# Strengthening and Stiffening of Ramie Yarns by Applying Cyclic Load Treatment

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**ABSTRACT:** A cyclic load treatment was developed by applying a load on ramie yarns up to a proper value and then unloading for different number of cycles under high temperature or wet state. The results of tensile tests revealed that compared to the untreated yarns, a significant increase of around 20–50% in tensile strength was obtained for the cyclic load-treated yarns. Young's modulus of cyclic load-treated yarns was increased drastically, one to two times higher than the initial value. The number of cycles had an influence on improving the tensile properties of ramie yarns. After the individual heat or wet treatment without cyclic load, it was found that tensile strength of treated yarns remained unchanged as the original value while Young's modulus was decreased remarkably, which implies that the introduction of cyclic load to individual heat or wet treatment plays a crucial role in strengthening and stiffening of ramie yarns. It was considered that the improved effect was correlated with the decreased microfibrillar angle and the increased orientation of amorphous region in fiber microstructure because the crystallinity and crystalline orientation of ramie yarns calculated from X-ray diffraction diagrams showed little change after cyclic load treatment. © 2008 Wiley Periodicals, Inc. J Appl Polym Sci 109: 889–896, 2008

**Key words:** fibers; mechanical properties; supramolecular structures; X-ray

## INTRODUCTION

The main drawback of difficult recycling and disposal in conventional synthetic fibers used in reinforced plastic composites, such as glass and carbon fibers, has hindered their development in spite of their superior mechanical and thermal properties.[1] For ecological concerns, natural fibers have been gaining attention with the potential to replace synthetic fibers as the reinforcement in engineering polymeric materials. These fibers are renewable environmentally friendly materials in combination with the advantages of abundance, low-cost, lightweight, and less wearing of machines during processing.[2] In the recent years, the increasingly focus on the preservation of natural sources and environment production has led to a high demand for natural fibers in the application of composite industry, such as automobile, aeronautic, building, and furniture industries.[3,4]

Plant-based natural fibers are classified into bast (jute, ramie, flax, hemp, and kenaf), leaf (sinsal, pineapple, and screw pine), and seed (coir, cotton, and oil palm) fibers. They are rich in cellulose and possess good mechanical properties. Their quality is varied with growth area, climate, maturity as well as exaction technique.[5,6] To obtain clean single fibers with high performance, the raw fiber bundles need to be preprocessed. Different methods have been invented and adopted, such as retting and scutching process,[7] steam explosion technique,[8,9] thermomechanical process,[10] as well as degumming by alkali or enzymatic.[11,12] After preprocessing, many varieties of plant fibers have been investigated to yield reinforcing elements and various applications of plant fibers as reinforcement in composites have proved encouraging.[13–17] However, in most cases, the overall physical properties of plant fiber-reinforced composites cannot reach those of glass fiber or carbon fiber-reinforced composites. This is in general attributed to two reasons, of which one is due to the poor compatibility between fiber and matrix, and the other is that plant fibers are not strong enough to meet the industrial demand of fiber/matrix composites.

Many surface modification techniques have been carried out to improve the fiber-matrix interface, involving physical methods (plasma treatment,[18,19] liquid ammonia treatment,[20] etc.) and chemical modification (impregnation, chemical coupling,[21,22] etc.). Nevertheless, the majority of chemical modifications have inherent problems of uniformity and reproducibility,[22,23] and on the other hand, a negative influence on the mechanical properties of plant fibers was also reported in physical methods.[18] The mercerization treatment, one of the oldest methods using alkaline solution to modify cellulose fibers, in most cases, can improve the surface wetting but also enhance the mechanical strength of fibers.[24–27] Recent

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**TABLE I**
**Physical and Chemical Properties of Ramie Fibers**

| Density (mg/m$^3$) | Microfibril angle (°) | Moisture content (wt %) | Chemical composition (wt %) | | | | |
|---|---|---|---|---|---|---|---|
| | | | Cellulose | Lignin | Hemicellulose | Pectin | Wax |
| 1.50 | 7.5 | 8.0 | 68.6–76.2 | 0.6–0.7 | 13.1–16.7 | 1.9 | 0.3 |

research have shown that by an alkali treatment under isometric conditions or applying tensile load during mercerization,[28,29] the strength level of plant fibers can be increased drastically. Yet the challenge of this technique lies in the environmental and safety considerations, because the wastes of alkali solutions are becoming increasingly unacceptable. Therefore, recently, great interest has been focused on developing new physical methods to strengthen natural fibers and accordingly to improve the performance of resulting composites.

