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A new application of bagasse char as a solar energy absorption and accumulation material

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ABSTRACT: This study is concerned with the relationship between carbonisation conditions and properties of the resultant bagasse char, and the challenging proposal for the use of fine bagasse char particles as high-performance solar light collectors. Bagasse char was obtained by carbonising raw bagasse at temperatures of 200–900°C for three hours in nitrogen (N_2) gas. Characterisation of the resultant bagasse char was performed by elemental analysis (EA), scanning electric microscope (SEM) observation, estimation of colour, nominal bulk density and evaluation of specific surface area and pore structure by N_2 gas absorption/desorption. The most typical property of the resultant bagasse char is its unique pore structure, which is clear in SEM observation. The largest specific surface area of bagasse char in this study was about 600 m^2/g, which is as large as commercial activated carbon materials. Macro-, meso- and micro-porous structures in the bagasse char induce many important characteristics, such as increased hydrophilicity, very low bulk density and excellent light absorption and accumulation. We also suggest the use of bagasse char as an excellent heat insulation material. The energy used for air conditioning in a private house or office building can be decreased by more than 50–60% by use of this insulator on the roof or walls.

KEY WORDS: bulk density, carbonisation, collector, dispersion, EA, gas absorption/desorption, heat insulator, hydrophilic, particle, porous structure, SEM, specific surface area

In the face of problems such as global warming, fossil resource depletion and fossil energy saving, the rapid development of sustainable new energy systems such as solar energy, wind energy and biomass energy are required. The Japanese Government's 2006 'New Energy Strategy' made the commitment to decrease final energy consumption by 30% by 2030 (METI 2006). At the UN Congress, the Japanese Prime Minister also declared a reduction of 25% in carbon dioxide emissions by 2025 in comparison with 1990. Unfortunately, Japan experienced a nuclear disaster on March 11th 2011, and it is possible that this accident may impact on the energy strategy in many countries.

Biomass, which is sustainably produced by photosynthesis from CO_2 and H_2O, is the only sustainable and carbon-neutral option amongst many potential materials. Therefore, biomass char made by the carbonisation of biomass is also an eco-friendly material. Sugarcane is one of the most useful mass-produced plants. More than 1·71 billion tons of sugarcane was harvested annually worldwide in 2010, and several hundred million tons of trash and bagasse are simultaneously discarded as by-products or wastes from sugar milling factories (FAOSTAT 2012). Bagasse, which is collected in sugar milling factories by farmers and then granulated, squeezed, washed, cleaned and dried, therefore presents itself as a most useful biomass resource, and potential new applications of bagasse in many fields must be developed.

The past two decades have seen a number of studies on bagasse char. Tsaia *et al.* (2006) reported on various kinds of biomass char obtained using rice straw, sugarcane bagasse and coconut shells, and Shinogi & Kanri (2003) discussed the relationship between carbonisation condition and properties of resulting carbonaceous materials, with the specific surface area of bagasse char reported by Shinogi & Kanri (2003) being lower those in the results reported below. Katyal *et al.* (2003) noted that, from the viewpoint of carbon content in bagasse char and its application, the most suitable temperature for the carbonisation of bagasse was above 500°C. Zandersons *et al.* (1999) presented a carbonisation process from raw bagasse to bagasse char through transitional stages. Luoa & Stanmorea (1992) reported the bagasse char combustion kinetics on the basis of a TGA study, and Shiyi Qu *et al.* (2007) studied methods for obtaining organic compounds by the pyrolysis of bagasse. The relationship between pyrolysis conditions and the structure of the resultant char has been reported by Cetin *et al.* (2004).

Carbonaceous materials derived from bagasse have been proposed for use in, amongst other applications, cosmetics, fuel (gas, oil), chemicals and activated carbon (Bridgwater 2003). However, new applications of bagasse char in the area of light-sensitive functional materials have hitherto not been presented. We have previously shown that bagasse char carbonises at 500°C or greater, and that it is very hydrophilic and easily dispersed in water (Kondo *et al.* 2008). Furthermore, the bagasse char displayed superior heat absorption owing to its characteristic pore structure (Kondo *et al.* 2008). This is a

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very important property in terms of energy saving and solar light controlling for houses, buildings, plant-factories, etc. Here we present the carbonisation conditions and properties of the resultant bagasse char, as well as its potential applications as a heat insulator of houses and other buildings, and further high-end applications. The application of this system as a heat-insulator for houses could reduce the energy consumed in houses or office buildings by 50% (which is almost equal to 15% of the total energy consumption in Japan, for example).

The final goal of our study is to develop a high-performance solar energy absorption/accumulation system using bagasse char that can directly supply hot and cold water through an adsorption refrigerator.

1. Experimentation

1.1. Carbonisation of raw bagasse

1.1.1. Carbonisation conditions. The raw bagasse used in this study was supplied by the Miyako Sugar Mill company in Okinawa, Japan. At first, raw bagasse was completely dried at 100°C for 24 hours under an N_2 flow in an air oven dryer and then carbonised at 200–900°C with a temperature ramp rate of 5°C/minute in a muffle-type electric furnace, in which it was held at each carbonisation temperature for three hours before finally being cooled to room temperature.

