2004 BELTWIDE COTTON CONFERENCES, SAN ANTONIO, TX – JANUARY 5-9

THE TACTILE BEHAVIOR OF TEXTILE MATERIALS: NEW PERSPECTIVES
PART II: FABRIC SURFACE CHARACTERISTICS

Mounir Hassan, Yehia El Mogahzy, Fatma Kilinc, and Ramsis Farag
Auburn University
Auburn, AL
Rezk A. El-Bialy, Ahmed S. El-DEeb, and Ahmed Tolba
Mansoura University
Mansoura, Egypt

Abstract

Tactile behavior of fabric may be described by two main categories of parameters: surface parameters and mechanical (or low deformation) parameters. This paper deals primarily with fabric surface characteristics. It represents a small part of a larger study titled “Developing Design-Oriented Model of Fabric Comfort” directed by Dr. Yehia El Mogahzy. This study was conducted over three year period from 2000 to 2003 and involved top scientists from three major U.S. Universities: Auburn University, Georgia Tech, and North Carolina State University. Some International assistance was also provided. The primary objective of this study was twofold:

1. To establish a clear characterization of fabric and garment comfort using three independent but coordinated approaches: (a) structural modeling of the fabric/skin interaction phenomena, (b) experimental analysis of specially-designed fabrics and garments, and (c) empirical modeling of the fabric comfort phenomenon using a combination of physical, neural-network, and fuzzy logic analysis.
2. To develop a comfort design/manufacturing program to assist spinners, weavers, knitters, and garment manufacturers in producing fabrics of desirable levels of comfort suitable for different modes of applications including: normal/relaxing modes, high physical activity modes, and special task modes.

In this part of the study, the focus is on fabric surface analysis. The driving force of this analysis is the comfort model developed by El Mogahzy et al [1, 2] in which the comfort phenomenon was described by a single index representing the ratio between the true area of fabric/human skin contact and the corresponding apparent area. This ratio was found to be directly related to fabric surface characteristics including surface geometry, number of asperities in contact, surface hardness, and fabric friction. Accordingly, two main categories of parameters are evaluated: (1) surface friction characterized by inter-fabric frictional force at different levels of lateral pressure, coefficient of friction, and frictional parameters ‘a’ and ‘n’ and (2) fabric porous structure characterized by pore size and pore size distribution. These parameters are tested using a specially designed set of single-jersey knit fabrics.

Introduction

The importance of fabric surface in relation to fabric comfort, particularly tactile comfort, is well realized. The continuous intimacy between human skin and clothing dictates a fabric surface that is wearer-friendly even at the most still situations. The dynamics of interaction between human skin and fabric surface is also well recognized. As human moves, clothing reacts to every movement by moving towards and away from the skin in response to body movements.

The relationship between fabric surface and human skin will primarily depend on the following two factors:

1. The level of fabric/skin contact
2. The degree of fabric/skin intimacy

The level of fabric/skin contact may be divided into two main categories: level A and level B. In the wearing process, the fabric surface may be in direct contact with the skin (e.g. underwear, bras, swimwear, sleepwear, and socks). This may be termed level “A” contact. On other hand, when multiple layers of clothing are used, inter-fabric contact occurs (e.g. outerwear, jackets, and sweaters). This may be termed level “B” contact. The importance of this categorization lies in the fact that each level is associated with a different tactile mechanism and different design criteria.

From a design viewpoint, each level of contact will be associated with a different sensitivity level to some of the design parameters. For instance, level A contact is expected to be more sensitive than level B to factors such as yarn structure (twist, irregularity, hairiness, fiber stiffness), weave type (woven or knit), fabric style or pattern (single jersey vs. interlock, or plain weave vs. twill), and fabric surface finish. Obviously, the effects of these factors will extend to level B contact but to a lesser extent. At this level, the key factor will be fabric/fabric surface compatibility. Indeed, some of the factors that may be undesirable at level A contact can indeed be tolerated or even desired at level B contact. For example, excessive hairiness at level

A contact may not be desirable on the basis of skin irritation and possible prickliness particularly when fibers are stiff. At level B contact, this may be tolerated or even accepted on the ground that excessive hairiness may create many fiber cross bridges between fabric layers that can form still air pockets, which are useful for thermal insulation. To our knowledge, the issue of fabric layer compatibility at level B contact has not been investigated in previous literature, except perhaps from a fashion viewpoint. In the larger part of this study (not published here), multiple-layer analysis is performed.

The degree of fabric/skin intimacy may vary from very low intimacy in which relaxed clothing is used to very high intimacy in which, by virtue of its wearing function, clothing exerts high pressure against the skin. The degree of fabric/skin intimacy is largely dependent on the degree of fit and tightness of clothing. In today's fashion, this has become an important factor since some clothing is designed for tight or very tight fit and other is designed for relaxed fit. In this regard, a key tactile issue is the trade-off between meeting the fashion and look criteria and the comfort criteria.

The two factors discussed above will obviously vary in their importance and effects depending on the level of physical activity being performed by human and the surrounding environment. In view of the immense work that was done in the area of fabric surface characteristics in relation to comfort and tactile behavior, it would seem that the subject matter is now fully understood. Certainly, each investigation has added a new dimension to the state of today's knowledge. However, a universal approach toward developing a relationship between fabric surface characteristics and tactile comfort has not been established. Instead, empirical correlations were developed between surface characteristics and tactile parameters in many investigations [e.g. 3-11]. These correlations are highly dependent on a multiplicity of factors including: the fabric or garment type, the method of testing, and the range of values of external parameters (e.g. lateral pressure, type of contacting elements, area of contact, and speed). In additions, most investigations dealt with fabrics from a ready-made garment, a factor that obscures the relative effects of different basic design factors such as fiber type, yarn structure, and fabric style.

In this study, we approached the issue of the relationship between fabric surface characteristics and tactile behavior on the basis of a structural comfort model that was developed by El Mogahzy et al [1,2]. This model assumes that tactile comfort is primarily a function of the level of fabric/skin contact, and the degree of fabric/skin intimacy discussed earlier. According to this model, a single parameter that can fully characterize tactile comfort is the so-called Area Ratio, AR, which is the ratio between the true area of fabric/skin (level A), or fabric/fabric (level B) contact and the apparent area of contact, A_t/A_a. The general form of the Area-Ratio model is as follows:

$$\frac{A_t}{A_{app}} = C_M\, K^{-\gamma}\, M_a^{\;1-\gamma}\, P^{\gamma} \qquad (1)$$

where C_M is a constant characterizing the pressure distribution over the true contact area, K is an index of surface hardness under compression, M_a is the number of contacting asperities per unit area of apparent contact, P is the lateral applied pressure, and γ is a highly material-related constant that depends on the shape of pressure-contact area curve [11, 12].

In the context of fabric surface characteristics, the above equation clearly indicates that the tactile behavior of fabrics is influenced by two key surface-related parameters, namely the number of asperities in the contact area, M_a, and the shape of the pressure-contact area. Indeed, the above equation was directly driven from the adhesion theory of friction [13] and the theoretical development published earlier by El Mogazy and Gupta [11, 12].

From a physical and psychological viewpoint, human body is typically sensitive to the slightest irritation resulting from fabric rubbing against the skin. In a typical clothing system, fibers represent the immediate media touching the skin (level A) or separating the fabric layers (Level B). As a result, the mechanism involved in fabric/skin or fabric/fabric contact primarily involves a complex combination of many factors that simultaneously result in different levels of roughness or irritation sensation. Figure 1 shows some of these factors at the fiber level. In this part of the study, our focus is primarily at the fiber level through evaluation of design criteria primarily driven by fiber length and fiber arrangement resulting from the use of a certain yarn type or yarn structure. These design criteria were made possible through a set of single jersey fabrics made of the same fabric structure (cpi, wpi, yarn count, thickness, weight, stitch length, etc) and the same surface finish but from different yarns types (ring, compact, and MVS), and different cotton/noil content ratio. This set allows evaluation of the roles of fibers and yarn structure on fabric tactile behavior; a direction of research that should be emphasized to assist defining cotton fibers in terms of their end-product performance.

Materials and Methods

The material in this part of study is represented by a set of single jersey knit fabrics (28 cut, 50CPI/36 WPI) that were produced from three different yarn types: conventional ring-spun yarn, Elite Compact yarn, and Murata MVS air-jet yarn. In addition, each yarn type was made from four different preparatory methods: 100% cotton carded sliver, 100% cotton combed sliver, 80% cotton/20% comber noil sliver, and 90% cotton/10% comber noil sliver. Yarns used in this set were all of 30's

English count. Values of fabric thickness and fabric weight of different fabrics are listed in Table 1. In order to restrict the analysis to the effects of yarn type and preparation, it was important that all fabrics be dyed and finished using the same procedure. All fabrics were bleached in a soft flow jet, dyed and finished. We should point out that this set of fabrics was manufactured by Cotton Incorporated of the U.S.A. and kindly presented to us to perform tactile analysis. Details on the fiber and yarn characteristics of these fabrics can be found in Cotton Incorporated Technical Report [21].

Inspection of fabric samples of the first set (samples 1 to 12) revealed that the general appearance of combed fabrics for all spinning systems was always better than the carded control and cotton/noil blends. The combed fabric was less cloudy, had the lowest neps and white specs, and looked more uniform. In addition, the depth of shade was darker with the combed fabric samples. These trends can be attributed to the presence of short fibers and comber noils in the yarns from which the fabrics were made.

