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Water Resistance, Compression Strength and Dynamic Mechanical Analysis of Corrugated Board Coated with Bio-Based Materials

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ABSTRACT

Water resistance is a major concern for corrugated board and this property can be enhanced through coating with bio-based materials. This research investigated the water resistance, compression strength and dynamic mechanical properties of corrugated board coated with bio-based materials. Four types of bio-based materials were observed—namely, hydrophobic modified starch, zein, stearic acid and beeswax. Low-level concentrations of all bio-based materials (1–3%, w/w) were investigated. The results showed that the water contact angles of corrugated boards coated with hydrophobic starch, stearic acid and beeswax increased significantly, ranging from 3 to 9%. In the case of zein coating, the water contact angle decreased with respect to its concentration. Further testing of the compression strength of coated corrugated boards indicated a significant decrease of edge crush test for most treatments, except for hydrophobic starch coating. However, the flat crush test values remained unchanged. The results of dynamic mechanical analysis showed that the storage modulus of corrugated boards increased after coating.

Keywords: corrugated board, bio-based materials, mechanical properties, water resistance, dynamic mechanical analysis

INTRODUCTION

Corrugated boxes are the most widespread form of packaging for transportation and storage of a variety of goods. Corrugated board is usually constructed from three, five or seven layers of kraft liners of a particular basis weight, and is generally called “single wall,” “double wall” or “triple wall” corrugated board, respectively. The board is composed of selected flutes shaped according to the types of protection required. More information about corrugated board materials can be found elsewhere (Kellicutt, 1959; Kline, 1991; Soroka, 2000; Biancolini and Brutti, 2003; Yam, 2009).

Mechanical and dynamic mechanical properties of corrugated board are important indicators for predicting the goods protection capability of corrugated boxes or cushioning materials made from corrugated board (Maltenfort, 1996; Worrakittiwanich *et al*., 2009). During transportation, corrugated boxes are usually subjected to dynamic compression load generated by random vibration of the vehicle (Rouillard *et al*., 2007). Flute shapes and the overall structure of corrugated board must be able to withstand this stress in order to prevent any damage to the products.

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One critical drawback of corrugated board is its hydrophilic characteristic. Corrugated board usually absorbs water from the environment, especially when stored under high humidity conditions or when coming into contact with high-moisture products such as fresh agricultural produce or frozen foods. Absorption of moisture reduces the physical and mechanical strength of corrugated board causing corruption of the flute structures and failure of the corrugated package during storage and distribution. Surface treatments such as sizing, coating and laminating are usually used on the kraft liner to improve the physical strength as well as water barrier properties (Falat and Sasthav, 2001; Rhim *et al*., 2006). In some cases, hydrophobic adhesive is used to improve the water resistance of the glue used in the corrugation process.

A water barrier can be formed by changing the wettability of the paper surface with sizing agents, or through coating with hydrophobic materials. Paraffin wax applied in a molten form was commonly used to produce a water barrier; but thermoplastics applied by extrusion were found to provide a more durable coating. However, the properties of thermoplastics and paraffin waxes makes it difficult to separate, recycle or compost paper-based materials after use; wax particles cannot be cleanly separated from paper fiber during mechanical pulping (Parris *et al*., 2002; Vaswani, 2005). Moreover, extensive coating of hydrophobic substances on kraft paper before the corrugation process may inhibit glue absorption between the facing liners and the flute medium, causing potential board separation. Therefore, direct coating of the corrugated board surface may be required.

