Front. For. China 2008, 3(4): 480–486
DOI 10.1007/s11461-008-0072-1

RESEARCH ARTICLE

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Hydrolysis of bamboo fiber cellulose in formic acid

Abstract Bamboo fiber dissolution and hydrolysis in formic acid were studied. After hydrolysis, formic acid can be recovered in a clean state and reused. Solid water-soluble sugars were obtained. After being dipped into the formic acid solution for 30 min, the bamboo fibers started to swell. After one hour, the bamboo fibers gradually started to dissolve in the formic acid solution. The color of the liquor/solution turned green and dark. In the end, the bamboo fibers became thoroughly dissolved in the liquor after four hours. There was a clear hierarchical tissue structure on the fiber surface, as observed by AFM before treatment. The differential structure disappeared after 30 min of treatment. The fiber surface became plump and glossy. After six hours reaction at 60°C, the solid sugar mixture recovered contained glucose, cellobiose, cellotriose, cellotetrose, cellopentose and cellohexaose. A significant fraction of the sugar products consisted of monomeric glucose. More than 54.5% of the bamboo fiber mass had been transformed into monomeric glucose.

Keywords bamboo fibers, cellulose, formic acid, hydrolysis, dissolution, sugars

1 Introduction

Cellulose, the most abundant of renewable organic substances in nature, is the polymer of β-glucose units. Cellulose is the primary component in herbaceous and woody plants. Up until now, cellulose is mainly used as building material or processed directly into paper or fiber. As petroleum reserves gradually decrease, the exploitation cost increases rapidly. Exploration for a feasible pathway to transform abundant and renewable cellulose into clean fuel such as bio-ethanol and other chemicals to supplement or gradually replace the oil-based chemicals or energy becomes increasingly urgent (Sun and Cheng, 2002; Rostrup-Nielsen, 2005; Liu et al., 2006).

Cellulose is a linear homopolymer of (1–4)-linked β-D-glucopyranose, which further forms into a macro molecule with a highly stable crystalline lattice structure. Cellulose is strongly resistant to attack both by enzymes and chemical agents such as acidic compounds. The enzymatic hydrolysis process of cellulose is a slow process and is not a prospective method for industrial practice in the immediate future (Gan et al., 2003; Zhang and Lynd, 2003). Chemical hydrolysis, usually acid hydrolysis, is one of the more viable methods which had been developed as a promising way of sugar production from cellulose. The hydrolysis of cellulose in mineral acids is strongly affected by its acid concentration and temperature. It is well known that high concentrations, more than 0.5 mol/L, even 10 mol/L, of mineral acid such as sulfuric acid, hydrochloric acid or phosphoric acid (Iranmahboob et al., 2002) and high temperatures, over 90°C, are required simultaneously in the acidic hydrolysis process to produce reducing saccharides from cellulose (Choi and Mathews, 1996). Between the two factors of acid concentration and temperature, if one varies to a considerable extent, another factor needs to follow with significant changes in order to maintain substantial hydrolysis. For example, when acid concentration decreases below 0.5 mol/L, the temperature usually needs to be higher than 120°C and even over 250°C. If temperature is decreased to 90°C, concentrated strong acid of more than 1.0 mol/L is required. Moreover, the combination of high temperatures and strong mineral acids, employed simultaneously for hydrolysis of cellulose, leads to corrosion of reaction equipment, production and accumulation of non-sugar by-products, such as inhibitors to subsequent chemical and biological conversion and also to obstacles to the recovery of reaction agents and resultant saccharides (Sasaki et al., 1998).

Translated from *Biomass Chemical Engineering*, 2007, 41(2): 5–10 [译自: 生物质化学工程]

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The common acid hydrolysis process of cellulose is heterogeneous and occurs on the structural surface of crystalline lattices of cellulose molecules (Gan et al., 2003; KoheiIkari and Suzuki, 2004). Whether it is possible to realize a homogeneous reaction, when the cellulose dissolves into the reactants and completely miscible with the reactants, is opened to exploration. Bursting the crystalline structure forces the hydrolysis reaction of cellulose not only to take place on the surface of cellulose, but also in the inner space of the cellulose lattice.

