Effect of acrylonitrile styrene acrylate on mechanical, thermal and three-body abrasion behaviors of eucalyptus fiber reinforced polyvinyl chloride composite

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Abstract
The effect of different content (0–20 wt%) Acrylonitrile-styrene-acrylic (ASA) on mechanical, thermal and three-body wear behaviors of eucalyptus fiber/polyvinyl chloride (EF/PVC) composites were studied in this research. The results show that the mechanical properties of the composites such as impact strength, tensile strength, flexural strength and flexural modulus increased with increasing ASA content lower than 15 wt%. The addition of 15 wt% and 20 wt% ASA can improve thermal stability of the EF/PVC composites in the early period of the heating, and the effect weakened on later stage due to the thermal degradation of ASA, which occurred in the temperature range 416°C–442°C. The three-body wear resistance of the EF/PVC composites can be improved by ASA, and the abrasive wear mechanism of the composites was predominated by linear travel, sand particle plough and cut action, ASA and PVC plastic deformation, and fibers debonding.

1. Introduction

Due to the excellent advantages, such as environmentally friendly, usage flexibility, lightweight, natural recyclable and biodegradable, natural fibers have recently become an attractive reinforcement for polymers [1]. A new type of composite material with superior properties has been produced using plant fibers as reinforcement and polymers as matrix, which have been widely used as exterior construction materials such as fencing and decking [2, 3], adding nature fibers like kenaf, sisal, bamboo, flax, hemp, jute, and wood fibers significantly improves thermal stability, mechanical and working properties of the composites [4–7].

As the matrix of nature fiber reinforced polymer composites (NFPCs), polymers play a key role for the material properties, so enhancement of polymer is another important point to improve the properties of NFPCs. For the past few years, blending has been widely used as a practical method for improving polymer properties due to its economic and practical characteristics [8], and various core-shell structure particles, for instance, methacrylate-butadiene-styrene terpolymer and acrylonitrile-butadiene-styrene terpolymer are used as impact modifiers in polymer industry to gain more flexibility with enhanced mechanical properties [9–12]. Acrylonitrile-styrene-acrylic (ASA) terpolymer is a resin which also has a core-shell structure while poly (butylacrylate) (PBA) is the soft core and styrene-acrylonitrile (SAN) copolymer is the hard shell, the PBA rubber core is encased by the SAN copolymer shell [13]. Poly (vinyl chloride) (PVC) is a typical commodity polymers for lots of applications particularly in the building and construction market on account of its multifunctionality, energy efficiency, low cost, chemical resistance and long-life [14, 15], however, the brittleness of PVC limits its application and is sensitive to temperature [16, 17]. ASA terpolymer not only can be applied as normal plastics, but also can utilized as a toughening modifier for polymers, in order to expand the application of PVC, lots of researches applying ASA as impact modifier for PVC have been reported. Sarawut Rimdusit et al investigated the effect of ASA content on characteristics of PVC/ASA composites, it was found that the impact strength, glass transition temperature, thermal stability and outdoor weathering durability of the blends could be enhanced by the presence of ASA in the blends [18]. Du Y et al explored the plastic and dynamic rheology behavior of
PVC/ASA blends, and discussed the influences of blending on modulus and complex viscosity, they found that ASA can not only be used as an impact modifier for PVC at proper content, but also can decrease the balance torque and processing time [19]. Wang C et al demonstrated the effect of carbon nanotube on the thermal stability, plasticizing function and mechanical properties of the PVC/ASA composites, it was found that ASA can be utilized as an impact modifier, the impact strength reinforces from 2.26 to 7.26 kJ·m⁻² when 12 wt% ASA was added into PVC matrix, but the tensile strength decreases [20]. Zhang Y et al studied a novel rigid PVC/ASA copolymer blends, it was found that ASA was able to enhance many properties of PVC, such as toughness, heat resistance, thermal stabilization, and resistance to irradiation photochemical degradation [21]. Zhang X et al studied effect of temperature, core-shell structures and contents of ASA on the properties of PVC/ASA composites, the results showed that the hard shell of ASA is miscible with PVC matrix, so that the interface adhesion between ASA and PVC is good, increasing the content of soft PBA can significantly improve the toughness of the blends at room temperature, however, the decrease of temperature limits the flexibility of PBA chain, which leads to the ASA terpolymer has little toughening effect on PVC at −30 °C moreover, the improvement of toughness did not sacrifice the thermal deformation temperature [22, 23].

