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ORIGINAL ARTICLE

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Effects of alkali, mild steam, and chitosan treatments on the properties of pineapple, ramie, and sansevieria fiber bundles

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Abstract This study focused on the effects of treatments of alkali, mild steam, and chitosan on the surface morphology, fiber texture, and tensile properties of pineapple, ramie, and sansevieria fiber bundles. The fibers were treated with NaOH (2%), mild steam (0.1 MPa), and chitosan solutions (4% and 8%). The properties of these treated fibers were characterized and compared with the untreated fibers. Field emission scanning electron microscopy (FE-SEM) was used to observe the surface morphology of those fibers. X-Ray diffraction (XRD) spectroscopy was used to observe the fiber textures. Tensile properties of the treated and untreated fibers were also recorded. SEM micrographs showed that the surfaces of the NaOH-treated fibers were more damaged than those of the steam-treated fibers. The 4% chitosan solution covered the fiber surface more uniformly than the 8% chitosan solution. The steam-treated fibers had higher values of degree of crystallinity, crystallite orientation factor, and crystallite size than the NaOH-treated fibers. Ramie fiber showed greater mechanical properties than the other fibers. The values of tensile strength, Young's modulus, and toughness of the steam-treated fibers, which were similar to those of the 4% chitosan-coated fibers, were higher than those for the other treatments.

Key words Plant fiber · Fiber treatments · Morphology · Fiber texture · Tensile properties

Introduction

Plant fibers known to provide good physical properties have been widely used as construction materials, paper, and clothes.[1] The seven nonwood plant fiber bundles were characterized in our previous study.[2] Ramie bast, pineapple leaf, and sansevieria leaf fibers showed great potential in mechanical properties.

Chemical, thermal, and physical treatments have been applied to improve the mechanical properties of fibers.[3–7] The mechanical properties of plant fibers are largely related to the amount of cellulose, which is closely associated with the degree of crystallinity and the crystallite orientation of the fiber with respect to the main fiber axis.[3] The crystalline structure of cellulose can be disrupted by substituting the hydroxyl group with some chemical functionality by alkali treatment.[4]

The steam treatments by explosion process (SEP) and refining process (SRP) have recently been applied to extract plant fibers.[5–7] These processes involve the application of high temperature and pressure on cellulosic materials. The SEP or SRP gives clean fibers but they are still rough and damaged on the surface. In this research, the mild steam process with low temperature and pressure was used to obtain clean fibers with smooth surfaces and increased degree of crystallinity.

Chitosan is a deacetylated product from chitin, which is a naturally occurring polysaccharide that is available in large amounts from the epidermis of crustaceans such as crabs and shrimps. In recent years, a number of investigations have been carried out to exploit the potential applications of chitosan. Umemura et al.[8] found that the chitosan developed excellent bonding properties in three-ply plywoods. Liu et al.[1] and Hsieh et al.[9] found that cotton fiber and woolen fabrics coated with a small concentration (~2%–3%) of chitosan did not improve their mechanical properties. However, the investigations of chitosan-coated plant fibers have not been fully exploited.

In this study, the fibers were treated with alkali, mild steam, and chitosan to obtain high performance in terms of the mechanical properties. The properties of each of the treated fibers were characterized to identify the appropriate natural fibers for use in composite products.

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Materials and methods

Materials

Three decorticated nonwood plant fiber bundles, that is, pineapple [*Ananas comosus* (L.) Merr] leaf fiber, sansevieria [*Sansevieria trifasciata* Prain] leaf fiber from Subang, West Java, Indonesia, and ramie [*Boehmeria nivea* (L.) Gaudich] bast fiber from Wonosobo, Central Java, Indonesia, were used as raw materials. The samples were air-dried to a moisture content of 6% to 8%.

Chitosan powder with average molecular weight of 35000 from Kimica (Japan), NaOH pellets (98%), and acetic acid (99.7%) from Nakarai (Japan) were purchased and used for fiber treatments.

Alkali treatment

The fibers were immersed in a NaOH solution of 2% (w/v) at 95°C in a covered bath for 2 h. The ratio of solution to fibers was 100:1 (v/w). The treated fibers were then rinsed with distilled water, neutralized with 2% acetic acid, rinsed again with distilled water until neutral, and dried at 50°C in a vacuum oven.

Mild steam treatment

The fibers were steamed by using boiling water in a screen-covered bath at a steam pressure of about 0.1 MPa for 2 h. The fibers were then dried at 50°C in a vacuum oven.

Chitosan treatment

The 4% and 8% chitosan solutions were prepared by stirring chitosan powder in 1% acetic acid solution (w/v). The fibers were immersed in chitosan solution at room temperature for 2 h. The ratio of solution to fibers was 100:1 (v/w). The resulting fiber threads were air-dried for 5 days. The viscosities of the 4% and 8% chitosan solutions were 247 and 9344 mPa.s, respectively, as measured using a rotational viscometer.

