

FORMATION AND EVALUATION OF KRAFT FIBRE-REINFORCED UNSATURATED POLYESTER (UPE) COMPOSITES

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The effects of moulding pressure and initiator content on the performances of kraft fibre-reinforced UPE composites were investigated by means of tensile evaluation, DMA analysis, SEM analysis, and short-term creep tests. The results indicated that the prepared composites had much higher tensile strength and modulus and better creep resistance than traditional thermoplastic wood plastic composites (WPCs). These improved properties resulted from the incorporation of the strong kraft fibres as reinforcement. The combination of the fibers with the thermosetting UPE matrix produced enhanced kraft-UPE interfacial adhesion. Changes in moulding pressure and initiator level produced various effects in the properties of composites. As the moulding pressure increased from 6 MPa to 25 MPa, the mechanical properties and creep resistances increased gradually until a moulding pressure of 20 MPa was reached; after this point, the values decreased. With an increase in the initiator content from 0.3 PHR (parts per hundred parts of resin) to 1.0 PHR, the tensile strength and interface adhesion first increased, then decreased, while the instantaneous strain and maximum strain values (measured in the creep tests) decreased gradually.

Keywords: Wood-plastic composites; Kraft fibre; Unsaturated polyester; Molding pressure; Initiator level; Mechanical properties

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INTRODUCTION

Over the past few decades there has been increasing interest in using bio-based fibres to reinforce plastics. This is due to their relatively high strength and stiffness and low density, and also because of environmental concerns; there is a need to limit the use of finite resources, as well as to manage waste disposal (Bledzki and Gassan 1999; Mohanty et al. 2002). Many studies have been made to investigate the potential uses of natural fibres from various plants. Fibres from sources such as wood, bamboo, cotton, flax, hemp, sisal, jute, kenaf, banana, pineapple leaf, milkweed, bagasse, peach palm, waste newspaper, etc., have been widely investigated (Acha et al. 2007; Ashori 2010; Burgueno et al. 2005; de Farias et al. 2009; Idicula et al. 2006; Lee and Mariatti 2008; Nourbakhsh et al. 2009). Wood flour and wood fibre are the bio-based materials most commonly applied to reinforce thermoplastics. These products are defined as WPCs and have many applications in everyday life. The popularity of WPCs can be attributed to their particular advantages. WPCs can be easily processed, similar to wood, but they require far less maintenance than solid wood treated with preservatives. These composites also have some advantages such as no free formaldehyde release, better

rigidity and stiffness than plastics, and resistances to cracking and splitting (Klyosov 2007). WPCs are therefore considered to be a desirable alternative to solid wood. They have been used not only for indoor applications such as furniture and interior paneling, vinyl facings on doors, and consoles and seat backs in automobiles, but also outdoors for deck floors, railings, fences, landscaping timbers, cladding and siding, park benches, and windows (Ashori 2008; Beg and Pickering 2008; Thompson et al. 2009). The number of such applications continues to grow.

The polymer matrices for WPCs, however, are mainly thermoplastic polyolefins, including polyethylene, polypropylene, polystyrene, and polyvinylchloride. Because these polymers are composed of linear molecules without crosslinks, exposing them to long-term stresses—even stresses far below their yield strength—will result in obvious creep (Bodig and Jaynem 1982). Creep is the tendency of a solid material to move slowly or permanently deform under the influence of sustained stresses. It is commonly known as viscoelastic deformation due to the combination of elastic deformation and viscous flow (Park and Balatinecz 1998). Not only the polymer matrices but also the wood components in WPCs can be responsible for creep. Creep is a function of the material properties, exposure time, exposure temperature, applied structural load, etc. (Turner 2001). Creep and creep rupture (time dependent failure) are therefore the main disadvantages of WPCs being used in applications with long-term loads, e.g., in beams, columns, floors, window frames, and roofing systems. Though the load applied may be much lower than the yield strength of the WPC (e.g., 20%), obvious deformations or deflections may be produced in a WPC structure under long-term load, resulting in excessive distortion and a sharp reduction in the expected service life (Lee et al. 2004).