This study was designed to explore a new mechanical treatment to improve the tensile properties of a natural fiber, ramie. Ramie fiber (*Boehmeria nivea*) belongs to *Urticaceae* or *Nettle* family and is obtained from the outer part of stem of the plant native to Asia (China, Japan, Philippine) and Brazil. It is a traditional textile fiber due to its excellent properties such as long length and high strength. The easily recycling of ramie fiber ensures it environmentally safe, and the low density makes it possible to be used in reinforcing composites, which combine good mechanical properties with a low specific mass. In terms of specific modulus (modulus/specific gravity), ramie fiber can be comparable to the characteristics values of well-known E-glass fiber. On the other hand, the specific strength (strength/specific gravity) of ramie fiber is substantially lower than that of E-glass fiber.[30] In this work, a cyclic load application was performed on ramie yarns for the purpose of giving improved structural and tensile properties of the yarns, because through applying the proper load with a cyclic form, the molecular chains in ramie fiber was expected to be extended along the fiber axis and an increased crystallinity and orientation of microfibrils may be achieved. Because the molecule movement is accelerated with the increasing temperature or relative humidity, cyclic load applications under high temperature or wet conditions were investigated. To interpret the inner microstructural changes in the ramie yarn treated by the cyclic load, X-ray diffraction (XRD) measurement has been used.

## EXPERIMENTAL

### Materials

Ramie yarns were supplied by TOSCO (Type No.25) with a fineness of about 66 tex, and a tenacity of 30 cN/tex were used in this study. The physical and chemical properties of ramie fibers are listed in Table I, which were reported in literature.[29] It was found that the percentage of lignin is very low in the ramie fiber, which is different from other natural fibers.

To prepare for the cyclic load treatment and tensile test, fiber-reinforced plates were attached with epoxy adhesive on both ends of the yarns. The shape and dimensions of specimens in cyclic load treatment were the same as tensile test, as shown in Figure 1.

### Cyclic load treatment

The cyclic load treatment of ramie yarns was carried out using a servohydraulic machine (Survopulser, EHF-EB10, Shimadzu, Japan) in two conditions, namely, high temperature and wet conditions. In a temperature chamber equipped to the Shimadzu EHF-EB10, the ramie yarns were first preheated for 10 min at 100 and 150°C, respectively, without loading and then cyclic loaded at the same corresponding temperatures. The wet cyclic load process was conducted by first immersing the ramie yarns in water for 2 h and subsequently removing them from water and applying cyclic load. To avoid the evaporation of water in the cyclic load application, the wet state of the yarns was maintained by spraying water into the yarns.

The moisture content of ramie yarns was tested by oven-drying method using the following equation:

$$\text{Moisture content } (\%) = \frac{W_m - W_d}{W_d} \times 100 \qquad (1)$$

where $W_d$ is the mass of dried yarns conditioned in the vacuum containers and $W_m$ is the mass of moisture-absorbed yarns. It was found that the moisture content of a ramie yarn sample in ambient environment was 6.66%, while a totally wet sample has a moisture content of 96.6%.

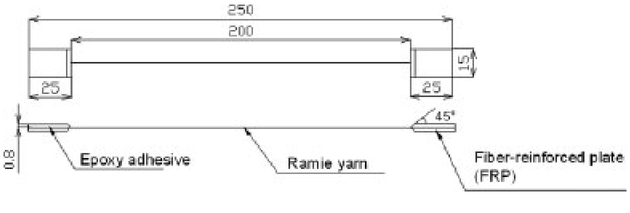

**Figure 1** Shape and dimensions of ramie specimen for both cyclic load treatment and tensile test (Unit: mm).

**TABLE II**
**Cyclic Load Applied on Ramie Yarns Under High Temperature Conditions and Wet Condition, Respectively**

| Specimen type | Condition | Cyclic load applied (*N*) |
|---|---|---|
| HT100 | 100°C | 11.60 |
| HT150 | 150°C | 9.63 |
| WT | Wet | 17.5 |

For clarification, the yarns treated by high temperature cyclic load were labeled as HT100 and HT150, respectively, and the wet cyclic load-treated yarns were called as wet-treated (WT) samples. The final treated samples were hereinafter denoted as ''sample-number of cycles.''

