

Study of moso bamboo's permeability and mechanical properties

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In this article, moso bamboo blocks were first treated with hydrochloric acid solvents with different concentrations or microwave treatments with various microwave output power and treatment durations. The results showed that the crystalliferous region of cellulose of moso bamboo blocks formed porous or swelling type structures under hydrochloric acid pretreatment conditions; the mechanical strength of the moso bamboo decreased when the percentage of hydrochloric acid pretreatment solvents increased from 0 to 3%. When the moso bamboo blocks were treated with microwave, the internal water was transformed into steam, and the water vapor destroyed the cell walls of the vessel, sieve tube, and parenchyma cells in the moso bamboo block, resulting in a significant improvement in the permeability of moso bamboo. In order to ensure that the moso bamboo samples did not burn by microwave heating, the samples had to be immersed in water. The process of water gasification inside the Moso bamboo was not violent. Therefore, the mechanical strength of the moso bamboo had decreased only slightly, and a weak relationship was found between the mechanical strength of the moso bamboo samples and the microwave treatment durations.

1. Introduction

There are more than 1200–1500 species of bamboo in the world, and 90% of the bamboo in Asia are found in Southeast Asia.¹ Moso bamboo (*Phyllostachys pubescens mazeri* ex H. de Lebaie) accounts for ~70% of the total bamboo forest.² With the advancement of science and technology and the tight supply of timber, the bamboo industry has been developing rapidly in China since the 1990s. Now, many new methods are required for the processing of bamboo to make it durable, inexpensive and usable. Therefore, detailed studies are needed to aid and promote its application in the modern world.^{3–6}

As is well known, the cellulose in mature moso bamboo is ~40–60%; the hydroxyl groups in cellulose molecules could easily lead to the formation of hydrogen bonds between the oxygen-containing groups. These hydrogen bonds combine to make many cellulose molecules forming a crystalline structure. Because about

two-thirds of the cellulose is distributed in the outer region of the green moso bamboo, this region has excellent physical and mechanical properties.^{7,8} In previous studies, we found that the composite materials, made of the moso bamboo green blocks, were unable to achieve satisfactory bond quality.⁹ The poor bond quality was caused by two problems. The primary reason for this problem is that the distribution of the main tissue system (the vessel, sieve tube, and parenchyma cells) in moso bamboo is longitudinal, with no horizontal transmission systems.¹⁰ According to the theory of mechanical adhesion, the adhesive that is spread on the moso bamboo block surface enters exposed pores (cell cavities), where it is solidified and anchored.¹¹ Because the glue surface of bamboo lamination usually occurs in the horizontal direction of bamboo blocks, and the moso bamboo blocks have no horizontal transmission system (cell cavities), the bond quality is poor. The outer sections of moso bamboo green blocks have poor wettability of the adhesive to each other. It is difficult for

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the adhesive to spread well on the moso bamboo block surface. Low permeability of bamboo blocks causes many problems during moso bamboo manufacturing. Impregnating low permeability moso bamboo blocks with preservatives or resins is extremely difficult. Thus, in this study, moso bamboo blocks were first treated with hydrochloric acid solvents with different concentrations or microwave treatment with different microwave output power and varying treatment durations; and then, the rates of water absorption and water loss were quantified. The objective of this study was to evaluate the effects of hydrochloric acid and microwave treatments on the permeability and mechanical properties of the moso bamboo blocks.

2. Experimental

2.1 Materials

Mature moso bamboo samples were collected from Franklinton, Louisiana, USA. Bamboo blocks, of 80mm (length) × 20mm (width) × 5mm (thickness), for hydrochloric acid treatment and microwave tests, 12 specimens per concentration of hydrochloric acid and microwave tests, of which half with knots and half without knots, were obtained. The mechanical properties of the bamboo specimens were quantified in accordance with GB/T 15780-1995 (Testing methods for physical and mechanical properties of bamboos).

2.2 Methods

2.2.1 Hydrochloric acid and microwave treatment method – application to moso bamboo samples

In this study, moso bamboo samples were first treated with seven levels of hydrochloric acid solvents (0, 0.5, 1.0, 1.5, 2.0, 2.5, and 3.0%) for 3 hours. The treatment temperature was 100 °C. All acid-treated bamboo samples were cleaned in cold distilled water. Before the experiment began in the microwave, the bamboo samples were immersed in water until equilibrium of water absorption was attained, and then, the samples were treated with microwave at various output powers (0, 200, 400, 600, 800, 1000, and 1200W) and different treatment durations (0, 2, 4, 6, 8, and 10 minutes). In order to ensure that the moso bamboo samples did not burn during microwave heating, the samples were immersed in water during the microwave irradiation process. After completing the hydrochloric acid and microwave treatments, moso bamboo blocks were kept and stored in a cool, dry place until the air-dried moso bamboo blocks were having equilibrium moisture content. After weighing the moso bamboo samples, these samples were immersed in distilled water. Standard measurement of the moso bamboo samples provided changes in weight. The evaluation of the permeability changes of the moso bamboo blocks, using the water absorption rate, was based on the equation of the water absorption rate (Equation 1):

$$1. \quad \text{WAR} = (W_2 - W_1) / W_1 \times 100\%$$

where WAR is the water absorption rate (%), W_1 is the air-dried weight of the moso bamboo samples, and W_2 is the water absorption weight of the moso bamboo samples.