There have recently been few reports of ASA’s influence on the properties of nature fiber/PVC/ASA composites. Sarawut Rimdusit et al prepared coconut fiber reinforced composites based on PVC/ASA matrix, the results showed that under same fiber content, the impact strengths of the coconut fiber reinforce PVC/ASA composites are significantly higher than those of PVC wood composites and polyolefin wood composites, and the PVC/ASA blend has excellent impact strength and thermal properties, is a kind of high impact wood composite matrix material with good thermal dimensional stability [24]. Jiang L et al explored the possibility of reinforcing micro-silica (MS) and ASA/PVC/sorghum straw composites and developed a new type of corrosion and wear-resistant material, proving that MS and ASA could reinforce the PVC matrix with better toughness, strength, and heat resistance [25]. Eucalyptus is one of the most widely used genera in the global commercial timber plantation industries since it is a high-quality and high-yield tree [26]. Studies were conducted to investigate the mechanical and physical properties of reinforced polymer composite eucalyptus fiber (EF) [27, 28]. Zhang KP et found that the 5% NaOH alkali-treated eucalyptus fiber reinforced PVC (EF/PVC) composites had a noticeably improved mechanical properties and three-body abrasion resistance [29, 30]. There is no study about ASA modification on the EF/PVC composites.

The aim of this work was to study the effect of the ASA content on the mechanical, thermal and three-body abrasion behaviors of alkali-treated EF/PVC Composites.

2. Experimental

2.1. Materials

ASA with core-shell particles (PW-978B) and SG-5 PVC used in this work was brought from Taiwan Chimei Plastics Co. Ltd, China and Tianjin Tongxingguo Trading Co., Ltd, China respectively. Other composite additives were maleic anhydride (type 400A) as a graft binding agent and non-toxic Ca/Zn composite (type 603) as a stabiliser, obtained from Guangzhou Yinghong Chemical Co., Ltd, Guangzhou, China, and PE (polyethylene) wax, H-108, supplied by WujiangMeiqi Plastic Material Co., Ltd, Suzhou, China.

Eucalyptus (Eucalyptus robusta Smith) was collected from Guangxi Fenglin Wood Industry Co., Ltd, Guangxi, China with a density of 0.611 g·cm⁻³. Before use, the air-dried eucalyptus was crushed, ground and subsequently filtered and eucalyptus fibers particle size 149 μm was obtained. The eucalyptus fibers were subsequently submerged in 5% of NaOH concentrations at 100 °C for an hour, eventually the treated fibers were filtrated from the liquid and washed with deionized water until the rinsed solution was neutral.

The sand abrasive particles used in three-body abrasive wear test were collected from the Yellow River in Lanzhou, China. To get particle size of 0.50 mm, the sand was washed, air-dried, and screened with mesh screens.

2.2. Specimen preparation

Prior to any processing of specimen preparation, the pour ASA and PVC were dried separately in a DZF-6012 vacuum oven (Shanghai Yiheng Scientific Instrument Co., Ltd, Shanghai, China), at 60 °C for 24 h, and the rinsed fibers were dried for 16 h at 90 °C in a DHG-9055A electrical thermostatic drum-wind drying oven (Shanghai Yiheng Scientific Instrument Co., Ltd, Shanghai, China), then cooled to room temperature in the ovens, obtaining a moisture content of less than 3%.