Weight change

The weight changes of fibers treated with alkali, mild steam, and chitosan were determined by measuring the difference in weight of the samples before and after the treatments. The air-dry samples were weighed before treatments. After the treatments, the samples were conditioned at 20°C and 65% relative humidity (RH) for 1 week and weighed again. The treated fibers had moisture content values of 7%–9%, which is similar to untreated fibers.

Table 1. Measurement conditions for X-ray diffraction

Parameter	Value
X-Ray	Ni filter CuKα
Accelerating voltage	40 kV
Accelerating current	200 mA
Diversion slit	1 degree
Scattering slit	1 degree
Receiving slit	0.3 mm
Scanning speed	1 degree/min

Morphological observation

The untreated and treated fibers were observed using field emission scanning electron microscopy (FE-SEM; Jeol JSM 6700F). The samples were covered with a thin layer of platinum using a Jeol JFC-1600 coater before observation. The observation was performed in electron mode at a beam current of 10 μA and an accelerating voltage of 1.5 kV.

Degree of crystallinity, Herman's crystallite orientation factors, and crystallite size

A Rigaku RAD II C system on Ultrax 18 with a symmetrical transmission mode was used. The measurement conditions were kept constant as shown in Table 1.

Powder diffraction was adopted for investigating the crystallinity and crystallite size. The untreated, alkali-treated, and steam-treated fibers were cut into lengths of less than 1 mm and then pressed into pellets of 2 cm in diameter. A 2θ scan of 5° to 45° was used. The degree of crystallinity (DC) was calculated by the ratio of the area in a diffractogram corresponding to the crystalline region to that of both crystalline (F_c) and amorphous regions (F_a).[10,11]

$$\mathrm{DC} = \frac{F_c}{F_c + F_a} \tag{1}$$

The diffraction curves were corrected by air-scattering diagram.

The meridianal (004) reflection was selected for determination of the crystallite orientation. The untreated, alkali-treated, and steam-treated fibers were rolled on a stainless steel wire frame (Fig. 1). The orientation patterns were obtained by keeping 2θ fixed (34.6°) and rotating the sample through 360° along the normal direction of the sample surface. The value of Herman's crystallite orientation factor (f_c) was determined from the following equation:[12–14]

$$f_c = 1/2(3 < \cos^2\phi > - 1) \tag{2}$$

where

$$< \cos^2\phi > = \frac{\int_0^{\pi/2} I(\phi)\cos^2\phi \sin\phi d\phi}{\int_0^{\pi/2} I(\phi)\sin\phi d\phi} \tag{3}$$

ϕ is the polar angle against the longitudinal direction of fiber and I (ϕ) represents the measurement of X-ray intensity.

The crystallite size [$L(hkl)$] was calculated by Scherrer's equation (Eq. 4), where $K = 0.9$ and $d(2\theta)$ is the half width for the diffraction peak in radians. θ is the diffraction angle.[13,14]

$$L(hkl) = \frac{1}{\beta} = \frac{K\lambda}{\cos\theta d(2\theta)} \quad (4)$$

Tensile test

According to our previous research,[2] the fiber bundles were glued to paper frames with a 10-mm gauge length. The total number of test specimens was in the range of 55 to 59 for each species and cut into lengths of 20–25 mm. Then the diameters of each specimen at five randomly selected locations were measured using an optical microscope (Micro Square DS3USV).

Prior to mechanical testing, fiber specimens were conditioned at 60% relative humidity and 20°C for 1 week. The moisture content of fiber specimens after conditioning varied from 6% to 9%. The mechanical properties of fibers were determined by using an Instron model 4411 test machine with a cross-head speed of 1 mm/min. The specimens that fractured at the end of the paper frame or near the grip were excluded from subsequent data analysis.

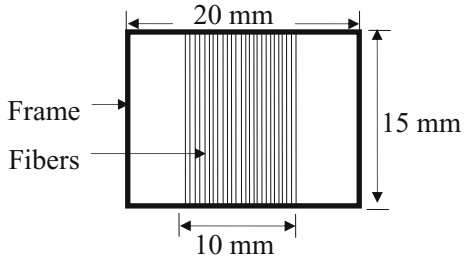

Fig. 1. Crystallite orientation specimen

Statistical analysis

Data obtained from the mechanical measurement were statistically evaluated using analysis of variance.

Results and discussion

Physical properties

Table 2 shows the weight change and diameter of untreated and treated fibers. Results showed that the diameters of fibers were increased by chitosan treatments and slightly decreased by alkali and steam treatments, except for pineapple fiber. The diameter of Sc8 showed an increment of 28% in comparison with S, whereas Rd decreased by 33% when comparing with R (see Table 2 for definition of sample notation).

The fiber weights were changed by all treatments. The weight of fiber decreased after alkali and steam treatments. The weight of Pd, Sd, and Rd showed decreases of 28.9%, 23.4%, and 21.5%, respectively. Rs, Ss, and Ps showed decreases of 10.1%, 6.0%, and 4.8%, respectively. On the other hand, the weight of fiber was increased by chitosan treatment within the range of 6.7%–12.9% depending on the chitosan concentrations.

