Effects of Temperature and Time of Carbonization on the Properties of Bamboo (*Dendrocalamus asper*) Carbon

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Abstract

Lignocellulosic materials such as wood and bamboo have special characteristics when carbonized at high temperature. For example the electrical conductivity of wood and bamboo increases when carbonized at temperature of 800°C or higher. This property can be used for developing smart materials such as fiber reinforced concrete which has function as sensors for load, damage or temperature. In this experiment, betung bamboo (*Dendrocalamus asper*) was carbonized at different temperatures and times of carbonization. The purpose of this experiment was to observe the effect of temperature and time of carbonization on the properties of bamboo carbon. Bamboo in the form of particles were carbonized at temperature of 400°C for 300 min and continued at temperatures of 700, 800, or 900°C for 45, 60, or 90 min. Carbon properties such as yield, fixed carbon, volatile matters, and ash content were determined. Structure properties were studied by X Ray Diffraction (XRD), morphological properties were observed by Scanning Electron Microscope (SEM), and electrical conductivity was measured using LCR meter. Result shows that increasing temperature and time of carbonization have significant effects on the structure and other properties of bamboo carbon. Carbonization at temperature of 800°C for 60 min was considered as an optimum condition.

Keywords: bamboo, carbonization temperature, carbonization time, carbon properties.

Introduction

Indonesia has a great potential of bamboo with more than 150 species of bamboo with trunk diameter from 2cm to more than 20cm grow at all of the regions (Dransfield and Widjaja 1995). Bamboo has been utilized since ancient time for many aspects of people daily life especially in the rural area such as material to build house, house hold appliances, handicraft, food, water transportation tool, musical instruments, traditional ceremony, and others. In recent years, bamboo has been developed for pulp and paper, and composite materials. In addition, bamboo also has a positive contribution to the global climate change as source of carbon stock (Lou *et al*. 2010). Bamboo charcoal also has been used for a long time for fuel, activated carbon, water purifier, gas absorbent; and recently for advanced materials such as electric capacitors (Abe *et al*. 2003, Kim *et al.* 2006, Zhang *et al*. 2009, Sakuma *et al*. 2012).

Carbon properties of many species of bamboo especially from China and Japan have been studied extensively (Zuo *et al*. 2003, Abe *et al*. 2003, Abe *et al*. 2004, Wakisaka *et al*. 2006). However, a detail study on the carbon properties of Indonesian betung bamboo (*Dendrocalamus asper*) is not yet done. The data of carbon properties of bamboo are very important for developing many further applications.

Lignocellulosic materials such as wood and bamboo have special characteristics when carbonized at high temperature. The electrical conductivity of wood and bamboo increases significantly when carbonized at temperature of 800°C or higher (Nishimiya *et al*. 1993, Subyakto *et al*. 2004, Kim *et al*. 2006). This property can be used for developing advanced materials (Byrne and Nagle 1997). Smart concrete, which has function as sensors for load, damage or temperature has been developed from concrete reinforced with synthetic carbon fiber (Chung 2001, Wang *et al*. 2002, Yao *et al*. 2003, Wen and Chung 2007). The synthetic carbon fiber can be substituted with cheaper natural carbon fiber such as from bamboo that has sufficient electrical conductivity. The purpose of this research was to explore the properties of betung bamboo carbon, especially to observe the effects of temperature and time of carbonization on the structure, morphology, and electrical conductivity of bamboo carbon.

Materials and Methods

Mature betung bamboo (*Dendrocalamus asper*) obtained from Bogor, West Java was used as raw materials. Bamboo trunk was cut, the node parts were taken out, so that only internodes parts were used. The trunks were split up and processed using a bamboo crusher and a hammer-mill to obtain bamboo particles. The particles were sieved to obtain homogenous size of particles and then dried in an oven to moisture content less than 5%. Bamboo particles were carbonized at temperature of 400°C for 300 min in an electrical furnace. The char particles were taken out, cooled at room temperature for 24 h, and put in other type of an electrical furnace and carbonized at varied temperatures of 700, 800, 900°C for varied time of 45, 60, and 90 min. Carbon properties such as yield, fixed carbon, volatile matters, and ash content were determined. Structural properties were studied by X Ray Diffraction (Shimadzu 7000), morphological properties were observed by Scanning Electron Microscope (JSM 63660 LA), and electrical conductivity was measured using LCR meter (Krisbow KW06-489). Chemical components (cellulose, hemicellulose and lignin) of raw bamboo particles (that was not carbonized) were also measured.

