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Research Article

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Effects of Environmental Aging on the Durability of Wood-Flour Filled Recycled PET/PA6 Wood Plastic Composites

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ABSTRACT

Outdoor building materials made of wood require preservatives containing chromated copper arsenate and other carcinogenic substances but still are subject to decay, hence they need to be replaced every few years. Wood plastic composite (WPC) is a novel environmental-friendly composite of wood flour/fiber reinforced thermoplastic polymers (i.e. plastic). As WPC is made of plastic to evenly cover the wood flour, it has a lower moisture content than wood. In this study, maleic anhydride grafted polyolefin (POE-g-ma) and methyl methacrylate-butadiene-styrene copolymer (MBS) were used as impact modifiers to prepare recycled WPCs (rWPCs) from recycled polyethylene terephthalate (rPET) and recycled polyamide 6 (rPA6) blends (PET/PA6). The thermal properties of the WPCs with different mixing ratio polymer blends of rPET to rPA6 (E60/A40, E50/A50, and E40/A60) were investigated, as well as their mechanical properties after accelerated weathering. Furthermore, the creep property of rWPC was also investigated under different applied loading and environmental aging conditions. The higher PET content resulted in lower flowability and a higher initial decomposition temperature, with the E60/A40 rWPC having better mechanical properties. During the 10-hour creep test, the rWPC strain changed significantly with environmental aging and higher loadings. In conclusion, the rWPC composed of 60:40 PET to PA6 is more suitable for outdoor building applications.

KEYWORDS

Recycled polyethylene-terephthalate (rPET); Recycled polyamide 6 (rPA6); Recycled wood plastic composites (rWPCs); Thermal properties; Mechanical properties after accelerated weathering; Creep under environmental aging

1. Introduction

Wood plastic composites (WPCs) are a novel environmentally friendly composite material composed of wood powders or fibers reinforced with thermoplastic resins. WPCs inherit the intrinsic properties of their constituents, for example, they are resistant to corrosion and humidity as well as being durable and recyclable. Compared to wood, they are more resistant to cracks and bending properties. They are also easier to process and are more environmentally friendly than traditional plastics, hence, have been extensively applied in outdoor applications, such as decking, trails, and landscape gardening. WPCs originated in Italy in the 1970s and were popularized in North America in the early 1990s. By the start of the 21st century, they had spread to India, Singapore, Malaysia, Japan, and China [1].

WPCs are normally produced as pellets by adding wood flour as a filler to a polymer matrix through a compounding process, then WPC products are produced through an extrusion or injection molding process under high pressure and temperature. Due to their outdoor applications, WPCs are frequently exposed to ultraviolet rays and humidity, causing degradation and reducing the life span. Moreover, humidity has a substantial impact on WPCs, expanding the cell walls of wood fibers due to water absorption and diffusion, causing macroscopic cracks within the WPCs and degrading their mechanical properties.

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Core-shell impact modifiers are often used to improve the toughness of the polymer matrix as (1) the rubbery core provides resistance to impact, especially at low temperature, whereas the grafted glassy shell provides rigidity and compatibility to the polymer matrix, keeping the particles desired shape and dispersibility; (2) the rubber particle diameter, particle diameter distribution, crosslink density, grafting degree, shell thickness, shell composition, and overall composition can be individually studied and optimized. methyl methacrylate-butadiene-styrene copolymer (MBS) has a soft core (butadiene-styrene copolymer) and a hard shell (PMMA) and is often used as an impact modifier because of its stiffness, high modulus, and good miscibility with the polymer [2].

Maleated coupling agents interact well with the functional surface of lignocellulosic materials and the matrix. During grafting, maleic anhydride can react with the hydroxyl groups in the amorphous region of the cellulose structure, removing hydroxyl groups from the fiber cells, producing a brush of long-chain polymer coating on the surface of the lignocellulosic material, and reduces hydrophilicity [3]. This bonding between the anhydride groups of the maleic anhydride and the hydroxyl groups of the lignocellulosic materials creates a bridging interface for efficient interlocking [4].

Zykova [5] investigated ethylene octene copolymers as a matrix to produce a WPC from flax straw and wood flour as fillers, reporting improved mechanical properties when wood flour was used compared to flax straw, with reduced tensile

properties with the increasing ethylene octene copolymer content [6].

Polyethylene terephthalate (PET) is widely used as a thermoplastic polymer for fabricating molded objects and textiles due to its comprehensive properties, such as anti-creep, anti-fatigue, anti-friction, and dimensional stability. However, its poor impact strength limits its extensive application as an engineering plastic, hence, it is often blended with other polymers [7, 8]. Furthermore, PET and wood sawdust wastes are major waste components and challenging materials for the manufacture of WPCs. To the best of our knowledge, there are only two studies on WPCs made from recycled PET (rPET) [9, 10], and a few more studies using natural fillers in a PET matrix [11–13].

PA6 is extensively used in the manufacture of automobile parts, engineering products, and textiles because of its high mechanical strength, modulus, and good processing ability. However, it has a high affinity for water, so its mechanical properties are often considerably affected by water absorption. It is also a notch-sensitive thermoplastic because of a markedly lower resistance to crack propagation than to crack initiation [14]. Thus, PA6 has been modified with polymers such as polyamide 66 [15], polypropylene [16], poly-(butylene-terephthalate) [17], and acrylonitrile-butadiene-styrene [18]. PET, as a semi-crystalline polymer, is cheaper than PA6 with contrasting properties, for example, it has a higher deflection temperature and lower water sorption than PA6 [19], therefore it is suitable for blending with PA6. However, PA6 and PET blends are immiscible and exhibit poor interfacial adhesion and low mechanical properties [20], which can be improved by effective compatibilizers including EPR-g-MA [21], ethylene-propylene-diene monomer (EPDM) [22], glycidyl methacrylate (GMA)-grafted poly(ethylene octene) (POE-g-GMA) [23] and their derivatives (e.g., SEBS-g-maleic acid anhydride and EPDM-g-maleic acid anhydride) [24]. Also, the addition of epoxy can improve the

mechanical properties of the PA6/epoxy/PET composites because of the chain extension of PA6 and improved interaction between PA6 and PET [25,26]. In rPET/PA6 blends, POE-g-GMA is an effective compatibilizer to increase interfacial adhesion between rPET and PA6. PA6 also has a high moisture content, so to reduce the water absorption of PA6 and the cost of preparing WPC, rPET is blended with rPA6, then filled with wood flour to prepare rPET/PA6 WPCs. Moreover, durability is the extent of resistance that the properties of the developed WPC have to maintain in environmental aging conditions. The aging behavior and mechanism of the virgin polymer are usually less complex than the composite materials. This is due to the presence of different components in the composite such as fillers, fibres, additives, plasticizer, antioxidant etc., where the oxygen from the environment could transfer from one component to another component through the polymer matrix [27]. However, few studies have characterized the durability, such as thermal, mechanical and creep properties of rPET/PA6 WPC, especially after environmental aging.

In this study, the thermal, mechanical and creep properties under different environmental aging conditions of rWPCs made from two impact modifiers (i.e. POE-g-ma and MBS) added to recycled PET/PA6 blends filled with recycled teak wood flour were investigated, as shown in **Figure 1**.

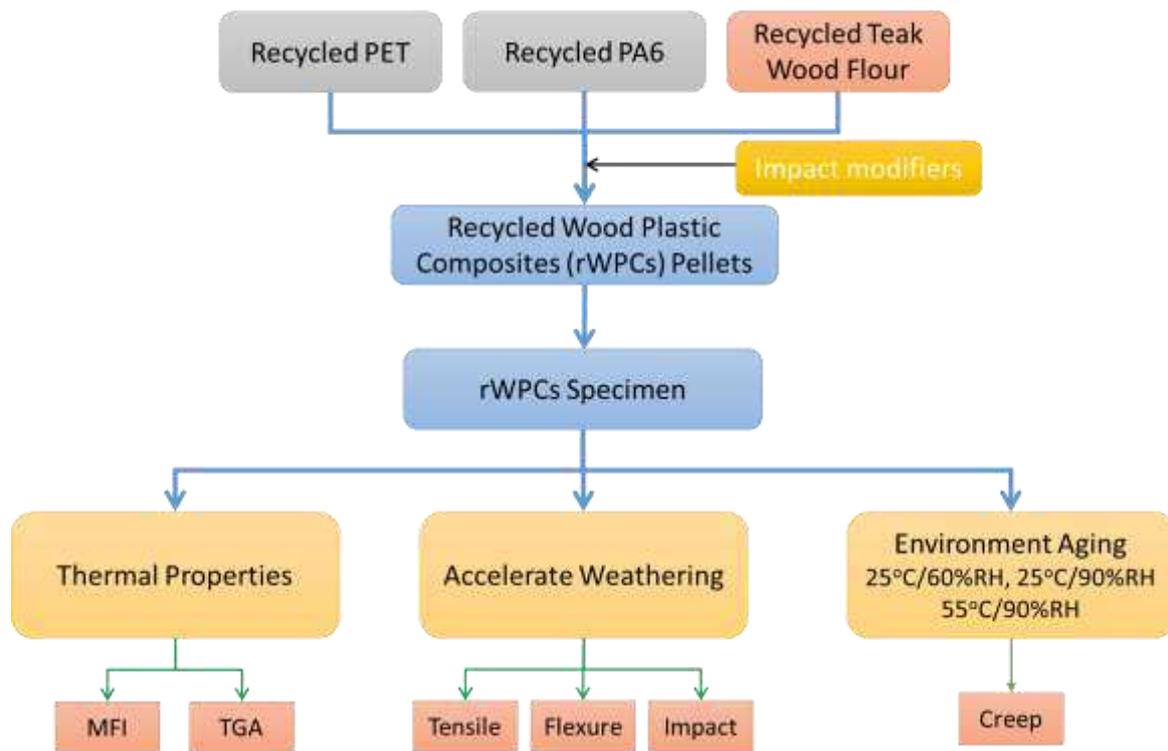


Figure 1. Schematic illustration of this study

2. Experimental

2.1 Materials

Recycled PET and recycled PA6 were supplied by Libolon Enterprise Co., Ltd., Taiwan, recycled from waste textiles. POE-g-ma was purchased from Prowin Plastech Co., Ltd., Taiwan, and MBS was purchased from Formosa Plastics Co., Ltd., Taiwan. Recycled teak wood flour was used as a filler and the average particle size distribution of the wood flour was 100 mesh (150 μm). Epoxy resin was used as a reactive compatibilizer (Nan-Ya Plastics Co., Ltd., Taiwan).

2.2 Preparation of recycled PET/PA6 WPCs

The three PET/PA6 rWPC mixture formulations shown in Table 1 were compounded in a twin-screw extruder machine to manufacture recycled WPC pellets

and prepare specimens via injection molding according to the American Society for Testing and Materials (ASTM) standard. The operating procedures were as follows:

- a. Pure plastic pellet removal of moisture: as moisture affects the mechanical properties of WPC, it must be removed before the compounding process. All recycled plastic pellets (rPET and rPA6) and recycled wood flour were placed in an oven to remove moisture. The wood flour was dried in the oven for 8 h at 100°C reducing the moisture content from 8.4% to 0.2%. The recycled plastic pellets were dried in an oven for 4 h at 140°C for rPET and 80°C for rPA6.
- b. Compounding process: Wood flour was compounded with recycled PET/PA6 in a twin-screw extruder for melt blending of the mixed materials (Kobe Steel Group; L/D = 43.5; $\psi = 30$ mm) at a rotation speed of 180 rpm and a temperature range of 220–250°C from the barrel to the die zone as shown in [Figure 2\(a\)](#).
- c. Injection molding process: After compounding, the rWPC pellets were dried in the oven at 105°C for 4 h before injection molding as shown in [Figure 2\(b\)](#). The test samples were molded to form tensile, bending, and impact specimens with a Battenfeld 75-ton injection molding machine (WITTMANN BATTENFELD GmbH). The injection molding parameters were 100°C for the mold temperature and 210–250°C from the barrel to the nozzle.