A SYH-5 3D linking mixer (Changzhou Feima Drying Equipment Co., Ltd, Changzhou, China) was used to mix the ASA, PVC, alkali-treated eucalyptus fiber, and additives such as coupling agent, stabiliser, and PE wax. The content ratio of eucalyptus fiber and additives was held constant in this study, with the ASA content varying...
from 0 to 20 wt % to the sum of ASA, PVC, and eucalyptus fiber. Five samples of mixtures were prepared, table 1 showed the ratio of components in the blends.

The five blends were then placed into a SY-6216 inter-meshing twin-screw extruder (Shiyuan Precision Instruments Co., Ltd, Guangdong, China) separately for extrusion, the temperature profiles of four zones from the hopper to die were controlled at 150, 155, 160, and 165 °C respectively during processing, with a rotational speed of 20 rpm for screw. The extruded samples of composite had a thickness of 6 mm and width of 25.5 mm, and the lengths of samples were verified and controlled by the extrusion period. The solidified samples were then cut into desirable shapes for further tests.

2.3. Characterization

2.3.1. Mechanical properties of the pure and ASA modified EF/PVC composites

The impact strength of the pure and ASA modified EF/PVC composites were evaluated on a digital impact tester (XJJ-5, Xiamen Forbs Testing Instrument Co., Ltd, Xiamen, China) according to GB/T 1043.1-2008 while the impact energy is 2 J. The average impact strength values were calculated from 10 tests on each sample at room temperature (20 ± 1 °C). The morphological structure of impact fracture surface was observed by a Hitachi S-3400N scanning electron microscopy (SEM) (Hitachi Ltd, Tokyo, Japan) after being coated with gold.

The tensile properties of the composites were investigated using a universal electronic testing machine CMT2502 (Shenzhen SANS Testing Machine Co., Ltd, Shenzhen, China) with a loading speed of 2 mm·min⁻¹ according to ASTM D 638-14. The average values for each sample were determined from five independent measurements.

The composite’s flexural property was obtained on a CMT6104 electronic universal testing machine (MTS Industrial Systems Co., Ltd, China), in accordance with ASTM D 790-10. The tests were conducted at a loading velocity of 2 mm·min⁻¹, and the results were averaged from five independent measurements.

2.3.2. Thermal properties of the pure and ASA modified EF/PVC composites

Analysis of thermogravimetry (TG) was performed to examine and estimate the thermal properties of the composites using a synchronous thermal analyzer STA-449 F5 Jupiter (NETZSCH Scientific Instrument Trading (Shanghai) Co., Ltd, China) over a temperature range of 25 °C–600 °C with a heating rate of 20 °C·min⁻¹. The weights of all specimens were maintained at 3–5 mg and in powder form. The flow rates of the shielding gas and sweep gas were both 50 ml·min⁻¹.

2.3.3. The FTIR spectra of the pure and ASA modified EF/PVC composites

Fourier-transform infrared (FTIR) spectra of the composites were recorded with a resolution of 4 cm⁻¹ on a Nicolet iS50 FTIR spectrometer (Thermo Fisher Scientific (China) Co., Ltd, Shanghai, China). The measurements were conducted over the range of 400–4000 cm⁻¹, and the number of scans is 32.

2.3.4. Three-body abrasive wear test of the pure and ASA modified EF/PVC composites

A three-body abrasive wear tester (MLS-225; Zhangjiaokou Taihua Machine Co., Ltd, Zhangjiaokou, China) was used for the three-body abrasive wear test in accordance with ASTM G65, the wear tester schematic diagram is shown in figure 1.

The wear tests were carried out with the following parameters: load applied 100 N, sliding velocity 2.80 m·s⁻¹ (the corresponding rotational speed for the rubber wheel is 300 r·min⁻¹), and sliding distance 3.0 km at room temperature (20 ± 1 °C). Sand particles with a particle size of 0.50 mm were used as abrasives, before each test the specimen (6 × 25.5 × 57 mm⁻³) was installed at the lower end of the vertical beam and pressed by the applied load against the rimming rubber wheel. The abrasive container was then filled with sand particles and sealed. A new specimen was used for each test, and the surfaces of the specimen were cleaned with absolute ethanol and air-dried to avoid undesirable impurities before and after test. A minimum of three independent specimens were tested for each ASA content material.