Cellulose is difficult to dissolve in any solvent, although several solvents have already been discussed. Still, these solvents are not efficient substances to use commercially because of their weak solvency and length of time needed for dissolving cellulose. The complicated chemical composition of the solvent system also requires several chemicals to be mixed, in which cellulose can only be weakly hydrolyzed (Sjöholma et al., 2000; Potthast et al., 2003). Although some of the strong acids such as sulfuric acid and phosphoric acid can hydrolyze cellulose, a high acid concentration above 70% is needed. Thus, it does not provide any promise leading to substantial industrial applications (Sasaki et al., 1998; Iranmahboob et al., 2002; Håkansson and Ahlgren, 2005).

Establishment of a homogeneous system of hydrolyzing cellulose is of great importance to conversion and utilization of cellulose. The objective of this study is to search for an effective means of dissolving and hydrolyzing cellulose. Formic acid with hydrochloric acid as the catalyst has been discovered to dissolve cellulose effectively. During the dissolution process, clean hydrolysis of cellulose is achieved and a solid water-soluble sugar mixture is obtained. Glucose is the most important component among the resultant soluble sugars and sugar-oligomers. Hydrolysis of cellulose in formic acid is a new homogeneous reaction system. The solvent itself is both a reactant and also a catalyst. Formic acid can be easily recovered and reused.

2 Experimental

2.1 Hydrolysis of cellulose

Bamboo fibers, from bleached sulfite bamboo pulp were obtained from the Jiangmen Sugar Cane Chemical Factory (Group) Co., Ltd. In our experiments, bamboo fibers were placed in the reactor that contained 78.22% formic acid, 17.78% water and 4% hydrochloric acid, measured by weight. Reactions were carried out at different temperatures and resident times. After hydrolysis, formic acid was extracted by a depressurization procedure. The reaction products were collected for further analysis after washing, filtration and desiccation.

2.2 HPLC analysis

An HPLC system consists of a Waters 600E system controller, a Waters 717 automatic sampler, a Waters 410 differential refractometer and a Waters Sugar pak I column. The mobile phase is pure water and run at a flow rate of 1.1 mL/min. The LC system was operated at 90°C. We injected 10 μL sample volumes. Standard samples and hydrolyzate samples were filtrated by a 0.45 μm filter before analysis.

2.3 X-ray diffraction analysis

X-ray diffraction was performed with D/MAX-IIIA instrument with 12°/min scanning speed. The cellulose powder samples were laid on glass sample holders (35 mm × 50 mm × 5 mm) and analyzed under plateau conditions. Cu radiation generated at a voltage of 40 kV and a current of 30 mA was used. A scanning scope between 2–50° was employed.

2.4 FTIR analysis

FTIR spectra were recorded, between 400 and 4000 cm^{-1}, using a NEXUS spectrometer. The discs were prepared by first mixing 1 mg of dried sample with 100 mg of KBr (for spectroscopy) in an agate mortar. The resulting mixture was successively pressed at 10 MPa for 3–4 min.

2.5 AFM analysis

The samples were analyzed using an Auto Research AFM with a contact pattern bearing an ULB-6 probe.

3 Results and discussion

3.1 Dissolution of bamboo fibers in formic acid

At the start of the experiments, bamboo fibers were placed in a formic acid solution which contained 4% (w/w) hydrochloric acid as the catalyst. The starting liquor contained 78.22% HCOOH, 17.78% H_2O, and 4% HCl, all by weight. After 30 min, bamboo fibers began to swell and gradually dissolved. After one hour, the color of the liquor/solution changed to green. After two hours, the bamboo fibers had been thoroughly dissolved in the liquor. The color of the liquor became darker. Four hours later, a completely miscible solution of bamboo fibers in formic acid was obtained. The color progression of the bamboo fibers in the formic acid solution is shown in Fig. 1. We can conclude that formic acid is able to dissolve bamboo fiber cellulose.

