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Evaluation of Wood–based Activated Carbon Fibers Paperboard as Food Moisture–proof Material in Different Water Activity Food System

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This study used Wood–Based Activated Carbon Fibers Paperboard (WACFP) to investigate the water activity (Aw), color difference (△E*) change, and percent weight with various Aw foods in the environment systems at the relative humidity of (RH) 90 and 40% and temperature of 25°C, which were expected to be references for food moisture–proof material. From the Aw result, WACFPs was 0.47–0.50, which was lower than the habitat for general microorganisms. WACFP with 40% wood–based activated carbon fibers (WACFs) had better stability for high, intermediate, and low Aw foods (HAwF, MAwF, and LAwF) in the RH 90 or 40% environment than the other specimens. In the RH 90% environment, the hygroscopic ability of WACFP was 4.49–6.18%; while that at RH 40% was 1.69–2.20%. According to the simulation results of WACFPs, as food moisture–proof material in HAwF, MAwF, and LAwF in the RH 90% environment, WACFPs had a good stability in MAwF. The Aw change was 0.02–0.03, the △E* change was 1.24–2.70, and the percent weight was −0.26–0.31%. In terms of RH 40%, better stability occurred in HAwF, where the difference of Aw was 0.02–0.03, the △E* change was 1.23–2.83, and the percent weight was −1.22 – −1.24%. The developed WACFP; therefore, can be an optional food moisture–proof material for different Aw food systems.

Key words: Food Moisture–Proof Material, Water Activity (Aw), Wood–Based Activated Carbon Fibers (WACFs), Wood–Based Activated Carbon Fibers Paperboard (WACFP)

INTRODUCTION

Activated carbon fibers (ACFs) have the high contact performance of powdered activated carbon and the reproducibility and unlikely pulverization of granular activated carbon; moreover, ACFs can not be secondary pollution to the treated substances. This characteristic is resulted from the fiber form and high aspect ratio (Asakura *et al*., 2004), and due to their high fiber strength, good workability, and changeful shape, ACFs can be prepared into paper form, fabric form, honeycomb form, and wave form. At present, ACFs are extensively used in organic solvent adsorption and recovery, air cleaning, sewage treatment, water treatment, and deodorization (Liu, 1998). Wood–based activated carbon fibers (WACFs) prepared from wood pulp or recycled paper waste as a precursor have the natural fiber form and surface pore structure of wood, and there are monolayer and multilayer adsorption phenomena on the pore wall. Furthermore, WACFs prepared by steam activation have larger specific surface area and adsorbability than traditional granular, powdered, or commercial carbons, as well as can be applicable to gas/liquid adsorption. WACFs also have excellent adsorbability, and the Ames test result shows it is free of cytotoxicity and mutagenicity (Lin *et al*., 2015a). Lin *et al*. (2015b) also indicates that toxicity test results show no adverse effect on animals fed with WACFs for 28 days, meaning there is no the safety problem in the food. In addition, according to Brunauer–Deming–Deming–Teller (BDDT) classification (Gregg and Sing, 1982), WACFs are presented in Type Ⅳ, and the monolayer and multilayer adsorption phenomena are generated in the pore wall, which are applicable to gas/liquid adsorption (Lorenc–Grabowska and Gryglewicz, 2007).

Food storage duration is significantly correlated with water activity (Aw); as Aw represents the free water in food, which is defined as the ratio of the equilibrium vapor pressure of food (P) to the saturated vapor pressure of pure water at the same temperature (P_o), i.e. $Aw=P/P_o$. When food Aw is 0.0–1.0, they are high Aw foods (HAwF, >0.9), intermediate Aw foods (MAwF, 0.6–0.9), and low Aw foods (LAwF, <0.6). The minimum Aw for the growths of bacteria, yeast, fungi, halophilic bacteria, dryness enduring bacteria, and osmotic pressure enduring yeast are 0.90, 0.87, 0.80, 0.72, 0.62, and 0.60, respectively; while growth fails if Aw is lower than 0.60, thus, high moisture and intermediate moisture foods are need to be treated in special ways or mixed with preservatives and desiccant before preservation (Nicolau and Turtoi, 2006; Fontana, 2008). Silica gel and calcium oxide (CaO) mainly use for the commercial food moisture–proof material, but the appearance of silica gel is a transparent particle which can be eaten as crystal sugar, possibly resulting in uncomfortable pain, and for CaO it is white or gray–white with toxicity, that, if eaten, results in an illness of the intestines and stomach (National Poison Center, 1990).

Lin *et al*. (2015a) adds WACFs in wood pulp to make WACFP, which is put in the Aw food system, and the results show that it is with the effectiveness of moisture proof. Hence, it is one of the feasible methods to

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replace the food moisture–proof material made of chemical constituents on the present market by using its characteristics and safety properties, and to be another option for food gas/liquid adsorbing material. In this study, the different proportions of WACFs were added in wood pulp to make WACFP into food moisture–proof material, where Silica gel is used as the control group, and HAwF, MAwF and LAwF were placed in the environmental systems at the temperature of 25ºC with either relative humidity 90 and 40% to evaluate the Aw, color difference change, and percent weight of the foods, in order to evaluate the feasibility of using WACFP as a high efficiency gas/liquid adsorbing material for different Aw food systems in various simulation environments.