Based on the previous studies, when the cyclic load applied was chosen as 70% level of the mean fracture load of untreated ramie fiber, the tensile properties were improved significantly. Accordingly, based on the measured fracture load, results of untreated ramie yarns in the conditions of high temperature (100 and 150°C) or wet state, the cyclic load applied was calculated respectively, as shown in Table II. The speed of cyclic load was 15 mm/min, and the distance of clamped support was 200 mm. The number of load cycles was varied from 5 to 20 for high temperature samples while from 5 to 30 for wet samples. The typical cyclic load process of HT100 samples with 10 cycles was given in Figure 2. It was found that the elongation of the first cycle was larger than that of the other cycles, indicating that the slack deformation was formed in the first cycle.

Prior to tensile strength measurements, the HT100 and HT150 samples were cooled down and WT samples were dried off naturally followed by a storage of 1 day at ambient temperature.

### Individual heat or wet treatment

Individual heat or wet treatments without cyclic load application were performed to evaluate the contribution of cyclic load to the improvement effect of mechanical properties of ramie yarns. Heat treatment was carried out by heating the samples freely in 100 and 150°C, respectively, for 10 min. In wet treatment, the ramie yarns were soaked in water without loading for 2 h. After the heat treated and WT samples were stored in ambient temperature for 1 day, their tensile strengths were tested. These samples were symbolized as HT100-0, HT150-0, and WT-0, respectively.

### Tensile test

The tensile tests were carried out using Shimadzu EHF-EB10 at a constant rate of elongation of 6 mm/min over an initial gauge length of 200 mm. All measurements were conducted on single yarn specimens with at least 10 replicates for each sample group in ambient environment.

The yarn fineness was determined by weighing method. A single yarn randomly selected from the sample was cut to a length of 50 mm and then weighed on a sensitive microbalance.[31] The average of more than 30 readings was reported. Tex was calculated and the cross-sectional area was then determined from the tex and the density of fiber using the following relation:

$$\text{Cross-sectional area} = \text{Tex}/\text{Density} \tag{2}$$

where the density of ramie fiber was taken as 1.5 g/cm$^3$.[29]

### Wide angle X-ray diffraction

Wide angle X-ray diffraction (WAXRD) patterns of finely powdered samples were recorded using a D/Max-3D diffractometer (Rigaku, Japan). The diffractometer provided Ni-filtered Cu K$\alpha$ radiation with an accelerating voltage of 40 kV and an anode current intensity of 200 mA. The deflection angle had a range from 6 to 40°, with a 6°/min scanning speed. The crystallinity index was calculated by the ratio of the integral intensity of crystalline portions (lattice plane: [101], [101$^{-}$], [002], and [040]) to the total intensity of the sample.

The crystalline orientation factor was determined from the azimuthal intensity distribution of the equatorial reflections at 22.9° according to the following equation:

$$\text{Crystalline orientation factor } (\%) = \frac{180 - W_{1/2}}{180} \times 100 \tag{3}$$

where $W_{1/2}$ is the half width of the azimuthal intensity distribution for the meridional reflection at the (002) plane.

