

REZUMAT – ABSTRACT

Evaluarea comportamentului la compresiune al structurilor fibroase

În general structurile fibroase sunt realizate din fibre cu o dispunere întâmplătoare și aerul din porii formați din aceste fibre. O caracteristică importantă a acestor compoziții este comportamentul lor mecanic la presiune și relaxare. În această lucrare, a fost utilizat un studiu experimental unificat și sistematic pentru cuantificarea și caracterizarea comportamentului la compresiune și revenire al mai multor compoziții fibroase orientate aleatoriu prin intermediul unui sistem de măsurare integrat mecanic și conductiv in situ. Au fost caracterizate curbele de forță, modulul, efortul și pierderea de energie în timpul ciclurilor de compresiune și de revenire. O histereză considerabilă a apărut între operațiile de compresiune și relaxare, ceea ce reprezintă o dovadă a existenței efectelor fenomenelor de alunecare și frecare ale fibrei. Efortul, pierderea de energie și rata de revenire au demonstrat o relație exponențială neliniară în raport cu ciclurile.

Cuvinte-cheie: compresiune, revenire, compoziție fibroasă, ciclu, histereză

Evaluating compressive behavior of general fibrous assemblies

General fibrous assemblies are made of loose fibers and air filling in the pores formed by these fibers. An important characteristic of these assemblies is their mechanical behavior under compression and release. In this paper, a unified and systematic experimental investigation was used to quantify and characterize the compressional and recovery behavior of several randomly oriented fibrous assemblies via mechanical and conductive in situ integrated measurement system. An attempt was made to characterize the curves of force, modulus, work and energy loss during compressional and recovery cycles. Considerable hysteresis occurred between the compression and release operations which is an evidence for the existence of fiber slippage and frictional effects. Work, energy loss and recovery rate of work turned out to have a nonlinear exponential relationship with cycles.

Keywords: compression, recovery, fibrous assembly, cycle, hysteresis

INTRODUCTION

General fibrous assemblies are made of loose fibers and air filling in the pores formed by these fibers. These fibrous assemblies are of the first hierarchical level, otherwise known as simple or primary fibrous assemblies. An important characteristic of these assemblies is their mechanical behavior under compression. In most end-uses of textile products, such as carpet, pillows and nonwoven fabrics, fibrous assemblies are subjected to repeated compressional forces followed by recovery. Mechanical behavior under compressional forces has a significant value adding effect to the end-use products. Many of these materials used in these applications fail because of the loss of ability to recover from deformation due to fiber failure and slippage. Products lose their liveliness due to repeated compressional forces and changes in the fiber architecture of the assemblies [1].

Extensive works have been done in the field of compression properties of general fiber assemblies. However, nearly all have been of an empirical analysis in the fiber compression and release characteristics fitting a series of equations, or parameters have been derived from these characteristics. The pioneered work done by Van Wyk over sixty years ago provided the only theoretical basis on which to explain the relationship between the pressure and volume of a fibrous assembly during compression [2].

Theoretical derivation was based on the bending behavior of a rigid beam with equally spaced supports and by neglecting fiber slippage, friction and time dependent behavior. Dunlop showed that fiber friction and slippage have a major effect on the compressive behavior [3]. Neglect of fiber slippage and friction effect may be one of the major reasons causing the Van Wyk's results to deviate from the experimental values. Neckář derived a bi-dimensional deformation equation based on the Van Wyk's theory by taking the effect of uncompressed areas between contacting fibers into consideration [4]. Sebestyen and Hickie reported the compressional behavior of wool fiber mass at pressures ranging from medium to high and a relationship between fiber mass density and applied pressure was given in a power law form [5]. Komori, T. introduced a formula for compressional mechanics of a fiber mass treated as the assembly of the fiber elements whose individual bending behaviors are combined into the overall response of the mass [6]. Carnaby, G. A. and Pan, N. predicted the compressional behavior of fibrous assembly at large deformations, especially the compression hysteresis [7].