Various biopolymers can be used to enhance the water resistant properties of paper-based materials, including polysaccharides such as modified starches as well as proteins and lipid-based substances (Butkinaree *et al*., 2009). Starches are common bio-based coating materials for kraft paper and other paper-based packaging; they are used to obtain better surface smoothness and mechanical properties (Whistler and BeMiller, 1993; Larotonda *et al*., 2005). Starch may also be modified before coating for ease of processing and for better water resistant properties of the coated surfaces (Jansson and Järnström, 2005). Some protein-based biopolymers, such as zein that contain various non-polar amino acids are also commonly used as food coatings to prevent moisture loss (Gennadios, 2001). Zein can also be used for paper coating to achieve better resistance to water vapor and oil; however, the mechanical properties of the paper may be adversely affected (Parris *et al*., 2002). Lipid-based fatty acids such as stearic or palmitic acid can be used as paper coating substances to improve the water resistance. Besides fatty acids, natural waxes such as beeswax are also applied onto the substrate surface in order to decrease the water vapor transmission rate through paper products or plastic films (Shogren, 2002; Monedero *et al*., 2009). Not only single bio-based material coatings, but also combinations of coating substances (for example, modified starch, protein and lipid) for paper-based materials are frequently utilized (Khaoula *et al*., 2005; Fabra *et al*., 2008; Butkinaree *et al*., 2009; Sothornvit, 2009) to enhance the overall performance of paper packaging materials by increasing the water and oil resistance, improving the barrier properties for gases and water vapor, and enhancing mechanical properties.

The present research investigated and compared the water resistant properties as well as the mechanical and dynamic mechanical properties of corrugated board materials after coating with different bio-based materials derived from polysaccharide, protein and lipid, specifically hydrophobic modified starch, zein, stearic acid and beeswax. This study also included the investigation of mixed bio-based material coatings for their potential improvement of both water resistance and compression strength.

MATERIAL AND METHODS

Materials

The corrugated board material selected for this study was a double-wall board composed of three layers of liners with two flutings—B and C flutes. The B flute is a smaller flute (flute height is approximately 3 mm) positioned near the top surface, while the C flute is a bigger flute (flute height is approximately 4 mm) positioned near the bottom surface. This double-wall corrugated board can be used for heavy-duty transportation boxes. The board can also be used as cushioning material and in paper pallets for distribution of goods. The corrugated board was purchased from Siam Kraft Industry Co., Ltd. (Thailand). All of the liners were composed of KA grade kraft paper with a basis weight of 150 $g.m^{-2}$, while both flutings were CA grade with a basis weight of 125 $g.m^{-2}$. The overall thickness of the board was approximately 7 mm. The structure of the double-wall corrugated board used in this study, as well as the potential load direction, is displayed in Figure 1.

Biopolymers selected for the study consisted of hydrophobic starch, zein, stearic acid and beeswax. The hydrophobic starch was a specially modified starch (Filmkote-370^{TM}) purchased from the National Starch & Chemical Co. (Thailand). The zein and stearic acid were purchased from Fluka (Switzerland), and the beeswax was imported from Germany. The beeswax used for this research was a long-chain wax alcohol (C24–C44) containing 70% carbon acids (C16–C18), 13–18% hydrocarbons (C25–C35), 10–15% free wax acids (C24–C32) and 1% free wax alcohols (C34–C36). The melting point of the beeswax was approximately 62–64 °C. For mixtures of combined bio-based material coating solutions, Tween 60^{TM} (purchased from ACROS Organics, USA) was used as an emulsifier.

Preparation of hydrophobic starch coating solutions

Hydrophobic starch coating solutions were prepared at 1, 2 and 3% (w/w, dry weight basis) using distilled water. All solutions were

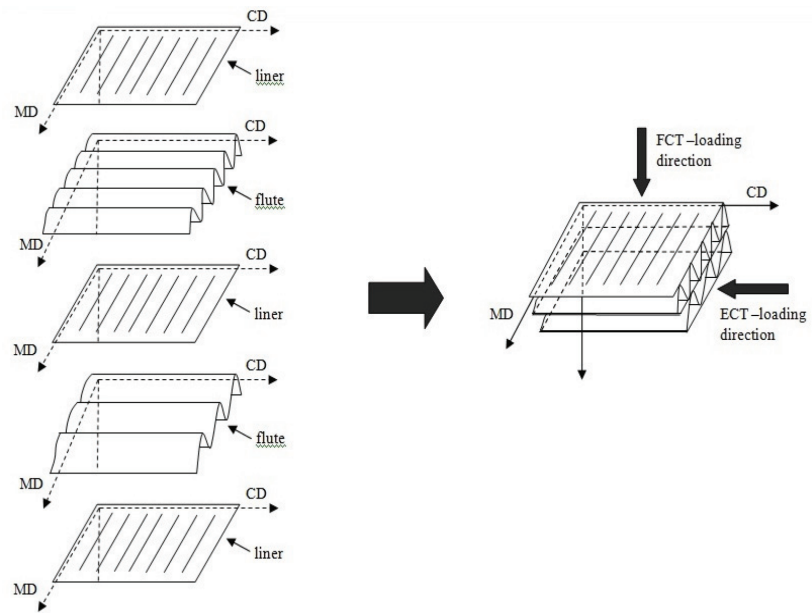

Figure 1 Structure and load direction of double-wall corrugated board. (MD = machine direction; CD = cross machine direction)

