The flame retardancy and mechanical properties of jute/polypropylene composites enhanced by ammonium polyphosphate/polypropylene powder

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ABSTRACT: Surface flame retarded jute/polypropylene composites (J/P/A) were prepared via a modified strategy: the mixture of PP and APP powder was spread over the surface of jute/PP nonwoven felts, and then transformed into the flame retarded layer by the hot pressing process. The flame retardancy and thermal properties of composites were analyzed by limit oxygen index (LOI), horizontal burning rate (HBR), thermogravimetric analyses (TGA), and differential scanning calorimetry (DSC). We demonstrated that the flame retardancy and mechanical properties of composites was significantly improved compared with those obtained by presoaking the nonwoven fiber felts in flame retardant (FR) solvent before hot pressing. The mechanism of thermal degradation of jute fiber and flame-retardant mechanism of composites were analyzed by Fourier transform infrared (FTIR), nuclear magnetic resonance (NMR), and scanning electron microscope (SEM). © 2016 Wiley Periodicals, Inc. J. Appl. Polym. Sci. **2016**, *133*, 43889.

INTRODUCTION

Nowadays, the demand for natural fiber reinforced polymer composites in various applications such as automotive components, building materials and the aerospace industry is increasing due to the degradable property, energy absorption, low density, relatively low cost of the natural fibers, and the good mechanical properties of natural fiber-based composites.[1–4] Among various natural fibers, jute fiber gets more research and applications because low cost, widely available, and high production.[1,5,6] However, jute fiber is easy burn at higher temperature to highly restrict the type of polymer matrix and the processing technics used in the jute fiber/thermoplastic composites. Polymers with melting point lower than 200 °C, such as polypropylene, polyethylene, polylactic acid, has been proved to be suitable to incorporate with jute fiber to prepare the composites with moderate mechanical properties.[7–11] Generally, there are two approaches to prepare jute/thermoplastic composites: melting blend of short jute fiber with thermoplastic particles to make short fiber reinforce composites[12–15]; nonwoven needle punching of jute fiber blend with thermoplastic fiber to make fiber felt reinforced composites.[16–18] The nonwoven needle punching combining with hot-compression technology is efficient for preparation of fiber reinforced composites because lower temperature, lower pressure and lower energy adopted

during the process.[19] Compared with melting blend technology, higher content and longer length of natural fiber can be used in the needle punching process. The longer fiber entangle and stick together during the needle punching and hot-compression process, which qualified the composites with good toughness.[20] Thus the fiber felt composites are more suitable to be used as the interior part of the automobile, train, or aircraft.

Jute fiber reinforced composites qualified with high-performance mechanical properties and effective flame retardancy at the same time are practical requirements for applications. Although many researches[21–25] have focused on the type and content of the flame retardant (FR) used in the composites, fewer have studied the introduction way of FR. According the experiences from the practical application of the fiber felt composites, it is worth noting that the mechanical properties of the composites are seriously affected by the introduction way of FR. To date, most of the fire resistant fiber felt composites reported have been was produced by presoaking the fiber felts in FR solvent to make FR adhered or grafted on the fiber.[26–28] However, the compatibility between the fiber and polymer may be worsen by the introduction of FR, furthermore the fibers in the presoaked felts become hard and brittle after soaking and drying process, consequently the mechanical properties of the composites will decrease in different degrees.[26,28] Thus, it is still a challenge to improve the flame
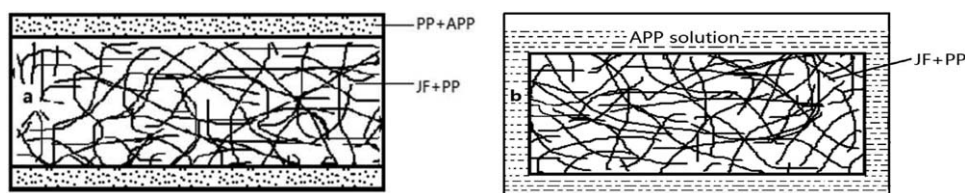
Figure 1. Two preparation ways of composites: (a) Compression with spraying PP and APP powders; (b) Compression with soaking J/P composites.

retardancy of the materials without sacrificing of their mechanical properties. Chun-yan Gao[29] sprayed FR powder on the fiber felt and penetrated them into the whole felt by vibration, but the flammability and the mechanical properties of the composite were not good. Because it is difficult to make the FR powder dispersed uniformly in the whole nonwoven felt by vibration.

In this work, we presented a surface enhanced method to improve both the flame retardancy and mechanical properties of natural fiber reinforce composites. Surface enhanced jute/polypropylene composites were prepared by nonwoven needle punching process at first, and then the mixed powder of APP and PP were sprinkled on the surface of the nonwoven felts, and transformed into the flame retarded layer during hot pressing process. To verify the enhance effect on fire resistance of the flame retardant surface layer, FR pretreated jute/PP composites (F-J/P) were also prepared by presoaking the nonwoven fiber felts in FR solvent. Thermal stability of the jute/PP composites, thermal decomposition mechanism, the effects of the contents of APP and PP powder on the flame retardancy and mechanical properties of the jute/PP composites were studied in detail, aiming at preparing a natural fiber reinforced composites with good flame retardancy and mechanical properties.

