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Quantification of deformation response at cyclic compression of polymer fibrous systems

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ABSTRACT

The difficulty in qualitative evaluation of deformation properties of polymer fibrous assemblies lies in the fact that these materials differ from materials such as wood, concrete, steel, etc., as a consequence of the manifestation of non-linear and plastic deformation. In this work, an attempt was made to quantify repeated compression performance of textile fibrous structures by using the concept of energy. Particular attention was paid to the nonelastic deformation of polymer fibrous systems under compression. Starting from the fact that the compression curve governs the energy-absorption characteristics of materials subjected to repeated stress, deformation components were determined by calculating the energy-absorbing properties and specific parameters – the irreversible compression work of all-cycle compression and the compression work of viscoelastic deformation of all-cycle compression. These parameters made it possible to estimate the compression hysteresis and then calculate the share of deformation components at lateral compression of polymer fibrous systems.

1. Introduction

Nature and man-made polymer fibers are widely applied materials in practice and they are available with a great range of mechanical properties. Fibrous polymer structures exhibit non-linear deformations, substantial plastic flow and no apparent rupture. Fibers can be easily assembled in a number of different two- or three-dimensional structures using highly automated techniques such as stitching, weaving, braiding and knitting.

From the aspect of suitability for a particular use, an engineering material needs to be evaluated by answering two questions: To what extent the material resist the deforming force that will be applied? and to what extent will the material recover when the deforming force is removed [1]? Therefore, the mechanical behavior of fiber assemblies is of great interest in many fields of engineering such as fiber reinforced composites, paper, and textiles manufacturing. Lateral compressional behavior of fibrous assemblies is one of the most important properties of textile materials used for garment or insulating materials. It is also of considerable practical interest in composite structure, where the compatibility of the lateral compression and recovery behavior of the fiber (or fiber assembly) and matrix has a strong influence on the ultimate properties of the composite. In addition, the cyclic compressional loading behavior of fibrous assemblies is an important consideration in the design of industrial products made of these materials.

Polymer fibrous material is considered to be an imperfectly elastic body, since it exhibits a strain lag or hysteresis upon the removal of stress. This hysteresis loss is due to an inter-fiber friction and viscoelastic nature of the fibers and their assemblies at a mesoscopic level within the fabric. So, the deformation resulting from the compression of a fabric may be divided into two components, one taking place immediately (elastic deformation), another one over a period of time (delayed deformation) further subdivided into recoverable (viscoelastic, primary creep) and irrecoverable (plastic, secondary creep) [2]. Some physical concepts involve the determination of the compression properties of the material by using simple “end-point” deformation (thickness at the start, at maximum load and at the end of the cycle). However, the fact is that between the initial and final points of cyclic compressional loading any number of lines may exist, each one indicating certain load-deformation behavior. Therefore, for this study the idea was to determine the deformation response of polymer fibrous assemblies by utilizing the concept of energy. It should be noted that the determination of elastic deformation components of polymer fibrous assembly in terms of energy (or work done) has been introduced since 1940s of the 20th century [3]. The authors determined the resilience as the amount of energy returned by the sample upon the removal of compression load expressed as the percentage of the energy stored up as

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potential energy in the sample under compression. However, there has not been an attempt so far, at least as evidenced by the literature, to determine nonelastic deformation components at cyclic compression of polymer fibrous systems. Therefore, an attempt was made in this study to quantify hysteresis response with respect to nonelastic (viscoelastic and plastic) deformation.

2. Material and method

Various natural (cotton and hemp), regenerated (viscose) and synthetic (acrylic) polymer fibers were chosen to produce fibrous systems on the same circular knitting machine under controlled conditions so as to obtain as similar as possible construction of the plain knitted fabrics. The method employed in compression test involved lateral compression of the sample (normal to its plane), recording the corresponding changes in thickness and load, and also removing the load while recording the recovered thickness of the sample [4,7]. The method applied gives reproducible results. In this experiment five successive compression cycles (loading–unloading) were performed for each knitted fabric without moving the sample and the thickness measurement over a pressure range of 0.45–2560 cN/cm^2 with the progressively increased (or decreased) compression stages. Each knit was investigated by making five separate tests on different portions of the knit, so the thickness measurement was the average of these five tests.

The energy-absorption properties of the knitted fabrics were evaluated from the compression-release curves by calculating the area below the compression curve as the indication of work done or energy absorbed by the fabric (WC_{tot}), the area below the release curve indicating the energy released upon the removal of compression load (WC_{el}) and the area occupied by a hysteresis loop as a measure of nonelastic compression work or the energy lost (WC).