heated and stirred at 85 ± 5 °C using a hot plate stirrer (Heidolph, Germany) at 500 rpm until the opaque solutions became clear. After that, the hydrophobic starch coating solutions were kept in a water bath and the temperature maintained at 65 ± 1 °C before coating. Treatments were referred to as H1, H2 and H3 for hydrophobic starch at 1, 2 and 3 %, respectively.

Preparation of zein, stearic acid and beeswax coating solutions

Zein, stearic acid and beeswax were dissolved in 90% ethanol. The concentration levels of each substance were set at 1, 2 and 3% (w/w, dry weight basis). The solutions were heated and stirred at 65 ± 5 °C using a hot plate stirrer at 500 rpm until the opaque coating solutions became clear. The coating solutions then were kept in a water bath to maintain the temperature at 65 ± 1 °C. Coating solutions were referred to as Z1, Z2 and Z3, S1, S2 and S3 and B1, B2 and B3 for the zein, stearic acid and beeswax at 1, 2 and 3 % concentration levels, respectively.

Preparation of mixed biopolymer coating solutions

Mixed biopolymer coating solutions were composed of hydrophobic starch (3%, w/w) with stearic acid (1% (HS1), 2% (HS2) and 3% (HS3), w/w) and hydrophobic starch (3%, w/w) with beeswax (1% (HB1), 2% (HB2) and 3% (HB3), w/w). Hydrophobic starch solution was used as a matrix for the mixtures. The intention behind using modified hydrophobic starch was to increase the compression strength of the corrugated board, while stearic acid and beeswax were added to improve the water resistant properties of the board.

Hydrophobic starch 3% (w/w, dry weight basis) in distilled water was heated and stirred at 85 ± 5 °C using a hot plate stirrer at 500 rpm until the solution turned clear. Tween 60^{TM} (10% by weight of stearic acid or beeswax) was added to enhance the solution compatibility (Butkinaree *et al*., 2009). The coatings were homogenized using a T10 basic homogenizer (IKA®, Japan) on level 4 for 1 min; then, either stearic acid or beeswax at 1%, 2%, and 3% (w/w) were added to the mixture. The coatings were kept heated for 10 min and then homogenized for 5 min. After that, the coating solutions were kept in a water bath at 65 ± 1 °C for approximately 10 min before coating and further analysis of the solutions.

Preparation of specimens and coating method

Corrugated board was cut into pieces 250 mm (machine direction, MD) by 320 mm (cross machine direction, CD). Approximately 10 g of coating solution was applied on the corrugated board surface using a rod coating technique (film coater PI-1210; Tester Sangyo, Japan). One side of the corrugated board was coated and dried at room temperature (30–35 °C) for 24 hr; then the other surface of the corrugated board was coated using the same technique.

Coating solutions and corrugated board testing

The viscosity of the coating solutions was measured using an RVDV-III Ultra Rheometer (Brookfield Engineering, USA). Each viscosity measurement was conducted at a speed of 100 rpm and the temperature of the coating solution was maintained at 65 ± 1 °C. The water and oil resistance of the corrugated board were analyzed by contact angles using an OCA 15EC goniometer (Data Physics, Germany). To determine the compression strength, corrugated board samples were subjected to an edge crush test (ECT) and a flat crush test (FCT) (following TAPPI T811 and TAPPI T825, respectively) using a Testometric Micro 350 (England). The dynamic mechanical properties of corrugated board were analyzed with the compression mode in the flat crush load direction using an Eplexor® dynamic mechanical thermal analyzer (Gabo, Germany). Coated corrugated boards were cut into 15 × 15 mm test samples using a Kongsberg XL cutting table

(EskoArtwork, USA) for precision in providing an equal number of flutes per unit length of test samples. The static load was set at 10.00 N, the maximum strain was set at 40% and the dynamic force was set in the range of 0.75–8.00 N. The frequency of the dynamic force and the temperature of the test were kept constant at 10 Hz and 27 ± 1 °C, respectively. Before any testing, coated corrugated board samples were conditioned at 27 ± 1 °C, 65 ± 2% RH, for 24 hr (ISO 187) in a KBF 240 climate chamber (Binder, Germany). Statistical analysis was tested at the 95 % level using analysis of variance and Duncan's multiple range test.