Works have been in progress for decades, but a detailed insight into the compressive behavior of fibrous assemblies still remains elusive. There is a lack of well-established knowledgebase to characterize

the compressional and release behavior of these systems, although these behaviors are of considerable importance. Having a systematic and thorough insight of the compressive behavior will aid us to design fiber assemblies with better resilience. In this work, the focus will be on a systematic analysis of the compressional and recovery behavior of fibrous assemblies. Experimental studies have been undertaken to characterize these behaviors. This work extends to several natural fibrous assemblies since many natural fibrous assemblies have unparalleled compression recovery properties. We are attempting to find the basic mechanisms of compression and recovery for these systems and particularly interested in work and energy loss during repeated successive compression and release cycles and to understand the reason for compression hysteresis.

EXPERIMENTAL DETAILS

Materials and preparation

Compression experiments were conducted on three different randomly oriented fibrous assemblies. The materials used as test specimen were cotton, kapok and cashmere fibrous assemblies. The corresponding average length, diameter and density of constituent fibers are respectively presented in table 1. The specimens were pre-conditioned at specific climatic conditions ($20 \pm 2^\circ\text{C}$, $65\% \pm 5\%$ relative humidity) for more than 24 hours until equilibrium temperature and moisture content was reached.

Table 1

Material	Average fiber length [mm]	Average fiber diameter [μm]	Fiber density [g/cm^3]
Cotton	23.56	23.56	1.54
Kapok	34.64	34.64	0.30
Cashmere	40.00	15.00	1.32

Experimental setup and measurement

The apparatus testing the compressional and recovery properties of general fibrous assemblies is shown in figure 1 and described in detail in Ref [8]. The apparatus designed to measure the macroscopic and microscopic compressive and recovery properties consists mainly of three parts. The first part is a cylinder (the upper chamber) which is connected to a force sensor and boosted by a stepping motor. The second part is a CCD camera moving up and down to capture changes of microstructure in situ during compression and release state. The third part is a cylindrical vessel equipped with another force sensor in the bottom of the lower chamber to record the passive force during compression and recovery state.

This upper chamber compresses the fibrous assemblies in the lower chamber into different thicknesses and densities with uniform velocities, similar to the principle of syringe. Due to the application of the force, the fibrous assembly undergoes compressive

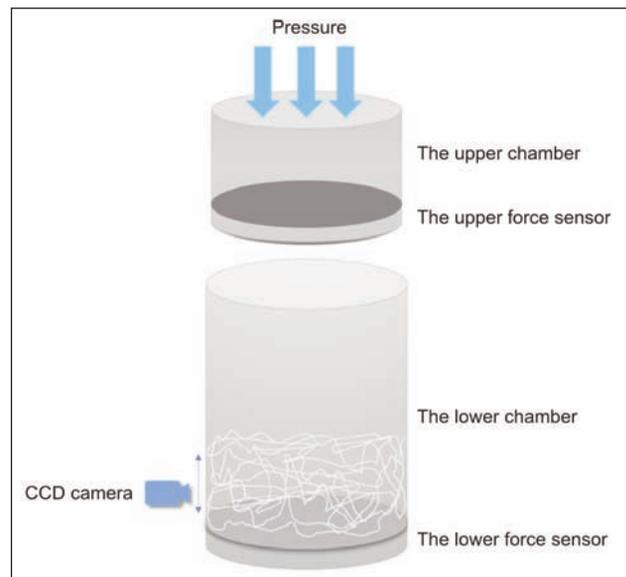


Fig. 1. Principle diagram of compressional apparatus

deformation. Trapped air will be removed quickly through the holes on the surface of the cylinder, thus the time dependent effect of consolidation of fibrous assembly due to removal of trapped air from the system can be eliminated. The system is connected to an Instron that measures the force and the deformation, from which the stresses and the strains can be measured. The compressive cycle is then followed by a recovery phase, where the applied load is removed at a chosen rate and the fibrous assembly is allowed to expand naturally. The recovery could be tested by relaxing (reducing the force or stains) at a certain rate or by suddenly removing the force and measuring the time dependent displacement recovery of the assembly. In our measurements, we applied the required compressive displacements and measured corresponding force, and then slowly removed the displacements and measured corresponding forces. The fibrous assembly went through several successive cycles of compression and recovery in order to separate the effect of fiber slippage, friction and even damage in the fibrous assembly. Compression resulting from fiber slippage is not fully recoverable, thus the loss of resilience in the fibrous assembly may be a direct measure of fiber slippage and damage, which may be an undesirable effect for many of the end uses. We have completed our experiments on three different natural fibrous assemblies as mentioned above to understand the macroscopic force displacement relations.