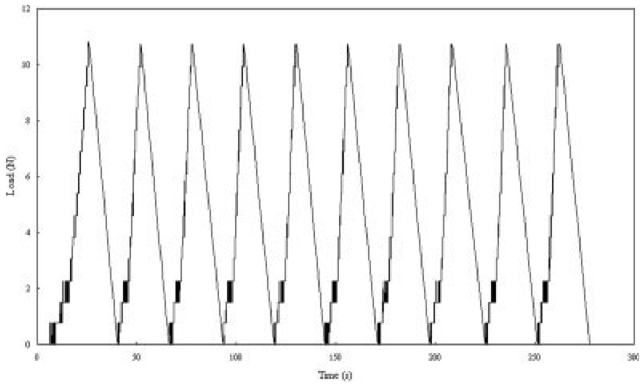

**Figure 2** Typical cyclic load process of HT100 samples by applying cyclic load for 10 cycles.

**TABLE III**
**Tensile Properties of Ramie Yarns Untreated and Treated by Cyclic Load Under High Temperature Condition and Wet Condition, Respectively**

| Specimen type | Tex | Cross-sectional area (mm$^2$) | Fracture load ($N$) ±SD[a] | Tensile strength (MPa) ±SD | Fracture strain (%) ±SD |
|---|---|---|---|---|---|
| Untreated | 66.7 | 0.044 | 19.76 ± 1.66 | 444.6 ± 37.4 | 3.05 ± 0.21 |
| HT100-5 | 66.5 | 0.044 | 22.93 ± 1.84 | 547.3 ± 43.9 | 2.95 ± 0.30 |
| HT100-10 | 65.5 | 0.044 | 22.99 ± 1.68 | 553.7 ± 40.4 | 3.00 ± 0.30 |
| HT100-20 | 63.0 | 0.042 | 20.87 ± 1.39 | 529.7 ± 35.3 | 2.57 ± 0.20 |
| HT150-5 | 58.6 | 0.039 | 20.62 ± 1.10 | 527.8 ± 28.2 | 2.82 ± 0.21 |
| HT150-10 | 57.1 | 0.038 | 21.11 ± 1.91 | 544.9 ± 49.4 | 2.81 ± 0.24 |
| HT150-20 | 56.8 | 0.038 | 19.79 ± 1.08 | 523.0 ± 28.5 | 2.57 ± 0.19 |
| WT-5 | 58.7 | 0.039 | 23.10 ± 1.73 | 590.5 ± 44.2 | 2.64 ± 0.21 |
| WT-10 | 58.0 | 0.039 | 23.65 ± 1.71 | 611.7 ± 44.2 | 2.63 ± 0.20 |
| WT-20 | 55.6 | 0.037 | 24.87 ± 2.27 | 670.8 ± 61.1 | 2.71 ± 0.20 |
| WT-30 | 54.4 | 0.036 | 24.01 ± 1.53 | 661.7 ± 42.2 | 2.87 ± 0.15 |

[a] Standard deviation.

## RESULTS AND DISCUSSION

### Tensile properties of yarns by cyclic load treatment

Table III shows the measured results of tensile properties of ramie yarns untreated and treated under high temperature as well as wet conditions for different number of cycles. The yarns became finer with the increase of the number of cycles, perhaps due to the repeated extending. Compared to the untreated ramie yarns, an increase of ~ 25% in tensile strength was obtained for HT100 samples applied for tension up to 10 cycles. As the number of cycles was increased to 20, the tensile strength was increased less. The similar trend was found for HT150 samples, where the increment of tensile strength rose till to 10 cycles while fell at 20 cycles. This indicates that the number of cycles has an optimum value on the improvement of tensile strength because as the number of cycles exceeds a critical value, the treatment process may create new defects caused by fatigue damage, resulting in a decrease of tensile strength.

As increasing the heating temperature from 100 to 150°C, the tensile strength of samples was decreased a little. It is possible that at higher temperature, the concomitant oxidation and chain degradation[32] occurred in the ramie yarns could have disadvantages on improving the tensile properties.

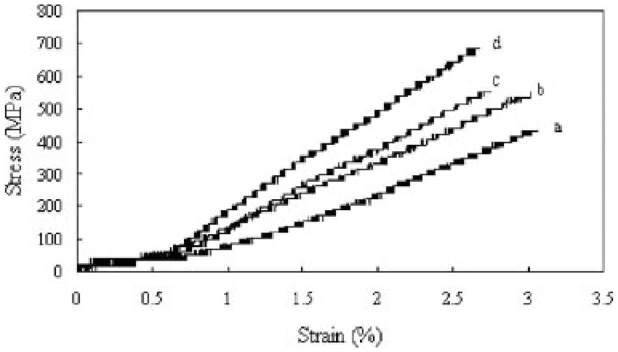

**Figure 3** Typical stress–strain diagrams of ramie yarns: (a) untreated; (b) HT100-10; (c) HT150-10; (d) WT-20.

The tensile test results of wet ramie yarns applied for cyclic load were also investigated. It was found from Table III that the tensile properties of wet cyclic load-treated ramie yarns were greatly improved. The highest increase of about 50% was achieved after the wet yarns were applied for 20 cycles load. As increasing the number of cycles to 30, no further enhancement in tensile strength was observed.

