Mechanical and Morphological Properties for Sandwich Composites of Wood/PVC and Glass Fiber/PVC Layers

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ABSTRACT: This work manufactured sandwich composites from glass fiber/poly(vinyl chloride) (GF/PVC) and wood/PVC layers, and their mechanical and morphological properties of the composites in three GF orientation angles were assessed. The effects of *K* value (or viscosity index) of PVC and Dioctyl phthalate (DOP) loading were of our interests. The GF/PVC was used as core layer whereas wood/PVC was the cover layers. The experimental results indicated that PVC with low *K* value was recommended for the GF/PVC core layer for fabrication of GF/WPVC sandwich composites. The improvement of PVC diffusion at the interface between the GF and the PVC core layer was obtained when using PVC with *K* value of 58. This was because it could prevent de-lamination between composite layers which would lead to higher mechanical properties of the sandwich composites, except for the tensile modulus. The sandwich composites with 0° GF orientation possessed relatively much higher mechanical properties as compared with those with 45° and 90° GF orientations, especially for the impact strength. Low mechanical properties of the sandwich composites with 45° and 90° GF orientation angles could be overcome by incorporation of DOP plasticizer into the GF/PVC core layer with the recommended DOP loadings of 5–10 parts per hundred by weight of PVC components. © 2010 Wiley Periodicals, Inc. J Appl Polym Sci 116: 3427–3436, 2010

Key words: thermoplastics; reinforcement; mechanical properties; processing

INTRODUCTION

Wood polymer composites (WPC) are now increasingly utilized for buildings and constructions, automotives, gardening and outdoor products as well as marine applications,[1] although their mechanical strengths are still lower than the natural woods. A number of methods and techniques have been proposed to improve the mechanical properties and tribological resistances of the WPC products, especially for structural and engineering applications.[1–17] Such methods and techniques include additions of synthetic fibers,[2–6] nanoparticles[7–9] or long fiber,[8–11] chemical and physical surface treatments[12–15] and selections of appropriate processing techniques.[16,17] Tungjitpornkull et al.[3] suggested that the mechanical moduli and strengths of the wood/PVC (WPVC) composites increased with increasing glass fiber (GF) contents. Rizvi and Semeralul[4] found the tensile properties of the wood/HDPE composites were improved by addition of 5% GF whereas Jiang et al.[5] did not find positive effects when adding short GFs into WPVC composites. Faruk and Matuana[7] investigated the effect of nanoclay addition into wood/high-density polyethylene (wood/HDPE) to enhance the mechanical properties of the wood/HDPE composites. They also suggested that mechanical property improvement for the wood/HDPE composites could be achieved by melt blending technique carried out by incorporating the nanoclay into the HDPE before adding the wood particles. They[8] also used multiwalled carbon nanotubes (CNT) to improve the tensile and flexural properties of wood/PVC composites so that the mechanical properties of the CNT filled wood/PVC composites were similar to those of the northern white cedar wood.

Our previous work[17] produced sandwich wood/PVC composites with unfilled PVC core layer. The GF was placed in the center part of the PVC core layers to form GF/PVC core layer within the wood/PVC cover layers, and the mechanical properties and the effect of glass-fiber orientation of the wood/PVC sandwich-composites were then studied. It was found that the GF/PVC and wood/PVC sandwich composites with fiber orientation angle of 0° gave the maximum mechanical properties. However, a de-lamination between the neat PVC layer and the

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GF in the PVC core layer was observed and this resulted in lower mechanical properties. The de-lamination had occurred as a result of difficulty for the PVC to penetrate into the glass fiber at the GF/PVC core layer. This was because the extremely high viscosity of the molten PVC core layer. In this respect, it was very interesting to reduce or eliminate the de-lamination by improving the diffusion within the GF/PVC core layer to improve the mechanical properties of the GF/WPVC composites.

There have been a few methods available for improving the process-ability or flow-ability in polymer and polymer composite systems.[18–20] These included incorporations of chemical plasticizers and wetting agents, and selections of polymers with appropriate molecular weights. Liang et al.[18] reported that the addition of Di-allyl orthophthalate (DAOP) reactive plasticizer into PVC significantly improved the process-ability by reducing the melt viscosity. This had benefit in lowering the processing temperature of plasticized PVC without encountering the decomposition of PVC during processing. Yan et al.[19] used long-chain linear polyester (LP) with Di-octyl phthalate (DOP) had a synergistic effect on the mechanical properties of the PVC. Elgozali and Hassan[20] found that addition of plasticizer in PVC without filler decreased the tensile properties whereas the result was completely reversed in PVC contained filler. De Albuquerque et al.[11] showed that the mechanical properties of polyester composites reinforced with jute roving were improved by addition of a wetting agent (trade name of BYK-A515), as compared with those without the wetting agent.

This work extended from our previous work[17] and involved production of sandwich composites of wood/PVC (WPVC) as cover layers and GF/PVC as core layer. The GF was placed in the middle part of the PVC compound sheets. This work focused on the effects of Dioctyl phthalate (DOP) plasticizer loading and viscosity (*K* value) of neat PVC core layer on the mechanical and morphological properties of the sandwich composites. This was aimed to reduce the de-lamination between the PVC and GF at the core layer and to improve the diffusion level within GF/PVC core layer. This was believed to enhance the mechanical properties of the GF/WPVC sandwich composites. Scanning electron and optical micrographs of the fracture composite samples were used to substantiate the mechanical properties of the GF/WPVC sandwich composites.