The increased diameter and weight of fibers after chitosan treatment are caused by the chitosan solution effectively coating the surface of the fibers. Liu et al.[1] mentioned that the chemical reaction between the amino group of chitosan and the hydroxyl group of cellulose occurred on the treated fibers. The decreased diameter and weight of fiber after alkali and steam treatments are caused by the

Table 2. Physical and texture properties of the untreated and treated nonwood plant fiber bundles

Fibers	Diameter among specimens (μm)	Weight change (%)	Degree of crystallinity (%)	Crystallite orientation factor	Crystallite size (Å)
P	40.3 ± 6.1		63.7	0.134	34.6
Pd	41.5 ± 5.1	–28.9 ± 6.3	57.9	0.083	29.8
Ps	44.9 ± 7.0	–4.8 ± 1.3	65.6	0.171	37.5
Pc4	49.6 ± 9.2	+7.1 ± 2.1	–	–	–
Pc8	45.9 ± 9.4	+11.1 ± 3.5	–	–	–
R	39.8 ± 8.6		74.6	0.210	35.2
Rd	26.5 ± 6.6	–21.5 ± 5.4	68.5	0.199	30.7
Rs	39.7 ± 9.7	–10.1 ± 3.1	77.0	0.231	37.9
Rc4	42.1 ± 8.3	+6.7 ± 1.5	–	–	–
Rc8	49.7 ± 4.8	+9.1 ± 2.9	–	–	–
S	92.1 ± 8.4		55.9	0.090	25.9
Sd	82.8 ± 6.1	–23.4 ± 5.9	57.1	0.125	27.3
Ss	79.3 ± 7.1	–6.0 ± 1.7	57.7	0.180	30.1
Sc4	114.9 ± 9.6	+10.7 ± 2.8	–	–	–
Sc8	118.5 ± 8.0	+12.9 ± 3.5	–	–	–

Diameter and weight change data are given as averages and 95% confidence interval
P, Untreated pineapple; Pc4, 4% chitosan-coated pineapple; Pc8, 8% chitosan-coated pineapple; Pd, 2% NaOH-treated pineapple; Ps, steam-treated pineapple; R, untreated ramie; Rc4, 4% chitosan-coated ramie; Rc8, 8% chitosan-coated ramie; Rd, 2% NaOH-treated ramie; Rs, steam-treated ramie; S, untreated sansevieria; Sc4, 4% chitosan-coated sansevieria; Sc8, 8% chitosan-coated sansevieria; Sd, 2% NaOH-treated sansevieria; Ss, steam-treated sansevieria