Bamboo fibers during dissolution were observed using an AFM. The AFM images before formic acid treatment

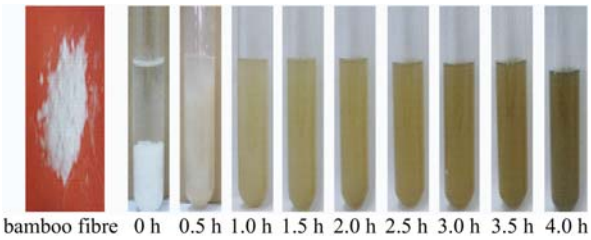

Fig. 1 Progression of bamboo fiber dissolution in formic acid solution
The starting liquor contained 78.22% formic acid, 17.78% water and 4% hydrochloric acid; all by weight. 1.00 g of bamboo fibers were added to 24.00 g of the earlier mentioned formic acid solution.

show a distinctive hierarchical tissue on the surface of microfibrils as shown in Fig. 2. Differential stereoscopic strips are clearly displayed. However, the structural shapes disappeared after the formic acid treatment for 30 min. The fiber surface became smooth and plump. This behavior indicated that the inner rigid bonding of crystalline microfibrils had been loosened and the lattice of the crystal became swollen (Fig. 2).

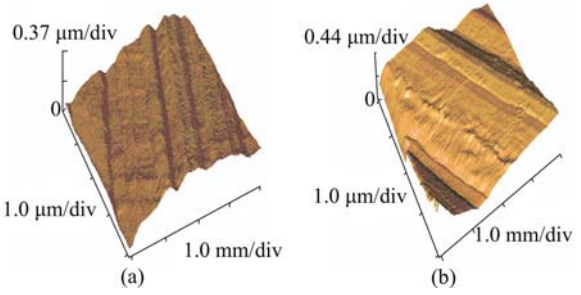

Fig. 2 AFM images of bamboo fibers during dissolution in formic acid
Notes: 1 control; 2 after a treatment for 30 min.

3.2 Change of crystalline index of bamboo fiber during dissolution in formic acid

Figure 3 shows the X-ray diffraction profiles of the bamboo fibers. Representative peaks are observed at $2\theta = 14.7^\circ$, 16.3° for (101) plane; $2\theta = 22.5^\circ$ for (002) plane; and $2\theta = 34.5^\circ$ for (004) plane. In these diffraction profiles, the peaks at $2\theta = 22.5^\circ$ of the control cellulose sample are higher and sharper than those after formic acid treatments for 30 min and 90 min. The diffraction intensity of the shoulder of the peak around $2\theta = 20^\circ$ decreased to a noticeable extent. The separation between peaks at $2\theta = 14.7^\circ$ and 16.3° in the treated samples is ambiguous, but is considerably clearer than in the control sample. We can conclude that the crystalline intensity of bamboo fibers was reduced gradually, which was especially evident on the 101 and the 002 lattice planes (Fig. 3).

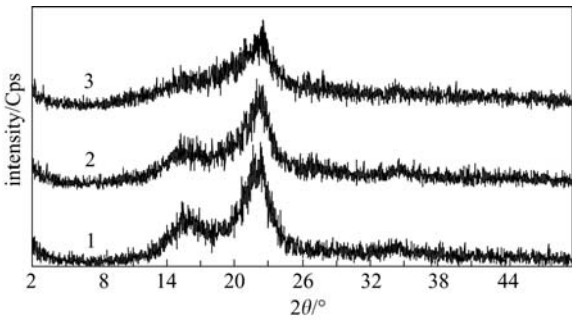

Fig. 3 X-diffraction profiles of bamboo fibers during treatment by formic acid
Notes: 1 control; 2 after a treatment for 30 min; 3 after a treatment for 90 min.