1.2. Characterisation of the resultant bagasse char

Each sample of bagasse char was coated with a thin gold layer using a plasma coating system. The fine structure of the bagasse char was then observed with a scanning electron microscope (SEM) (SSX-550, Shimadzu Corp., Japan). The total carbon content of the resultant bagasse char was calculated from the carbon content evaluated with a Shimadzu NC-Analyzer NC-90A; each sample of bagasse char was completely dried at 120°C for 24 hours in an air oven before measurement. The specific surface area was automatically estimated using a Trister 3000 (Shimadzu Co., Japan), and micro- and meso-pore volume distribution in the bagasse char was measured by N_2 adsorption at 77°K with a Molecular Probe (MP) and the Barret–Joyner–Holenda (BJH) method using an ASAP-2420 Accelerated Surface Area and Porosimetry system (Shimadzu Co., Japan); the sample was outgassed at 10 μmHg and 120°C for one hour before measurement. The colour property of the resultant bagasse char was evaluated using a CR-300 Colour Meter (Minolta Co., Japan) and characterised by L-value, a-value and b-value, based on the CIE standard. The L-value indicates the white–black tendency, where L = 100 means pure white (MgO plate) and L = 0 means pure black, such as piano black. The a-value indicates its position on the red–green scale, and the b-value indicates its position on the blue–yellow scale. The nominal bulk density of the resultant bagasse char was measured according to the JIS K-7365(1999) standard. Elemental analysis (EA) was undertaken as follows: 20 ml of 0·5 w% HNO_3 aqueous solution was added to 0·1 g of bagasse char and the mixture was heated at 80°C for 24 hours and then filtered on No.6 filtration paper (Adavantec Co., Japan) to separate the precipitate and extract. The amount of each component in the resultant extract was measured and calculated with an ICPS-8100 Inductively Coupled Plasma Optical Emission Spectrometer (Shimadzu Co., Japan).

1.3. Evaluation of the absorption and accumulation of light and heat by the bagasse char

Bagasse char, produced as above, was milled in a mechanical blender (HBB250S, Hamilton Co.) and then graded by sieving to obtain particles of <150 μm diameter. These fine particles of bagasse char were well dispersed in a water (H_2O) and ethylene glycol (EG) mixed solution (H_2O/EG = 70 w%/30 w%) at bagasse char contents of 0%, 0.1%, 0.3% 0.5% and 1% by weight. Light transmittance and absorption of each solution were measured with a UV-VIS Spectrometer (UV-1600, observation range of 200–900 nm, Shimadzu Co., Japan) and a FT-IR Spectrometer (FTIR-MPA, observation range of >900 nm, Brucker Co., Germany).

1.4. Simulation of the amount of electricity used for air conditioning in a standard Japanese private house

In order to apply our results to the operation of a solar light collector or a heat insulator, a thin transparent tank of 5 mm depth and filled with bagasse char particles suspended in water was designed. This device can absorb light in the range of wavelengths from visible light (VIS) to infra-red (IR) and it can therefore be expected to function as a solar light collector. This device's shape, without metal pipes and fins, is quite different from current commercialised solar collectors. If this solar heat collector is effective, its liquid absorbs almost all incident solar radiation. Thus, when installed on the roof of a building, it can also function as a solar heat protector and insulator when cooling the building.

The simulation to estimate the performance as an insulator was undertaken as follows. A model house for the simulation was as a two-storey single unit house constructed of reinforced concrete. It was designed as an ordinary two-storey Japanese house, with a floor area of 64 m^2 (8 m × 8 m) and ground-floor ceiling height of 3 m. The total floor area was 128 m^2 (64 $m^2 \times 2$) and the total two-storey wall height was 6 m. Heat transfer between indoor and outdoor air was calculated under the following conditions. The working liquid was regarded as 0·5 wt% bagasse char and it was presumed to absorb 90% of solar radiation. Hourly air temperature and solar radiation data on July 17th at Naha city in Okinawa, Japan were used. The roof and the walls were made of 18 cm-thick concrete. Steady-state heat conduction was adopted and there was no heat source inside the house. Natural indoor air temperature fluctuations of the following three cases were calculated:

Case 1: A conventional house (control case).
Case 2: A model house with a high-performance heat insulator made of bagasse char installed on the entire rooftop (64 m^2).
Case 3: A model house with a high-performance heat insulator made of bagasse char installed on the entire rooftop (64 m^2), as well as on the east and west walls.

The cooling loads of these cases were also calculated when the natural indoor air temperature was fixed 28°C by air conditioning when the natural indoor air temperature was greater than 28°C. Electricity consumption (kw) to maintain the room temperature at 28°C during the summer daytime was simulated for the above three cases.

2. Results and discussion

2.1. Value-chain from sugarcane to bagasse char

Figure 1 and Table 1 show the materials, masses and expected values for each step from sugarcane to bagasse char. A large amount of sugarcane, more than 1·3 billion tons, is harvested annually worldwide, resulting in by-product trash and bagasse, several hundred million tons of which are discarded as waste. In this study, we started with 100 kg of sugarcane for easy evaluation. One hundred kilogrammes of sugarcane are converted to 12·8 kg of sugar, as well as 24·6 kg of bagasse and

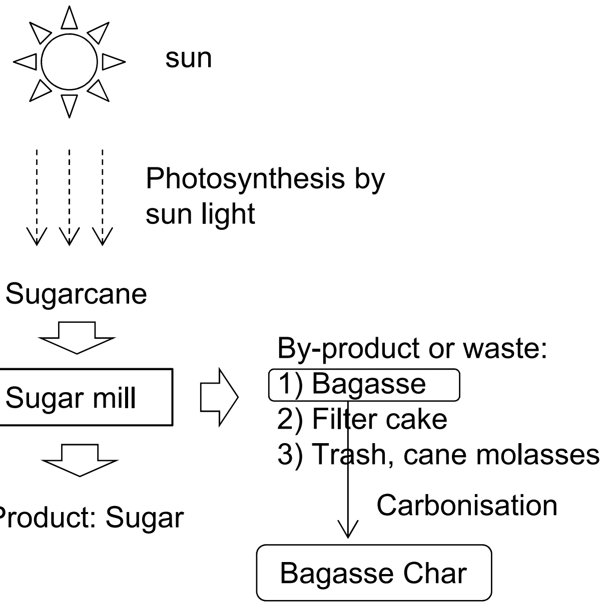

Figure 1 Material flow from sugarcane to bagasse char.