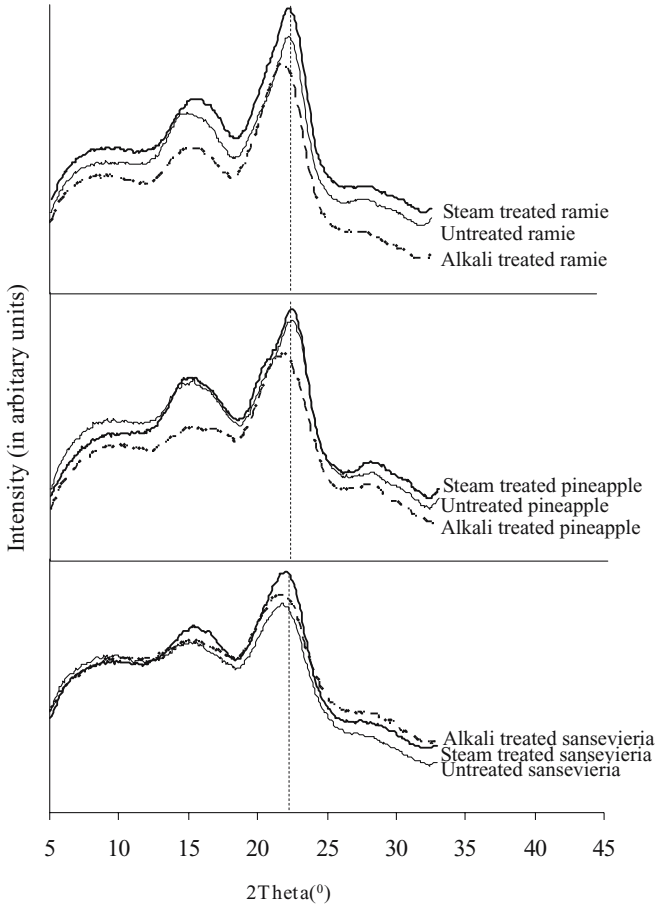

Fig. 2. X-Ray diffraction diagrams of untreated and treated fibers

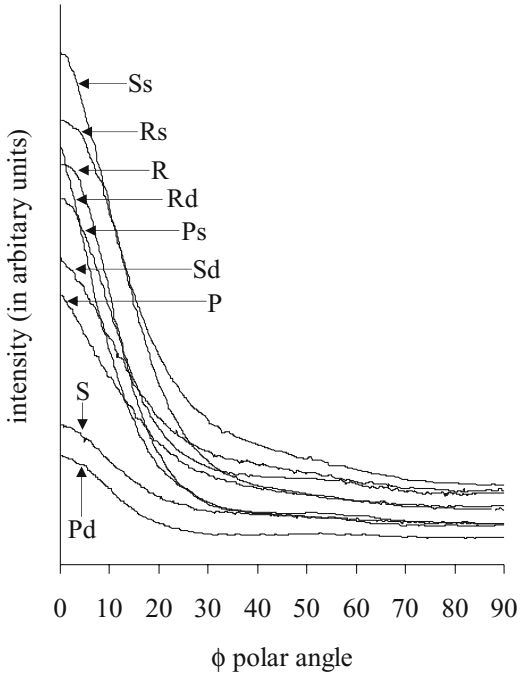

Fig. 3. Orientation distributions of cellulose crystallite in the fiber samples. *P*, Untreated pineapple; *Pd*, 2% NaOH-treated pineapple; *Ps*, steam-treated pineapple; *R*, untreated ramie; *Rd*, 2% NaOH-treated ramie; *Rs*, steam-treated ramie; *S*, untreated sansevieria; *Sd*, 2% NaOH-treated sansevieria; *Ss*, steam-treated sansevieria

chemical and thermal treatment effectively removing some components (lignin, wax, and oils) from the surface of the fibers. Gomes et al.[15] found that alkali treatment brought about a reduction in lignin and decreased the weight and diameter of the fiber.

X-Ray diffraction investigation

The textures of untreated, alkali-treated, and steam-treated fibers were investigated by an X-ray diffraction (XRD) technique. The XRD diagrams of the various treated fibers are shown in Fig. 2. The degree of crystallinity, crystallite orientation factor, and crystallite size of untreated and treated fibers are shown in Table 2.

The changes of the XRD diagrams of fibers at $2\theta = 22.5°$ were assigned to the [200] lattice plane of cellulose. The alkali and steam treatments of all fibers resulted in diffraction diagrams that were similar to those of the untreated fibers. Therefore, the alkali and steam treatments had no effect on the transformation of the cellulose crystal structure transition.

In natural cellulose fibers, the intermediate regions in the ordered structure play an important role in the determination of the degree of crystallinity. With the higher concentration of NaOH, the intermediate regions gradually become disordered.[16,17]

In Table 2, the untreated S and R showed low and high degrees of crystallinity of 55.9% and 74.6%, respectively. A similar degree of crystallinity for ramie and pineapple fibers were also found in other research.[18–21] For the treated fibers, Sd and Rs showed low and high degrees of crystallinity of 55.1% and 77.0%, respectively. Other researchers[18–21] found simi-lar degrees of crystallinity for alkali-treated ramie and pineapple fibers. However, the degree of crystallinity of the steam-treated S and P have not been investigated before.

For sample R, the fiber after steam treatment showed higher degrees of crystallinity than those obtained with untreated and alkali-treated samples. The degree of crystallinity of R and P decreased slightly, and that of S increased after alkali treatment. Zhou et al.[20] found different results for the crystallinity of alkali treatment. Their results showed that the crystallinity of the fiber treated with NaOH for 10 min at 25°C increased with NaOH concentration for concentration up to 8%.

Fiber orientation was determined in terms of the crystalline region with the result shown in Table 2. Figure 3 shows orientation distributions of cellulose crystallite in the fiber samples. The orientation distributions of steam-treated fiber were sharper than for untreated and alkali-treated fiber. The steam treatment for all fiber provided higher values of f_c than untreated and alkali-treated fibers. The maximum and minimum values of f_c were obtained for Rs and Pd, respectively. Zhou et al.[20] found that the crystallite orientation decreased with increasing NaOH concentration on treated ramie.