RESULTS AND DISCUSSION

Characteristic curves of active and passive force

A series of compressional experiments were completed to understand the macroscopic force-displacement behaviors during compressive state. Figure 2, a–c shows force and displacement curves of cotton, kapok and cashmere fibrous assemblies that provided us with non-linear constitutive relationships for fibrous assemblies. Small differences were found

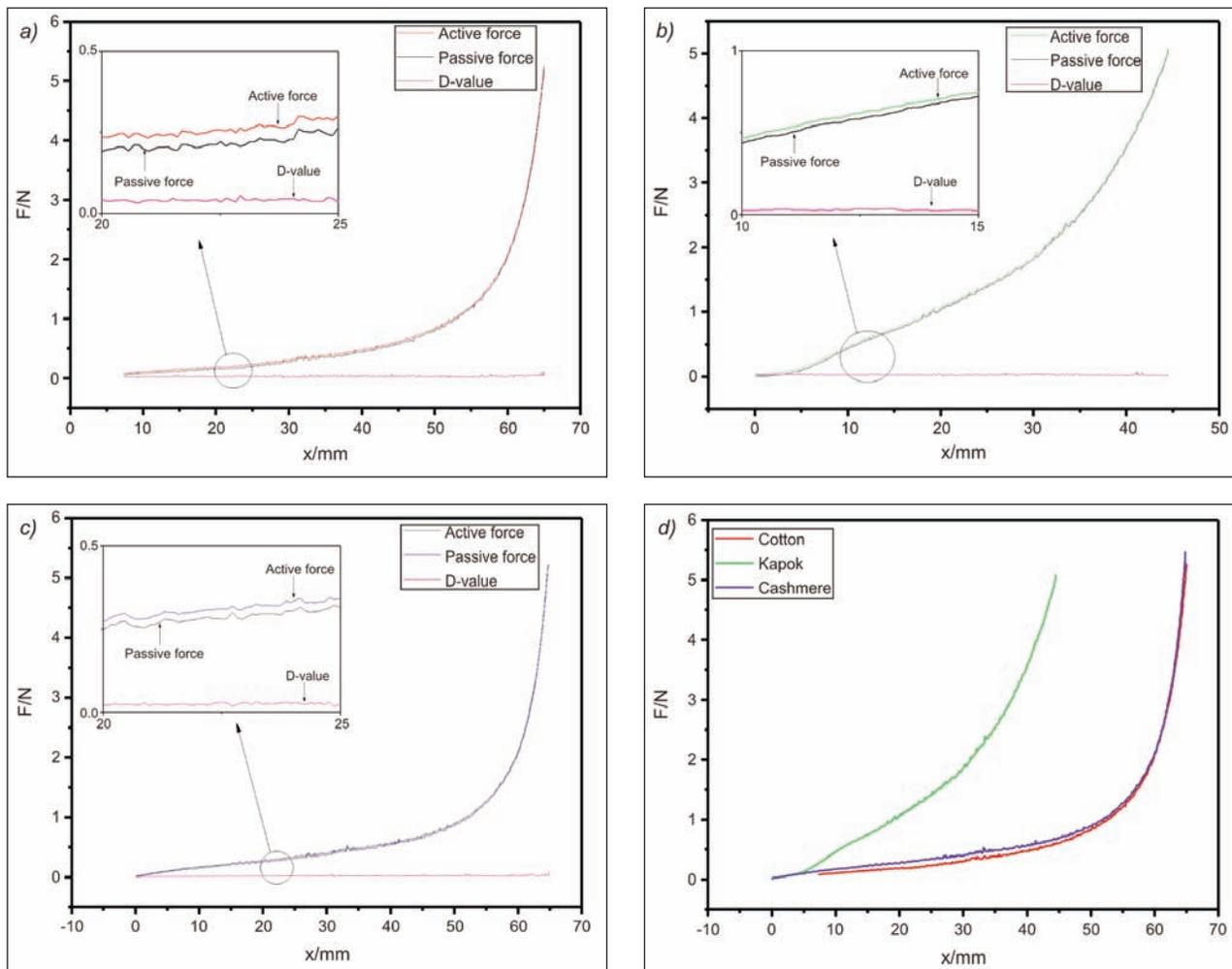


Fig. 2. Force-displacement curves of general fibrous assemblies

between active and passive force, and active forces are slightly larger than passive forces resulting in a nearly zero D-values (the difference between active force and passive force). This is mainly because of the time-dependent of force transmission. Active force-displacement curves of cotton and cashmere are similar with only small difference while Kapok is quite different because the original weight of three different fibrous assemblies are same and the density of kapok is much smaller than the other two fibers leading to a larger packing density of kapok fibrous assembly (figure 2, *d* as an illustration).

