loss, measured at a 100% wet skin condition, indicates the highest predicted metabolic activity level that a wearer may sustain and still maintain body thermal comfort while in a highly stressed state in the test environment.

3. Dynamic sweating hot plate apparatus:

It consists of five distinct parts: an Amico-Aire unit; a guarded hot plate; a diffusion cell; a computer interface unit and a data acquisition program. Momentary vapor pressure gradient is created using a diffusion column with a shuttering device housed in an environmental chamber. Fabrics moisture vapor regulation performance is judged by

S_2 - rate of increase in the microclimate relative humidity occurring during a two-minute period after initiation of the sweat pulse;

S_5 - rate of increase in the microclimate relative humidity occurring during a two-minute period after initiation of the sweat pulse;

DRH_{max} - the maximum increase in microclimate humidity created by the simulated sweat pulse, and

T_d - Time required for the microclimate humidity to return to a steady level after termination of the sweat pulse.

Fabrics possessing the best moisture vapor regulation performance should display the lowest values of these quantities.

Finally, the combined buffering response was estimated by

the vapor regulation index $(B_d) = D/(S_2 \cdot DRH_{max} \cdot T_d)$

where D is a constant (1000) used to give the B_d value a certain range.

Higher values of B_d, indicate advantageous moisture vapor modulating capabilities in transient sweating conditions.

4. Moisture vapor transmission rate:

The rate of moisture vapor diffusion through the fabric is determined according to the Simple Dish Method, similar to ASTM E96-80. A sample is placed on a water dish (82 mm in diameter and 19 mm in depth) allowing a 9 mm air space between the water surface and specimen. A vibration free turntable carrying 8 dishes rotates uniformly at 5 meters per minute to insure that all dishes are exposed to the same average ambient conditions during the test. The assembled specimen dishes are allowed to stabilize for two hours before taking the initial weight. They are weighed again after a 24 hour interval. Then the rate of moisture vapor loss (MVTR) is calculated in units of g/m^2-24 hours. A higher MVTR value indicates there is a greater passage of moisture vapor through the material.

2.4.2.3. Absorbency Lab:

1. Horizontal wicking – Gravimetric Absorbency Testing System (GATS) :

Two parameters most commonly used to characterize the properties of absorbent products are the rate of absorbency and the total absorbent capacity. The former determines the rapidity with which fluid is imbibed while the latter determines the total capacity of the material to absorb and hold fluid.

In GATS the amount of water supplied from the fluid reservoir equal to the amount the specimen can absorb is automatically weighed by a fluid sensor. The GATS is interfaced with a recorder which provides a plot of the amount of fluid absorbed by fabrics sample of 62 cm^2 as a function of time.

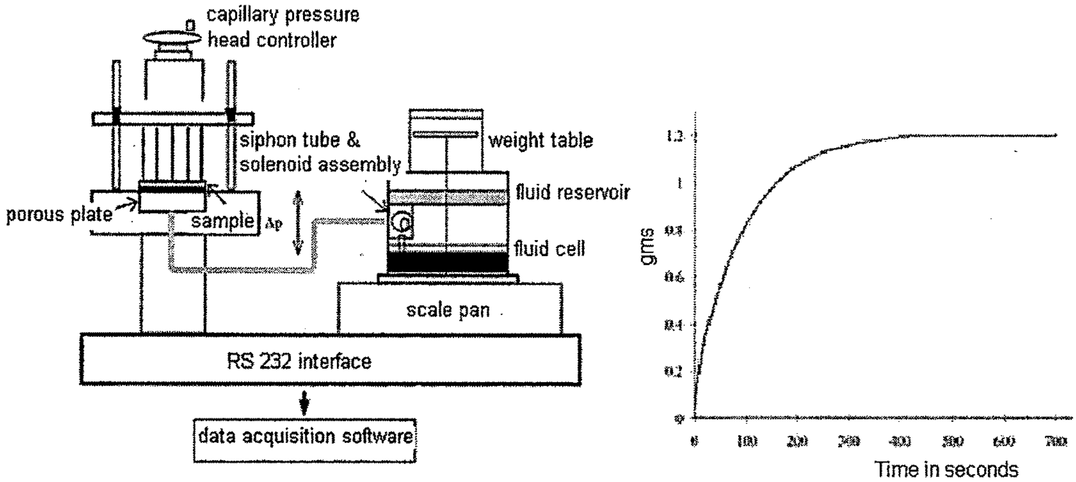


Figure 31. Gravimetric Absorbency Testing System (GATS)

- Maximum absorbent capacity, V is the total amount of fluid absorbed in grams for a given sample area of 62 cm^2
- Specific absorbent capacity, C = grams of fluid/grams dry fabric weight

  = V/ W, W is Weight of dry fabric in grams.
- Flow rate, Q_o = grams fluid/min,

  = V/T, T is Time in seconds.
- Specific Flow Rate, Q = grams fluid/grams dry fabric· min.