RESULTS AND DISCUSSION

The viscosity of all coating solutions decreased when the temperature of the coatings was increased from 65 °C to 75 °C (Table 1), since the cohesive forces between the molecules of the substances were reduced when heated (Bansal, 2005). The viscosity of the beeswax was highest followed by the hydrophobic starch solution whereas no significant differences were found in the viscosity of zein and stearic acid. At concentrations of 1–3 % (w/w), significant differences in the solution viscosity were only recorded for beeswax and hydrophobic starch because of their high molecular weights compared to the other coatings.

The viscosities of the coating solutions containing hydrophobic starch at 3% (w/w) with stearic acid were higher than the viscosities of coating solutions containing hydrophobic starch with beeswax because stearic acid has a lower molecular weight than beeswax. Moreover, the stearic acid coating solution was more stable in the hydrophobic starch matrix, while some of the beeswax separated slightly from the hydrophobic starch matrix. (This could be observed when solution samples were taken.) Therefore, the

Table 1 Viscosity of coating solutions.

Coating solution	Viscosity (cP) at	
	65 °C	75 °C
H1	1.44 ± 0.04^{fgh}	0.94 ± 0.03^{h}
H2	2.05 ± 0.00^{e}	1.82 ± 0.08^{efg}
H3	2.83 ± 0.12^{d}	2.77 ± 0.05^{d}
Z1	1.67 ± 0.07^{efg}	1.50 ± 0.10^{efgh}
Z2	1.68 ± 0.13^{efg}	1.52 ± 0.10^{efgh}
Z3	2.01 ± 0.16^{ef}	1.87 ± 0.23^{efg}
S1	1.26 ± 0.19^{gh}	1.26 ± 0.16^{gh}
S2	1.34 ± 0.20^{gh}	1.26 ± 0.19^{gh}
S3	1.41 ± 0.23^{fgh}	1.37 ± 0.24^{gh}
B1	3.95 ± 0.36^{c}	3.82 ± 0.26^{c}
B2	4.95 ± 0.76^{b}	4.65 ± 0.10^{b}
B3	5.74 ± 0.87^{a}	5.06 ± 0.71^{ab}
HS1	3.01 ± 0.11^{d}	2.90 ± 0.07^{d}
HS2	3.80 ± 0.13^{c}	3.75 ± 0.43^{c}
HS3	4.86 ± 0.11^{b}	4.80 ± 0.80^{b}
HB1	2.86 ± 0.13^{d}	2.56 ± 0.06^{de}
HB2	2.97 ± 0.08^{d}	2.99 ± 0.05^{d}
HB3	3.33 ± 0.17^{cd}	2.96 ± 0.04^{d}

^{abcdefgh} Values with different superscript letters in each column are significantly different ($P < 0.05$).

viscosity of the combined hydrophobic starch and beeswax coating solution was not as high as expected when compared to the viscosities of single substances. Since the viscosities of all coating solutions in this study were quite low, a rod coating technique can be performed effectively. According to a previous study, the viscosity of a coating solution that can be effectively applied by the rod or roller coating technique can be as high as 12 cP for hydrophobic starch at 8% (w/w) (Kukiatkulchai, 2007).

According to Table 2, before coating, the corrugated board had an average grammage of 803 g.m^{-2}. This grammage was made up from the combined weight of the three liners and two flute media plus the additional weight of the glue. After coating with all bio-based materials, the overall grammage was increased slightly (coating weights ranged from 2 to 8 g.m^{-2}). This coating weight was the combined weight of both top and bottom surfaces of the corrugated board. Therefore, the coating weights on each side of the surface were approximately 4 g.m^{-2} or lower, depending on the type of coating solution. In fact, the rod coating technique applied in this study can effectively give a coating weight of up to 11 g.m^{-2} (Anderson, 2008). The highest coating weight was found in the coating solutions using both hydrophobic starches with beeswax and the hydrophobic starch with stearic acid. Although the grammage was slightly increased, the thickness of the corrugated board before and after coating showed no significant

Table 2 Properties of coated corrugated boards.