Packing density is a physical quality which is often used to describe the compactness of loose fibrous assembly. It is defined as the ratio of the volume of fibers to the volume of fibrous assembly (including pores between fibers and within fibers). Active force and packing density curves of cotton, kapok and cashmere fibrous assemblies are illustrated in figure 3. The force increases with the increase of packing density. The notable differences in force and packing density curves of three fibrous assemblies are mainly due to the differences of single fibers in stiffness and elasticity.

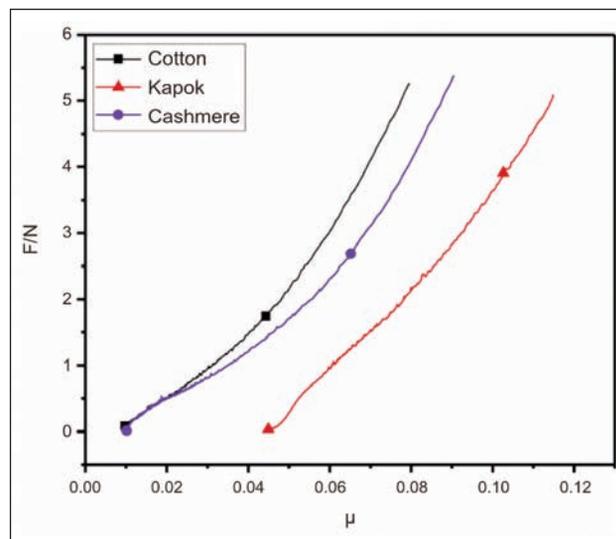


Fig. 3. Active force-packing density curves of general fibrous assemblies

Bulk modulus analysis

A series of modulus and strain curves of cotton, kapok and cashmere fibrous assemblies are plotted in figure 4, *a-c*. Similar modulus curves can be observed in cotton and cashmere fibrous assemblies, and modulus keep steady in the range of 0 to 0.8