Table 1 Material and value-chain from sugarcane to bagasse char

	Material	Mass (kg)	Cost ($/kg)	Value ($/kg)
Raw material	sugarcane	100	0·0499	4·99
Product	sugar	12·8	0·7241	9·27
Waste	**bagasse**	**24·6**	0·0125	**0·33**
	filter cake	7·2	0·0125	0·09
↓	cane molasses	3·1	0·0125	0·04
New application	**bagasse char**	**2·6**	12·4844	**32·46**
	(activated carbon)	**5·3**	7·4906	**39·70**

* $1 = 80·14 JPY (June 21 2011)

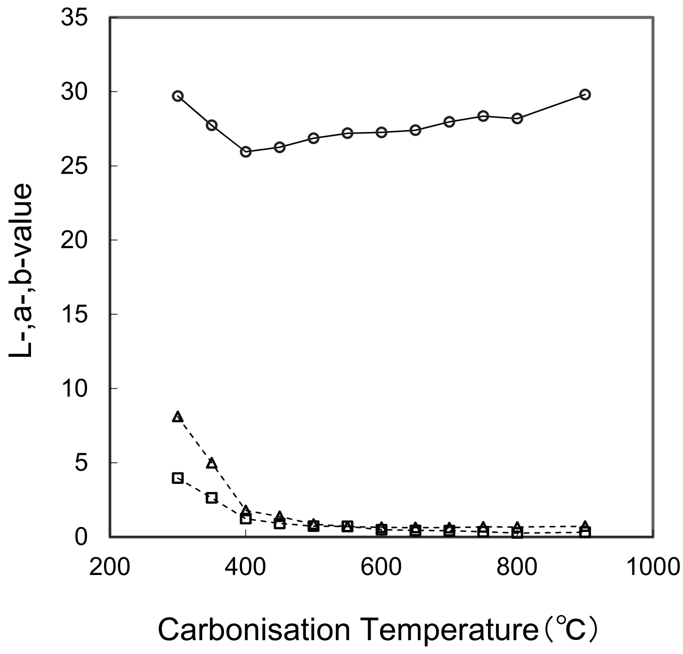

Figure 2 Relationship between colour properties and carbonisation temperature of bagasse char. L-value, a-value and b-value are represented by closed circles (○), open rectangles (□) and open triangles (△), respectively.

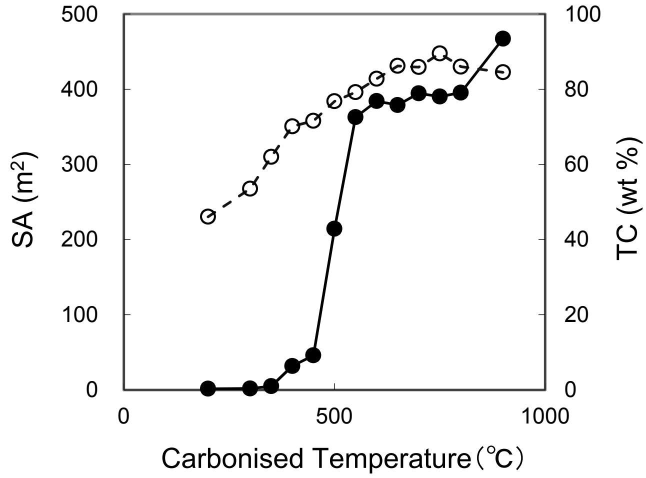

Figure 3 Relationship between the specific surface area (SA; closed circles •) and total carbon content (TC; open circle ○) of bagasse char against carbonisation temperature. Both SA and TC increase with increased temperature. SA increases rapidly at temperatures greater than 500°C.

7·2 kg of filter cake as by-products. From 24·6 kg of bagasse, 2·6–5·3 kg of bagasse char can be obtained by carbonisation, the actual amount strongly depending on the carbonisation conditions.

Next, we considered the value of the by-products generated. Sugarcane is sold by farmers to the sugar mill for $0·0499/kg and bagasse is returned to farmers for about $0·0125/kg. So, 100 kg of sugarcane generates $9·73 in total, as shown in Table 1. On the other hand, activated carbon for industrial use is sold for several tens of dollars/kg or more, which is expensive compared with the value of raw bagasse. Thus, if we could produce activated carbon from bagasse, we could generate $32·46–39·70 from 2·6–5·3 kg of bagasse char. This is the essential reason for this study's research and development of a new application for bagasse char.

2.2. Relationship between carbonisation conditions and properties of the resultant bagasse char

Properties such as colour, specific surface area (SA) and total carbon content (TC) varied markedly according to the carbonisation conditions (Figs 2, 3). The colour of the bagasse char obtained at 200°C to 500°C gradually changed from yellow to black, with the colour of bagasse char obtained at over 500°C remaining almost black (Fig. 2). Figure 2 shows that the L-, a- and b-values decreased with increases in the carbonisation temperature up to 400°C, but the L-values increased at temperatures greater than 500°C. In other words, it can be seen that the carbonisation of bagasse is complete at temperatures greater than 500°C.

The values of SA in bagasse char obtained at temperatures lower than 400°C are as low as 30 m^2/g (Fig. 3), indicating that the microporous structure in the bagasse char is not generated at temperatures below 400°C. However, the SA values rapidly increases at temperature greater than 500°C, to SA values exceeding 450 m^2/g. This increase is attributed to the formation of a large number of both meso- and micropores in the bagasse chars.