  = Q_o / W

2. Vertical wicking:

The water transport rate is measured according to a vertical strip wicking test. One end of a strip (25mm wide X 170 mm long) was clamped vertically with the dangling end immersed to about 3 mm in distilled water at 21°C. The height to which the water was transported along the strip is measured at 1, 5 and 10 minute intervals and reported in centimeters (cm). Higher wicking values show greater liquid water transport ability.

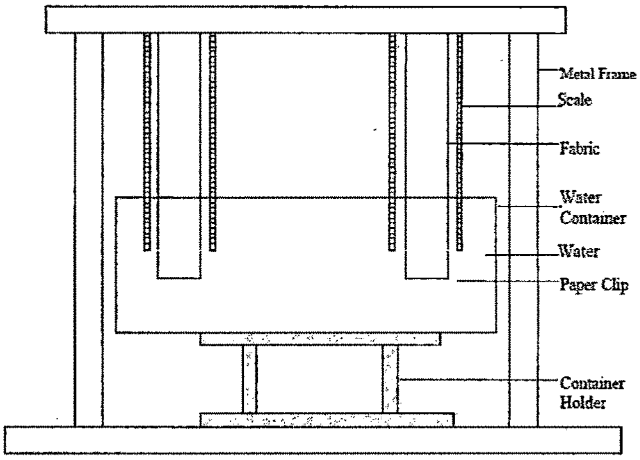


Figure 32 . vertical strip wicking test

3. Drying

The rate of drying of test materials is measured using 3.5 inch diameter circle test specimens. Dry weight of the test specimens is determined. Then one cubic centimeter (one gram) of distilled water is evenly distributed over the fabric surface. The specimens are weighed every 15 minutes until they return to their approximate original dry weight. The average drying time in minutes is calculated for each test material.

2.4.3. Fabric assurance by simple testing - FAST[20]:

SiroFAST system instruments have been developed by CSIRA , Australia for measurement of important physical, mechanical and surface properties of fabric which provides guide lines for limits of these properties for problem free tailoring in garment manufacture for wool and wool blend products. It is much simpler than KESF system.

It involves three instruments and a test method.The tests are performed in the order SiroFAST-1(5 replicates), SiroFAST -2 (3warp and 3 weft replicates), SiroFAST-3 (3 warp, 3 weft, and 6 bias replicates (3 left-bias and 3 right-bias))with test samples of 150 mm X 50 mm. The samples are then steam released and the SiroFAST-1 tests repeated. The dimensional stability test (SiroFAST-4) requires a separate sample (300 X 300 mm). In practice, about half a metre of fabric at full width is required to carry out the whole range of tests and allow reasonable sampling across the piece. The properties measured are as follows.

Instrument	Parameter		Symbol	Unit
FAST - 1	Fabric thickness@ 2 g/cm2		T	mm
(Compression meter)	Fabric surface thickness		ST	Mm
	(difference of thickness measured at 2 g/cm^2			
	and 100 g/cm2 pressure)			
	Relaxed surface thickness (difference		STR	Mm
	between relaxed-ST and ST)			
FAST – 2	Bending rigidity	warp way	B-1	µN m
(Bending meter)		weft way	B-2	µN m
FAST – 3	Extensibility at 100 gf/cm width	warp way	E_{100}-1	%
(Extension meter)		weft way	E_{100}-2	%
FAST – 4	Relaxation shrinkage	warp way	RS-1	%
(Test method)		weft way	RS-2	%
	Hygral expansion	warp way	HE-1	%
		weft way	HE-2	%
Chemical Balance	Fabric weight at 20 C and 65% R.H.		w	g/m^2

SiroFAST-1 Compression meter measures fabric thickness on 10 cm^2 area at two loads, 2 g/cm^2 and 100 g/cm^2. The surface thickness is the difference between two values. Measurements of released thickness and released surface layer thickness are obtained after the fabric has been relaxed in steam.