The typical stress–strain diagrams of the samples untreated and treated under the optimized conditions, namely, HT100-10, HT150-10, and WT-20, are presented in Figure 3. It can be seen that for untreated ramie yarns the strain was proportional to the stress in agreement with Hookean behavior. After cyclic load treatment, the linear behavior was maintained. On the other hand, it is shown in Figure 3 that the slopes of the stress–strain curves were evidently raised. From the slope of the linear part of the stress–strain diagrams, Young's modulus of the untreated and treated ramie yarns can be calculated by considering yarn diameters. Data of Young's modulus calculated are documented in Figure 4. The Young's moduli of the treated ramie yarns were increased drastically, of which the most significant increase was found in wet cyclic load-treated group, with an increase of around 111–123%. As the number of cycles was increased, Young's moduli of HT100 and HT150 samples were improved more while the enhancement of Young's modulus of wet samples almost remained constant.

### Tensile properties of yarns by individual heat or wet treatments

The tensile properties of yarns treated in heat and wet conditions, respectively, without cyclic load

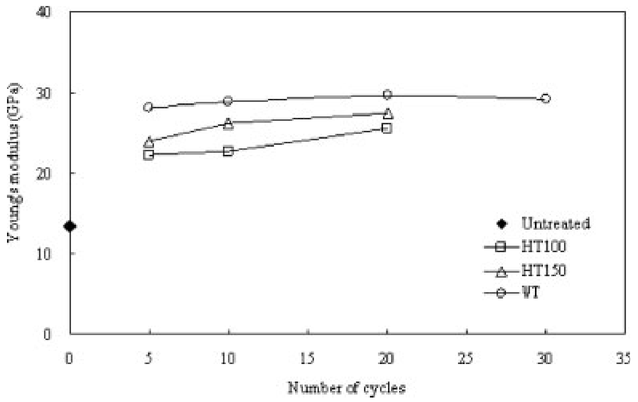

**Figure 4** Young's modulus as a function of number of cycles for the high temperature or wet cyclic load-treated ramie yarns.

were studied. As presented in Table IV, in comparison with the untreated samples, the tensile strengths of individual heat or WT ramie yarns did not change significantly. However, the Young's moduli of heat or WT yarns were much lower than the original value of untreated samples, 13.28 GPa. This is contrary to the improved mechanical properties of cyclic load-treated groups that have high strength and modulus. Thus, it can be considered that the introduction of cyclic load process to the individual heat or wet treatment plays an important role in strengthening and stiffening ramie yarns.

### Structural change

The information concerning the resulting changes in the fiber microstructures of HT100, HT150, and WT samples after different number of cycles was evaluated by XRD technique. Figure 5 reveals that the treated ramie yarns have similar XRD diagrams as that of the untreated yarn, in which a sharp and strong diffraction peak at $2\theta = 22.9$ and Iacgr; assigned to the diffraction of the [002] lattice plane, another two overlapped diffraction peaks at $2\theta = 14.9^\circ$ and $16.7^\circ$ assigned to the [101] and [101$^{-}$] lattice planes and the weakest diffraction peak at $2\theta = 34.3\theta$ assigned to the [040] lattice plane. Nevertheless, when compared, these peaks for HT100-10 sample were stronger and sharper than those for the untreated while weaker peaks occurred in HT150-10 sample. In addition, little difference was observed before and after wet cyclic load application.

The data of the crystallinity calculated, from the XRD diagrams, were listed in Table V. In comparison with untreated yarns, a slight higher crystallinity was found in HT100 sample while the crystallinity of HT150 sample was lowered a little. The wet cyclic load-treated samples experience no obvious change in crystallinity. On the other hand, the increase of the number of cycles did not have a significant effect on the crystallinity.

