Electrometric Estimation of Fiber-To-Fiber Contact in a General Fiber Assembly

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ABSTRACT

The fiber-to-fiber contact has been considered to be fundamental problem of micromechanics, since the mechanical properties of fibrous assemblies are largely related to the number of fiber-to-fiber contacts. Also, other important properties of fiber assemblies, such as heat conduction, filtration, electrical conduction, and evaporation, are strongly related to bulk fiber arrangement and pore distribution. However, experimental estimation of the number fiber-to-fiber contacts, which is essential in checking the findings of each theory, is a difficult task. Fiber-to-fiber contact in fiber assemblies plays a crucial role in their electrical resistance. Measurement of compression dependence of electrical resistance of a fiber assembly is an effective method for estimating spatial distribution of fiber-to-fiber contact. We have proposed a method and equation to estimate the number of fiber-to-fiber contacts starting from the compressional properties of the electrical resistance of a fiber assembly. Tests carried with samples of different fiber assemblies, both loose staple fibers and woven or knitted fabrics, clearly showed that compressional properties can be accurately approximated by a power function, as predicted by all actual theoretical approaches. However, experimental power index data of the power function vary in a range from 1.5 up to 3.23, which shows that the problem of fiber-to-fiber contact in fiber assemblies remains complex, and more accurate theoretical approaches are needed to describe the phenomenon.

The electrometrical method that we propose is a valuable tool for estimating fiber-to-fiber contact and experimentally testing theoretical approaches that tend to describe compressional properties of fiber assemblies. However, more detailed and properly designed tests are needed to verify the method.

INTRODUCTION

Fiber-to-fiber contacts have been considered to be a fundamental problem of micromechanics, since the mechanical properties of fibrous assemblies are largely related to the number of fiber-to-fiber contacts. Also, other important properties of fiber assemblies, such as heat conduction, filtration, electrical conduction, and evaporation are strongly related to bulk fibers arrangement and pore distribution [1-9].

Fiber assemblies are entangled materials made of fibers arranged together in various manners with no permanent cross-link such as sheep wool, glass wool or steel wool. They exhibit a specific non-linear mechanical behavior which is not fully understood. A fiber assembly contains a tremendous amount of fibers of the same or different types, whose behavior is a function of the property of the building block and the way these building blocks are organized in the assembly. When non-bonded fibrous assemblies, such as most yarns, woven, nonwoven, and knitted fabrics in which individual fibers have not been chemically or thermally bonded to one another, are subjected to external loads, their subsequent deformation involves fiber deformation and fiber slipping over their neighbors. The overall result of this process is the change of fiber to fiber contact inside the fiber assembly and the volume fraction of the space between fibers [5, 10-12].

Contact modeling is a crucial point in understanding the general behavior of any type of loose fiber assembly. In the early models for fiber-to-fiber contact, the fiber has been assumed to be straight [13, 14] and geometrical probability has been applied to estimate the quantity of fiber-to-fiber contact [15-18]. More refined analytical models were developed including fibers orientation [19, 20], non-overlapping [17, 21], crimp [22], large deformations [23], and slippage at contacts [16, 24, 25]. These works opened the field for the simulation of the compression of entangled materials. Several authors used finite elements methods to perform their studies [26-29]. In addition, the yield at the contact point was considered, since it is significant when external load is presented. The actual formulas appear far more complicated compared with previous ones, but the calculation is made possible with current computing power [30-32].

Experimental verification of the findings of these models remains problematic because there is little experimental data on the properties of fiber to fiber contact. There is always a requirement for new techniques for measuring comprehensive data of fiber-to-fiber contact directly**.** Microscopic techniques and image analysis have been used for measuring fiber-to-fiber contact directly in a sheet, including examining the plane (x-y plane) of very thin fiber networks. The image analysis method for detecting the parameters seems more appropriate. In recent years, with the development of computer, image analysis has played a more important role in the fabric industry. Nevertheless this technique overcomes the limitations of only measuring the surface fibers, only a few fiber diameters thick. However, it cannot measure the inter-bond distances [33-35].