After the water absorption in the moso bamboo samples attained equilibrium, the moso bamboo samples were dried at the same temperature (80 °C). The evaluation of the permeability changes of the moso bamboo blocks, using the water loss rate, was based on the equation of the water loss rate (Equation 2):

$$2. \quad \text{WLR} = (P_2 - P_1) / P_1 \times 100\%$$

where WLR is the water loss rate (%), P_1 is the weight before the moso bamboo samples were immersed in water, and P_2 is the weight after the moso bamboo samples were dried.

2.2.2 Evaluation of main mechanical properties of moso bamboo samples treated with hydrochloric acid and microwave

After finishing the hydrochloric acid and microwave treatment, the moisture content, for testing the mechanical properties of the samples, was adjusted in the constant temperature and humidity box. In order to test the mechanical properties, it must be ensured that the moisture content of the samples used for testing the mechanical properties is 12%. All the testing of the mechanical properties of the moso bamboo samples was done in accordance with GB/T 15780-1995. The test stipulations included optimal pretreatment solvent concentration and microwave treatment conditions.

3. Results and discussion

3.1 Moso bamboo pretreatment – analysis of mechanical properties

The effect of hydrochloric acid or microwave pretreatment on the mechanical properties of the moso bamboo samples was investigated, and the results are shown in Figures 1–3. As seen in Figure 1, the main mechanical properties of the moso bamboo, such as tensile strength, bending strength, compressive strength, and shear strength, decreased when the percentage of pretreatment of hydrochloric acid solvents increased from 0 to 3%. Under hydrochloric acid pretreatment conditions, the tensile strength, parallel to the grain of the moso bamboo, decreased from 19.72 to 11.63 KN/cm² when the percentage of hydrochloric acid solvents increased from 0 to 3%. Bending strength decreased from 14.87 to 5.35 KN/cm² when the percentage of hydrochloric acid pretreatment solvents increased from 0 to 3%. Compressive strength, parallel to grain of bamboo, decreased from 6.13 to 2.82 KN/cm² when the percentage of hydrochloric acid pretreatment solvents increased from 0 to 3%. Shear strength, parallel to grain of bamboo, decreased from 1.29 to 0.74 KN/cm² when the percentage of hydrochloric acid pretreatment solvents increased from 0 to 3%.

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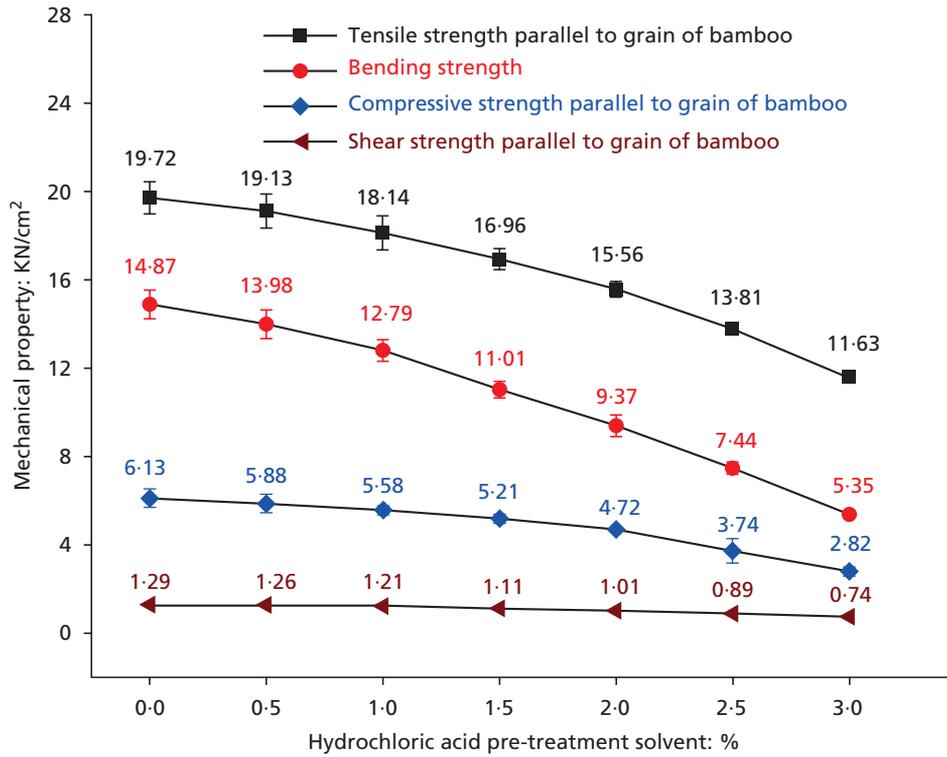