Table V also presents the crystalline orientation factors of untreated and cyclic load-treated ramie yarns. No distinct change of the crystalline orientation factors can be found between the untreated and treated samples, which agree to the results in the study of Zhang et al.[33] using heat treatment with tension on lyocell fibers and Yamanaka et al.[34] treating ramie fibers by water drawing method. Because ramie yarn is a nonthermoplastic polymer with highly oriented crystals, in cyclic load application, the crystallite cannot be destroyed, and no recrystallization can take place even in high temperature or wet state. Therefore, it is considered that the crystallinity and crystalline orientation of ramie yarns did not improve significantly in this work.

## DISCUSSION

Plant-based natural fibers have spiral structures formed by the microfibrils of the cellulose macromolecules, which can be illustrated schematically as in Figure 6(a). The single fiber, with a diameter of about 10–20 μm, consists of a microfibrillar cellulose phase and a matrix phase (mainly hemicellulose and lignin). The angle between microfibril and fiber axis is regarded as microfibrillar angle, θ. The microfibril, having a diameter of around 10 nm, is made up of 30–100 cellulose molecules, where the crystalline regions are embedded in and continuous with a matrix of noncrystalline parts. The orientation of the molecules is along the microfibrils.

The mechanical properties of plant fibers, such as tensile strength, stiffness, and elongation, are largely dependent on the internal structure and chemical composition of fibers. For instance, higher cellulose content and smaller microfibrillar angle are in gen-

**TABLE IV**
**Tensile Properties of Individual Heat Treated and Wet-Treated Ramie Yarns Without Applying Cyclic Load**

| Specimen type | Fracture load (N) ±SD | Tensile strength (MPa) ±SD | Fracture strain (%) ±SD | Young's modulus (GPa) ±SD |
|---|---|---|---|---|
| HT100-0 | 20.00 ± 1.76 | 449.9 ± 39.6 | 3.63 ± 0.24 | 6.65 ± 2.58 |
| HT150-0 | 19.19 ± 1.97 | 431.8 ± 44.4 | 3.56 ± 0.22 | 6.23 ± 1.54 |
| WT-0 | 20.14 ± 1.95 | 453.1 ± 43.9 | 3.91 ± 0.16 | 5.63 ± 1.85 |

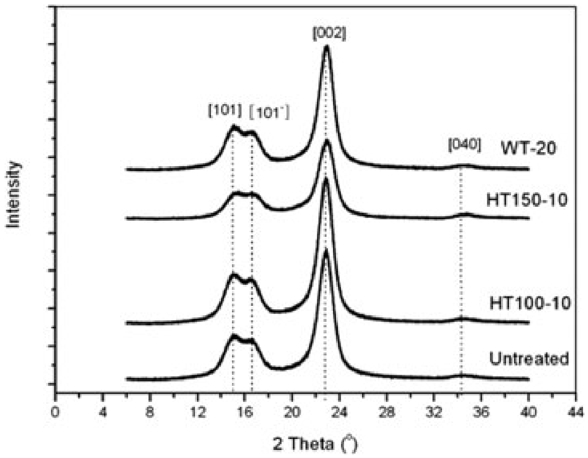

**Figure 5** X-ray diffraction patterns for ramie fibers untreated and cyclic load treated under different conditions (present: untreated; HT100-10; HT150-10; WT-20).

eral correlated to better tensile properties.[35,36] In this study, because the chemical composition of ramie yarns is unaffected by cyclic load treatment, the evolution of tensile properties should be attributed to the changes of internal structural parameters, such as crystallinity, crystalline length as well as orientation with respect to the fiber axis, and so on. According to the reported results, compared to the untreated yarns, the tensile strength of ramie yarns treated by cyclic load had an increase up to 50% and especially Young's modulus of treated yarns were increased as high as twice although the crystallinity and crystal orientation changed little. This is in accordance to with the research work of Zhang et al.[33] and Abe et al.[37] Zhang et al. reported that after heating the lyocell fiber with appropriate tension, an improved mechanical property was achieved, because amorphous orientation was increased sharply. In the study of Abe et al, the increase of tensile modulus of cotton fibers after water-drawing treatment was ascribed to the fact that the molecular chains in amorphous region were extended by water treatment. From these studies, it is suggested that in the case of ramie yarns in this work, the improved tensile properties can be supposed to relate to the general orientation, mainly the part of amorphous orientation.