EXPERIMENTAL

Materials

The following materials were obtained from commercial suppliers and used as received. APP with a polymerization degree <20 was obtained from Zhenjiang Star Flame Retardant (China). Polypropylene fibers with the length of 50mm and the melting point of 170 °C were supplied by Jiangsu Constant God Fiber Materials (China). Jute fibers were purchased from Jute Mills Corporation (Bangladesh). Polypropylene powder was purchased from Jinjiang oil chemical factory of Jilin chemical industry (China). Sodium hydroxide was obtained from Beijing chemical industry factory. Silane coupling agent KH791 was purchased from Nanjing forward chemical.

The Preparation of Jute/Polypropylene Composites

Jute fibers were cut into 50 mm length to compatible with PP fibers of 50 mm length, due to the similar length of different fibers could improve the dispersion uniformity during carding and needle punching process. Needle punched nonwoven felts were prepared by blending the neat jute fibers and PP fibers in the weight ratio of 1:1. The blended fibers were fed to the lattice of the roller and clearer card at a uniform and predetermined rate, passed through a cross-lapper to form a web of 1250 g m^{-2}. The web was then fed to the needling zone to prepare the nonwoven felt. A punch density of 200 punches dm^{-2} was applied on each passage of the webs reversing the face of the web

alternatively. The nonwoven felts were cut into the size of 170 × 170 mm^2. Then uniformly mixed powders of APP and PP with different proportion were spread over the top and bottom surface of the nonwoven felts, as show in Figure 1(a). Here after, surface enhanced jute/PP composites (J/P/A) were referred to J/P (APP$_x$/PP$_y$) in detail, where x and y represented the percentage of APP and PP powders in the composites. For the properties comparison, another set of nonwoven felts presoaked with FR solvent were prepared, as show in Figure 1(b), where in jute/PP felts were treated by sodium hydroxide, KH791 and 15% APP solution by sequence. The amount of flame retardant was introduced to the jute/PP composites can be calculated as follows[30]:

$$\text{add}-\text{on}\% = \frac{W_a - W_b}{W_b} \times 100\% \tag{1}$$

where W_b and represented the mass of Jute/PP composite before and after flame-retardant treatment, respectively. By calculation, the amount of APP in the pretreated jute/PP composite was about 6% in this test, this composite was abbreviated to F$_{APP6}$-J/P, as shown in Table I. Jute/PP plate samples with a thickness about 2 mm were prepared by hot-pressing at 180 °C and 4 MPa.

CHARACTERIZATION

Flame Retardancy Measurements

The limit oxygen index (LOI) and horizontal burning test were used to measure the flame retardancy of samples. LOI values were measured by an LOI instrument (JF-3 Analytical Instrument Factory, Nanjing China) according the GB2406-82 (China)

Table I. Limit Oxygen Index (LOI) and Horizontal Burning Rate (HBR) of all Samples

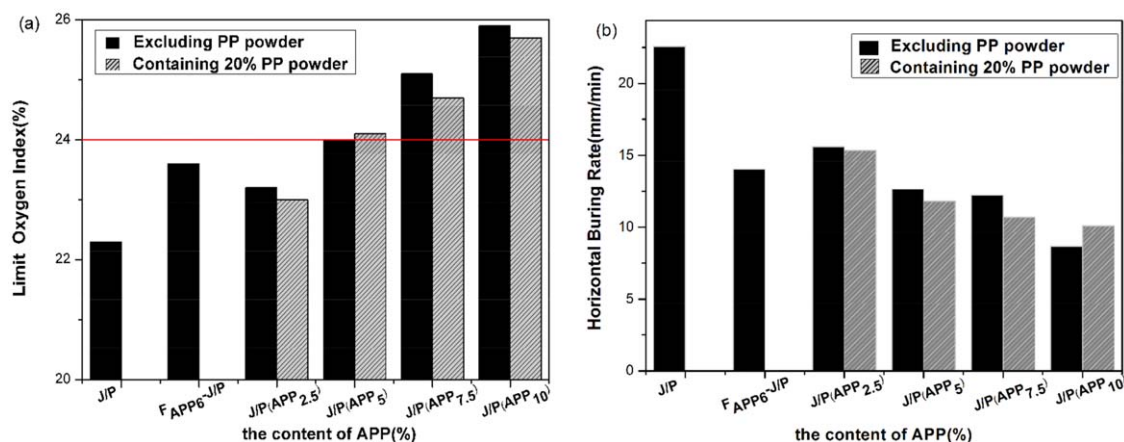| Samples	Limit oxygen index (%)	Horizontal burning rate (mm min^{-1})
J/P	22.3	22.56
F$_{APP6}$-J/P	23.6	14.01
J/P(APP$_{2.5}$/PP$_0$)	23.2	15.61
J/P(APP$_5$/PP$_0$)	24.0	12.64
J/P(APP$_{7.5}$/PP$_0$)	25.1	12.22
J/P(APP$_{10}$/PP$_0$)	25.9	8.66
J/P(APP$_5$/PP$_5$)	23.6	12.66
J/P(APP$_5$/PP$_{10}$)	23.8	12.95
J/P(APP$_5$/PP$_{15}$)	23.9	13.12
J/P(APP$_5$/PP$_{20}$)	24.1	12.40
J/P(APP$_{2.5}$/PP$_{20}$)	23.0	15.35
J/P (APP$_{7.5}$/PP$_{20}$)	24.7	10.70
J/P(APP$_{10}$/PP$_{20}$)	25.7	10.09

Figure 2. The LOI (a) and HBR (b) of jute/PP composites with different concentration of APP. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

oxygen index method with test specimen bars (100 mm × 10 mm × 2 mm). Horizontal burning test was performed using a burning test instrument (H1011D, Changchun, China), with specimens size of 150 mm × 75 mm × 2 mm. Burning length and time were recorded to calculate the burning rate.