Figure 1. Mechanical properties of moso bamboo samples treated with seven concentrations of hydrochloric acid solvents

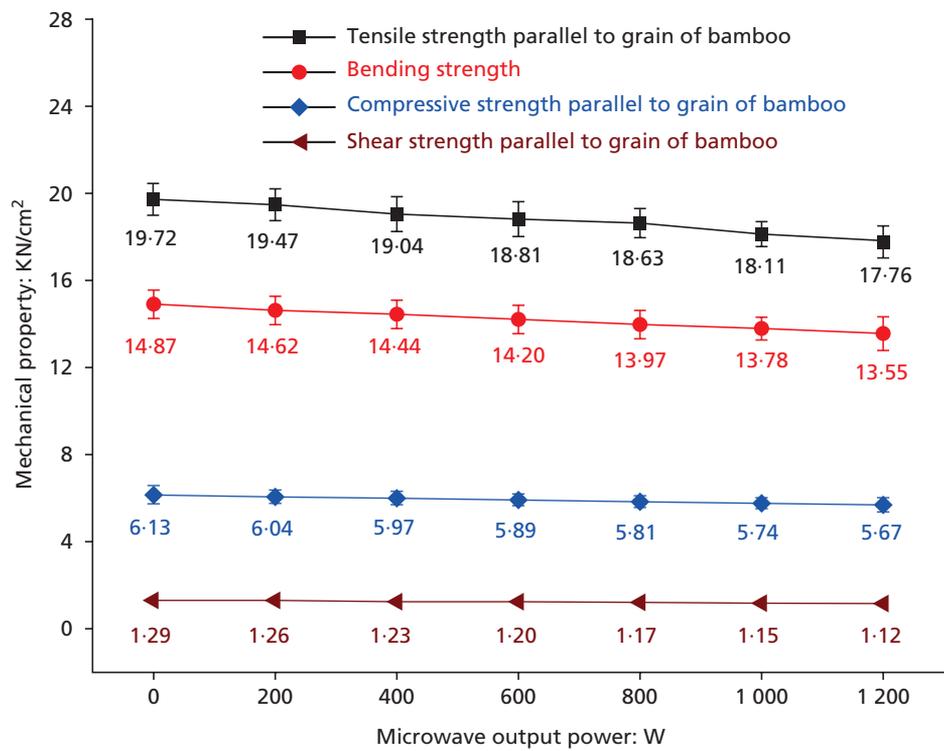


Figure 2. Mechanical properties of moso bamboo samples treated with different microwave output power

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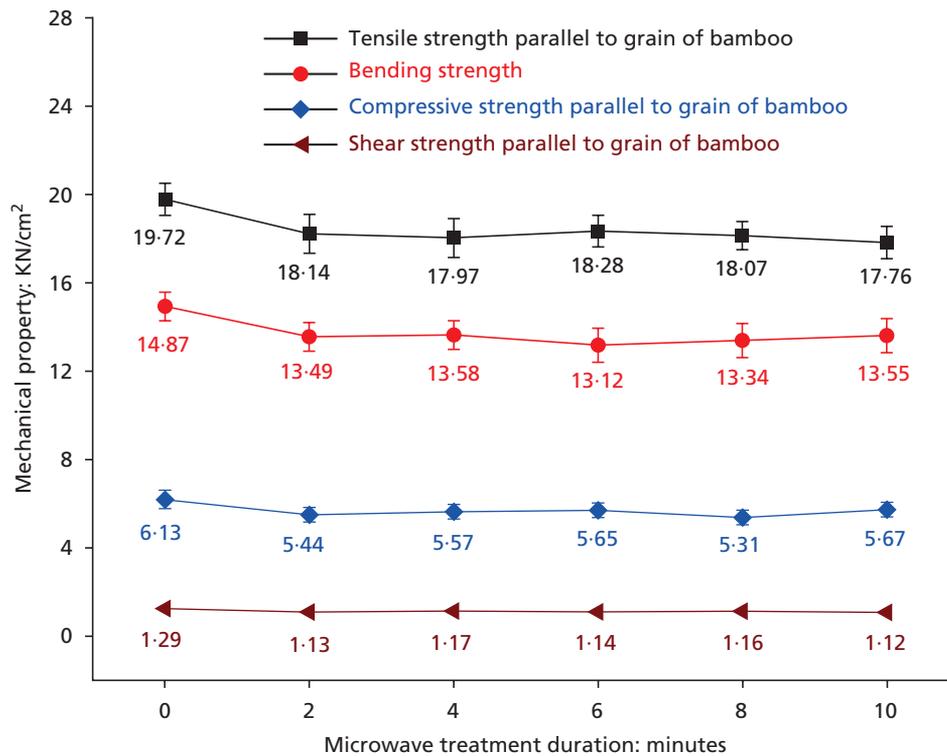


