Effect of Adhesive Spreading Rate on the Performance of Laminated Compressed Oil Palm Trunks

Noor Afeefah Nordin,[a] Othman Sulaiman,[a,*] Rokiah Hashim,[a] Nurjannah Salim,[b] Mohammed Nasir,[a] Masatoshi Sato,[c] and Salim Hiziroglu [d]

The large availability and cheap price of oil palm (*Elaeis guineensis*) trunk makes it an attractive raw material for value-added applications, but its low density and high carbohydrate content are highly undesirable. In this work, oil palm trunk (OPT) was steam-pretreated and compressed at high temperature. The compressed OPT was laminated using polyvinyl acetate (PVAc) using either 250 or 500 g/m^2 adhesive spread rate (ASR). Soil burial testing was performed for three months on two different samples to study the deterioration and weight loss by bio-organisms. The laminated, compressed OPT formed with high PVAc ASR was found to be more durable against bio-organisms. The thermal stability of the compressed OPT was studied by thermogravimetric analysis (TGA), and it was observed that the weight loss was lower for steam-pretreated samples compared to those without steam pretreatment. Moisture absorption-desorption testing of compressed OPT was performed, and a hysteresis curve was generated. It was found that laminated, compressed OPTs with 500 g/m^2 ASR had lower moisture absorption than those with 250 g/m^2 ASR.

Keywords: Durability; Dimensional stability; Thermal stability

*Contact information: a: Division of Bioresource, Paper & Coatings Technology, School of Industrial Technology, Universiti Sains Malaysia, 11800 Minden, Penang, Malaysia; b: Faculty of Industrial Sciences & Technology Universiti Malaysia Pahang, Malaysia 26300; c: Graduate School of Agricultural and Life Science, The University of Tokyo, 1-1-1, Yayoi, Bunkyo-ku, Tokyo 113-8657, Japan; d: Department of Natural Resource Ecology and Management, Oklahoma State University, Stillwater, OK 74078-6013, USA; *Corresponding author: othman@usm.my*

INTRODUCTION

Malaysia is one of the world's biggest producers of palm oil and was estimated to have 5 million hectares of oil palm plantations in 2013 (Malaysian Oil Palm Statistics 2014). The huge scale of oil palm plantations results in a substantial waste of biomass sources such as oil palm trunks (OPTs), oil palm fronds (OPFs), leaves, and empty fruit bunches (EFBs) after harvesting. These residues could lead to major environmental problems if not managed properly. However, OPT cannot be used as commercial timber because of its low density and mechanical strength; instead, OPTs are currently used for some selective structural and non-structural purposes. Improved utilization of OPT as an alternative wood material in wood-based products not only would reduce the pressure on the traditional timber but also would help to solve the growing problem of waste disposal. There have been various investigations of how to utilize OPTs in combination with other wood based materials such as in laminated veneer lumber and plywood manufacture (Nordin *et al*. 2004; Sulaiman *et al*. 2008).

There is increasing research interest in modifying and exploiting non-commercial wood as an alternative wood source (Hill *et al*. 2012). Two such methods are compression/ densification and thermal modification, each of which could be applied to OPT. The aim of such modifications is to improve the properties of the wood (strength, stiffness, hardness, and resistance to biological attack) without using chemicals, which are often toxic (Kutnar *et al*. 2009). Although wood modification has been practiced since the early 1900s, recent research activity has increased dramatically over the past decades. The first example of commercial wood compression was in Germany in the 1930s, named lignostone under the brand name Lignofol (Kollman *et al.* 1975; Rowell and Konkol 1987). Other examples of commercially compressed wood include Compreg and Staypak, developed by the Forest Product Laboratory, Madison, WI, USA. Compreg is a resin-treated, compressed wood, whereas Staypak is not impregnated with any resin (Seborg *et al*. 1962). Salim *et al*. (2012) optimized the manufacturing conditions of compressed wood from OPTs and utilized them as raw materials for various purposes. In compressed OPT, wood is compressed in the transverse direction to prevent cell damage; otherwise, mechanical and physical properties are adversely affected (Kollman *et al*. 1975). This method of compressed wood preparation is now being practiced on species such as hybrid poplar, spruce, and fir (Fang *et al*. 2012).