Using the first set of fabric samples, a design of experiment was developed in which different combinations of five different associated factors were considered using a 3x2x2x3x4 full-factorial design. Different factors and levels associated with this design are listed in Table 2.

The fabric surface was characterized using two main parameters: fabric friction and pore size. Fabric friction was tested using a straightforward setup shown in Figure 2 in which the apparent contact area is well-defined. This method can be used for fabric-to-metal or fabric-to-fabric friction. In case of fabric-to-metal friction, a flat metal plate is connected to an Instron® cross-head, over which a wood block of known dimensions (2.5"x2.5") covered by the fabric sample is placed. The block is connected via a thin thread to an Instron® load cell. The thread is passing over a freely rotating roller guide with very small capstan effect. The sliding motion is activated by moving the flat plate downward with the Instron® cross-head. The force required to slide the block over the flat metal surface is measured and a stick-slip profile (Figure 2.c) is generated. When fabric-to-fabric friction is tested, a sand paper is mounted on the flat plat. The fabric sample is then mounted over the sand paper. This prevents any lateral movement within the fabric sample during sliding. The second fabric surface is created by mounting the fabric to the wood block as described for the fabric-to-metal friction test.

Fabric pores are the minute openings in the fabric structure. The existence of pores in the fabric structure is a natural consequence of the method of fabric formation. Pores can be controlled in size and number through many design options including: fabric structure and style, geometrical features within a given fabric structure, yarn structure, and fiber properties. In this study, pore analysis is performed using image analysis of different fabric structures. This approach required obtaining precise microscopic images (transmitted) of the fabric to determine pore size and pore's size distribution. These images are then analyzed to determine a number of parameters. Figure 3 illustrate the different parameters of pore size and pore frequency considered in this study. The reason for using many parameters lies in two important points:

1. Pore size may not always follow a symmetrical normal distribution due to the possibility of some open areas that are free of fiber hairs entanglement leading to pores of size greater than the modal size
2. The frequency of pores of a certain size (small or large) is expected to have significant effects on fabric tactile and thermal behavior depending on the size category of pores

Results and Discussions

Fabric Friction

1. Inter-Fabric Coefficient of Friction. According to the design of experiment discussed earlier, a multiple-way Analysis of Variance (ANOVA) was performed using the following general model:

$$SS(\mu) = SS(P) + SS(SP) + SS(YT) + SS(S) + SS(D) + SS(Error)$$

Table 3 shows the basic output of this analysis. As can be seen in this Table, the largest factor influencing the average coefficient of friction (as determined by the F-statistic and associated probability) was the lateral pressure (P) applied on the fabric. This is obviously expected by virtue of the classic Amonton's relationship of friction, F = μP, where F is the friction force per unit area and P is the lateral pressure, and μ?is the coefficient of friction. The second most important factor is the fabric side. This is expected on the basis that the face of the single-jersey fabric is structurally different than the back. This point is illustrated in Figure 4. The third important factor is spinning preparation. As indicated earlier, the different levels of this factor imply different levels of comber noils and short fiber content. Accordingly, changes in the surface behavior associated with these levels are expected.

The ANOVA Table also reveals that the yarn type was the least important factor. This result seems to be surprising due to the well known substantial differences in the surface structures of the three yarn types considered. It was important, therefore to perform further analysis to have better insight into the effect of yarn type on fabric surface friction. Specifically, it was important to evaluate whether the yarn type factor exhibits interaction with other factors considered in the experiment. Table 4 shows another ANOVA Table involving interaction factors between yarn type and fiber content. This analysis was a result of ANOVA trials involving interaction effects between yarn type and all other factors that revealed that the only significant interaction was that between spinning preparation and yarn type. The results of this ANOVA indicate that the overall significance of the ANOVA model slightly deteriorated after the addition of the interaction factor. In addition, they indicate that the YT*SP interaction was more significant than the yarn type factor alone and fabric direction.

The outcome of the analysis above reveals the following important points:

1. Spinning preparation, which is represented by the level of comber noils in the cotton mix, has the highest effect on surface friction of single-jersey knit fabrics. This point is illustrated in Figure 5 which shows that at all levels of lateral pressure, fabrics made from 100% combed yarns exhibited lower friction (smoothness) than those made from 100% carded yarns. The results also show that the addition of comber noils resulted in slight increase in surface friction.
2. The single-jersey fabrics produced at all pressure levels exhibited significant fabric side effect. As can be seen in Figure 6, at all pressure levels, the coefficient of friction of fabric back was higher than that of fabric face.
3. The effect of yarn type becomes significant when it is analyzed in view of spinning preparation and the preparation used. This point is illustrated in Figure 7. As can be seen in this Figure, fabrics made from combed yarns of exhibit lower friction than those made from carded yarns, regardless the yarn type. When fabrics made from carded yarns are compared, the fabric made from compact yarn is found to exhibit the highest friction and fabrics made from carded conventional ring and MVS exhibit approximately the same level of friction. When fabrics made from combed yarns are compared, the fabric made from MVS yarn is found to exhibit the highest friction, followed by fabric made from combed compact yarn. The addition of comber noils during preparation generally resulted in higher friction, however, this effect was not consistent when fabrics made from compact yarns with added noils were compared with those made from 100% carded yarns. This may be a result of the better utilization of short fibers in the yarn.

2. Friction Parameters "a" and "n". In the analysis represented above, the coefficient of friction, μ, was determined from the classical law of friction, $F_A = \mu .P$ (where F_A is the frictional force per area, and P is the lateral pressure). This law typically assumes that the coefficient of friction, μ, is constant at all levels of lateral pressure and is independent of the area of contact. This assumption has been questioned in many previous literatures [e.g. 16-20], and it was generally found to be inappropriate for materials deforming elastically or viscoelastically under lateral pressure including fibrous structures.

Many formulae have been developed to model the friction phenomenon of different materials. For polymeric materials, many attempts were made to develop more realistic relations [16-20]. In a more recent study [10, 11], Gupta and El Mogahzy performed theoretical and experimental analyses aiming at evaluating different relationships between the frictional force and the normal force for fibrous materials. They concluded that the best expression that can characterize this relationship is Howell's equation:

$$F_A = a\,P^n \qquad (1)$$

The above relationship indicates that the frictional coefficient, defined by the ratio F/N, is not constant as suggested by the classic friction law. Instead, it is a function of the normal force, N, applied on the contacting area. This is revealed by the following equation:

$$\mu = \frac{F_A}{P} = aN^{n-1} \qquad (2)$$

Gupta and El Mogahzy [11, 12] provided physical interpretations to the friction parameters 'a' and 'n'. In general, the frictional parameter 'n' is primarily material-related (largely depends on contact geometry and deformational behavior). For materials deforming plastically under pressure, n is 1.0 and a = μ., which is the case of the classic law of friction. For pure elastic deformation, n is typically 0.666. For materials behaving visco-elastically (e.g. polymeric materials), the parameter 'n' will typically range from 0.666 to 1.0. The parameter "a", on the other hand is more complicated in nature and it is largely sensitive to a host of factors surrounding the friction media. These include: the pressure distribution, surface hardness, material shear strength, and surface morphology or geometry. These factors were expressed in the following equation [11]:

$$a = S.C_M.K^{-n}.m^{1-n} \qquad (3)$$

where S is the specific shear strength (or shear strength per area), C_M is a constant characterizing the pressure distribution over the true contact area, K is an index of surface hardness under compression, and m is the number of contacting asperities. Note that, when materials behave plastically, C_M is unity, n is one, and the shear strength, S, is the frictional force per unit area (per the adhesion theory). Since in this case, the hardness constant, K, is equal to the yield pressure of material. This results in equation 3 approaching the classical law of friction F = μ N.

In this part of the study, the parameters 'a' and 'n' were determined from the relationship between the coefficient of friction, as defined by the classical law ($\mu = F_A/P$), and the lateral pressure P. Most investigations that dealt with this relationship for different polymeric or fibrous materials [e.g. 11-12, 16-20] found that the coefficient of friction typically decreases with the increase in normal force (or the pressure applied on the apparent area of contact) in a manner that can generally be described by equation 2. Figure 8 shows that the relationship between coefficient of friction and lateral pressure for the three yarn types considered in this study follows the general form of equation 2 with n values of 0.531 for fabrics made from ring and compact yarns, and of 0.565 for fabrics made from MVS yarns. Note that the wide spread of points around each pressure level is a result of the many factor combinations that were considered in the design of experiment described in Table 2.

Analysis of Variance Associated with the Parameter "a" and "n"

Following the procedure discussed earlier, analysis of variance of the factors influencing the parameters "a" and "n" was performed using a 3x4x2x2 full-factorial design of experiment. Factors, levels, and response variables associated with this design of experiment are listed in Table 5. According to this design of experiment, a multiple-way Analysis of Variance (ANOVA) was performed using the following general model:

$$SS(n) = SS(YT) + SS(FC) + SS(S) + SS(D) + SS(Error)$$

&

$$SS(a) = SS(YT) + SS(FC) + SS(S) + SS(D) + SS(Error)$$

Table 6 shows the basic output of this analysis of variance performed for the friction parameter "n". As can be seen in this Table, the overall model is generally weak as indicated by the low F-value and the high corresponding probability (Prob >F). In addition, none of the factors considered in the analysis revealed a significant effect on the value of the friction parameter "n". These results were largely expected on the ground that this friction parameter is primarily a material-related parameter. Since all yarns were made from the same type of material (cotton) and also of the same cotton mix, significant changes in the parameter "n" were not observed.