Results and Discussion

The chemical components of raw bamboo particles (that was not carbonized) were measured. Results show that the chemical components of betung bamboo (*Dendrocalamus asper*) were as follow: 47.8% cellulose, 19.2% hemicellulose, and 28.4% lignin. These results were comparable to the Japanese bamboo (*Phyllostachys heterocycla*) which contains 40.1% cellulose, 22.3% hemicellulose, and 22.1% lignin (Wakisaka *et al*. 2006).

Carbon Properties

Results of carbon properties such as yield, fixed carbon, volatile matters, and ash content at various carbonization temperatures and times were presented in Figures 1, 2, 3, and 4. As shown in Figure 1, the carbon yield decreases as carbonization temperature and time increase. When carbonized at temperature of 400°C for 5 h, the yield was 37%, and it decreased to 3 ~ 22% when the bamboo was carbonized at higher temperatures of 700 ~ 900°C. At carbonization temperatures of 700, 800, and 900°C; increase of time of carbonization also decreases the yield. The lowest yield (22%) was resulted at carbonization temperature of 900°C for 90 min. Abe *et al.* (2003) and Wakisaka *et al*. (2006) observed similar trends. Abe *et al*. (2003) carbonized and activated *P. pubescens* using CO_2 and got the yield of 63% and 47% at carbonization temperatures of 850 and 950°C, respectively. Wakisaka *et al*. (2006) used the same activated gas for *P. heterocycla* and obtained the yield of 80, 63, and 12% at carbonization temperature of 850, 900 and 950°C, respectively. Zuo *et al*. (2003) studied carbonization mechanism of bamboo and stated that at high carbonization temperature, cellulose, hemicellulose and lignin were decomposed; therefore the carbon yield becomes lower.

Figure 2 shows the fixed carbon of bamboo carbon that carbonized at various temperatures and times. Fixed carbon of bamboo carbon that carbonized at 400°C was 74.24% and increases with the increase of carbonization temperature. However, the fixed carbon percentages of bamboo at carbonization temperature of 700, 800, and 900°C for 45, 60, and 90 min were nearly the same (around 90%), except that of 700°C for 45 min was lower (84%). Similar result was obtained by Zuo *et al*. (2003). They obtained fixed carbon of 73 and 83% for bamboo (*Phyllostachys sp*) carbonized at 400 and 600°C, respectively. They also measured the elemental content of carbon (C), oxygen (O) and hydrogen (H); and the result showed that at carbonization temperature of 600°C the contents were C (84%), O (10%), and H (3%).

Figure 3 shows the volatile matters of bamboo carbon that carbonized at various temperatures and times. It can be seen that volatile matters decreases with the increase of carbonization temperature, while it seems no effect of carbonization time especially at temperature of 800 and 900°C. In the carbonization temperature of 400°C, the volatile matters was more than 20%, while at the carbonization temperature of 700 ~ 900°C the volatile matters were less than 5%. Wakisaka *et al*. (2006) determined the contaminants of bamboo (*P. heterocycla*) that carbonized at 800°C (in percent) as follow: Na (1.7), Mg (2.3), Si (5.3), P (4.2), S (3.7), Cl (0.4), K (77.0), and Ca (5.4).

The ash content of bamboo carbon that carbonized at various temperatures and times is presented in Figure 4. Ash content increases from carbonization temperature of 400°C (4.25%) to higher carbonization temperature. The ash contents of bamboo carbon carbonized at carbonization temperatures of 700, 800, and 900°C were 6 to 10%. Increasing carbonization time decreases the ash content.

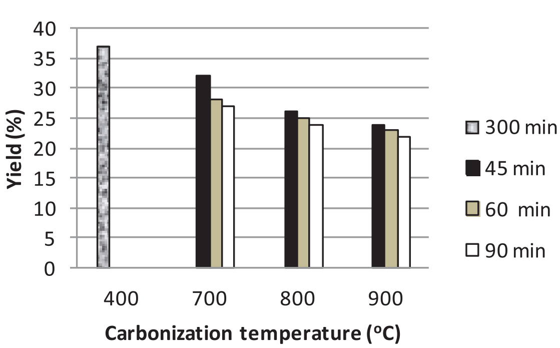

Figure 1. Yield of bamboo carbon.