MATERIALS AND METHODS

Test materials

1. Wood pulp: Nadelholz unbleached kraft pulps (NUKP) and Laubholz unbleached kraft pulps (LUKP), supplied from Cheng Loong Pulp, Taiwan.
2. Silica gel: procured by Feng Chang Co., Ltd., Taiwan
3. Water activity (Aw) foods: toast, cotton candy, and handmade biscuits as high, intermediate, and low Aw food (HAwF, MAwF, and LAwF), which were bought from Nabeisi Bread, Chiayi, Taiwan.

Experimental

Preparation of Wood–based activated carbon fibers (WACFs)

Referring to the method of Lin *et al.* (2015a) to prepare WACFs, 60 g LUKP by absolute dry weight was carbonized for the first stage at nitrogen flow 200 mL/min, carbonization temperature of 850ºC, and heating rate 10ºC/min, and then, Stage II activation was implemented at steam flow 90 mL/h and activation temperature of 850ºC for 60 min. Finally, it was cooled at nitrogen flow 200 mL/min for 4 h, and removed at normal temperature to obtain WACFs. The specimen code is WACFs–L850, the yield is 14.32%; the iodine index is 1007.43 mg/g; the BET specific surface area is 775 m^2/g, according to Brunauer–Deming–Deming–Teller (BDDT) classification (Gregg and Sing, 1982), which are presented in Type Ⅳ (Lin *et al.*, 2015a).

Wood–based activated carbon fibers paperboard (WACFP) making method

Referring to the making method of Lin *et al.* (2015a), the basis weight of WACFP was 360 g/m^2, NUKP 20% and LUKP 80% were mixed using the beater method, mixed with 0, 10, 20, and 40% WACFs–L850 by weight, made by a cylinder paper machine, and the CNS11212 method of making handmade paper for physical testing. The WACFP codes are WACFP–L10, WACFP–L20, and WACFP–L40, the control group is PBO (without WACFs).

Determination of moisture content (MC) and Aw of WACFP

The moisture contents of the various WACFP specimens were determined according to the CNS3086 Method of Test for the Determination of Moisture Content in Pulp and Paper, and Aw of WACFP specimens is determined by placing 1 g fine weighed specimen in the Aw meter (Rotronic Hygromer A2).

Determination of MC and Aw of food

The MC in various foods was determined by referring to the test method of Lin *et al.* (2015a), while Aw is determined according to CNS5225 Food Water Activity Determination. The food Aw>0.9 is HAwF; the Aw 0.6–0.9 is MAwF; Aw <0.6 is LAwF (Nicolau and Turtoi, 2006; Fontana, 2008).

Hygroscopic ability of WACFP

Referring to the test method of Lin *et al.* (2015a), about 1 g of air–dried BPO, WACFP–L10, WACFP–L20, and WACFP–L40 were placed in the programmable constant temperature and humidity machine (TERCHY HRM, Taiwan), the hygroscopicity test was implemented at relative humidity (RH) 90 or 40% and the temperature of 25ºC, the weights were measured at 0.25, 0.5, 0.75, 1.0, 1.5, 2.0, 3.0, 6.0, 12.0, and 24.0 h, and measured once every 12 h, then the percent weight was calculated till the moisture equilibrium. The computing equation is percent weight (%) = [(specimen weight – air–dried weight of specimen) / air–dried weight of specimen]*100

Tests for WACFP as gas/liquid adsorbing material in food

This test is designed by the Laboratory of Environmental Functional Materials, Department of Wood–Based Materials, National Chiayi University in Taiwan, where different weight proportions of WACFs were made into WACFP, applied to HAwF, MAwF, and LAwF, and placed in high and low humidity environments (90 and 40%) to simulate different Aw food systems, in order to evaluate the gas/liquid adsorbing material (WACFP and foods) effect. The test items were the Aw, color difference change, and percent weight. The Aw and color differences change investigated the changes in food state, i.e. testing the food. The WACFPs were tested according to percent weight to evaluate the adsorption and desorption results of various WACFPs and foods at different RHs. The test items were the WACFPs, and HAwF, MAwF, and LAwF. Basically, all specimens were tested once every 6 h till the test food became moldy according to visual observation.