Figure 3. Mechanical properties of moso bamboo samples subjected to six lengths of microwave treatment durations

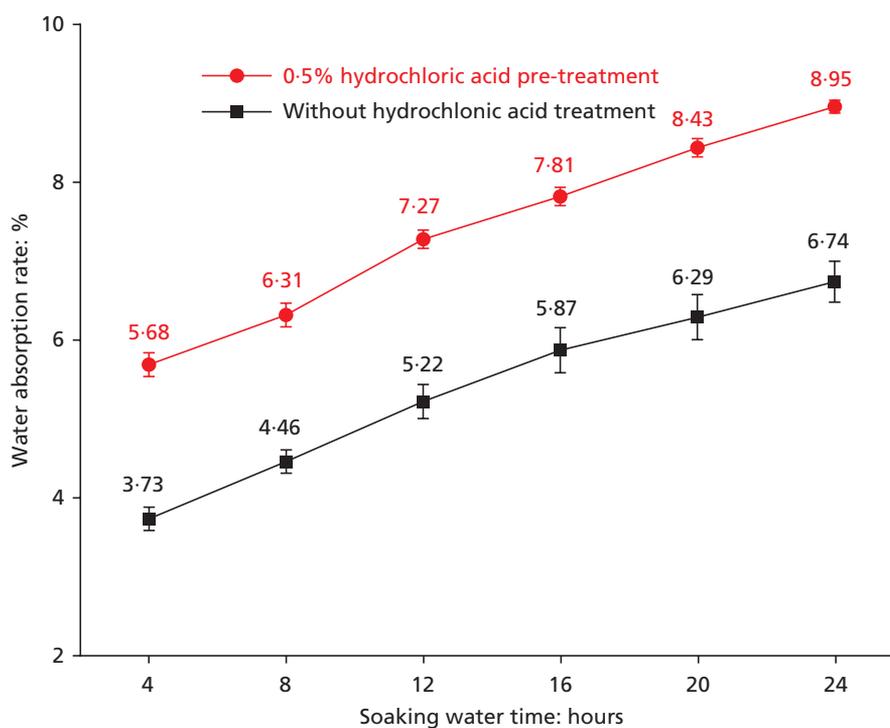


Figure 4. Water absorption rate of moso bamboo samples treated with six durations of soaking water time

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The reason for the rapid decline in these main mechanical properties of the moso bamboo sample may be attributed by multiple factors. As is known, the moso bamboo consists of 55% cellulose, 20% hemicellulose, and 25% lignin from microeconomics standpoint. When the moso bamboo blocks were treated with hydrochloric acid solvents at 100 °C, hemicelluloses were hydrolyzed into simple sugars, and the crystalliferous region of the cellulose formed porous or swelling type structures. Because the crystalliferous region of the cellulose was damaged, the main mechanical properties, that is, the mechanical strength of the moso bamboo samples decreased significantly. In order to ensure the quality of the final product of moso bamboo, we had deliberately chosen to treat the moso bamboo blocks with 0.5% hydrochloric acid pretreatment solvents.

The influence on the main mechanical properties of the moso bamboo samples, which were treated with various microwave output power or different microwave treatment durations, are shown in Figures 2 and 3. As can be seen in Figures 2 and 3, the main mechanical properties of the moso bamboo, that is, the mechanical strengths, had decreased slightly when the microwave output power increased from 0 to 1200 W. For example, the tensile strength, parallel to the grain of the moso bamboo, decreased from 19.72 to 17.76 KN/cm² when the microwave output power increased from 0 to 1200 W. An important finding is that there is a

weak relationship between the main mechanical properties of the moso bamboo samples and the microwave treatment durations.