In compression, low-density wood is modified to become high-density wood that can be used for certain structural applications. Furthermore, compressing wood not only improves its physical and mechanical properties, but it also facilitates the homogenous application of adhesive to the wood surface. The roughness of a veneer's surface is a major factor affecting adhesive distribution and penetration. Smoother surfaces require less adhesive to be covered prior to lamination compared to rough surfaces (Hashim *et al*. 2011). Uniform distribution of the adhesive improves the bonding between the laminated panels and results in products with better properties (Candan *et al*. 2010).

Compressing wood can greatly enhance the properties of wood. Thermal treatment can be used to further improve wood. Previous studies have revealed that the properties of compressed wood are improved significantly by compression with a hot press (Wang and Cooper 2005; Candan *et al*. 2010). Recently, many studies have been reported that the densification and thermal modification together improves the properties of wood. These methods can be viscoelastic thermal compression (VTC) and thermo-hygro mechanical densification (THM), which improves the stiffness and hardness of wood (Kutnar *et al.* 2009; Bustos *et al*. 2011). Steam treatment can also be combined with heat treatment during the densification process, which improves the dimensional stability of the compressed wood (Fang *et al*. 2012). Salim *et al.* (2013) reported the effect of steaming on the properties of compressed oil palm trunk.

Chung *et al*. (1999) studied the resistance to fungal attack of various types of wood composites against bio-fungi and concluded that that the magnitude of bio-deterioration varies with the composition of the composite. Wood that contains more carbohydrates was more susceptible to bio-deterioration and exhibited the highest weight loss after prolonged exposure. Blenchette *et al*. (2004) studied the bacterial attack on wood composites and found that bacteria also degraded wood cell walls, along with insects and termites, in outdoor environments where fungal degradation is not a problem.

Various studies have been performed on the durability of compressed wood (Lee *et al*. 2013; Sandberg *et al*. 2013). However, there is limited information available on the durability of laminated compressed OPTs. Therefore, a thorough study on the durability of laminated compressed OPTs in exterior conditions was carried out. The vision of such work is to develop a laminated compressed OPT with enhanced physical properties (smoothness, stiffness, hardness), mechanical properties (load bearing, tensile strength, and shear strength), and biodegradation resistance to meet the requirements of certain structural applications. Thus, the objective of this work was to evaluate the durability of laminated compressed OPT in outdoor conditions. The thermal properties and dimensional stabilities of laminated compressed OPT were also being evaluated. Positive results from laminated compressed OPTs could provide an abundant, cheap raw material for use as a wood alternative for various structural purposes.

EXPERIMENTAL

Sample Preparation

Oil palm trunks (OPTs) were harvested from a plantation located in Ladang Pelam, Kedah, Malaysia. The OPTs were cut to dimensions of 20 cm length x 20 cm width x 4 cm thickness along the tangential direction, and a total of 36 samples were prepared. Samples were subjected to steam in an autoclave chamber at 130 °C for 120 min. The optimum manufacturing condition was based on previous research by Salim *et al.* (2012). The steamed samples were dried in the oven of 50 °C to reduce water content before being subjected to hot pressing. Low drying temperature was chosen to avoid warping of the samples. The steamed samples with moisture content below 10 % were chosen to compress the samples using a laboratory Molding Test Press Model Fabricate GT-7014-A30 at 200 °C and 9.81 MPa for 60 min. A thickness bar of 1 cm was used during the pressing to obtain a final compressed OPT with 1 cm thickness. The dimension of each sample was measured before and after compression with a precision of 0.01 mm, and the basic properties were reported (Nordin *et al*. 2013). Samples that were not subjected to stem treatment were prepared to be used for thermogravimetric analysis (TGA). Specifications of the material were reported in Salim *et al.* (2013). Laminating of the samples was done by using Polyvinyl Acetate (PVAc) adhesive. The adhesive was supplied by Casco Adhesives Sdn. Bhd, Selangor, Malaysia. The PVAc was mixed with hardener, chromium (III) nitrate nanohydrate, to avoid creep during the application on the surface of substrate. The mixing proportion of the adhesive determines the glue formulation. The adhesives were spread manually on the compressed OPT in single glue line using glass rod. The adhesive was spread evenly on the surface of the panel before the two pieces were assembled together. The amount of adhesive required to be applied on the surface of the compressed OPT was calculated based on the following Eq. 1:

$$\text{Spread rate (g/m}^2\text{)} = \text{Weight of adhesive (g)} / \text{Area of panel (m}^2\text{)} \qquad (1)$$

