

Natural Fibre-Reinforced Thermoplastic Composites from Woven-Nonwoven Textile Preforms: Mechanical and Fire Performance Study

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Abstract

Partially and fully biodegradable natural fibre – reinforced composites have been prepared using a novel patented woven-nonwoven technology. Natural fibres included jute and sisal, whereas the matrices were of synthetic polymers derived from petroleum (polypropylene (PP)) or natural (polylactic acid (PLA)) resources. The physical, mechanical and flammability properties of these partially and fully biodegradable composites have been studied and compared with those of similarly produced glass-fibre reinforced PP and PLA composites with a view to enabling their use in automotive applications. Mechanical test results showed that the tensile and flexural moduli of the PLA composites were higher than respective PP composites. In comparison, sisal composites have higher tensile and flexural moduli than jute composites. The fire performance of the composites studied by cone calorimetry showed that while natural fibre reinforcement had no effect on time-to-ignition, peak heat release was significantly reduced. PLA composites had lower burning propensity compared to respective PP composites.

Keywords: A. Polymer-matrix composites (PMCs); A. Fabrics/textiles; A and E. Preforms; B. Mechanical properties; Fire performances

1. Introduction

The use of natural fibres / fabrics as composite reinforcement is not a new concept as they were even used about 100 years ago, mostly as wood products with simple and relatively cheap components [1,2].

Prior to and during World War II, wood products and composites were commonly used in aeroplanes and automobiles [3]. All this changed however with the development of high performance fibres such as glass, carbon and aramid due to their excellent mechanical and inherent flame retardant properties, leading to widespread use of the derived composites in aerospace, marine, automotive and construction industries. Over the past decade or so there has been a renewed interest in natural fibre composites, mainly due to a big push from policy makers of many European countries to force automotive industry to reuse and recycle materials. This has led to the use of bio-based materials in automotive manufacturing. However, over the years the performance requirements and regulations in terms of mechanical behaviour, resistance to environmental conditions and fire/heat have also changed and need to be addressed.

Natural fibres from plant origins (lignocellulosic fibres) have certain advantages over glass fibres, in particular low density, low abrasive wear, availability worldwide, renewable and biodegradable nature, economical production and recyclability. Their disadvantages however, are low compatibility with hydrophobic polymer matrices, much lower tensile strength than glass fibres, thermal sensitivity at the temperature of compounding processes, moisture absorption and flammability. Flax, hemp, and jute fibres have been reported in literature to be used as reinforcement for both thermoplastic and thermoset matrices [4-9]. The choice of matrix material however, is limited by the thermal sensitivity of natural fibres at temperatures above 180-200°C [4,7-9]. Thermoplastic composites are processed by melt blending/pressing at the softening/melting temperature of the polymer. Examples of available thermoplastics that have suitable processing temperatures are polyethylene (M pt, melting point = 137-146 °C), polypropylene (M Pt = 160 - 220 °C), polystyrene (M Pt = 177-277 °C), and polyvinyl chloride (M pt = 177-212 °C). Out of these polymers, polypropylene is a more popular choice for natural fibre-reinforced composite, especially in automotive applications [7,10], hence is also subject of the present work.

Besides these petroleum based synthetic polymers, biopolymers are an attractive alternative material for the matrix in order to achieve fully bio-degradable composites [3,4,10-13]. Examples of bio-degradable polymers are polylactic acid (PLA), polybutylene succinate (PBS), polyhydroxyalkanoates (PHA), poly(ϵ -caprolactone) and starch [3,4,14]. Out of these bio-degradable polymers, PLA, a linear aliphatic polyester derived from renewable source (corn), is the most suitable matrix material (M Pt = 173-178°C [15]) for thermoplastic composites.

In this work natural fibre reinforced composites have been prepared using woven jute and sisal fabrics as reinforcements for polypropylene (PP) and polylactic acid (PLA) matrices. During composite

production uniform wetting of the reinforcing fibres with molten thermoplastic polymer is important for better adhesion and hence, mechanical properties. For better mechanical and interfacial properties of the composites, reinforcing fabrics were needle-punched with polypropylene and polylactic acid fibre webs prior to composites fabrication process by hot-press technique. The effects of fibre and matrix type on mechanical and fire behaviour have been analysed.

2. Experimental

2.1 Materials

Plain woven jute, sisal and glass fabrics were used as reinforcing fabric for the production of textile preforms. The area densities of jute, sisal and glass fabrics were 174, 62 and 280 g/m² respectively (Table 1). Different area densities of the fabrics were due to the limited commercial availability of fabrics of similar weave. Jute and sisal fabrics were sourced from the National Institute of Textile Technology Research and Design (NITTRAD), Bangladesh and E-glass from Glasplies, UK. Polypropylene and biodegradable polylactic acid fibres were used as matrix for the production of thermoplastic composites. Reinforcing fabrics were needle-punched with polypropylene (PP) and polylactic acid (PLA) fibre webs to produce base fabrics. The length of polypropylene fibre was 50 mm and the fibre linear density was about 3.3 dtex, the length of biodegradable polylactic acid fibre was 40 mm and the fibre linear density was about 2.2 dtex.

2.2. Production of textile preforms

Woven fabrics from natural fibres were needle-punched with PP and PLA fibre webs to produce textile preforms based on our previously patented procedure [16] and as described below:

In the first step of this process, nonwoven webs were produced from PP and PLA fibres of required weight (see Table 1) by using Automatex carding machine. In the second step, each nonwoven web and the reinforcing fabric (Fab) were fed together to the Automatex needlepunching machine for needle-punching. This is shown as a schematic in Fig. 1(a). The woven fabric/thermoplastic fibre ratio was kept as 40:60 (w/w). The important parameters during the production of the woven-nonwoven textile preforms were: the feeding apron speed setting to the needle punching machine 0.8; the delivery speed setting 1.2; and the number of strokes setting 250. The area densities of the textile preforms obtained varied from 328g/m² (sisal/PLA) to 500 g/m² (jute/PLA).

