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Textile Research Journal 2007; 77; 205
DOI: 10.1177/0040517507076748

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Textile Research Journal Article

Fibrous Materials as Soft Matter

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Abstract This paper proposes a new type of soft matter, namely fibrous materials. The common characteristics of soft matter that are shared by fibrous materials, such as the multiphase composition, porous and highly deformable structures, and the non-negligible contributions of entropy to the material behavior are illustrated. More importantly, some unique problems, complex and interesting, yet more or less unrealized, or ignored in dealing with fibrous materials are highlighted. The study includes the packing geometry of fibers, macro–micro behavioral inconsistencies, friction and self-locking mechanisms, bi-modular behavior, and allometric or scaling problems. The fabric wrinkling or crumpling problem and its peculiar fracture behavior and failure criteria are discussed. This paper also elucidates the significance of treating fibrous materials as soft matter and the great potential of such study to materials in general and to biomaterials in particular.

Key words fibrous soft matters, multiphase, porous, deformation, in-affinity, fiber packing

A fiber is, in essence, only a concept referring to the shape or geometry of an object, i.e., a slender object characterized by a high aspect ratio (length vs. thickness) with a small transverse dimension (thickness or diameter). The term fibrous material is used for any bulk media formed by fibers of various types, organic or inorganic. Textiles, on the other hand are a subgroup of fibrous materials with special purposes in providing body protection and decoration for human beings; in a similar manner to the air surrounding us, fabrics are so critically indispensable for us that many rarely pause to think about textiles from a materials science point of view. People expect the cloth used in their apparel to be soft, pliable, and have the desirable durability, be comfortable and yet not too heavy; but seldom wonder why and how textiles are able to offer such wide array of wonderful functions. On one hand, this seeming ignorance of the materials by the scientific community at large, may testify, in a twisted way, to the irreplaceable position of textiles; but on the other hand, has led to the current rather bewildering situation that fibrous materials in general, and textiles in particular, although arguably the first type of designed engineering materials, remain perhaps the least understood.

In recent decades however fibrous materials have found an increasingly expanding and burgeoning range of applications in new areas such as fiber-reinforced composites for use in numerous materials and civil engineering applications and fiber-based products in the medical and biological fields. There has been a gradual realization of the incredibly

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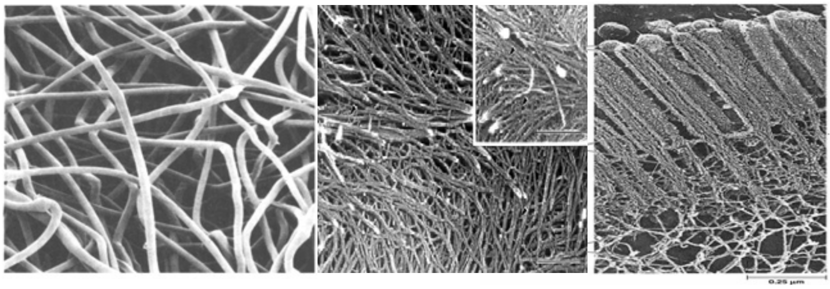

(a) (b) (c)

Figure 1 Fibrous materials (a) nonwoven; (b) cells of pea *(Pisum sativum)* plants, http://www.sciencemag.org/cgi/content/full/306/5705/2206/FIG1; (c) muscle, image captured by Anatomical Pathology Lab Plus, Auckland.

large potential and benefits of research into fibrous materials, especially since most biomaterials, plants or body muscles, are formed by fibrous constituents as well.

From a materials science point of view, fibrous structures can be viewed as a mixture of fiber and air, dry or conditioned, and are inherently heterogeneous due to the existence of macro-pores. Owing to the mixed physical and geometrical features of the distinct phases; fibrous materials generally are not isotropic and they behave differently when viewed in different directions. One way to elucidate the complexity in dealing with fibrous media is to consider them as porous media, albeit with a highly changeable configuration, i.e., significant entropy contribution, fitting squarely in the arena of the so-called *Soft Matter* [1].