Some important studies have indicated that creep deformation may be directly related to the interfacial properties and compatibility between the polar wood fibres and the non-polar polymeric matrices. Some coupling agents (such as maleated polypropylene, maleated polyethylene, and silane) have the potential to improve the compatibility and interfacial adhesion between the plastic and the wood flour, leading to expectations of improvements in the mechanical properties and creep resistances (Acha et al. 2007; Bengtsson and Oksman 2006b). Polymer science explains that crosslinking will transform linear polymers into three-dimensional networks. This occurs via chemical bonds that effectively restrain not only the motion of polymer chains, but also the irreversible slippage of whole polymer molecules past one another. This improves the mechanical properties and creep resistance of polymer materials, with a strong dependence on the crosslinking density (Bower 2002).

Kraft fibres are renewable, bio-based fibres that have lower production costs and lower energy consumption during production than glass fibres. They are widely used in paper-making. Due to the length of the fibres and their low lignin content, kraft fibres are considered as adequate reinforcements for high-strength composites. Typically, UPE resin is used to prepare Fibre-Reinforced Plastics (FRPs), a group consisting mostly of glass fibre-reinforced composites. This resin is rich in polar ester groups, which indicates that it may show better compatibility with polar wood than non-polar thermoplastic matrices for WPCs, such as polyethylene and polypropylene. In addition, the cost of UPE resin is comparable to that of polyethylene on the current market. Very few studies on kraft fibre-reinforced UPE composites have been reported so far. This research was

therefore intended to develop a kraft fibre-reinforced UPE composite with good mechanical strength and good creep resistance, which can be applied for structural and engineering applications. In the present study, the primary focus was to determine the impact of moulding pressure and initiator level on the performances of the composites.

EXPERIMENTAL

Materials and Preparations

The bleached, 70.2 g/m² kraft paper used in this research was a commercial product from a local paper mill and was prepared from pine and fir. UPE resin 191#, with a solid content of 66.3%, and commercial methyl ethyl ketone peroxide (MEKP) (the initiator) were provided by Harbin Fiber-Reinforced-Plastic (FRP) Institute. Reagent grade styrene (>98%) was purchased from Tianjin Kermel Chemical Reagent Co., Ltd., China. A wood flour-reinforced polypropylene composite (labeled as WPC0, with a wood flour content of 60wt%) was extruded in a composite laboratory using an SJS-30 double-screw extruder (Ruiya Polymer Equipment Co., Nanjing, China). The polypropylene T30s was purchased from Fushun Petrochemical Company (Fushun, China) with a MFI of 3.3. Poplar wood flour with particle sizes between 40 and 100 meshes was oven dried to moisture content below 2.5% before extrusion. Maleated polypropylene purchased from Sino Qingdao Chemical Industry Co. was introduced, at a 4wt% level, as the coupling agent. The WPC0 sample acted as a control.

Compounding and Processing

The 191# UPE resin was diluted with styrene to a solid content of 60% to increase its fluidity and wettability in the kraft paper. Various quantities of commercial MEKP initiator (0.3, 0.5, 0.7, and 1.0 PHR, relative to the diluted liquid UPE resin) were then added. A total of 19 kraft paper sheets with dimensions 24.0cm×20.0cm were dried in an oven at 103°C for 6 hours, and were then weighed (W_1 , g). A rubber roll was then used to spread the MEKP-containing UPE resin onto the oven-dried kraft paper (spreading sufficient resin). This was left for 5 min to allow the resin to impregnate the paper. All 19 resin-spread paper sheets were stacked regularly and cold pressed (the pressure was the same as the moulding pressure) for 1 minute to form a composite plate and to squeeze out any excess resin. The cold-pressed plate was then placed between two Teflon films and hot pressed at 125°C under various moulding pressures (6, 10, 15, 20, and 25 MPa), for a duration of 400 s. Finally, the composites were placed in an oven at 125°C for 2 hours for post-curing before specimens were cut for characterization.