The reason for the weak relationship between the main mechanical properties, that is, the mechanical strengths of the moso bamboo samples and microwave treatment durations may involve two factors. Firstly, the distribution of the main vascular tissue system of the moso bamboo is longitudinal, with no horizontal transmission system. The traditional anti-fungal chemical reagents are always difficult to immerse the internal part of moso bamboo blocks. Similarly, this is also a challenge for the water to escape from bamboo blocks internally. Before the microwave experiment began, the bamboo samples were immersed in water until equilibrium was reached. During this process, the moso bamboo blocks had absorbed a lot of water. The microwave treatment process led to heating the moso bamboo blocks inside and outside at the same time. When the water inside the moso bamboo block was transformed into steam, its volume changed significantly. The water vapor could not easily exhaust from the moso bamboo blocks. Finally, the water vapor destroyed the cell walls of the vessel, sieve tube, and parenchyma cells of the moso bamboo block, resulting in a decline of its mechanical properties. Secondly, before the microwave experiment began, in order to ensure that the moso bamboo samples did not burn by microwave heating, the samples were immersed in water during the microwave irradiation

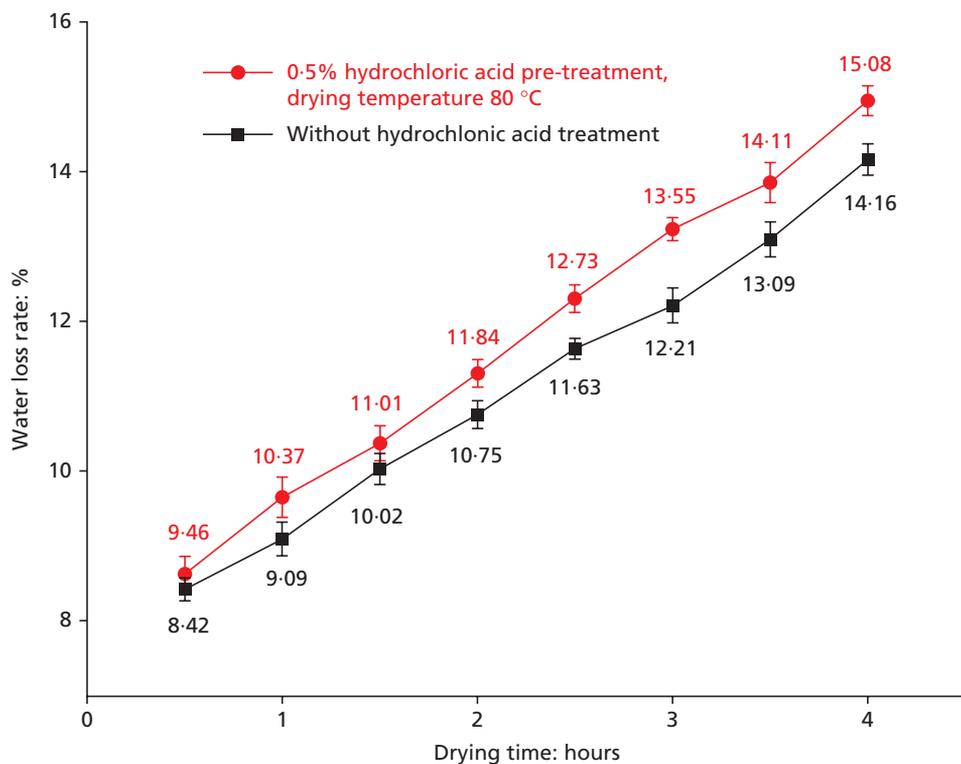


Figure 5. Water loss rate of moso bamboo samples treated with eight lengths of drying time

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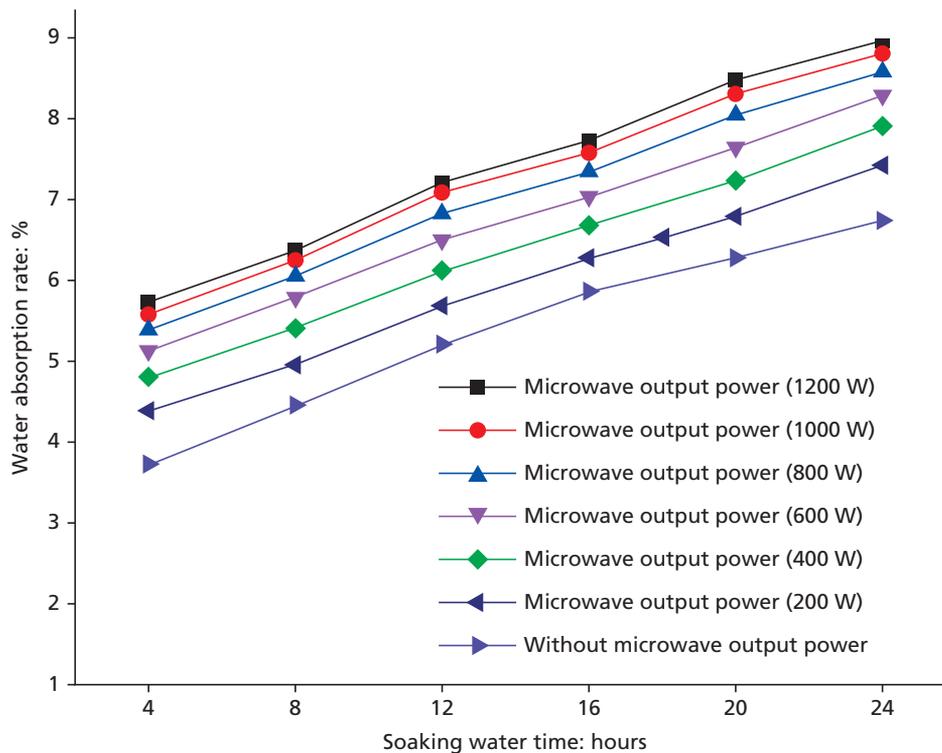