The specific wear rate (Wₜ, 10⁻⁸ (mm³/N·m)) was calculated by determining the weight loss and density of the test specimen and using equation (1) [31],
where $\Delta M$ (mg) is the weight loss of the test sample which was measured using an AUY 220 electronic analytical balance (Shimazu (China) International Trade, Co., Ltd, Tianjin, China) with an accuracy of 0.1 mg. $L$ is the sliding distance (m), $F$ is the applied load (N), and $\rho$ is the specimen density (g cm$^{-3}$) which was measured using a TD-120 high precision touch screen plastic density tester (Taizhou Tiande Instrument Equipment Co., Ltd, Taizhou, China).

A profile and roughness tester (SRA; Shanghai Optical Instrument Factory, Shanghai, China) was used to measure the roughness of worn surfaces in parallel with the wear sliding, during measurement. The roughness before the wear test was 0.24 $\mu$m which was averaged from five measurements in different regions of the specimen surface.

Similar to the observations of the impact fracture surface, the Hitachi-S3400N SEM (Hitachi Ltd, Tokyo, Japan) was used to perform morphological analysis of worn surfaces at 5 KV operating voltage. Prior to the actual SEM analysis, the MSP-1S Magnetron sputter coater (Vacuum Device Inc., Tokyo, Japan) sputtered the worn surfaces of the specimens with gold.

3. Results and discussion

3.1. Analysis of mechanical properties and fracture surfaces

The effect of ASA content on impact strength of alkali-treated EF/PVC composites is shown in figure 2. From the figure, it can be observed that impact strength of the EF/PVC composites showed a slightly increase with the increase of ASA content from 0 to 15 wt%, the highest impact strength of the composite is 8.01 KJ m$^{-2}$ when ASA content is 15 wt% (sample No. ASA15), which is 16.09 % higher than pure EF/PVC composite (sample No. ASA0), although the value was found to decrease a little when the ASA content continuously increases (ASA20), the impact strength of ASA20 higher than that of pure EF/PVC composite (ASA0). So the impact strength of the EF/PVC composites was enhanced by the addition of ASA.

This enhancement of the impact strength might have been caused by following three reasons. First, ASA that was added into EF/PVC composites is core-shell terpolymers, the rubbery core (PBA) of ASA can provide impact resistance [19]. Second, ASA has improved the interfacial interaction between eucalyptus fiber and PVC, and an appropriate level of interfacial interaction between the fibers and the polymer matrix is the key factor to improve the impact strength of NFPCs by facilitating fiber pullout or debonding energy dissipation [24]. Third, ASA has an ability of forming optimal energy dissipation phase morphology with the PVC in the polymer matrix, those phase in ASA can be able to effectively initiate and terminate crazes while subjected to an external stress, energy was transformed into deformation of the rubber particles in the ASA with this crazing, therefore, deformation of the composites can effectively be stopped and impact strength was enhanced [18, 32].

In figure 3, effect of ASA content on tensile strength of the alkali-treated EF/PVC composites was illustrated. In general, compared with the pure EF/PVC composite (ASA0), the tensile strength of the composites was enhanced by the application of ASA. Further, it can be observed that the tensile strength of the composites increased significantly with increasing ASA content lower than 15 wt%. This improvement of tensile strength
could be attributed to the acrylonitrile and styrene segments (as a graft shell in the ASA), they have rigid units (glassy shell) and larger interaction with PVC molecules, which can provide rigidity and reinforce the tensile strength of materials [19, 25]. Same with enhance trend of impact strength, the composite with 15 wt% ASA content (ASA15) had the highest tensile strength among all of the samples, which is 1.3 times higher than pure EF/PVC composite (ASA0), and when ASA content is above 15 wt%, the tensile strength will decrease with increasing ASA content. This decrease might have been caused by phase separation in the PVC/ASA matrix which will appear while ASA content was added to a certain level, because of the larger compatibility between the ASA molecules than with PVC [19].

