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Characteristics and performance analysis of a natural desiccant prepared from coconut coir

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ABSTRACT: The objective of this paper is to investigate the use of coconut coir (*Cocos nucifera*) as a desiccant for moisture adsorption in an engineering process. The physical, thermal, chemical, and adsorptive properties of un-boiled, 0.5 h, and 1 h boiled dried coconut coir were analysed. Coconut coir surface characteristics were examined by scanning electron microscope and pore size distribution and surface area were examined by mercury porosimeters. Chemical composition has been investigated using energy dispersive X-ray spectroscopy. Moisture adsorption isotherms of dried coconut coir were determined by the static method. Measurements of heat capacity revealed that boiling the coconut coir decreases the specific heat capacity from 4.33 to 3.83 kJ/kg K at 75 °C. Boiling, however, decreases the adsorption efficacy. The recommended time for boiling should be limited to no more than half an hour. The study confirmed the feasibility of using coconut coir as a desiccant.

KEYWORDS: agricultural waste management, adsorption isotherm, pore size distribution, coconut surface structure

INTRODUCTION

Since Thailand generates a large amount of agricultural waste, it is important to seek a method to dispose of this material that increases its value, promotes the use of natural products, and assures good environmental management. In Thailand the amount of coconut (*Cocos nucifera*) production is about 1.9 million tonnes/year. Energy potential evaluation of agricultural wastes[1] indicated that waste-production ratio of coconut coir is about 0.362, meaning that coconut coir, as agricultural waste, is produced at a rate of 0.69 million tonnes/year. The portion of coconut coir used to produce energy is about 0.2 million tonnes/year, and about 0.08 million tonnes/year is used in other applications such as for cultivating seedlings and plants, as fertiliser, or coir fibre. A large amount of coconut coir (0.41 million tonnes/year) is still not used for good purposes. Thus, many researchers are searching for alternative uses of coconut coir as a building material[2–4]. Dried coconut coir and durian can also be used as a desiccant for air conditioning[5,6]. In this article, coconut coir, the fibrous mesocarp consisting of the middle layer between the tough exocarp and the endocarp or hard shell, is investigated as a potential desiccant.

A desiccant is a substance that adsorbs water, commonly used to remove humidity that would normally degrade or even destroy products sensitive to moisture. The term desiccation refers to the state of extreme dryness or the process of extreme drying, an extreme form of dehydration. In fact, natural fibres have been successfully converted into a desiccant (sorbent) by either using unmodified fibres, where most of raw materials need to be cut into small pieces or transformed into powder, or using fibres modified by physical or chemical methods. Examples of modified fibres are desiccants based on starch[7] and activated carbon from rubber wood[8].

Adsorption isotherms are useful in determining the adsorption capacity, which indicates the effectiveness of a desiccant or an adsorbent. Moisture adsorption characteristics of dried materials have been deeply studied especially for food materials such as barley[9] or amaranth starch[10].

The aim of this study is to analyse the feasibility

of using mature coconut coir as a desiccant and to analyse the effect of boiling on the potential of the mature coconut coir in the state of extreme dryness as a desiccant. Analyses for exploring pore size distribution, surface area characteristic, specific heat capacity, chemical composition content, and water vapour adsorption characteristics were performed. This knowledge can help in the development of applications such as dehumidification systems, essential for hot, humid climates like that in Thailand.

MATERIALS AND METHODS

Coconut coir desiccant preparation

In this study, the mature coconut coir was considered, as it is widely available in the country. Three types of coconut coir are considered namely non-boiled, 0.5 h, and 1 h boiled mature coconut coir. To prepare the desiccant, the coconut coir was cut into small cubes about 2 cm in length. Afterwards, the mature coir was boiled for the specified time and then washed. The moisture content of products is reduced to 2% in dry basis. The dry matter of coconut coir was determined gravimetrically by drying it in an oven (MEMMERT, Model UE 200-800) at 105 °C for 72 h. Dry-basis moisture content (M_{d}) was calculated as the weight ratio of water to dry matter, or $M_d = (W - d)/d$, where W is weight of coconut coir and d is dry weight of coconut coir.

Physical analysis

In order to analyse the surface characteristic of the samples, we used a Scanning Electrometer (LEO, Model 1455 VP). The measurement was conducted at the Scientific Instrument Center for Standards and Industry, King Mongkut's University of Technology Thonburi. The scanning electron microscope was operated at variable-pressure mode in order to be suited to non-destructive analysis of the surfaces of hygroscopic materials.