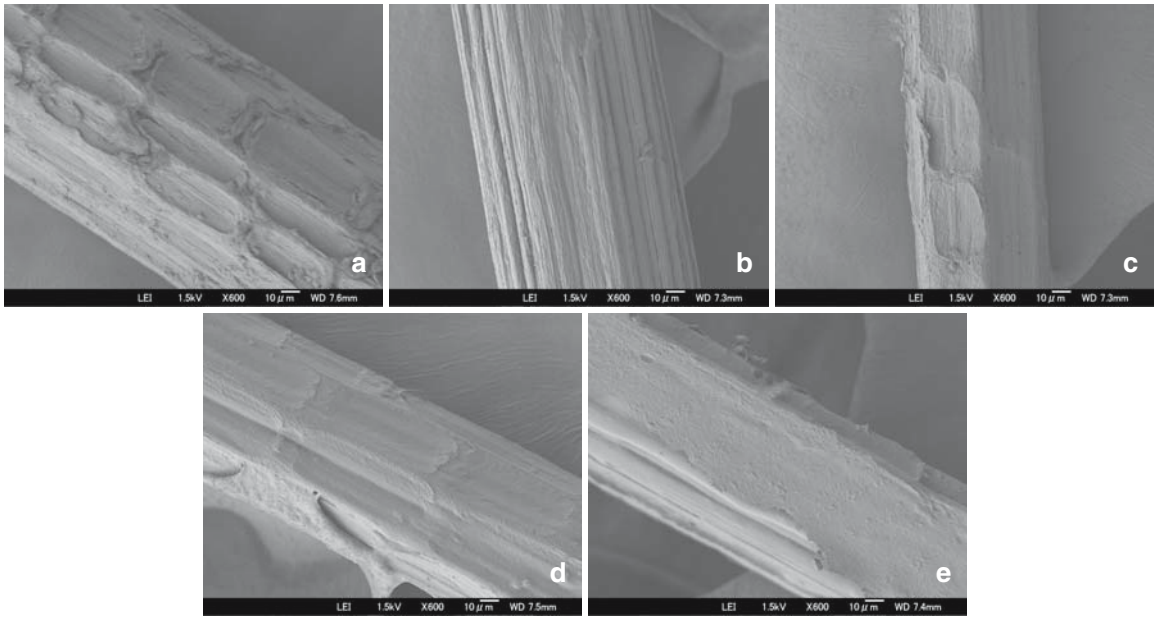

Fig. 4a–e. Scanning electron micrographs of surface morphology of sansevieria fiber. **a** Untreated sansevieria, **b** 2% NaOH-treated sansevieria, **c** steam-treated sansevieria, **d** 4% chitosan-coated sansevieria, **e** 8% chitosan-coated sansevieria. *Bars* 10 μm

Table 2 also shows the lateral size of the crystallite calculated from the diffraction of the [200] lattice plane. It was observed that the steam treatment for all fibers gave slightly higher values of $L(hkl)$ than untreated and alkali-treated fibers. The maximum and minimum values of crystallite size were 37.9 and 25.9 Å for Rs and S, respectively. Hindeleh and Johnson[14] found the crystallite size of ramie fiber was 32.1 Å.

Morphological characteristics

Surface morphology of each fiber was observed using FE-SEM. Figure 4 shows SEM micrographs of the surface of untreated and treated S, as representative of other fibers. The observation of the fiber surface revealed that the fibers were bundles of aggregated monofilaments. The alkali-treated fiber (Fig. 4b) looked cleaner than the others, and fiber bundles were more separated, with a highly serrated surface. This finding proves with certainty that the treated fiber changed into a porous bundle structure. Mohanty et al.[4] mentioned that alkali treatment removes a certain amount of lignin, wax, and oils covering the external surface of the fibers. The existence of lignin on the untreated fiber gives it a rougher surface than that of alkali-treated fiber.

On the other hand, Fig. 4c shows that the fibers after steam treatment have not drastically changed compared with untreated fiber. Nevertheless, the surface of steam-treated fiber was slightly smoother than untreated fiber, and any surface material that may have been present (lignin, wax, or oils) was probably removed. As the pictures show, the monofilaments of the steam-treated fiber was visible.

Figure 4d, e shows the surfaces of fibers coated with 4% and 8% chitosan solutions. The surface conditions of chitosan-coated fibers did not drastically change and were similar to those of steam-treated fiber. The 4% chitosan treatment gave more uniform coverage on the fiber surfaces than the 8% chitosan treatment. The reason for this difference was thought to be that the 4% chitosan solution had a lower viscosity than the 8% solution.

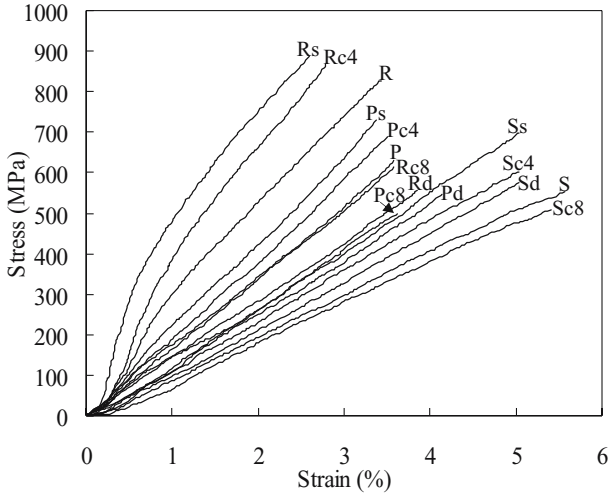

Fig. 5. Typical stress–strain curves for untreated and treated fibers. *Pc4*, 4% chitosan-coated pineapple; *Pc8*, 8% chitosan-coated pineapple; *Rc4*, 4% chitosan-coated ramie; *Rc8*, 8% chitosan-coated ramie; *Sc4*, 4% chitosan-coated sansevieria; *Sc8*, 8% chitosan-coated sansevieria

Tensile properties

Typical stress–strain curves of untreated and treated fibers obtained during tensile testing are shown in Fig. 5. Slopes

Table 3. Mechanical properties of the untreated and treated nonwood plant fiber bundles