Thermal Analysis

ATGAQ50 instrument was used for thermogravimetric analyses (TGA) of the composites from 25 to 700 °C at a heating rate of 10 °C min^{-1} under nitrogen gas flowing at 60 mL min^{-1}. About 5 mg of sample was used in each test.

Differential Scanning Calorimetry (DSC)

The thermoanalysis of the composites was performed by differential scanning calorimetry (DSC) using a thermal analyzer (TA Instrument, USA, Model no. Q20). Each sample with a weight of about 5 mg was heated at the temperature range of 50 °C to 500 °C by a heating rate of 10 °C min^{-1} in a Tzero aluminum crucible in a nitrogen environment purged at 50 mL min^{-1}.

Fourier Transform Infrared

Fourier transform infrared (FTIR) spectra were obtained by TENSOR 27 FTIR spectrometer (Germany Bruker) in the range of 600–4000 cm^{-1} with attenuated total reflection method.

Solid-state Nuclear Magnetic Resonance (NMR)

[13]C analysis were performed on Bruker AVANCE III 400 WB spectrometer equipped with a 4 mm standard bore CPMAS probe head whose X channel was tuned to 100.62 MHz for ^{13}C and the other channel was tuned to 400.18 MHz for broad band ^{1}H decoupling. The experiments were conducted using a magnetic field of 9.39T at 297 K at a contact time of 2 ms. A total of 1500 scans were recorded with 3s recycle delay for each sample. All ^{13}C CP MAS chemical shifts were referenced to the resonances of adamantane ($C_{10}H_{16}$) standard (dCH$_2$ = 38.4).

Morphology Observation

The morphology of charcoal layer after burning composites were observed using a scanning electron microscope (1000-B, Germany). The surface morphology and fracture morphology of composites were also observed.

Mechanical Properties

Tensile strength and flexural strength of all samples were determined according to TL52448 standard using a universal testing machine WSM-5KN (Changchun intelligent instrument equipment). The specimens' size of tensile and flexural test was 100 mm × 25 mm × 2 mm. All samples were tested five times, and the average values were used as the final data.

RESULTS AND DISCUSSION

Flame Retardancy

Limit oxygen index and horizontal burning test were effective methods in evaluating flame retardancy. The LOI and HBR results of jute/PP composites without flame retardants (J/P), F_{APP6}-J/P and J/P/A were listed in Table I. Jute/PP composites contained APP showed better flame retardancy than J/P, which were shown obviously in Figure 2. The results confirmed that APP could act as good flame retardant in jute/PP composites. In comparison with the F_{APP6}-J/P sample, the LOI of the J/P(APP$_5$/PP$_0$) sample was higher, and the HBR was lower, although the amount of the APP in J/P(APP$_5$/PP$_0$) sample was less than the F_{APP6}-J/P sample. For the J/P/A composites, LOI increased and HBR decreased with the increasing of APP concentration, and was not up to the level by containing 10 wt % APP. Compared with the LOI value of 22.3 reported by Chunyan Gao,[29] the LOI was higher than 24 when the content of APP was higher than 5% in J/P/A. According to JISD 1201-77 of Japanese,[31] the composites with LOI ranged from 24 to 27 was regarded as the third grade of fire resistant material. This suggested that the flame retarding surface layer was efficient to improve the flame retardancy of the composites. In the J/P/A composites, the addition of PP powder was to form a uniform FR layer, it had a little effect on the LOI and HBR of J/P(APP$_x$/PP$_y$).

Thermal Properties

The thermogravimetric analysis (TGA) and derivative thermogravimetric (DTG) curves were used to determine the weight loss and to identify the decomposition of material at a certain temperature. The thermal properties of JF, PP, J/P, F_{APP6}-J/P, and J/P(APP$_5$/PP$_{20}$) were compared by TGA and DTG as shown in Figure 3, and the detailed data was summarized in Table II. In
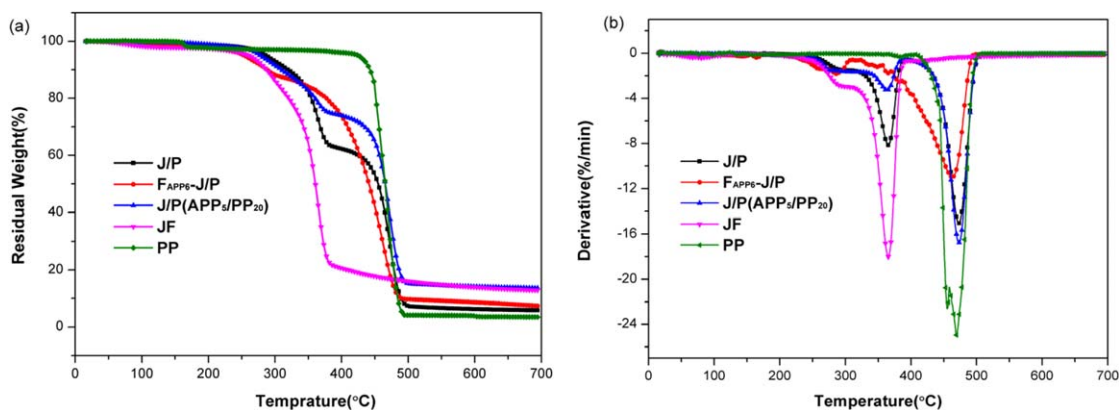
Figure 3. TGA curves (a) and DTG curves (b) of the jute/PP composites. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

this experiment, the initial decomposition temperature was the temperature at which a 5% weight lost occurs.