The expression of Segal (Segal et al., 1959; Yang et al., 2002; Cao and Tan, 2005; Mihranyan et al., 2004) was used to calculate the crystalline index:

$$I_{Cr} = 100(I_{hkl} - I_{am})/I_{hkl} \quad (1)$$

where I_{Cr} is the crystalline index, I_{am} the amorphous zone diffraction intensity of 2θ equal to 18° and I_{hkl} the crystalline zone diffraction intensity on the 002 lattice plane. Tables 1 and 2 show the crystalline indices as calculated from the X-ray diffraction data of bamboo fibers. The crystalline index decreases from 71.1% to 66.0% after the sample had been treated for 30 min. Ninety minutes later the crystalline index decreased further to 56.4%. As the X-ray diffraction crystalline index dropped gradually, the cellulose also dissolved in a stepwise fashion in formic acid. Table 1 shows the intensity of diffraction peaks in the crystalline zone and the amorphous zone of bamboo fibers. The intensity of X-ray diffraction peaks declined during treatment. However, the decrease was clearer in the amorphous zone than in the crystalline zone. Therefore, the effects of formic acid on the amorphous zone and the crystalline zone were different. The effect in the crystalline zone was more distinct than in the amorphous zone. As a result, the crystalline lattice of cellulose imploded and eventually the rigid framework of the crystalline lattice of cellulose was crushed.

Table 1 Characteristic X-ray diffraction peaks of bamboo fibers

sample	peaks	location/°	intensity/Cps
control	101	15.38	487
	$10\bar{1}$	16.32	446
	002	22.28	948
	040	34.36	241
after a treatment for 0.5 h	101	15.24	418
	$10\bar{1}$	16.64	396
	002	22.24	792
	040	34.56	224
after a treatment for 1.5 h	101	15.69	288
	$10\bar{1}$	16.64	298
	002	22.56	698
	040	34.84	191

Table 2 X-ray diffraction crystalline index of bamboo fibers

sample	$2\theta = 18^\circ$ peak intensity/Cps	002 peak intensity/Cps	I_{Cr}/%
control	274	948	71.1
after a treatment for 0.5 h	269	792	66.0
after a treatment for 1.5 h	304	698	56.4

The FTIR spectra of bamboo fibers during dissolution and hydrolysis are shown in Fig. 4. The peak of -OH stretching near 3400 cm^{-1} and the peak of $–CH_2$ stretching near 2900 cm^{-1} are distinctive features of cellulose. During formic acid treatment, the bamboo fibers adsorb some material containing –OH. Formic acid is the suspect with its –OH groups. The absorbed –OH resulted in a peak at 1637 cm^{-1}. The peaks at 1370 and 1430 cm^{-1} are the bending vibration of –CH and –OH bonds, respectively. The peak of $–CH_2$ swaying was at 1317 cm^{-1}; –CH bending at 1333 cm^{-1}; $–CH_2$ bending at 1372 cm^{-1}. The peak of 1430 cm^{-1} is attributed to the bending of the $–CH_2$ bond because of the effect of hydrogen bonds in cellulose. The peaks at 1063, 1058, 1112, 1030 and 896 cm^{-1} were responsive to the stretching of C–O–C–O–C bonds in cellulose. The major difference of the FTIR spectra between cellulose samples of control and that after the formic acid treatment for 1.5 h was in the regions between 3340 and 3375 cm^{-1} and between 1420 and 1730 cm^{-1} (Fig. 6). These two regions are –OH stretching of intramolecular hydrogen bonds and –OH bending of substances with hydroxyl absorbed by cellulose, respectively (Hinterstoisser et al., 2001; Ruan et al., 2004; Oh et al., 2005a; Takács et al., 2005). After the treatment for 1.5 h, the absorption specific to bands in the region of wave numbers between 3340 and 3375 cm^{-1} and between 1420 and 1730 cm^{-1} was more intensive than that of the control sample, especially at 1721 cm^{-1}. Thus, a certain amount of H_2O and other chemical agents with –OH bonds was absorbed into the cellulose crystal lattice. Clearly, HCOOH is the candidate. Probably novel single or series-chained bonds of OH···O were formed.