EXPERIMENTAL

Raw materials

TABLE I
Characteristics of Suspension PVC Used in this Work

Characteristics	PVC grade (SIAMVIC) 258RB	266PS	271GC
K value (cyclohexanone)	58	66	71
Viscosity index (cm^3/g)	82	109	129
Polymerization degree	680	1000	1270
Apparent bulk density (g/cm^3)	0.56	0.50	0.47

- Suspension PVC was supplied by Vinythai Public. (Bangkok, Thailand) in the form of powder. PVC with three *K* values were used in this study; the trade names were SIAMVIC-258RB, SIAMVIC-266PS and SIAMVIC-271GC with *K* values of 58, 66 and 71, respectively. The properties of three PVC resins (*K* value. Viscosity index, polymerization level) are listed in Table I. The main additives of PVC, supplied by V.P. Wood. (Bangkok, Thailand), were listed in Table II.
- Wood particles with the average particle size of 100–300 μm were used and supplied by V.P. Wood. (Bangkok, Thailand). The wood content in all PVC compounds was fixed at 50 part per hundred (pph) by weight of PVC powder and the wood particles were chemically surface-treated with 1.0 wt % N–2(aminoethyl)–3–aminopropyl trimethoxysilane ($M_w = 222.4$) as suggested by our previous work.[13] The detailed experimental procedure on the silane surface treatment was already given elsewhere.[13]
- DOP ($M_w = 390$), supplied by V.C. Industry. (Bangkok, Thailand), was used for studying the effect of DOP contents on the mechanical property investigations of GF/WPVC sandwich composites.
- The GF, supplied by Gratetrade interbusiness. (Bangkok, Thailand) in form of E–woven mat (EWM), was used as reinforcement for WPVC composites in this work. The GF had a surface weight density of 600 g/m^2 and was chemically surface-coated by 3-methacryloxypropyl trimethoxysilane (this being referred to as "KBM503") which had an average molecular weight of 248.4. From the previous work,[17] the EWM was necessarily modified by taking out fiber bundles of one direction from the initial EWM as this allowing a sufficient space for molten PVC composite to penetrate for effective reinforcement.

Specimen preparation of GF/WPVC sandwich composites

The GF/WPVC sandwich composites were in this work referred to as sandwich composites of GF/PVC core layer and WPVC cover layers. The sandwich composites were prepared by compression molding technique as shown in Figure 1(a). The

TABLE II
Ingredients for Making PVC Compounds

Ingredients	Concentration (pph)
Suspension PVC	100.0
Emulsion PVC grade SIAMVIC® 167GZ	4.0
Pb-Ba based organic stabilizer (PF 608A)	3.6
External lubricant (Finalux® G-741)	0.6
Calcium stearate	0.6
Calcium carbonate (Omyacarb®-2T)	12.0
Processing aids (PA-20)	6.0
Wood flour	50.0
Dioctyl phthalate (DOP)	Varied

experimental procedures were described in three sequential steps as follows:

Step 1: production of GF/PVC core layer

The first step involved making GF/PVC core layer using compression molding technique. The experiment was commenced by dry-blending PVC powder with various necessary additives as were listed in Table II using a high speed mixer for 5 min to obtain PVC compound. The PVC compound was filled within two steel square molds whose dimensions were 180 × 180 × 1 mm^3 and then preheated at temperature of 180°C for 3 min before being compression-molded under a pressure of 18 MPa at the mold temperature of 180°C for 3 min, and cooled down for 5 min to obtain a PVC compound sheet. The prepared GFs were placed between two PVC compound sheets and were then plate-shaped by a compression molding machine (LAB Tech hydraulic press Type LP-S-20, Bangkok, Thailand) to obtain the GF/PVC core layer using the same processing conditions as used for the production of PVC compound sheets. The average thickness of the GF/PVC core layer used in this work was 2.3 mm. In this section, two experimental variables were of our interests, *K* value of PVC and DOP loading. This was aimed to enhance the diffusion level within GF/PVC core layer and also to improve the mechanical properties of the GF/WPVC sandwich composites.

Step 2: production of WPVC cover layers

This procedure involved preparation of two WPVC cover (or skin) layers having a fixed wood content of 50 pph (or 33.3% by weight) using compression molding technique. The wood particles were first placed on a tray and subjected to heat treatment in an oven at 80°C for 24 h until the weight of the wood was constant. The experimental procedure for preparing the WPVC layer was similar to that as described for the GF/PVC core layer, except for that the wood particles of 50 pph was incorporated during the dry-blending process, and the mold thickness used for this purpose was 2 mm. The WPVC composite was preheated at temperature of 180°C for 5 min and compress-molded under a pressure of 18 MPa at the mold temperature of 180°C for 5 min, before being cooled down for 5 min. The average thickness of the WPVC cover or skin layer used in this work was 1.4 mm for each side.

Step 3: production of sandwich composites of GF/PVC and WPVC layers

This step produced sandwich composites of GF/PVC core layer and WPVC cover layers. The WPVC layers and GF/PVC layer were was preheated at temperature of 180°C for 5 min and then compression-molded using a pressure of 18 MPa at the mold temperature of 180°C for 3 min. This gave a complete GF/WPVC composite sample as shown in Figure 1(a). The GF/WPVC sandwich composite samples were then cut in three different angles to the fiber orientations as shown in Figure 1(b), these being 0°, 45°, and 90° to study the effect of fiber orientation angles on the mechanical properties of the GF/WPVC sandwich composites. The thickness of the GF/WPVC sandwich composites used in this work was 5.1 mm. The geometries (shape and dimensions) of the cut composite specimens were based on the mechanical characterization methods used.