Aw determination

About 3.5 g PBO, WACFP–L10, WACFP–L40, and Silica gel (positive control group) of air–dried weight were placed in tightly sealed bags (ONY/PE), as provided by Great & Power Top Co., Ltd., together with HAwF, MAwF, and LAwF, respectively, and then sealed by a capper. The HAwF, MAwF, and LAwF (without WACFP) were used as the negative control groups, placed in the environmental systems at the temperature of 25ºC, and RH 90 and 40%, respectively, and the Aw of HAwF, MAwF, and LAwF were determined every 6 h. The codes of the Aw food specimens for different Aw food systems

Table 1. Abbreviation of Aw foods for the tests of WACFP as gas/liquid adsorbing material in food

Specimen	Use in HAwF[1)]	Use in MAwF	Use in LAwF
PBO[2)]	HAwF–PBO	MAwF–PBO	LAwF–PBO
Silica gel	HAwF–Silica gel	MAwF–Silica gel	LAwF–Silica gel
WACFP–L10[3)]	HAwF–WACFP–L10	MAwF–WACFP–L10	LAwF–WACFP–L10
WACFP–L40	HAwF–WACFP–L40	MAwF–WACFP–L40	LAwF–WACFP–L40

[1)] Aw: Water activity; HAwF: High Aw food; MAwF: Intermediate Aw food; LAwF: Low Aw food
[2)] PBO: the control group without WACFs (Wood–based activated carbon fibers)
[3)] WACFP–L10: WACFP, Wood–based activated carbon fibers paperboard, with 10, and 40% WACFs–L850 by weight (%)

Table 2. Air–dried moisture content and water activity of WACFP, Silica gel and different Aw foods

Specimen[1)]	Air–dried moisture content (%)	Water activity
Silica gel	8.97 ± 0.65[2)]	0.37 ± 0.01
PBO	8.59 ± 0.27	0.52 ± 0.00
WACFP–L10	8.67 ± 0.38	0.50 ± 0.00
WACFP–L20	8.80 ± 1.46	0.48 ± 0.01
WACFP–L40	8.91 ± 0.12	0.47 ± 0.00
Toast	33.02 ± 3.90	0.95 ± 0.00
Handmade biscuits	4.47 ± 0.21	0.39 ± 0.00

[1)] See the Table 1
[2)] Mean ± standard deviation

in various simulation environments are shown in Table 1.

Determination of color difference ($^{\triangle}E^*$) change

As above, the $^{\triangle}E^*$ of different Aw foods in different environmental systems were determined at the same duration as Aw determination. The $^{\triangle}E^*$ of various food specimens was determined by a color difference meter (MINOLTA, CR–400). The results are represented by L*, a*, b* and the calculated $^{\triangle}E^* = [(^{\triangle}L^*)^2 + (^{\triangle}a^*)^2 + (^{\triangle}b^*)^2]$ 1/2 (Macdougall, 2010).

Determination of percent weight

When the Aw and the $^{\triangle}E^*$ were determined, the weight changes of different Aw foods and WACFPs were evaluated, and represented by the percent weight. The equation is percent weight (%) = [(specimen weight – air–dried weight of specimen) / air–dried weight of specimen] × 100

Statistical analysis

The test results are represented by a mean (standard deviation), and the control group and test group are compared by Duncan's Analysis. If the ρ value is smaller than 0.05, meaning a significant difference between the test group and the control group, it is represented by different superscript upper case letters.

RESULTS AND DISCUSSION

Aw and Hygroscopic ability of WACFP

The water activity (Aw) is significantly correlated with the food storage time, which not only dominates the moisture transfer between food and the atmosphere, but also influences the microbial growth response. Each microorganism has a limiting Aw, and microorganisms cannot grow, generate spores, or toxins if the Aw is lower than this limit value (Beuchat, 1981; Robertson, 2005; Powitz, 2007). In other words, the growth of micro–organisms is no longer possible when the Aw is below 0.65–0.95 (Chang *et al.*, 2006). Table 2 shows the air–dried moisture content and Aw of various WACFPs, Silica gel, and various Aw foods. The air–dried moisture content in the WACFPs was 8.59–8.91%, that in Silica gel was 8.97%, and those of the toast, cotton candy, and handmade biscuits were 33.02, 18.77, and 4.47%, respectively. The Aw of Silica gel was 0.37, while that of WACFPs was 0.47–0.52, which is lower than the Aw for the growth of all microorganisms (Chang *et al.*, 2006), and this result is similar to (Lin *et al.*, 2014; Lin *et al.*, 2015a). The Aw of toast, cotton candy, and biscuits were 0.95, 0.66, and 0.39, respectively, representing high Aw food (HAwF), intermediate Aw food (MAwF), and low Aw food (LAwF), respectively (Gowen *et al.*, 2007; Fontana, 2008).

Figure 1 shows the hygroscopic ability of PBO, WACFP–L10, WACFP–L20, and WACFP–L40 at RH 90 and 40% with a temperature of 25°C. At RH 90%, the percent weight of moisture absorption curve of various WACFPs reached the peak at about 12 h, while the percent weight was increased by 4.49–6.18%, and there was no significant difference among the various points till 96 h, according to Duncan's multiple range test analysis. Therefore, the moisture absorption curve becomes bal-