Figure 6. Water absorption rate of moso bamboo samples treated with six durations of soaking water time

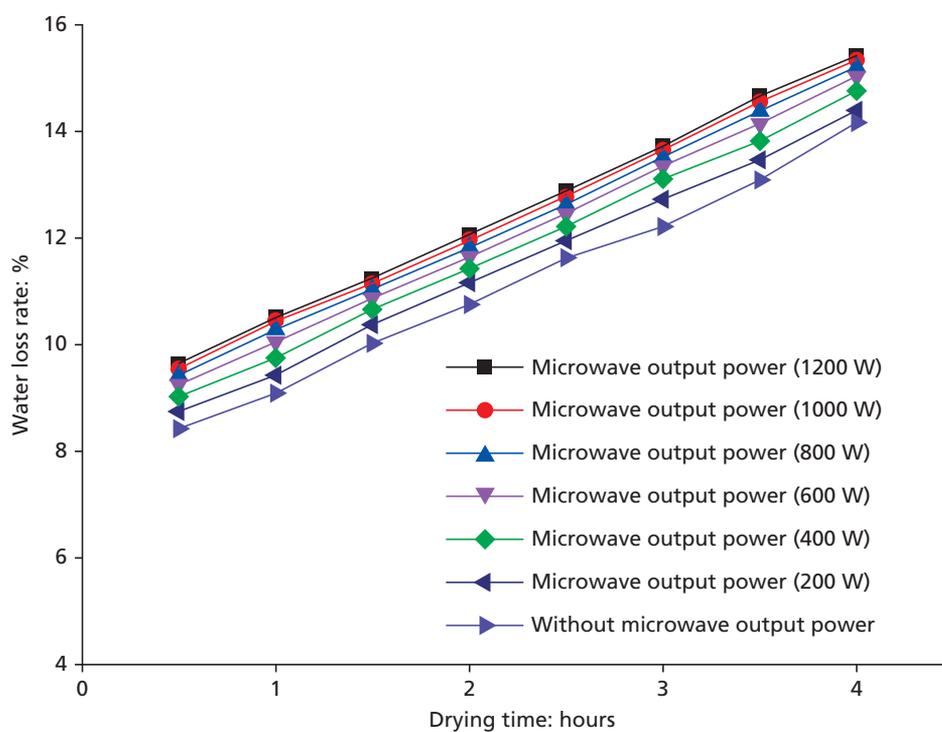


Figure 7. Water loss rate of moso bamboo samples treated with eight durations of drying time

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process. When the water inside the moso bamboo block was transformed into steam, the gasification process was not violent. Therefore, the main mechanical properties of the moso bamboo had decreased slightly, and a weak relationship was found between the main mechanical properties of the moso bamboo samples and the microwave treatment durations.

The influence of the water absorption rate and the water loss rate of the moso bamboo samples, treated with 0.5% hydrochloric acid are shown in Figures 4 and 5. As shown in Figure 4, the water absorption rate of the treated and untreated moso bamboo samples increased when the soaking water time of the moso bamboo samples increased from 4 to 24 hours. In the same way, as shown in Figure 5, the water loss rate of the treated and untreated moso bamboo samples increased when the drying time of the moso bamboo samples increased from 0.5 to 4 hours (80 °C). The influence of the water absorption rate and the water loss rate of the moso bamboo samples, treated with different microwave output power, are shown in Figures 6 and 7. As shown in Figure 6, all the water absorption rates of the moso bamboo blocks, treated with different microwave output power, were higher than the untreated moso bamboo blocks. Meanwhile, the water absorption rate of the moso bamboo samples increased with the increase in the microwave output power from 0 to 1200. As shown in Figure 7, the water loss rate of the moso bamboo blocks, treated with different microwave output power, were higher than the untreated moso bamboo blocks. The water

loss rate of the moso bamboo samples increased with increase in microwave output power from 0 to 1200W.