SiroFAST-2 Bending meter measures fabric bending length using the cantilever bending principle on strip of 5 cm wide. From the values of bending length and mass/ unit area of fabric, the bending rigidity as a measure of the stiffness of a fabric is calculated. Bending rigidity is related to handling in garment making.

SiroFAST-3 Extensibility meter measures the extensibility of a fabric under three different loads (5, 20 and 100 g/cm of width) on sample of 100mm x 50mm size. The loads are chosen to simulate the level of deformation the fabric is likely to undergo during garment manufacture.

SiroFAST-3 is also used to measure the bias extensibility of the fabric (at 45° to the warp direction) under a low load (5 g/cm width). Bias extensibility is used to calculate shear rigidity as a measure of the ease with which a fabric can be deformed into a three-dimensional shape.

Formability = Bending Rigidity X (Extension at 20 g/cm - Extension at 5 g/cm) / 14.7.

Formability measures degree of compression in the fabric plane sustainable by it before buckling.

SiroFAST-4 Dimensional stability test is a test method for measuring the hygral expansion and relaxation shrinkage of fabric. Fabric is dried in a convection oven at 105°C and its dry dimensions (L1) is measured. The fabric is then relaxed by wetting in water and its wet dimensions (L2) is measured. Lastly, the fabric is dried again at 105°C and its final dry dimensions (L3) are measured.

$$\text{Relaxation shrinkage (\%)} = \frac{(L1 - L3)}{L1} X\,100$$

$$\text{Hygral Expansion (\%)} = \frac{(L2 - L3)}{L3} X\,100$$

The SiroFAST instruments are interfaced with a computer which does the data handling automatically and produces a control chart to interpret the data.