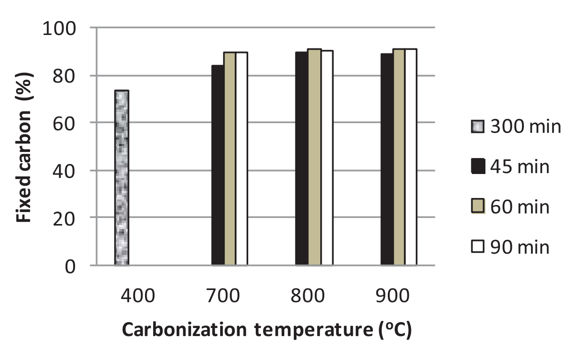

Figure 2. Fixed carbon of bamboo carbon.

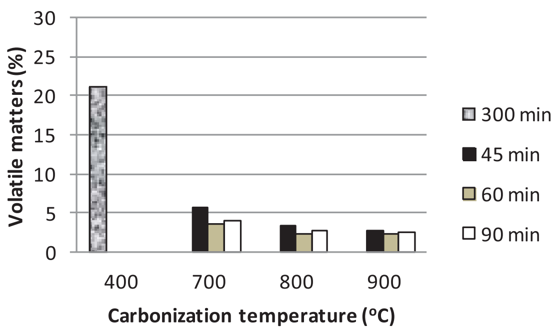

Figure 3. Volatile matters of bamboo carbon.

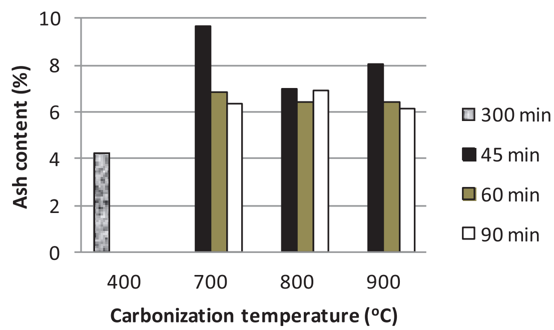

Figure 4. Ash content of bamboo carbon.

XRD Analysis

The x-ray diffraction patterns of bamboo fibers and bamboo carbon at various temperatures and times of carbonization is presented in Figure 5. The typical pattern of cellulose at peak 002 of the 2θ angle = 22.6° was observed (Chen *et al*. 2011; Budiman *et al*. 2011; Liu *et al*. 2012; Brito *et al*. 2012). This peak was disappeared when bamboo was carbonized at various temperatures and times of carbonization, starting at lowest carbonization temperature of 400°C to the highest of 900°C. Cellulose structure was changed to carbon structure. It can also be seen the effects of temperature and time of carbonization on the crystallinity of bamboo carbon (Figure 6). Increasing carbonization temperature increases the crystallinity, while the carbonization time did not affect the crystallinity. The crystallinity of bamboo carbon carbonized at 400°C was 27% and increased to 60% at 900°C.