Mechanical characterizations

The mechanical properties of GF/WPVC sandwich composites were investigated through tensile,

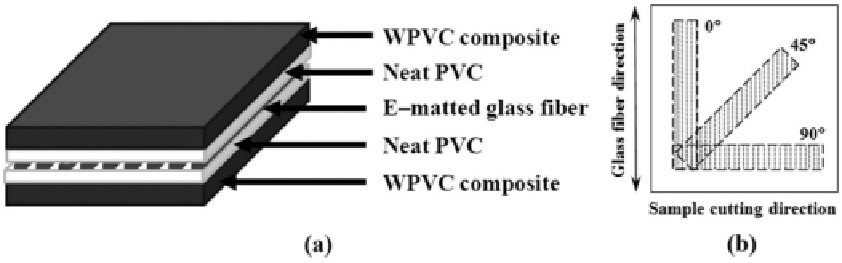

Figure 1 Description of GF/WPVC sandwich composite sheets (a) Layer structure of GF/WPVC sandwich composites (b) Sample cutting directions of GF/WPVC sandwich composites for varying fiber orientation angles.

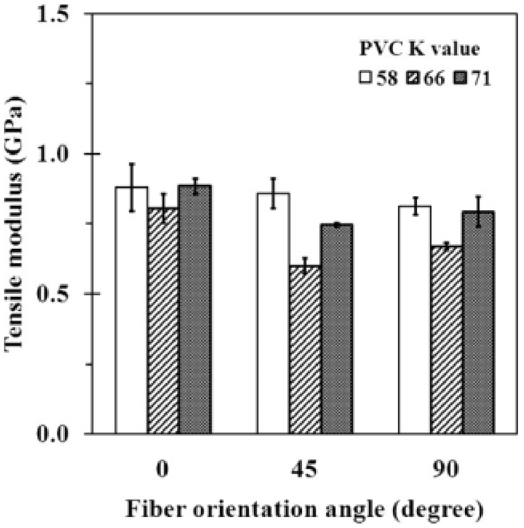

Figure 2 Effect of *K* value of PVC in GF/PVC core layer on tensile modulus for GF/WPVC sandwich composites.

flexural and impact properties. Tensile testing was performed on a SHIMADZU tensile tester (Tokyo, Japan) at crosshead speed of 5 mm/min. The tensile test procedure followed the ASTM D638 (2008) Specimen Type I. The flexural property was determined according to ASTM D790 (2003) (the specimen dimensions of 15× 120 mm^2, support span of 86 mm, and a crosshead speed of 2.4 mm/min). The Izod impact test procedure followed the ASTM D256 (2002) for determination of impact properties of the GF/WPVC composites, the tests being performed on a Zwick GmbH impact tester (Ulm, Germany) with the notched side facing the pendulum. It should be noted that the mechanical property results reported in this work were averaged from 10 determinations. A high resolution digital camera was used to visualize the cross-sections of the GF/WPVC sandwich composites for de-lamination investigations.

Morphological Investigations

The distribution and orientation of GFs in WPVC composites, and interfacial adhesion between the WPVC cover and GF/PVC core layers were morphologically investigated using a JEOL (JSM-6301F) SEM machine at 15 kV accelerating voltage. The fracture surfaces of the GF/WPVC composites for SEM examinations were obtained after impact-testing. The details of the experimental procedures and sample preparations for SEM studies can be found in the work by Sombatsompop and Chaochanchaikul.[13] Cross-section of the GF/WPVC sandwich composite layers was also investigated using an optical microscope (×5, BHM Metallurgical Microscope, OLYMPUS, Japan).

RESULTS AND DISCUSSION

Effect of *K* value of PVC

Figures 2–5 shows the effect of *K* value (viscosity) of PVC in the GF/PVC core layer on mechanical properties of GF/WPVC sandwich composites for different fiber orientation angles. It was found that for a given fiber orientation angle, increasing the *K* value of PVC decreased the mechanical properties of the GF/WPVC composites, except for tensile modulus in Figure 2. The effect of *K* value on the tensile modulus was very small as compared to other mechanical properties and the tensile modulus differences were within the experimental error limits. Comparing the tensile modulus (Fig. 2) with the tensile strength and elongation at break (Fig. 3), it seemed that the effect of *K* value on the tensile strength and elongation was more significant than that on the tensile modulus. This may be because the tensile modulus is regarded as mechanical response at small deformation whereas the tensile strength and ultimate