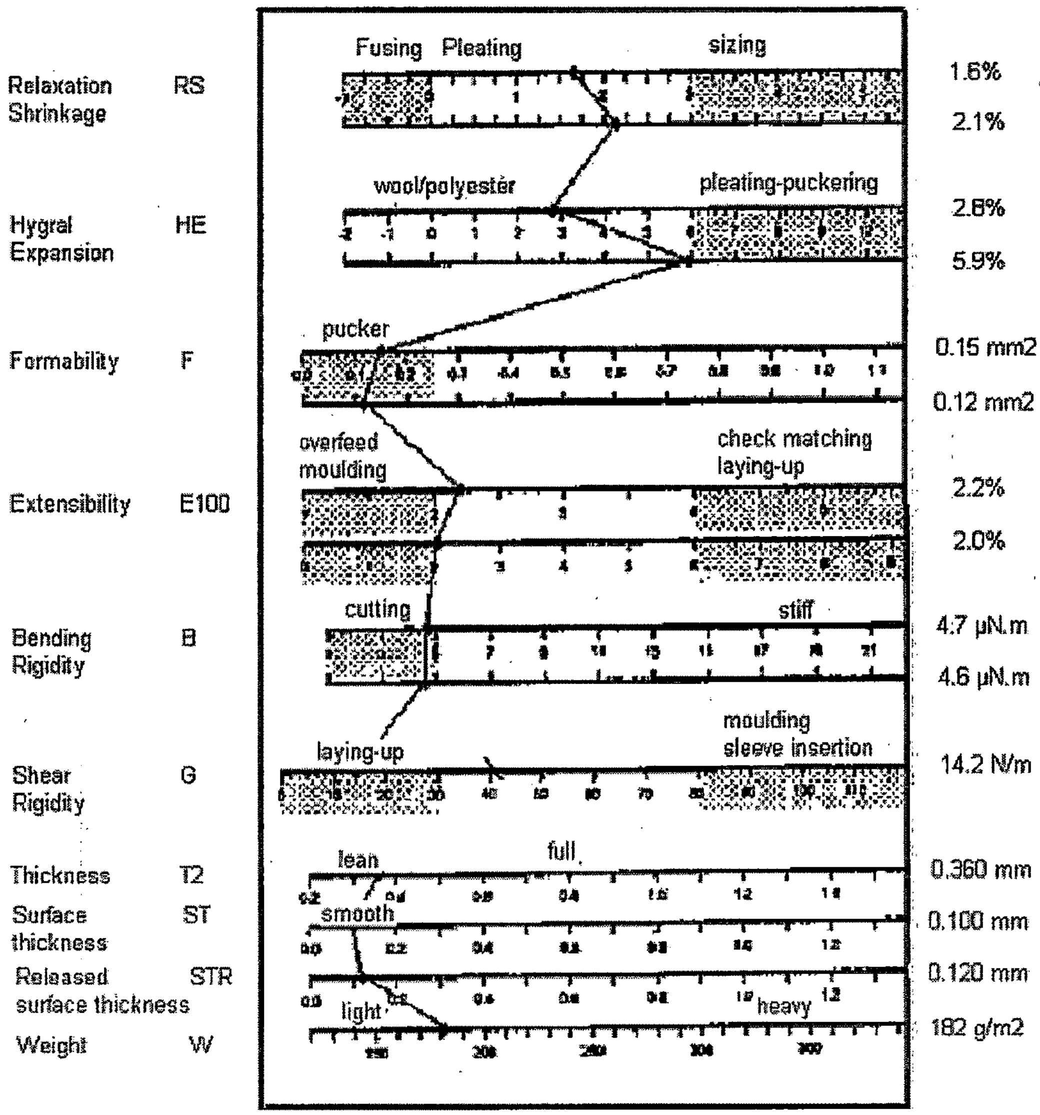


Figure 33. FAST control chart.

FAST control chart called 'snake chart' can be used as fabric finger print. Shaded regions are likely to cause problems in cutting, laying or stitching and/or make up into the garments having poor finished appearance. Thses limits habe been determined from experience and slightly different zones would be used for other applications, such as women, dress goods or pleated skirts.

A wide range of information can be obtained from direct observation of the fingerprints position in relation to the 'grey zones' on the SiroFAST chart. Software allows users to adjust limits to meet changing garment designs and skill levels in their factories.

The mechanical and dimensional properties measured by SiroFAST can, either individually or in combination, affect all major process stages involved in the production of garments.

a. Relaxation shrinkage: If the relaxation shrinkage exceeds 3%, final garment is smaller than planned. If the fabric has insufficient relaxation shrinkage (less than 0.5%) then problem can occur during sewing and pressing around the sleeve where some shrinkage is required to shrinkage away any residual fullness and take up excessive fabric. Negative relaxation shrinkage causes fabric to grow when relaxed I manufacture and wear. This is achieved by correct over feed and width setting in the stenter and controlling tension in dry finishing.

b. Hygral expansion: upto 6% can be tolerated in garments. Excessive hygral expansion (>6%) will manifest poor appearance as the garment panel increases with increases in moisture content of the fibres. This gives rippling or puckering of the fabric at the junction of support. The pleating problems result from inappropriate dimensional stability.

c. Formability: It depends on bending rigidity and the extensibility. Inadequate formability increases the likelihood of seam pucker. If it is less than 0.25 mm^2 the fabric is unable to take compression and pucker along seams. It depends on the crimp of yarn. The fabric dimension in stenter and dry finishing can control it.

d. Extensibility: if it less than 2% then the fabric is difficult to stretch during seam over feed. It is difficult to create fullness at the sleeve head. If it greater than 4% in wrap it make cutting difficult unless fabric is stabiles on vacuum table.

e. Bending rigidity: fabric with low bending rigidity may also have low formability and as a result be prone to seam puckering. If the shear rigidity is too high then the fabric will not readily form smooth three dimensional shapes as

Required in garments. if it less than 5μNm the fabric bends and folds very easily and it can be difficult to cut, handle and sew. A vacuum table can be used to facilitate cutting.

f. Shear rigidity: As shear rigidity has a large effect on fabric drape, it will affect garment appearance. It depends on yarn interaction. A tight fabric ahs higher shear rigidity. If it is less than 30 N/m then the fabric is easily distorted and can skew or bow during handling, laying and sewing. If it is greater than 80 N/m the fabric can be difficult to form or shape at the sleeve head.

g. Thickness/surface thickness: There are two limits for this.1.Relaxed surface thickness-an increase from 0.1mm to 0.18mm results in a difference in handle.

h. Weight: The lighter the fabric it is more difficult to make garment.

It is not an FOM system and can not be aimed to predict the subjective perception of fabric handle. But is suitable to take the guesswork out of product development by the fabric producer and finishers for the process optimization.

2.4.4. Fabric Objective Measurement (FOM) techniques:

The woven fabric design is based on the mechanics of textiles. Many models and theories explaining the design concept have been developed to improve the quality of fabrics as well as their suitability for specific applications. References of some of the designs based on structure and material properties of woven fabrics are included in this study.