The distribution of micro- and mesopores in bagasse char, estimated using MP and BJH methods based on the adsorption/desorption isotherms of N_2 gas, are presented in Figures 4 and 5, respectively. It is apparent that both micropores of 2 nm (20 Å) or less in diameter, as defined in IUPAC (McCusker *et al.* 2001), and mesopores of 2–50 nm (20–500 Å) diameter are

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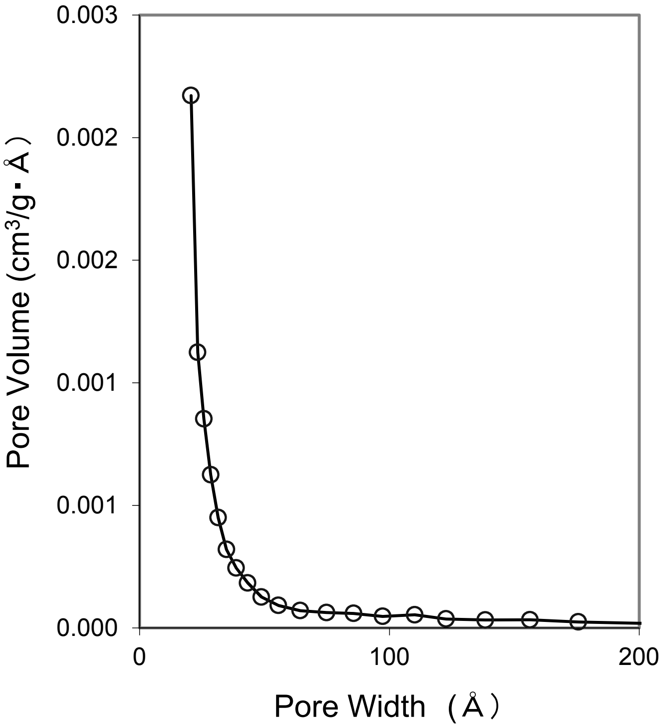

Figure 4 Relationship between pore volume and pore diameter as measured by the BJH method in the meso-pore range. N_2 absorption/desorption isotherms are obtained at 77°K.

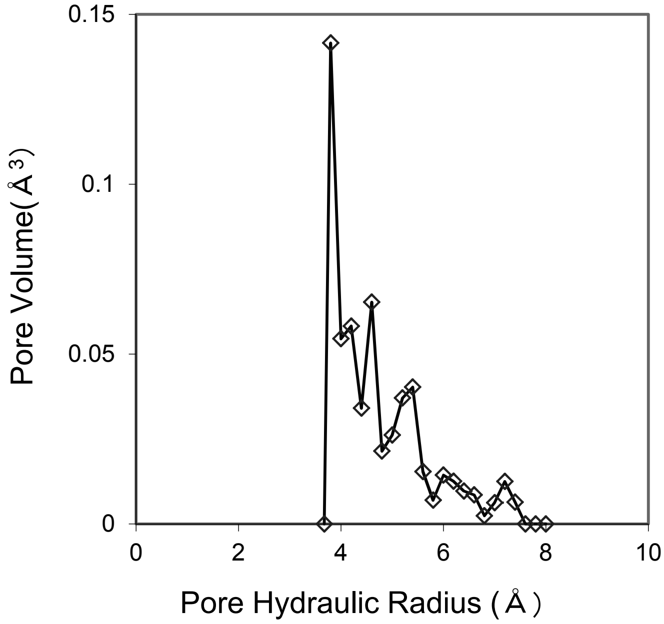

Figure 5 Differential pore volume versus pore hydraulic radius of bagasse char evaluated by the MP method in the micropore region. Several peaks are observed in the micropore region.

generated. The diameters of macropores in the bagasse chars, as observed by SEM, are around 10–30 µm, and seem to reflect the sugar storage chamber and vascular structure of sugarcane. Meso- and micropores are too small to be observed by SEM; however, the SA values in Figure 3 confirm a large number of such pores in the cell wall, reflecting volume shrinkage or volatilisation of organic components during carbonisation. Figure 5, therefore, shows the results of porosity distribution measured by the MP method, with several peaks of micropores in the bagasse char, with radii of 0·38 nm (3·8 Å), 0·42 nm (4·2 Å), 4·6 nm (4·6 Å), 5·4 nm (5·4 Å), 6·0 nm (6·0 Å) and 7·2 nm (7·2 Å). These micro-, meso- and macropores (see SEM images) play a vital role in solar heat absorption and accumulation (see below). The volume of each pore and the ratio of mesopores to