PP showed the highest initial decomposition temperature 425.1 °C and the lowest char residue 3.46% at 700 °C. Jute fiber showed the lower initial decomposition temperature 259.7 °C and higher char residue 12.85% at 700 °C. This was because the hydrogen bonds between adjacent hydroxyl groups of jute fiber contributed to form cross-linked structure by losing water at high temperature, which preferred to transform into char.[32] The thermal decomposition process of jute fiber had two stages: (1) 215–290 °C, this stage attributed to the evaporation of water from fiber and the thermal decomposition of hemicellulose; (2) 310–396 °C, was attributed to the thermal decomposition of cellulose,[33] that was the breakage of 1,4 glycoside bond. J/P began to decompose at 286.3 °C ($T_{-5\%}$) and remained 5.83% residue at 700 °C. A three-step degradation process of J/P was observed, which corresponded to the two stages of jute fiber and one stage of PP respectively.

The addition of APP decreased the initial decomposition temperature of jute/PP composites, but increased the residual char and slowed down the decomposition rate of jute fiber. The residual char of F_{APP6}-J/P increased to 7.38% at 700 °C, while that reached to 13.66% of J/P(APP$_5$/PP$_{20}$). This suggested that the composite with the presence of APP over the surface was easy to char-forming than FR solvent pretreated composite. APP released phosphoric acid and non-flammable gas (NH_3, H_2O), which improved the char formation of composite and decreased permeation of residual char layer to improve barrier

function of residual char.[32] As a result the surface char layer contained phosphorus ester could act as thermally stable char, which contributed to flame protection of the whole matrix.

The decomposition pattern were different between J/P(APP$_5$/PP$_{20}$) and F_{APP6}-J/P. J/P(APP$_5$/PP$_{20}$) had three decomposition stages, which was same as J/P. F_{APP6}-J/P had only two stages: the first one between 215 and 305 °C, while the second stage occurred in 315–504 °C range, which was combined the thermal decomposition of cellulose and PP. This was because the lignin and pectin were eliminated by alkaline solvent, and APP retarded the decomposition of cellulose.

The DSC curves of J/P, F_{APP6}-J/P, and J/P(APP$_5$/PP$_{20}$) were shown in the Figure 4, the three endothermic peaks around 127, 163, and 473 °C in the J/P composite were attributed to the softening point, melting point and decomposition point of PP. The peak around 365 °C in J/P was the decomposition point of cellulose, which shifted to 377 °C in J/P(APP$_5$/PP$_{20}$), and was not observed in F_{APP6}-J/P. Liangbo Yu did not find similar exothermic or endothermic peaks in the thermal degradation of alkalized jute fiber due to the sufficient removal of lignin.[34] Compared with J/P, the exothermic peaks could be found in the composites contained APP. The exothermic peaks indicated the reaction between the phosphoric acid of APP and hydroxyl of jute fiber.[35] In the curve of F_{APP6}-J/P a prominent exothermic peak at temperature near 260 °C was observed, while J/P(APP$_5$/PP$_{20}$) exhibited two small exothermic peaks from around 266 and 285 °C, this might because the reaction heat of hydroxyl

Table II. TGA and DTG Data of the Jute/PP Composites

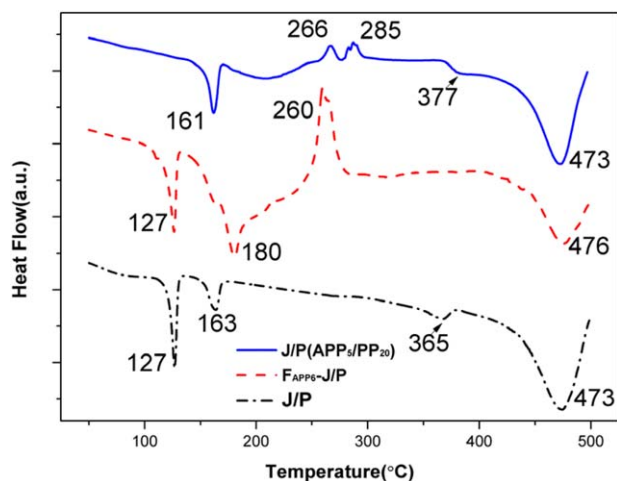| Samples | $T_{-5\%}$ (°C) | Stage 1 | | Stage 2 | | Stage 3 | | Residue at 700 °C (%) |
		T (°C)	V (%/min)[a]	T (°C)	V (%/min)	T (°C)	V (%/min)	
JF	259.7	215–315	2.9	315–396	18.0	—	—	12.85
PP	425.1	—	—	—	—	415–504	25.0	3.46
J/P	286.3	215–290	1.6	310–396	8.2	396–504	15.0	5.83
F_{APP6}-J/P	252.1	215–305	2.0	—	—	315–504	11.1	7.38
J/P(APP$_5$/PP$_{20}$)	277.6	215–290	1.6	310–396	3.3	396–504	16.8	13.66

[a] The thermal decomposition rate of composites.