Density and Resin Content Determination

After trimming about 20 mm off the length and width of the composites, the length (a , mm), width (b , mm), thickness (c , mm) and weight (W_2 , g) of the composite samples were measured. The composite density (kg/m³) was calculated as $10^6 \times W_2 / (a \times b \times c)$. The resin content (%) of the kraft fibre-reinforced UPE composites was obtained by dividing the resin mass in the composite ($W_2 - W_3$) by the weight of the trimmed composite (W_2), i.e., $(W_2 - W_3) / W_2 \times 100$, where the resin mass in the composite

was obtained by subtracting the total mass of 19 kraft paper sheets with the same area as the composite ($W_3 = 19 \times [W_1 / (240 \times 200)] \times a \times b$) from the trimmed composite weight W_2 .

Tensile Strength and Modulus

A single tensile test was conducted for the composites according to the ASTM Standard D638 2000 using a Universal Testing Machine (SANS Co., Shenzhen, China) with load speed of 100 mm/min. Tensile strength test specimens were cut from the composites by a machining center with the following dimensions: $W = 3.18$ mm, $L = 9.53$ mm, and $G = 7.62$ mm, where W is the width of the narrow section, L is the length of the narrow section, and G is the gauge length according to ASTM D638 2000. The thickness of the narrow section of the composites was about 2 mm.

Short-term Creep Test

The short-term creep was tested, and the data were processed according to the method reported by Lee and co-workers (Lee et al. 2004). The specimen size was the same as the tensile test specimens. The creep specimens were subjected to a constant stress (40% of the tensile strength) for 6 hours. The stress was then removed and the deformation recovery was further recorded using a PC computer for 1 hour.

Dynamic Mechanical Analysis

The mechanical damping parameter ($\tan\delta$) was measured as a function of temperature in a Dynamical Mechanical Analyzer (DMA242, Netzsch Co., Germany). The measurements were carried out in three-point bending mode, using rectangular specimens with dimensions of 50 mm \times 10 mm \times 2 mm over a temperature range of 20°C to 300°C with a heating rate of 5°C /min under nitrogen flow. The samples were scanned at a fixed frequency of 10 Hz with a static force of 0.2 N and a dynamic force of 0.8 N.

SEM Analysis

The composite specimen (with dimensions of 50 mm \times 10 mm \times 2 mm) was immersed in liquid nitrogen for 5 minutes for quick freezing (quenching) and was then immediately broken by an impact force. A fractured surface was selected from the quenched sample for SEM examination. All SEM samples were coated with approximately 10 to 20 nm of gold before examination with a QUANTA-200 SEM (FEI Co., USA) with a working distance of about 10 mm at 12.5 kV.

RESULTS AND DISCUSSION

The forming (or moulding) pressure is important in the formation of the fibre-reinforced composites, both in forcing the liquid polymers (in solution or melt state) to disperse evenly and thoroughly throughout the reinforcements (allowing an even distribution of the polymer matrix in the composite) and in densifying the reinforcement-polymer mixtures, producing good mechanical properties via reduction of the quantity of void spaces in the composite. At high mould pressures, more liquid resin or polymer melt is forced into the reinforcements to fill the in-between voids, which leads to more

effective bonding between the reinforcements and the polymer. This in turn results in improved stress transfer from resin to fibres, which results in better mechanical properties in the composite (properties such as tensile strength, flexural strength, and inter-laminar shear strength). Composites formed at higher moulding pressures generally have higher density and a lower void (or defect) content, producing higher-strength composites. When liquid thermosetting resin is used, the resin is a fluid before curing. This means that the excess liquid resin can be squeezed out from the reinforcements, forced by the moulding pressure, reducing the matrix content in the composite. The moulding pressure may therefore have significant effects on many of the properties of composites, including resin content, density, mechanical properties, and creep behaviors.

Table 1. Physical and Mechanical Properties of WPC and Kraft Fibre-reinforced UPE Composites (KUC)

Composite ID	Moulding pressure (MPa)	Initiator content (PHR)	Density (kg/m ³)	Resin content (%)	Tensile strength (MPa)	Tensile modulus (MPa)
KUC0506	6	0.5	1368	41.3	101.39 (4.44)	326.28 (31.28)
KUC0510	10	0.5	1373	38.1	105.28 (4.46)	328.10 (24.57)
KUC0515	15	0.5	1374	33.1	110.97 (3.31)	346.61 (34.04)
KUC0520	20	0.5	1418	31.0	104.04 (5.27)	437.81 (34.95)
KUC0525	25	0.5	1420	28.3	89.19 (3.47)	323.90 (20.66)
KUC0315	15	0.3	1397	32.5	83.26 (3.25)	310.25 (33.45)
KUC0515	15	0.5	1374	33.1	110.97 (3.31)	346.61 (34.04)
KUC0715	15	0.7	1371	34.0	100.99 (4.75)	397.43 (29.21)
KUC1015	15	1.0	1456	33.9	94.41 (5.27)	438.00 (21.86)
WPC0	NA	NA	1124	40.2	39.63 (4.09)	114.85 (25.97)