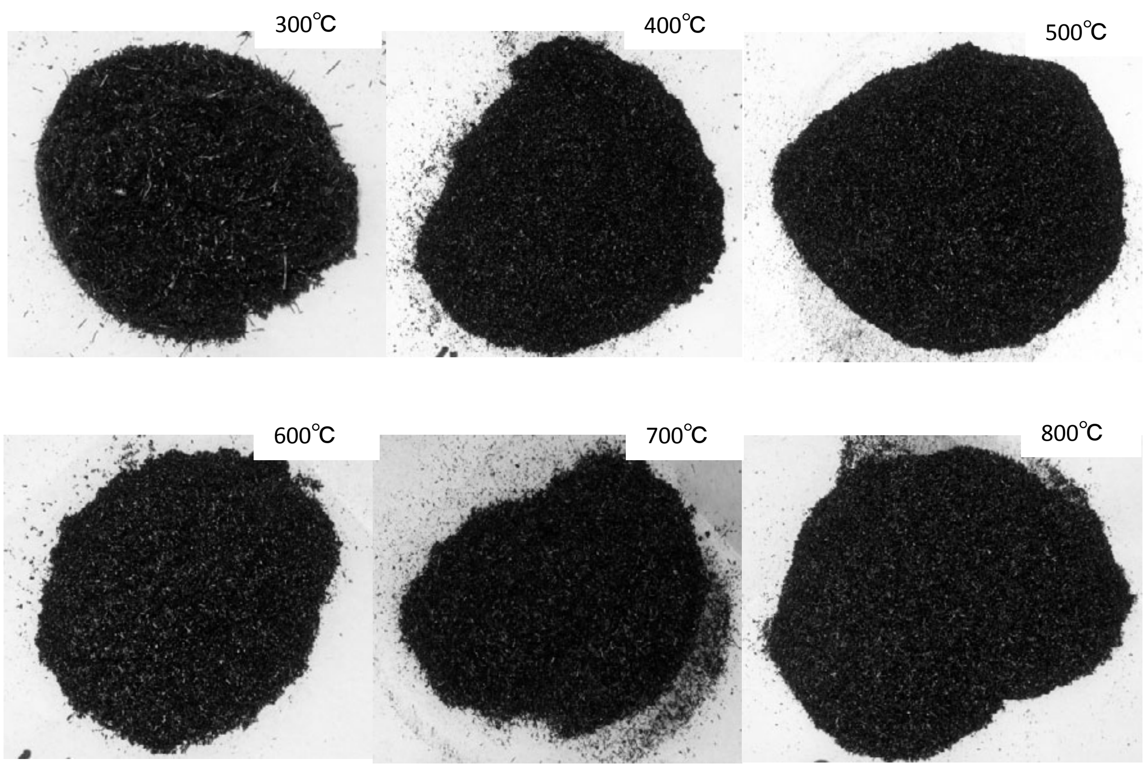

Figure 6 Photos of bagasse char obtained under various carbonisation conditions. The values 300°C, 400°C, 500°C, 600°C, 700°C and 800°C on the photos indicate the carbonisation temperature.

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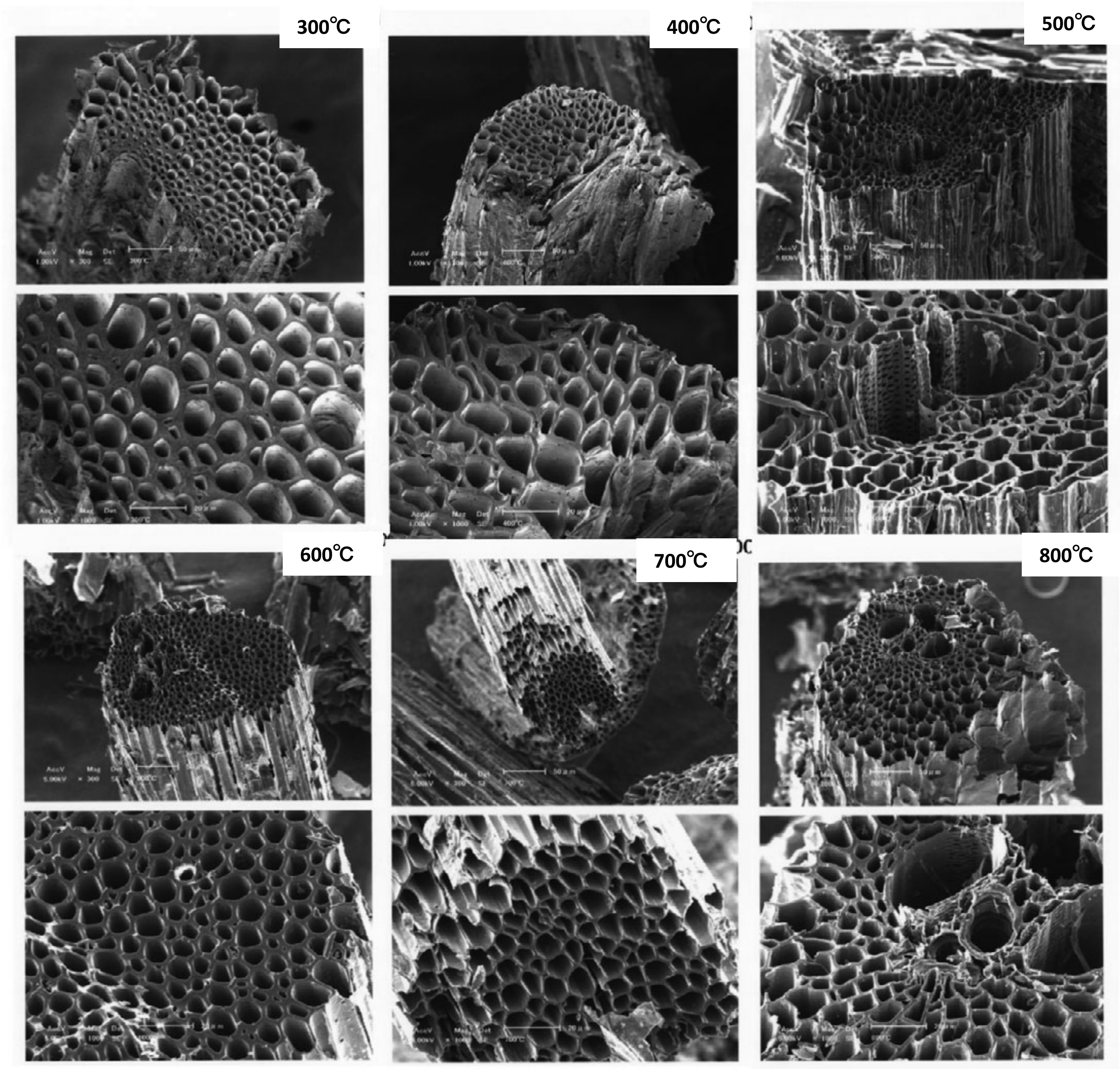

Figure 7 SEM images of bagasse char. The typical porous structures reflecting the vascular structures of the original sugarcane are well preserved in bagasse char. The values 300°C, 400°C, 500°C, 600°C, 700°C and 800°C on the photos indicate carbonisation temperature.