The flexural properties of the alkali-treated EF/PVC composites at varied ASA content is reported in figure 4. From the figure, the flexural strength and flexural modulus of the composites were found to show a similar trend to that of impact and tensile strength, where both flexural strength and modulus showed the increasing tendency with the increasing ASA content from 0 wt% to 15 wt%, and the flexural strength increased from 36.30 MPa at ASA0 to 55.17 MPa at ASA15 while the flexural modulus increased from 3.33 GPa to 3.84 GPa, the increase could be primarily due to the enhancement for flexural resistance provided by SAN (as a graft shell in the ASA) and better compatibility between the fiber and PVC/ASA matrix [25]. Meanwhile both of

![Figure 2. Impact strength of pure and ASA modified EF/PVC composites.](image2)

![Figure 3. Tensile strength of pure and ASA modified EF/PVC composites.](image3)
the flexural strength and flexural showed a slight decrease while ASA content continuous increase to 20%, this
decrease may ascribe to the soft nature of the PBA core in ASA [23].

SEM micrographs of the impact fracture surfaces of pure EF/PVC and 15 wt % ASA modified EF/PVC composites (ASA0 and ASA15 respectively) are shown in figure 5. Overall, there are no obvious droplets and clear-cut boundaries of fibers, ASA and PVC on fracture surfaces, indicating that the components of composites are miscible [23]. Compared with ASA modified EF/PVC composites (figure 5(b)), figure 5(a) shows a relatively smooth surface and more fibers were exposed to the outside, which implying brittle fracture. On the other hand, ductile characteristics such as microlayer and corrugated structure can be observed in figure 5(b), some voids and gaps were induced, this is mainly due to the interaction between SAN grafted on the PBA core and PVC matrix, which made the interface adhesion between ASA and PVC stronger, and led to the cavitation of rubber particles [23]. Meanwhile, at ASA15 more fibers were embedded in the PVC/ASA matrix, indicating that the fiber-matrix dispersion and compatibility with the ASA modification were better. Thus, it can be affirmed that the impact strength and tensile strength of EF/PVC composites can be enhanced with ASA.

3.2. Analysis of FTIR spectra properties

Figure 6 presents the effect of ASA content on FTIR spectra of the alkali-treated EF/PVC composites. Similarity of the FTIR spectra curves in figure 6 proved that all samples had similar chemical functional groups, the typical absorption peaks of the composites included 3500–3300 cm⁻¹ for O–H stretching vibration in fiber, 2935–2900 cm⁻¹ for C–H asymmetric stretching vibration in fiber, PVC and ASA, 1735–1700 cm⁻¹ for C=O stretching vibration in fiber and ASA, 1425 cm⁻¹ for C–H deformation in fiber and PVC, 1250–1230 cm⁻¹ for C–O and Si–C stretching vibration in fiber, 1100–970 cm⁻¹ for stretching vibrations of C–O and C–C.

![Figure 4. Flexural properties of pure and ASA modified EF/PVC composites.](image)

![Figure 5. SEM micrographs of the impact fracture surfaces of the composites.](image)
deformation in fiber and PVC, and 700–600 cm$^{-1}$ for C–Cl stretching vibration in PVC (21, 22, 25, 29). It should be noted that, although the spectra of ASA0 was close to that of ASA5 which meant that lower content ASA did not change the structure of the EF/PVC composites, most of the typical peaks was weakened and shifted to higher transmittance value with the addition of ASA, indicating that the ASA modification enhanced the matrix cladding for the fiber, and ASA15 had a highest spectra curve among all samples, which is in agreement with the aforementioned mechanical results.