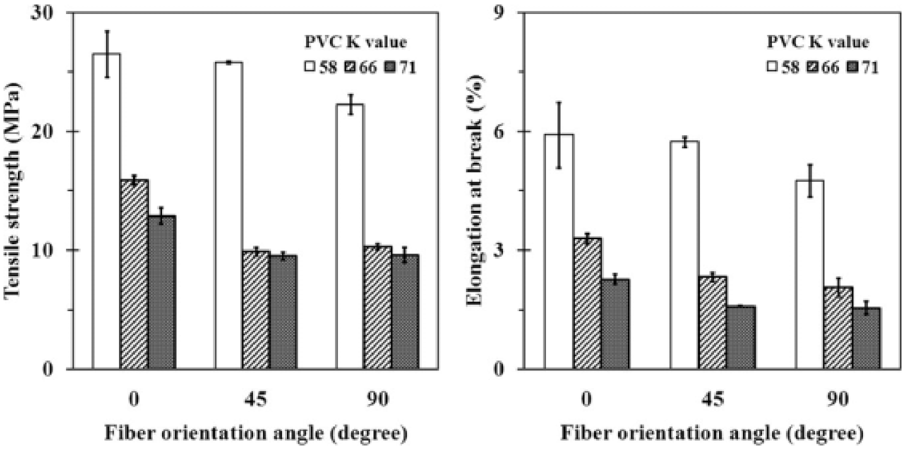

Figure 3 Tensile strength and elongation at break of GF/WPVC sandwich composites at different *K* values in GF/PVC core layer.

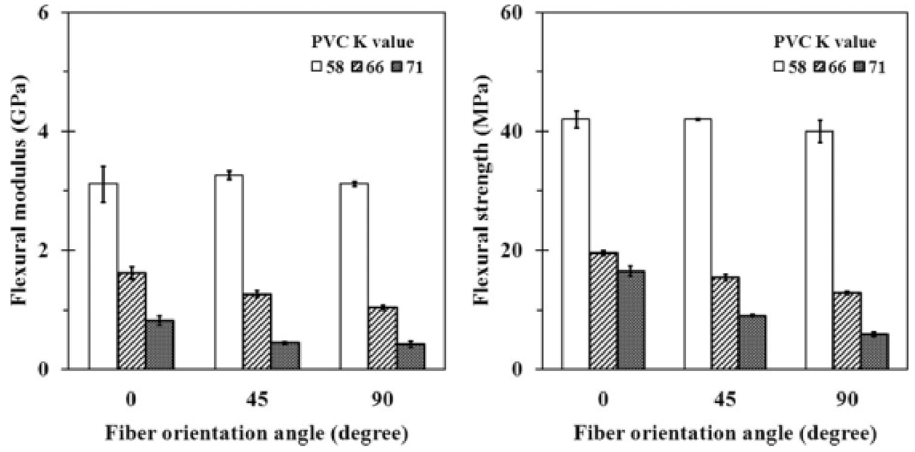

Figure 4 Flexural properties of GF/WPVC sandwich composites using different *K* values of PVC in GF/PVC core layer.

elongation are mechanical responses at large deformation. The former property is usually (also in this case) influenced by the PVC matrix while the latter one is associated with a number of factors including PVC matrix and interfacial bonding between PVC and GF. In this work, the effect of GF presence and its orientation probably played more significant than those of the *K* value of PVC. Therefore, it was expected to observe more changes in the ultimate properties like tensile strength or elongation at break. The effect of *K* value on the mechanical properties of the GF/WPVC sandwich composites appeared to be very pronounced for the *K* values of PVC from 58 to 66. The differences in the mechanical properties of GF/WPVC composites with different *K* values of PVC were caused by different diffusion levels between the GF and PVC within the GF/PVC core layer. This resulted from different initial molecular characteristics of PVC cores (viscosity index and polymerization level) as given in Table I. The GF/PVC core layer with high *K* values of PVC of 66 and 71 had less diffusion level than that with *K* value of 58. The composite samples with *K* values of PVC of 66 and 71 tended to produce air-gap within the PVC core layers and thus resulted in lower mechanical properties. The diffusion mechanism could physically be explained by Figure 6 which shows the cross-sectioned GF/WPVC sandwich composites with different *K* values of PVC after the molding process. It can be clearly seen that the GF/WPVC sandwich composites with *K* values of PVC of 66 and 71 exhibited de-laminations (with appearance of air-gap) between the GF mats and PVC in the core layer whereas this was not seen for the GF/WPVC sandwich composite with *K* value of PVC of 58. For deeper understanding for the diffusion mechanism, a schematic diagram for diffusion effect between the GF/WPVC composites with low (a) and high (b) PVC core viscosities is provided in Figure 7 which suggested an interdiffusion between

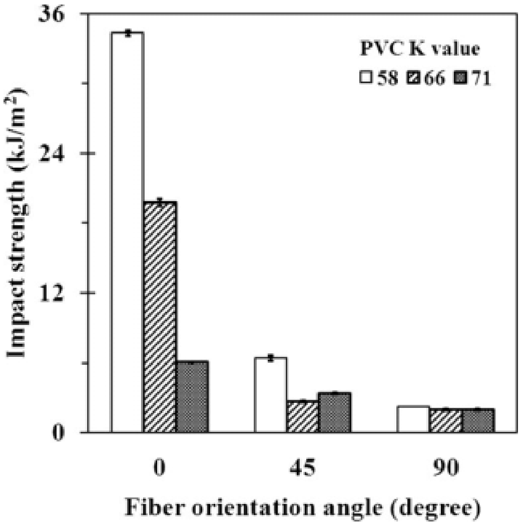

Figure 5 Impact strength of GF/WPVC sandwich composite at varying *K* values of PVC in GF/PVC core layer.