2.4.4.1 Over view of some FOM models [39,41,44,45,47,48]:

Hearle[21] explained in detail the generalized features of computer-based system for the calculation of the mechanical properties of textile structures.

Grosberg and Leaf[22] presented the possibility of producing more tractable solutions for design problems in contrast with the complexity of analyzing fabric mechanical behavior on the basis of Peirce's principle. They developed a model consisting of series of equations to produce a well designed fabric. The equations are based on yarn linear density(T), Flexural rigidity(B), thread spacing(p), modular length(l), fabric weight(W), fabric cover(K) and mechanical properties such as Young's modulus(E), Flexural rigidity per unit width(B) and shear modulus(G).

Leaf and his co-workers[51] illustrated the idea of treating particular mechanical properties as some specific functions of yarn and a fabric structural parameters.

Ping and Greenwood[52] worked on the designing of fabrics by means of weave with predetermined physical properties. The series of experiments conducted by them indicates that the weave affects both the tearing strength and the stiffness of the fabrics.

Mohar[46]presented the concept of using engineering principles as an aid to design the fabrics with desirable aesthetic characteristics. The approach uses the objective measurement of basic mechanical and physical properties of fabrics, e.g. fabric tensile, drape, shear, bending, lateral compression and surface properties. Relationships are reviewed between these properties of fabrics and aesthetic characteristics, e.g. fabric handle, drape, tailorability and garment appearance.

Kawabata , Niwa[23] has discussed various objective methods of evaluating the fabric handle developed.

Zubanda[53] presented the design and construction of a computer-based data acquisition system to meet the specified levels of quality and mechanical and physical performance. The purpose of the work is to measure the reproducibility of fabric mechanical and surface properties accurately by using KES-F.

Dhingra[76] described a method for the design and optimization of wool fabrics by using a database incorporating fabric mechanical and dimensional properties. This system's input are tensile, shear, bending etc., measured by KES-F.

Jinlian HU, Wenxiang Chen, and Newtonthe[24] applied Stevens Law $Y = K * X^b$ between sensation magnitude on psychological scale and stimulus intensity on a physical scale to the fabric primary hand evaluation. Data from 39 men's worsted suiting fabrics were considered for the primary hand values Y judged through subjective testing by the experts. These include three primary hands namely, stiffness (HV1), smoothness (HV2) and fullness (HV3). X are the 16 mechanical or physical properties of six group tests of bending, shearing, tensile, compression, surface thickness and weight tested on the Kawabata's evaluation system (KES). Multiple regression Equations for the prediction of Y, the fabric hand values obtained through stepwise regression $\log Y = a + \sum_{i=1}^{n} b_i \log x_i$, where a, b are arbitrary constants and n =16 the number of parameters demonstrates that the bending, surface and compression properties of the fabric are the most important to fabric primary hand values.

2.4.4.2 Principle component analysis technique:

Ninh Pan and S.Haig Zeronian[25] suggested an alternative approach to the objective measurement of fabric by Instron. The collinearity test in multivariate analysis of KES-FB's 16 parameters shows a possibility of information overlap or superfluous elements. By Principal component analysis (PCA) nine parameters are derived from the original 16 parameters of KES-FB. A test of collinearity gives $|Vs|$ of the covariance matrix of selected parameters' matrix Xs is almost $3x10^5$ times greater than the previous matrix X. In D-optimal Method statistical analysis the significance or sensitivity of a parameter is determined by its Generalized Conditional Variance value (GCV value). These Principal components ranked according to their eigen values accounting for 85% of the variance is considered satisfactory to represent nearly all information can be easily evaluated by Instron. Instead of multiple linear regression analysis of KESF system, a graphical technique of a circular diagram produced from these nine selected parameters is used to establish an expression for performance. The circular chart has nine radii evenly distributed representing 9 selected parameters. The values of parameters are normalized as $X_j' = (X_{jmax} - X_j) / (X_{jmax} - X_{jmin})$ on a scale ranges from 0 to 1. For each fabric a chart connecting the points on the each radii depending on the value of the tested parameter is obtained called the finger print to represent the fabric more concisely. Satisfactory fabric performance can be expected from appropriate level of all properties. Extremes may give poor handle.