Fibers	Strain (%)	Tensile strength (MPa)	Young's modulus (GPa)	Toughness (MPa)
P	3.7 ± 0.7	635 ± 143 b	24.6 ± 5.8 a	9.9 ± 3.3 a
Pd	4.3 ± 0.7	548 ± 141 a	23.9 ± 0.7 a	9.9 ± 3.0 a
Ps	3.3 ± 0.6	729 ± 171 c	35.5 ± 1.1 b	14.9 ± 4.1 b
Pc4	3.5 ± 0.5	689 ± 170 bc	39.1 ± 1.2 b	13.2 ± 3.9 b
Pc8	3.8 ± 0.9	502 ± 92 a	26.4 ± 0.8 a	10.0 ± 2.9 a
R	3.4 ± 0.4	830 ± 174 b	43.4 ± 1.6 b	16.4 ± 3.0 b
Rd	3.9 ± 0.7	554 ± 127 a	21.3 ± 0.7 a	13.6 ± 3.0 a
Rs	2.6 ± 0.5	892 ± 163 b	76.5 ± 1.6 d	19.5 ± 2.9 c
Rc4	2.8 ± 0.3	875 ± 141 b	62.4 ± 1.4 c	18.7 ± 2.6 c
Rc8	3.5 ± 0.7	610 ± 138 a	26.7 ± 1.1 a	15.2 ± 3.0 b
S	5.3 ± 1.0	560 ± 99 b	13.6 ± 0.2 b	12.6 ± 2.3 b
Sd	5.0 ± 0.9	577 ± 82 b	13.3 ± 0.2 b	12.9 ± 2.2 b
Ss	5.0 ± 1.0	697 ± 86 c	18.4 ± 0.2 d	14.8 ± 2.2 c
Sc4	5.0 ± 0.8	601 ± 86 b	15.7 ± 0.2 c	15.0 ± 2.3 c
Sc8	5.4 ± 0.9	510 ± 100 a	11.9 ± 0.2 a	10.7 ± 2.0 a

Diameter data are given as averages and 95% confidence interval
Values in the same column in each fiber with different letters are significantly different by Tukey's test ($P < 0.05$)

of stress–strain curves of all fibers treated with steam and 4% chitosan were higher than those for untreated fibers, while the slopes of the stress–strain curves of all fibers treated with alkali and 8% chitosan were lower than those for untreated fibers. The curves showed some plastic deformation until breakage in all fibers. The fracture strain of the fiber increased slightly after treatment with alkali, and 8% chitosan solution and decreased after treatments with steam and 4% chitosan solution. The tensile strength and Young's modulus of Rs were higher than those of other fibers. High toughness values were obtained for Rs (19.5 MPa) and Rc4 (18.7 MPa).

The mechanical properties of untreated and treated fibers are shown in Fig. 6 and Table 3. Rs provided higher values of the average tensile strength and Young's modulus than other fibers (892 MPa and 76.5 GPa, respectively). The lowest tensile strength and Young's modulus were for Sc8 (510 MPa and 11.9 GPa, respectively). The tensile strength of Rs is higher than that of nylon (75 MPa), polypropylene (80 MPa), aluminum (200 MPa), and steel (760 MPa), but lower than spider silk (1200 MPa). In addition, the Young's modulus of Rs was higher than polypropylene (2 GPa), polyethylene (2.5 GPa), polystyrene (3.5 GPa), and aluminum (70 GPa), but lower than Kevlar 49 (127 GPa).[22,23] Analysis of variance showed that the differences in the tensile strength and Young's modulus of the fibers were significant ($P < 0.05$). Therefore, the steam treatment improves the tensile properties of fibers.

The large confidence interval (Table 2) indicates the large variation in the mechanical properties of fibers, which is often observed for natural fibers as found in our previous study and by other authors.[2,24–26] Plots of mechanical properties versus diameter of the fiber specimens are presented in Fig. 6 and help to evaluate the large variation in the mechanical properties. The plots show a decreasing tendency in the tensile strength and Young's modulus with increasing diameter of the untreated and treated fibers. Similar relation-