2.3 Weathering aging conditions.

Accelerated weathering aging was according to the SAE J1960 standard. The specimens were placed in the Weather-Ometer (Ci-4000, Atlas Material Testing Technology GmbH), which had a water-cooled xenon arc lamp as the light source. The specimens were exposed to accelerated weathering conditions for 30 days as detailed in [Table 2](#). The light cycle had an illuminance of 0.55 W/m², with a temperature and humidity of 47°C/50% RH, whereas the dark cycle had a

temperature and humidity of 38°C/95% RH. The use of the xenon arc lamp accounted for the effects of UV as well as visible light.

2.4 Creep test under environmental aging.

The rWPCs were treated under three temperature and humidity conditions to determine the effects of environmental aging on the specimens: 25°C/60% RH, 25°C/90% RH, and 55°C/90% RH for 10 hours.

Creep is the slow and continuous deformation of the material under constant applied stress. Generally, the time-strain curve can be divided into three stages, with the slope of the curve representing the creep strain rate and the end of the curve is the fracture time. **Figure 3 [28]** illustrates that strain rate during the first state gradually decreases to achieve creep strain beginning called transient-state creep (primary creep); the creep strain during the second state with steady strain rate was called steady-state creep (secondary creep). Finally, creep strain rate in the third state rapidly increases until fracture was called the third state creep (tertiary creep). The total strain ϵ is composed of elastic strain ϵ^e and creep strain ϵ^c and can be described as follows:

$$\epsilon = \epsilon^e + \epsilon^c \dots\dots\dots(1)$$

As ϵ^e is a constant value which does not vary with time, the total strain rate $\dot{\epsilon}$ can be obtained by differentiating equation 2:

$$\dot{\epsilon} = \frac{d\epsilon}{dt} = \frac{d(\epsilon^e + \epsilon^c)}{dt} = \frac{d\epsilon^c}{dt} \dots\dots\dots(2)$$

The creep test equipment used in this study is shown in **Figure 4** and two different loadings of 4 MPa and 6 MPa were applied. Constant stress was obtained by placing the applied loading at the bottom of the specimen to assess the creep strain

over 36000 seconds, then the time-strain curves of specimens under different temperatures and applied stresses were plotted.

Table 1. Formulation of rWPCs

rPET/rPA 6	Compatibilizer (Epoxy)	Wood Flour	MBS	POE-g-ma
E60/A40 (100 phr)	3 phr	30 phr	3 phr	3 phr
E50/A50 (100phr)	3 phr	30 phr	3 phr	3 phr
E40/A60 (100phr)	3 phr	30 phr	3 phr	3 phr

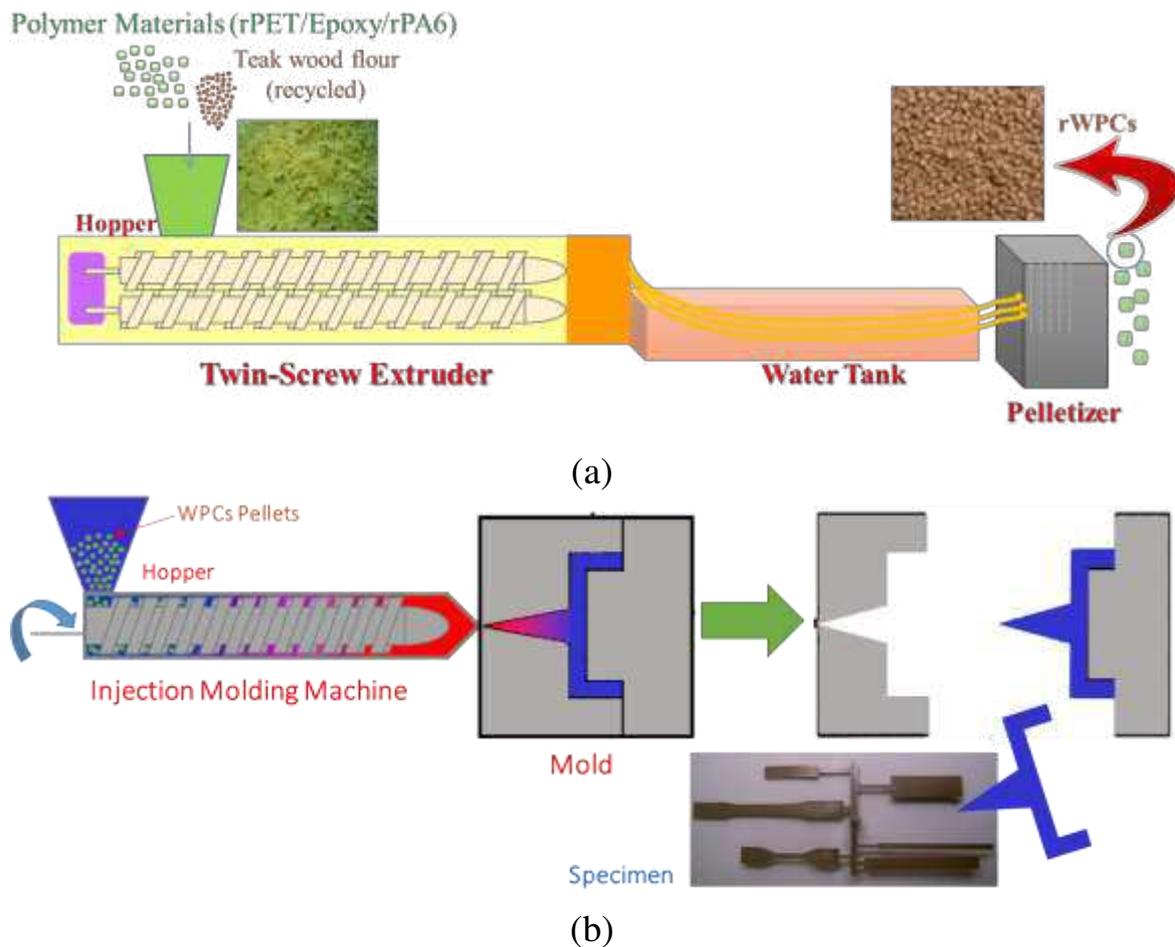


Figure 2. rWPC preparation: (a) compounding process for fabricating the rWPC pellets; (b) injection molding for fabricating the rWPC specimens

Table2. Accelerated weathering aging cycles

<i>Cycle segment</i>	<i>Light (Min)</i>	<i>Dark (Min)</i>	<i>Water spraying</i>
1	-	60	○
2	40	-	X
3	20	-	○
4	60	-	X

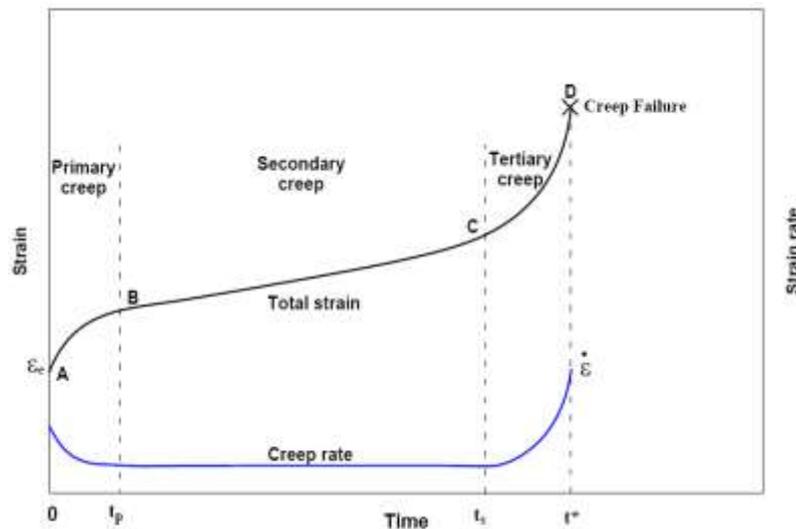


Figure 3. Creep strain [28]

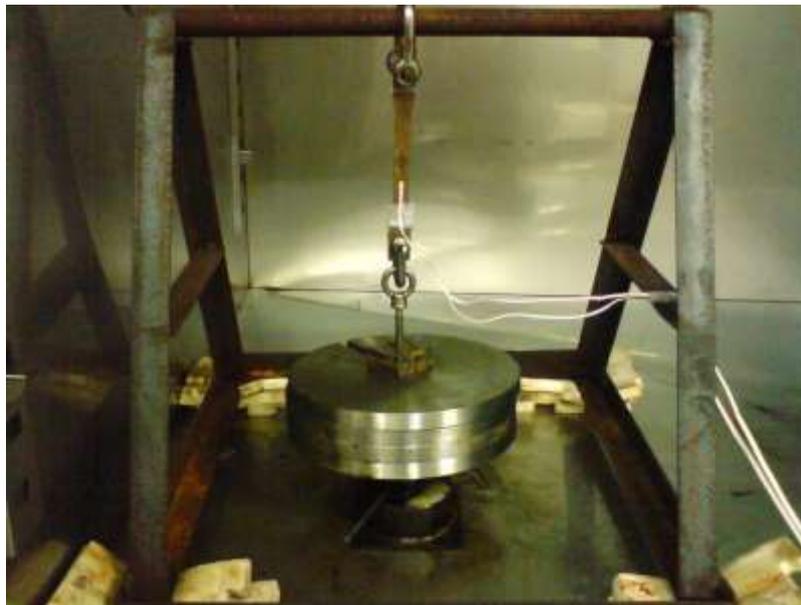
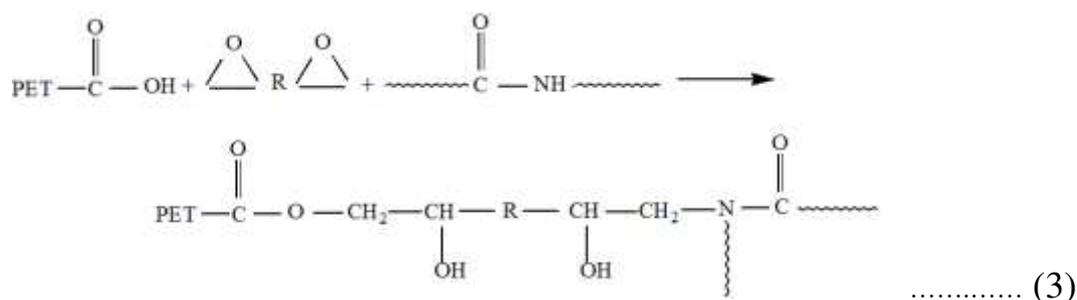


Figure 4. Creep test equipment

3. Results and discussion

3.1. Compatibility of PET/ PA6 blends

The PET and PA6 blend without any compatibilizer has a weak interface with poorer properties than those of neat PET or PA6, hence, considerable efforts have been made to improve the compatibility of the recycled PET/PA6 blends. It has been shown that the blending of PET and PA6 in the melting process will produce a polyester-polyamide block copolymer, which improves compatibility. Also, the addition of a reactive compatibilizer, such as epoxy resin, can improve the compatibility of PET/PA6 blends [25], as the epoxide reacts with the terminal functional group of the PET and PA6, enhancing their physical properties:



The grafting of carboxyl-terminated polybutadiene to polyamide was accomplished using an epoxy resin in the temperature range of 190-230°C, similar to the temperature range used in the present study (220 to 250°C), which implies the compatibilized reaction will occur in PET/PA6 blends. Graft copolymers are efficient compatibilizers for polymer blending, which can reduce interfacial tension and may toughen the polymer blends. The main advantage of using compatibilizers in polymer blends is the suppression of coalescence achieved through stabilizing the interface [29]. Generally, a polymer filled with abundant fillers (e.g., wood flour) will decrease the mobility of polymer chains, gradually becoming brittle [30, 31]. In this study, PET/PA6 blends filled with wood flour were used to fabricate WPCs and POE-g-ma and MBS were used as impact modifiers to toughen the rWPCs.