Durability Test

The durability of the samples was evaluated using a soil burial method based on (ASTM G 160-12, 2012) under field conditions. The compressed OPT (non-laminated, laminated with 250 g/m^2 and 500 g/m^2 ASR) samples were placed in an oven at 105 °C for 24 h, and their weights were measured. A total of 36 samples (4 replicates for each type of sample) with lengths of 20 cm in tangential direction were halfway buried into the soil at the research site located in Lembah Burung, Universiti Sains Malaysia for three months. At specified intervals, the samples were removed from the soil, cleaned properly, and weighed after being dried in an oven at 105 °C for 24 h. Weight measurements were done with precaution and to an accuracy of 0.01 g. Weight measurements of the samples were taken initially and sequentially every month until the third month, when the tests were completed. In addition, visual observations of individual samples were also done periodically to assess the level of damage sustained by the OPT from outdoor exposure. The weight loss of the samples was determined based on Eq. 2. The standard deviation was calculated for all samples.

$$\text{Loss in mass (\%)} = [(m_1 - m_2) / m_2] \times 100 \quad (2)$$

In Eq. 2, m_1 is the initial oven-dried weight (g) and m_2 is the final oven-dried weight (g).

Thermo-gravimetric Test

The thermal analysis was conducted at the School of Chemistry, Universiti Sains Malaysia, using model TGA-50 (Shimadzu). The test was carried out to evaluate the thermal durability of the samples when they have been subjected to high temperature. Two different compressed OPT samples, one steam-pretreated and another without steam pretreatment, were studied. Since adhesive spread does not give any difference in this test, comparisons were made between steam-treated and unsteamed samples. The temperature of the TGA was raised from ambient temperature to 1000 °C with a heating rate of 10 °C/min under a 50-mL/min inert (nitrogen) flow. The TGA data were based on the weight loss percentage against the temperature. The data were analyzed using the Freeman-Caroll method (Hatakeyama *et al*. 1994). The degradation reaction can be described by Eq. 3,

$$\ln [(-dW/dt)/W] = E_a(-1/RT) + \ln A \quad (3)$$

where A is the pre-exponential factor, E_a is the apparent activation energy, R is the universal gas constant, and T is the absolute temperature.

Dimensional Stability Test

Dimensional stability (shrinkage and swelling) tests were carried out to determine the changes in the dimensions of the wood in response to the changes in humidity when exposed to the outdoor environment. A test sample of compressed OPT laminated with 250 g/m^2 and 500 g/m^2 ASR with the size of 6 cm x 2 cm x 2 cm (length x width x thickness) was prepared for the relative humidity (RH) test. Test samples were treated with anti-blue solution, at a ratio of 0.02 L of anti-blue-to-1 L of water, to avoid fungal attack. The samples were immersed in the solution for 15 min and were subsequently dried in an oven at 105 °C for 24 h. The oven-dry weight of the samples was taken before and afterwards with the sample kept in the humid chamber. The test was carried out in an adjustable humidity chamber, testing machine Model GT-7005-T (Gotech), in the School of Industrial Technology, Universiti Sains Malaysia. The RH test was based on previous research by Sarmin (2009) with some modification of the samples' size.

RESULTS AND DISCUSSION

Soil Burial Analysis

Figure 1 illustrates the weight loss of the laminated and non-laminated compressed wood samples as a result of soil burial test. The highest weight loss was 61.37% for the control samples, whereas the samples laminated with 500 g/m^2 adhesive spread rate (ASR) had the lowest weight loss when exposed to field conditions for three months. However, the weight loss of all compressed OPTs increased with increasing exposure duration. The samples laminated with 500 g/m^2 ASR of PVAc had more resistance against all microorganisms than samples with 250 g/m^2 ASR of PVAc. Since the sugar and starch contents are very high in OPT, it is a very attractive food material for microorganisms. These carbohydrates were consumed quickly, and longer burial resulted in greater weight loss of the compressed OPT, with or without lamination. The chemical composition of PVAc, which does not facilitate the growth of bio-organisms, could be the reason for the slower degradation.