3.3. Analysis of thermal properties
The curves of thermal weight loss for pure and ASA-modified EF/PVC composites are shown as figure 7, and the main thermal degradation process parameters are set out in table 2. In general, the weight loss curve trends corresponding to the ASA content are basically the same; it is clearly seen that there are two significant degradation and weight loss stages for all samples during the heating process below 600 °C. The first stage, the range of thermal degradation temperature is approximately from 240 to 350 °C with a high mass loss of 34.2% to 45.0%, and this can be attributed to the decomposition of hemicellulose (200 °C–350 °C), cellulose (275 °C–350 °C) and lignin (250 °C–500 °C) in the fiber, as well as the dehydrochlorination reaction of

![Figure 6. FTIR spectra of pure and ASA modified EF/PVC composites.](image)

![Figure 7. Thermal weight loss curves of pure and ASA modified EF/PVC composites.](image)
PVC (250 °C–350 °C). The second stage, ranging from 380 to 500 °C where there is a lower mass loss of 10.7% to 23.3%, was due to the thermal degradation of the de-HCl PVC (350 °C–525 °C) and ASA (416 °C–442 °C) [25, 33].

Furthermore, there is an obvious inflection point at 320 °C in the first stage, the mass loss of ASA modified composites is more than that of pure EF/PVC composites while below 320 °C, but the thermal degradation of ASA15 and ASA20 slowed down and the weight loss is less than that of ASA0 while the heating process kept on from 320 °C, the thermal stability of EF/PVC composites was enhanced with proper content of ASA, this enhance might have been caused by the higher thermal stability of the SAN that existed in the ASA, the heat resistance of the composites was enhanced by the diffusion of the SAN component into the PVC component (SAN shell compatibility with PVC molecules) [20, 25]. Meanwhile, during the second stage, compare to pure EF/PVC composites (ASA0), the weight loss curves of ASA modified composites (ASA5, ASA10 and ASA20) were broader and lower with more mass because of the thermal degradation of ASA, which occurred in the temperature range 416 °C–442 °C. But the weight loss curve of ASA15 is very close to that of ASA0 after 430 °C, and the amount of residue of ASA15 at 600 °C is also higher than those of ASA0, which proved that the weight loss caused by ASA degradation was offset by the thermal stability enhancement of ASA.

### Table 2. Degradation parameters of pure and ASA modified EF/PVC composites.

| Sample No. | First stage | Second stage |
|------------|-------------|--------------|
|            | Temperature range (°C) | Mass loss (%) | Temperature range (°C) | Mass loss (%) | Residue at 600 °C (%) |
| ASA0       | 243–338     | 41.2         | 442–494              | 10.7          | 35.8                  |
| ASA5       | 244–338     | 42.0         | 380–493              | 15.6          | 32.6                  |
| ASA10      | 247–342     | 45.0         | 383–494              | 20.9          | 23.9                  |
| ASA15      | 252–335     | 34.2         | 388–491              | 18.8          | 36.5                  |
| ASA20      | 252–334     | 34.5         | 390–493              | 23.3          | 30.4                  |

Figure 8 presented the effect of ASA content on $W_s$ of the three-body abrasive wear for EF/PVC composites. As seen from figure 8, compared with pure EF/PVC composite, the $W_s$ decreased for all ASA modified EF/PVC composites, and it can also be observed that the $W_s$ value decreased with increasing of ASA content. In other words, the wear resistance of the EF/PVC composites clearly improved with the modification of ASA, a credible explanation for this improvement is that the ASA modified EF/PVC composites had an enhanced structural strength, which led to stronger load-bearing capacity and required more energy for material de-bonding of the...
Moreover, during the three-body wear test, the temperature of the friction interface increases due to the accumulation of sliding heat, which leads to the rapid increase of adhesive contact and friction, the thermal stability of EF/PVC composites was enhanced and weight loss decreased with 15 wt% and 20 wt% of ASA, which was supported by the analysis of thermal properties in section 3.4, this enhancement of thermal stability decrease of weight loss could be the another reason of wear resistance improvement of ASA15 and ASA20.