Figure 4. DSC curves of the jute/PP composites. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Figure 6. NMR of jute and calcined jute at 600 °C. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

group in lignin with phosphorous acid was different from that in the cellulose reaction system.

Thermal Decomposition Mechanism of Jute Fiber

The TG curves of composites showed that the addition of APP affected thermal decomposition of composites. Consequently, the molecular structure changes of jute fiber with different calcinations temperature were studied for further demonstrating the thermal decomposition mechanism of composites. The FTIR analysis of jute fibers calcined at different temperatures presented in Figure 5. In the FTIR spectrum of jute fiber, it could be seen that —OH stretching vibration (3331 cm^{-1}), —CH stretching vibration (2921 cm^{-1}) and —CH bending vibration (1458 cm^{-1} and 1371 cm^{-1}) gradually weakened with increasing temperature and disappeared in the range of 280–300 °C. It indicated that dehydrogenation reaction of jute fiber had occurred completely below the temperature of 300 °C. The peak position of C=O vibration band shifted from 1739 to 1710 cm^{-1} from 200 to 400 °C, meanwhile the intensity of C=O, C=C vibration band (1645 cm^{-1}) and C—O vibration band (1028 cm^{-1}) decreased and reached a minimum at 400 °C, due to the breakage and rearrangement of hemicelluloses and

cellulose chemical bond in the thermal degradation stage, which were correspond to the two stages of TG analysis. With the temperature further increased, the intensities of the peak at 1590 and 1028 cm^{-1} were enhanced, which was caused by the change of char structure. The structure of polymer experienced the crosslinking, aromatization, and graphic carbon formation stages during the burning process.[36]

To explore the structure change of jute fiber at higher temperature, both the original jute and the calcined jute at 600 °C were characterized by ^{13}C NMR (shown in Figure 6). The resonance peaks of the unheated jute fiber observed at 64, 72, and 104 ppm were assigned to C—C, C—O, C=O, and C=C, respectively, which was consistent with those reported by Suvendu Manna.[37] After treated at 600 °C, the ^{13}C NMR spectrum of calcined jute fiber showed only one signal peak at 127 ppm, probably originated from aromatization process.[38]

The Flame-Retardant Mechanism of Composites

To study the flame-retardant mechanism of composites, FTIR spectra of jute, JF/APP and APP calcined at 600 °C were shown
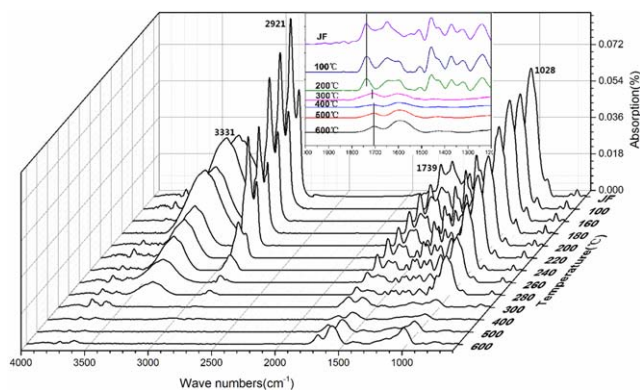

Figure 5. FTIR of jute fiber calcined at different temperatures. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]
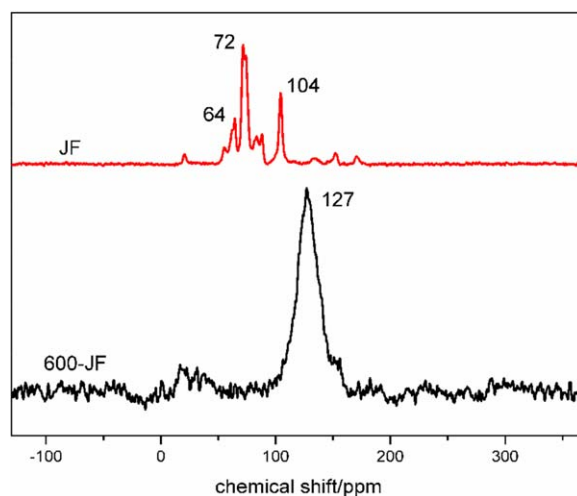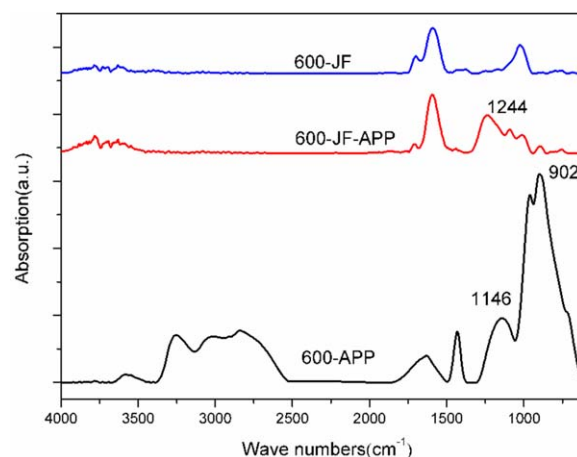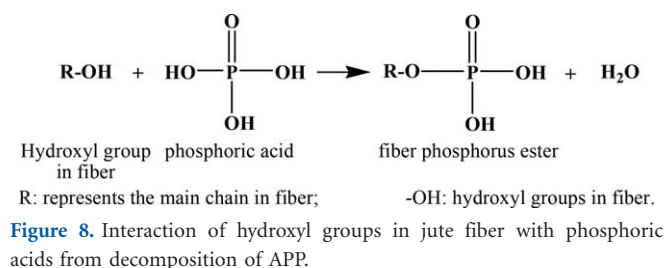