Coating solution	Physical properties			Contact angle (degree)	Compression strength	
	Grammage (g.m^{-2})	Thickness* (mm)	Moisture content (%)		Edge crush test (kN.m^{-1})	Flat crush* test (KPa)
Control	803.673 ± 7.15^{d}	7.046 ± 0.02	8.85 ± 0.18^{b}	121.99 ± 1.09^{e}	6.38 ± 0.11^{a}	113.71 ± 3.58
H1	805.248 ± 6.52^{c}	7.046 ± 0.02	9.64 ± 0.14^{a}	125.81 ± 3.95^{d}	6.48 ± 0.08^{a}	115.66 ± 5.70
H2	805.305 ± 4.19^{c}	7.047 ± 0.01	9.54 ± 0.09^{a}	127.00 ± 0.81^{cd}	6.48 ± 0.08^{a}	117.54 ± 5.51
H3	806.179 ± 5.85 ^{bc}	7.047 ± 0.02	9.25 ± 0.12^{a}	120.90 ± 1.18^{ef}	6.49 ± 0.37^{a}	117.50 ± 6.39
Z1	804.709 ± 3.77^{c}	7.046 ± 0.01	9.28 ± 0.35^{a}	117.47 ± 1.12^{f}	6.07 ± 0.09^{b}	117.89 ± 7.65
Z2	805.159 ± 5.35^{c}	7.047 ± 0.01	9.50 ± 0.08^{a}	113.43 ± 0.25^{g}	6.14 ± 0.09^{b}	119.61 ± 7.10
Z3	807.935 ± 4.66^{bc}	7.047 ± 0.02	9.85 ± 0.07^{a}	109.67 ± 1.06^{h}	6.13 ± 0.11^{b}	114.47 ± 5.43
S1	808.310 ± 3.45^{bc}	7.046 ± 0.01	9.62 ± 0.17^{a}	128.96 ± 0.9^{bcd}	5.88 ± 0.11^{c}	117.31 ± 8.22
S2	809.370 ± 8.22 ^{b}	7.046 ± 0.02	9.37 ± 0.17^{a}	129.33 ± 0.92^{bcd}	5.87 ± 0.14^{c}	117.42 ± 3.41
S3	810.228 ± 8.02 ^{b}	7.047 ± 0.01	9.27 ± 0.13^{a}	129.98 ± 0.42^{bc}	5.87 ± 0.24^{c}	117.98 ± 8.22
B1	808.294 ± 3.19 ^{bc}	7.047 ± 0.01	9.58 ± 0.31^{a}	131.36 ± 0.71^{ab}	5.63 ± 0.23^{d}	114.29 ± 7.82
B2	810.778 ± 5.70 ^{b}	7.047 ± 0.02	9.60 ± 0.03^{a}	131.22 ± 2.54^{ab}	5.67 ± 0.12^{cd}	116.63 ± 9.25
B3	810.780 ± 6.09 ^{b}	7.047 ± 0.01	9.60 ± 0.18^{a}	133.76 ± 2.04^{a}	5.68 ± 0.07^{cd}	115.11 ± 3.52
HS1	810.431 ± 5.63 ^{b}	7.047 ± 0.01	9.28 ± 0.15^{a}	120.14 ± 1.39^{ef}	6.06 ± 0.10^{b}	118.53 ± 2.77
HS2	811.488 ± 4.81^{ab}	7.048 ± 0.01	9.32 ± 0.09^{a}	120.34 ± 1.52^{ef}	5.82 ± 0.19^{c}	114.36 ± 5.46
HS3	813.168 ± 8.09 ^{a}	7.047 ± 0.02	9.33 ± 0.11^{a}	121.57 ± 1.66^{e}	5.72 ± 0.14^{cd}	115.92 ± 6.52
HB1	814.513 ± 5.61 ^{a}	7.047 ± 0.01	9.35 ± 0.15^{a}	123.87 ± 0.45^{de}	6.09 ± 0.14^{b}	119.78 ± 6.69
HB2	815.273 ± 4.87 ^{a}	7.048 ± 0.02	9.38 ± 0.06^{a}	124.50 ± 2.05^{d}	6.04 ± 0.15^{b}	115.72 ± 4.35
HB3	810.431 ± 5.63^{b}	7.047 ± 0.01	9.28 ± 0.15^{a}	126.44 ± 2.19^{cd}	5.96 ± 0.15^{bc}	114.48 ± 6.46

^{abcd} Values with different superscript letters in each column are significantly different ($P < 0.05$).