At a given voltage, the electrical resistance of a fiber assembly depends on the electrical properties of the fibers and fiber-to-fiber contact. An approximating function describing the compression behavior of the electrical resistance of a fiber assembly with fiber volume fraction results in similar functions derived in all theoretical approaches to explain the compression behavior of fiber assemblies. Both dependencies are described by a power function [36, 37]. This makes the attempts to use these relationships to estimate bulk density of fiber-to-fiber contacts in a fiber assembly realistic. An attempt was made by the author of this paper in 1999[37] using compression behavior of the electrical resistance of a fiber assembly. A more recent attempt using the same idea was made by Jia et al [38]. The method assumes that electrical current in fiber assemblies passes through fiber-to-fiber contacts and dependence of electrical resistance of the fiber assembly is related directly to the change of the number of fiber to fiber contacts. Using the above mentioned assumptions, we propose a method to estimate the bulk density of fiber to fiber contact inside a fiber assembly.

TEST PROCEDURE AND MATERIALS

When considering electrical resistance of a fiber assembly, the situation becomes complex because of the influence of shape and compression parameters of both sample and measuring electrodes on I-V (current - voltage) characteristics. All existing methods for measuring DC resistance of fiber assemblies are based on data obtained for current and voltage from a single test, which exclude the possibility of any specific information about the compressional behavior of the fiber assembly. We propose a method, called multiple steps, which considers the compression behavior of the fiber assembly and calculates electrical resistivity of a fiber assembly based on a set of data I-V taken for different volume fractions v_f. The calculated resistivity, a parameter that we use to characterize electrical properties of a type of fiber, results in being independent from kind of sample and measuring procedure [36, 37].

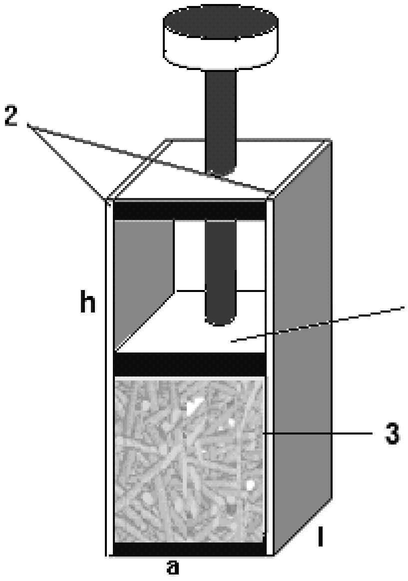

FIGURE 1. Measuring cell: 1- metallic electrode, 2- compressing piston, 3-fiber assembly.

The fiber assembly to be tested (3) was placed in a parallelepiped cell, shown in *Figure 1.* The two vertical parallel electrodes (1) are metallic, while other sides are made of PMMA. The textile samples within the cell can be pressed to different volume fractions by means of a piston (2). The electrical resistance of compressed sample was measured with e teraohm-meter at 400 volts DC. We took special care to maintain a continuous check of humidity and temperature. Generally, fibers were oriented randomly within the cell. Three cells of different dimensions were used: The sides a, b, and l of cell 1 were, respectively, 3x4x10 cm, of cell 2 3x10x4 cm, and of cell 3 4.2x8x5 cm.

The tests procedure involved measurement of the electrical resistance of the sample for at least ten fiber volume fractions. We used cotton, wool, PET and PAN loose fibers in this study, as well as 33% cotton/67% PET fabric, 100% cotton fabric, 100% wool fabric, and 100% polyurethane fabric to study the influence of sample type on the results. All samples were commercial products treated with commercial finishes.

ESTIMATION OF FIBER TO FIBER CONTACT IN A FIBER ASSEMBLY

The basic assumption for the estimation of fiber to fiber contact in a fiber assembly is: any fiber assembly within a cell of geometrical volume V can be considered as an assembly made of fibers with volume V_0 and air filling in the pores. In general, orientation and density of fibers is random and not homogenous, its local compressions are always present. If we consider the fiber assembly to be a two-component system, fibers and air pores, then the properties of the system are entirely determined by the concentration, distribution and intrinsic properties, of its constituents. This is also true for electrical properties of fibrous assemblies.

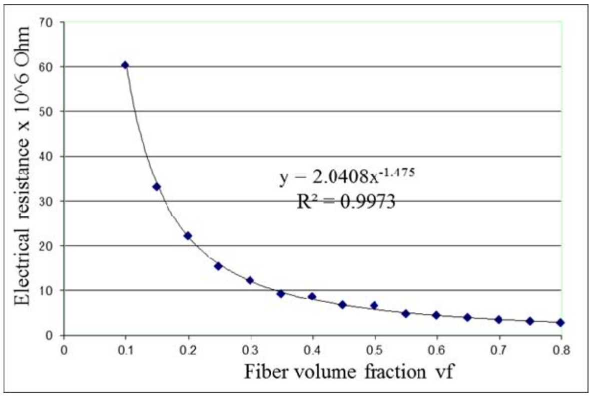

FIGURE 2. A typical experimental power function approximation of dependence of electrical resistance of a 100% cotton fabric disassembled and cut in 3 cm length pieces with fiber volume fraction. Power index is b=1.475. Correlation coefficient is R^2=0.9973.