The pore size distribution and surface area is also important because smaller pores have greater affinity for water than larger pores. Automated Mercury Porosimeters (Quantachrome, Model PoreMaster 60GT) were used to determine the pore size distribution since this method is suitable for determining larger pores such as mesopores or macropores. The samples of non-boiled, 0.5 h boiled, and 1 h boiled mature coir were operated at the same pressure range of 1–30 000 psia. The initial masses of the specimens were 0.1770 g, 0.1339 g, and 0.1754 g for non-boiled coir, 0.5 h boiled coir, and 1 h boiled coir, respectively.

Thermal analysis

Specific heat capacity was determined by a Differential Scanning Calorimeter (Perkin Elmer, Model DSC 7) following the standard test method of ASTM: E 1269-01[11].

Chemical analysis

Mature coir specimens were analysed for chemical properties because fibre chemistry directly relates to adsorption capability. The test method was carried out according to the Technical Association of the Pulp and Paper Industry (TAPPI). The specimens for chemical analysis were ground to a fine particle size (40–60 mesh) with a Wiley mill (Standard model No. 3) to permit complete reaction of coir with the reagents used in the analysis. Chemical methods to analyse coir typically use the entire amount of material without further fractionation. The fine particles were stored in an air-tight container for chemical analysis. Lignin, cellulose, pentosans, and ash content were determined to provide information for evaluation and application of the adsorption processes. The carbohydrates in wood were hydrolysed and solubilised by sulphuric acid. Then, the acid-insoluble lignin was filtered off, dried, and weighed. In this method of determination (TAPPI 222om-98), lignin (also known as 'Klason lignin') is defined as a woody specimen constituent insoluble in 72% sulphuric acid. Holocellulose contains all carbohydrates in wood and is also the sum of the cellulose and hemicellulose. The principle is based on the specimen treated with $NaClO_2$ and delignified. The residue is holocellulose (TAPPI Useful Method 249-75). Determination of alpha-, beta-, and gamma-cellulose can be applied to coconut coir by TAPPI-203-om-93 method. Alpha-cellulose is the pulp fraction resistant to 17.5% and 9.45% sodium hydroxide solution under conditions of the test. Beta-cellulose is the soluble fraction which is reprecipitated on acidification of the solution. Gamma-cellulose is the fraction remaining in the solution. Boiling in 3.85 N hydrochloric acid transforms pentosans into furfural which is collected in the distillate and the contents were determined colorimetrically with orcinol-ferric chloride reagent (TAPPI 223cm-84). The ash content is an approximate measure of the mineral salts and other inorganic matters in the plant fibre. The ash in wood is the inorganic residue after combustion at a temperature of 575 ± 25 °C. The ash content is calculated on the basis of the dry weight of the original sample, after the sample is ignited at 575 ± 25 °C (TAPPI 211om-93).

The sample was also examined by using en-

ergy dispersive X-ray spectroscopy (EDS), which is performed in conjunction with a scanning electron microscope (SEM). EDS is the standard procedure for identifying and quantifying the elemental composition of sample areas as small as a few cubic microns (ASTM: E 1508-98)[12]. The EDS values reported are the average of six measurements.

Adsorption isotherms

Standard values of relative humidity were generated using selected aqueous salt solutions for obtaining atmospheres of constant relative humidity ranging from 11.3% to 97.3% at temperatures of 25 °C, 35 °C, and 50 °C. A saturated salt-water system was prepared according to standard practice (ASTM: E 104-85)[13]. The equilibrium moisture content of coconut coir was determined by the static method. In this method, 2500 cm^3 air-tight plastic containers containing saturated salt solutions, which provided an environment of constant relative humidity, were placed in an electric oven to provide constant temperatures (25 °C, 35 °C, and 50 °C). Petri dishes with 10 g of the previously prepared samples were placed inside the plastic container. A digital temperature controller was used to set the desired temperature (accuracy ± 0.2 °C). The weight of each sample was checked regularly until the variation among successive measurements was less than 0.002 g. Specimens were weighed using a digital balance (OHAUS Adventurer model AR 2140) to readability of 0.0001 g. The samples achieved equilibrium moisture in about 8 weeks. Each point of the isotherm represented an average of two measurements.