Values in parentheses are the standard deviations

Table 1 reports the basic physical and mechanical properties of kraft fibre-reinforced UPE composites formed at various moulding pressures ranging from 6 MPa to 25 MPa. The results indicated that changes in the moulding pressure had various effects on the kraft fibre-reinforced composites. The density of the cured UPE resin (about 1180 to 1285 kg/m³) was lower than that of the wood substance (about 1500 kg/m³). Composites formed at higher moulding pressures showed a slightly higher density because more liquid UPE resins were squeezed out during compounding; this was evidenced in the resin content results. As the moulding pressure was increased gradually from 6 MPa to 25 MPa, the resin contents of the composites decreased linearly from 41.3% to 28.3%. The tensile strength of the kraft fibre-reinforced composites increased with decreasing resin content until a content of 33.1% was reached (corresponding to 15 MPa of moulding pressure). This can be attributed to the improved interfacial adhesion produced by the closer contact between the resin and the kraft fibres under higher moulding pressures, as indicated by the DMA test results shown in Fig. 2. Further increases in the moulding pressure caused too much resin to be squeezed out. This was due to the fact that the remaining resins filling the voids between the fibres could not withstand large stresses, resulting in a decrease in the tensile strength. The composite

formed with 15 of MPa moulding pressure had the highest tensile strength (110.97MPa), 24.4% higher than that of the composite formed at 25MPa (89.19MPa). Table 1 shows that the moulding pressure had a similar effect on the tensile modulus, but the highest modulus (437.81MPa) was exhibited by the composite formed at 20MPa, 35.2% higher than that shown by the composite with lowest modulus (323.9MPa).

In order to meet the necessary mechanical requirements and to produce a viscosity suitable for forming processing, UPE resin will typically contain a reactive diluent (typically a monomer-like styrene) that crosslinks the linear UPE resin into a three-dimensional network in the presence of an initiator. It was found that the kinetic mechanism was dominated by near-azeotropic copolymerization at the beginning of the curing reaction, while styrene conversion became much more favourable than that of polyester C=C bonds later in the reaction. The transition point between near-azeotropic copolymerization and the crosslinking length of styrene over the whole conversion range varied with the initiator contents (Huang and Leu 1993). Appropriate initiator content is therefore a crucial factor in achieving complete curing and crosslinking density, through which optimum mechanical properties and chemical resistance can be achieved. In other words, the initiator content can have a significant impact on many properties of the UPE-based composites.

Table 1 also shows the basic physical and mechanical properties of kraft fibre-reinforced UPE composites compounded at various initiator levels (0.3, 0.5, 0.7, and 1.0 PHR). The kraft fibre-reinforced UPE composites had similar densities ranging from 1371 to 1456kg/m³, with a maximum difference of 6.2%. They had similar resin contents ranging from 32.5% to 34.0%, with a maximum difference of 4.6%. These results indicated that the initiator level had a small effect on both the density and the resin content, depending mainly on the moulding pressure and the quantity of UPE resin spread on the wood fibres. As the initiator content increased gradually from 0.3 PHR to 1.0 PHR, the tensile strength of the kraft fibre-reinforced composites first increased from 83.26 MPa to 110.97 MPa, then decreased to 94.41 MPa, showing a maximum difference of 33.4%. The tensile modulus showed a monotonically increasing tendency with values increasing from 310.25 MPa to 438.00 MPa, with a maximum difference of 41.1%. The effects of the initiator content on the mechanical properties of the composites were attributed to the changes in the crosslinking density of the cured polymer matrix and the interfacial adhesion produced by the varying initiator content. The free-radical polymerization mechanism explains why the higher the initiator content (or the higher the number of radicals), the faster was the polymerization rate, the higher was the crosslinking density, and the shorter was the crosslink chain length (Flory 1953). In the presence of higher initiator levels, therefore, the UPE resin formed shorter chains but higher crosslinking densities, so that the tensile strength and modulus of the composites were higher than those of composites formed with lower initiator levels. According to the report of Janigova and co-workers (2001), the higher number of radicals in the UPE-kraft system could result in covalent bonds between the kraft fibres and the UPE resin (i.e., interfacial adhesion), via the recombination of radicals formed at the kraft fibre surface (after the attack of initiator radicals) and UPE macro-radicals; however, at initiator contents higher than 1.0 PHR, the system formed too many active centers during hot pressing at 125°C, leading to a very high rate of polymerization. This resulted in