By treating fibrous materials as a branch of soft matter, it will greatly facilitate more extensive and rigorous research on them to obtain a better understanding and develop more sophisticated applications. Another advantage of embracing manufactured fibrous material into the soft matter area is that unlike most of its counterparts in biomaterials, *textile is made from a design so that its macro properties allow for alternation or optimization*, which in turn enables them to work as a potential model for studying other natural biomaterials, or serve as tools to validate the theoretical models developed for such biomaterials. Figure 1 shows the similarities between fibrous materials and biomaterials. The following sections present some challenging issues in dealing with fibrous materials.

Non-affinity or Disconnection between the Macro and Micro Behaviors

The behavior of fibrous materials at the micro and at the macro levels is often different in nature. For instance, when sitting on a thick cushion filled with fibers, you are compressing the cushion; but a closer examination will reveal that most if not all fibers are actually experiencing bending deformation [2–4]. Furthermore, by assembling hydrophobic fibers, a fibrous wipe can be formed which behaves as if hydrophilie and is able to take up spilled water [5]. The same cotton fiber can be made into a summer T-shirt, crisp and cool, or a winter flannel coat, fluffy and warm. Such a weak connection between, or even independence of, the properties of the system and its constituents renders a unique challenge for any attempt to link the microstructural analysis to the macroscopic performance to form a basis for any product design and application.

Packing and System Configuration of Fibrous Materials

The macro-system properties of materials are determined to a large extent by their internal structures. The same is true for fibrous materials such that the *formats* in which the fibers are arranged or oriented become a critical issue; changing fiber orientation is the major technique used by industry to adjust product performance. Fiber orientations in fact dictate virtually all the properties of the system.

It is therefore logical that research on fibrous materials should start from the fiber arrangement or packing problem. Fiber packing formats in terms of the system geometrical features are the fundamental attributes for any such materials, and will determine each of the individual physical properties of the materials including the mechanical and fluid transport behavior. According to the published literature, the problem of fiber packing was initially studied by Van Wyk in his analysis of the compressibility of wool by looking into the geometrical characteristics of a fibrous mass in 1946 [2]. Other related works have since followed [6–11]. Komori and colleagues have examined the details of such geometrical features in a fiber assembly as the mean fiber contact density and the mean fiber length between two fiber contact [12], and the fiber and pores distribution in the fiber assembly [12–14]. Pan has furthered the analysis [15–18].

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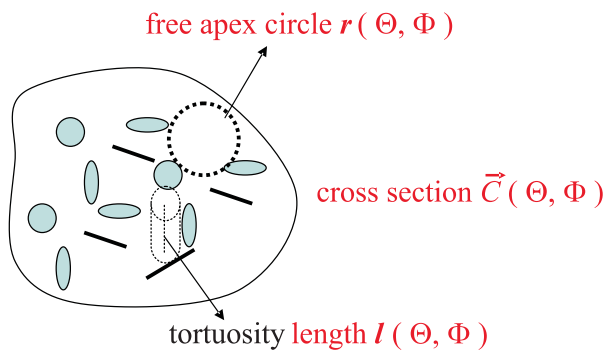

Figure 2 Pore and the tortuosity distributions.

For instance, the distribution of the porous areas at a direction (Θ, Φ) of a cross-section in Figure 2 can be represented by an infinite number of circular areas whose radius r is distributed according to $f(r)$ as [14, 18]:

$$f(r) = 2\pi\nu(r+\rho)e^{\pi\nu\rho^2}e^{-\pi\nu(r+\rho)^2} \tag{1}$$

and the distribution of the "tortuosity" or the free pore depth $f(l)$ at the direction (Θ, Φ) is [14, 18]

$$f(l) = \frac{1}{l_m}e^{-\frac{l}{l_m}} \tag{2}$$

where $v = v(\Theta, \Phi)$ is the average number of fiber cut ends on the cross-section, $\rho = \rho(\Theta, \Phi)$ the average radius of the fiber cut ends, and $l_m = l_m(\Theta, \Phi)$ the mean length of the free distance. All of them can be calculated in [18]. For a fibrous materials with a given fiber orientation probability density function, *pdf*, pore and tortuosity distributions can be entirely characterized analytically[18].