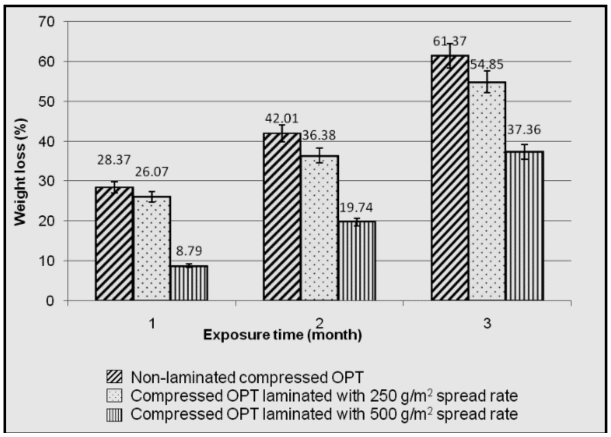
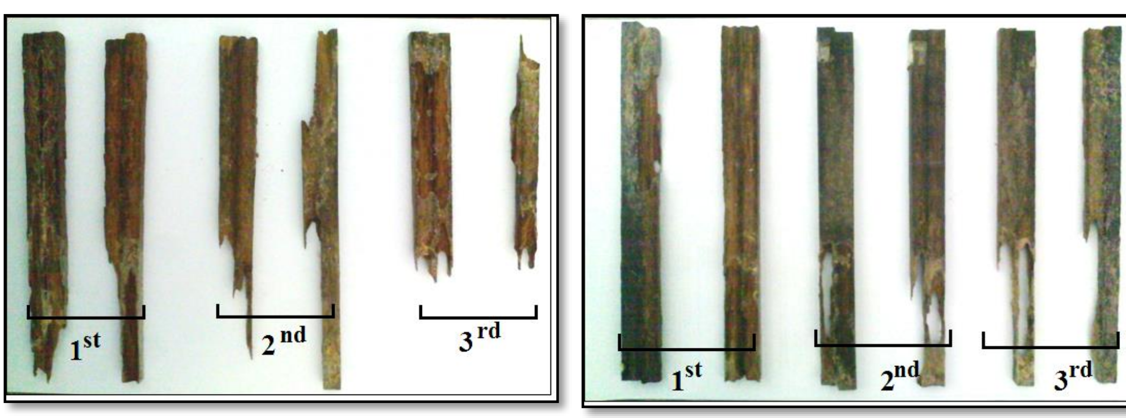


Fig. 1. Percentage weight loss of laminated and non-laminated compressed OPT

A visual observation of both of the compressed OPT samples is displayed in Fig. 2. After three months of soil burial, the parts of samples buried in the soil were completely damaged in the case of the sample laminated with 250 g/m^2 ASR, as shown in Fig. 2 (A). However, the aerial part of samples was only partially damaged, which could be because fewer microbes were found in the air than in the soil. In contrast, the sample laminated with 500 g/m^2 ASR exhibited less weight loss, as shown in Fig. 2 (B). It displayed the least weight loss, 8.79% in the first month, and a similar trend was observed in the following months. At the end of the three months, the maximum damage observed was 37.36%. However, under similar environmental conditions, the sample laminated at 250 g/m^2 ASR withstood 54.85% damage after three months.

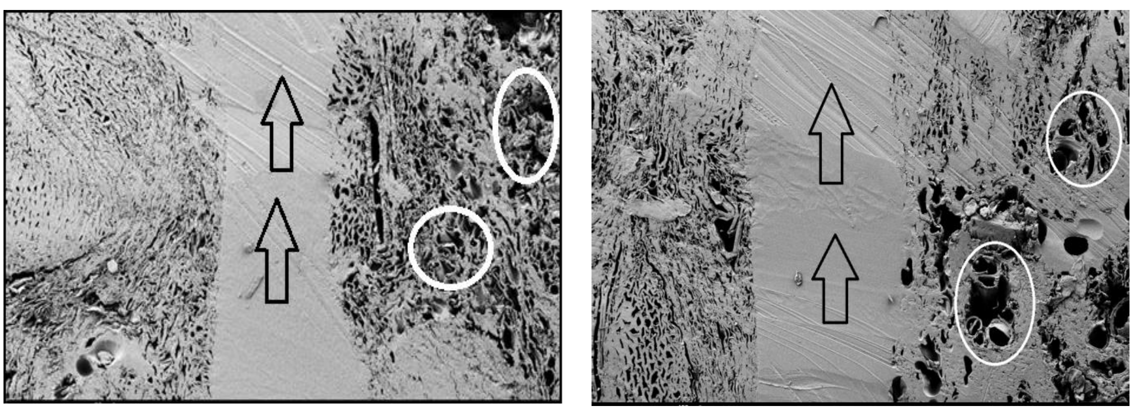


(A) (B)

Fig. 2. Soil burial tests of compressed OPT samples retained after the 1st, 2nd, and 3rd months. (A) laminated with 250 g/m^2 spread rate PVAc, (B) laminated with 500 g/m^2 spread rate PVAc

In almost all cases, the glue line was retained without being attacked, as indicated in Fig. 3 A, B. Sulaiman *et al*. (2009) studied the durability of OPT and rubberwood laminated veneer lumber and observed similar trends of biological deterioration.