3.2. Melt flow index test (MFI) of the rWPCs

The MFI indicates the fluidity of plastic during processing and is used as a reference for the processing conditions, such as injection molding or extrusion. The higher the MFI, the lower the viscosity and molecular weight of the plastic, and the better the flowability. Figure 5 shows that the higher the PA6 content, the higher the MFI. However, due to the addition of wood flour up to 30 phr, the highest MFI obtained was 6 g/10 min, which is insufficient for the flowability required for

injection molding. Figure 5 also shows that the flowability of the rWPC with added MBS impact modifier is better than that with POE-g-ma at E60/A40 and E50/A50 rWPC. However, due to the high flowability of polyamide 6, the MFI of the E40/A60 rWPC was similar to the rWPC with added POE-g-ma and MBS.

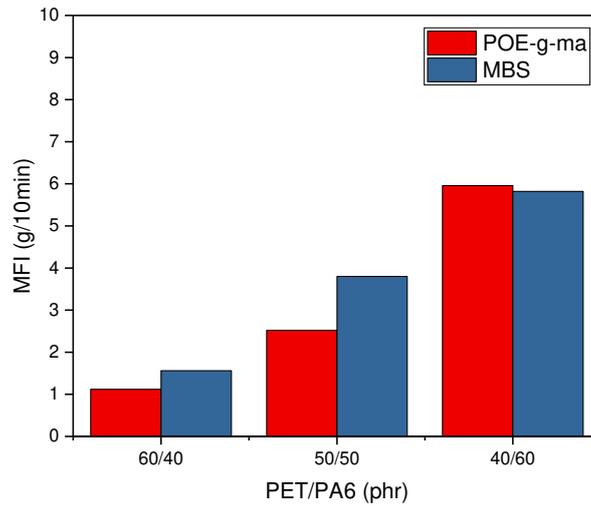


Figure 5. MFI of rWPC with the different impact modifiers

Table 3. MFI of rWPC with the different impact modifiers

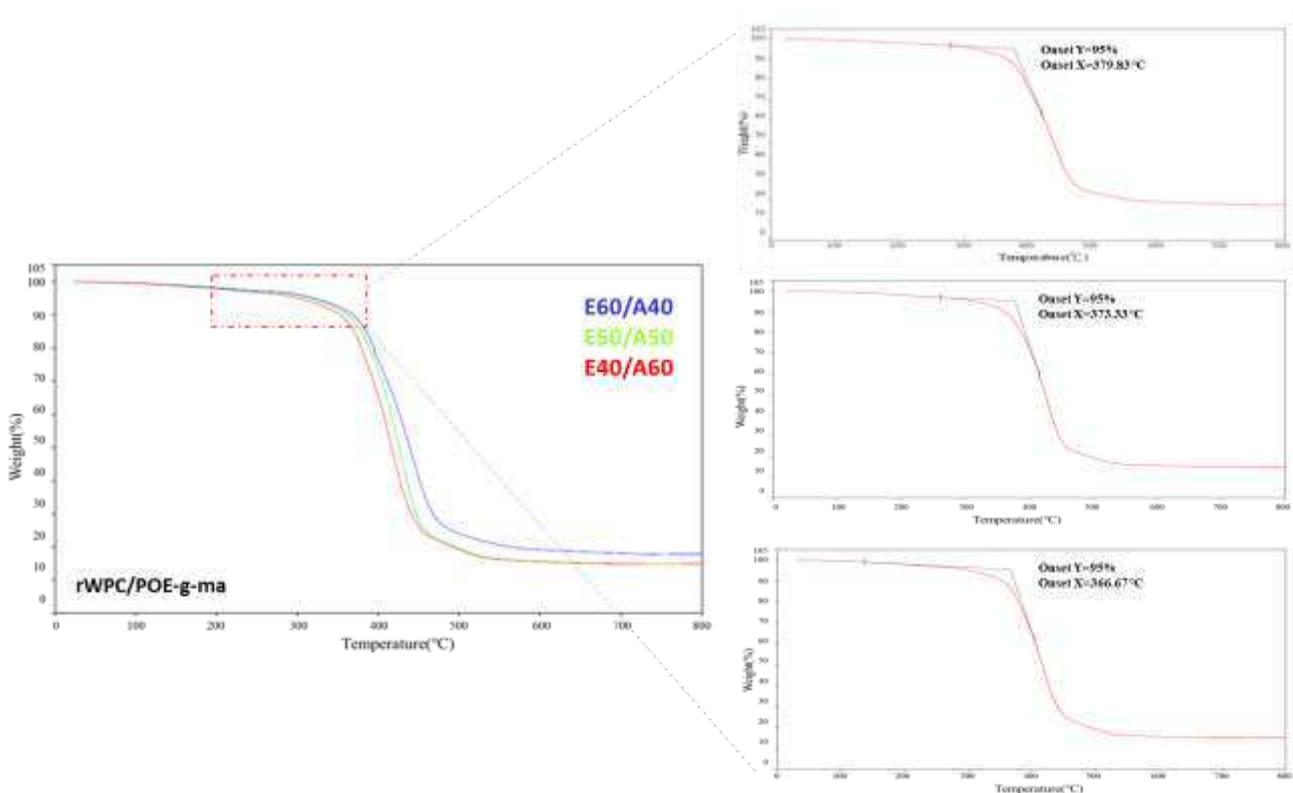
rWPC (rPET/rPA6)	Impact Modifier	MFI (g/10min)
E60/A40	POE-g-ma	1.12
	MBS	1.56
E50/A50	POE-g-ma	2.52
	MBS	3.80
E40/A60	POE-g-ma	5.96
	MBS	5.82

3.3 Thermal properties of rWPC

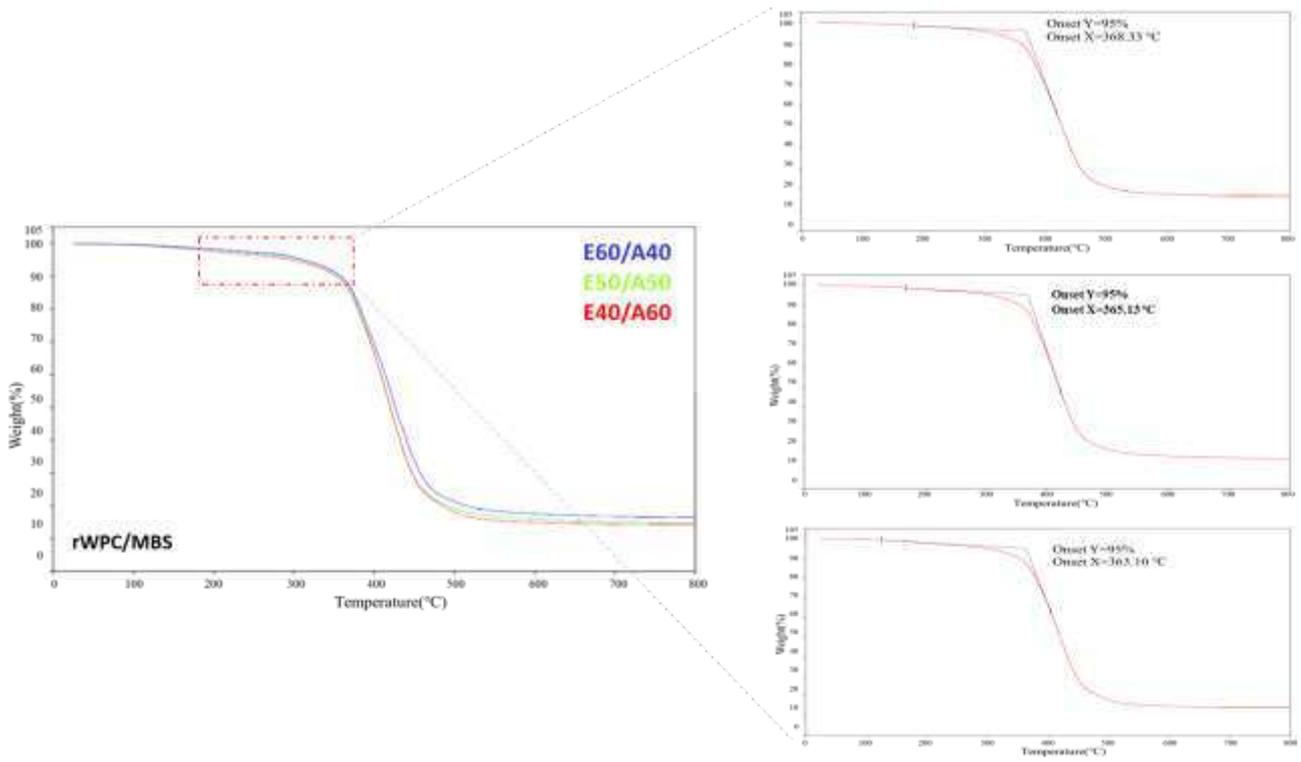
The thermal stability of the polymer matrix is very important for setting the process parameters and the design of the material formulations. Since the production of WPC requires the blending of wood flour and plastic at high temperatures, this will not only cause plastic degradation but also wood flour carbonization, which will

affect the usability of the end product.

From **Figure 6**, when the thermal weight loss reached 5%, the decomposition temperature (T_{d05}) of POE-g-ma added to rWPC for E60/A40, E50/A50 and E40/A60 was 379.83°C, 373.33°C, and 366.67°C, respectively, and the T_{d05} of MBS added to rWPC for E60/A40, E50/A50 and E40/A60 was 368.33°C, 365.13°C, and 363.10°C, respectively. The decomposition temperature of PET is ~420°C, 320°C for PA6, therefore as the PA6 content increases, the initial decomposition temperature of the rWPC is reduced. Furthermore, the heat resistance of the rWPC with POE-g-ma is better than that of the MBS composite because POE is a polyethylene (PE) copolymer with a very high decomposition temperature (about 500°C).



(a)



(b)

Figure 6. TGA thermograms of rWPC with (a) POE-g-ma and (b) MBS

3.4 Effect of accelerated weathering on the mechanical properties of PET/PA6 rWPCs

The environmental aging process includes thermal aging, climatic aging (i.e. solar radiation, oxygen, temperature, water, atmospheric pollution, etc.), and biological degradation, which cause a variety of aging effects. For example, an increasing temperature increases the absorption of UV radiation, thereby affecting the mechanical properties, as well as the appearance of the WPC. Most WPCs are used outdoors, hence their resistance, especially to UV, impacts their lifespan.

As shown in **Figure 7–9 and Table 4**, the mechanical properties, such as tensile and flexural strength, of the three different rWPC after 30 days of accelerated weathering were significantly lower than before aging. Also, before accelerated weathering treatment, the mechanical properties of the 40/60 rWPC were better than the 60/40 and 50/50 rWPC, whereas, after accelerated weathering, there was no

significant difference in the tensile and flexural strengths of the three different PET/PA6 ratios, indicating that the degradation of PA6 was more significant after accelerated weathering.