Table 2 Mineral constituents of bagasse chars by ICP analysis.

Carbonised temperature (°C)	Mineral (mg/g)													
	B	Na	Mg	Al	Si	P	S	K	Ca	Mn	Fe	Cu	Zn	Total
300	0·065	0·365	0·267	0·155	0·363	0·292	1·014	3·667	0·672	0·009	0·073	0·001	0·009	6·951
350	0·107	0·468	0·096	0·225	0·473	0·324	0·889	5·112	0·722	0·004	0·045	0·008	0·005	8·479
400	0·064	0·427	0·305	0·176	0·440	0·701	1·888	7·938	1·899	0·011	0·101	0·000	0·057	14·01
450	0·064	0·432	0·545	0·197	0·461	0·770	2·753	8·563	1·309	0·022	0·117	0·001	0·098	15·33
500	0·101	0·528	0·276	0·363	0·587	0·674	1·721	9·057	1·689	0·012	0·139	0·005	0·049	15·20
550	0·070	0·488	0·505	0·302	0·495	0·978	2·094	10·46	1·826	0·019	0·185	0·020	0·034	17·47
600	0·310	1·083	0·208	0·808	0·982	0·261	1·382	9·946	2·155	0·010	0·088	0·015	0·038	17·29
650	0·072	0·487	0·199	0·229	0·460	0·304	0·796	10·35	1·324	0·008	0·096	0·009	0·022	14·36
700	0·057	0·428	0·208	0·313	0·570	0·295	0·653	10·41	1·654	0·008	0·121	0·000	0·060	14·78
750	0·064	0·428	0·404	0·448	0·705	0·265	0·730	10·99	2·917	0·012	0·321	0·000	0·064	17·35
800	0·180	0·750	0·291	0·652	0·894	0·301	0·924	10·57	4·890	0·011	0·125	0·013	0·130	19·73
900	0·098	0·621	1·153	0·595	1·081	1·161	2·888	11·46	3·743	0·033	0·112	0·004	0·221	23·17

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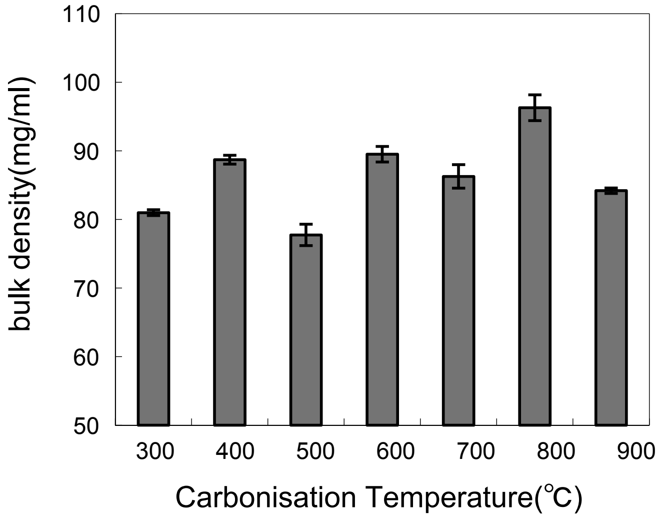

Figure 8 Relationship between the bulk density of the bagasse char and carbonisation temperature. Bulk densities of the resultant bagasse chars are very small, with a minimum value of about 78 mg/mL.

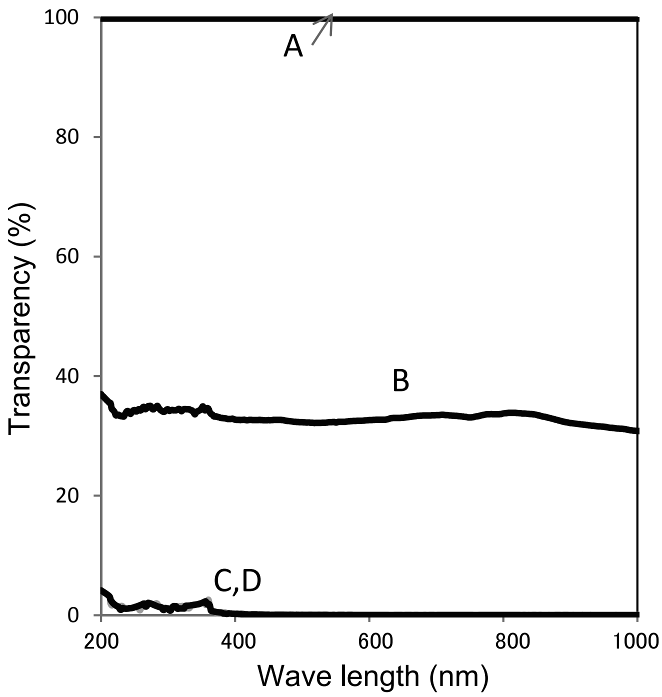

Figure 9 Wave length dependence on the transparency of bagasse char dispersed in water in the UV to NIR range: (A) 0 wt.% (=reference) bagasse char content in water; (B) 0·1 wt.% bagasse char content in water; (C) 0·5 wt.% bagasse char content in water; (D) 1 wt.% bagasse char content in water.

the total pore volume were calculated and the results indicated (i) that total pore, mesopore and micropore volumes were 0·126 cm^3/g, 0·080 cm^3/g and 0·460 cm^3/g, respectively; and (ii) that mesopores occupied 63·5% of the total pore volume. The existence of large numbers of mesopores in the bagasse char is expected to play an important role in its applications as functional materials such as activated carbon and air filters.

Figures 6 and 7 show optical photos and SEM images of the bagasse char. These "honeycomb-like" pore structures have their origins in the sugarcane's vascular organ structure. The results of EA by ICP-analysis (Table 2) show that the bagasse char includes an Si component, which works as reinforcement, forming a hard and heat-stable vascular structure. The SEM images show that the typical porous structures of bagasse char continue straight through the stem to the end of each leaf.