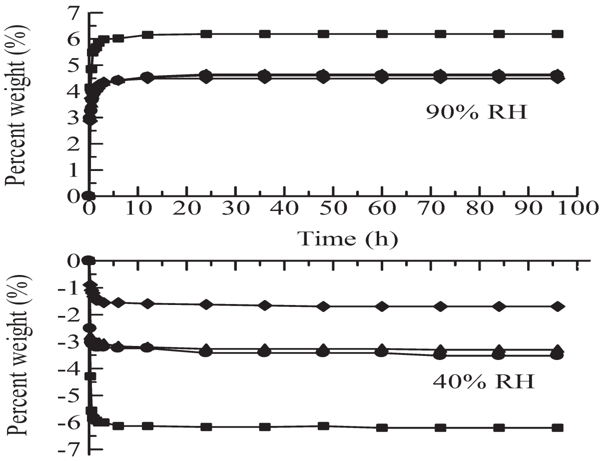

Fig. 1. Hygroscopic ability of WACFP with 0, 10, 20, and 40% WACFs–L850 by weight at RH 90% and 40% with 25°C
Legends —◆—: PBO; —▲—:WACFP–L10;—●—: WACFP–L20; —■—: WACFP–L40

anced after 12 h, and moisture absorption increased with WACFs in the WACFPs. According to Duncan's multiple range test analysis of RH 40%, the curve reached the valley and became balanced after about 24 h, the percent weight was decreased by 1.69–2.20%, and the higher the content of WACFs, the more significant the moisture desorption. Aw is the main cause of the moisture absorption and desorption phenomena, as it balances the RH in the air. In other words, if the specimen Aw is identical to the ambient RH, the specimen is without the moisture absorption and desorption phenomena, meaning there is the moisture absorption phenomenon when the Aw is lower than the ambient RH; and there is the moisture desorption phenomenon when the Aw is higher than the ambient RH (Chang *et al.*, 2006; Lin *et al.*, 2015a). In addition, the Aw of various WACFPs was 0.47–0.52, there was the moisture absorption phenomenon at RH 90%, and the moisture desorption phenomenon at RH 40%. The proportion of WACFs in the WACFP contributes to its moisture absorption and desorption, where the higher the weight (%), the better the moisture absorption and desorption, as the hysteresis loop formed by the nitrogen adsorption/desorption isotherm of WACFs–850 is Type H3 with adsorption/desorption effect (Lin *et al.*, 2015a, b). Therefore, WACFPs can be regarded as a moisture adsorbing and desorbing material, which varies with ambient RH.

Aw variation of food treated with WACFP

The moisture in food can be divided into free water and bound water. The amount of free water is the level of Aw, which is regarded as one of important indices for inspecting food preservation (Maltini *et al.*, 2003; Sandulachi, 2012). Table 3 shows the Aw change of WACFP–L40, Silica gel and different AwF at RH 90% with 25°C during different storage time. Aw decreased slightly with storage time for different WACFP whatever the AW food was. The Aw stability of HAwF–WACFP–L40 was better than the other specimens, and the variation was about 0.02; followed by HAwF–PBO and HAwF–WACFP–L10, where the variation was about 0.03. According to Duncan's multiple range test analysis, there was a larger change that showed a significant difference for the Aw of HAwF–Silica gel and HAwF after 12 h. It is indicated the BPO, WACFP–L10, and WACFP–L40 has

Table 3. Water activity change of WACFP, Silica gel and different AwF at RH 90% with 25°C during different storage time

Food	Time (h)	PBO [1)] with various AwF	Silica gel with various AwF	Aw of AwF	WACFP–L10 with various AwF	WACFP–L40 with various AwF
HAwF	0	0.95 ± 0.00 ^{aD} [2)]	0.95 ± 0.00 ^{aE}	0.95 ± 0.00 ^{aE}	0.95 ± 0.00 ^{aE}	0.95 ± 0.00 ^{aD}
	12	0.93 ± 0.00 ^{abC}	0.93 ± 0.00 ^{abBCD}	0.93 ± 0.01 ^{bC}	0.93 ± 0.00 ^{bC}	0.93 ± 0.00 ^{aA}
	36	0.93 ± 0.00 ^{bC}	0.93 ± 0.00 ^{bCD}	0.93 ± 0.00 ^{bBC}	0.92 ± 0.00 ^{aB}	0.93 ± 0.00 ^{bAB}
	48	0.92 ± 0.00 ^{abA}	0.91 ± 0.00 ^{aA}	0.91 ± 0.01 ^{abA}	0.92 ± 0.00 ^{bA}	0.93 ± 0.00 ^{cBC}
MAwF	0	0.66 ± 0.00 ^{aABC}	0.66 ± 0.00 ^{aAB}	0.66 ± 0.00 ^{aA}	0.66 ± 0.00 ^{aA}	0.66 ± 0.00 ^{aAB}
	12	0.66 ± 0.01 ^{aAB}	0.67 ± 0.00 ^{cC}	0.68 ± 0.00 ^{dB}	0.67 ± 0.00 ^{bcAB}	0.66 ± 0.00 ^{abB}
	168	0.67 ± 0.00 ^{bBC}	0.67 ± 0.00 ^{bBC}	0.68 ± 0.00 ^{cB}	0.67 ± 0.00 ^{bABC}	0.66 ± 0.00 ^{aB}
	378	– [3)]	0.66 ± 0.00 ^{aA}	–	0.68 ± 0.00 ^{cD}	0.67 ± 0.00 ^{bC}
LAwF	0	0.39 ± 0.00 ^{aA}	0.39 ± 0.00 ^{aA}	0.39 ± 0.00 ^{aA}	0.39 ± 0.00 ^{aA}	0.39 ± 0.00 ^{aA}
	12	0.40 ± 0.00 ^{aB}	0.40 ± 0.00 ^{aA}	0.40 ± 0.00 ^{aB}	0.40 ± 0.00 ^{aB}	0.40 ± 0.00 ^{aB}
	336	0.53 ± 0.00 ^{cE}	0.49 ± 0.00 ^{aD}	0.59 ± 0.00 ^{dE}	0.53 ± 0.00 ^{cE}	0.52 ± 0.00 ^{bE}
	522	0.62 ± 0.00 ^{dF}	0.55 ± 0.00 ^{aF}	0.70 ± 0.00 ^{eF}	0.61 ± 0.00 ^{cF}	0.59± ± 0.00 ^{bF}
	882	–	0.68 ± 0.01 ^{aI}	–	–	–