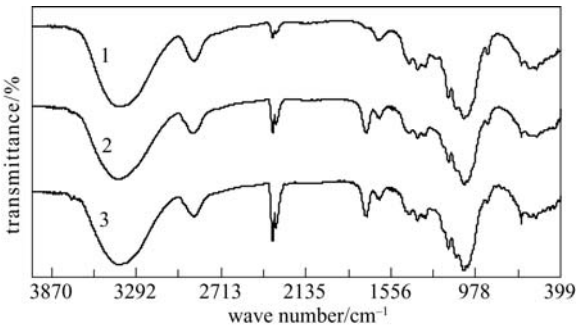

Fig. 4 FTIR spectra of bamboo fiber during treatment by formic acid
Notes: 1 control; 2 after a treatment for 0.5 h; 3 after a treatment for 1.5 h.

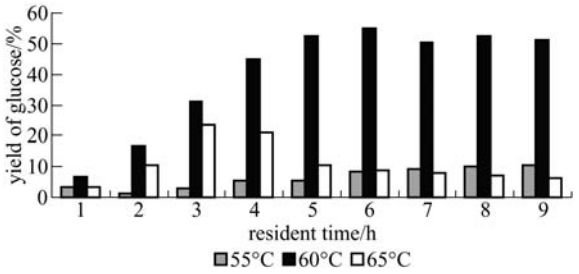

Fig. 5 Effect of residence time (from 1 to 9 h) and temperature (from 55 to 65°C) on the release of glucose from bamboo fibers in formic acid

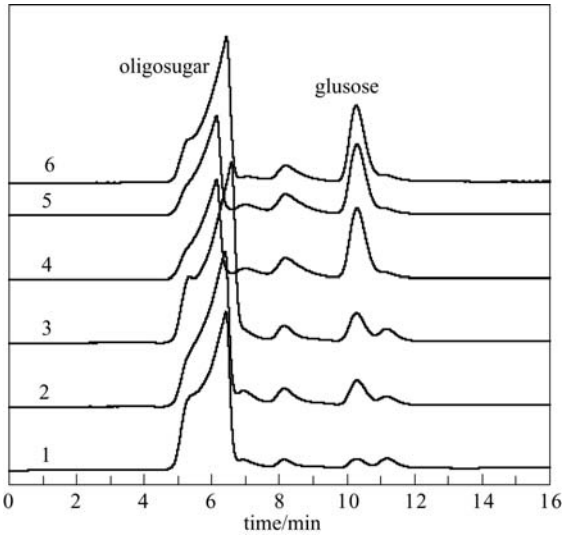

Fig. 6 HPLC spectra of hydrolysates of bamboo fibers in formic acid at 60°C for different treatment times (1 h, 2 h, 3 h, 4 h, 5 h, 6 h). The spectra from 1 to 6 correspond to the samples after treatments of 1 h to 6 h.

The intensity of intermolecular hydrogen bonds affects the shift of –OH vibration in the FTIR spectra. The peak shifts to a higher wave number if the intensity of intermolecular hydrogen bonds is weak (Oh et al., 2005b). From the FTIR spectra of bamboo fibers observed, the peak of –OH failed to shift away from 3400 cm^{-1}. It is probable that only intramolecular hydrogen bonds were formed when formic acid molecules penetrated into the crystalline lattice of cellulose. Thus, the rigid molecular framework of bamboo fibers imploded causing cellulose to dissolve in the formic acid solution. Hydrolysis took place following the dissolution. Because of the dissolution, hydrolysis became a homogeneous reaction. There were no differences between the initial crystalline zone and the amorphous zone. As a result, complete hydrolysis was achieved.