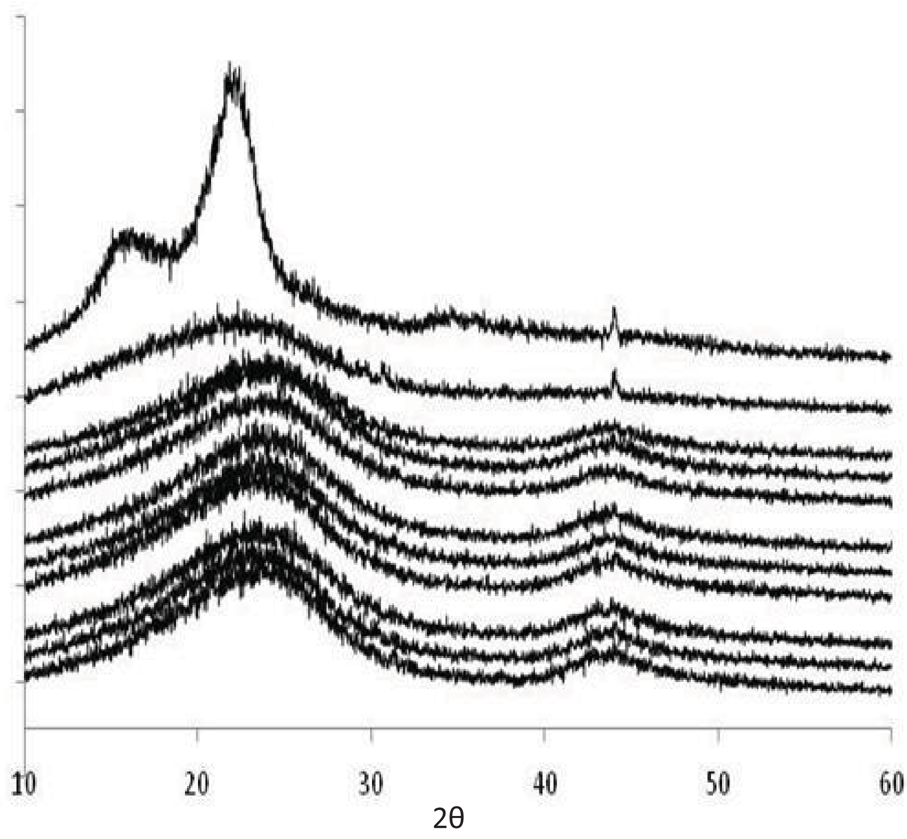

Figure 5. XRD results of bamboo carbon at various carbonization temperatures and times.
Notes: from top to bottom: un-carbonized bamboo, carbonized at 400°C 5h, 700°C 45 min, 700°C 60 min, 700°C 90 min, 800°C 45 min, 800°C 60 min, 800°C 90 min, 900°C 45 min, 900°C 60 min, 900°C 90 min.

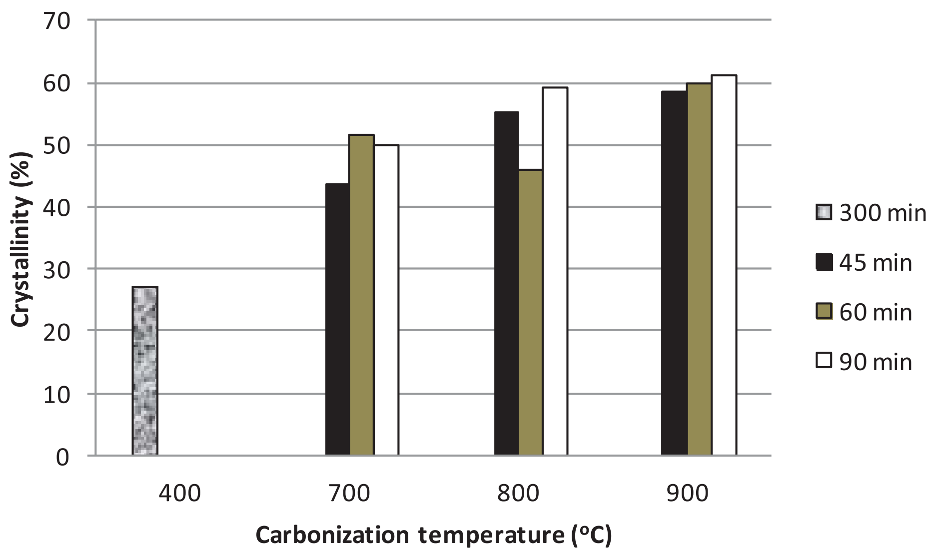

Figure 6. Crystallinity of bamboo carbon carbonized at various temperatures and times.

SEM Images

SEM images of bamboo carbon that carbonized at temperature of 700°C (for 90 min), 800°C (for 45 min), and 900°C (for 90 min) is presented in Figure 7. It shows that at 700, 800 and 900°C the cell structure of bamboo is still maintained. However, the cell wall after carbonization was thinner compared to the original cell wall, due to the diminished of cell wall substructure as observed in carbonized wood (Ishimaru *et al*. 2007).