Modelling of adsorption isotherms

Eight isotherm equations with two parameters were selected for fitting the experimental data for the adsorption isotherm for mature coconut coir. The selected equations are listed in Table 1. Isotherm models were developed using nonlinear regression techniques with SPSS.

RESULTS AND DISCUSSION

Chemical composition of mature coir

The results of the chemical analysis of the three types of mature coir (not boiled, 0.5 h boiled, and 1 h boiled) are shown in Table 2. It can be seen that the boiling process augments lignin, celluloses (alpha, beta, and gamma cellulose), and pentosan content, while decreases the ash content. The sum of the percentage chemical composition (wt %) of each sample adds up to more than 100% because pentosans is one component of hemicelluloses (Table 3). The wood components that affect moisture adsorption capacities are lignin and ash. The lower the lignin content, the higher the sorption capacity because low lignin content gives rise to low density and easy accessibility of adsorbate to active sites. Ash substance provides carbonyl and hydroxyl groups to increase oxide surface area for adsorption. Cellulose is the most abundant lignocellulosic material and a stable compound. Cellulose is mostly found in cell walls of plants and each cell wall is connected with a middle lamella layer. This layer contains a lot of lignin and so cellulose is less affected by moisture adsorption of plants. In our case, the bulk content of lignin, celluloses, and pentosans remained constant, while the ash content decreased due to the removal by hot water of extraneous components such as inorganic compounds, tannins, gums, sugars, starches, and colouring matter. Lower ash content probably results in a lower oxide surface area for adsorption and the removal of extraneous components gives higher density structure of coconut coir resulting in lower water adsorption of boiled samples. In this way, the boiling process causes the adsorption capacity to decrease.

Energy dispersive X-ray spectroscopy

The elemental composition of three types of coconut coir was determined by EDS (Table 3). The amounts of elements in each type of coconut coir were comparable. However, because of the oxidation reaction, the oxygen content of boiled coconut coir was lower and the carbon content was higher than non-boiled coconut coir. Oxide groups affect the active surface area and so more oxygen results in an increased adsorption capacity. Carbon is the energy source for microbes that help to break down the materials slowly during decomposition. It can be seen that boiled coir contains a higher alpha-cellulose content and has lower beta-cellulose content than non-boiled coir (Table 2). This indicates a higher integrity of cellulose, meaning more durability of materials. Thus the boiling process enhances the chemical stability to improve performance and durability of the coconut coir material. In addition, the boiled and washed coir of cement boards had higher average modulus of rupture than cement boards prepared with washed coir or coir that had not been washed and boiled (non-pretreatment)[3]. Although the boiling process improves the mechanical properties of the coir, it decreases the adsorption capacity and should therefore be limited to more than 0.5 h.

Table 1 Estimated average parameter constants and errors from different models for adsorption isotherms for mature coir.

Models[a]	M_d	Parameter constants		x	MBE	RMSE	MRD	R^2
		a	b	c				
Smith (1947)	$a-b(1-h)$	24.023	31.148	-	−0.0001	5.0	5.5	0.77
Oswin (1946)	$a\left[\frac{h}{1-h}\right]^b$	5.2463	0.57930	-	−0.29	1.2	0.82	0.99
Henderson (1952)	$\left[\frac{\ln(1-h)}{-a}\right]^{1/b}$	0.26430	0.79770	-	−0.88	1.5	0.28	1.0
BET (1938)	$\frac{abh}{(1-h)(1-h+bh)}$	0.97970	12229	-	2.4	4.4	1.0	0.84
Halsey (1948)	$\left[\frac{-a}{\ln h}\right]^{1/b}$	18.964	1.6363	-	−0.38	1.7	1.5	0.98
Iglesias and Chirife (1981)	$a+b\,h/(1-h)$	4.0283	1.0007	-	0.0011	3.2	1.8	0.92
Modified BET	$\frac{(a+b)ch}{(1-h)(1-h+ch)}$	0.91070	0.21800	31896	1.9	4.1	0.92	0.86
GAB (1985)	$\frac{abch}{(1-ch)(1-ch+bch)}$	4.3733	2.2473	0.91130	−0.015	0.44	0.20	1.0

[a]From Ref. 18

h = relative humidity; MBE = mean biased error; RMSE = root mean square error; MRD = mean relative deviation

Table 2 Chemical composition of mature coconut coir.