All composite samples were exposed to both UV radiation and water spray, which cause losses of mechanical properties. Regardless of the ratio of the rWPC, after xenon arc lamp exposure, oxidative degradation of the plastic matrices will occur due to breaking of the polymer macromolecular chains, increasing the brittleness and decreasing the strength of the rWPC, especially of the 40/60 PET/PA6 rWPC.

Exposure to UV radiation with water spray can change the polymer crystallinity, which initially increases during exposure to UV radiation and water spray, then decreases [32]. As the rWPC is exposed to UV radiation, chain scission occurs and more mobile short chains recrystallize [33] but as chain scission continues, the crystalline regions are affected and crystallinity decreases. It is expected that after one month of accelerated weathering, there would be a decrease in the crystallinity of the polymers, resulting in a decrease in the mechanical properties of the rWPC. However, the tensile and flexural strengths of the rWPC decreased after 30 days of accelerated weathering and the impact strength increased. As shown in Figure 8 and Table 4, the impact strength of the rWPC with the ratio of E60/A40 remained unchanged before and after accelerated weathering. First, photodegradation will cause molecular chain fractures in the material, leading to re-crystallization of the polymer matrix and a neat lattice arrangement which can accelerate the stress transmission [34]. Secondly, the toughening effect due to the moisture absorption of PA6 increases the absorption of impact energy, therefore, the weather resistance of rWPC is better when it is impacted. Also, when the PA6 content increases, the toughening effect caused by moisture absorption exceeds the effect of polymer re-crystallization, allowing water molecules to fill the holes in the

polymer matrix. Thus, when POE-g-ma or MBS is added in the plastic ratio of E40/A60, the impact strength of rWPC is increased by 215% and 202% compared to E60/A40, respectively.

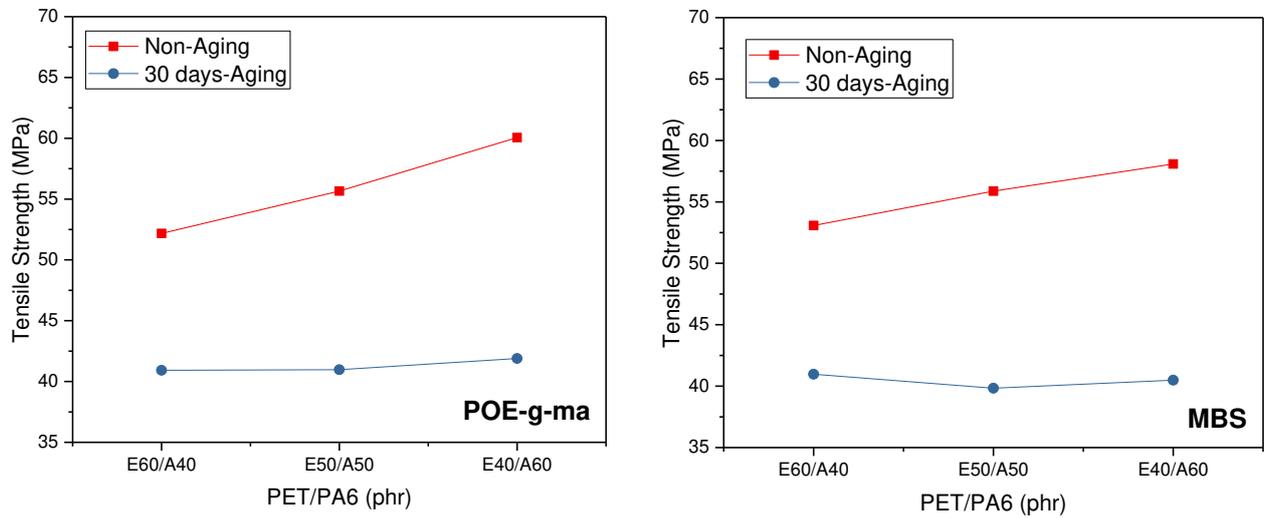


Figure 7. Tensile strength of the different rWPCs under accelerated weathering: (a)POE-g-ma; (b)MBS

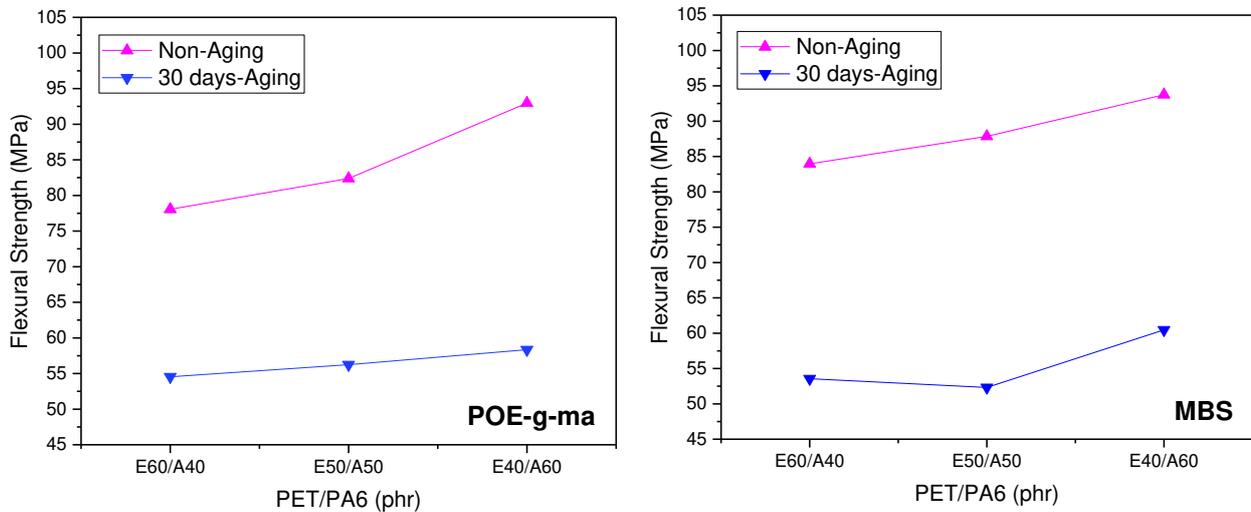


Figure 8. Flexural strength of the different rWPCs under accelerated weathering: (a)POE-g-ma; (b)MBS

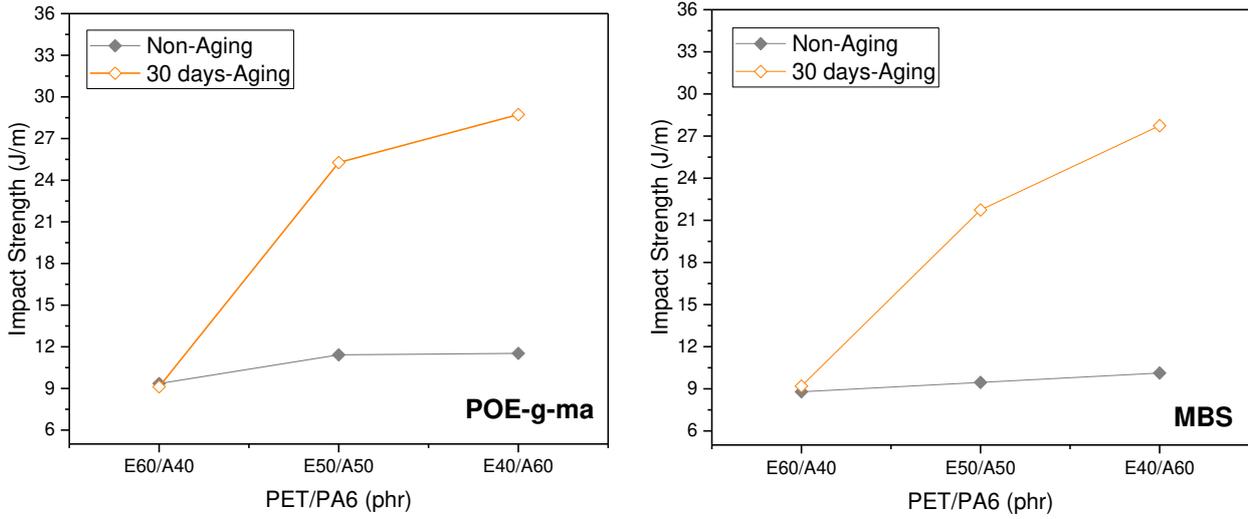


Figure 9. Impact strength of the different rWPCs under accelerated weathering: (a)POE-g-ma; (b)MBS

Table 4. Mechanical properties of the rWPCs exposed to accelerated weathering

rWPC (PET/PA6)	Impact Modifier	Accelerated Weathering	Tensile Strength (MPa)	Flexural Strength (MPa)	Impact Strength (J/m)
E60/A40	POE-g-ma	0 day	52.17	78.06	9.35
		30 day	40.92	54.54	9.12
	MBS	0 day	53.07	83.96	8.79
		30 day	40.97	53.56	9.19
E50/A50	POE-g-ma	0 day	55.66	82.39	11.42
		30 day	40.97	56.24	25.27
	MBS	0 day	55.88	87.85	9.46
		30 day	39.83	52.31	21.74
E40/A60	POE-g-ma	0 day	60.06	92.97	11.53
		30 day	41.89	58.35	28.73
	MBS	0 day	58.09	93.74	10.12
		30 day	40.49	60.47	27.74

3.5 Effect of temperature and humidity on the creep property of PET/PA6 rWPCs

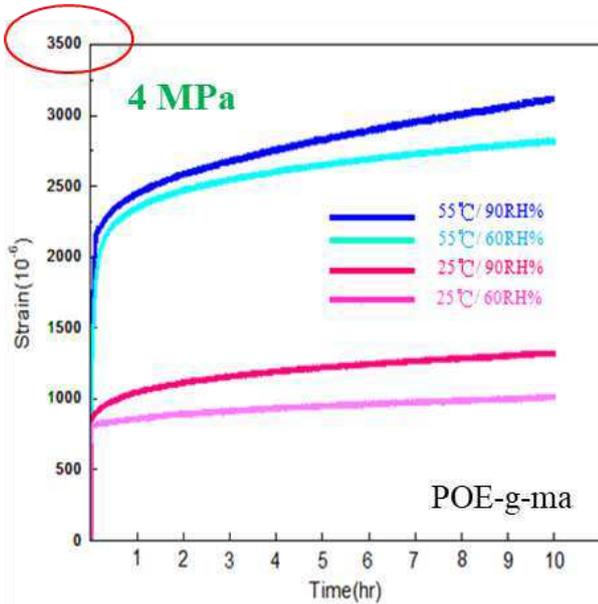
The creep resistance behavior of the rWPC under different environmental conditions was investigated when the PET content increased to 60% (E60/A40). Both temperature and applied loadings influence creep rate because the creep strain rate increases with increasing temperature and applied loadings. Moreover, the increase of temperature and applied loadings decreases the duration of the transient-state creep.

Figures 10 and 11 show that the creep strain was higher at 55°C than 25°C regardless of whether POE-g-ma or MBS was added and the test loadings of 4 MPa and 6 MPa. This is because the molecular activity of the material increases while the molecular bonding force decreases with increasing temperature, thereby increasing the slip degree of the viscous molecules. Moreover, infiltration of water molecules increases the porosity of the material exposed to high humidity, leading to an increase in the creep strain rate. Hence, temperature and humidity rapidly affect the creep strain during the transient creep phase, and continue increasing the amount of creep strain during the steady-state. With the increasing applied loadings in the same temperature-humidity conditions, the transient-state rapidly achieves a steady-state. Moreover, steady creep behavior occurred more with increasing temperature and humidity under the applied loadings of 4 MPa and 6 MPa.