When an electrical voltage U is applied to fiber assembly, an electrical current I will pass through it. Electrical resistance of the fiber assembly will be R = U/I. At a given voltage, the electrical resistance of a fiber assembly depends on the electrical resistance of the fibers and on the number of fiber-to-fiber contacts, because electrical resistance of the air pores is very high. Therefore, the number of fiber-to-fiber contacts is fundamentally important in determining the electrical properties of fiber assemblies. It is at these contacts that movement of electrical charges through the fiber assembly takes place. The electrical resistance of fibers does not change during the measurement procedure, if the voltage and conditioning of the fibers remain unchangeable. So, any compressional dependence of electrical resistance of the fiber assembly is related to changes of the number and area of fiber-to-fiber contacts. Thus, we expect the electrical resistance of fiber assembly to have a reciprocal dependence with fiber-to-fiber contacts within the fiber assembly. The number of fiber-to-fiber contacts in a cross section will determine the true area available for charges to pass through the fiber assembly. It is difficult to observe these contacts directly and, hence, to measure their number.

Two typical resistance/fiber volume fraction ($v_f = v_0/v$) experimental dependencies are shown *in Figure 2* and *Figure 3*. In *Figure 2* a typical resistance/fiber volume fraction experimental dependency with fiber volume fraction for a fiber assembly of 100% cotton fabric disassembled and cut into 3 cm length pieces is shown. The data of the variation of the electrical resistance of the fiber assembly as a function of fiber volume fraction were approximated via a power function

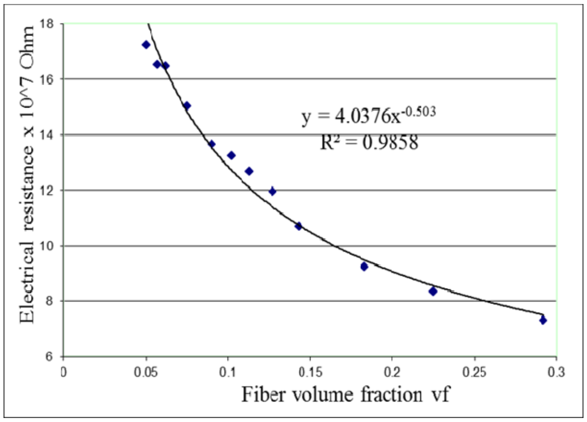

FIGURE 3. A typical experimental power function approximation of dependence of electrical resistance of a 100% loose wool fiber assembly with fiber volume fraction. Power index is b=0.503. Correlation coefficient is R^2=0.9858.

The power index is b=1.475 and the correlation coefficient is $R^2=0.9973$. In *Figure 3* is shown a typical resistance/fiber volume fraction experimental dependency of a fiber assembly with fiber volume fraction for 100% loose wool fibers. The data of the variation of the electrical resistance of the fiber assembly as a function of fiber volume fraction were approximated via a power function. The power index is b=0.502 and correlation coefficient is $R^2=0.9858$. In both cases the power function fits the experimental data very well, as predicted by all theoretical approaches of the compressional behavior of fiber assemblies.

Let try to estimate the spatial number of fiber-to-fiber contacts in a fiber assembly using power approximation function of dependency of the electrical resistance, *R,* of a fiber assembly with fiber volume fraction. For a general fiber assembly, the approximation power function can be described by [36, 37]:

$$R = R_0 \cdot v_f^{-b} \tag{1}$$

Where:

R_0 – electrical resistance of fiber assembly compressed until it is transformed into a compact homogenous mass.

v_f – fiber volume fraction

$$v_f = \frac{V_0}{V} \tag{2}$$

Where:

V_0 – Volume of fibrous material, it is $V_0 = m/d$

m – Mass of fiber assembly, d – density of fibrous material

V – Volume of the fiber assembly within the cell

In this case, the parallelepiped cell volume of the fiber assembly within the cell will be $V=alh,$ where a, l, and h are length, wideness and height of the cell (as shown in *Figure 1*)

Assuming that the resistivity of the fibrous material remains constant during the measurement procedure, electrical resistances R and R_0 can be calculated by:

$R = \rho\frac{a}{S}$, and $R_0 = \rho\frac{a}{S_0}$

Where: S is the effective area of a cross section *of* the sample; it is the sum of all area of fiber-to-fiber contacts in a cross section of fiber assembly parallel to metallic electrodes. Considering that *n* is the mean of fiber-to-fiber contacts in a cross section of fiber assembly and s_0 *is the* mean area of each contact, the effective area of a cross section *of* the sample S is:

$S = n \cdot s_0$

S_0 is the area of cross section of fiber assembly compressed until it is transformed into a compact homogenous mass, it is $S_0=V_0/a$.