[1)] Abbreviation is the same as Table 1.
[2)] Mean ± standard deviation; separation within lines by Duncan's multiple range tests at 5% significant level. The horizontal direction (AwF with different WACFP and the others) is a, b, c, d and e; The vertical (AwF with variation time) is A, B, C, D, E, F, H and I
[3)] – : Food surface has occurred fungi

better Aw stability with HAwF than Silica gel.

In the Aw test for WACFPs in MAwF, the Aw increased with storage till the test food became moldy according to visual observation, as based on the deterioration or spoilage time. The Aw variation of MAwF was about 0.02. The MAwF–WACFP–L40 had the steadiest Aw, and there was no significant change in the Aw; followed by MAwF–PBO, MAwF–Silica gel, and MAwF–WACFP–L10, where the Aw was only increased by about 0.01 after 330 h (the result was not show in Table 3). The Aw of MAwF–WACFP–L40 had insignificant difference from the initial time to about 330 h, according to Duncan's multiple range test analysis. Therefore, it is inferred that the WACFP–L40 in MAwF can stabilize food Aw.

The Aw test for various WACFPs in LAwF was also based on the deterioration or spoilage time, when the Aw variation was about 0.31, the Silica gel had better effect on the Aw of LAwF, and the variation was about 0.16 until 552 h. As the Aw variation of LAwF–Silica gel was from 0.39 to 0.68, followed by LAwF–WACFP–L40, from 0.39 to 0.69. The variations of LAwF–PBO, LAwF–Silica gel, LAwF–WACFP–L10, and LAwF–WACFP–L40 were greater than these of HAwF–L10 or –L40 and MAwF–L10 or –L40 by 8–10 times, but after 24 h they were significantly different, except for LAwF. However, it is showed the spoilage of LAwF–L10 and –L40 can be delayed for 186–360 h.

In the scope of the above results, the WACFP–L40 has better Aw stability for HAwF, MAwF, and LAwF than the other specimens in RH 90% or 40% environments. The Aw variation of HAwF, MAwF, and LAwF is resulted from the free water in the food and the free water in the environmental system becoming gradually balanced, meaning that when the HAwF with Aw of 0.95 is placed at RH 90%, its Aw decreases gradually with time; whereas, the MAwF and LAwF with Aw of 0.66 and 0.39 increase gradually, till it balances the ambient RH, resulting in the Aw variation (Chang *et al.*, 2006). Moreover, in an environment at RH 90% with 25°C, the WACFPs used in different Aw food systems are compared with each other, and the results show that the application to MAwF has the best Aw stability, the difference for the variation (between changed Aw and original Aw) is 0.02–0.03, followed by HAwF at about 0.02–0.04. At RH 40%, HAwF has the best stability, followed by LAwF (results no show in Table).

The higher the food Aw, the faster the deterioration or spoilage is in the RH 90% environment. The HAwF with Aw of 0.95 spoils in 48 h, the MAwF spoils in 240 h. The LAwF spoils in 522 h; however, when Aw increases from 0.39 to 0.60, deterioration may be accelerated. Therefore, if the Aw of food is controlled below 0.60, the microbial growth response can be decreased (Labuza *et al.*, 1970; Labuza, 1975; Torreggiani and Welti–Chanes, 1995). In addition to the Aw of food, the moisture absorption of WACFP and a low RH environment can extend food storage time. MAwF and LAwF treated with WACFP can be preserved longer than food not treated with WACFP in a RH 90% environment by 138–288 h. In the RH 40% environment, the Aw of HAwF and MAwF reaches equilibrium with ambient RH, and Aw decreases gradually, meaning there is feasibility in prolonging storage life. Therefore, as the level of Aw is significantly related to microbial growth and reproduction, decreasing the Aw of food contributes to prolonging storage life (Rockland and Stewart, 1981; Abdullah *et al.*, 2000; Barbosa–Cánovas *et al.*, 2008).

Color difference variation of food treated with WACFP

People always use sense organs to judge the color, flavor, and taste of food. However, judging color only with the naked eye is too subjective to implement quantitative analysis. A color difference meter uses the three variable principles of the human eye for color judgment, i.e. simulating the process of judging color by eye, in order to remove the effect of human factors and subjective ideas on the determination result, and render color judgment more objective (Okano *et al.*, 1995).