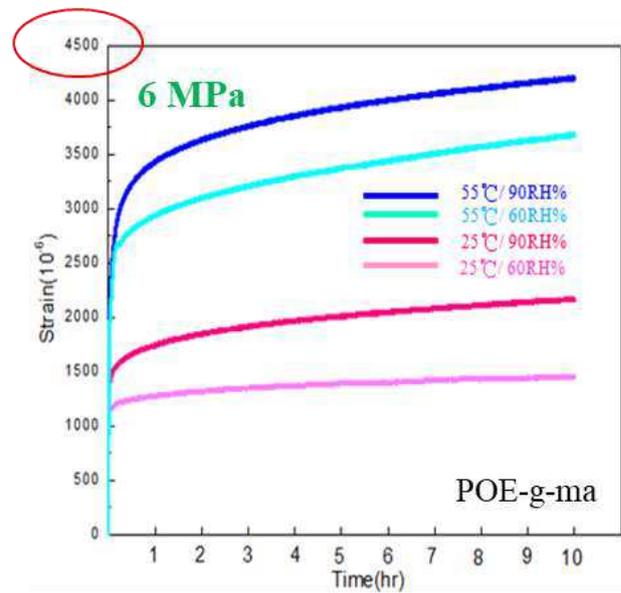
Additionally, the total dislocation density of a material is a function of the external stress and can be described as follows [35]:

$$\sigma = \sigma^* + \alpha M G b P_f^{0.5} \dots\dots\dots(3)$$

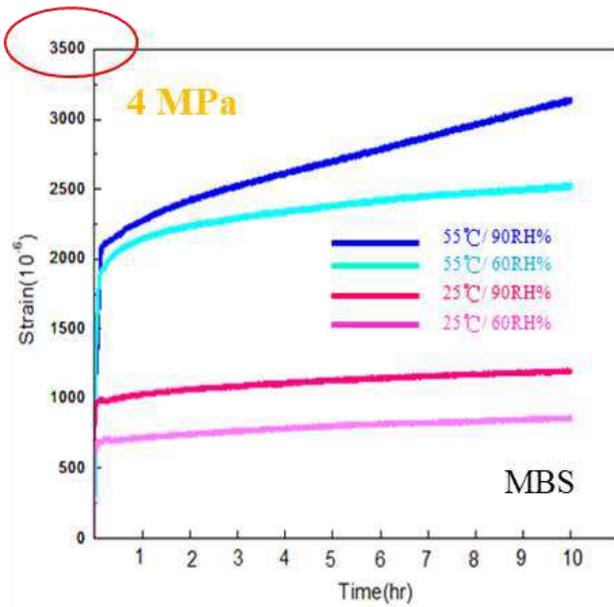
where σ^* is threshold stress above which dislocation multiplication is possible, α is the dislocation interaction constant, M is the Taylor factor, G is the shear modulus, b is the magnitude of the Burgers vector, and P_f is the average spacing of free dislocations and is proportional to the total dislocation density. A material stressed at a constant temperature above certain threshold stress will have numerous mobile dislocations, becoming immobilized by the interaction with other dislocations or other obstacles, such as boundaries or precipitates, during creep. This will lead to strain hardening since the stress field around the dislocation clusters will effectively prevent further dislocation glide [35]. In this study, wood flour plays a critical role in strengthening composites because of the outstanding anti-creep strain separated particles distributed among plastic substrate to inhibit the viscous flow and elasticity in polymer chains under applied stress.



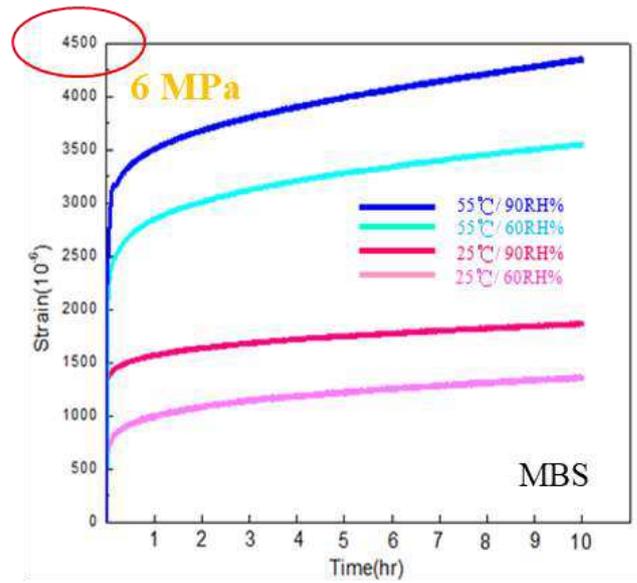
(a)



(b)

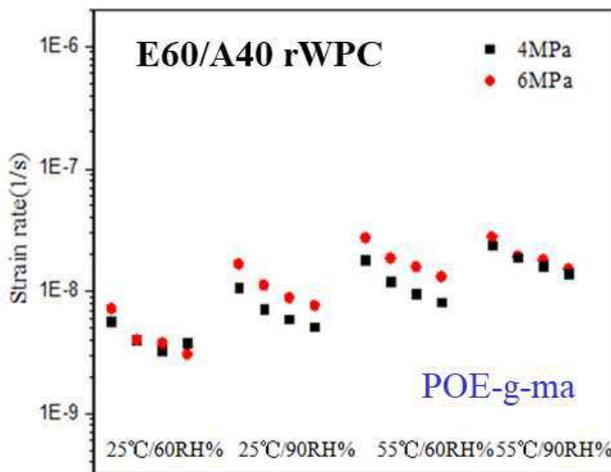


(c)

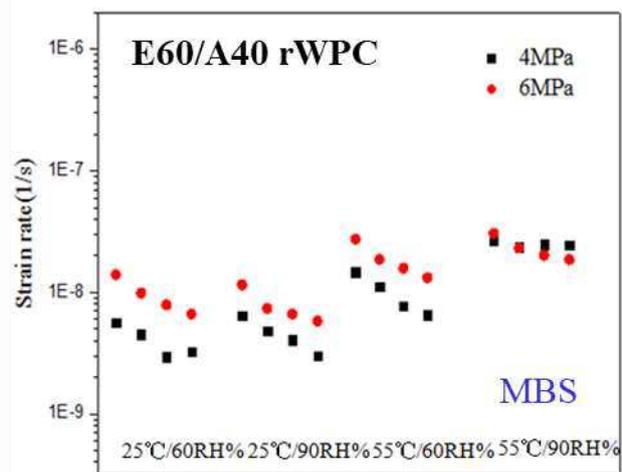


(d)

Figure 10. Creep strain of E60/A40 rWPC exposed to environmental aging and tested under different loadings: (a) POE-g-ma under 4 MPa; (b) POE-g-ma under 6 MPa; (c) MBS under 4 MPa; (d) MBS under 6 MPa



(a)



(b)

Figure 11. The strain rate versus temperature and humidity conditions for E60/A40 rWPC under loadings of 4 MPa and 6 MPa. (a) POE-g-ma; (b) MBS

4. Conclusion

The recycled PET/PA6 WPC with a higher PET content is less flowable (i.e. E60/A40) but the MFI value is sufficient for the manufacture of outdoor building products via extrusion. The highest initial decomposition temperature was obtained with the 60/40 PET/PA6 rWPC. Before accelerated weathering treatment, the mechanical properties of the 40/60 rWPC were better than the 60/40 of 50/50 rWPC, however, there was no significant difference in properties after accelerated weathering, indicating that the degradation of PA6 was more significant after accelerated weathering. Also, high temperature, high humidity, and higher applied loadings had significant effects on the creep strain rate of the rWPCs. In conclusion, the E60/A40 rWPC performs better in terms of thermal and aged mechanical properties, and considering the material cost of PET and PA6, the E60/A40 rWPC is more suitable for outdoor building applications.