Chemical composition	Non-boiled coir (%)	0.5 h boiled coir (%Wt)	1 h boiled coir (%)	Standard
Lignin	35.3	39.8	41.2	TAPPI-T222-om-98
Holocellulose	51.5	53.2	56.8	TAPPI-Useful Method 249-75
Alpha-cellulose	26.7	31.1	31.3	TAPPI-T203-cm-88
Beta-cellulose	11.4	8.1	10.0	TAPPI-T203-cm-88
Gamma-cellulose	13.4	14.0	15.5	TAPPI-T203-cm-88
pentosans	16.9	18.6	20.1	TAPPI-T223-cm-84
ash	4.8	3.4	2.6	TAPPI-T211-om-93

Surface characteristics

The surface morphology analysis of coconut coir desiccant was observed with SEM as shown in Fig. 1. The surface characteristics of all coconut coir desiccants are not very different from the outside. The surface characteristics of coconut coir are divided into two portions: tissue and fibre. It is found that the surface morphology of tissue and fibre of each type of coconut coir looks similar at 500 × magnification. Coir fibre has small pores and there are voids between the tissues.

Pore size distribution and surface area

The experimental result showed that non-boiled coir desiccant cannot operate at high applied pressure because the fibre of non-boiled coir is too soft to sustain high force (the pieces of specimen of un-boiled coir was broken down), so only 0.5 h boiled and 1 h boiled could be measured. Thus it was concluded that un-boiled coir is weaker than the boiled coir. The total volume of mercury intruded up to the maximum pressure was 4.16 and 2.52 cm^3/g for 0.5 h boiled coir and 1 h boiled coir, respectively (Fig. 2). The pore diameters in boiled coir (0.5 h and 1 h) were 0.0711–145 μm with the maximum of the pore size distribution at around 10 μm (Fig. 3). The cumulative surface area represents the surface area of all voids and pore spaces filled up with mercury at a given pressure. The surface area of 0.5 h boiled coir was higher than that of 1 h boiled coir (Fig. 4). The total surface areas were 31.1 and 21.4 m^2/g for 0.5 and 1 h boiled coir, respectively.

Table 3 Average element quantification of mature coconut coir by EDS.

Type	Element (wt %)					
	C	O	F	Na	Cl	K
Non-boiled coir	64.0	31.3	0.83	0.45	1.38	2.11
Boiled mature of 0.5 h	65.5	31.7	0.67	0.29	0.80	1.22
Boiled mature of 1 h	67.2	27.2	1.09	0.93	2.16	1.75

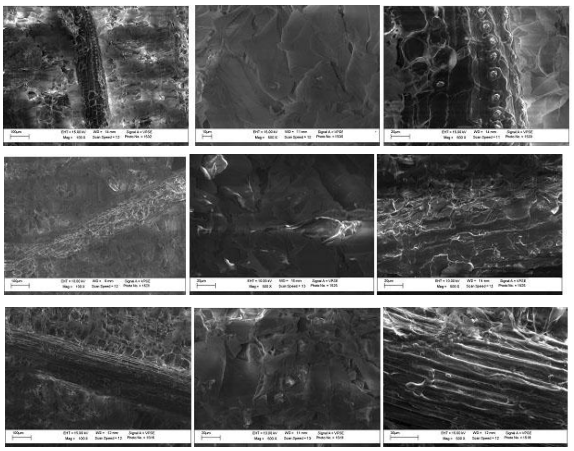

Fig. 1 Scanning electron micrographs of mature coir: (a) non-boiled; (b) 0.5 h boiled; (c) 1 h boiled. Left: overall surface characteristic (100 ×); Middle and right: tissue and fibre portion in longitudinal section (500 ×).

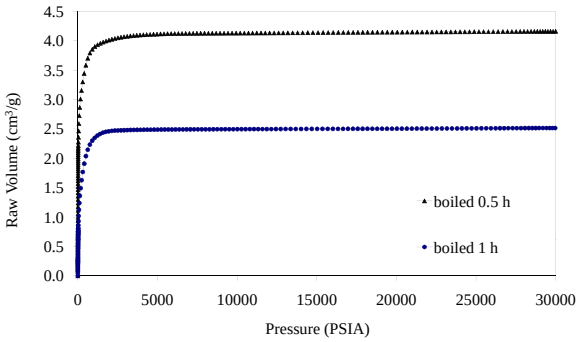

Fig. 2 Raw volumes versus pressure.