According to the results of WACFPs in three different Aw food systems (not show the result's Table), at RH 90% the application in MAwF had the minimum $^{\triangle}E^{*}$ change, which was 1.24–2.70, followed by HAwF, 2.26–5.22. At RH 40%, HAwF had the minimum variation, 1.23–2.83, followed by LAwF. When WACFP–L40 was used with the HAwF, MAwF and LAwF in RH 90% environment system, the $^{\triangle}E^{*}$ change was smaller than the other specimens (PBO, Silica gel), which were 1.19–5.17, 0.40–0.89, and 1.19–21.97, and they were 0.35–1.23, 0.15–2.23, and 0.50–1.92 at RH 40%.

The results in LAwF treated with WACFPs and Silica gel showed that the $^{\triangle}E^{*}$ change was 21.97–22.09, where the difference from HAwF and MAwF was 5.21–24.82 times, as the biscuit absorbs ambient moisture during test, meaning the Aw of LAwF before deterioration or spoilage increased from 0.39 to 0.68–0.71 (Table 3). This is because the moisture content in the biscuit increases markedly, and the specific gravity of the oil and fat in it is lower than water. Therefore, the oil and fat gradually float to the surface layer, the brightness is increased (Esteban *et al.*, 2012), and the color differential value ($^{\triangle}E^{*}$) is increased.

Percent weight of food treated with WACFP

Effect of high humidity environment system on WACFP and different Aw foods

Figure 2 shows the percent weight of treating PBO, Silica gel, WACFP–L10, and WACFP–L40 in HAwF, MAwF, and LAwF, at RH 90% with 25°C. Figure 2 (a) indicated the percent weight curve of WACFP and Silica gel in HAwF, which increased from 0% (initial) to 8.29–14.43% (end), while the WACFP–L10 had the maximum moisture (14.43%), followed by PBO; but there were no significant difference between WACFP–L10 and –L40 in accordance with Duncan's multiple range test analysis. Figure 2 (b) showed the percent weight curve of MAwF, where the reference point was the deterioration and spoilage of MAwF, meaning the percent weight of PBO, WACFP–L10 and –L40 was 1.48–1.53% after 240 h, and

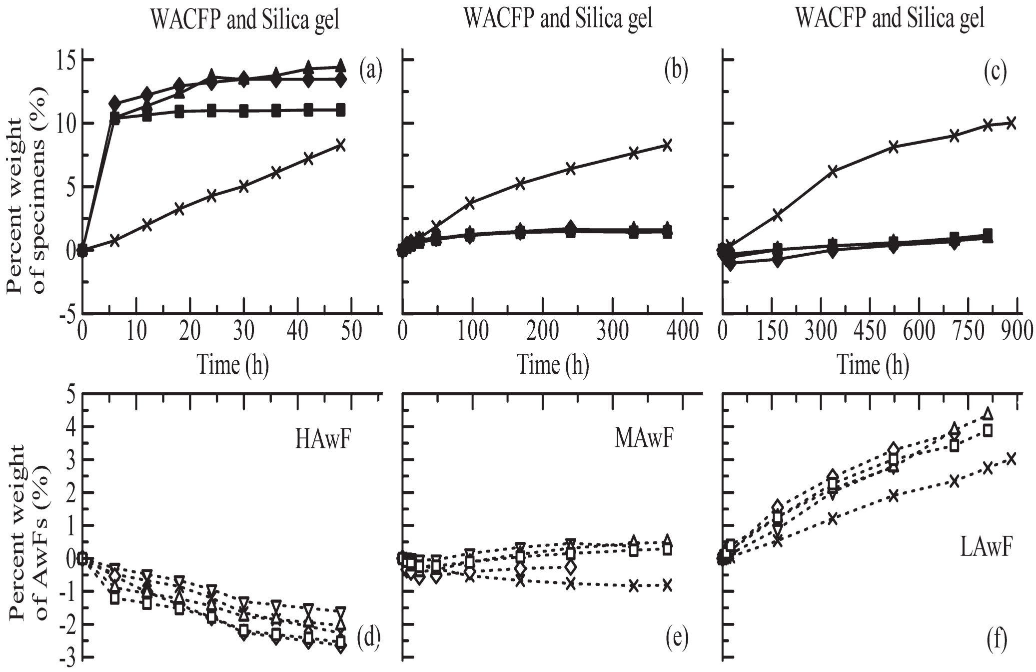

Fig. 2. Percent weight of WACFPs, Silica gel and HAwF, MAwF and LAwF in RH 90% at 25℃ during different storage time.

Legends —◆— : PBO; —×— : Silica gel; —▲— : WACFP-L10; —■— :WACFP-L40; - -◇- -: AwF-PBO; - -×- - : AwF-Silica gel; - -▽- - : AwF only; - -△- -: AwF-L10; - -□- - : AwF-L40

Notes: WACFP is Wood-based activated carbon fibers paperboard. HAwF is high water activity food. MAwF is intermediate water activity. LAwF is low water activity food.