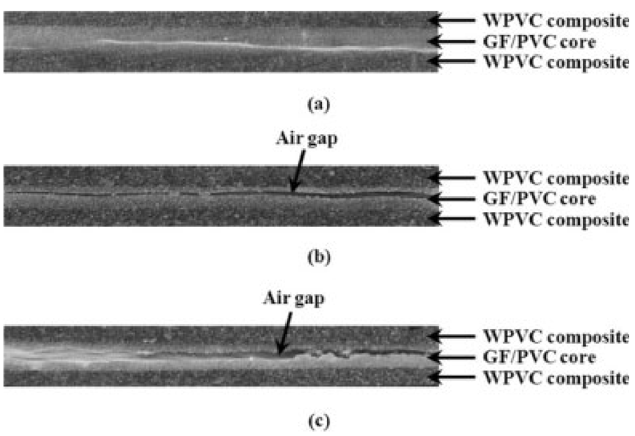

Figure 6 Cross sectional views of GF/WPVC sandwich composite samples (a) *K* value at 58 (b) *K* value at 66 (c) *K* value at 71.

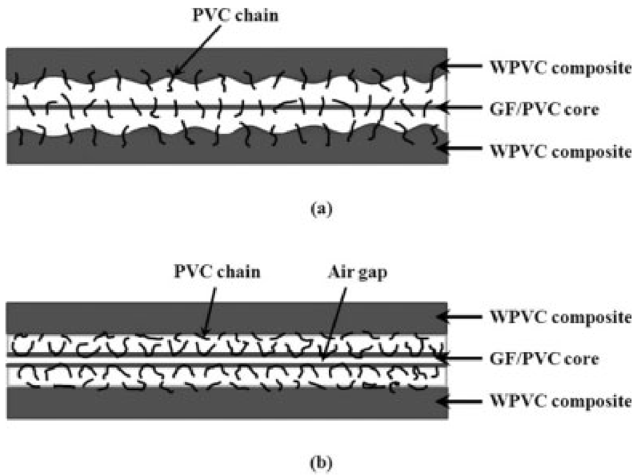

Figure 7 Schematic diagram for qualitative assessment of PVC diffusion in GF/WPVC sandwich composites (a) Using low *K* value of PVC (b) Using high *K* value of PVC.

WPVC and GF/PVC layers as a result of capability for WPVC layer to penetrate into the GF/PVC core layer during the compression molding. It was thought that the diffusion occurred at both interfaces of GF-PVC and GF/PVC-WPVC layers for the composites with *K* value of 58 (low *K* value) whereas the PVC diffusion was hardly seen at the interfaces of GF and PVC for the core layers with *K* values of 66 and 71. Therefore, the mechanical properties of the GF/WPVC sandwich composites with *K* value of 58 would be higher. The higher mechanical properties of the GF/WPVC sandwich composites with *K* value of 58 without any de-lamination could be substantiated using SEM micrographs as shown in Figure 8, the SEM specimens being obtained after the impact testing. It can be observed that the WPVC and GF/PVC layers were adhered to one another. This was evidenced by compaction and good aggregation of the GF bundles, forming a relatively good composite lamination without air gaps. The GF bundles in the GF/WPVC sandwich composites with *K* values of 66 and 71 [Figs. 8(b,c)] contained large air gaps within the irregular compactions of GF bundles and orientations.

When considering the effect of fiber orientation angle, it was found that the GF/WPVC sandwich composites with 0° GF orientation had much higher mechanical properties than those with 45° and 90° GF orientations, the effect being more remarkable for the impact strength. This statement was in line with our previous work.[17] The explanation for this was that, the mechanical properties of the sandwich composites with 0° fiber orientation was dependent on both interfacial bonding and the tensile force transferred along the fiber length, while those for the composites with the other two orientation angles (45° and 90°) were only influenced by the interfacial bonding between the GF and the PVC matrix due to the direction of exerted force to the fiber orientation in the PVC matrix.

It was worthy noting from the results in Figures 2–5 that the mechanical properties of GF/WPVC composites were greatly affected by diffusion level (de-lamination) between the GF and PVC within the GF/PVC core layer which was related with the *K* value of PVC used (evidenced by SEM results in Fig. 8), and by the GF orientation. The tensile and flexural properties in Figures 2–4 were more affected by the effect of *K* value of PVC whereas the impact properties in Figure 5 were more dependent on the fiber orientation. The effect of GF orientation was marginal for tensile and flexural properties (Figs. 2–4). This may be because the PVC diffusion into the glass fiber for the GF/WPVC composites with *K* value of 58 had overruled the effect of GF orientation.

Effect of DOP addition

In this section, PVC with *K* value of 58 was deliberately selected for production of GF/PVC core layer for studying the effect of DOP plasticizer on the mechanical properties. Figure 9 shows the effect of DOP loading on tensile modulus of GF/WPVC