Some of the research results in this area have been applied to study the compressional [3, 19, 20] and shear [21] behaviors of general fiber assemblies, leading to considerable progress in those areas. Furthermore, the fiber packing problem has also been studied in fiber-reinforced composite materials [22–24].

Further modifications have been made to the original model. For a given volume of the fiber mass, there are two competing factors affecting fiber contact. Pan has taken into consideration of the steric hindrance effect, i.e., the interference of existing fiber contacts on the successive new contact to be made [16, 17]. On one hand, an existing contact reduces the effective contact length of a given fiber and hence diminishes the chance for new contacts (the steric hindrance effect). On the other hand, the existing fiber contact point will also abate the free volume of the fiber mass, and consequently increase the chance for successive fibers to make new contacts.

The research on this problem is still very primitive. However, a thorough study of a structure formed by individual fibers is extremely challenging. It is worth mentioning that the problem of the micro-geometry in a fibrous material can be categorized into a branch of complex problems in mathematics called packing problems [25–28]. Take for example the sphere-packing problem, also known as the Kepler problem, which has been an active area of research for mathematicians ever since it was first posed some 300 years ago, and remains unsolved until even today [27]. Yet, it seems that the sphere packing should be the simplest packing case, for one only needs to consider one parameter, i.e., the diameter of the spheres, and ignore the deformation due to packing. Therefore it does not seem to be the case that the fiber packing problem, with two parameters of fiber length and diameter and being highly prone to deformation, can be solved completely anytime soon.

Friction and Self-locking Mechanisms

Friction is the only mechanism by which fibrous materials are formed. In ropes or yarns, the friction is brought into play via tension on fibers of helical conformation due to twist., whereas in a piece of fabric, the friction takes place at the interlacing points of yarns, crimped after the weaving process to accommodate the perpendicular counterparts. This crimp serves the same critical purpose as helices in a yarn to provide pressure upon stretching so as to enhance the fabric.

Galileo [29] was fascinated by the fact that short fibers can form a long and strong rope via friction between fibers induced by twisting, although a relatively rigorous account for the mechanism has not been available until recently. Staple (short) fibers are assembled into a continuous strand (yarn) by virtue of twist, which leads to a helical conformation of individual fibers in the yarn. Upon stretching, the tension on the helical fibers will generate lateral pressure to bind the fibers together to sustain the stretching as described by Hearle [30]. If the external stretching is non-existent, the yarn is just a loose assembly of collected fibers held together by the weak adhesion and maybe some fiber entanglements; the yarn has virtually no strength. So it is truly fascinating that the very stretching which attempts to break the yarn is in fact reinforcing the yarn simultaneously. The twist (the fiber helicity) level obviously determines the ultimate outcome. This self-protective mechanism associated with the helical configuration may play a role in many other cases including DNA helices and other biopolymers (Figure 3).

Upon stretching, the tension in the fiber is built up from zero at the fiber ends to the maximum somewhere along

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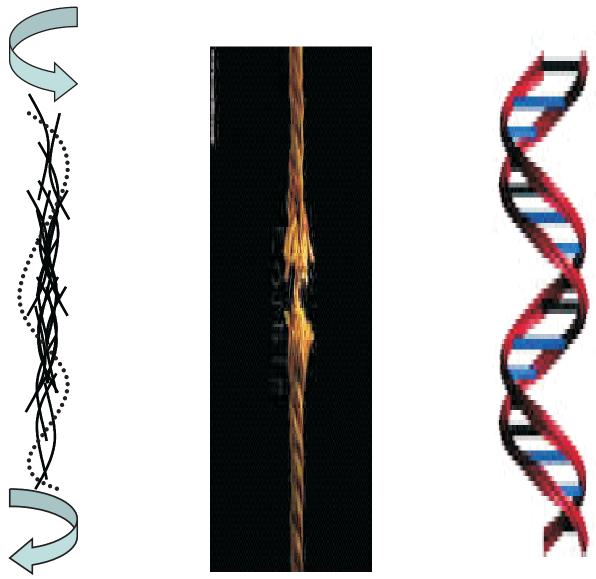