3. Results and discussion

Compression behavior of polymer fibrous systems is controlled by fiber bending, slippage with friction at contact points and irreversible fiber rearrangement reflected in the hysteresis during loading and unloading cycles. The load thickness graphs shown in Fig. 1a and b follow the pattern typical for textile fabrics [4–7], reinforced composite materials [8,9], and fiber assemblies in general [10,11].

The compression-release curves for the fifth cycle (Fig. 1b) were shifted to the left from the original compression-release curve together with the reduction of the hysteresis loop area with repeated cycling. The nonlinear response indicating the viscoelastic and plastic deformations of a material resulted from bending and slipping of fiber segments against the resistance due to crimp and inter-fiber friction. Due to irrecoverable fiber rearrangement at the previous compression cycles, the knitted fabrics became less compressible, and the nonelastic deformation also decreased. The thickness change does not go away with further cycles indicating that the mechanical conditioning of the sample was completed in five cycles [4]. Since the total deformation at any point on a compression-release curve is the sum of the immediate elastic, viscoelastic and plastic components, they all

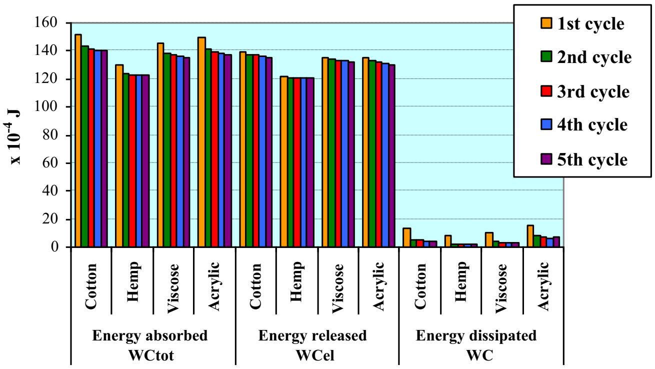

Fig. 2. Energy-absorption properties of the knitted fabrics for five successive compression cycles.

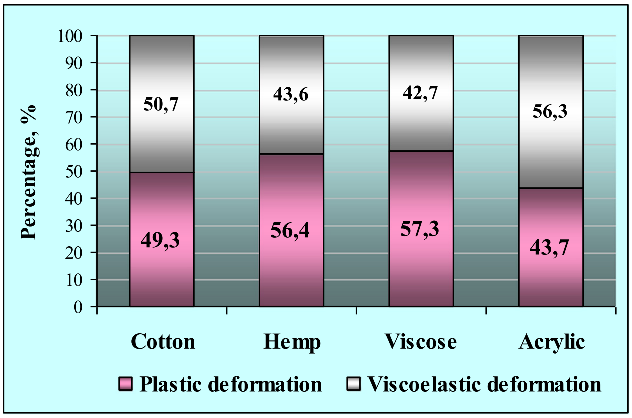

Fig. 3. Percentage of plastic and viscoelastic deformation components at five-cycle compression of the knitted fabrics.

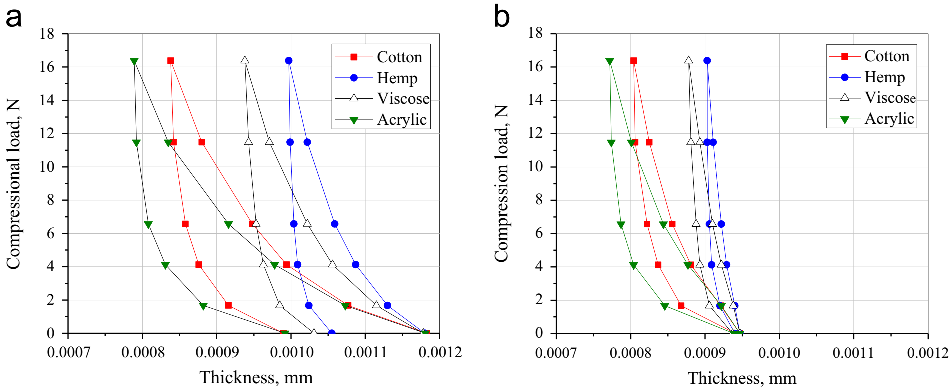

Fig. 1. Compression-release curves of the knitted fabrics at the 1st cycle (a) and at the 5th (b) cycle.