When a fiber is applied for a cyclic load, in a treatment cycle, the molecular chains of the fiber are extended and reverted under loading and immediately unloading. With repeated loading and unloading in the direction of fiber axis, the deformation can occur by an increase in length of microfibrils and of noncrystalline regions in between, and the molecular chains may be reorganized to orientate toward the direction of the load.[38] Consequently, the microfibrils are expected to extend and incline toward to the fiber axis resulting in a decreased microfibrillar angle, and at the same time, the lengths of amorphous cellulose chains between crystalline regions are oriented and become more nearly uniform, schematically as given in Figure 6(b). It is known that the tensile strength of polymer materials is mainly correlated to the internal stress concentration and defects, especially on the amorphous orientation, rather than the state of crystallites, whereas the modulus is greatly relied on not only the crystallinity but also the orientation. When a tensile force is applied to such a treated yarn, the decreased microfibrillar angle ensures more mircrofibril along the fiber axis to bear the force, and a greater number of chains have to tauten or rupture simultaneously as a result of more evenly strained chains in order for the yarn to break. Therefore, the cyclic load-treated yarns exhibit improved tensile properties.

As described previously, the ramie fiber is composed of cellulose, lignin, hemicellulose, and other impurities (Table I). Because the percentage of lignin and wax in the chemical composition of ramie is very low, their influence on the crystallinity of ramie fiber can be negligible although at high temperature, the lignin with low glass transition temperature could degrade and wax materials would be softened leaving cellular microfibrils. Nevertheless, these reduced bonding agents in cellulose structure could make the microfibrils more easily to be stretched under the axial tension. This can be account for the increased fracture strain of heat-treated ramie yarns without cyclic load treatment (Table IV). As the cyclic load is applied on the high-temperature-treated samples, the molecular chains are rearranged to yield the higher general orientation and microfibrils are tilted and closed to the fiber axis, resulting in an increased tensile strength and Young's moduli.

In the semicrystallized fibers, water is not easy to be accessible in the dense packed crystalline regions, while it is accessible for the amorphous regions composed of tie-molecules, loose chain loops, and ends of macromolecules. When a cellulose fiber absorbs

**TABLE V**
**Crystallinity and Orientation of Ramie Yarns Applied by Cyclic Load Under High Temperature or Wet Condition**

| Specimen type | Crystallinity (%) | Crystalline orientation factor |
|---|---|---|
| Untreated | 77.57 | 97.8 |
| HT100-5 | 80.71 | 97.4 |
| HT100-10 | 81.14 | 97.1 |
| HT100-20 | 81.57 | 96.9 |
| HT150-5 | 75.65 | 98.0 |
| HT150-10 | 75.79 | 98.0 |
| HT150-20 | 73.75 | 98.1 |
| WT-5 | 76.75 | 98.0 |
| WT-10 | 76.44 | 97.9 |
| WT-20 | 76.95 | 97.9 |
| WT-30 | 76.47 | 98.1 |