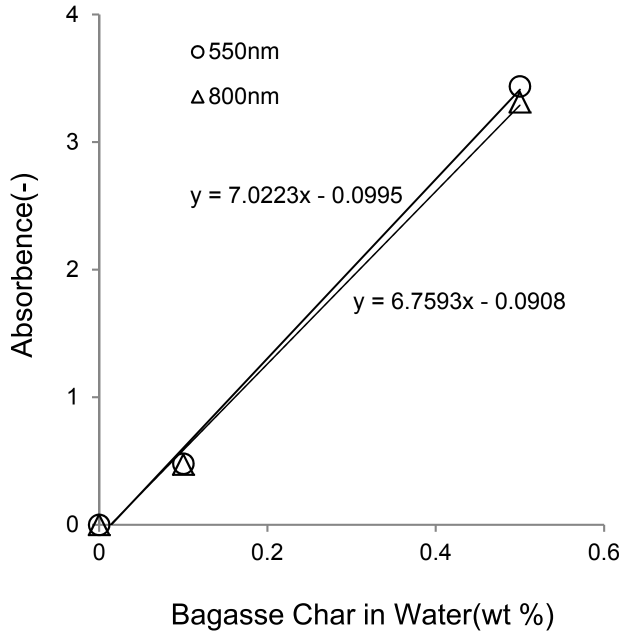

Figure 10 Relationship between the absorbance of bagasse char dispersed in water and bagasse content. The two lines observed at different wave lengths (Δ:800 nm and ○:550 nm) show identical tendences.

Fine particles of the bagasse char are quite easily dispersed in water without the need for any dispersant. This means that the bagasse char in this study has excellent hydrophilicity, due to the presence of macropores and residual mineral constituents such as K^+, Na^+, Ca^{2+} and Mg^{2+} in the bagasse char, and the char's very low bulk density (Fig. 8).

2.3. Absorption and accumulation properties of solar light and heat by the bagasse char

2.3.1. Properties of the bagasse char used in this study. The nominal bulk density of the bagasse char exhibits a minimum value around 500°C (Fig. 8). The crystallisation in the bagasse char begins at temperatures greater than 500°C, and so the bulk density of the bagasse char gradually increased after 500°C. Furthermore, the results of elemental analysis (EA), summarised in Table 2, show that the content of the various mineral constituents gradually increases due to volume shrinkage with increases in the carbonisation temperature.

2.3.2. Preparation of the bagasse char dispersed water for light absorption testing. Fine particles of the bagasse char were ultrasonically dispersed in water for 30 minutes. The bagasse char particles were found to be well dispersed and stable in the water for more than a day. Carbonaceous materials are generally very difficult to disperse in water due to their strong hydrophobicity, but the bagasse char in this study is easily dispersed in water due to its strong hydrophilicity and its very large pore volume. This hydrophilicity is particular to the bagasse char and not observed in other carbonaceous materials such as wood char, bamboo char or palm char. Thus, the higher hydrophilicity and high degree of porosity of the bagasse char affords excellent properties, such as higher water retention, as compared to other biochar materials such as palm char and wood char.

2.3.3. Light absorption by the bagasse char dispersed in water. Figure 9 shows the light absorption properties of the bagasse char dispersed in water, and reveals uniform absorp-

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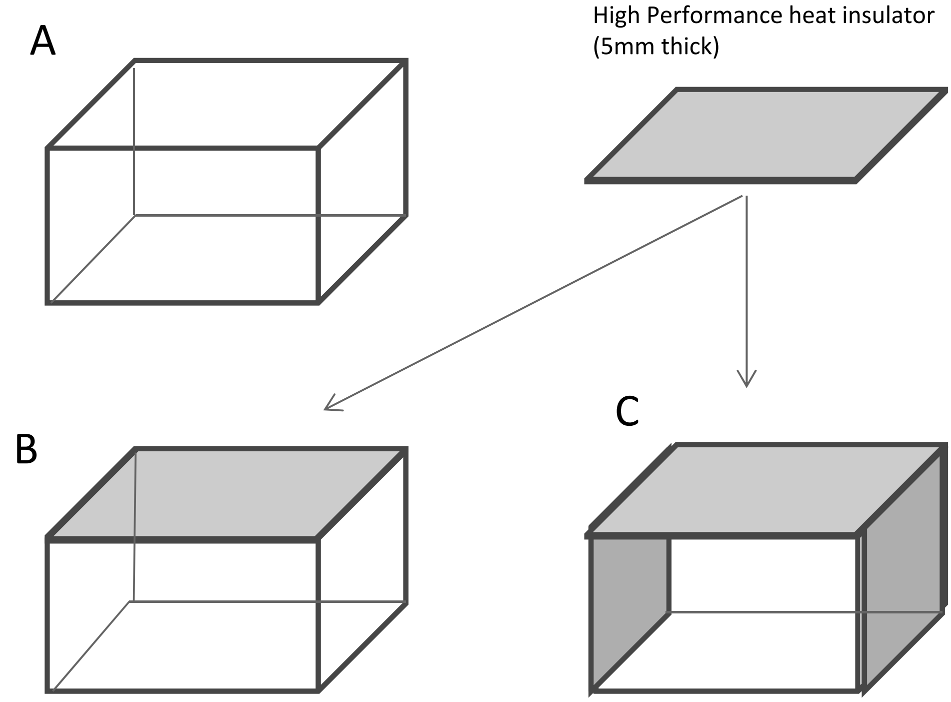

Figure 11 Simulation models of energy saving achieved by the installation of a heat insulator containing bagasse char: (A) Case 1 (control); (B) Case 2, in which the high performance heat insulator is installed on the roof; (C) Case 3, in which the high performance heat insulator is installed on the roof and on the east and west walls of the model house.