Figure 7. FTIR of jute, JF/APP and APP at 600 °C. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Figure 8. Interaction of hydroxyl groups in jute fiber with phosphoric acids from decomposition of APP.

in Figure 7. The FTIR spectrum of APP at 600 °C showed the typical absorption peaks of 1146 and 902 cm^{-1} assigned to phosphoric acid and hypophosphorous acid, which was the thermal decomposition products of APP. While compared with the spectra of pure fiber and APP, one new peak (1244 cm^{-1}) appeared in JF/APP blends. The peak assigned to POO— group, which was generated by esterification reaction of phosphoric acid of APP and hydroxyl of jute fiber. The esterification reaction was shown in Figure 8. This result was in good agreement
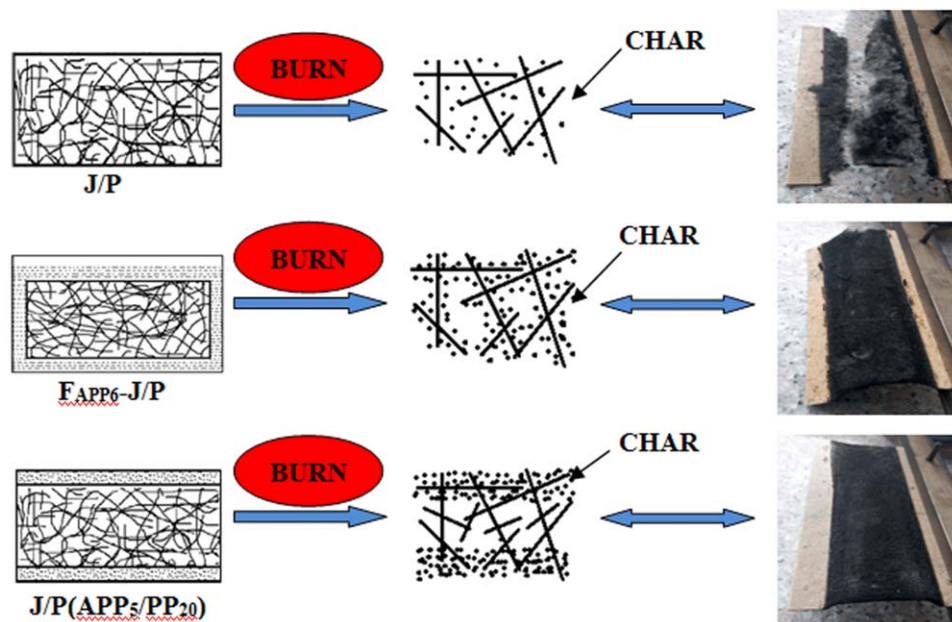

Figure 9. Schematic of the char formation. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]
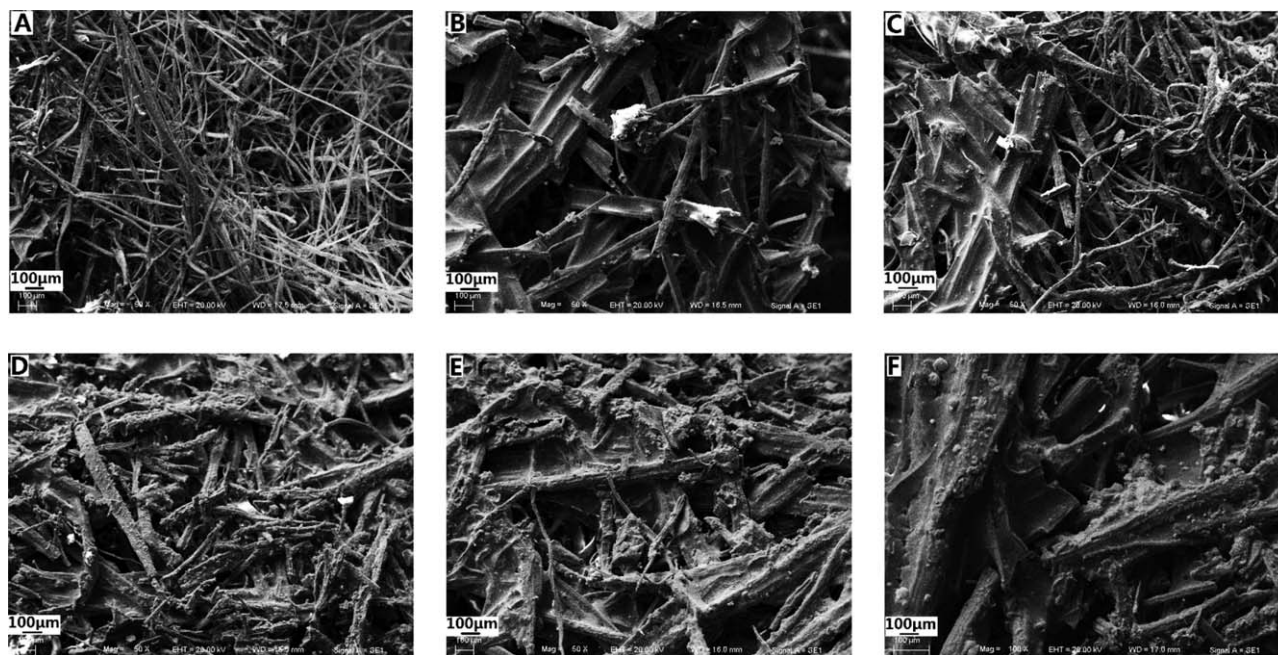