bursting of the moulded composite panel. As a result, the composites prepared with an initiator content of 1.3 PHR were ruptured into a number of pieces, and the composite with 1.0 PHR of initiator showed some cracks.

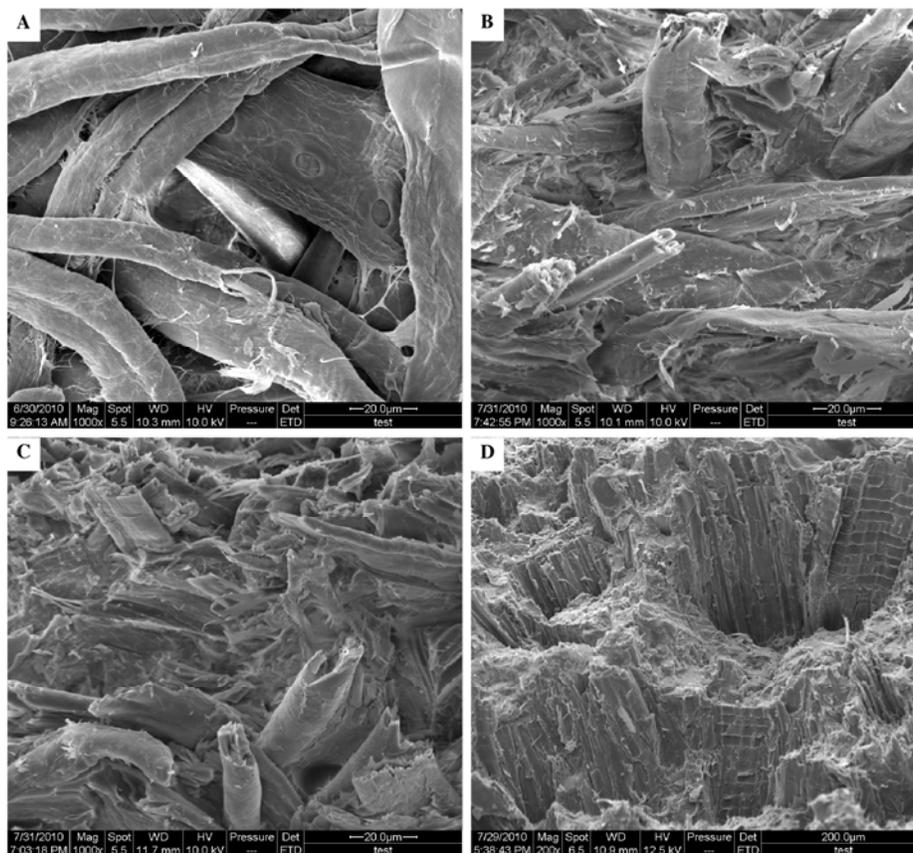


Fig. 1. SEM photos of kraft fibres (A), kraft fibre-reinforced UPE composites KUC0715 (B) and KUC 0515 (C), and WPC0 (D)