3.3 Effect of temperature and residence on hydrolysis of bamboo fibers

Given our discussions in the previous sections, bamboo fibers dissolve in formic acid solution. The acidity of

formic acid resulted in the fissure of glucosidic bonds of the cellulose molecules in bamboo fibers. A hydrolysis reaction took place. After hydrolysis, the formic acid could be extracted by a depressurization procedure and solid hydrolysates were obtained. In the hydrolysis of bamboo fibers, the resident time and temperature are important factors. In order to find the optimal reaction conditions, the effects of reaction temperatures (55°C, 60°C, 65°C) and resident times (1 through 9 h) were investigated. At 55°C and 60°C, the yields of glucose continuously increased with resident time. However, at 65°C, the yield of glucose initially increased and then decreased after 3 h (Fig. 5). At 55°C, the yield of glucose increased at a slower rate than at 60°C. Thus, the hydrolysis of cellulose was strongly dependent on temperature. High temperatures can enhance the transformation ratio of cellulose to glucose. However, glucose degrades in a mineral acid solution as reported elsewhere (Mosier et al., 2002; Lloyd and Wyman, 2005; Johansson et al., 2006). The data in Fig. 5 also shows that the rate of glucose degradation is faster than that of cellulose hydrolysis to glucose over 65°C. After 3 h, the yield of glucose decreased gradually over time. However, continued increases with the extension of resident time were observed at 55 and 60°C. Thus, the degradation rate of glucose increased with an increase in temperature. The optimal hydrolysis condition of bamboo fibers was found to be at 60°C for 6 h. The yield of monomeric glucose was 54.5%. HPLC analysis also shows that the yield of glucose clearly increased with the prolongation of resident time at the optimal temperature of 60°C (Fig. 6). The percentage of glucose in the water-soluble sugar/sugar oligomers mixture gradually increased. Water-soluble sugar mixtures in the solid hydrolysates were analyzed by HPLC. Glucose, cellubiose, cellotriose, cellotetrose, cellopentose and cellohexose were detected in the hydrolysates (Fig. 7).

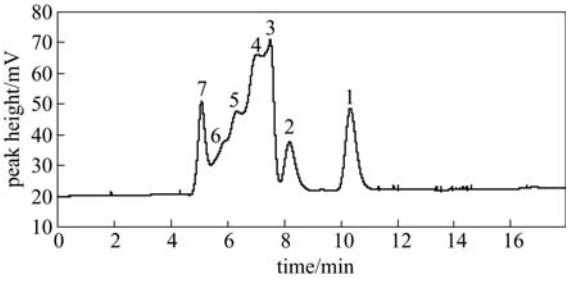

Fig. 7 HPLC spectra of hydrolysates of bamboo fibers in formic acid
Notes: 1 glucose; 2 cellobiose; 3 cellotriose; 4 cellotetrose; 5 cellopentose; 6 cellohexose; 7 residual formic acid.

The yield of reducing sugars was measured by the DSN method as shown in Table 3. The yield of reducing sugars was enhanced with the increase of resident time at 55 and 60°C, The enhancement was more pronounced at 60°C than at 55°C. After 6 h, it was about 33.4% at 55°C and 75.8% at 60°C. At 65°C, the yield of reducing sugars first increased and then decreased as the treatment time was extended. The maximal yield was 53.4% after 4 h treatment. It can be concluded that at high temperatures the reducing sugars are also severely degraded. The optimal condition was at 60°C for 5 h. The transformation of cellulose to reducing sugars was 79.7%.