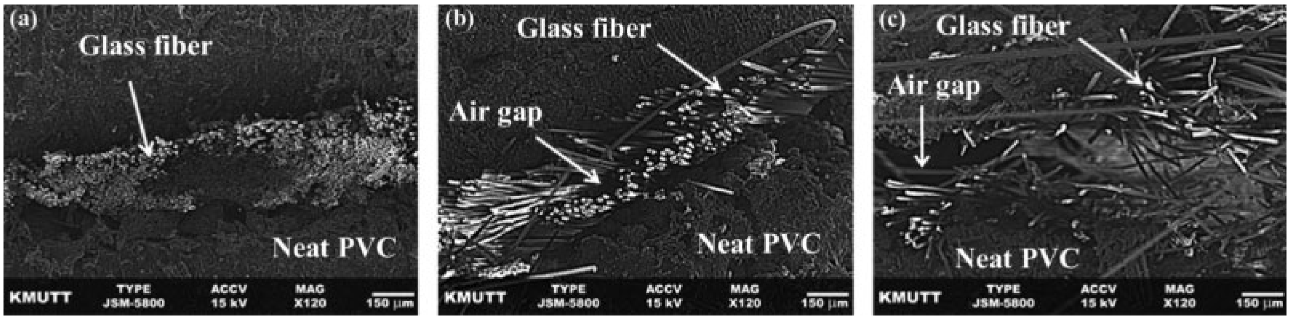

Figure 8 SEM micrographs of cross-sections for GF/WPVC sandwich composites obtained after the impact testing (a) *K* value at 58 (b) *K* value at 66 (c) *K* value at 71.

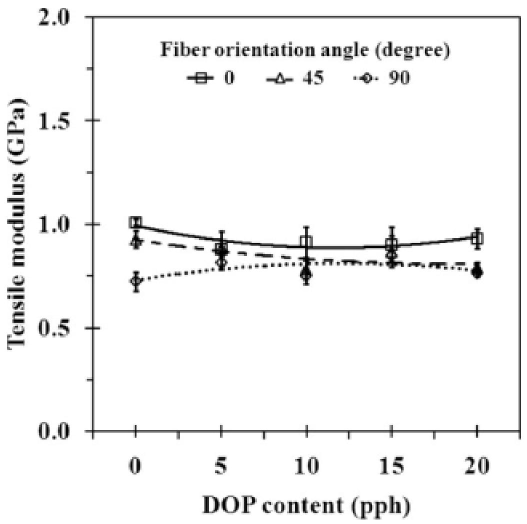

Figure 9 Effect of DOP plasticizer in GF/PVC core layer on tensile modulus for GF/WPVC sandwich composites.

sandwich composites. Within the limits of the experimental errors, the addition of DOP had no effect on the tensile modulus for all fiber orientation angles. The results of tensile strength and elongation at break are given in Figure 10. It was evidenced that the tensile strength and elongation at break of GF/WPVC sandwich composites with 0° fiber orientation were relatively higher, the reason for this involving the force direction and interfacial bonding effects which were already mentioned earlier. It was interesting to note that the addition of DOP plasticizer had no effect on the tensile strength and elongation at break of the GF/WPVC sandwich composites with 0° fiber orientation, but very much improved the tensile strength and elongation at break of the composites in other two directions (45° and 90°) at optimum DOP concentrations at 5–10 pph. This implied that the intrinsic properties of the GF were dominant for the GF/WPVC composites with 0° fiber orientation angle whereas the interfacial bonding played the significant role for the GF/WPVC composites with 45° and 90° fiber orientation angles. It was also indicated that using DOP at the optimum loadings offered a practical benefit for improvement of the lower mechanical properties of the GF/WPVC sandwich composites in 45° and 90° fiber orientations as previously observed in the *K* value effect. The improvement of the tensile strength and elongation at break by the DOP plasticizer for the composites with 45° and 90° fiber orientations involved lowering the viscosity of the PVC core layer which then enhanced the flow-ability of the molten PVC.[18] As the flow-ability was occurring, the penetration levels of molten PVC through the GF in PVC core layer, and at the interface between the WPVC and GF/PVC core layers would increase. As a consequence, the tensile strength and elongation at break of the GF/WPVC sandwich composites was improved. At the DOP concentrations of higher than 10 pph, the tensile strength and elongation at break of the GF/WPVC sandwich composites appeared to decrease. It was postulated that excess DOP loading (greater than 10 pph) would not participate in the improvement of the interfacial bonding, but instead, acted as minor phase in polymer blend and softened the PVC core layer. This behavior could be referred to as plasticization effect.[21] Therefore, the tensile strength and elongation at break of the GF/WPVC sandwich composites worsened. To substantiate the claim on the effect of DOP content, the optical micrographs of the GF/WPVC composite cross-sections viewed at the WPVC and GF/PVC interfaces with and without DOP plasticizer are given in Figure 11. The results suggested that the GF/WPVC sandwich composites with no DOP [Fig. 11(a)] had a straight interface line whereas GF/WPVC sandwich composites with the DOP loadings of 10–20 pph [Figs. 11(b,c)] exhibited wave-like interfaces,

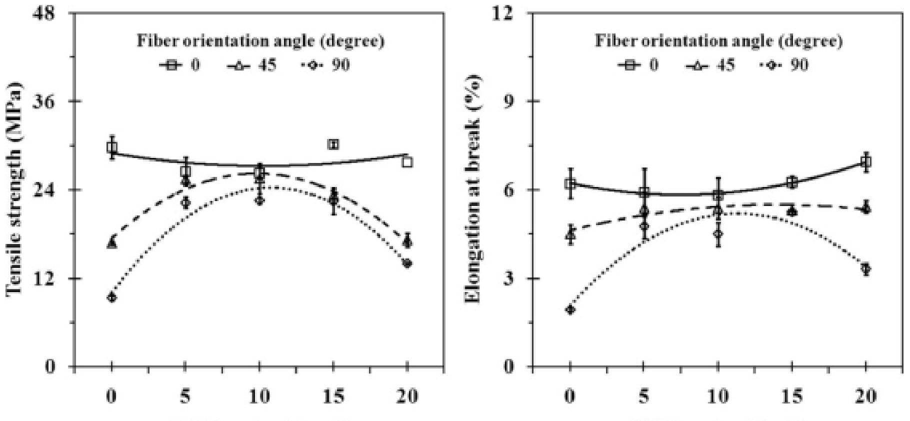

Figure 10 Tensile strength and elongation at break of GF/WPVC sandwich composites at different DOP loadings in GF/PVC core layer.