*No significant differences found among treatments in the same column.

difference. On the other hand, the moisture content of coated corrugated board was significantly increased; no significant differences were found among all coating solutions. The increase in the moisture content could have been due to the ability of the bio-based coating substances to partially absorb moisture due to their hydrophilic nature (Petersen *et al*., 1999). Moreover, the bio-based film which formed on the coated surface of the corrugated board might also prevent vaporization of any free water or moisture that might have been absorbed during the coating process into the structure of the corrugated board beneath the coating layer.

The water contact angle of the coated corrugated board samples increased with higher concentrations of hydrophobic starch, stearic acid and beeswax (Table 2). However, at 3% concentration, the water contact angle of the hydrophobic starch coating decreased. Some studies also have shown that a higher concentration or thicker layer of hydrophobic-modified starch coating can increase the water absorption of the coated surface, because the more hydrophilic part of the coating can come directly in contact with water (Petersen *et al*., 1999).

Among all the coatings, beeswax showed the highest water contact angle of up to 133 ° compared to 120 ° for the uncoated corrugated board. The water resistant property of beeswax is due to the high content of esters of long-chain fatty alcohols and acids, as well as long-chain alkanes (Hagenmeier and Shaw, 1992). The contact angle of the corrugated board surface was quite high originally due to surface sizing during the paper-making process, especially for kraft papers intended to be used as top and bottom surfaces of the corrugated board. However, heavily sized paper might reduce the absorptivity of any additional coating of substances on the surface; as a consequence, a lower coating weight was detected (Kimpimäki, 1998; Lipponen *et al*., 2004).

The result was the opposite for zein coating, since the water contact angle decreased to 110 ° at a 3% concentration of zein. Zein can be used to coat paper surfaces for grease-proofing and to reduce water vapor permeability (Parris *et al*., 2002). However, a higher coating weight may be required to obtain such results (Anderson, 2008). Zein is an example of the use of biopolymers that are hydrophilic in nature; therefore, to achieve better water resistance for zein film, coating with an additional layer of beeswax will contribute to a more hydrophobic surface (Krochta and DeMulder, 1997; Han *et al*., 2006).

For a mixture of the hydrophobic starch and beeswax, the water contact angles were not as high as for the beeswax coating alone. This may have been due to the compatibility of the two substances. Although Tween 60^{TM} was added to the coating solution as a colloidal stabilizer, and although the temperature of the mixture was well maintained before coating, visible beeswax phase separation could be observed during the coating process. This can prohibit good film formation of both the hydrophobic starch and beeswax on the coated surface. Moreover, a previous study indicated that starch-lipid complexes can be found in such a coating solution; and since beeswax contains a larger molecular structure, more starch-lipid complexation can be induced, which interferes with good film formation of the coating (Gällstedt and Hedenqvist, 2004). Therefore, a lower contact angle can be observed. Although lipid-based coatings provide a good moisture barrier, there are certain disadvantages (brittleness, lack of homogeneity and the presence of pinholes and cracks in the surface of the coating) which can occur when using a thicker layer coating (Anderson, 2008).