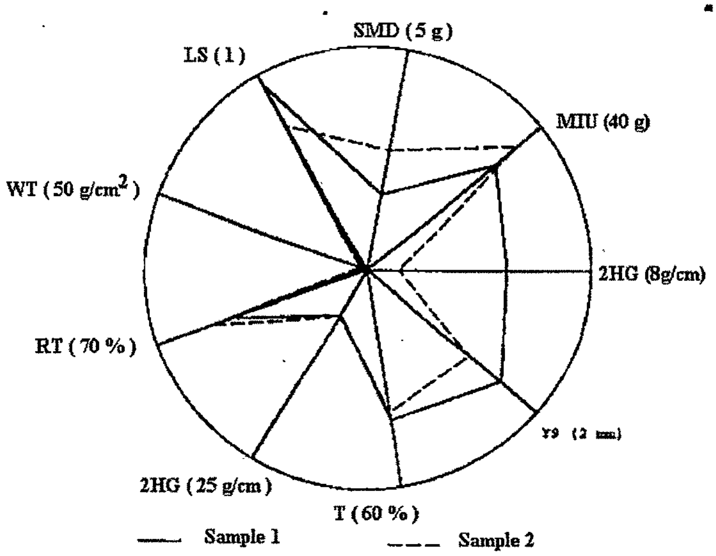


Figure 34. Circular chart

a) The fabric in group say same weave are represented by one circular graph to compare their properties differing due to sett.

b) Similarly the graph also compares the two fabric to check the effect of change of any parameter. Say similar fabrics produced from different blends can be compared to ascertain their similarity or differences.

c) It compares fabric for handle with the reference sample.

It is concluded from the analysis that high bending hysteresis and shear hysteresis indicates high yarn bending stiffness, a tight weave structure and high inter yarn friction or low mobility. Twill weaves with loose structure gives lower value for these two properties. Further it is observed that smoother the yarn lower the surface frictional coefficient. But plain weave and coarser yarn count gives undulated surface resulting higher geometrical roughness. Also weave structure has an effect on the fabric tensile energy.

2.4.4.3 Multiple factor analysis technique :

Howrth and Oliver[26] used multiple factor analysis technique to replace subjective judgments by laboratory tests to eliminate personal element in identifying the handling quality of worsted suiting fabric. Using Kendall's technique of paired comparison among the 27 commercially obtained suiting fabrics, a total of $^{27}C_2$ = 27X26/2 = 351 pairs are judged by 25 unskilled laboratory assistants on basis of some psychological investigations. It was found that 86% of decisions for which a particular fabric has been preferred, are made on the basis of 8 properties viz. smoothness, softness, firmness, coarseness, thickness, weight, warmth, harshness and stiffness. These eight most frequently occurring terms are then investigated for each property individually for 12 samples selected from 27 above which differ appreciably in their desirability of handle make total $^{12}C_2$ = 12 x 11 / 2 = 66 pairs. These were allotted to three observers with 22 pair to each. Each observer performs the tests three times thus it makes total of nine judgments. Total number of times each fabric is judged better than the other in a pair is denoted the rank score of the fabric. According to their rank for each of these eight subjective factors, fabric samples are given Sheppard score 0- poor to 6-excellent. Using Fisher and Yates method, ranked data has been converted to normal deviation for plotting against experimental data and their correlation coefficient has been calculated.

Objectively following tests related to handle quality are performed.

Smoothness: Frictional force is measured between the drum covered with fabric under the test and a small wooden friction piece covered with goldbeater skin. The force is measured by electrical strain gauge and the mean force produced during sliding (dynamic frictional force) is measured.

1. Cloth weight(w oz/ sq.yard) using BS standard
2. Cloth thickness (g in 1/1000 inch) was measured at range of pressures.
3. Stiffness was measured in the similar terms as has been prescribed by Peirce and included in BS Handbook.

   a) Bending length c (average of warp and weft way) of 1 inch wide strip which bend under its own weight through unit angle.

   b) Fluxural rigidity $G = 3.39\ wc^3$.

   c) Bending modulus $q = 732\ G / g^3$.

5. Hardness is the ratio of difference in pressure to the difference in thickness at a pressure of 0.01 lb. and 1 lb per sq. inch.
6. Cloth cover $K = n / \sqrt{N}$ n = threads per inch and N = indirect count. Since fabric were square average of warp and weft were taken.

These objective tests complete the battery of tests on twelve samples. The smoothness is excluded as no measurement of smoothness is found which correlate well with the subjective impression of smoothness.