Substituting *R* and R_0 in Eq. (1), we can easily find the mean number of fiber-to-fiber contacts *n* in a cross section of fiber assembly:

$$n = \frac{V_0}{a \cdot s_0} \cdot v_f^b \tag{3}$$

The number of fiber-to-fiber contacts in the unite volume of fiber assembly n_0 can be calculated from Eq. (3), assuming that for each fiber-to-fiber contact a layer of fiber with mean thickness D is needed, where D is the mean diameter of each fiber in fiber assembly. The volume of a mono layer one fiber diameter thick V_s is:

$$V_s = \frac{V \cdot D}{a}$$

And

$$n_0 = n \cdot \frac{a}{V \cdot D} \tag{4}$$

Using Eq. (4), Eq. (3) can be easily transformed to:

$$n_0 = \frac{1}{D \cdot s_0} \cdot v_f^{(b+1)} \tag{5}$$

The area of each fiber-to-fiber contact s_0, generally speaking, depends on compression of fiber assembly v_f and diameter *D* of fibers. We can assume that the relation between the area of each fiber-to-fiber contact and the diameter of a fiber can be expressed by:

$$s_0 = k(v_f) \cdot D^2$$

Where - $k(v_f)$ is a parameter that takes into consideration the deformation of the fibers at the point of contact because of increasing pressure during compression. It can take values from 0 to 1, depending on the kind of fiber and value and distribution of compression within the fiber assembly.

Eq. (5) shows that the density of fiber-to-fiber contacts n_0 in a fiber assembly is a function of the mean diameter of the fibers D, the mean area of each contact s_0 and the fiber volume fraction v_f within the measuring cell. The mean diameter D of the fibers and fiber volume fraction v_f can be measured with a sufficient accuracy, while the mean area of each contact s_0 is very difficult to be accurately measured, as it continuously changes during compression.

Eq. (5) can be easily transformed substituting mean diameter D with metric number N_m, which is a parameter commonly used in the textile industry. Assuming that fiber assembly is composed of fibers whose density is d, the metric number can be expressed by:

$$N_m = \frac{4}{\pi \cdot D^2 \cdot d} \tag{6}$$

Substituting density D from Eq. (6), Eq. (5) can be transformed to:

$$n_0 = \frac{(\pi \cdot d \cdot N_m)^{0.5}}{2 \cdot s_0} \cdot v_f^{b+1} \tag{7}$$

Also, the length of fibers contained in unit volume of fiber assembly L compressed to fiber volume fraction v_r can be calculated by:

$$L = N_m \cdot d_v = N_m \cdot d \cdot v_f$$

Where ${}_v$ is the mass of fibers per unit volume of the fiber assembly compressed to volume fraction v_r.

Further more, the number of fiber-to-fiber contacts in unit length of fiber n_l can be calculated by:

$$n_l = \frac{n_0}{L} = \left[\frac{\pi}{d \cdot N_m}\right]^{0.5} \cdot \left[\frac{v_f^b}{2 \cdot s_0 \cdot}\right] \tag{8}$$

A BRIEF ANALYSIS OF THEORETICAL EXPECTANCIES

Van Wyk's theory for an idealized model shows that fiber-to-fiber contacts vary with the square of the fiber volume fraction [13]. For random distribution of cylindrical fibers Van Wyk calculates that mean distance between to consecutive contacts in a fiber l_m is given by:

$$l_m = \frac{2V}{\pi \cdot D \cdot L} \tag{9}$$

Where L is the length of fibers contained in the volume V of fiber assembly.

Eq. (9) can easily be transformed to an equation similar to Eq. (7):

$$n_0 = \frac{\pi \cdot D \cdot L^2}{2V^2} = \frac{8}{\pi \cdot D^3} \cdot v_f^2 \tag{9$_1$}$$

According to Eq. (9_1), Van Wyk's model predicts that fiber-to-fiber contacts vary with the square of fiber volume fraction v_f.