Figure 9 illustrated the roughness profile samples for worn surfaces of the pure and ASA modified EF/PVC composites. In summary, compared to the original surface roughness of 0.24 μm, the surface roughness of all composites was obviously increased after the wear test, which could be attributed to the removal of material and the wear mass loss of the specimen surface during the three-body abrasive wear test. And the average worn surface roughness values from five measurements were 8.57, 7.06, 6.22, 5.04 and 5.01 μm for ASA0, ASA5, ASA10, ASA15 and ASA20, respectively, the roughness value of the worn surface decreased as ASA content increased, this could be due to the improvement of wear resistance and decrease of surface material removal at ASA modified composites, which was proved in last paragraph about the analysis of WS.

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Typical SEM micrographs of the three-body abrasive worn surfaces of pure EF/PVC (ASA0) and 20 wt% ASA modified EF/PVC composite (ASA20) which had a lowest WS and surface roughness value according to earlier analysis, are shown in figure 10 (figures 10(a) and (b) respectively). A visual examination of figure 10
indicates that typical abrasive wear behaviors took place on ASA0 and ASA20 samples, since the obvious abrasive wear features, such as furrows and pits, could be seen clearly on both of SEM micrographs. For three-body abrasive wear mechanisms, the furrows should be caused mainly from the linear travel of sand particles, plastic deformation of ASA and PVC, as well as debonding of fibers, and the pits are the expression of material removal from the sample surface which is generated by a plough and cut action from sand abrasives \[25, 29\]. It should be noted that, compared with figure 10(a), the furrows and pits on most area of worn surface for ASA20 were smoother and shallower, which meant ASA20 has an improve wear resistance due to modified influences of ASA, the same conclusion was verified by the fact of gradual decrease of the Ws and surface roughness with increased ASA content. Furthermore, as can be seen, some of the eucalyptus fibers were exposed in figure 10(a), while most of fibers are still covered by PVC/ASA matrix material in figure 10(b), implying that ASA modified EF/PVC composite has a better compatibility between the fiber and matrix. This observation is in good agreement with the enhanced impact strength of the ASA modified EF/PVC composites, as mentioned in section 3.1.

4. Conclusions

This work focused primarily on the influence of the content of acrylonitrile-styrene-acrylic (ASA) on the mechanical, thermal and three-body wear behavior of eucalyptus fiber/polyvinyl chloride (EF/PVC) composites. Conclusions are as follows:

1. The mechanical properties of EF/PVC composites such as impact strength, tensile strength and flexural properties can be improved by ASA. The composites show the best impact strength, tensile strength, flexural strength and flexural modulus when the ASA content is 15 wt\%, but a slight decrease could be found for all of them while the ASA content continually increases to 20 wt\%.

2. The addition of 15 wt\% and 20 wt\% ASA in the early heating period can improve the thermal stability of the EF/PVC composites, and the effect weakened at a later stage due to the thermal degradation of ASA occurring in the temperature range 416 °C–442 °C.

3. ASA modified EF/PVC composites have a significant improvement on three-body wear resistance compared to pure EF/PVC composites (ASA0), which was supported by the decrease of the specific wear rate (Ws) and the worn surface roughness while ASA content increased, as well as the typical abrasive wear features on worn surface of the 20 wt\% ASA modified composites were smoother and shallower than that of ASA0. The three-body abrasive wear mechanism of the composites was predominated by the linear travel, plough and cut action of sand particles, plastic deformation of ASA and PVC, and debonding of fibers.