Figure 3 Twisting fibers into a rope (a), rope breaking (b) and a DNA helices (c).

the fiber length, ideally at the center. The tension distribution along the fiber length is linear at the portion of fiber length where slippage occurs. However, at the portion tightly gripped via inter-fiber friction, a hyperbolic tension distribution has been derived by Pan [31, 32]. The distribution of the friction-generated shear stress within a yarn was also developed. As we increase the twist level to a critical point, a self-locking mechanism takes place where fibers no longer slide over each other in a tensioned yarn. Instead, they bind each other to form a thread with considerable strength. Considering a fiber with both slipping ends of length $\lambda l_f/2$, Pan [32] has proposed a relationship between this slipping proportionality λ and other related factors as

$$\lambda = \frac{\tanh(\mu n\bar{s})}{\mu n\bar{s}} \quad (3)$$

where n is a factor determined by and increases with the twist level alone for a given yarn system, termed the dimensionless twist, the revised fiber aspect ratio $\bar{s} = s(1-\lambda)$, the fiber aspect ratio $s = l_f/D_f$, where l_f is the fiber length, D_f the diameter, and μ the fiber-fiber frictional coefficient.

When λ equals 1, the fiber is completely slipping. As soon as the yarn twist level reaches a critical point, the λ value will drop, revealing that the central portion of the fiber is gripped tightly, which in turn triggers a further reduction of λ until the whole fiber is held over its entire length, and a self-locking mechanism forms. This whole process in an ideal or a variation-free case would take place abruptly as predicted by equation (3) and plotted in Figure 4.

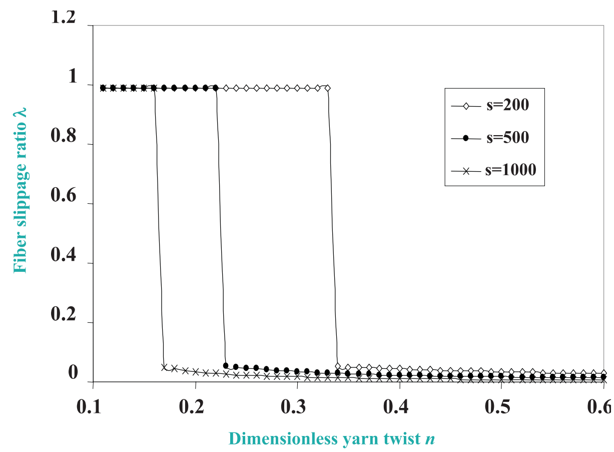

Figure 4 Fiber slippage ratio λ vs. the dimensionless yarn twist n.

However, several complex problems have yet to be solved. First, in all the existing analysis, fiber to fiber contact in a yarn is assumed to be line contact. Yet in more realistic cases, fibers are in discrete point contact. This will completely alter the distributions of both the tensile and shear stresses in individual fibers. Furthermore, several competing factors are involved in prediction of the optimal twist level at which a staple yarn acquires the maximum strength, including the twist level, the fiber volume fraction of the yarn, the statistical variations and the complex yarn fracture behavior as discussed in Refs [33–36].

Knowing the critical role twist plays in generating yarn strength, people tend to think yarn twist to fabric strength is just as important. Actually, it appears that a woven fabric with twistless yarns can be made, which possesses strength at par with ordinary woven fabrics of comparable types. So, making fabrics using twisted yarn is mainly to facilitate the weaving process (e.g., preventing individual fibers from fraying away), as once yarns are in the fabric it is the interlacing points where the fibers are held together via friction. In other words, twist is not a decisive factor in fabric strength, but friction remains the key in not only fabric, but in all other textiles. This makes textiles the most efficient, convenient and even smart materials.