A more realistic model of Pan, Komori and. Makishima *et al* predicts a lesser dependence on the fiber volume fraction [15-17, 21, 39-41]. Considering results obtained by Pan the, spatial density of fiber-to-fiber contacts is expected to increase approximately linearly with fiber volume fraction. Komori *et al* predicted a relationship of higher power between the spatial density of fiber-to-fiber contacts density and volume fraction, accepting the linear relationship obtained by Pan as a limit case.

He *et al* carried an experimental study of fiber-to-fiber contacts on the surface of the paper. Results obtained showed that the geometry of the cross section of the fibers and length of the fibers do not influence significantly fiber-to-fiber contacts. Also, distance between consecutive contacts was better described by a two-parameter Weibull probability density function, than with a not negative exponential probability density function proposed earlier by Berner [35].

Pan, in an attempt to improve model of fiber-to-fiber contact introduced by Komori dhe Mikishima, showed that maximum value of volume fraction v_f, which is achieved when all fibers are regularly and fully packed together, is not 1 but a little smaller, π/4. The modified theory gives a more accurate prediction for the mean value of fiber-to-fiber contacts and for mean distance between to consecutive contacts in an unbonded or bonded fiber assembly. Pan, also, predicted a power function relationship between the spatial density of fiber-to-fiber contacts density and volume fraction with power index two [41-43].

Barbieri et al. employed discrete element simulation to study the influence of static friction on the mechanical response of assemblies of unbonded semi flexible fibers. Considering that contact between fibers leads to normal and transverse forces at contact points, first term is a repulsive that acts between two nonconsecutive segments when their distance becomes less than the fiber diameter, leading to normal forces at contact points, while second interaction term leads to friction between fibers. They showed that the evolution of the pressure, *P*, as a function of the difference between the current density and the density at transition for different friction coefficients fall on a single curve; i.e., friction affects the packing density but does not change the shape of the pressure curve. The pressure follows a power law $P \sim v_r^3$ with an exponent 3 in agreement with Van Wyk's analysis. This means that, fiber assembly reacts like a fluid with a resistance to isotactic compression [41].

Considering the very brief analysis we made above, linking the overall behavior of fiber assemblies to that of their individual fibers remains challenging. Most experimental data are compared to the seminal dimensional analysis of Van Wyk. More refined micromechanical models have been developed for shear and compression, accounting for the distributions of fiber orientations, fiber-to-fiber contact distances and slippage. However, all models include highly simplifying assumptions; even the number of parameters considered is increasing steadily [27, 44, 45].

EXPERIMENTAL VERIFICATION OF THE METHOD

All theoretical approaches that tent to explain compressional behavior of fibrous assemblies and describe the relationship between properties of individual fibers with mechanical properties of fiber assemblies predict a power relationship between the spatial density of fiber-to-fiber contacts and volume fraction. Power index, however) is not the same in different theoretical approaches. It is reasonable that the first thing that any experimental method for measuring fiber-to-fiber contacts must check is the power index. In the case of straight cylindrical fibers model the power index of relationship between spatial density of fiber-to-fiber contacts and fiber volume fraction the power index is two. In other more realistic models straight fiber model was replaced by true path the formulas appear far complicated compared with previous ones and power index differs from one model to the other [30].

Electrometrical method for estimation of fiber-to-fiber contacts in fiber assemblies, that we proposed above, predict that relationship between spatial density n_0 of fiber-to-fiber with fiber volume fraction v_f , given by Eq. (5), is a power function with power index (b+1), where b is defined experimentally by measuring the electrical resistance of fiber assembly in different volume fractions.

We conducted systematic tests using three different parallelepiped cells, whose dimensions are given earlier. We tested the same fiber sample using each cell in alternating order.

We measured the resistance of loose fiber assembly within every cell for at least ten fiber volume fractions. Then we approximated the data of variation electrical resistance of the fiber assembly as a function of fiber volume fraction using a power function. The results of calculation for power index b, together with their respective standard deviation, are shown in *Table I*. Every result is the mean of five sets of tests with the same fiber sample for all three cells. *Table I* lead to the following conclusions:

The power index of the regression approximation generally changes different cells are used for testing. Also, when the same cell is used for testing, different fiber types have different power index. In general, the power index depends on the way we place the fibers in the cell

Generally, loosed fiber assemblies composed by long staple fibers (wool type fibers: wool, wool type PET, wool type PAH) have smaller values of power index. Fiber assemblies composed by short staple fibers (cotton type fibers: cotton type PET, cotton, hydrophilic cotton, polyurethane) have a value of power index b greater than fiber assemblies composed by long staple fibers. We do not have any plausible explanation for these effects, but this is clear evidence that fiber-to-fiber contacts in fiber assemblies are very sensitive to kind and geometry of fibers.