The compression strength of corrugated board was investigated through an edge crush test (ECT) and a flat crush test (FCT). Based on established studies, smaller flutes give higher FCT values while bigger flutes show higher ECT values

(Kline, 1991; Kirwan, 2005). As a consequence, B flutes are located on the top surface of corrugated board to provide good printing pressure resistance as well as good print quality. After coating with bio-based polymers, FCT values of the corrugated board remained unaffected. However, ECT values decreased for all coatings, with the exception of the hydrophobic starch coating at all concentrations, whereas ECT values showed no significant differences from uncoated corrugated board (Table 2). These results were in accordance with previous research, which indicated a decrease in mechanical strength—namely, tensile strength or Young's modulus of paper—after coating with bio-based materials (Gällstedt and Brottman, 2005; Kjellgren *et al*., 2006), primarily due to interference by the coating substances, which reduced the interaction force between paper fibers. However, another previous study showed no change in the compression strength of paper after coating with alginate and soy protein (Rhim *et al*., 2006). In the present study, the ECT value of zein-coated corrugated board was lower than that of samples with a hydrophobic starch coating, but was still higher than with a lipid-based coating. In general, the compression strength of corrugated board depends largely on the board structure, with less influence from any additional coating on the board surface. However, in the case of hydrophobic modified starch, starch molecules can penetrate into the paper surface; this might result in higher compression strength. The increase in ECT values of the corrugated board was more noticeable when all kraft liners and media were coated directly with modified starch before the corrugating process, since the compression strength of corrugated board depends on the combined compression strength of each liner and medium. The opposite was found for FCT results, because FCT values depend mainly on the compression strength of the flute structure and flute integrity (Kirwan, 2005). During the coating process, most of the bio-based substances are absorbed into the top and bottom layers of kraft liners, and did not influence the rigidity of the flute structure; therefore, the maximum compression resistance of the top surface of the corrugated board was not affected.

Dynamic mechanical analysis of coated corrugated board samples revealed that the board became more elastic on the flat crush load after coating with bio-based materials (Figure 2). The flat crush load was selected for investigation because double-wall corrugated boards are usually used as cushioning material as well as in corrugated board pallets which need good flat-crush resistance. The elasticity of the corrugated board was expressed by higher storage modulus (E′) values. Information on the theory behind the concept of dynamic mechanical analysis can be found elsewhere (Ferry, 1980; Meyers and Chawla, 1999).

According to the study results, corrugated board samples demonstrated greater elasticity after coating with bio-based materials. The E′ values of corrugated board increased significantly with an increase in the concentration of bio-based materials. This finding was in agreement with previous research, which indicated greater flexibility of starch film with an increased amount of glycerol (Jonhed *et al*., 2008). Another report, by Dagnon *et al*. (2010), also indicated that the E′ values of kraft paper were significantly enhanced through impregnation of the paper with biopolymers. For hydrophobic starch at 3% (w/w) concentration, elasticity of the coated corrugated board was less than at lower concentrations, since a lower amount of starch was able to penetrate the structure of the kraft paper. The E′ value decreased with an increase in dynamic force; at a certain point (approximately at 6.5 N), the corrugated board was permanently damaged. At this point, the E′ value of the corrugated board coated with all bio-based coatings came very close to 2 MPa. The E′ value of uncoated corrugated board was less than 2 MPa at all test levels of dynamic force. Mixed bio-based material coatings resulted in lower E′ values