Compared with the wood flour-reinforced polypropylene composite (WPC0, control), the kraft fibre-reinforced UPE composites showed somewhat higher density values and significantly higher tensile strength and modulus, even for resin contents of only 28.3% (see Table 1). The kraft fibre-reinforced UPE composites had densities between 22% and 29.5% higher than the control, but the tensile strength and modulus values were between 156% and 180% and between 182% and 281% higher than those of the control, respectively. This comparison indicated that the kraft fibre-reinforced UPE composites had much higher strength-to-weight ratios than the traditional wood flour-reinforced thermoplastic composite. This was due to a few key reasons: a) The kraft fibres showed superior reinforcing efficiency compared with the wood powder due to the larger length/diameter ratio and lower lignin content, b) the low-viscosity crosslinkable liquid UPE resin was not only easy to blend evenly with the kraft fibres, but also had a much higher cohesive strength than the thermoplastics after crosslinking, and c) the kraft fibre-reinforced UPE composites have better interfacial adhesion between matrix and wood than non-polar thermoplastic WPCs because of the abundant polar ester groups of

UPE resin that can improve the compatibility between UPE and wood. Interfacial bonding also can benefit from covalent bonds between the kraft fibres and the UPE resin resulted from the recombination of radicals. The SEM photos shown in Fig. 1B and Fig. 1C confirmed the high level of compatibility between the UPE and the wood fibres, similar to the compatibility levels in the 4% maleated polypropylene-compatible WPC (Fig. 1D). SEM also confirmed that the kraft fibres gave better reinforcement than wood flour because of their long fibre shape and their smaller-sized cross fibre direction (5 to 25 μm , Fig. 1A) compared with wood flour/particle (80 to 150 μm Fig. 1D).

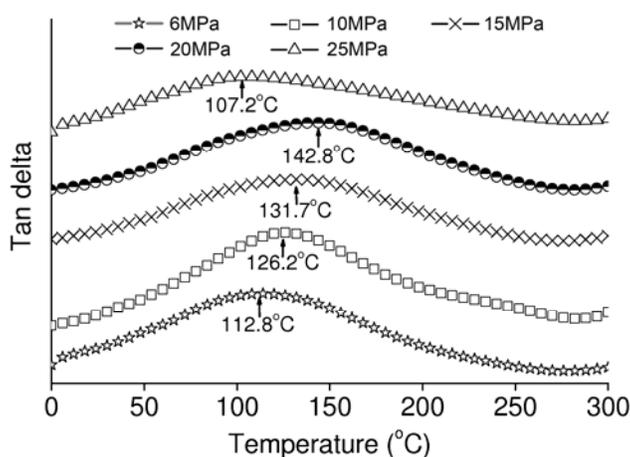


Fig. 2. $\tan\delta$ versus temperature, for kraft fibre-reinforced UPE composites formed with various moulding pressures

The interfacial adhesion between the UPE resin and the wood fibres was confirmed by changes in $\tan\delta$ with temperature, as shown in the DMA tests for the kraft fibre-reinforced UPE composites (see Fig. 2 and Fig. 3). The $\tan\delta$ peaks for the composites (starting at about 10°C and ending at about 280°C) were much broader than those of most pure polymers. According to the report from Acha and co-workers (2007), the observed broad peaks was explained as being due to molecular motion at the interfacial region of the composites, and the width of the $\tan\delta$ peak could be indicative of the increased volume of the interface.

Figure 2 shows that the $\tan\delta$ peak temperatures of the composites increased with the moulding pressure until a pressure of 20 MPa was reached, then decreased with further increases in moulding pressure, exactly corresponding to the trends shown by the tensile modulus. This should be attributed to the closer contact between the resin and the kraft fibres under higher moulding pressures. Higher moulding pressures could therefore be considered as a remedy for poor compatibility between the polar wood fibres and the weak-polar UPE resin. In the case of the 25 MPa moulding pressure sample, however, the fact that the $\tan\delta$ peak temperatures were the lowest of any sample measured implied poor interfacial adhesion. This was due to the fact that too much UPE resin was squeezed out, as indicated by the lowest resin content (28.3%). This meant that insufficient resin was available for the formation of a continuous and good resin-fibre interface along the fibres.