Table 7 shows the basic output of this analysis of variance performed for the friction parameter "a". Here, the model is more significant as indicated by the high F-value and the low corresponding probability (0.0002). It should also be pointed out that the overall model associated with the friction parameter "a" is substantially less significant than that of the coefficient of friction (Tables 3 and 4). This can be explained on the ground of two important points: (a) the pressure factor of the previous analysis has a great effect on the coefficient of friction, μ, while the parameter "a" is determined over the pressure range used, and (b) the parameter "a" is likely to be influenced by other factors that are not included in the model and were not considered in the experiment (e.g. sliding speed, and sliding environment). Nevertheless, one can clearly see that the factors that significantly influenced the coefficient of friction, μ, also influenced the friction parameter "a". The ANOVA also reveals that the largest factor influencing the friction parameter "a" is the fabric side. The second important factor is spinning preparation. As indicated earlier, the different levels of this factor imply different levels of comber noils and short fiber content. Accordingly, changes in the surface behavior associated with these levels are expected. The third factor influencing the friction parameter "a" is yarn type. Finally, fabric direction came last with less significance.

Again, the significant effect of fabric side is expected on the basis that the face of the single-jersey fabric is structurally different than the back. The effect of fabric side on the parameter "a" is similar to that on the coefficient of friction, μ. This point is illustrated in Figure 9 for different yarn types, which shows that the value of the parameter "a" is higher for the fabric back than the fabric face. However, one can see that the difference between the back and the face varies with the yarn type. This indicates an interaction effect between yarn type and fabric side. The results of Figure 9 also indicate that the largest difference between the back and the side is witnessed for the case of fabrics made from MVS yarns. Figure 10 shows the effect of spinning preparation on the friction parameter "a". Similar to the effects on the coefficient of friction, μ, combed yarn resulted in fabrics of the lowest values of the parameter "a".

The results of Figures 9 and 10 also show that fabrics made from MVS yarns generally have the lowest values of friction parameter 'a'. This trend was particularly obvious for fabric face and for carded yarns. One possible interpretation of this trend is that the wrapper fibers of MVS yarns may be creating gaps in the fabric interface that lead to lower areas of contact, consequently lower friction. Fabrics made from Elite Compact yarns were generally similar to those made from conventional ring spun yarns, but they were consistently higher than those made from MVS fabrics. This trend may be explained on the ground that the lower hairiness expected in the Elite Compact yarns resulted in more intimate interfacial contact (higher contact area), and consequently higher friction.

Pore Analysis

As indicated earlier, fabric pores are the minute openings in the fabric structure and their existence is a natural consequence of the method of fabric formation. For this particular set of samples, all fabrics were made of the same fabric style and dyed and finished similarly. Accordingly, pore size and pore frequency should ideally be the same for all the fabrics. However, since these fabrics were made from different yarn types and at different spinning preparation methods, structural differences in the yarn are expected to influence the pore size. Figures 11 and 12 show comparison of pore size and pore frequency, respectively for the different fabrics examined in this study. Figure 13 shows the variability in pore size for the same fabrics. The results of these Figures can be summarized in the following points:

1. For knit fabrics made from carded yarns, conventional ring-spun yarns seem to produce the smallest pore size and the largest percent of small pores (= 30 micron). Both Elite Compact and MVS carded yarns yielded similar pore size and similar percent of small pores. The variability in pore size, expressed by standard deviation, is also the smallest for fabrics made from ring-spun yarns, which provides confidence in the observed trend. These results suggest that when knit fabrics are made from carded yarns, conventional ring-spun yarns seem to yield smaller pores and more consistent pore size than both Elite compact and MVS carded yarns. This may be partially attributed to the fact that carded ring-spun yarns have higher hairiness than both Elite Compact and MVS yarns leading to smaller pore size and more fiber bridging or higher percent of small pores.
2. Also, for knit fabrics made from carded yarns, all yarns yielded pore size distribution of positive skewness, which means that they all exhibited high frequency intensity at the small pore size and only few pores of large size. However, MVS carded yarns yielded the highest skewness of pore size distribution. This may be attributed to irregular and inconsistent fiber wrapping around the MVS yarn core resulting from the use of fibers of smaller staple length than the threshold fiber length of MVS yarns, which is typically in the medium to long staple length (fibers of this study were of about 1.12 inch). In other words, if fibers of longer staple length were used, the pore size distribution skewness would likely to decrease significantly.
3. For knit fabrics made from combed yarns, MVS yarns produced the smallest pore size and the largest percent of small pores. The Elite Compact combed yarn yielded the largest pore size and the smallest percent of small pores. The variability in pore size, expressed by standard deviation, is also the smallest for fabrics made from MVS combed yarns, which provides confidence in the observed trend. Indeed, all combed yarns had very close values of standard deviation, making the comparison quite reliable. These results suggest that when knit fabrics are made from combed yarns, MVS yarns may be the choice if small pores are desired. We should, however indicate that the courses per inch for combed MVS was slightly higher than that of ring or compact (53 vs. 50), which may have partially attributed to this trend. Overall, the results indicate that the MVS combed yarns yielded better compactness in the fabric structure than both Elite and conventional ring-spun combed yarns, It is well known that in addition to the effect of combing on removing short fibers, the MVS system also removes additional short fibers. Indeed, the approximately 8% fiber waste in this system is primarily short fibers. .
4. Also, for knit fabrics made from combed yarns, all yarns yielded pore size distribution of positive skewness, which means that they all exhibited high frequency intensity at the small pore size and only few pores of large size. However, MVS combed yarns yielded the highest skewness of pore size distribution (similar to the case of carded yarns). Again, this may be attributed to irregular and inconsistent fiber wrapping around the MVS yarn core resulting from the use of fibers of smaller staple length than the threshold fiber length of MVS yarns, which is typically in the medium to long staple length (fibers of this study were of about 1.12 inch). In other words, if fibers of longer staple length were used, the pore size distribution skewness would likely to decrease significantly. Note that the differences in pore size skewness between combed MVS fabrics and conventional ring, or Elite compact combed yarn fabrics are approximately similar to corresponding differences for carded yarns, which means that skewness provides a viable parameter of pore size.
5. The addition of noils to the primary cotton of ring-spun yarns has resulted in increase in pore size and a slight reduction in percent of small pores by comparison with fabrics made from carded ring spun yarns. This means that short fibers in the carded yarns created more fabric gaps than small fiber bridges. Compact Elite yarn fabrics followed an opposite trend and to a lesser extent for fabrics made from MVS yarns. These results indicate that the addition of comber noils may have been offset by the actions of the Elite Compact or the MVS spinning systems in utilizing or removing short fibers.

The results discussed above indicate that the method of spinning preparation in each spinning system represents a key factor in determining pore size and pore frequency. This means that through control of the settings and the parameters associated with spinning preparation for a given spinning system (e.g. mix fiber length and short fiber content, comber noil %, etc), one can ultimately control the pore size and pore size distribution of a certain fabrics made from a certain yarn count and using the same weave or knit pattern. The results also indicate that short fibers, which are typically reflected by hairiness in the fabric has a complex effect on pore size and pore size frequency. They may form small fiber bridges leading to small pore size and high frequency of small pores, particularly by comparison with combed yarns. On the other hand, excessive hairiness may indeed create more gaps in the fabric leading to large pore size and smaller frequency of small pores. Figures 14 and 15 clearly illustrate this point through the change in the directional effects of yarn hairiness on pore size and pore size frequency.

It is important, therefore that the level of yarn hairiness, which is largely a result of factors such as short fiber content in the cotton mix, residual short fibers in the yarn after preparation, or yarn type, to be incorporated in the design process of a certain fabric.

In the context of comfort, fabric pore size and pore frequency represent critical factors. A high frequency of very small pores can result in better thermal insulation as a result of the ability of small pores of entrapping air inside the fabric structure. On the other hand, large pores may provide tactile advantages such as better fabric flexibility.

When the three yarn types are compared, it will be important to determine the yarn type that can provide the greatest opportunity for controlling pore size in the fabric for a given yarn count and fabric style. Figure 16 shows the envelopes of pore size frequency for fabrics made from each yarn. These envelopes are basically cumulative frequency curves plotted for fabrics made from 100% combed yarns and 80%cotton/20%noils carded yarns. These two yarns represent the extreme treatments influencing yarn hairiness and fabric performance. As can be seen in Figure 16, Elite Compact yarns provide the largest opportunity for controlling the frequency of pore size, followed by MVS yarns. Conventional ring-spun yarns provide the least opportunity for controlling pore size at a given yarn count and given fabric style. For all types of yarn, frequency envelops largely close at extremely small particle size and extremely large particle size. This means that the opportunity to make a large difference in pore size frequency decreases for very small and very large particle size. Another important point revealed by the frequency envelops is that for both Elite Compact and ring spun yarns, fabrics of the highest percent of a certain pore size are produced at the 80%C/20%N treatment, while fabrics of the smallest percent of a certain pore size are produced at the 100% combed cotton treatment. For MVS yarns, an opposite trend is obtained; fabrics of the highest percent of a certain pore size are produced at the 100% combed cotton treatment, while fabrics of the smallest percent of a certain pore size are produced at the 80%C/20%N treatment. These points represent very useful guidelines in producing certain surface features or comfort levels by design.