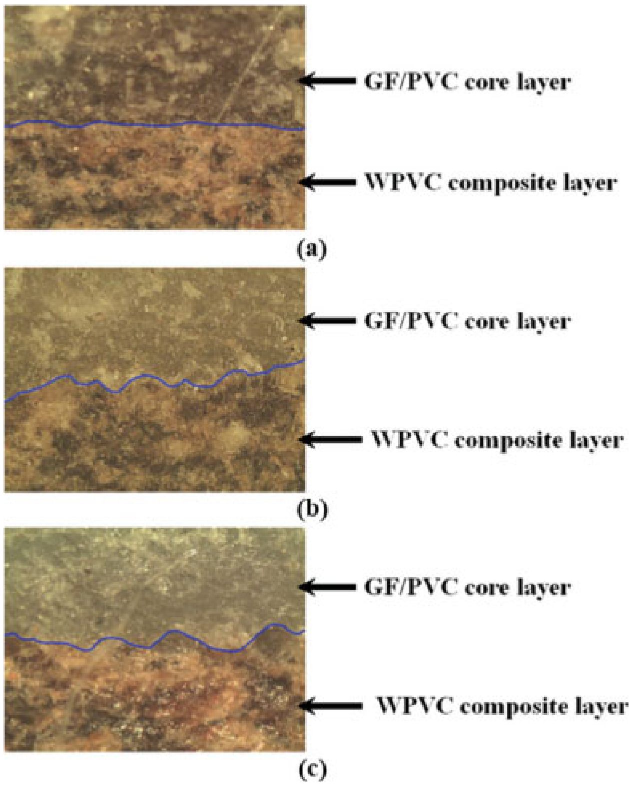

Figure 11 Optical micrographs of cross-sectional GF/WPVC composites for different DOP loadings (a) 0 pph (b) 10 pph (c) 20 pph. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

indicating interpenetration histories of the WPVC and GF/PVC layers during the lamination process.

Figure 12 illustrates relationship between flexural properties and DOP content for three different fiber orientation angles. The results indicated that there was no effect of fiber orientation on the flexural properties, this observation being in line with the previous work.[17] The optimum DOP content for the flexural properties of the GF/WPVC sandwich composites was 10 pph for the improved diffusion of molten PVC through the GF in PVC core layer, and at the interface between the WPVC and GF/PVC core layers. The decreases in flexural properties after 10 pph of DOP loading were caused by the plasticization effect.[22]

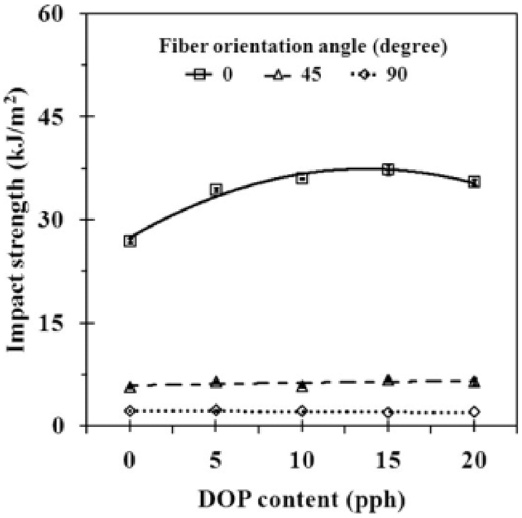

Figure 13 Effect of DOP dosages on impact strength for GF/WPVC sandwich composites.

The effect of the DOP incorporation on impact strength of the GF/WPVC sandwich composites is given in Figure 13. The differences in properties for GF/WPVC sandwich composites with different fiber orientations under impact deformation were greater than those under tensile deformation. The GF/WPVC sandwich composites with 0° fiber orientation were found to have more resistances to the crack propagation under impact loading than those with 45° and 90° orientations. The explanation involved the relationship between the applied

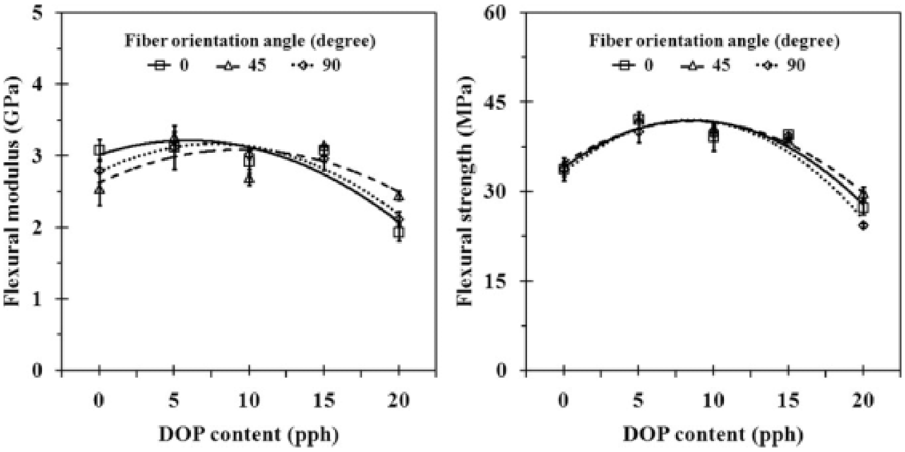

Figure 12 Flexural properties of GF/WPVC sandwich composites using different DOP contents in GF/PVC core layer.