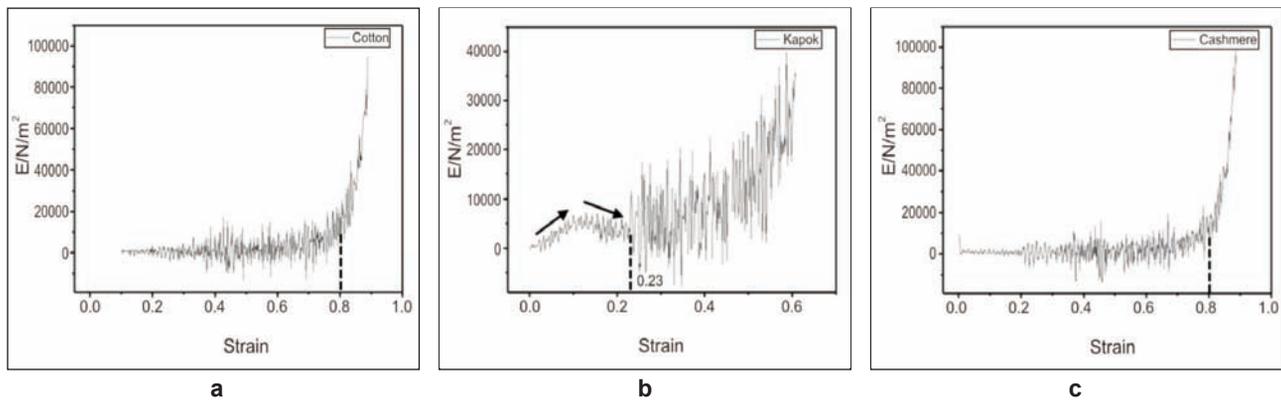


Fig. 4. a – Modulus and strain curve of cotton; b – Modulus and strain curve of kapok; c – Modulus and strain curve of cashmere

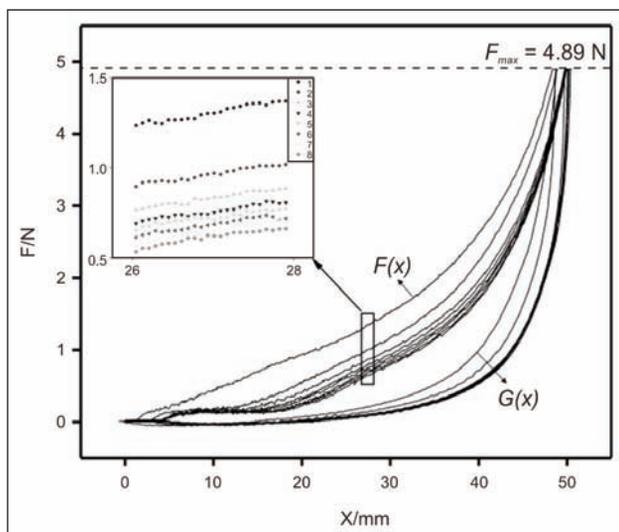


Fig. 5. Compression and release cycles of cashmere fibrous assemblies for eight successive cycles, plotted as compression force against displacement

while a sharp increase can be observed when the strain reaches the maximum value. The modulus characteristic curve of kapok fibrous assembly shows a different tendency with cotton and cashmere fibrous assemblies. Modulus increases and then decreases within the range of 0 to 0.23, and presents a reciprocating morphology and the overall trend is continuing to increase. The values of the bulk modulus of fibrous assemblies determined here are in excellent agreement with Liu, Q.'s [9] results.

Compression and recovery cycle curves

Compression force against displacement curves of cashmere fibrous assemblies for eight successive compressional and release cycles are illustrated in figure 5. It will suffice here to mention that the curves shift with each successive cycle of compression and release, but finally attain a steady position. The experimental results show that the compression and recovery curves of the fibrous assemblies are in a monotone downward curve, and the compression curve and the recovery curve do not coincide due to the coexistence of viscosity and elasticity of the

textile fibers. In addition, a considerable hysteresis occurs between the compression and release operations, which is an evidence for the existence of fiber slippage and friction effects.

Compression work W_C , recovery work W_R , energy loss E_L and recovery rate of work r_W can be calculated from a series of compression and release curves showed above. The corresponding formulas are showed below:

$$W_C = \int F(x) dx \quad (1)$$

$$W_R = \int G(x) dx \quad (2)$$

$$E_L = W_C - W_R \quad (3)$$

$$R_W = \frac{W_R}{W_C} \quad (4)$$

Where $F(x)$ and $G(x)$ are compressional and recovery characteristic functions of each successive circle.

Calculations of works and energy loss of eight successive circles are presented in table 2 and a histogram is illustrated in figure 6. As the cycling continues, a palpable decrease can be observed in compression work and energy loss resulting in a stable recovery work. An important factor neglected in the theory of Van Wyk is the part played by slippage and fiber friction effects that may occur during the compression of a general fibrous assembly. There is now substantial evidence to support the concept that such slippages and fiber friction occur and that they may

Table 2

n	$W_C / 10^{-2} J$	$W_R / 10^{-2} J$	$E_L / 10^{-2} J$	r_W
1	7.254	2.031	5.223	0.27998
2	6.262	2.011	4.251	0.32114
3	5.615	1.973	3.642	0.35138
4	5.420	1.971	3.449	0.36365
5	5.243	1.969	3.274	0.37555
6	5.086	1.915	3.171	0.37652
7	4.781	1.845	2.936	0.38590
8	4.576	1.775	2.801	0.38789