The Area-Ratio

As indicated earlier, the ratio between the true area of fabric/object contact and the corresponding apparent area represents a key comfort index. In this study, this ratio was determined at different levels of lateral pressure using an ink imprint method [22]. Following the procedure discussed earlier, analysis of variance of the factors influencing the area ratio (yarn type, fiber content, pressure, and side) was performed using a 3x4x3x2 full-factorial design of experiment. The output of this analysis is shown in Table 8. The analysis clearly indicates that the most significant factor influencing the area-ratio is the pressure applied on the area of contact. This is expected on the ground that at low pressure level the true area of contact will be very small in comparison with the actual area of contact. As the pressure increases, the true area of contact increases, consequently, the area ratio will also increase.

The ANOVA also reveals that yarn type has a significant effect on the area ratio. This point is illustrated in Figure 17, which shows that fabrics made from the Elite compact yarn always have smaller area ratio at the same pressure level than those made from conventional ring-spun yarn or MVS air-jet yarn. One possible explanation is that compact Elite yarn has significantly less hairiness than the conventional ring-spun yarn.

Spinning preparation method also influences the area ratio as indicated in the ANOVA table but at lesser extent than yarn type. Figure 18 shows area-ratio values at different preparation levels and for different levels of pressure. As can be seen in this Figure, fabrics made from 100% combed yarn always exhibited less area ratio than those made from 100% carded yarn. The results also indicate that as the percent of noils increases, the area ratio decreases to some point above which it increases. This effect is more obvious at high pressure levels. This means that there is a certain level of short fibers or noils at which an optimum area ratio is obtained.

References

1. El Mogahzy, Y. E., Farag, R., Kilinc, F. S, Design-Oriented Comfort Model, Presentation at the Beltwide Cotton Conference, Atlanta, GA, January 2002
2. El Mogahzy, Y. E., Farag, R., Kilinc, F. S., El Hawary, I., Fabric Comfort: New Concepts, Presentation at the International Textile Institute Conference, Cairo-Egypt-March 2002
3. Suzuki, K. Shindai, and M. Ohira, “Action of Interfacial Tension in Sliding Resistance of Wet Fabrics”, *Sen-I Gakkaishi* 29, 50-56, 1973.
4. Kawabata, S., and Masako Niwa, Recent Progress in the Objective Measurement of Fabric Hand, Textile Science 91 International Conference Proceedings, Vol.1, Technical University of Liberec, Czech Republic, 1991
5. Kawabata, S., The Development of Objective Measurements of Fabric Handle, Proceedings of First Japan-Australia Symposium on Objective Specifications of Fabric Quality, Mechanical Properties, and Performance. Kyoto, 1982, Textile Machinery Society of Japan, Osaka, Japan, pp 31-59, 1982.
6. Kawabata, S., The Standardization and Analysis of Hand Evaluation, Textile Machinery Society of Japan, Osaka, Japan, 1975.

7. Behery, H. M., Comparison of Fabric Hand Assessment in the United States and Japan, Text. Res. J., 56, 227-240, 1986. J. O. Ajayi and H. M. Elder, Fabric Friction, Handle, and Compression, J. Text. Inst. , Part 1, 88, No. 3, 232-241, 1997.
8. Chen, and A. Newton, "A Psychophysical Model *for* Objective Hand Evaluation: An Application of Stevens' Law", *J. Text. Inst.,* 84, 354-363, 1993.
9. Y. Li, "The Objective Assessment of Comfort of Knitted Sportswear in Relation to Psycho-Physiological Sensory Studies", Dept. of Textile Industries, The Univ. of Leeds, Leeds, UL, Ph.D. Thesis, 1988.
10. W. *J.* Kirk and S. M. Ibrahim, "Fundamental Relationship of Fabric Extensibility to Anthropometric Requirements and Garment Performance", *Text. Res. J.,* 57,37-47, 1966.
11. Gupta, B. S., and El Mogahzy, Y., Friction in Fibrous Materials. Part I: Structural Model, Text. Res. J. 61(9), pp 547-555, 1991
12. El Mogahzy, Y., and Gupta, B. S., Friction in Fibrous Materials. Part II: Experimental Study of the Effects of Structural and Morphological Factors, Text. Res. J. 63(4), pp 219-230, 1993.
13. H. G. Howell, K. W. Mieszkis and D. Tabor, "Friction in Textiles", Textile Institute and Butterworths Scientific Publications, 1959.
14. R. K. Gamsworthy, R. L. Gully, P. Kenins, R. *J.* Mayfield, and R. A. Westerman, "Identification of the Physical Stimulus and the Neural Basis of Fabric-evoked Prickle", J *Neurophysiology,* 1988,59,1083-1097.
15. R. K. Gamsworthy, R. L. Gully, R. P. Kandiah, P. Kenins, R. *J.* Mayfield, and R. A. Westerman, "Understanding the cause of Prickle and Itch from the Skin Contact of Fabrics", *Australian Text.,* 1988,8,26-29.
16. B. Lincoln, "Frictional and Elastic Properties of High Polymeric Materials", *J. Appl. Phys.,* 3, 260, 1952.
17. F. P. Bowden and D. Tabor, "The Friction and Lubrication of Solids", Clarendon Press, Oxford, London, 1954.
18. F. P. Bowden and D. Tabor, "The Friction and Lubrication of Solids, Part n", Oxford, London, 1964.
19. D. Tabor, "Friction, Adhesion and Boundary Lubrication of Polymers, Advances in Polymer Friction and Wear", Vol. 5A, 5-28, Plenum Press, NY and London, 1974.
20. D. Tabor, "Friction - The Present State of Our Understanding", *J. of Lub. Tech.* 103, No.2, PI69,1981.
21. Cotton Incorporated Fiber Processing Technical Services, Short Fiber Study: Ring and MVS Spinning Systems, Report No. 2002-1, FPL-00-241, Cotton Incorporated, Raleigh, NC, April 2002.
22. Kilinc , F, El Mogahzy, Y., Hassan, M., Farag, R., El Dieb, A., The Tactile behavior of Textile Materials: New Perspectives. Part I: Fabric Handle Behavior. Proceedings of Cotton Beltwide Conference, 2004

Table 1. Different Single-Jersey Knit Fabrics (all bleached in a soft flow jet, dyed and finished).

No.	**Type of Spinning**	**Content**	**Fabric Thickness (mm)**	**Fabric Weight (oz/yd^2)**	**% Short Fiber Content**	**Yarn Hairiness**
1	MVS	100% Cotton, Combed	0.581	4.4	9.9	---
2	MVS	100% Cotton/ Carded	0.570	4.3	6.2	---
3	MVS	80/20 Cotton/Comber Noil	0.615	4.3	12	---
4	MVS	90/10 Cotton/Comber Noil	0.616	4.5	17	---
5	Compact	100% Cotton/ Carded	0.608	4.3	9.9	4.5
6	Compact	100% Cotton, Combed	0.553	4.2	6.2	3.8
7	Compact	90/10 Cotton/Comber Noil	0.578	4.2	12	4.8
8	Compact	80/20 Cotton/Comber Noil	0.584	4.2	17	5.0
9	Ring	100% Cotton/ Carded	0.583	4.1	9.9	6.2
10	Ring	80/20 Cotton/Comber Noil	0.595	4.2	6.2	5.6
11	Ring	90/10 Cotton/Comber Noil	0.587	4.1	12.9	6.2
12	Ring	100% Cotton, Combed	0.563	4.1	17	6.3

Table 2. Factors, Levels, and Response Variables of the 3x2x2x3x4 Full Factorial Design of Knit Fabrics.

Factor	**Level 1**	**Level 2**	**Level 3**	**Level 4**
Yarn Type (YT)	Conv. Ring	MVS	EliTe Compact	----
Spinning Preparation (SP)	100% Cotton-Control (Carded)	100% Cotton-combed	90%/10% Cotton/ Comber Noil	80%/20% Cotton/ Comber Noil
Pressure (P)	P1 (9.467 Kg/m^2)	P2 (18.935 Kg/m^2)	P3 (28.402 Kg/m^2)	----
Side (S)	Back (B)	Face (F)	----	----
Direction (D)	Wales (W)	Course (C)	----	----

Table 3. ANOVA Table of Average Coefficient of Friction of Knit Fabrics (following DOE of Table 2).

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	9	14.174406	1.57493	273.5216
Error	134	0.77157	0.00576	Prob > F
C. Total	143	14.945977		<.0001

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Pressure (P)	2	2	12.03458	1045.033	<.0001
Yarn Type (YT)	2	2	0.002392	0.2077	0.8127
Spinning Preparation (SP)	3	3	0.650597	37.6634	<.0001
Side (S)	1	1	1.462084	253.9227	<.0001
Direction (D)	1	1	0.024754	4.299	0.04

Table 4. ANOVA Table of Average Coefficient of Friction of Knit Fabrics including interaction effects between yarn type and other factors.

Source	DF	Sum of Squares	Mean Square	F Ratio	
Model	15	14.460689	0.964046	254.2777	
Error	128	0.485288	0.003791		Prob > F
C. Total	143	14.945977		<.0001	

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Pressure (P)	2	2	12.03458	1587.126	<.0001
Spinning Preparation (SP)	3	3	0.650597	57.2007	<.0001
Side (S)	1	1	1.462084	385.6407	<.0001
Direction (D)	1	1	0.024754	6.5291	0.0118
YT*SP	6	6	0.286282	12.585	<.0001
YT	2	2	0.002392	0.3154	0.73

Table 5. Factors, Levels, and Response Variables of the 3x4x2x2 Full Factorial Design of Knit Fabrics.