Silica gel had the maximum moisture (6.43%). Figure 2 (c) obtained the percent weight of above three specimens was 0.39–0.42% after 522 h, and Silica gel had the maximum moisture (8.14%). The PBO, WACFP–L10 and –L40 were used in HAwF, MAwF, and LAwF after 6, 168, and 708 h, and the percent weight became balanced. The percent weight of WACFPs in HAwF, MAwF, and LAwF systems after moisture adsorption were 11.05–14.43%, 1.48–1.72%, and 0.39–0.61%, respectively, where HAwF had the highest moisture adsorption, followed by MAwF, meaning the WACFP regulated the moisture according to the food Aw. However, the moisture of Silica gel increased before the food deteriorates and spoils (final point for various AwF).

Figures 2 (d) to (f) show the percent weight curves of HAwF, MAwF, and LAwF for treating with WACFPs and Silica gel. Figure 2 (d) indicated that the percent weight change of HAwF was from −1.61 to −2.64% after 48 h, displaying the moisture desorption phenomenon. This phenomenon may be resulted from the food gradually reaching equilibrium with the ambient RH (Sahin and Sumnu, 2006), and the Aw of toast (HAwF) is 0.95 (Table 2), and in the RH 90% environment the free moisture content may dissipate, thus, decreasing the Aw. The final percent weight of HAwF–PBO, HAwF–Silica gel, HAwF–WACFP–L10 and HAwF–WACFP–40 were −2.27– −2.64%, while the HAwF only was −1.61%. Figure 2 (e) showed that the percent weight change of MAwF–PBO, MAwF–silica gel, MAwF, MAwF–WACFP–L10 and MAwF–WACFP–40 was –0.26, −0.76, 0.46, 0.31, and 0.15%. The MAwF–PBO and MAwF–Silica gel were in the state of moisture desorption; whereas, the MAwF only, MAwF–WACFP–L10 and MAwF–WACFP–40 were in the moisture adsorption state. Figure 2 (f) showed they were between 1.91 and 3.29% after 240 h, which were greater than LAwF–Silica gel; but LAwF–PBO had the largest increase, and was insignificant difference with WACFP–L10 and –L40.

The percent weight of HAwF, MAwF, and LAwF shows that the WACFP and Silica gel not only absorb the moisture in the environment, but also absorb the moisture in the food. Gowen (2012) indicates that food storage life can be prolonged by decreasing the moisture in food. When the PBO, WACFP–L10, and WACFP–L40 have been used in HAwF, MAwF, and LAwF for 6, 168, and 708 h, the percent weight of them becomes balanced, but the Silica gel is on the contrary. Moreover, the WACFP is most suitable for MAwF, and the percent weight is the steadiest, at about −0.26–0.31%. In other words, the storage environment also affects food, meaning when the ambient RH is high, food deteriorates quickly (Rockland and Stewart, 1981; Abdullah *et al.*, 2000; Barbosa–Cánovas *et al.*, 2008), such as spoilage.

Effect of low humidity environment system on WACFP and different Aw foods

Figure 3 (a) shows the percent weight curves of WACFPs and Silica gel applied to HAwF in the environment of RH 40% and 25℃. The result indicated an increase from 0% to 3.61–4.21%, where the Silica gel had the highest moisture (4.21%), followed by WACFP–L40 (3.98%), and the percent weight curve of WACFPs

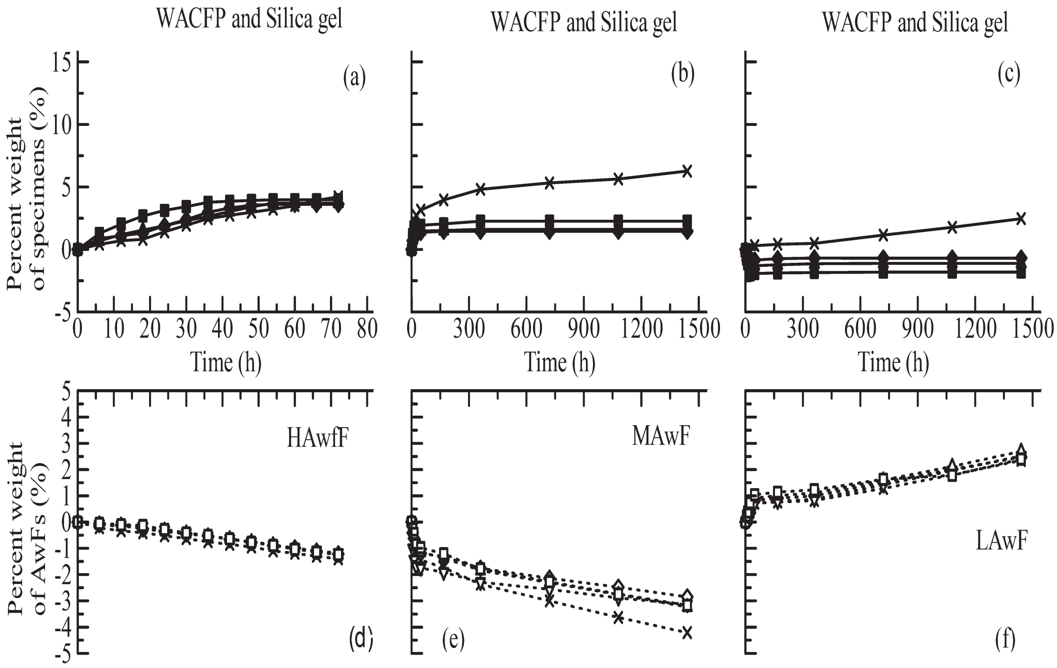

Fig. 3. Percent weight of WACFPs, Silica gel and HAwF, MAwF and LAwF in RH 90% at 25°C during different storage time.