Bi-modular Nature of the Fibrous Materials

Anisotropy is responsible for many of the challenges in dealing with fibrous materials. However, even in the same

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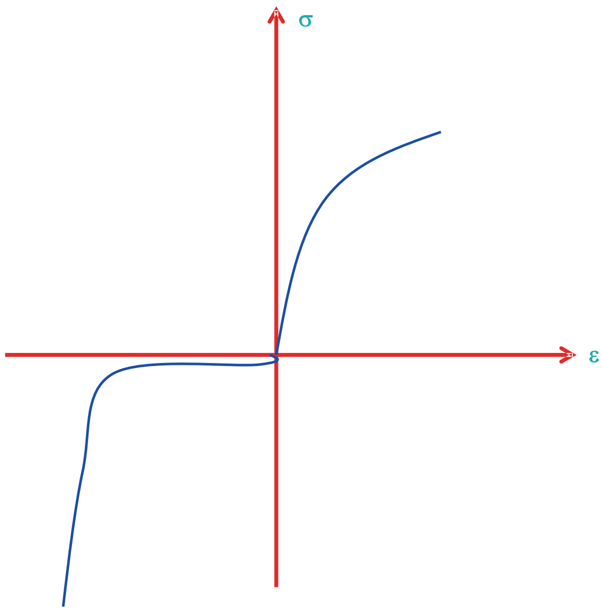

Figure 5 A bi-modular behavior.

direction, the materials behave differently depending on the sign of the force. In other words, for fibrous materials, the Young's modulus, as well as the entire stress–strain relationship, is quite different in tension versus in compression. Figure 5 depicts a typical example of dramatically different behaviors of a fabric under tension and compression in the longitudinal direction. The so-called "bi-modular" behavior is also prevalent in biomaterials. The pioneering work in this area was done mainly by Ambartsumyan and his collaborators and they further expanded the problem to two- and three-dimensional cases [37–39]. The problem picks up new momentum as interest in biomaterials increases.

Two issues are worth noting. First, the current approach of treating materials in engineering as inherently identical in both compression and in tension has to be re-examined. Furthermore, any modified model still needs to be evaluated to satisfy the following criteria: (1) the compliances S_{ij} and the moduli (stiffness) must be symmetric in any coordinate system in order for the strain energy to be positive, and therefore a potential function exist; (2) the values of compliances are restricted in relation to one another such that the compliance matrix is positive definite; and (3) the compliance matrix must be transformable between coordinate systems, i.e., it has to be a tensor [40–42].

Fabric Draping, Wrinkling and Crumpling, and the Fracture Behavior and Failure Criteria

No other solid sheets or films can fit on a human body or other solid objects as elegantly as textile fabrics (Figure 6).

Several factors contribute to this trait. First, the relative movement of the structural components over each other during fabric deformation allows the multi-curvature bending that is clearly unique only to fabrics and critical for its formability as studied by Hearle [30]. Another important factor is the unique response of fabrics to different types of stresses.

For an isotropic material, there is a simple relationship between the three parameters required to define the mechanical behavior of the material

$$G = \frac{E}{2(1+\nu)} \tag{4a}$$

where E and G are the tensile and shear moduli respectively and ν is the Poisson's ratio of the material. For normal solid materials, $0 < \nu < 0.5$ so that $2 < (E/G) < 3$. In other words, for ordinary materials, the tensile and shear moduli are of the same order of magnitude. Whatever the nature of the stress, the resistance of the material to the deformation does not change much. However, or fortunately, this is not the case for fabrics, it is reported [43] that for fabrics $E/G \to 200$, depending on the type of the fabric. In fact, a fabric will shear easily even under its own weight; once a fabric is laid onto an object, it will deform in bending and shear until it covers the object to the degree allow-

Figure 6 Examples of fabric draping.

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able by this E/G ratio. The main reason for the excellent formability of a fabric is due, of course, to the relative movement of individual yarns in the fabric subjected to a shear load, reflected by the unusually small shear modulus G value. Under such load, the yarns will reorient through sliding and slipping along the loading direction. This freedom of relative movement of yarns when the fabric is under shear or bias extension is the key to offer a very low bending and shear resistance, leading to an unusually high E/G ratio or an exceptional formability.

Since fabric can only be treated as orthotropic material for which equation 4(b) instead of 4(a) is applicable

$$\frac{E_L}{E_T} = \frac{\nu_T}{\nu_L} \quad (4b)$$

to define the limits for the values of Poisson's ratio between lengthwise L and transverse T directions.

There have been some more rigorous treatments of fabric drape [44], wrinkling [45] and crumpling [46–48].