Specific heat capacity

The results depicting the average heat capacity of the specimens of mature coir as a function of temperature are presented in Fig. 5. Correlations for the

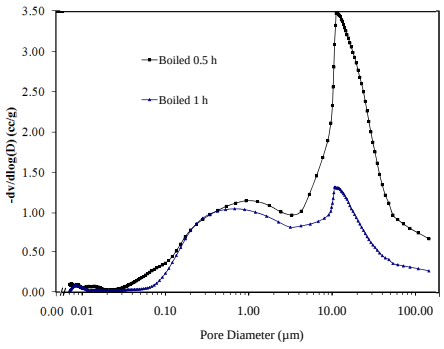

Fig. 3 Volume distribution versus pore size.

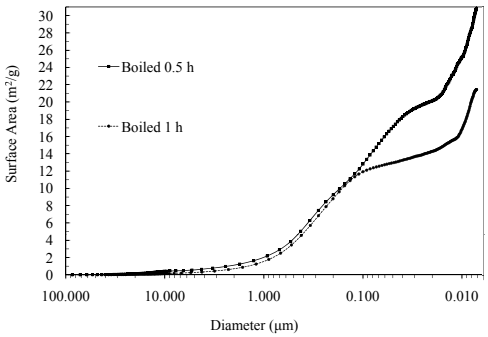

Fig. 4 Surface areas versus pore size.

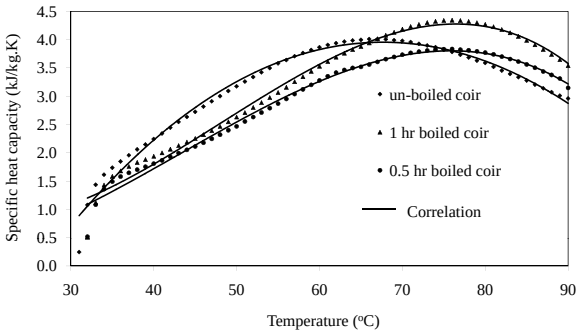

Fig. 5 Specific heat capacities of non-boiled and boiled mature coir.

heat capacities C_{p} of samples are represented by the following series expansions. For non-boiled coir:

$$C_{\mathrm{p}} = 2\times10^{-6}\,T^3 - 0.0026\,T^2 + 0.3271\,T - 6.7853$$

$$R^2 = 0.9826.$$

For 0.5 h boiled coir:

$$C_{\mathrm{p}} = -3\times10^{-5}\,T^3 + 0.0034\,T^2 - 0.0649\,T + 0.5277$$

$$R^2 = 0.9874.$$

For 1 h boiled coir:

$$C_{\mathrm{p}} = -4\times10^{-5}\,T^3 + 0.0056\,T^2 - 0.1759\,T + 2.3891$$

$$R^2 = 0.9856.$$

The correlation constants were determined from a least-squares fit by EXCEL. A comparison between specific heat capacity deduced from our correlation and actual data values indicates a good agreement (Fig. 5). The specific heat capacity for non-boiled coir is higher because its structure is less dense. The more porous nature also results in easy accessibility of moisture to active sites which in turn gives rise to a higher adsorption capacity.

MOISTURE ADSORPTION ISOTHERM

Effect of temperature on adsorption isotherm

It can be observed that the coconut coir has rather a weak adsorption affinity for water vapour at low vapour concentrations and higher adsorption affinity at high vapour concentrations (Fig. 6). Non-boiled coir has the lowest adsorption affinity for water vapour at low humidity. We noted that the intermediate moisture content, more than 20% of dry basis of mature coir, begins at 90% RH at 35 °C and begins at 94% RH for 50 °C. The experimental results indicate that the maximum capacities of moisture adsorption were 39%, 32%, and 23% dry basic for temperatures 25 °C, 35 °C, and 50 °C, respectively.

The moisture capacity adsorption at lower temperature is greater than that at higher temperature. This is due to the fact that the higher temperature increases the vapour pressure at the surface of the coconut coir and consequently increases the difference between the vapour pressure at the surface and at the ambient air. When the surface vapour pressure is greater than that of the surroundings, the coconut coir releases moisture. The adsorption values decrease as the temperature increases since the adsorption is an exothermic process.