Factor	Level 1	Level 2	Level 3	Level 4
Yarn Type (YT)	Conv. Ring	MVS	EliTe Compact	----
Spinning Preparation (SP)	100% Cotton-Carded	100% Cotton-Combed	90-10 Cotton/ Comber Noil	80-20 Cotton/ Comber Noil
Side (S)	Back (B)	Face (F)	----	----
Direction (D)	Wales (W)	Course (C)	----	----

Table 6. ANOVA Table of Average "n" Parameter of Knit Fabrics. Model: SS n (Average) = SS (Yarn Type) + SS (Fiber Content) + SS (Side) + SS (Direction) +SS (Error)

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	7	0.01436	0.00205	3.795
Error	38	0.020541	0.00054	Prob > F
C. Total	45	0.034902		0.0032

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
YT	2	2	0.01133	10.4807	0.000
Fiber Content (or Preparation)	3	3	0.00124	0.7658	0.520
Side	1	1	2E-05	0.0369	0.849
Direction	1	1	0.00145	2.6901	0.109

Table 7. ANOVA Table of Average "a" Parameter of Knit Fabrics. Model: SS a (Average) = SS (Yarn Type) + SS (Fiber Content) + SS (Side) + SS (Direction) +SS (Error)

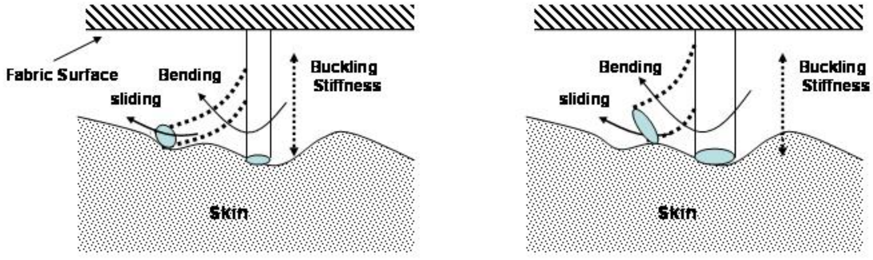
Source	DF	Sum of Squares	Mean Square	F Ratio
Model	7	11.703907	1.67199	7.2512
Error	38	8.762079	0.23058	Prob > F
C. Total	45	20.465986		<.0001

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
YT	2.000	2.000	3.60509	7.8174	0.0014
Prep	3.000	3.000	3.85961	5.5795	0.0028
Side	1.000	1.000	3.92391	17.0175	0.0002
Direction	1.000	1.000	0.39811	1.7265	0.1967

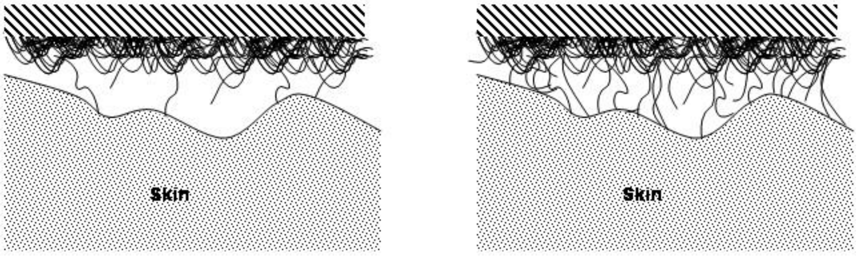
Table 8. ANOVA Table of Area Ratio of Knit Fabrics. Model: SS A-Ratio(Average) = SS(Yarn Type) + SS(Fiber Content) + SS (Pressure) + SS (Side) +SS(Error)

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	8	0.00898144	0.001123	11.7314
Error	62	0.00593332	0.000096	Prob > F
C. Total	70	0.01491477		<.0001

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
YT	2	2	0.00080825	4.2229	0.0191
FC	3	3	0.00062824	2.1883	0.0983
Pressure	2	2	0.00775393	40.5122	<.0001
Side	1	1	0.00000113	0.0118	0.9138

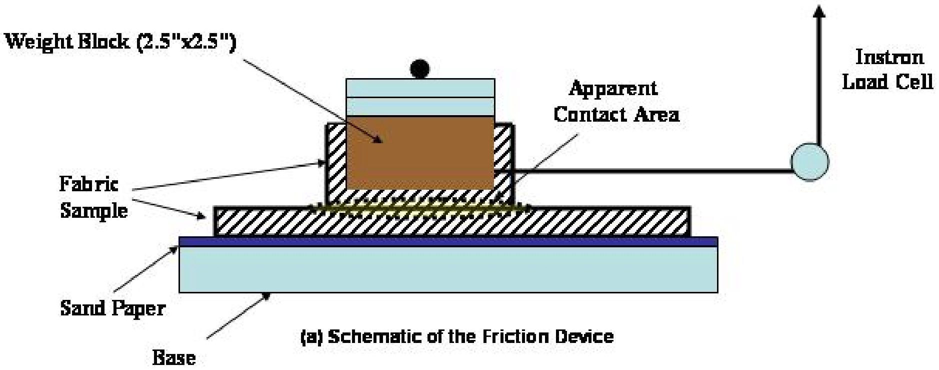


(a) Fine Fiber (b) Coarse Fiber

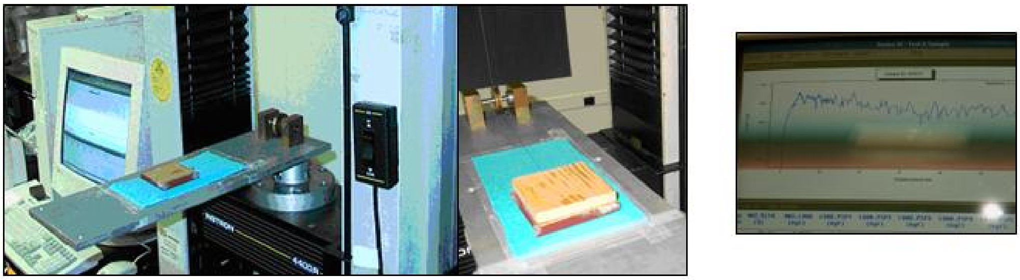


(c) Low Fiber Density (d) High Fiber Intensity

Figure 1. Important Factors Influencing Prickling Sensation.



(a) Schematic of the Friction Device



(b) Fabric Sample Mount

(c) Stick-Slip Profile

Figure 2. Fabric Friction Device.

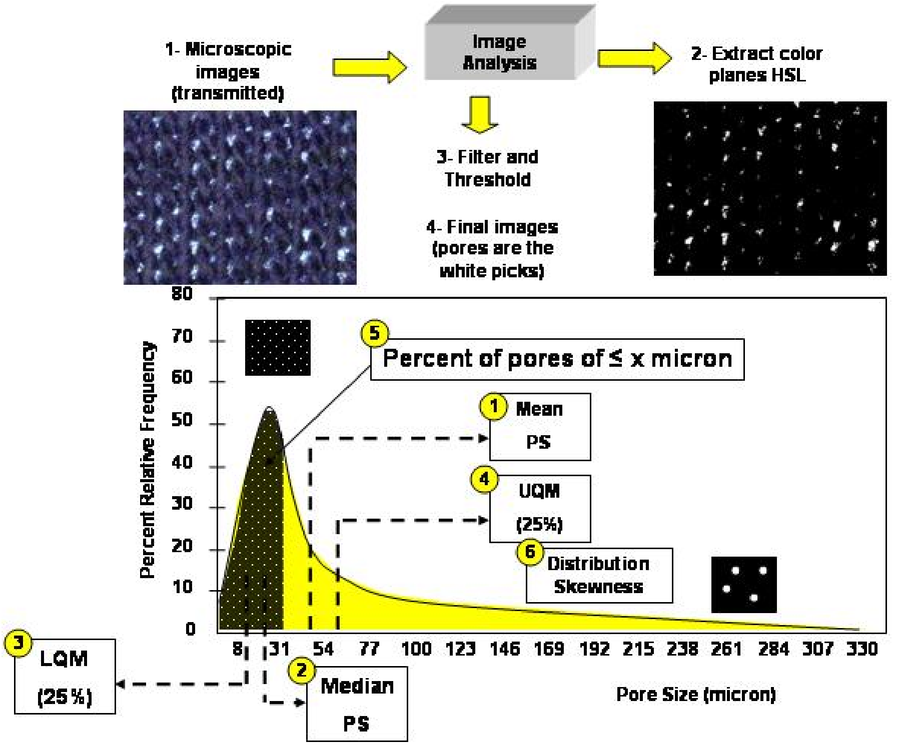


Figure 3. Illustration of Pore Size Parameters.