Thus eight subjective terms and seven objective tests make total fifteen tests for analysis. The correlation coefficient between all 15 tests taken in pairs i.e.

$^{15}C_2 = 15 \times 14 / 2 = 105$ are calculated. The entire correlation coefficient table is difficult to interpret, so L.L.Thurstone's[27] technique of multiple factor analysis with three principle components is found suitable which shows the data on a 3D model.

Subjective terms		Objective tests	
1	Smoothness	1	Cloth weight
2	Softness	2	Cloth thickness
3	firmness	3	C
4	coarseness	4	G
5	thickness	5	Q
6	weight	6	Hardness
7	warmth	7	Cloth cover
8	stiffness		

- Each test is represented by the vector length (h) equal to the test variance i.e. the spread of the measurements on all fabrics for that test.
- The angle between the vectors are determined by the vector length and the correlation coefficient according to $r_{12} = h_1 h_2 \cos\theta_{12}$
- The reference axes are found from the correlation table by centroid method. The first axis would be passing through the resultant of all the vectors and second axis would be at 90 degree to the first. These are called factor axis.
- The co-ordinates of the all vectors on these factor axes called the factor loadings are then calculated.

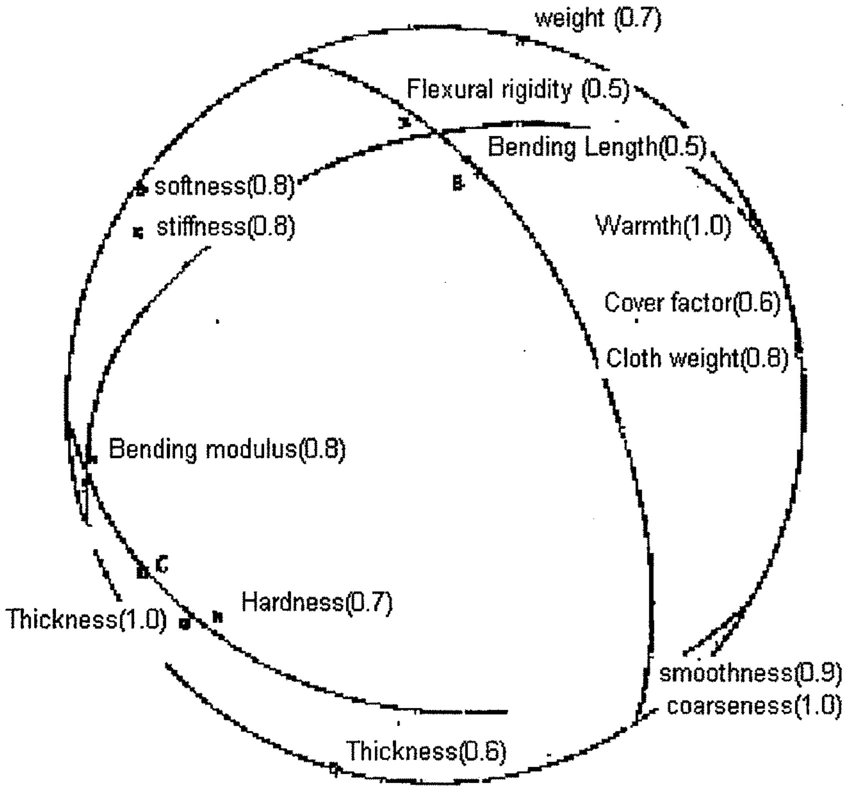


Figure 35. 3D Graphical model

A 3-D graphical model as shown in fig.31 is used to analysis the data.

Communality = (Factor A $)^2$ + (Factor B$)^2$ + (Factor C$)^2$. If the communality for all tests are unity then the data will lie on the surface and can be presented perfectly. The communality of tests are adjusted to unit length so their directions can be easily compared.

Interesting observation from the graph include:

1. smoothness and coarseness lies very close but on opposite axis indicates that they are inversely related.
2. objective thickness and hardness appear close but related in an inverse manner.
3. subjective weight and thickness appear to be close but they have a poor

communality indicating they do not fit wholly in the three factor scheme.

4. subjective warmth, objective weight and cover factor form a group showing they are related.
5. The subjective handle can not be related to any single physical test. The three factor scheme represents the relationship between the tests (objective) and the ranks (subjective), it is possible to select three physical tests a) stiffness b) smoothness & c) thickness to give complete description of the handle of worsted suiting.