The graph of adsorption isotherm for 0.5 and 1 h boiled mature coconut coir indicate that even at high relative humidity, the absorption capacity of boiled coir remains low. The maximum moisture content values are 22%, 20%, and 14% dry basic for temperatures of 25, 35, and 50 °C, respectively for coconut coir which was boiled for 0.5 h. The experimental result of the mature coir boiled for 1 h showed that the maximum adsorption capacities are 20%, 17%, and 18% dry basic for temperatures of 25, 35, and 50 °C, respectively. The effect of temperature on the vapour pressure at the surface of boiled or non-boiled coconut was similar.

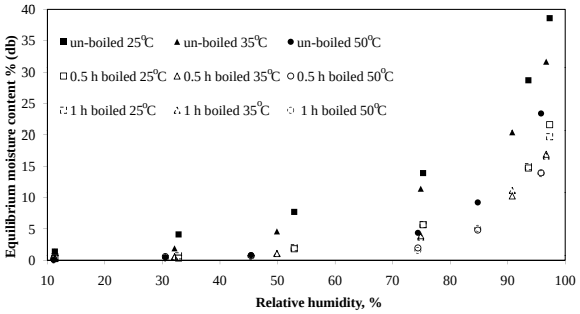

Fig. 6 Adsorption isotherms of non-boiled, 0.5 h boiled and 1 h boiled mature coconut coir at various temperatures.

Effect of boiling on adsorption isotherm

Boiled coconut coir had a weak adsorption affinity for water vapour even at high relative humidity (Fig. 6). The non-boiled mature coir has much higher moisture adsorption performance than the boiled mature coir because boiling is an oxidation process that results in the water extraction of extraneous components, such as inorganic compounds present in coconut coir decreasing the extraction of some component as ash content (see Table 2). These extractives provide carbonyl and hydroxyl groups so that the active surface area decreases. In addition, the carbon element content of 1-h boiled coir was higher than that of non-boiled coir by about 3.1% (see Table 3). Hence it can be seen that the moisture content capacity of coconut coir boiled for 0.5 h is not so different from that of coconut coir boiled for 1 h. It can be concluded that boiling coconut coir should be limited, not exceeding half an hour to ensure good adsorption ability and improve performance and durability of the coconut coir.

Hysteresis on sorption isotherm

The hysteresis loop shapes can be observed in Fig. 7 which shows sorption isotherms for various states of mature coir at various temperatures. In the case of mature coconut coir, a small hysteresis begins at about RH 45%, 50% and 60% for temperatures of 25, 35, and 50 °C, respectively. Increasing the temperature decreases the total hysteresis. The hysteresis loop is usually associated with filling and emptying the pore by capillary condensation so that desorption isotherms give higher water content than adsorption isotherms. In the case of boiled coir, the hysteresis is less.

Moisture adsorption modelling of coconut coir

Average errors for the different models of adsorption isotherms for non-boiled mature coir at temperatures

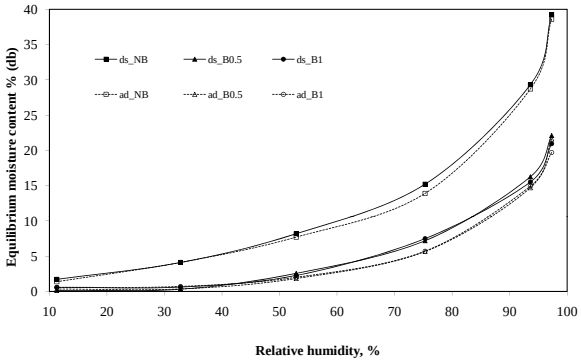

Fig. 7 Hysteresis loop on sorption isotherms of water vapour on mature coconut coir at a temperature of 25 °C.