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References

[1] Baiardo M, Elisa Z and Mariastella S 2004 Compos. Part A-Appl. Sci. Manufac. 35 703–10
[2] Hosseinzadeh O, Wang S, Taylor A M and Krim J 2012 Int. Biodeter. Biodegr. 71 29–35
[3] Catto A L, Montagna L S, Almeida S H, Silveira R M B and Santana R M C 2016 Int. Biodeter. Biodegr. 109 11–22
[4] Youcef B F, Nirmal U and Wong K J 2010 Mater. Design. 31 4514–21
[5] Lin X, Zhang Z, Tan S, Wang F, Song Y, Wang Q and Charles U P J 2017 Energ. Convers. Manage. 141 206–15
[6] Mohanty S and Nayak S K 2010 J. Reinf. Plast. Compos. 29 2199–210
[7] Fairuz F S, Mohd F B A, Kalam M A, Masjuki H H, Mustafa A, Sushella E M K and Hilmi A 2017 Particul. Sci. Technol. 35 512–24
[8] Dinesh M and Chikkakuntappa R 2013 Nucl. Instrum. Meth. B 310 67–74
[9] Radhakrishnan M N and Gopinathan M R 2012 Polym. Bull. 66 659–77
[10] Wang H L, Tan H S, Li Y J and Yu Y Z 2013 J. Appl. Polym. Sci. 129 3466–72
[11] Wu S T, Chen M, Wu G F and Zhou C 2015 J. Appl. Polym. Sci. 22 1–7
[12] Liu B J, Wang Y L and Gao Y 2017 J. Polym. Eng. 37 239–45
[13] Xiang B and Zhang J 2016 Compos. Part. B-Eng. 99 196–202
[14] Cappucci I R 2009 Plast. Addit. Compd. 11 22–3
[15] Bijhanmanesh M J, Etesami N and Darvishi R 2016 J. Appl. Polym. Sci. 133 44480
[16] Pan M W, Zhang L C, Wan L Z and Guo R 2003 Polymer 44 7121–9
[17] Ren L, Li Y, Zhang M Y and Han Y 2016 J. Vinyl. Add. Tech. 22 43–50
[18] Rindusit S, Wongmanit P, Damrongsaekkul S and Saramas D 2014 Eng. J. 18 105–18
[19] Du Y G, Gao J G, Yang J B and Liu X Q 2012 J. Polym. Res. 19 1–7
[20] Wang C, Li N, Huo L and Gao J 2015 Polym. Bull. 72 1849–61
[21] Zhang Y, Xu Y, Song Y and Zheng Q 2013 J. Appl. Polym. Sci. 130 2143–51
[22] Zhang X and Zhang J 2018 J. Appl. Polym. Sci. 135 46839
[23] Zhang X and Zhang J 2019 J. Polym. Eng. 39 407–14
[24] Rindusit S, Damrongsaekkul S, Wongmanit P, Saramas D and Tihtipakorn S 2011 J. Reinf. Plast. Compos. 30 1691–702
[25] Jiang L, He C, Fu J and Xu L 2019 Constr. Build. Mater. 223 133–41
[26] Forrester D J, Bauhus J, Cowie A L and Vanclay J K 2006 Forest. Ecol. Manag. 233 211–30
[27] Espinach F X, Granda L A, Torres Q, Duran J, Palmer P F and Matute P 2017 Compos. Part. B-Eng. 116 333–9
[28] Pereira T G T, Mendes J F, Oliveira J E, Marconcini J M and Mendes R F 2018 J. Nat. Fibers. 16 806–16
[29] Zhang K P, Cui Y T and Yan W B 2019 Bio. Resources. 14 1229–40
[30] Zhang K P, Cui Y T and Cai L P 2020 Bio. Resources. 15 1298–310
[31] Jeamtrakull S, Kositchaiyong A, Markpin T, Rosarptak V and SombatSompop N 2012 Compos. Part B-Eng. 43 2721–9
[32] Münstedt H 1981 Polym. Eng. Sci. 21 259–70
[33] Jiang L, He C, Fu J and Wang L 2018 Polym. Test. 70 73–80