Since fibers are best in carrying tension, when a fibrous material starts to break, at the micro level, fibers break almost exclusively due to extension, regardless of the nature of the macro deformation as discussed above. The nature of the materials allows fibers to move and retreat from the loading. All of these lead to several scientific challenges including analyses of wrinkling or crumpling of fibrous sheets and of very peculiar fracture behaviors and failure criteria as illustrated in Figure 7. For an isotropic material, its strength is identical, regardless of the direction, represented by a circle (owing to symmetry, only a quarter is drawn); whereas the strength–direction relationship for an ordinary anisotropic body can be illustrated by an ellipse.

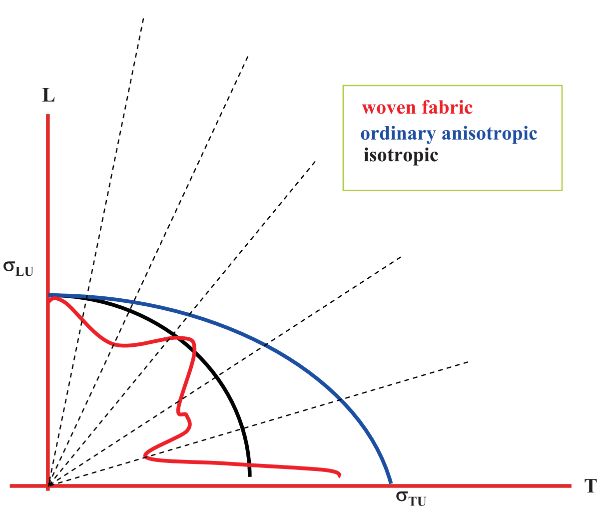

Figure 7 Various failure behaviors along different fabric directions.

However, this relationship for a woven fabric is much more complex, because of the different degrees of internal yarn re-orientation and movement when stretched in different directions of the fabric. Finally, this yarn re-orientation to self-reinforcing the resistance in the loading direction again reveals the adaptive nature of fibrous materials.

System Configuration and Entropy Change

Fibrous materials are made of individual fibers placed or oriented in various formats for different applications. Such geometrical configuration and its change should be significant, similar to the role played by the macromolecular configuration in polymers, in dealing with the mechanical behavior of a fibrous system. Any deformation of the material has to first alter the fiber configuration, i.e., the system entropy. However, no reported attempt has been found in analyzing a fibrous materials at macro-level while taking into account of the contribution of the entropy until a recent paper by Pride and Toussaint [49] dealing with the fracture of fiber bundles. Their theory postulates that the probability of observing a given emergent damage state is obtained by maximizing the emergent entropy as defined by Shannon, subject to energetic constraints. This theory yields the known exact results for the fiber bundle model with global load sharing and holds for any quenched-disorder distribution. It further defines how the entropy evolves as a function of stress, and shows how temperature and entropy contribute to a material's mechanics problem. Furthermore, a previously unnoticed phase transition is shown to exist as the entropy goes through a maximum. In general, this entropy-maximum transition occurs at a different point in strain history than the stress-maximum transition with the precise location depending entirely on the initial disorder distribution. It is expected that these types of approach will bring out an array of new advances and more accurate results in mechanics of fibrous materials, especially in the area of fracture and failure, for without considering the contribution from the system entropy change, any formulation of the problems would be, to say the least, incomplete.

Allometry or Scaling Laws in Fibrous Materials

Since fibrous materials are so complex, it is often difficult if not impossible to derive the material properties using the available physical laws and differential equations. Consequently, the allometric or scaling analysis often becomes the last, yet often robust, resort.

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For instance, the resistance for Ohmic conductor scales as

$$R_C \sim \frac{1}{A} \sim r^{-2} \quad (5)$$

where R_C is the resistance, r the radius, and A is the area of cross-section of the conductor .

For non-Ohmic bulk conduction without surface convection, He et al. [50] proposed that the scaling relation above should be modified into

$$R_C \sim \frac{1}{A^{\beta}} \sim r^{-2\beta} \quad (6)$$

where β is a material parameter relative to conductivity of polymer solution. When $\beta = 1$, it becomes the conductor case and for non conductors $\beta < 1$. R_C apparently increases when β decreases. It has been proved that for polymer solution jet $0.5 < \beta < 1$ should be valid [50].