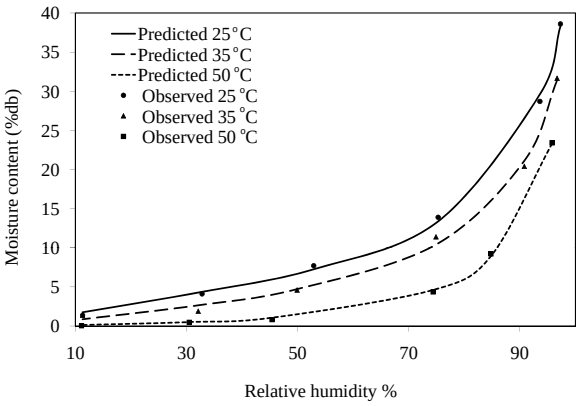

Fig. 8 Observed and predicted adsorption isotherm using gab equation for mature coir.

25, 35, and 50 °C were calculated (Table 1). The GAB equation was found to be the best estimator for predicting the equilibrium moisture content for mature coir because it gave the smallest MBE, RMSE, and MRD errors, and the highest coefficient of determination. Fitted adsorption isotherms for the mature coir to GAB's equation shows a reasonable agreement between the predicted and experimental data (Fig. 8).

CONCLUSIONS

This experimental study confirmed that despite the relatively low moisture adsorption ability compared to commercial industrial products, mature coconut coir used as a desiccant is an attractive alternative to conventional products as it would provide a sustainable use for agriculture waste.

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REFERENCES

1. Sajjakulnukit B (2003) National biomass energy program in Thailand. *Int J Energ Tech Pol* **1**, 449–66.
2. Asasutjarit C, Hirunlabh J, Khedari J, Charoenvai S, Zeghmati B, Cheul Shin U (2007) Development of coconut coir-based lightweight cement board construction and building materials. *Construct Build Mater* **21**, 277–88.
3. Asasutjarit C, Charoenvai S, Hirunlabh J, Khedari J (2008) Effect of pretreatment on properties of coir-based green composite. *Adv Mater Res* **47-50**, 678–81.
4. Khedari J, Nankongnab N, Hirunlabh J, Teekasap S (2004) New low-cost insulation particleboards from mixture of durian peel and coconut coir. *Build Environ* **39**, 59–65.
5. Rawangkul R, Khedari J, Hirunlabh J, Daguenet M (2003) Comparison of moisture adsorption properties of coconut coir and silica gel. In: Proceedings of International Conference on Sustainable Energy and Green Architecture, Bangkok, pp GA-220–15.
6. Khedari J, Rawangkul R, Chimchavee W, Hirunlabh J, Watanasungsuit A (2003) Feasibility study of using agriculture waste as desiccant for air conditioning system. *Renew Energ* **28**, 1617–28.
7. Beery Kyle E, Ladisch Michael R (2001) Chemistry and properties of starch based desiccants. *Enzym Microb Tech* **28**, 573–81.
8. Srinivasakannan C, Mohamad Zailani AB (2004) Production of activated carbon from rubber wood sawdust. *Biomass Bioenerg* **27**, 89–96.
9. Basunia MA, Abe T (2005) Adsorption isotherms of barley at low and high temperatures. *J Food Eng* **66**, 129–36.
10. Calzetta RA, Aguerre RJ, Suarez C (1999) Analysis of the sorptional characteristics of amaranth starch. *J Food Eng* **42**, 51–7.
11. ASTM (2001) Designation: E 1269-01, Standard test method for determining specific heat capacity by differential scanning calorimetry, pp 375–80.
12. ASTM (2003) Designation: E 1508-98, Standard guide for quantitative analysis by energy-dispersive spectroscopy, pp 991–8.
13. ASTM (1996) Designation: E 104-85, Standard practice for maintaining constant relative humidity by means of aqueous solutions, pp 1077–80.
14. Lahsasni S, Kouhila M, Mahrouz M, Kechaou N (2002) Experimental study and modelling of adsorption and desorption isotherms of prickly pear peel (*Opuntia ficus indica*). *J Food Eng* **55**, 201–7.
15. Mohamed LA, Kouhila M, Jamali A, Lahsasni S, Mahrouz M (2004) Experimental study of adsorption-desorption isotherms of bitter orange leaves. In: Proceedings of the 14th International Drying Symposium, pp B1404–10.
16. Suzuki M (1990) *Adsorption Engineering*, Elsevier, Amsterdam.
17. Francoise R, Jean R, Kenneth S (1999) *Adsorption by Powders and Porous Solids: Principles, Methodology and Applications*, Academic Press.
18. Rahman MS (1995) *Food Properties Handbook*, CRC Press.