Figure 3 indicates that the $\tan\delta$ peak temperatures of the composites increased with increasing initiator content until 0.7 PHR was reached, then it decreased with further increases in the initiator level, showing a corresponding tendency with the tensile strength. According to the free radical polymerization mechanism, higher initiator levels (or the more radicals there are) not only lead to a higher crosslinking density in the cured UPE resin (Flory 1953), but also contribute to the formation of covalent bonds between the kraft fibres and the UPE matrix. It has been reported that wood flour-filled LDPE composites showed improved interfacial adhesion after crosslinking with peroxide, compared with non-crosslinked composites (Janigova et al. 2001). The improved interfacial adhesion was attributed to the recombination of radicals formed at the wood filler surface (after attack from the peroxide oxy radicals) and polyethylene macro-radicals.

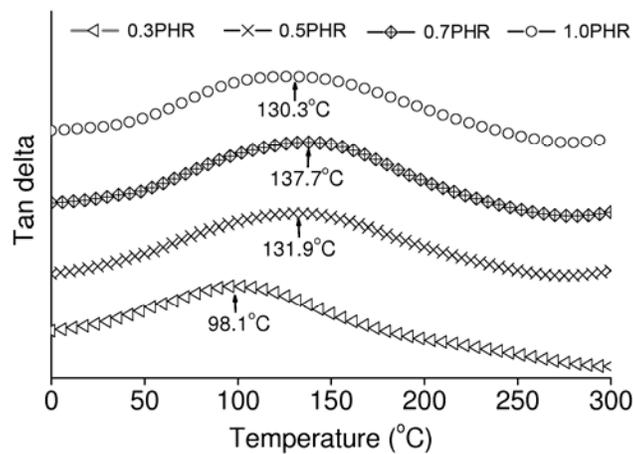


Fig. 3. $\tan\delta$ versus temperature, for kraft fibre-reinforced UPE composites made with various initiator contents

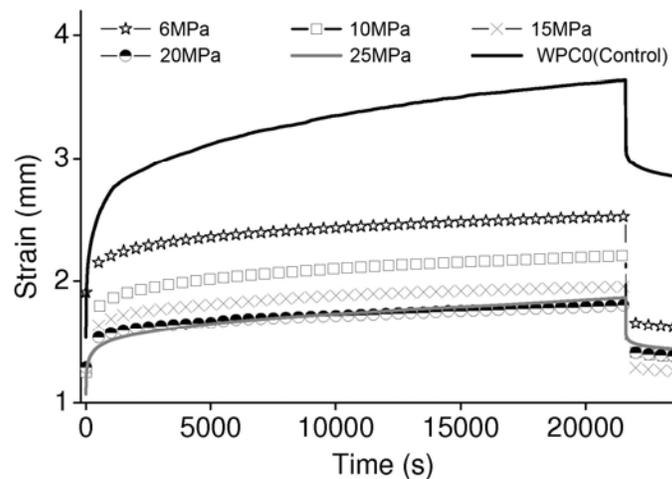


Fig. 4. Creep behaviors of WPC and kraft fibre-reinforced UPE composites, for various moulding pressures

The creep behaviors of the kraft fibre-reinforced UPE composites and the wood flour-reinforced polypropylene composite (WPC0) are presented in Fig. 4, Fig. 5, and Table 2. Under the same test conditions (exposed to 40% of the tensile strength for 6 hours at 25°C), WPC showed a significantly higher level of viscoelastic strain (3.123 mm) than the kraft fibre-reinforced UPE composites (ranging from 1.095 mm to 1.726 mm). These results indicated that the kraft fibre-reinforced UPE composites had higher creep resistance than the traditional thermoplastic WPC under the same conditions (a 45% to 65% reduction). It is likely that this was a result of the three-dimensional UPE matrix network and the covalent bonding between the kraft fibres and the UPE matrix (resulting from the recombination during hot pressing of radicals formed at the kraft fibre surface and UPE macro-radicals). This higher creep resistance—in combination with the much higher tensile strength as shown in Table 1—suggests that kraft fibre-reinforced UPE composites have significant potential for applications that require high strength but low levels of creep, such as structural parts.