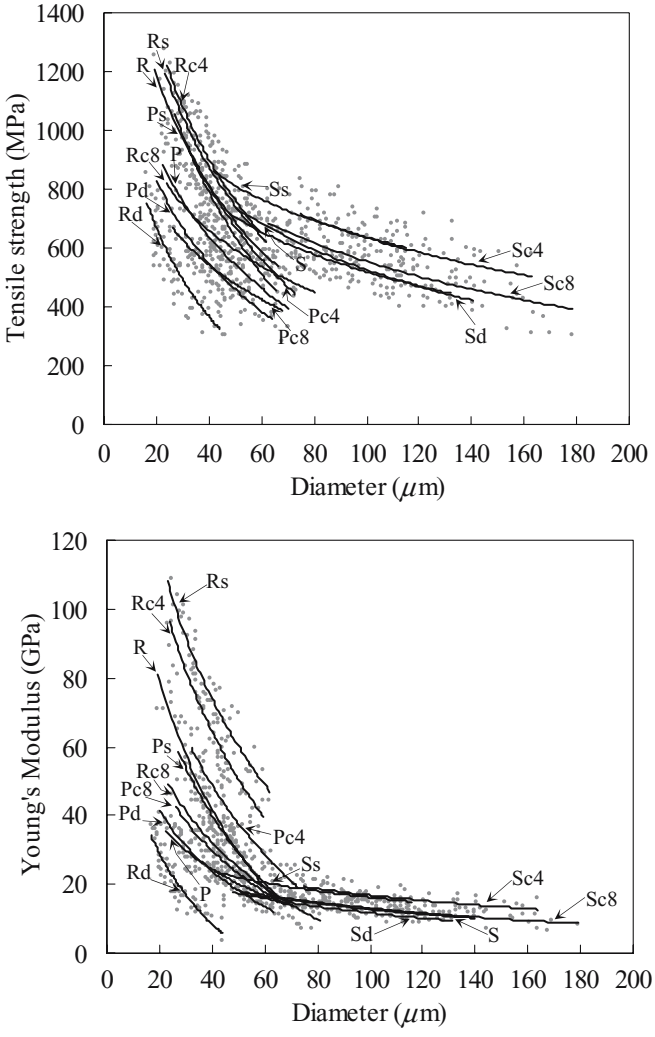

Fig. 6. Relationships between diameter and tensile strength (*top*) and Young's modulus (*bottom*) for untreated and treated fibers

ships were found in our previous study on untreated fibers and by other authors.[2,27,28] Rs, Rc4, and R samples with a narrow range of diameters showed a higher distribution of values for the tensile strength and Young's modulus than other fibers. The mild steam and 4% chitosan treatments improved the tensile properties of untreated fibers.

The decreases in tensile strength and Young's modulus of alkali-treated fibers were probably due to the decrease in the degree of crystallinity and crystallite orientation. During alkali treatment for 2h at high temperature (95°C), some materials (lignin, wax, oil) were removed from the surface of the fibers, and the fiber monofilaments become visible (Fig. 4b). In addition, high water absorption causes the swelling of cellulose fibers, resulting in poor mechanical properties.[3,5,20] Thus, the degrees of crystallinity and crystallite orientation of alkali-treated fibers were lower than others. This fact also may attribute to fiber damage.

Other researchers found that the tensile strengths of ramie and jute fiber were decreased with decreasing degree of crystallinity and crystallite orientation order.[14,16,17] Mohanty et al.[4] mentioned that high temperature, high alkali concentration, and high water absorption may depolymerize the native cellulose and delignify the fiber excessively, which can adversely affect the strength of the fiber.

The decreases in tensile strength and Young's modulus also occurred in the fibers coated with 8% chitosan solution. The reason seemed to be that the diameter of 8% chitosan-coated fibers was higher than other fibers with similar load values, which caused the tensile properties to be inferior to the others. In addition, the 8% chitosan solution, which has high viscosity, did not uniformly cover the surface of the fiber (Fig. 4e), and the fiber became slightly more rigid, making it easier to fracture during tensile test.

On the other hand, the increases in tensile strength and Young's modulus of steam-treated fibers were probably due to the increases in degree of crystallinity, crystallite orientation order, and crystallite size (Table 2). As shown in Fig. 4c, the fiber surface structure had not changed, while some materials (lignin, wax, oils) were removed, and the monofilament of the steam-treated fiber became visible. The increases in tensile strength and Young's modulus also occurred for the 4% chitosan-coated fibers. The reason appeared to be that 4% chitosan solution with its low viscosity had uniformly covered the surface of the fibers (Fig. 4d), and the solution was to interact easily with the fibers.

Research on the chitosan-coated plant fibers has not been fully exploited. Liu et al.[1] found that the low concentration (1%–2%) of chitosan solution did not improve the mechanical properties of oxidized cotton fiber. Bangyekan et al.[29] found that the tensile stress of chitosan film increases with the concentration of the chitosan solution. They also found that for the chitosan-coated cassava starch films, the tensile strengths of films increased only slightly with chitosan concentration up to a concentration of 2%, but that the strength observed with 4% chitosan solution was twice that observed for 2% chitosan solution. It can be concluded that 4% chitosan films or coated fibers, also used in our experiment, provided higher tensile properties than 2% chitosan solution.

Conclusions

The physical, morphological, and mechanical properties of untreated fibers and those treated with NaOH, mild steam, and chitosan solutions were characterized. SEM micrographs showed that the surface of NaOH-treated fiber was damaged. The 4% chitosan solution covered the fiber surfaces more uniformly than the 8% chitosan solution. The values of degree of crystallinity, crystallite orientation factor, and crystallite size of steam-treated fibers were higher than untreated fibers and NaOH-treated fibers. The values of tensile strength, Young's modulus, and toughness of the steam-treated fibers were similar to those of 4% chitosan-coated fibers, but were higher than those of the untreated fibers, the 8% chitosan-coated fibers, and the NaOH-treated fibers. The tensile properties of fibers showed a decreasing tendency with increasing fiber diameter. Ramie fiber shows higher mechanical properties than other fibers. The mild steam treatment was found to be an effective method to enhance mechanical properties of fibers that can be used for high-performance plant fiber composites.