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Figures

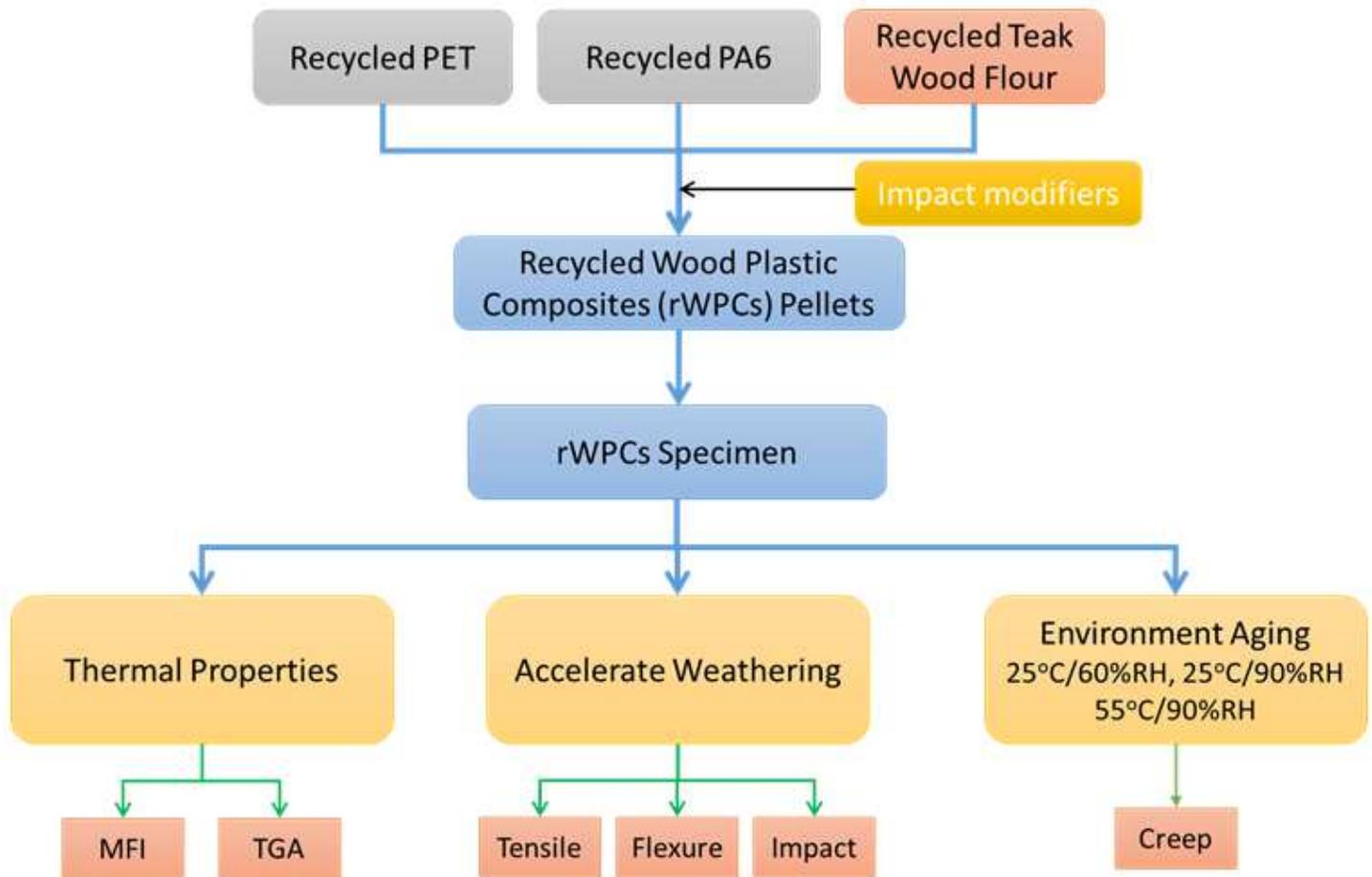


Figure 1

Schematic illustration of this study

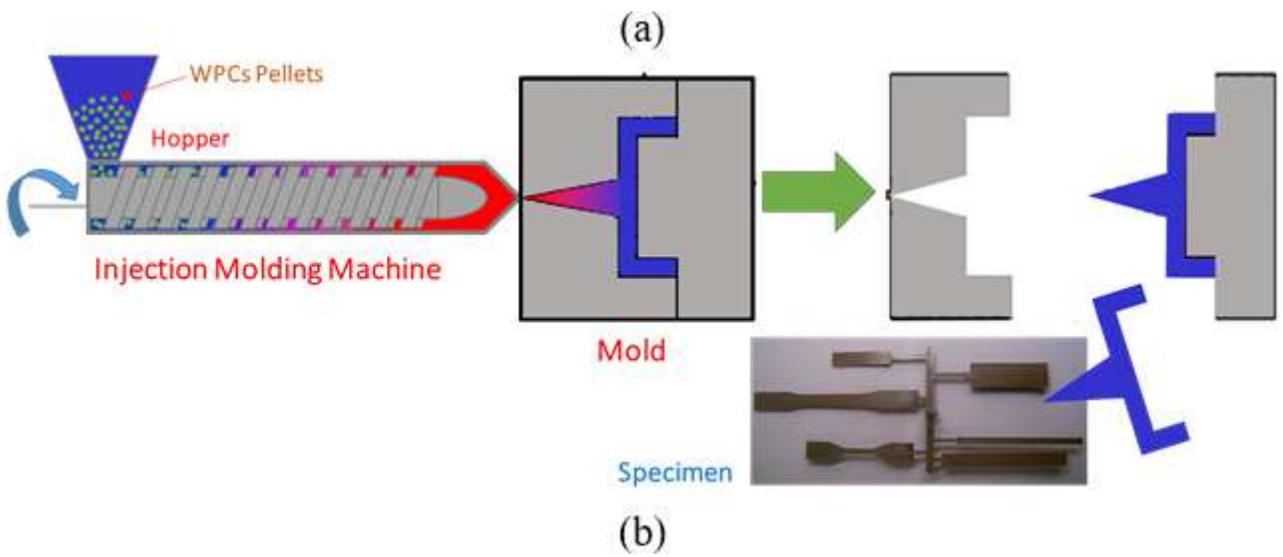
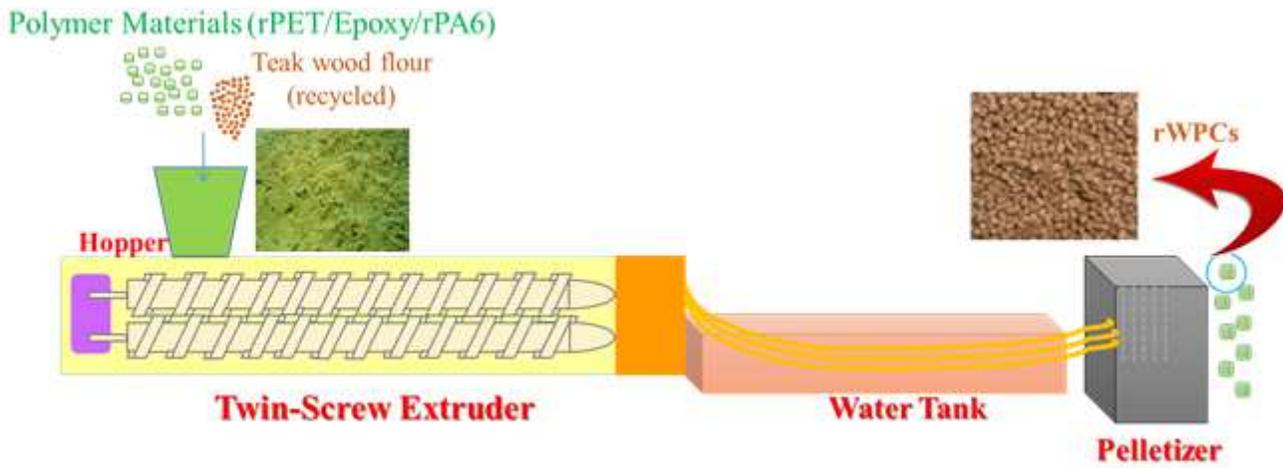


Figure 2

rWPC preparation: (a) compounding process for fabricating the rWPC pellets; (b) injection molding for fabricating the rWPC specimens

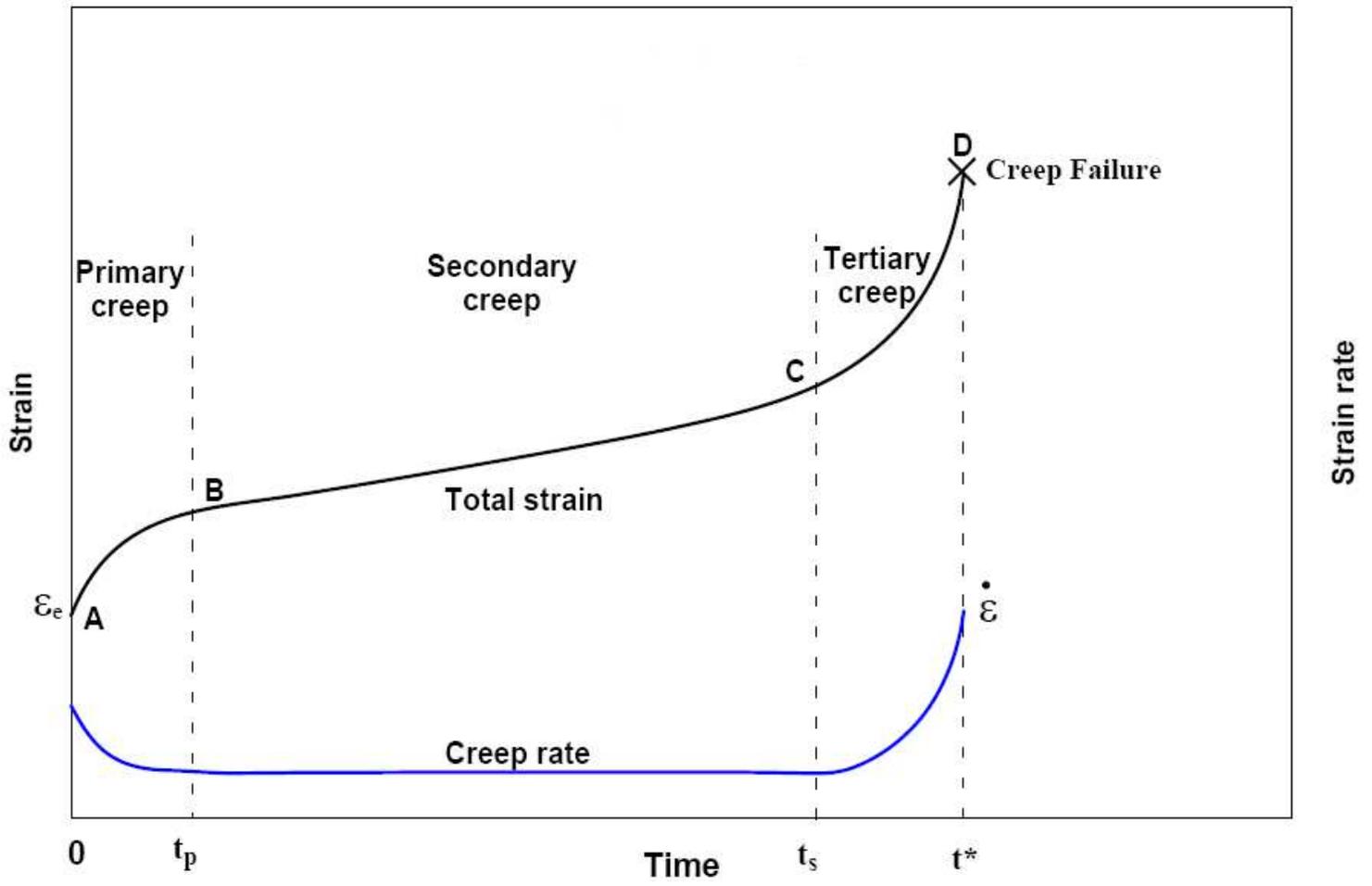


Figure 3

Creep strain [28]