Steaming of the OPT resulted in chemical changes in the samples. Upon steaming, the hemicelluloses, cellulose, starch, lignin, and some extractives were partially degraded. Salim *et al*. (2012) found that steamed samples experienced less biological deterioration compared to non-steamed samples. This could be due to the lesser amount of readily available food favorable to microorganisms in the samples. Therefore, steaming is one way to improve the durability of wood-based products for outdoor application. Figure 3 shows scanning electron microscope (SEM) images of the specimens after they were buried for three months. The adhesive was still intact within the compressed OPT. This indicates that the adhesive was not deteriorated by organisms during the test period. However, some structures of the compressed OPT were degraded because organisms consume fibers, parenchyma, and starch. Visual observation of both types of compressed, laminated OPT samples showed similar damage patterns (Figs. 3A and 3B). It was also observed that the parenchyma was more likely to be damaged first as compared to the vascular bundle. This could be due to the greater starch content found in parenchyma.

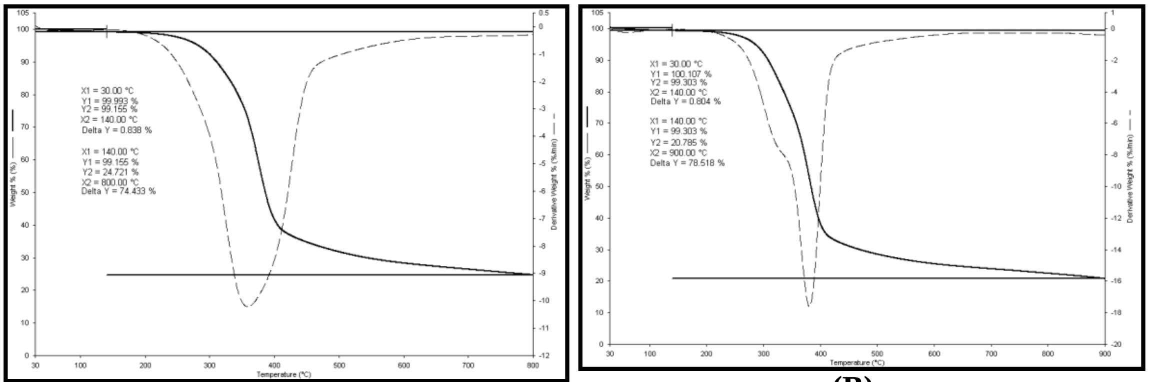


(A) (B)

Fig. 3. SEM image of compressed OPT at 100 µm, exposed to uncontrolled weather for 3 months: (A) laminated with 250 g/m^2 ASR sample, (B) laminated with 500 g/m^2 ASR sample (arrows show the glue line and circles show damaged parenchyma).

Thermal Stability Analysis

Thermogravimetric analysis was performed to determine the degradation rate of the compressed OPT samples, which was measured as the change in sample weight in relation to the change in temperature. Two compressed OPT samples, one steam-pretreated and another without steam pretreatment, were selected for TGA. Figures 4 (A) and 4 (B) illustrate the TGA results for both samples. Weight loss for both samples began at a temperature of 250 °C, and the samples were fully degraded when the temperature reached 300 °C. However, gradual weight loss was observed in both samples. The percentage weight loss was lower for the steam-pretreated samples as compared to that of non-steamed samples; the weight losses were 20% and 25%, respectively. The degradation of the samples corresponded to the thermal degradation of hemicellulose, water, and carbon dioxide (Sun *et al*. 2001). The results indicated that the samples subjected to steaming prior to pressing possessed better thermal resistance and experienced lower weight loss after degradation as compared to the samples without steaming. A study conducted by Inoue *et* *al*. (1993) suggested that steaming could minimize the thermal degradation of wood, which agrees with the results obtained in this study.