Figure 10. SEM images of the composites after combustion: (A) J/P; (B) F$_{APP6}$-J/P; (C) J/P(APP$_{2.5}$/PP$_{20}$); (D) J/P(APP$_5$/PP$_{20}$); (E) J/P(APP$_{7.5}$/PP$_{20}$); (F) J/P(APP$_{10}$/PP$_{20}$).

Table III. Tensile Strength (TS) and Flexural Strength (FS) of all Composites

Samples	Tensile strength (MPa)	Flexural strength (MPa)
J/P	13.79 ± 1.59	21.52 ± 4.71
F_{APP6}-J/P	10.33 ± 1.50	18.79 ± 2.66
$J/P(APP_{2.5}/PP_0)$	14.58 ± 1.26	22.75 ± 3.82
$J/P (APP_5/PP_0)$	15.70 ± 0.98	25.36 ± 2.93
$J/P(APP_{7.5}/PP_0)$	14.49 ± 1.24	22.86 ± 2.07
$J/P(APP_{10}/PP_0)$	14.70 ± 1.88	22.10 ± 1.72
$J/P(APP_5/PP_5)$	15.42 ± 0.83	29.22 ± 4.92
$J/P(APP_5/PP_{10})$	16.17 ± 1.43	30.36 ± 5.45
$J/P(APP_5/PP_{15})$	18.61 ± 1.73	31.18 ± 2.69
$J/P(APP_5/PP_{20})$	21.58 ± 0.73	39.20 ± 2.10
$J/P(APP_{2.5}/PP_{20})$	17.37 ± 2.12	31.83 ± 4.60
$J/P(APP_{7.5}/PP_{20})$	18.23 ± 2.12	33.36 ± 2.53
$J/P(APP_{10}/PP_{20})$	16.74 ± 2.40	29.98 ± 5.32

with the DSC examination result in the previous section. It was reported that phosphorus ester could react with the point where was sensitive to be oxidation, so phosphorus ester prevented oxidation of residual char.[39]

The schematic of char formation of composites were shown in Figure 9, and the digital photographs of the residual char after horizontal burning test were list in the right side in the schematic. After combustion, it was found that the residue of jute/PP composites containing APP was different from J/P. The

residual char structure of J/P was destroyed seriously and broken into pieces. Although the residue char of F_{APP6}-J/P was increased by APP, the residual structure was loose and broken in somewhere. The voids generated in the burning process favored the penetration of oxygen into the matrix, and reduced the flame retarding effect of APP. Compared to F_{APP6}-J/P, the residual char of $J/P(APP_5/PP_{20})$ was integrate and owned the self-standing ability. Although PP in the matrix melted under high temperature, the surface char layer as a barrier prevented the penetration of heat and oxygen into the matrix, which improved the flame retardancy and residual strength of composites. It could be concluded that the introduction of APP/PP film on the surface was more effective method to improve the flame retardancy of the composite.

SEM analysis was carried out to further characterize the microstructure of the residue. The residual morphology of composites was shown in Figure 10. The residue of J/P was incompact and jute fibers were very fine. The voids left by the melting PP could be seen in F_{APP6}-J/P, and jute fibers were covered by residue contained phosphorus. Compared with J/P and F_{APP6}-J/P, the residue structure of J/P/A was more compact, jute fibers were sticked together by the intumescence of APP. This confirmed the results of the schematic discussed above. The introduced APP/PP film on the surface of the composite acted as the maskant inhibited the initial combustion of composites.