Table 3 Yield of reducing sugars from hydrolysate of cellulose of bamboo fibers obtained with the DSN method

time/h	yield of reducing sugars/%		
	55°C	60°C	65°C
1	19.9	36.3	17.9
2	24.6	43.5	39.6
3	18.5	59.4	52.6
4	29.6	53.3	53.4
5	29.1	79.7	29.8
6	33.4	75.8	29.5

3.4 Discussion

Formic acid is a flat organic molecule, the average length of O=C–O–H bonds is 0.171 nm, the length of O=C–C–H bonds are 0.224 nm (Stein and Sauer, 1997; Goeppert et al., 2002; Jarvis, 2003). The bond length of hydrochloric acid is 0.128 nm. In the crystal lattice of our experimental cellulose and adjacent chains of cellulose microfibrils are linked by zigzag repeating O–H···O–H bonds. The distance of the adjacent up and down chains are about 0.450 nm and of two neighboring O1 bonds in the long molecular axis amounted to 0.240 nm. The stagger of intramolecular hydrogen bonds occurring between O3 and adjacent O5 of the following glucosidic residue is 0.331 nm, the length of intermolecular hydrogen bonds O6···O2 is about 0.238 nm, of bonds O3···O5 ranging from 0.272 nm to 0.279 nm (Zugenmaier, 2001). Therefore, the depression with an area of $0.238 \times 0.279 \times 0.240$ nm which is enclosed by the O6···O2 bonds of one chain, O3···O5 bonds of another chain and the distance of two neighboring O1 between adjacent up and down chains is the limit for other chemical molecules to get into the inner space of the crystal lattice of cellulose. Chemical molecules with their longest distance of bands more than 0.238 nm are not allowed to pass the depression of bands passage into the inner space of crystal cellulose. Therefore, formic acid with 0.224 nm and hydrochloric acid with 0.128 nm of intramolecular bands length could get through the limit to enter the inner space of crystal cellulose. Formic acid is a carbonyl compound and hydrogen bonds are easily formed between the formic acid and cellulose molecules. Once the formic acid penetrated into the crystal lattice, the crystalline lattice of cellulose markedly become swollen. The hydrogen bonds between the chains of cellulose molecules are broken down and new hydrogen bonds between formic acid and

cellulose molecules are formed. Eventually, the rigid framework of crystalline lattice of cellulose is crushed. Because of the hydrochloric acid as catalyst, the bamboo fibers dissolved in the formic solution and are hydrolyzed to glucose and oligosugar.

$$HCOOH + H_2O \longrightarrow HCOO^- + H_3O^+$$

$$[Glu-O-Glu-O-Glu]_n + nH_3O^+ \longrightarrow [Glu-O-Glu]_{n-1} + nGlu + nH^+$$

$$H^+ + HCOO^- \longrightarrow HCOOH$$

Glucose is not stable in an acid environment. When the cellulose hydrolyzes to glucose, degradation of glucose also takes place at the same time. In order to describe the integrated behavior of cellulose hydrolysis in an acid environment, the degradation kinetics of glucose must be studied. When the hydrolysis of cellulose is investigated, the following model can be established:

$$C \xrightarrow{k_{hyd}} G \xrightarrow{k_{deg}} HMF + H_2O \longrightarrow LA + FA \quad (1)$$

where C is cellulose, G is glucose, HMF is 5-hydroxyl methyl furfural, LA is levulinic acid, FA is formic acid, k_{hyd} is the rate constant for the hydrolysis of microcrystalline-cellulose to release glucose and k_{deg} is the rate constant for glucose degradation. Since bamboo fiber is a heterogeneous material, its physical and chemical properties will change during the process of hydrolysis. As a result, the establishment of the hydrolysis model becomes very different. In our investigation, the degree of polymerization of bamboo fibers gradually decreased and when the bamboo fiber resolved in the formic acid solution, the reaction became homogeneous. Model (1) can be used to predict the hydrolysis of cellulose and the degradation of glucose. In general, the kinetic constant of the hydrolysis of cellulose is determined by the catalyst and the conditions under which the reaction occurs.