TABLE I.

Fiber Assembly	Cell 1	Cell 2	Cell 3
	b±σ	b±σ	b±σ
Wool fibers	0.51±0.04	0.73±0.05	0.63±0.12
PET fibers, wool type	0.50±0.02	0.70±0.09	0.61±0.12
PET fibers, cotton type	1.08±0.08	1.04±0.11	0.57±0.05
Cotton fibers	0.76±0.04	0.72±0.04	0.67±0.06
Cotton fibers hydrophilic	1.20±0.01	1.17±0.02	1.06±0.04
PAN	0.50±0.04	0.61±0.10	0.63±0.09
Polyurethane	1.32±0.05	1.50±0.06	1.12±0.03

In *Table II* are shown experimentally measured values of power index b for five different fiber assemblies, composed of a single type of fibers or blends of two different types of fibers. The aim of our experiment is to clarify the influence of sample form (fibers, yarns, and fabrics) on the approximation function and power index b. To eliminate complications arising from the differences in fiber composition, we conducted these experiments using the same material. We tested fabric samples first, than disassembled the fabric into separate yarns and tested for resistivity. Ultimately, we cut the yarns into short lengths and tested them again. We used cell 1 for these tests, taking care when placing samples in the cell so that fibers were randomly distributed within the cell. We used at least ten values of fiber volume fraction to define the regression approximation of power function.

TABLE II.

Fiber assembly	Fabric	Yarn	Fibers
	b±σ	b±σ	b±σ
Polyuretan	2.23±0.13	1.45±0.10	1.27±0.08
Cotton	1.36±0.06	1.35±0.06	1.48±0.03
Wool	0.99±0.13	1.23±0.01	1.51±0.02
55% wool-45% PET	1.21±0.15	1.48±0.20	1.52±0.07
67% cotton-33% PET	1.05±0.07	1.07±0.06	1.18±0.04

Table II shows the results of experiments with five different fiber assemblies. We can draw the following conclusion from the data: The power index for a given fiber assembly varies with sample form, sample composition, and sample situation within the cell. In contrast to loose fiber assemblies, power index in the other samples varies in a wider range, from 1 up to 2.23 in the case of polyurethane fabric. However, resistivity of a given fiber assembly is not influenced by sample form, sample composition, and sample situation.

Data in *Table I* and *Table II* clearly show that the power function is the best approximation function of the variation of electrical resistance of the fiber assembly as a function of fiber volume fraction. Correlation R^2 of data for each approximation is as high as 0.99. This result accords with all actual theoretical approaches. However, power index of power function varies in a wide range with fiber assembly composition, sample form and sample situation (b+1 values vary from 1.5 in the case of loose wool fibers up to 3.23 in the case of polyurethane fabric, Eq. (5)), However, most of theoretical approaches predict a power index of two. Factors influencing the dependence can be mechanical and geometrical properties of the fibers, spatial distribution of the fibers etc. [29, 46] Nevertheless, we can not give a plausible explanation for the mechanism that each factor affect the value of index b, but it seems that problem remains complex and more accurate theoretical approaches are needed to describe the phenomenon.

CONCLUSIONS

Fiber-to-fiber contact in fiber assemblies plays a crucial role in their electrical resistance. Measurement of compression dependence of electrical resistance of a fiber assembly is an effective method to estimate spatial distribution of fiber-to-fiber contacts in fiber assemblies. We have proposed a method and equation to estimate the number of fiber-to-fiber contacts starting from the compressional properties of electrical resistance of fiber assembly.

Tests carried with samples of different fiber assemblies, both loose staple fibers and woven or knitted fabrics clearly show that compressional properties can be accurately approximated by a power function, as predicted by all actual theoretical approaches. However, experimental power index of power function varies widely, from 1.5 up to 3.23, which shows that the problem of fiber-to-fiber contacts in fiber assemblies remains complex, and more accurate theoretical approaches are needed to describe the phenomenon.

The electrometrical method that we propose is a valuable tool to estimate fiber-to-fiber contact and experimentally to test theoretical approaches to describe compressional properties of fiber assemblies. However, more detailed and properly designed tests are needed to verify the method.

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