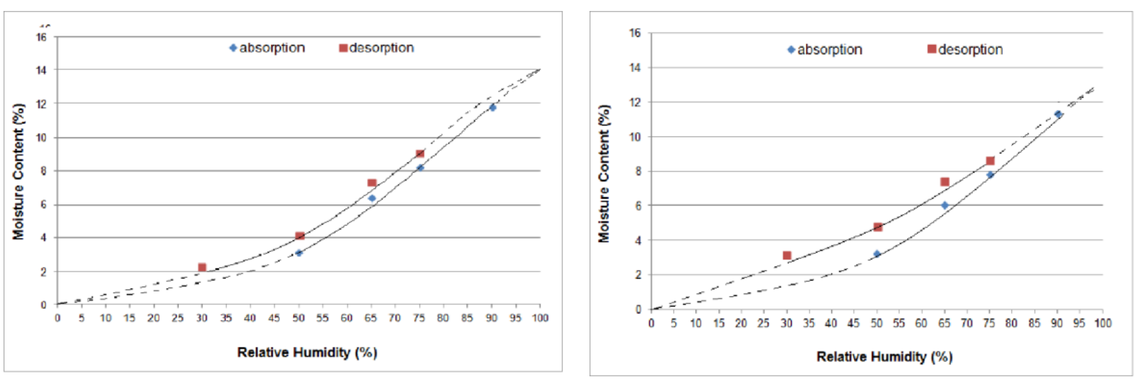


(A) (B)

Fig. 4. Thermogravimetric analysis curves: (A) compressed OPT without steam pretreatment, (B) compressed OPT with steam pretreatment

Dimensional Stability Analysis

Relative humidity (RH) testing was carried out to determine the adsorption and desorption behavior of the panels. For each level of RH, there was a corresponding MC of wood that determined the equilibrium moisture content (EMC) of the test sample. In this study, the rate of moisture change was recorded as a function of the change in RH. Figures 5(A) and 5(B) illustrate the adsorption and desorption curves of both samples, until 90% relative humidity was reached, as a moisture content *versus* RH graph.



(A) (B)

Fig. 5. Absorption and desorption curves of compressed OPT: (A) laminated with 250 g/m^2 adhesive spread rate, (B) laminated with 500 g/m^2 adhesive spread rate

The graph shows that the EMC was directly proportional to the RH and increased with increasing RH. From the graph, it is clear that the EMC was greater in desorption than in adsorption, which explains the observed hysteresis. A hysteresis curve was formed, in which the desorption isotherm was higher than the adsorption isotherm at any relative humidity (Zomorodian and Tavakoli 2010). The ratio of adsorption-to-desorption at the same RH is called the magnitude of hysteresis and was practically constant (Tsoumis 1991). The magnitude of hysteresis for the compressed OPT sample laminated with 250 g/m^2 ASR was 0.89, whereas that of the sample laminated with 500 g/m^2 adhesive spread rate was 0.84. In general, the values of hysteresis observed were below 1.00; thus, the results of this study agree with theory. Hysteresis occurs because of the linkage of the free hydroxyls of wood constituents when there is very little or no moisture in the wood. Hence, the number of available hydroxyls is smaller in the following adsorption.

CONCLUSIONS

1. The thermal degradation rate showed similar trend for both types of samples but the steam-treated sample exhibited lower weight loss compared to unsteamed sample.
2. The amount of polyvinyl acetate (PVAc) adhesive played an important role in the durability of the laminated, compressed oil palm trunks (OPTs). OPT laminated with 500 g/m^2 adhesive spread rate exhibited higher durability than that of the OPT laminated with 250 g/m^2 adhesive spread rate.
3. In soil burial tests, the highest durability was observed for OPT laminated with 500 g/m^2 adhesive spread rate (ASR), where the lowest weight loss was observed (37.36%). In the control sample, the highest weight loss was observed highest (61.37%) at the end of the three-month test.
4. The magnitude of hysteresis was slightly lower for 500 g/m^2 ASR as compared to that of 250 g/m^2 ASR; both samples exhibited very high shrinkage and swelling properties based on the results of relative humidity test.
5. On an overall performance basis, the steam-pretreated, compressed OPT laminated with 500 g/m^2 ASR possessed higher durability against bio-organisms, higher thermal resistance, and fairly good dimensional stability.

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