2.4.4.4 Weighted Euclidean Distance concept:[28,29].

All the above discussed methods for determining fabric handle are based on people's subjective preference which involves human psychology. Though there exists a good correlation within a group of people from same region and class. But this local reliability which governs the fabric hand evaluation has been the main draw back. The KESF-B system has the same limitation that fabric is judged by Japanese judges. It is quite evitable that this subjective evaluation may not be suitable for market other than Japan. Secondly the multiple regression analysis is often severely influenced by the non-linearity of the data measured by KESF instruments.

Pan, Yen and others proposed objective assessment of fabric handle from fabric mechanical properties. From the matrix containing fabric mechanical parameters obtained through KESF system, a new feature matrix is derived. This matrix is orthonormal and each component reflecting one aspect of fabric handle. From the correlation coefficient of these factors with Sixteen KESF parameters, eight factors are given nomenclatures as stiffness, fullness, smoothness, crispness, elasticity, droopiness, roughness and softness. And weighted Euclidean distance (WD) value, of total hand value is obtained for each sample to compare fabrics for over all handle characteristic.

Objective measurement of the total handle of fabric:

Experimentally 48 samples are measured for the 16 KESF parameters, each parameter is denoted by Xij', i =1 to 48, j = 1 to 16 componant of matrix X. Each component of Xij' are standardised i.e. Xij = (Xij'-Ej)/Vj where Ej and Vj are the values of mean and variance of the j^{th} variable. Then the covarience matrix V of standardised matrix X is calculated.

By definition of a General Euclidean Distance in mathematics, any two fabrics samples from above matrix described by vector X with j mechanical properties,

i.e. X1 = (X11,X12,... X1j) &

X2 = (X21,X22,... X2j)

then the difference of mechanical properties of the two fabrics is given by the Euclidean Distance between them

$$D(X1, X2) = \left(\sum_{k=1}^{j} (X_{1k} - X_{2k})^2 \right)^{1/2} \quad \text{...(36)}$$

Thus if a standard sample s is taken as the origin representing the vector X_s , the distance of other fabrics from origin is comparable for objective measurement of total handle.

To determine the weight of each mechanical property by Karhunen-Loeve (K-L) orthonormal expansion theorem of statistical pattern recognisation technique, each of the 48 fabric sample denoted by 48 vector Xij, i = 48(no. of samples), j =

16(mechanical properties) with mean vector E and covariance matrix V can be replaced by orthonormal vector Y = XR .

Thus after transformation the corresponding feature vectors of Xij are

$Y_{ip} = X_{ij}R_p = (Y_{i1}, Y_{i2}, Y_{i3}, \ldots Y_{ip})$

where $R_p = (R_1, R_2, R_3, \ldots R_p)$

R_1, R_2, ... R_p are the p eigenvectors corresponding to the p prior eigenvalues of the covariance matrix V of Xij. p≤ j (16 fabric parameters measured by KESF).

By definition, the weighted Euclidean distance between any sample and standard sample S is

$$WD_s = \left(\sum_{j=1}^{p} (W_j (Y_{1j} - Y_{sj})^2) \right)^{1/2} \quad \ldots\ldots(37)$$

where weight of j^{th} component of Yi, $W_j = \left(C_j / Tr\ V \right)^{1/2}$, Tr V is the trace of covariance matrix V and Cj is the corresponding eigen value associated with Ri.

By Jacobi algorithm, the n eigenvalues Cj and the eigenvectors Rj of the covariance matrix V of X are obtained. Ranking C in ascending order p prior values of C1,C2,...Cp (p<j) are chosen so that

$$\sum_{i=1}^{p} C_i \ / \ tr\ V \geq 0.85$$

Thus the value of WDs for all the samples are calculated. It denotes the difference in fabric handle more reasonably. Larger the value of WD_s greater the difference in total handle between a fabric and the standard fabric given as a preference by the customer and worse the handle of the sample. If no std. Fabric is provided the real origin i.e zero value can be used to compare different samples. From this by assigning WR – the preference rank given to each sample according to WD value,

Thus the basis of Kawabata's THV and TR(the preference rank given by THV) is tactile assessment hence influence of subjective factor and may be inevitable outside Japan market but WD and WR are purely objective and mathematical and can be assigned for any different market situation.

Thus though the fabric handle is a subjective response to physical stimuli but this objective measurement evaluation method is advantageous for different markets and fabric types.