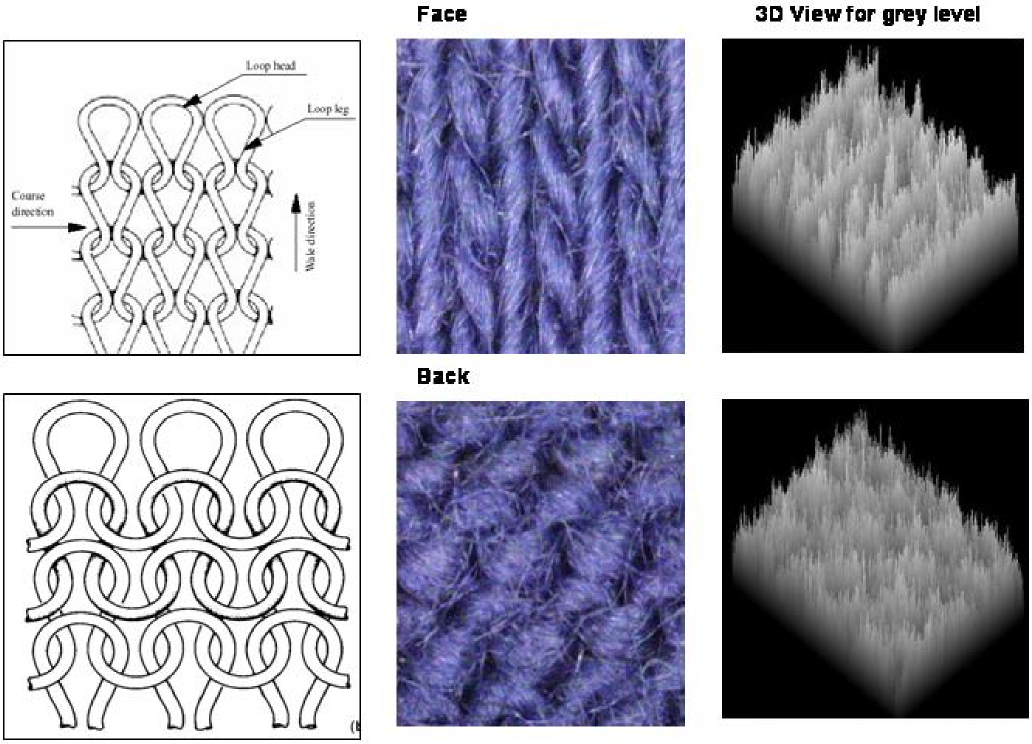


Figure 4. Face and Back Images of Single-Jersey Fabric.

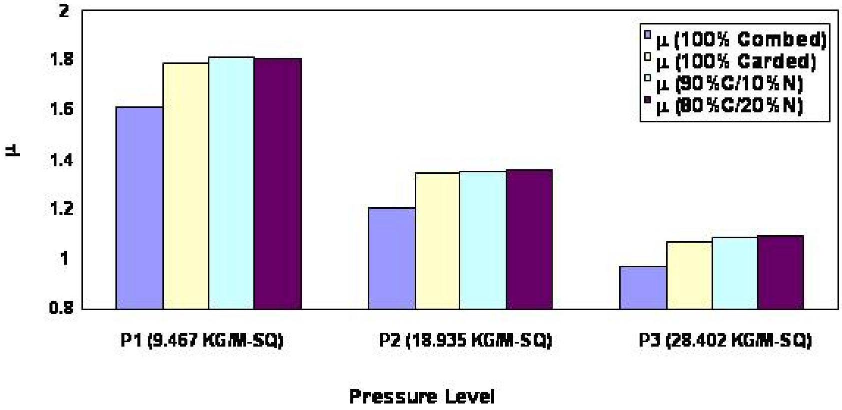


Figure 5. Effect of Fiber Content at Different Levels of Lateral Pressure on the Coefficient of Friction.

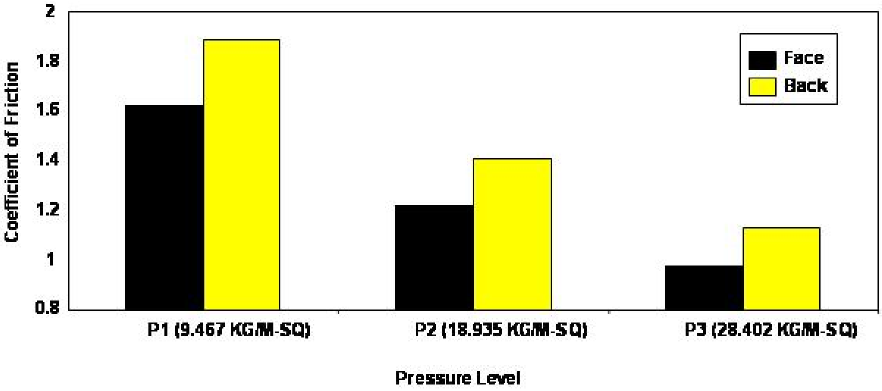


Figure 6. Effect pf Fabric Side at Different Levels of Lateral Pressure on the Coefficient of Friction.

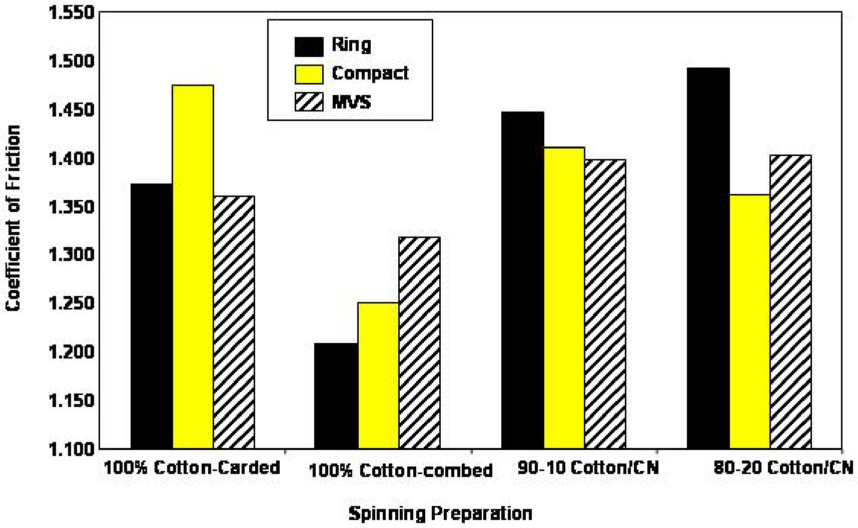


Figure 7. Coefficient of Fabric Friction at Different Spinning Preparation Levels for Different Yarn Types.

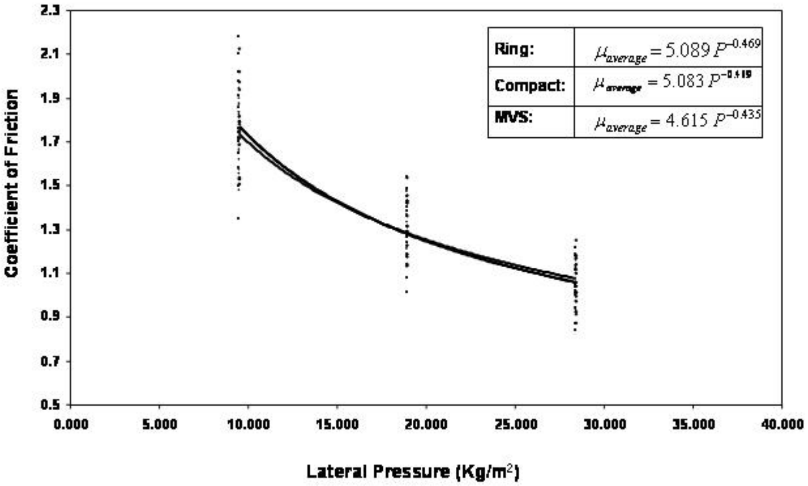


Figure 8. The Relationship between Coefficient of Fabric Friction and Lateral Pressure.

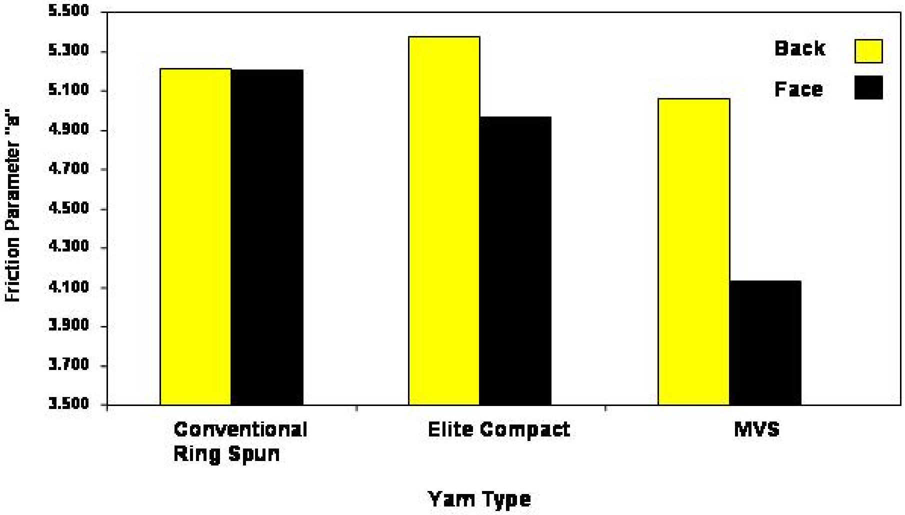


Figure 9. Effect of Fabric Side on the Friction Parameter ‘a’.