Furthermore, for porous media, if we consider the existence of macro-sized pores, then a "genuine" stress σ_g should be defined as

$$\sigma_g \sim \frac{F}{A^{\beta_\sigma}} \quad (7)$$

and similarly for strain

$$\varepsilon_g \sim \frac{\Delta l}{l_0} \beta_\varepsilon \quad (8)$$

It is conceivable that β_σ is a reflection of the area fraction and β_ε the line fraction; both can be derived based on the results by Pan in [18].

Likewise, other physical properties such as diffusivity or conductivity can also be defined as such to account for the effect of the pores. Furthermore, for the same fibrous material, a conjecture can be made that there should be some intrinsic connections between all those β coefficients, for they are all determined by the influences of the pores. Actually, the scaling technique has been applied in dealing with many complex problems in fibrous materials including fabric wrinkling [45], draping [44] and crumpling [46], showing great potential in studying various behaviors of the material.

Cloth–Body Interactions

As a subgroup of the fibrous materials, textiles serve a special purpose of protection and decoration of the human body. They are in constant contact and interactions with the human body in general and in close friction with body skin

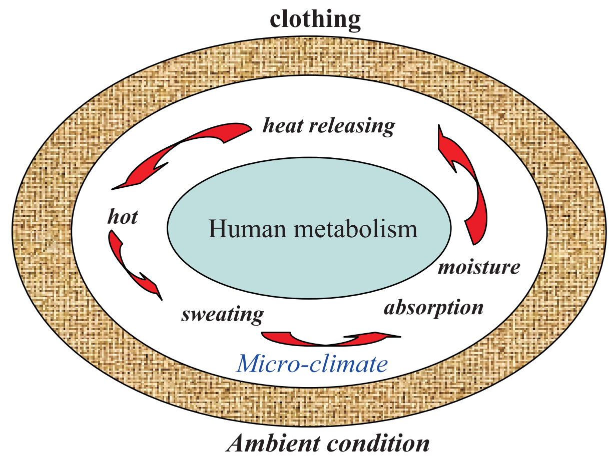

Figure 8 The vicious circle in deterioration of clothing comfort.

in particular, which is a unique problem that not many other engineering materials face. Two issues become critical in this application: first, the degree of comfort when wearing the textiles, since they form a microenvironment with the human skin. A proper equilibrium of both humidity and temperature are the determinant factors as to whether a comfort sensation is experienced by the wearer. More importantly, such equilibrium can be disturbed easily by human activity and the metabolism, given the heat–moisture coupling effect. As soon as either humidity or temperature varies to upset the equilibrium in the microenvironment. Such a feed-forward process or a vicious circle as shown in Figure 8 would trigger a quick deterioration of the comfort, thereby imposing a high demand on the clothing material to recover the equilibrium for comfort [51–54].

A second issue is the effects of physical friction between the skin and the textiles. An intense rubbing would cause rash, irritation and even blisters, which frequently incapacitate the wearers. The investigation of these issues has started to attract the attention of scientists [55–57]; however, the impact of skin–cloth abrasion on the cloth durability is the other side of the coin, for which there has been little research reported in the published literature.

Conclusions

Fibrous materials in general, and textiles in particular, although arguably the first type of engineering materials, remain poorly understood. The fiber science we know today has been largely derived out of polymer science and has been developed with, or as part of, polymer science, so

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that it focuses almost exclusively on single fiber properties using polymer science approaches. This article argues with many examples that the science of fibrous materials is very much different from fiber science: understanding of individuals cannot replace understanding of the total assembly, an analogy more or less like psychology versus sociology. The fibrous materials science, still in its adolescence, is a fundamental science and should be treated and cultivated just like other fundamental sciences: to encourage more of the scientific disciplines involved to develop it.

Acknowledgement

The authors would like to express their deep gratitude to their students and colleagues who have in different ways helped the completion of this work, especially Dr Wen Zhong and Dr Huiyu Sun.

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