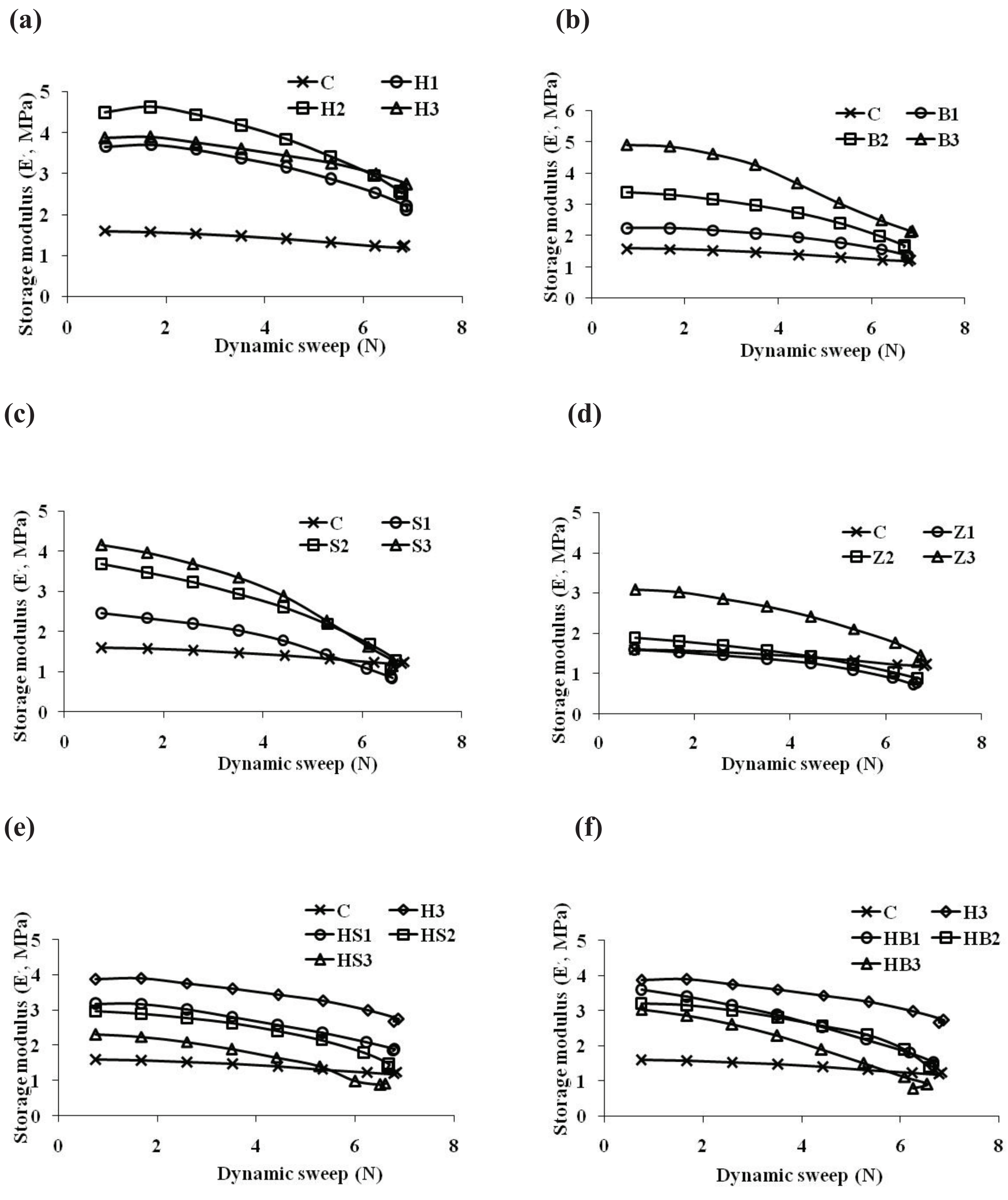

Figure 2 Storage modulus (E′) of biopolymer coated corrugated boards coated with: (a) hydrophobic starch at 1% (H1), 2% (H2) and 3% (H3), w/w; (b) beeswax at 1% (B1), 2% (B2) and 3% (B3) w/w; (c) stearic acid at 1% (S1), 2% (S2) and 3% (S3) w/w; (d) zein at 1% (Z1), 2% (Z2) and 3% (Z3) w/w; (e) hydrophobic starch (3%, w/w) with stearic acid (1% (HS1), 2% (HS2) and 3% (HS3), w/w); (f) hydrophobic starch (3%, w/w) with beeswax (1% (HB1), 2% (HB2) and 3% (HB3) w/w).

compared to single-substance coatings (Figures 2e–2f). This was due to the interference of both mixtures in the coating solution, which prohibited good film formation, thus reducing the flexibility of the coated substrate.

CONCLUSION

Bio-based materials can be used as alternative coatings for corrugated board in order to enhance water resistance properties. Water resistance of corrugated board was significantly increased by the beeswax and stearic acid coating and significant water resistance was achieved only with 1 % (w/w) concentration of the coating solutions. The water resistance properties of mixed bio-based coatings were lower than those of single-substance coatings due to the incompatibility of the components during film formation. The edge crush test of corrugated board was unchanged by applying a hydrophobic starch coating. However, edge crush tests were slightly decreased with other coatings. The flat crush test of coated corrugated board was unaffected by the coating, since the compression strength of the flat crush load depends mainly on the flute structure. Dynamic mechanical analysis further revealed that corrugated board was more elastic after coating with bio-based materials, and that the elasticity of the board depended on the coating weight and coating substances.

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