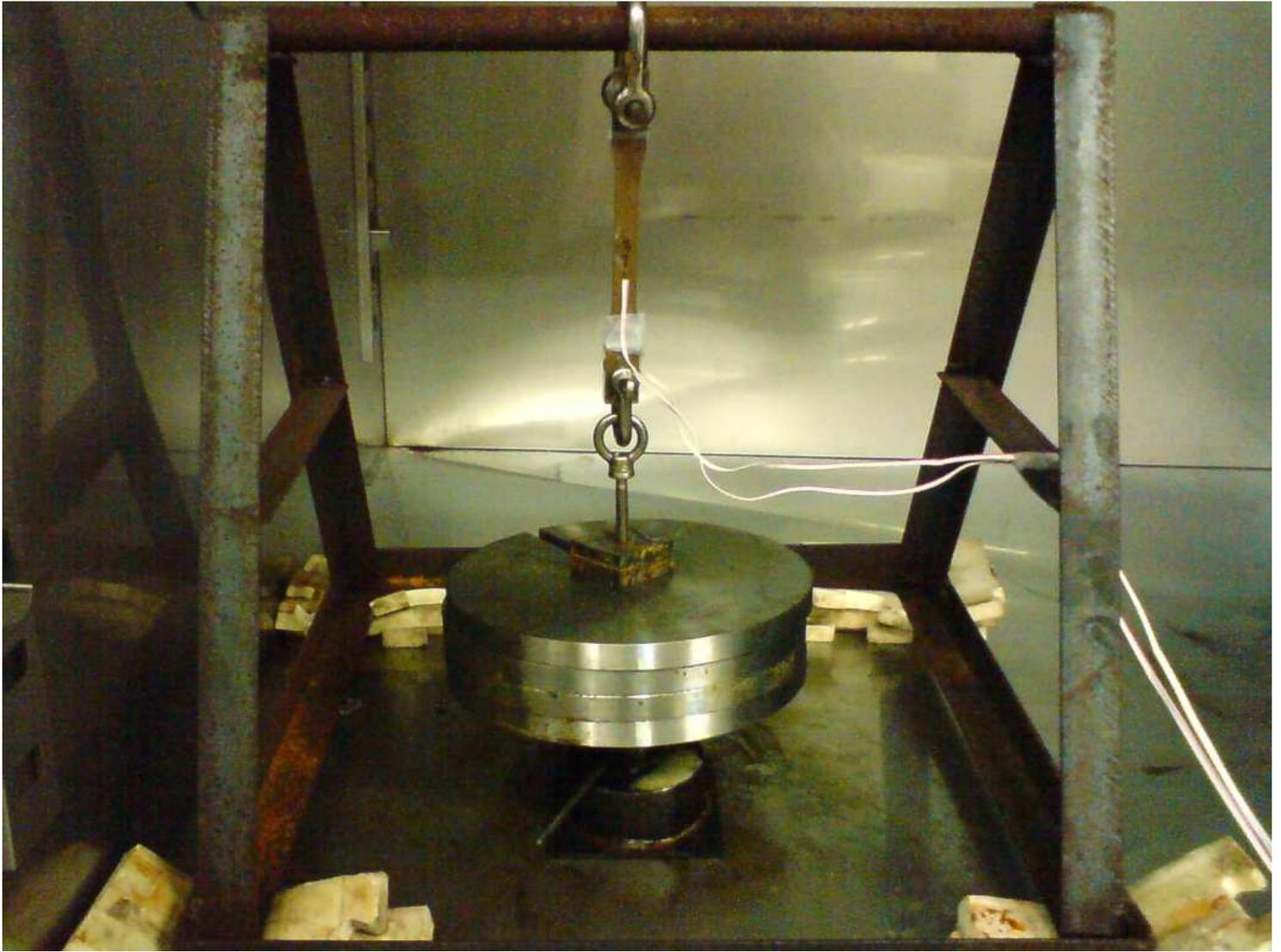


Figure 4

Creep test equipment

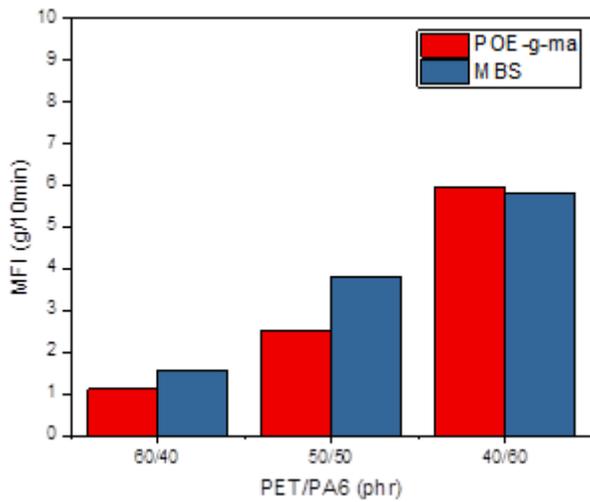
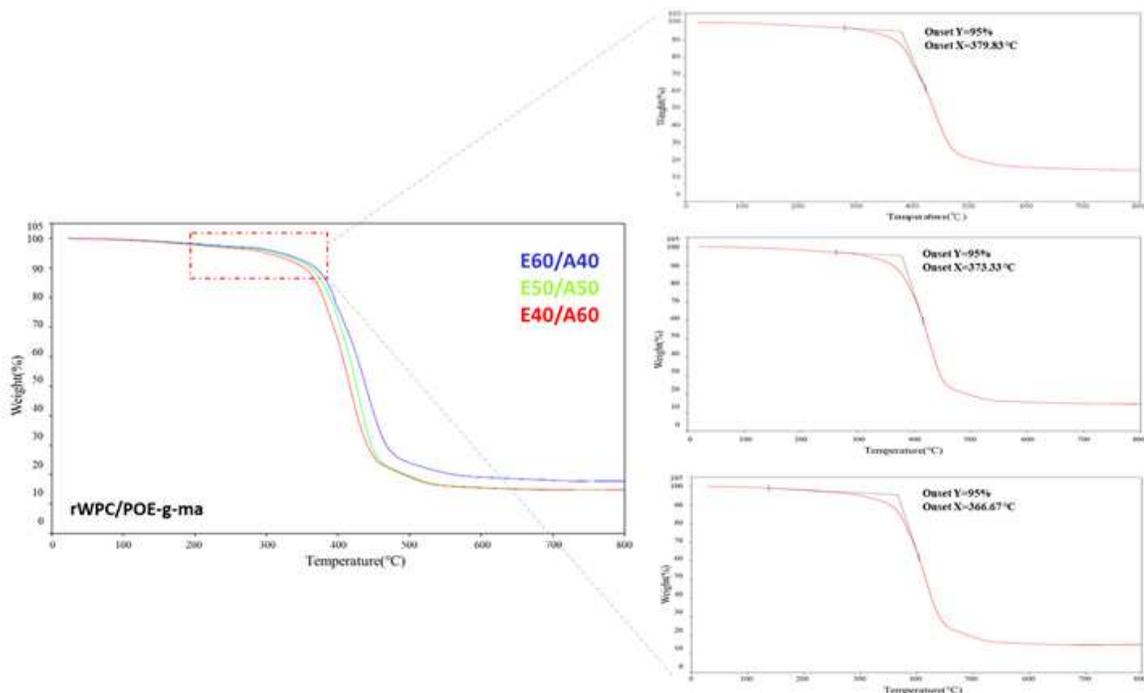
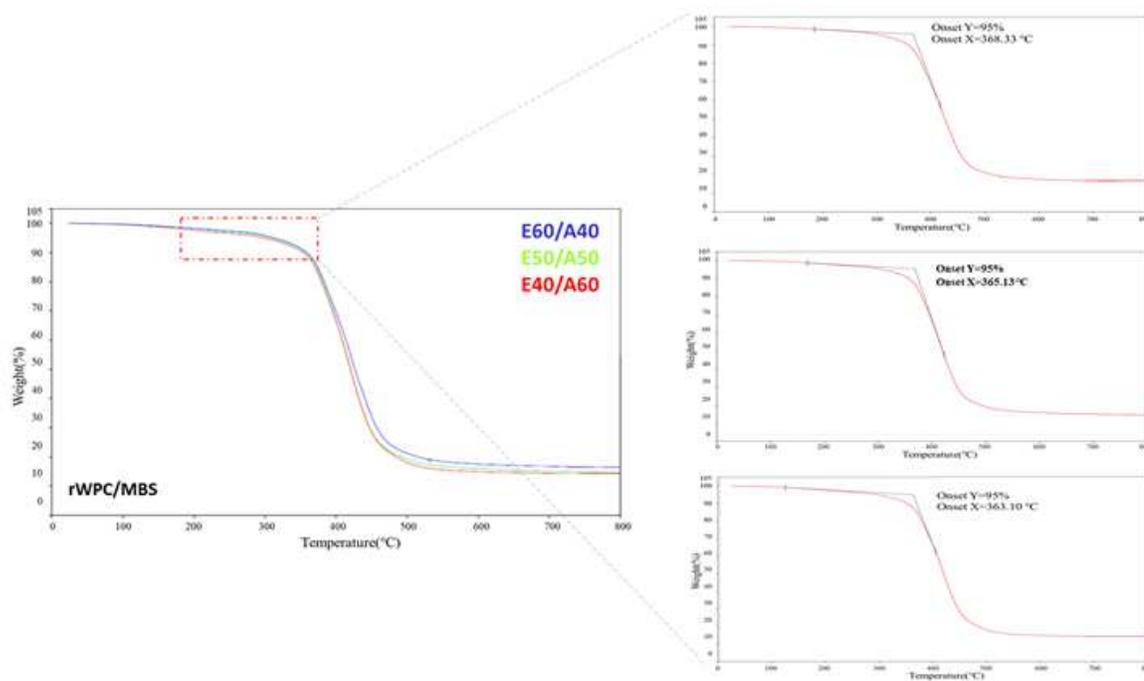


Figure 5

MFI of rWPC with the different impact modifiers



(a)



(b)

Figure 6

TGA thermograms of rWPC with (a) POE-g-ma and (b) MBS

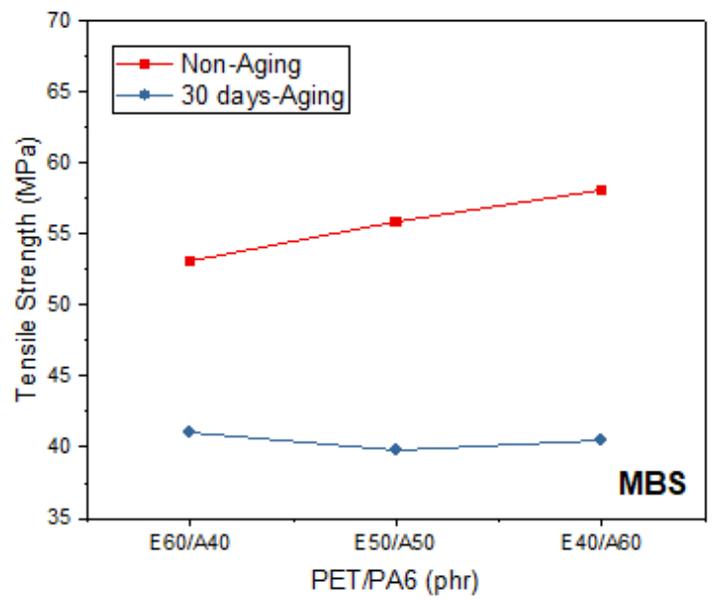
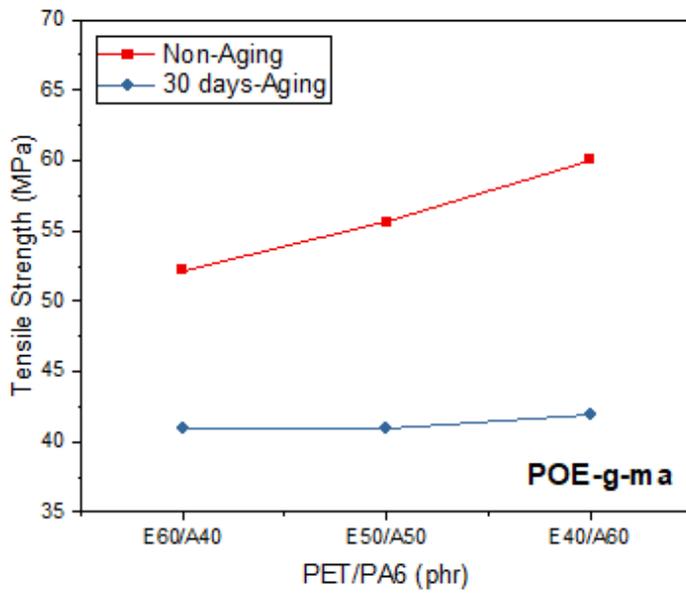


Figure 7

Tensile strength of the different rWPCs under accelerated weathering: (a)POE-g-ma; (b)MBS

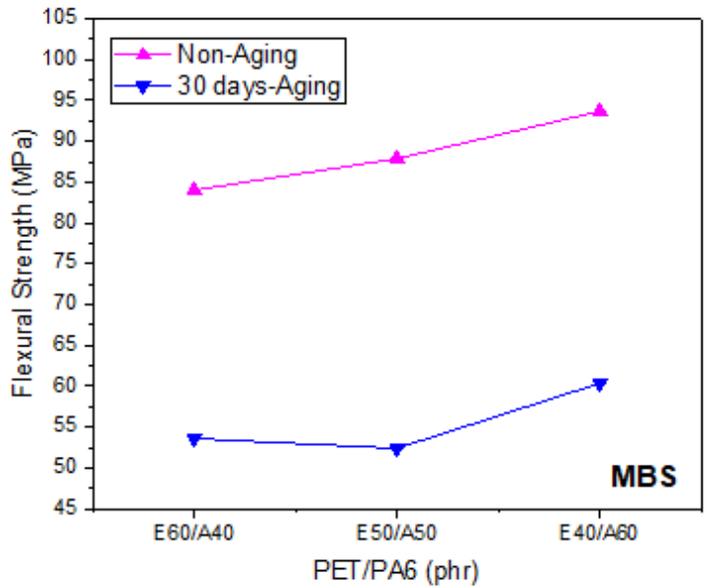
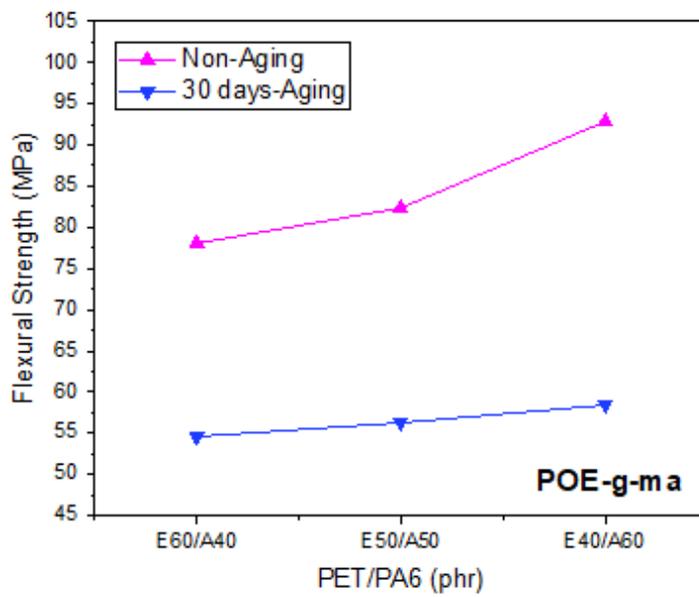