Electrical Conductivity

Electrical conductivity of bamboo carbon at various carbonization temperatures and times is presented in Figure 8. The electrical conductivity obtained in this research ranged from 30.8 S/m (carbonization temperature of 700°C, 45 min) to 136.9 S/m (carbonization temperature of 900°C, 90 min). The material with these values of electrical conductivity is classified as semiconductor (electrical conductivity=10^{-6} ~ 10^{5} S/m). The raw bamboo has an electrical conductivity of 5.6 x 10^{-8} S/m which classified as isolator (electrical conductivity less than 10^{-6} S/m). While bamboo carbon that carbonized at 400°C has an electrical conductivity of 2.0 x 10^{-6} S/m (semiconductor). The electrical conductivity of bamboo carbon is lower than those of synthetic carbon fibers. For example PAN (polyacrylonitrile) carbon fiber has an electrical conductivity of 10^{4} ~ 10^{5} S/m is classified as conductor (Mallick 2008). However, bamboo carbon with electrical conductivity of 10^{2} may be used as a load sensor for smart concrete, and this will be the subject for our next paper.

Increase of carbonization temperature increased the electrical conductivity which is similar to carbonized wood or other lignocellulosic materials (Nishimiya *et al*. 1995; Subyakto *et al*. 2004; Budiman *et al.* 2012) while the increase of carbonization time increased electrical conductivity only at carbonization temperature of 700°C, but it was not observed at 800°C or 900°C.

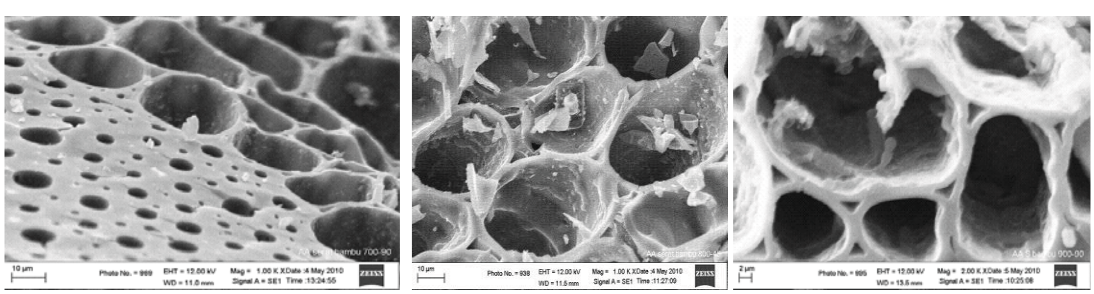

Figure 7. SEM images of bamboo carbon that were carbonized at temperature of 700°C (left), 800°C (center), and 900°C (right).

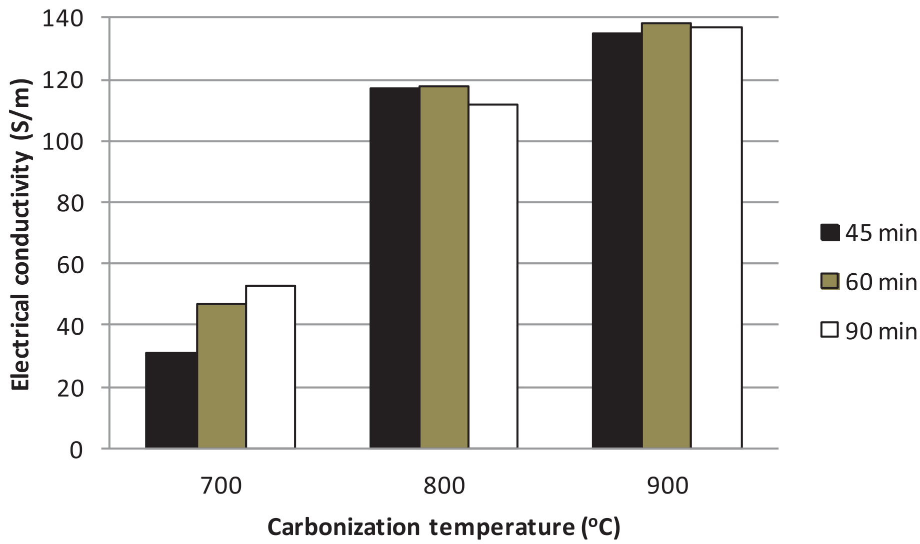

Figure 8. Electrical conductivity of bamboo carbon carbonized at various temperatures and times.

Conclusions

Betung bamboo (*Dendrocalamus asper*) fibers were carbonized at temperature of 400°C for 5 h and carbonized further at 700 ~ 900°C for 45 ~ 90 min, and the properties were determined. Increase of carbonization temperature significantly affected the carbon properties while increase of carbonization time was not. The carbonization temperature of 800°C for 60 min is considered as an optimum condition for bamboo to be developed as advanced materials.

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