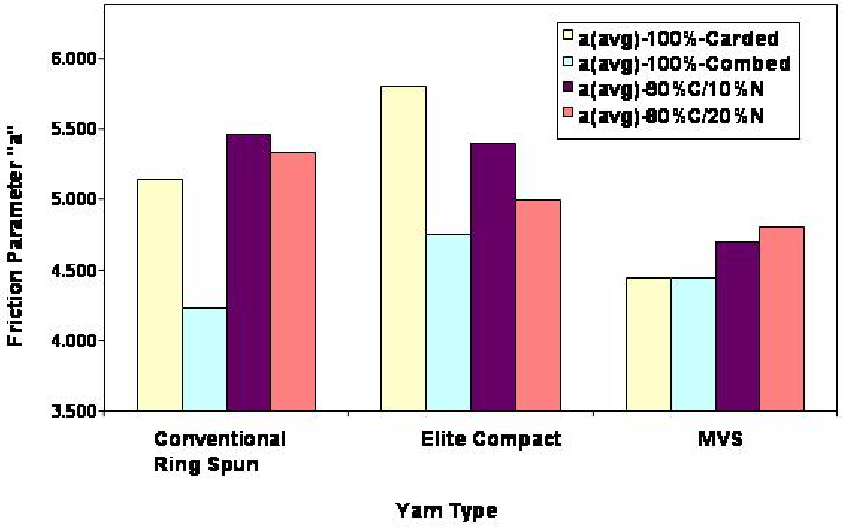


Figure 10. Effect of Spinning Preparation on the Friction Parameter ‘a’.

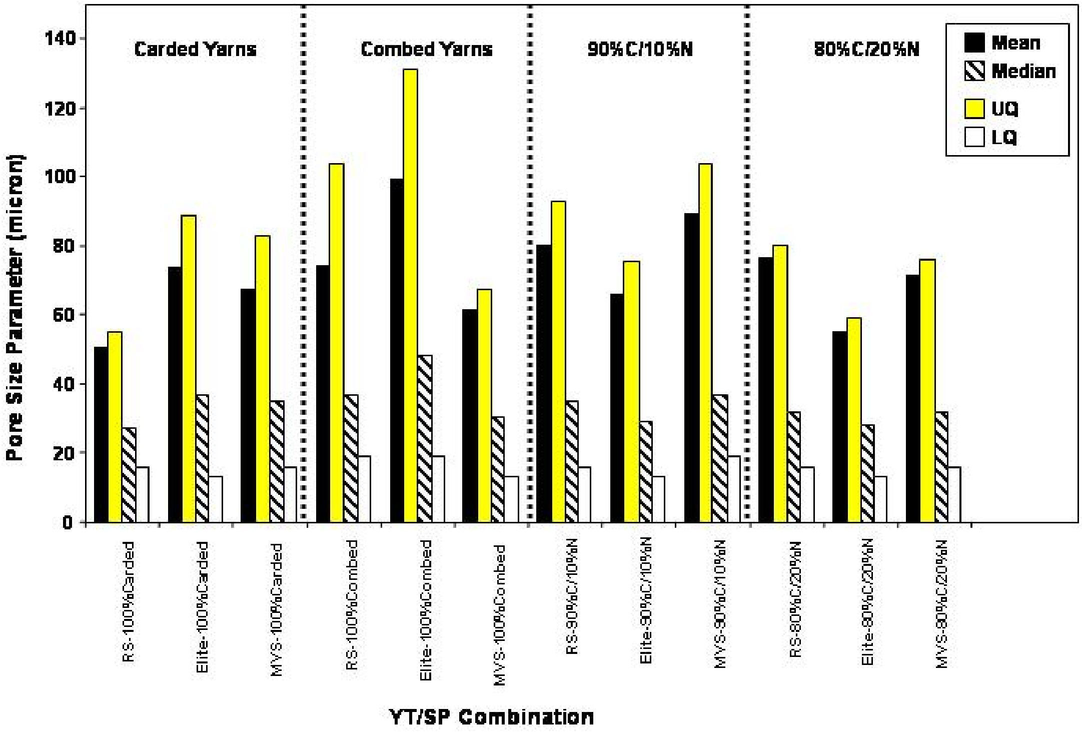


Figure 11. Pore Size Parameters at Different Yarn Type/Preparation Combinations.

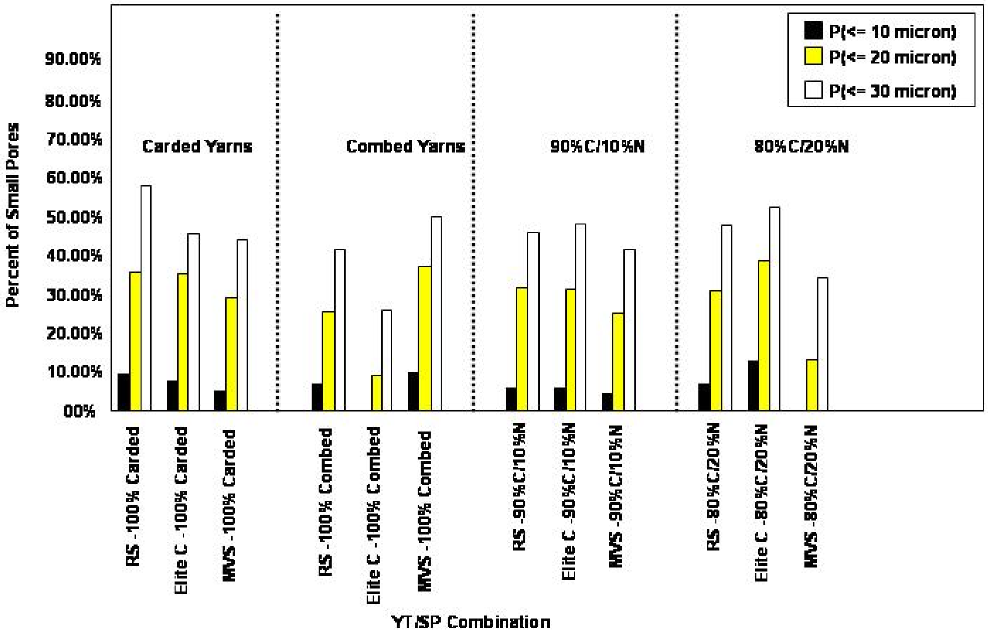


Figure 12. Percent Pores of Small Sizes (10, 20, and 30 micron) at Different Yarn Type/Preparation Combinations.

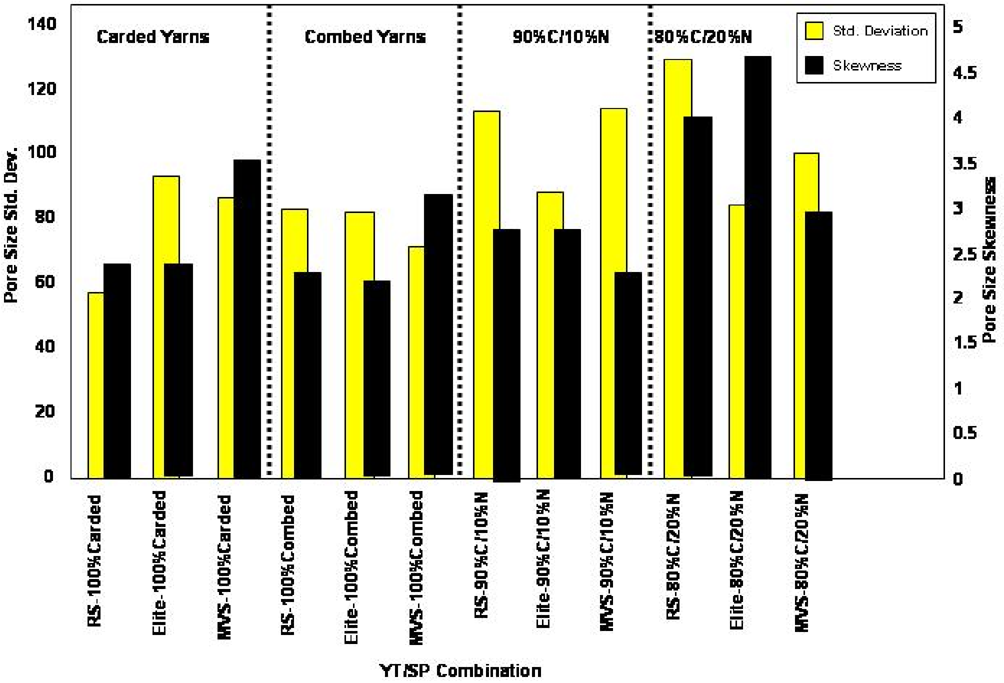


Figure 13. Variability of Pore Size Parameters at Different Yarn Type/Preparation Combinations.

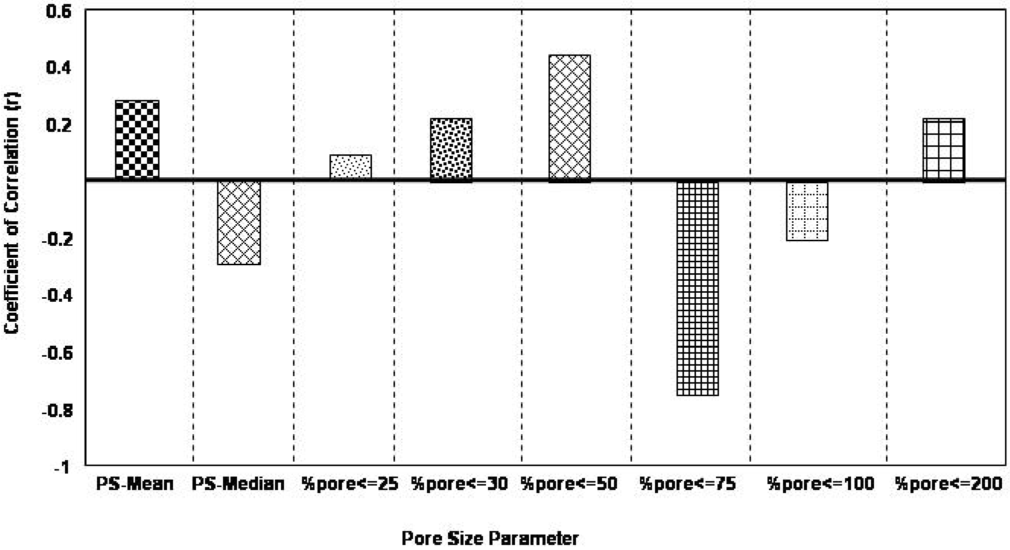


Figure 14. Coefficient of Correlation Between Yarn Hairiness and Different Pore Size Parameters [Excluding Combed Yarn Data].