Legends —◆—: PBO; —✕—: Silica gel; —▲—: WACFP-L10; —■—:WACFP-L40; - -◇- -: AwF-PBO; - -✕- -: AwF-Silica gel; - -▽- -: AwF only; - -△- -: AwF-L10; - -□- -: AwF-L40

Notes: See the Fig. 1.

became gradually balanced after 54 h. Figure 3 (b) was for WACFPs and Silica gel applied to MAwF, which was 1.47–6.27%, where the Silica gel also had the highest moisture, the balance of WACFPs was after 360 h, and the percent weight was 1.47–2.27%. Figure 3 (c) was for LAwF, the percent weight (−1.81 – −0.69%) of WACFPs was balanced till 720 h. Therefore, when PBO, WACFP–L10 and WACFP–L40 have been used in various AwFs for a period of time, the percent weight of food or WACFPs becomes balanced. The percent weight of HAwF, MAwF and LAwF were 3.62–3.98%, 1.47–2.27%, and −1.81 – −0.69%, and these results are the same as the trend in Figure 2, meaning WACFP can reach moisture equilibrium with an environment of RH 90 or 40%, and regulates the moisture according to the food Aw, but Silica gel cannot be. Besides, from the results of WACFPs in Fig. 2 and 3 (a), (b) and (c), the moisture at RH 90% was larger than that at RH 40%. In other words, WACFP not only absorbs the excess moisture in food as a food moisture–proof material, it also regulates the moisture with the ambient RH.

The percent weight curves of HAwF treated with the WACFPs, where the range of percent weight was −1.40 to −1.19% after 72 h. (Fig. 3 (d)). For MAwF, it was from −4.21 to −2.85% (Fig. 3 (e)). Figure 3 (d) and Figure 2 (e) show that the percent weight of HAwF and MAwF are negative tendency, representing the moisture desorption state, as the food gradually reaches equilibrium with ambient RH (Sahin and Sumnu, 2006). This is concerned with the original Aw of toast (HAwF) and cotton candy (MAwF), 0.95 and 0.66 (Table 2). Therefore, in the RH 40% environment, the free moisture is desorbed, and the Aw is decreased. Figure 3 (f) was for LAwF, where the percent weight was 2.35–2.70%, and WACFP–L10 had the maximum moisture absorption, 2.70%. Therefore, in an environment at RH 40% with 25°C, WACFP was most suitable for HAwF, −1.22 – −1.24%, indicating the variation of percent weight is relatively stable.

In the scope of the above results, in RH 90 and 40% environments, WACFP reaches moisture sorption equilibrium after a period of time, and regulates the moisture according to the foods' Aw, where the maximum moisture occurs in the HAwF, followed by MAwF. The WACFP regulates the moisture with the ambient RH. Taking HAwF as an example, the percent weight is 11.05–14.43% at RH 90%, but is 3.62–3.98% at RH 40%, meaning it is a variable moisture absorbing material in different RH environments.

CONCLUSION

The Aw of WACFPs was 0.47–0.50, and the Aw of HAwF, MAwF, and LAwF were 0.95, 0.66, and 0.39. According to the results of moisture adsorption and desorption abilities, in the RH 90% environment, the hygroscopic ability (expressed by percent weight) of WACFPs was increased by 4.49–6.18%; moreover, in the RH 40% environment, it was decreased by 1.69–2.20%. This also suggests that the moisture adsorption and desorption increase with the content of WACFs in WACFP. From the results of HAwF, MAwF, and LAwF, the food storage life at RH 40% was longer than that at RH 90%. The HAwF, MAwF, and LAwF with WACFP–L40 had the steadiest Aw, which was 0.01–0.23. From to the results of Aw and color difference change, the three of AwFs treated with WACFPs were stable, and the WACFP–L40 applied to food had the best result. In the RH 90% environment, the percent weight of WACFPs in HAwF, MAwF, and LAwF were 8.29–14.43%, 1.48–6.43%, and 0.39–8.14%. In the RH 40% environment, they were 3.62–3.98%, 1.47–2.27%, and −1.81– −0.69%. The WACFP–L10 and WACFP–L40 are most suitable for MAwF in a high RH environment, and for HAwF in low RH. And the WACFP–L40 has better results than the commercially available Silica gel,

AUTHOR CONTRIBUTION

Han Chien LIN designed this paper, performed the experiments, analyzed the data and the statistical analysis and wrote the paper. Noboru FUJIMOTO participated in the design of the study, supervised the work and provided resources. The authors assisted in editing of the manuscript and approved the final version.

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