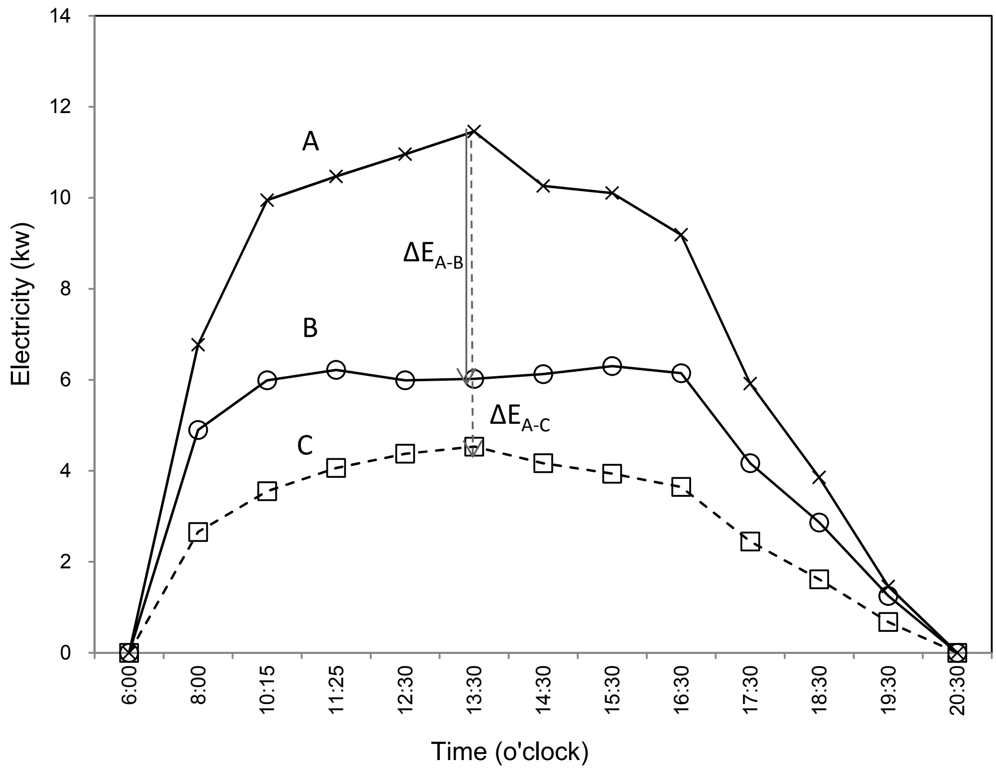

Figure 12 Calculated electricity required for air conditioning to maintain the room temperature at 28°C on a day in midsummer: (A) results for Case 1; (B) results for Case 2; (C) results for Case 3. $\Delta E_{A\text{-}B}$ and $\Delta E_{A\text{-}C}$ indicate the electricity saving for Case 2 and Case 3, respectively, as compared to the control (Case 1).

tion without any characteristic absorption spectra in the UV–VIS–IR region. This result also demonstrates that bagasse char is the best material for solar light absorption, with advantages including low cost, non-toxicity and light weight, as well as being environmentally more benign and an indigenous resource that is commonly available in many regions. Light absorption is increased by raising the carbonisation temperature as shown in Figure 2, which shows that the optimum carbonisation temperature for light absorption is around 500°C.

The relationship between bagasse content in water and light absorption is shown in Figure 9, with the relationship shown in Figure 10 confirming that this behaviour can be well explained by Lambert-Beer's Law (Eq. 1),

$$I = 100 \times 10^{-\varepsilon^{cl}} \quad (1)$$

where I is transparency (%), ε is the absorption coefficient (=constant), c is the bagasse content in water and l is the length of the light pass. The linearity of the relationships between absorbance and weight % of bagasse biochar in water confirms that the bagasse char is, as noted above, well dispersed in water. The absorption behaviour in the NIR–IR–Deep IR region also shows the same tendency. Thus, it is concluded that 0·5% by weight bagasse char dispersed in water can completely absorb all UV–VIS–IR light.

2.4. A potential new application of the resultant bagasse char as a high performance heat insulator

These results with regard to light absorbance confirm that bagasse char dispersed in water can act as a high performance heat insulator for buildings. Conventional passive heat insulators have many disadvantages, including high cost, thickness (more than 150 mm) and heavy weight, and difficulty in construction. Bagasse char, on the other hand, has many advantages as a heat-insulator system, including low cost, lower thickness (only 5 mm), light weight, and ease of installation on walls or roofs. Figure 11 shows the three types of model houses used for the simulation of the electricity consumption (kw) required to maintain room temperature at 28°C for one day in summer (July 17th) in Okinawa, Japan, for each of the three house models (Cases 1, 2 and 3 – see section 1.4) (Fig. 12). It can be seen that electricity consumption in Case 2 is almost half of the energy consumption in the control (Case 1), and Case 3 shows a two-thirds reduction in energy consumption compared with the control. These results suggest that bagasse char heat insulation shows considerable promise as an energy-saving device for low-energy buildings.

3. Conclusions

Bagasse char was obtained by carbonising raw bagasse at temperatures of 500°C or higher in N_2 gas. The resultant bagasse char has many unique characteristics: it is very hydrophilic; has very low bulk density (78 mg/mL); contains a range of macro-, meso- and microporous structures; and displays considerable capacity to absorb light and heat.

Bagasse char obtained in this study is easily dispersed in water and in this state absorbs and accumulates a wide range of UV–VIS–IR light energy. Thus, bagasse char has the potential to contribute to energy saving through its application as a high-performance heat insulator installed on the walls and/or roofs of buildings.

4. Acknowledgement

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