Commonly, the reaction obeys the Arrhenius equation:

$$K = A_0 \times e^{-E_a/RT} \quad (2)$$

where K is the kinetic constant, A_0 the exponential constant, E_a activation energy, R the universal gas constant and T is temperature. If the concentration of acid were to be considered, the Arrhenius equation could be written as Eq. (3) to predict the hydrolysis of cellulose (Aguilar et al., 2002).

$$K = A_0 \times [H^+]^m \times e^{-E_a/RT} \quad (3)$$

where $[H^+]$ is the concentration of acid and m is an empirical constant. This model presents the mechanism of cellulose hydrolysis and glucose degradation, in which the hydronium ion takes part. It can be seen from the model, that the speed of the hydrolysis of cellulose associates with the kinetic constant, k_{hyd}, of the hydrolysis, the ability of the solvent to dissolve the cellulose and the low degree of crystallinity are favorable conditions for the dissolution of cellulose. The kinetic constant, k_{hyd}, is correlated with the exponential constant A_0, the concentration of acid $[H^+]$, the activation energy E_a and the reaction temperature T. For certain reactions, A_0, E_a and the ability of the solvent to dissolve cellulose are constants. The low degree of crystallinity, high temperature, high concentration of acid and the long reaction time are conditions which can enhance the rate of hydrolysis of cellulose. At the same time, these conditions are not conducive to the stability of glucose, where high temperature and a high concentration of acid accelerate the degradation of glucose. Therefore, the reaction time must be short. The reaction time, reaction temperature and concentration of acid are major factors in the hydrolysis of cellulose.

4 Conclusions

Bamboo fibers were placed in a formic acid solution which contained 4% (w/w) hydrochloric acid. After 30 min, the bamboo fibers began to swell and gradually dissolved. After one hour, the color of the liquor/solution changed to green. After two hours, the bamboo fibers were thoroughly dissolved in the liquor. The color of the liquor became dark. Four hours later, a completely miscible solution of bamboo fibers in formic acid was obtained. The AFM images before the formic acid treatment show a distinctive hierarchical tissue on the surface of the microfibrils. Differential stereoscopic strips were clearly displayed. However, the structural shapes disappeared for 30 min. after the formic acid treatment. The surface of the fibers became smooth and plump. This behavior indicates that the inner rigid bonding of crystalline microfibrils had been loosened and the lattice of the crystal became swollen.

During the hydrolysis of bamboo fibers, the peaks at $2\theta = 22.5^\circ$ of the control cellulose sample were higher and sharper than those after the formic acid treatments for 30 and 90 min. The crystalline index decreased from 71.1% to 66.0% after the sample had been treated for 30 min. Ninety minutes later the crystalline index declined even further to 56.4%. The effect in the crystalline zone was more pronounced than that in the amorphous zone. As a result, the crystalline lattice of cellulose imploded and eventually the rigid framework of crystalline lattice of cellulose was crushed.

From the FTIR spectra of bamboo fibers, the peak of –OH failed to shift away from 3400 cm^{-1}. It is probable that only intramolecular hydrogen bonds were formed when formic acid molecules penetrated into the crystalline

lattice of cellulose. Thus, the rigid molecular framework of bamboo fiber burst, causing cellulose to dissolve in the formic acid solution. Hydrolysis took place following the dissolution. Because of the dissolution, hydrolysis became a homogeneous reaction. There were no differences between the initial crystalline zone and the amorphous zone. As a result, complete hydrolysis was achieved.

The hydrolysis ratio of the bamboo fibers increased with the reaction temperature and time. However, the degradation of glucose also increased with the extension of reaction time and temperature. The optimal hydrolysis condition of bamboo fibers was found to be 60°C for 6 h. The yield of glucose was 54.5% and that of reducing sugars was 79.7%.

Acknowledgements The authors are indebted to the Ministry of Education of China for financial support throughout this important technological research project (Grant No. 750548). We gratefully acknowledge the technical assistance provided by the State Key Laboratory of Pulp and Paper Engineering at the South China University of Technology.

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