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References

1. Liu XD, Nishi N, Tokura S, Sakairi N (2001) Chitosan coated cotton fiber: preparation and physical properties. Carbohydr Polym 44:233–238
2. Munawar SS, Umemura K, Kawai S (2006) Characterization of the morphological, physical and mechanical properties of seven nonwood plant fiber bundles. J Wood Sci 53:108–113
3. Mwaikambo LY, Ansell MP (1999) The effect of chemical treatment on the properties of hemp, sisal, jute and kapok for composite reinforcement. Die Ang Makro Chem 272:108–116
4. Mohanty AK, Misra M, Drzal LT (2001) Surface modification of natural fibers and performance of the resulting biocomposites: an overview. Compos Interfac 8:313–343
5. Mwaikambo LY, Ansell MP (2002) Chemical modification of hemp, sisal, jute and kapok fibers by alkalization. J Appl Polym Sci 84:2222–2234
6. Han G, Umemura K, Zhang M, Honda T, Kawai S (2001) Development of high-performance UF-bonded reed and wheat straw medium-density fiberboard. J Wood Sci 47:350–355
7. Xu J, Widyorini R, Yamauchi H, Kawai S (2006) Development of binderless fiberboard from kenaf core. J Wood Sci 52:236–243
8. Umemura K, Inoue A, Kawai S (2003) Development of new natural polymer-based wood adhesives I: dry bond strength and water resistance of konjac glucomannan, chitosan, and their composites. J Wood Sci 49:221–226
9. Hsieh SH, Huang ZK, Huang ZZ, Tseng ZS (2004) Antimicrobial and physical properties of woolen fabrics cured with citric acid and chitosan. J Appl Polym Sci 94:1999–2007
10. Dwianto W, Norimoto M, Morooka T, Tanaka F, Inoue M, Liu Y (1998) Radial compression of sugi wood. Holz Roh Werkst 56:403–411
11. Jayme VG, Knolle H (1964) The empirical X-ray determination of the degree of crystallinity of cellulosic material (in German). Das Papier 18:249–255
12. Sen RK, Chowdhury SK (1957) The crystalline orientation in different varieties of jute fibers of known strength. Text Res J 27:193–195

13. Tanaka F (1985) Orientation and texture of cellulose crystallite in *Pinus desinflora* wood. Doctoral Thesis, Kyoto University
14. Hindeleh AM, Johnson DJ (1972) Crystallinity and crystallite size measurement in cellulose fibers: 1. ramie and fortisan. Polymer 13:423–430
15. Gomes A, Goda K, Ohgi J (2004) Effects of alkali treatment to reinforcement on tensile properties of curaua fiber green composites. JSME Int J 47:541–546
16. Ray PK, Bandyopadhyay SB (1975) Some observations on the concept of the degree of crystallinity in cellulose fibers with reference to moisture effects. J Appl Polym Sci 19:729–733
17. Chidambareswaran PK (1976) Order in cellulose fibers. J Appl Polym Sci 20:2297–2298
18. Ray PK, Bag SC, Chakravarty AC (1975) The influence of gum on the crystalline structure in ramie fiber. J Appl Polym Sci 19: 999–1004
19. Isikawa A, Okano T, Sugiyama J (1997) Fine structure and tensile properties of ramie fibers in the crystalline form of cellulose I, II, III_I and IV_I. Polymer 38:463–468
20. Zhou LM, Yeung KW, Yuen CWM, Zhou X (2004) Characterization of ramie yarn treated with sodium hydroxide and crosslinked by 1,2,3,4-butanetetra-carboxylic acid. J Appl Polym Sci 91: 1857–1864
21. Saha SC, Ray PK, Pandey SN, Goswani K (1991) IR and X-ray diffraction studies of raw and chemically treated pineapple leaf fiber (PALF). J Appl Polym Sci 42:2767–2772
22. Hawatson AM, Lund PG, Todd JD (1992) Engineering tables and data. Kluwer, London, p 41
23. Mwaikambo LY, Ansell MP (2006) Mechanical properties of alkali treated plant fibers and their potential as reinforcement materials. I. Hemp fibres. J Mater Sci 41:2483–2496
24. Pickering KL, Abdella A, Ji C, McDonald AG, Franich RA (2003) The effect of silane coupling agents on radiata pine fiber for use in thermoplastic matrix composite. Compos Part A Appl Sci 34:915–926
25. Hornsby PR, Hinrichsen E, Trivedi K (1997) Preparation and properties of polypropylene composites reinforced with wheat and flax straw fibers. Part II. Analysis of composite microstructure and mechanical properties. J Mater Sci 32:1009–1015
26. Shibata M, Takachiyo K, Ozawa K, Yosomiya R, Takeishi H (2002) Biodegradable polyester composites reinforced with short abaca fiber. J Appl Polym Sci 85:129–138
27. Baley C (2002) Analysis of the flax fibers tensile behaviour and analysis of the tensile stiffness increase. Compos Part A Appl Sci 33:939–948
28. Zhang M, Kawai S, Sasaki H (1994) Production and properties of composite fiberboard I. Influence of mixing ratio of jute/wood fiber on the properties of boards. Mokuzai Gakkaishi 40:816–823
29. Bangyekan C, Aht-ong D, Srikulkit K (2006) Preparation and properties evaluation of chitosan coated cassava starch films. Carbohydr Polym 63:61–71