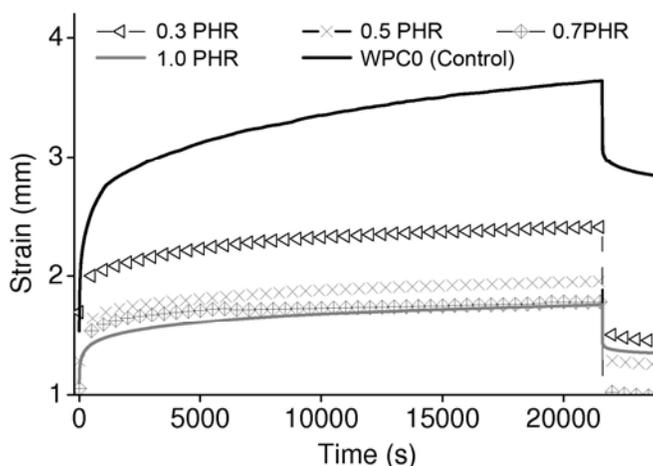


Fig. 5. Creep behaviors of WPC and kraft fibre-reinforced UPE composites, for various initiator levels

It is well known that thermoplastic polymers are generally composed of linear molecules. When a thermoplastic polymer sample is subjected to stress for long periods of time, the polymer chains will change their conformations (or even slowly slip apart) to approach a new equilibrium (or quasi-equilibrium) under the imposed stress. This is the formation of creep, occurring as a result of the viscoelastic characteristics of polymers (Bower 2002). The levels of creep, however, may be greatly reduced if the polymers are sufficiently crosslinked. After crosslinking, polymer chains are fixed by chemical linkages between chains and molecules, effectively restricting their motion. Many studies have confirmed that good interfacial adhesion can reduce the level of creep behavior in WPCs. For example, Bengtsson and Oksman (2006a) produced wood flour-reinforced HDPE composites with lower creep levels via silane crosslinking. The lower creep levels (compared with non-crosslinked composites) were due to the reduced viscous flow of the matrix after crosslinking, as well as the improved adhesion between the polyethylene matrix and the wood flour.

The instantaneous strain in the creep test occurred just after the stress was applied, representing the elastic deflection and the rigidity of the material. With an increase in the moulding pressure from 6MPa to 25MPa, both the instantaneous strain and total strain of the kraft fibre-reinforced UPE composites showed a reducing tendency in the creep tests. This indicated that the composites formed under higher moulding stress had high rigidity and better creep resistance because of the better interfacial adhesion resulting from the closer contact between the resin and the kraft fibres and the higher high-strength reinforcement content (or less UPE resin content). With increasing initiator levels from 0.3 PHR to 1.0 PHR, the instantaneous strain and total strain also decreased gradually. This was attributed to the higher crosslinking density of the UPE matrix and the higher number covalent bonds between the kraft fibres and the UPE matrix (resulting from the recombination during hot pressing of radicals formed at the kraft fibre surface and UPE macro-radicals) produced at higher levels of initiator.

Table 2. Creep Deflection Data for WPC and KUC Composites

Composite ID	Moulding pressure (MPa)	Initiator content (PHR)	Instantaneous strain (mm)	Maximum strain (mm)	Viscoelastic strain (mm)
KUC0506	6	0.5	1.908	2.524	1.726
KUC0510	10	0.5	1.344	2.213	1.530
KUC0515	15	0.5	1.251	1.956	1.374
KUC0520	20	0.5	1.219	1.805	1.507
KUC0525	25	0.5	1.101	1.866	1.588
KUC0315	15	0.3	1.697	2.412	1.665
KUC0515	15	0.5	1.251	1.956	1.374
KUC0715	15	0.7	1.123	1.784	1.095
KUC1015	15	1.0	1.099	1.760	1.451
WPC0	NA	NA	2.534	3.640	3.123

Viscoelastic strain refers to the strain remaining after the removal of stress.

CONCLUSIONS

1. Kraft fibre-reinforced unsaturated polyester composites showing good mechanical properties and creep resistances were prepared, using kraft fibres and unsaturated polyester resin at various moulding pressures and initiator contents.
2. Both the moulding pressure and initiator content had various effects on the tensile strength, tensile modulus, interfacial adhesion, and viscoelastic behavior of the kraft fibre-reinforced UPE composites.
3. The viscoelastic strain in these composites was reduced between 45% and 65%, while their tensile strengths and moduli were 156% to 180% and 182% to 281% higher than the control WPC, respectively. These results suggest that kraft fibre-reinforced UPE composites have significant potential to be applied in areas that require high strength but low creep levels.

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