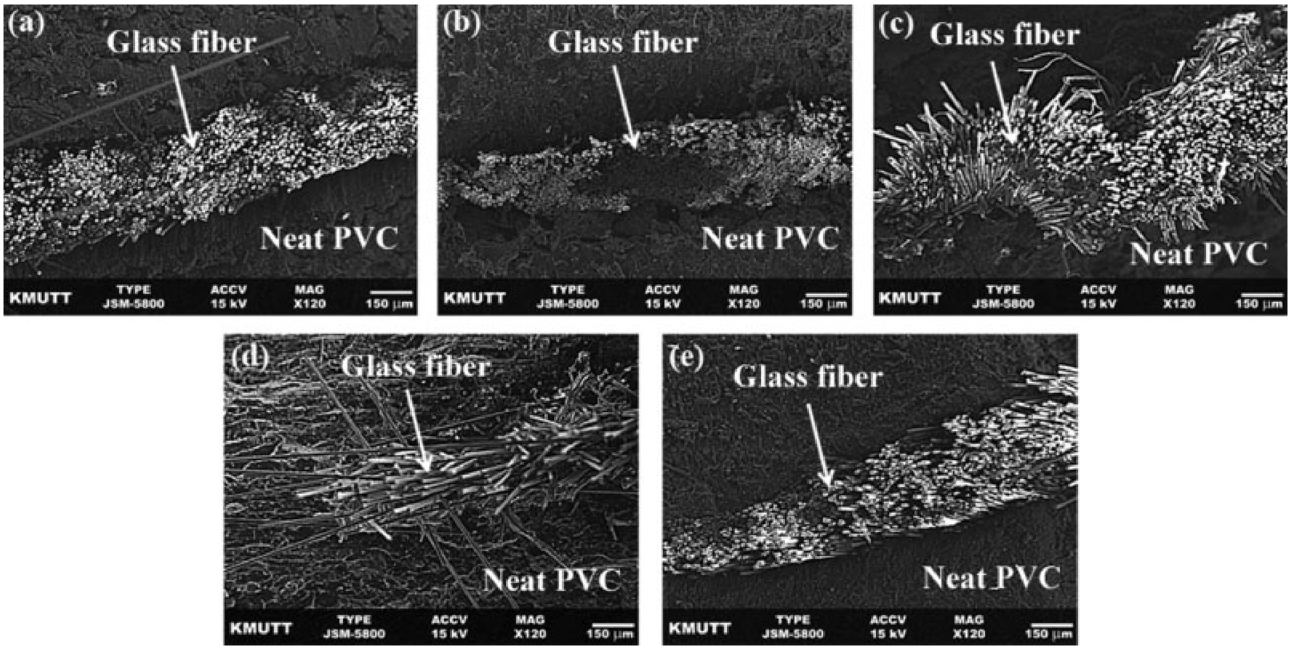

Figure 14 SEM micrographs of fracture GF/WPVC sandwich composites containing different amounts of DOP after impact testing (a) 0 pph, (b) 5 pph, (c) 10 pph, (d) 15 pph, and (e) 20 pph.

impact force direction and the fiber orientation angle. This view could be substantiated by Wang et al.[23] who studied the effect of fracture propagation direction on the impact strength of PP/EPDM blend and found that higher impact strength was obtained when the force direction was applied in parallel direction (analogous to 0° orientation angle referred in this work) to the elongated rubber phase and vice versa. The addition of DOP was found to increase the impact strength of the GF/WPVC sandwich composites because of the increased PVC diffusion at the interfaces within GF/PVC core layer and between GF/PVC and WPVC layers. The considerable increases in the impact strength can also be explained by the presence of fiber pull-out in the GF/WPVC composites. Figure 14 shows SEM micrographs of the GF/WPVC composites after the impact testing at varying DOP loadings. It can be seen that the fiber pull-out characteristics were obviously observed for the GF/WPVC composites with 10 pph DOP content. This observation was supported by Bagwell and Wetherhold.[24]

CONCLUSION

This work studied the effects of *K* value of PVC and DOP loading on mechanical and morphological properties of GF/WPVC sandwich composites. It was found that a given fiber orientation angle, the mechanical properties of the GF/WPVC sandwich composites decreased with increasing *K* value of PVC. Using PVC core layer with low *K* value could prevent a de-lamination at the interface between the GF and the PVC core layer, and this resulted in higher mechanical properties of the sandwich composites, except for the tensile modulus. The sandwich composites with 0° fiber orientation in the PVC core had superior mechanical properties than those with 45° and 90° orientations, especially for the impact strength. The presence of GFs and fiber orientation in WPVC sandwich composites had more significant effects on the impact properties due to layer penetration and fiber pull-out. The addition of DOP plasticizer was observed to have a pronounced effect on the mechanical properties of the composites at the fiber orientations of 45° and 90° with the optimum DOP loadings at 5–10 pph. Additions of DOP greater than 10pph induced the plasticization effect which worsened the mechanical properties of the sandwich composites.

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