The influence of water absorption rate and water loss rate of the moso bamboo samples, treated with different microwave treatment time, are shown in Figures 8 and 9. As shown in Figure 8, the water loss rate of the moso bamboo blocks, treated with different microwave treatment time, were higher than the untreated moso bamboo blocks. Meanwhile, the water loss rate of the moso bamboo samples increased with increase in microwave treatment times from 0 to 10 minutes. As shown in Figure 9, the water loss rates of the moso bamboo blocks, treated with different microwave treatment times, were higher than the untreated moso bamboo blocks. The water loss rate of the moso bamboo samples increased with increase in microwave treatment time from 0 to 10 minutes.

The reason for the water absorption rate and the water loss rate of the moso bamboo samples to increase rapidly may be due to multiple factors. First, the water absorption rate of the moso bamboo samples increased when the soaking water time in the treated and untreated moso bamboo samples was prolonged. The results of the calculation show that the change in the water absorption rate of the moso bamboo samples decreased with the extension of the soaking water times. In the early soaking water time, the moso bamboo material internal water content was low. The water dipped quickly into the moso bamboo interior

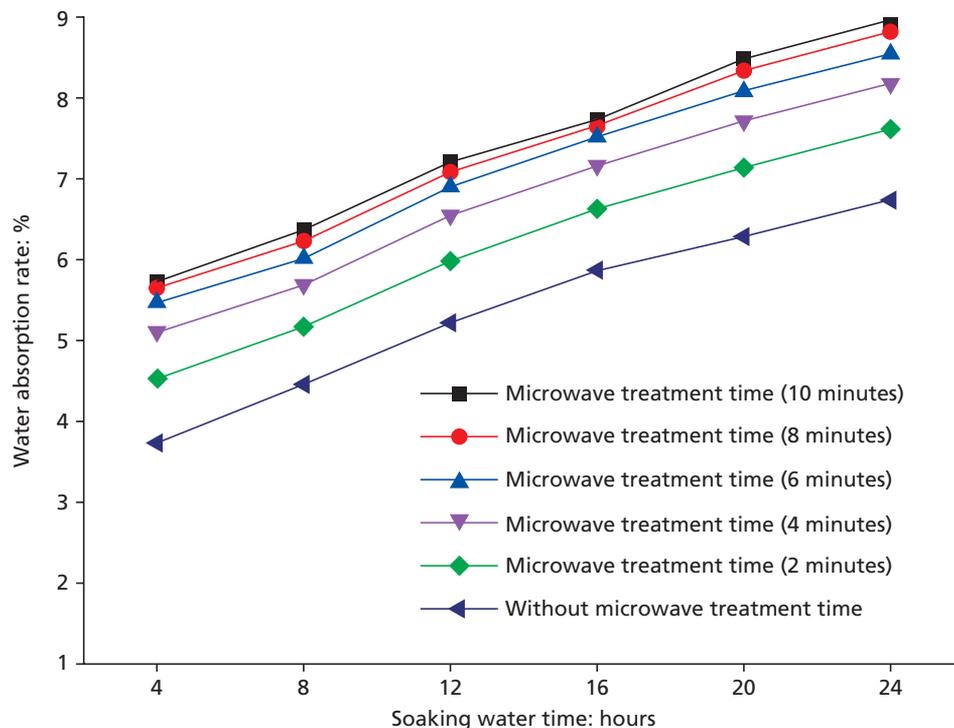


Figure 8. Water absorption rate of moso bamboo samples treated with six durations of soaking water time