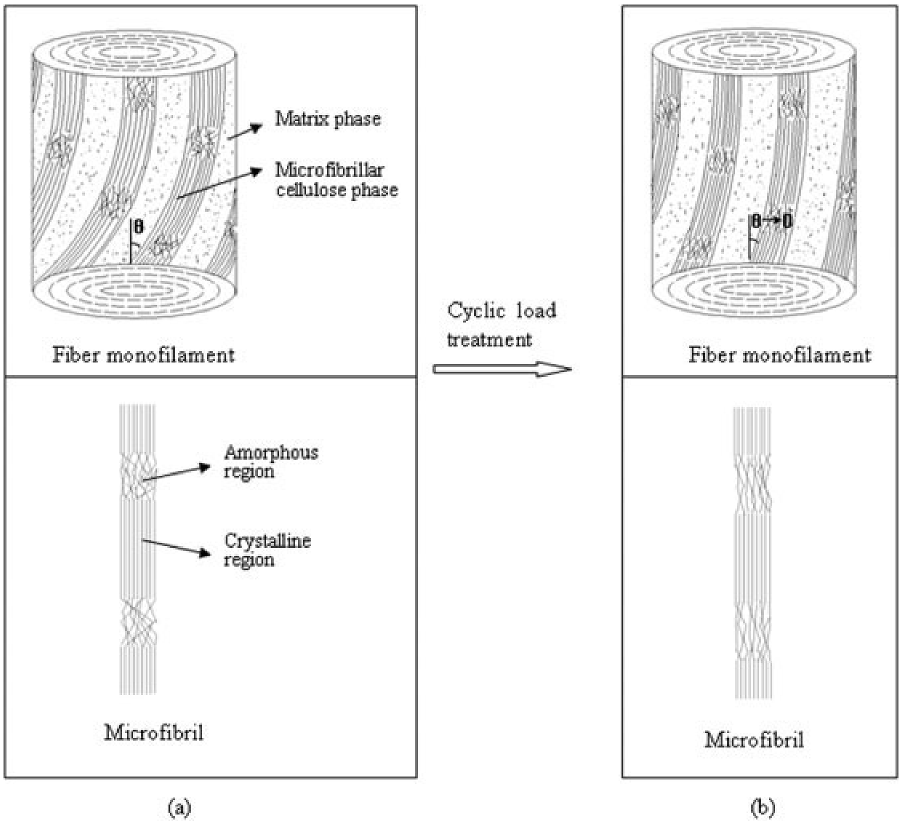

**Figure 6** Schematic representation of a structural change of ramie fiber and microfibril: (a) untreated; (b) cyclic load treated.

water, in the disordered or paracrystalline portions, new hydrogen bonds can be formed by breaking the bond between the primary OH of a glucose unit of one chain and the ring oxygen of another chain.[39] The original regular orderly cellulose structure is destroyed and consequently cellulose molecules are permitted to move more freely away each other without constraints. If applying a force, the relaxed cellulose network can change its shape more easily and most of amorphous chains, such as tortuous long molecular chains and loose chain loops, can be straightened along the fiber axis. During the process of drying off the fiber, water is evaporated and then the original hydrogen bonds opened may have the opportunity to rebuild at new sites, giving an optimized fiber microstructural configuration.

## CONCLUSIONS

A new modification method by applying the proper load with a cyclic form was developed, optimized, and performed on ramie yarns to improve the mechanical properties of natural fibers. The cyclic load application was carried out in three different conditions, namely, high temperature of 100 and 150°C as well as wet state.

Compared to the untreated ramie yarns, the tensile strength of cyclic load-treated yarns was found to have an increase of ~ 19–25% and 18–23% in the high temperature conditions of 100 and 150°C, respectively. The highest increase of around 51% in tensile strength was achieved for yarns treated by cyclic load in wet state with 20 cycles.

As increasing the number of cycles, the increment of the tensile strength of the high-temperature cyclic load-treated groups was rose up to 10 cycles and fell at 20 cycles, while that of the wet cyclic load-treated group was increased till to 20 cycles and then decrease. It is possible that the excess of number of cycles leads to the formation of the new defects and thus deteriorates tensile strength.

Young's modulus of cyclic load-treated ramie yarns that was determined from the stress–strain diagrams indicates a remarkable increase, in a range of about 67–123% higher than the original value of untreated yarns.

To evaluate the role of cyclic load process, individual heat treatment and wet treatment under the same conditions without cyclic load were studied and compared. The results show that yarns only treated by heating or water immersing have no improved tensile strength, and their Young's moduli are greatly lower than those of untreated ones.

An investigation of untreated and treated yarns with XRD technique revealed that no distinct difference in crystallinity was found for cyclic load-treated ramie yarns. Furthermore, the crystalline orientation estimated from the diffraction intensity shows little change between untreated and treated yarns, which implies that the improvement of the mechanical properties may be correlated to a decreased microfibrillar angle and an increased amorphous orientation in fiber microstructure.

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