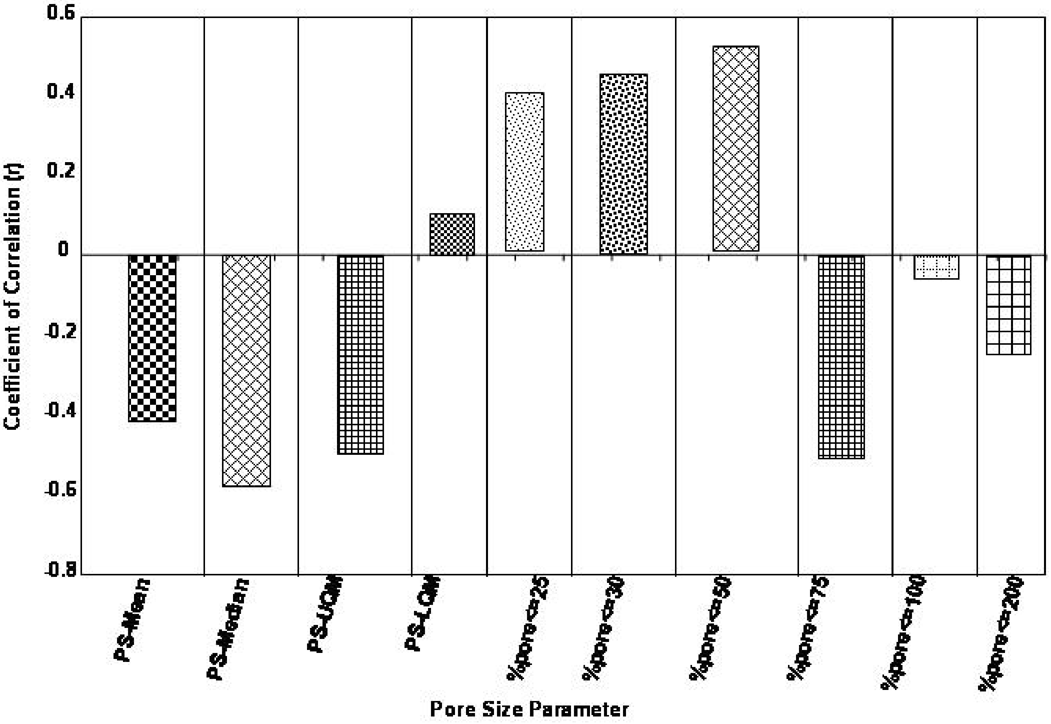


Figure 15. Coefficitent of Correlation Between Yarn Hairiness and Different Pore Size Parameters [All Data Including].

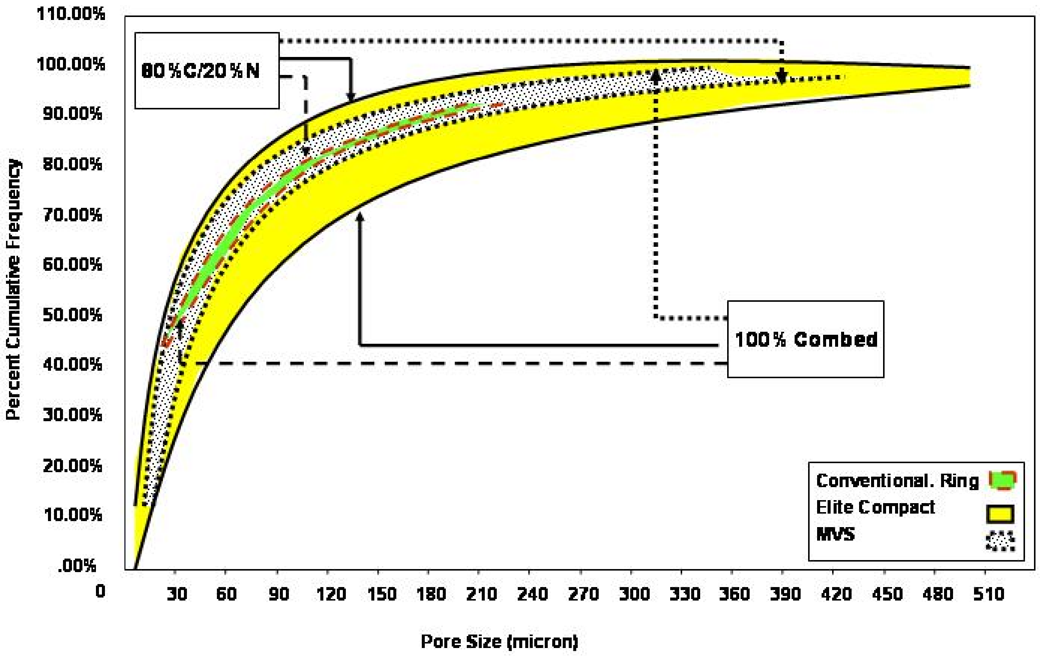


Figure 16. Pore Size Frequency for Different Yarn Type/Preparation Combinations.

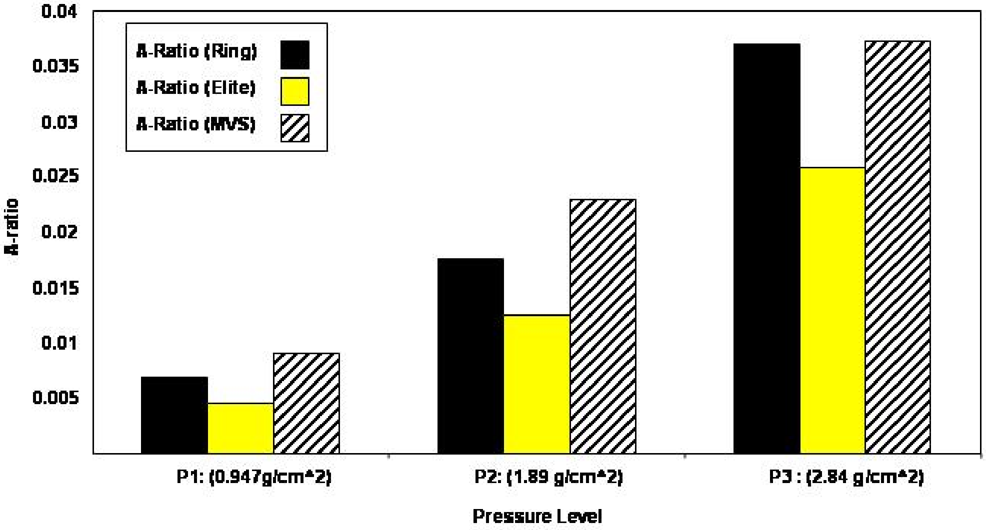


Figure 17. Area Ratio for fabrics of different yarn types.

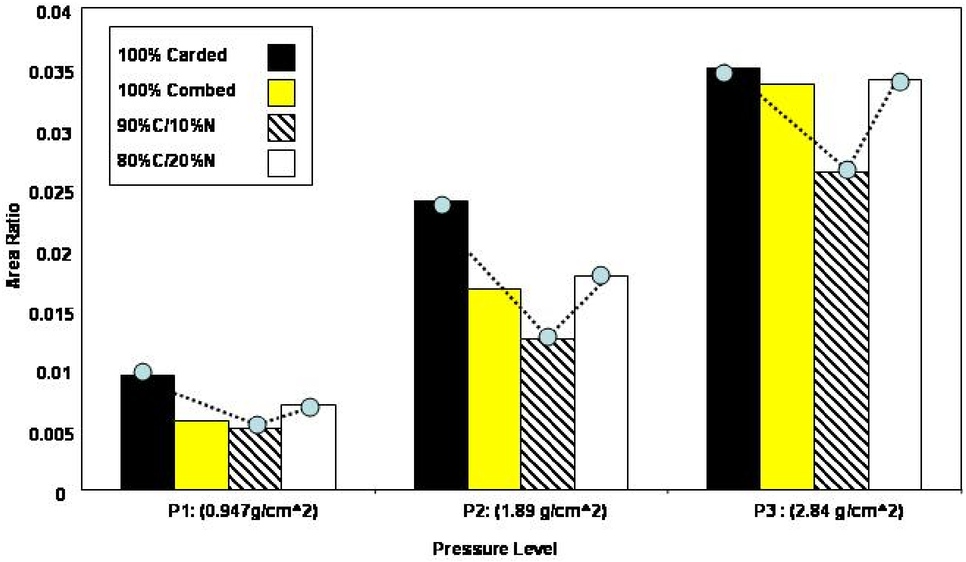


Figure 18. Area Ratio at Different Preparation.