Mechanical Properties

The flexural strength and tensile strength of jute/PP composites were listed in Table III. Compared with J/P, the flexural strength and tensile strength of F_{APP6}-J/P decreased 25%, 13%, indicated that jute/PP composite presoaked with FR solvent showed the
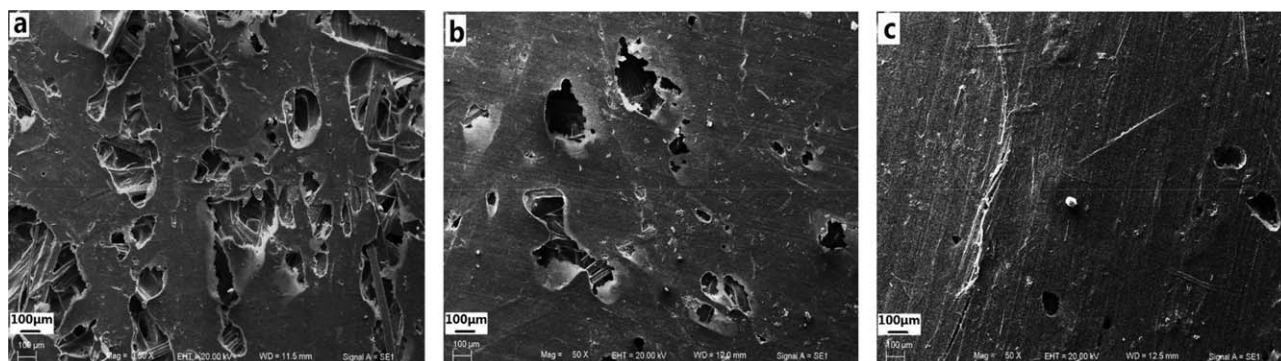

Figure 11. SEM images of the composite plate surface: (a) $J/P(APP_5/PP_0)$; (b) $J/P(APP_5/PP_5)$; (c) $J/P(APP_5/PP_{20})$.
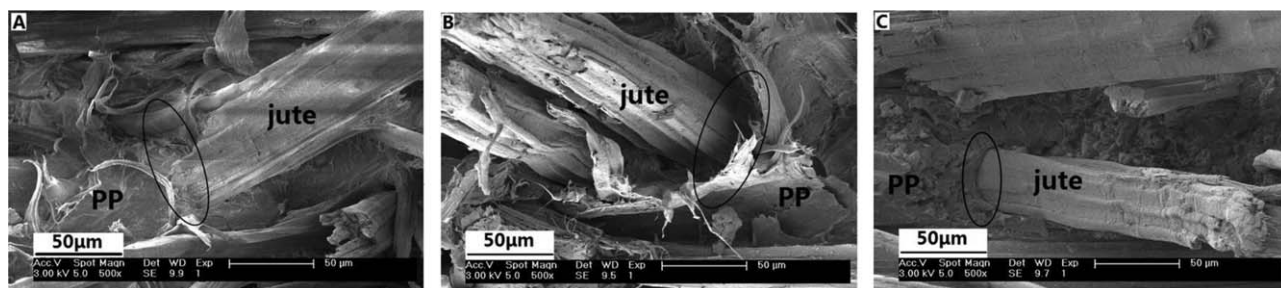

Figure 12. SEM morphology of composites: (A) J/P; (B) F_{APP6}-J/P; (C) $J/P(APP_5/PP_{20})$.

poor mechanical properties. This was because jute fiber became hard and brittle after soaking and drying process of jute/pp composites, which weakened the reinforcement effect of jute fiber. Moreover the compatibility between jute fiber and PP might be worsened by APP molecular.

In comparison with J/P, the mechanical properties of J/P/A increased sharply with the increasing PP powder content on the surface. The flexural strength and tensile strength of the J/P(APP_5/PP_{20}) sample increased by about 82 and 56%, respectively. This was attributed to the formation of PP film on the plate and the well-dispersion of APP powder during the hot pressing process.

Figure 11 showed the SEM images of the plate surface. It was clear that the PP film formed by melting of PP powder on the plate was integrate when the content of PP powder was 20%, while the composite with lower or without PP powder on the surface, showed an incomplete PP film. The presence of naked jute fiber and cavities on the surface had a negative contribution to the mechanical properties, because of their lower densities. This confirmed that mechanical properties of the composites enhanced remarkably by the presence of PP powder on the surface. While increasing the content of APP, the mechanical properties decreased due to the fact that a high loading of APP influenced the bonding of PP film and jute/PP nonwoven felts.

The tensile fracture morphology of composites was shown in Figure 12. The rough fracture surface and PP fibrils could be found in J/P, but the compatibility between jute fiber and PP was good. The gap between jute fiber and PP was quite large in F_{APP6}-J/P, and the compatibility between jute fiber and PP worsened by APP adhered to the fiber in pretreating process. As a result the mechanical properties of F_{APP6}-J/P decreased, which was consistent with the result reported by Li Shumao.[40] The mechanical properties of composites were greatly affected by the interfacial bond strength. In J/P(APP_5/PP_{20}), jute fiber tightly embedded in PP matrix, the tensile force could be transferred from the matrix to the fiber, indicated that jute fiber could act as reinforced phase in the composites.

CONCLUSIONS

Overlaying the melting mixture of PP and APP powder over the surface of jute/PP nonwoven composites is an efficient method to improve the flame retardancy and mechanical properties of the composites. This method effectively increased the LOI of jute/PP nonwoven composites and lowered their HBR. The residual char of J/P(APP_5/PP_{20}) was increased to 13.66% compared with J/P and F_{APP6}-J/P. These indicated that surface flame retarding layer improved the flame retardancy efficiently. The mechanism analysis showed that the introduced APP/PP film on the surface of the composite acted as the maskant inhibited the initial combustion of composites and prevented the penetration of heat and oxygen into the matrix. Compared with J/P and F_{APP6}-J/P, the mechanical properties of J/P/A were increased significantly, which depended strongly on the contents of PP and APP powder. The better flame retardancy and the best mechanical properties of jute/PP composites were obtained when the maskant was formed with 20 wt % PP and 5 wt % APP powder.

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