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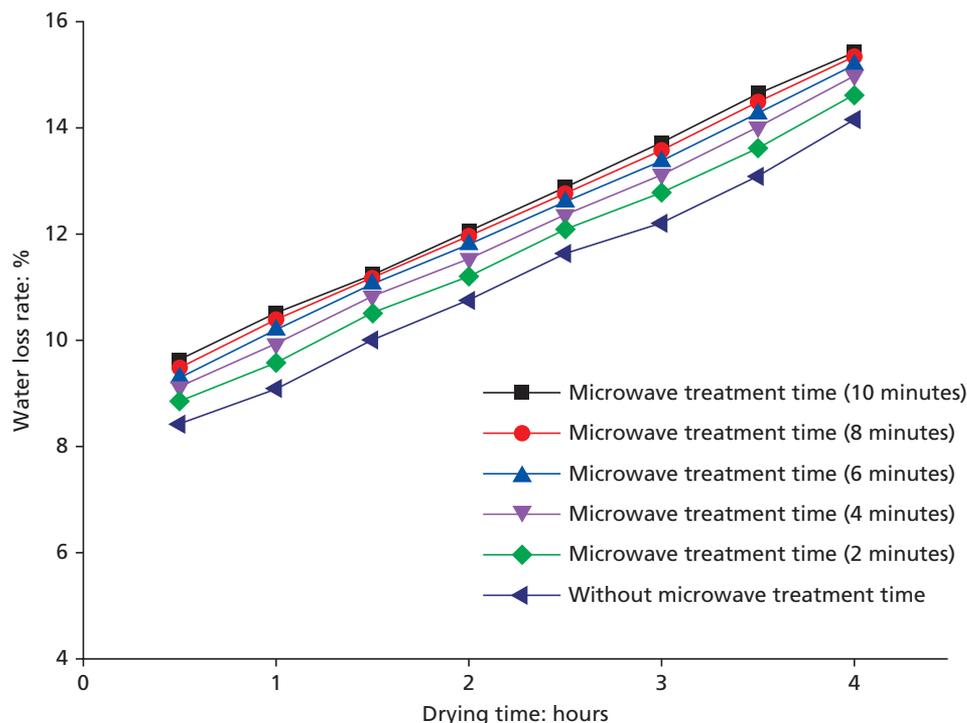


Figure 9. Water loss rate of moso bamboo samples treated with eight durations of drying time

under the action of the pressure difference; therefore, the moso bamboo samples absorbed water faster. But, with the extension of the soaking water time, and the increased internal pressure of the moso bamboo samples, the water absorption velocity of the moso bamboo samples decreased. The water absorption rate of untreated moso bamboo samples is lower than that in treated samples. This may be due to residual internal water of moso bamboo samples which were transformed into steam during treatment in microwaves. The internal sections of moso bamboo samples have a certain vapor pressure. The water vapor destroys the cell walls of the vessel, sieve tube, and parenchyma cells of the moso bamboo blocks. So the permeability of moso bamboo samples was obviously improved. Hence, the external water flowed more easily into the interior of the moso bamboo block under pressure. Therefore, the water absorption rate of treated moso bamboo samples is higher than that in untreated samples. Because the microwave output power, used in this experiment, is low (from 200 to 1200 W), the interior moisture evaporation rate of moso bamboo samples was relatively low. So the impact of the water vapor was only slightly destructive to the cell walls of the vessel, sieve tube, and parenchyma cells of the moso bamboo block; the main mechanical properties, that is, the mechanical strengths, of the moso bamboo had decreased slightly. Similarly, the weak component of the cell tissue of the moso bamboo samples might be destroyed by the water vapor during the microwave treatment process. The permeability of the moso

bamboo blocks was improved. Because of the formation of these new fluid channels, this was more conducive to the formation of a reasonable moisture gradient in moso bamboo blocks during the drying procedure. Moisture migration within the moso bamboo blocks occurred more smoothly so that the rate of water loss, in the treated moso bamboo block, increased during the same drying conditions than the untreated samples.

4. Conclusion

Under hydrochloric acid pretreatment conditions, because the crystalliferous region of cellulose in the moso bamboo block formed porous or swelling type structures, the main mechanical properties of moso bamboo decreased when the percentage of hydrochloric acid pretreatment solvents increased from 0 to 3%. In order to ensure the quality of the final product of moso bamboo, 0.5% hydrochloric acid solvents are the suitable concentration for pretreatment of moso bamboo. When the moso bamboo blocks were treated with microwave, the internal water was transformed into steam, and the water vapor destroyed the cell walls of the vessel, sieve tube, and parenchyma cells in the moso bamboo. The permeability of moso bamboo samples was greatly improved, moving water more easily into the moso bamboo block interior under pressure. Therefore, the water absorption rate of treated moso bamboo samples was higher than untreated ones. Moreover, because part of the moso bamboo block cell walls was destroyed, the main mechanical properties, that is, the mechanical

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strength, of the moso bamboo blocks declined. The weak part of the moso bamboo sample cell tissue might be destroyed by the water vapor during microwave treatment procedures, leading to the formation of a new fluid passage in the internal section of the bamboo blocks. The rate of water loss of the treated moso bamboo samples was greatly increased over the untreated ones. In order to ensure that the moso bamboo samples did not burn during microwave heating, the moso bamboo samples were immersed in water during the microwave irradiation process. When the moso bamboo block's internal water was transformed into steam, the gasification process was not violent. Therefore, the main mechanical properties of the moso bamboo had decreased only slightly, and a weak relationship was found between the main mechanical properties of the moso bamboo samples and microwave treatment durations.

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