Figure 8

Flexural strength of the different rWPCs under accelerated weathering: (a)POE-g-ma; (b)MBS

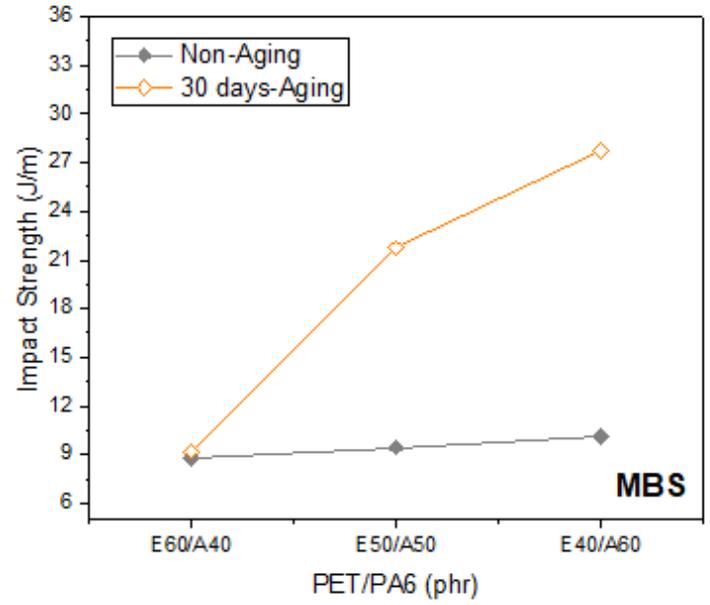
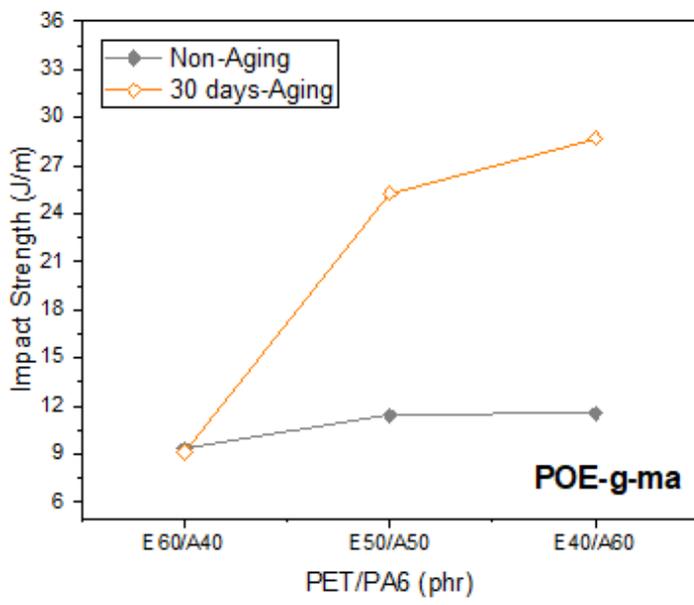
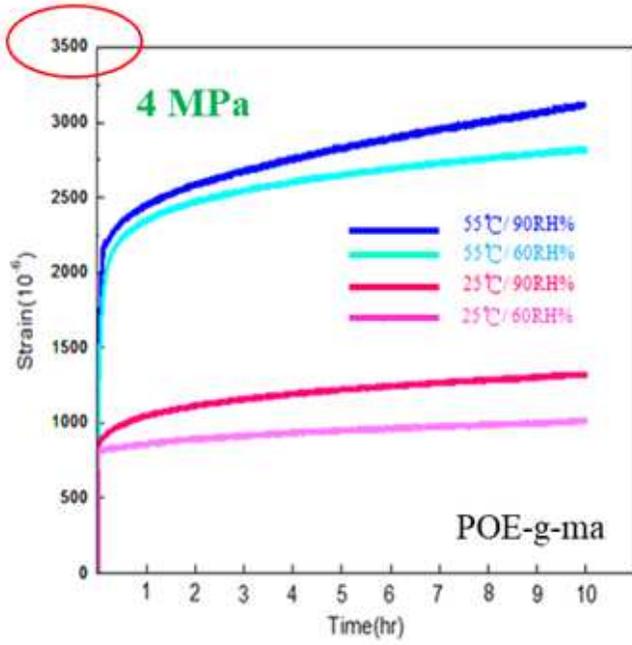
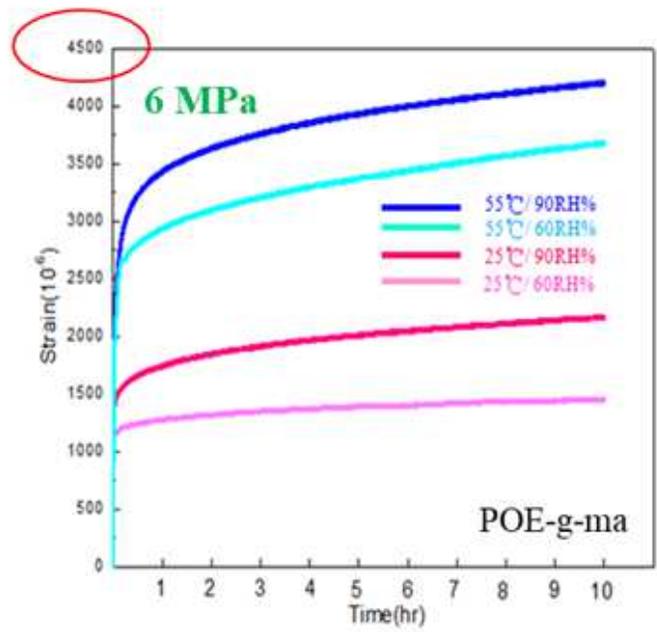


Figure 9

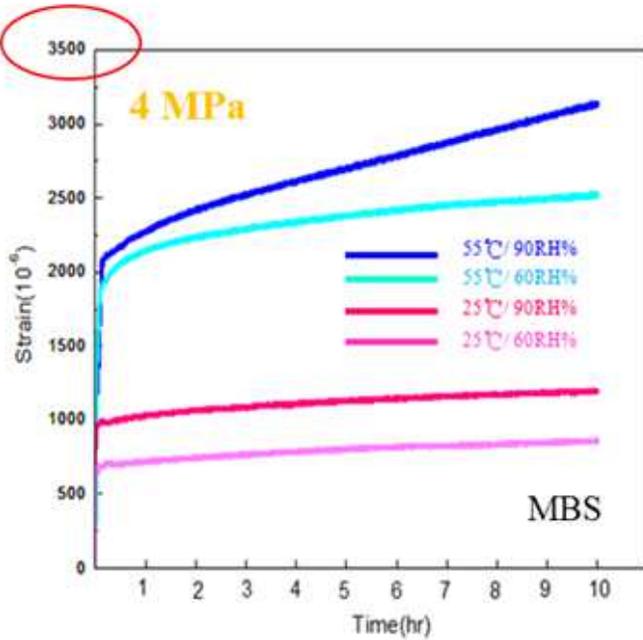
Impact strength of the different rWPCs under accelerated weathering: (a)POE-g-ma; (b)MBS



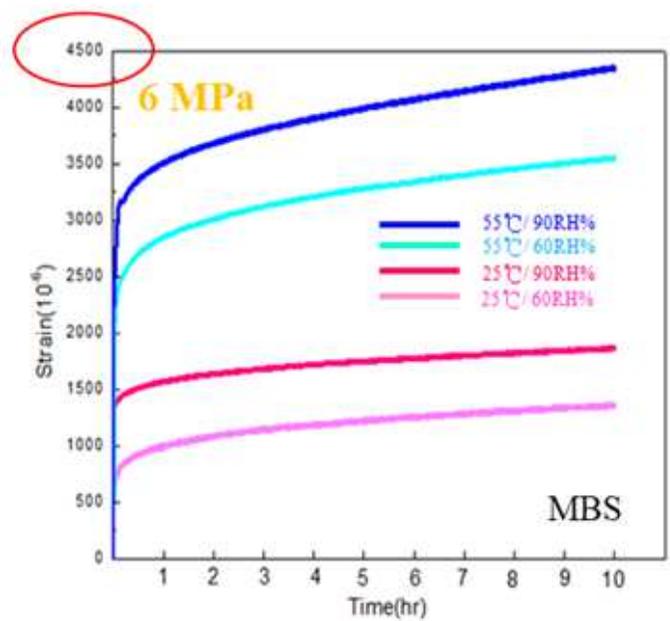
(a)



(b)



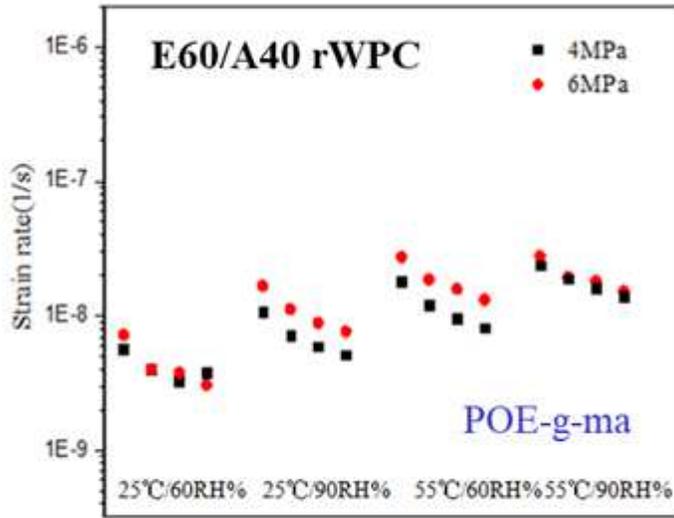
(c)



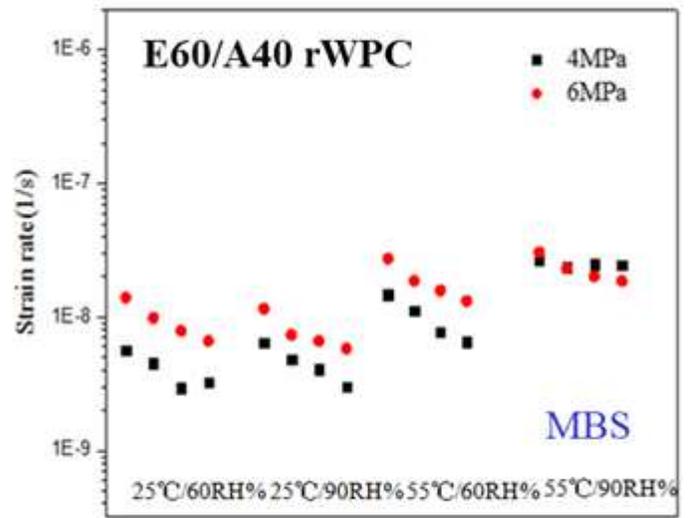
(d)

Figure 10

Creep strain of E60/A40 rWPC exposed to environmental aging and tested under different loadings: (a) POE-g-ma under 4 MPa; (b) POE-g-ma under 6 MPa; (c) MBS under 4 MPa; (d) MBS under 6 MPa



(a)



(b)

Figure 11

The strain rate versus temperature and humidity conditions for E60/A40 rWPC under loadings of 4 MPa and 6 MPa. (a) POE-g-ma; (b) MBS