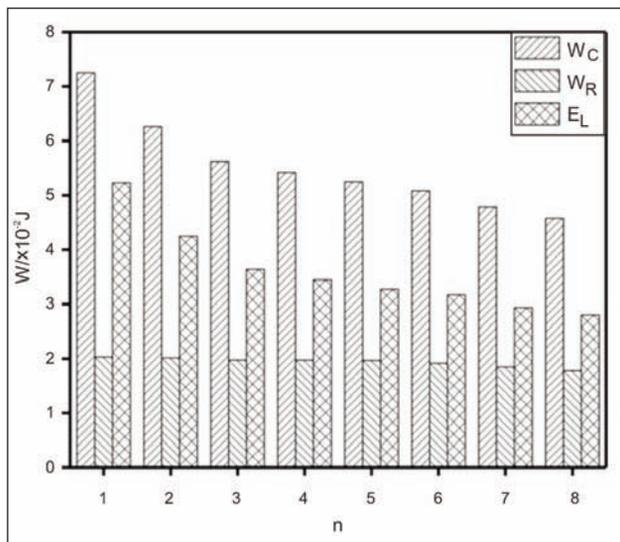


Fig. 6. Histogram of compression work, recovery work and energy loss during eight successive compression and recovery curves

have a considerable influence on the compression properties of fibrous assemblies.

The exponential model based on least square method was adopted for nonlinear fitting of experimental data, and a series of correlation coefficient R^2 excelling 0.97 was obtained (figure 7). It is obvious that there exist approximate nonlinear relationships between work and cycles as well as recovery rate of work.

CONCLUSIONS

A unified and systematic experimental investigation was used to quantify and characterize the compressional and recovery behaviours of randomly oriented fibrous assemblies via mechanical and conductive in situ integrated measurement system for variable density fibrous assemblies. Results show that small differences were found between active and passive force within three fibrous assemblies, and active forces are slightly larger than passive forces resulting in a nearly zero D-values because of the time-dependent of force transmission. Notable difference in active force and packing density curves of three

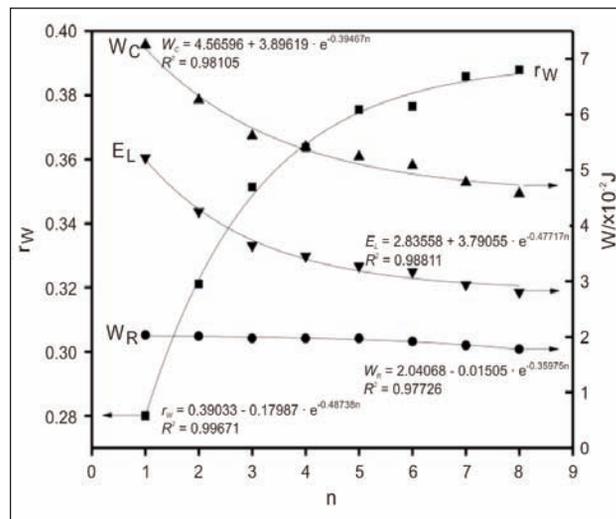


Fig. 7. Fitting curves of compression, recovery work, energy loss and recovery rate of work

fibrous assemblies mainly due to the differences of single fibers in stiffness and elasticity. Similar modulus and strain curves can be observed in cotton and cashmere fibrous assemblies while kapok fibrous assembly shows a quite different tendency.

Compressional and release curves shift with successive cycles and finally attain a steady position. The compressional and recovery curve do not coincide with each other due to the coexistence of viscosity and elasticity in the textile fibers. In addition, a considerable hysteresis occurs between the compression and release operations, which is an evidence for the existence of fiber slippage effects. As the cycling continues, a palpable decrease can be observed in compression work and energy loss resulting in a stable recovery work. Work, energy loss and recovery rate of work turned out to have a nonlinear exponential relationship with cycles.

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