2.3 Composite preparation

Composite materials were produced from these Fab/PP (40/60) and Fab/PLA (40/60) textile preforms by using hot-press technique (Fig. 1b). Eight layers of each fabric were placed between two aluminium plates, and heated at 190°C for 2.5 min under 20 kg/cm² pressure. After that the composite sample containing plates were cooled in another press operated under cooling conditions for 2 min at 10 kg/cm² pressure. The physical properties of the composites are given in Table 1. For glass fibre-reinforced composites, preform fabrics similar to Fab/PP or Fab/PLA could not be obtained due to needles breakage while processing the glass fabric. The composites were prepared by using alternate eight layers of each of glass woven fabric and PP or PLA nonwoven webs, following the similar procedure as above. PP and PLA cast resin samples were prepared by melt pressing their nonwoven webs using similar procedure as those for the respective components.

2.4 Mechanical properties measurement

2.4.1. Tensile testing: Tensile testing was carried out according to BS EN ISO 527 [17] using Instron 4303 universal testing machine. The gauge length of each specimen was 100 mm and polymeric tabs were bonded at their end to improve the gripping and ensure the failure within the gauge region. The tests were conducted using 50 kN load cell with the crosshead speed 0.5 mm/min. Tensile modulus and strength values were calculated from stress-strain curves using an extensometer, selective samples had strain gauges bonded to their surfaces to verify the results. Three replicate specimens of the size 160 mm x 25 mm x thickness as in in Table 1 for each sample were tested and results averaged.

2.4.2. Flexural testing: The three-point bending flexural test was carried out according to BS EN ISO14125 [18] using Instron 4303 universal testing machine. A 100 N load cell with the compression rate 1 mm/min was used on the samples with the span length of 100 mm. Tests were undertaken within the elastic range of the material due to limited number of samples. Three replicate specimens of the size 120 mm x 25 mm x thickness as in Table 1 for each sample were tested and results averaged.

2.4.3. Impact drop weight testing: The impact properties of the samples were investigated using an Instron Dynatub Mini-Tower drop weight impact machine in accordance with ASTM D7136 [19]. The samples, sized 100 x 100 mm², were fully clamped on the samples holder, which has a hole (76.2 mm diameter) in the centre. The clamped samples were impacted by dropping a steel impactor of 16 mm crosshead diameter, and 1.02 kg drop mass from 100 mm height to produce the impact energy of 2.0 J on the sample. This energy level was set by pretesting on trial samples of jute and sisal

composites so not to cause excessive surface damage. A high-speed data acquisition system (Dynatup® Impulse™ software data capture system) was used to obtain load - central displacement curves. Three replicate specimens of each sample were tested and results averaged.

2.5 Scanning Electron Microscopy

Tensile fractured surfaces of composites were gold coated using a Polaron Range SC7620 Sputter Coater with 60 s plasma exposition and examined using a Hitachi S-3400N scanning electron microscope (SEM).

2.6 Fire Testing

2.6.1. Limiting oxygen index (LOI): A Fire Testing Technology (FTT) LOI instrument was used to carry out the test according to ISO 4589. At least five specimens of dimensions 100 mm × 10 mm × thickness as in Table 1 were tested for each sample. Test was repeated twice to get the exact LOI value.

2.6.2. UL-94 testing:

The fire performance of the matrix and composite samples (length = 120 mm, width = 10 mm) was evaluated using a UL-94 flame-spread test according to ISO 1210 in both vertical and horizontal orientations. The specimen was clamped vertically and subjected to a flame of 20 mm height using a Bunsen burner and keeping a 10 mm distance between the end of specimen and the top of the Bunsen burner. A thin layer of cotton fibres was positioned 300 mm below the test specimen in order to catch molten/flaming drops. The flame was applied at the bottom end of the specimen for 10 s, and the burning time of the specimen after removal of the flame was noted. If the specimen extinguished before burning up to the sample holder, the flame was applied again for another 10 s and the burning time noted. If the sample self extinguished, it was rated V0; if burned for < 30 s without or with flaming drips, it was rated V1 or V2, respectively; and if burned for > 30 s or burned up to the sample holder, it was classified as 'fail'.

Flame spread rates in both vertical and horizontal orientations were also measured by slightly modifying the testing methodology, by recording the time taken by the flame to reach a specified distance. The first 10 mm of sample burning was not taken into account and so times of burning were recorded once the flame had reached a line drawn at 10 mm from the edge against which flame of 20 mm height was applied for 10 s as specified in the test and discussed above. A video film was taken of the burning of each sample from which times to reach 50 (t₁) and 100 mm (t₂) marks and/or to

achieve flameout were noted. Two replicate specimens of each sample were burnt and results averaged. The burning behaviour of each sample was observed and noted.

2.6.3. Cone calorimetry: A Fire Testing Technology cone calorimeter was used according to ISO 5660 / ASTM E1354 standard to perform experiments on horizontally oriented samples of 75mm x 75mm dimensions at 35kW/m² external heat flux. All experiments were conducted in triplicate and results were reproducible to $\pm 10\%$.

3. Results and Discussion

Composition of different composites is given in Table 1. Since the reinforcing fabrics (jute, sisal and glass) due to their commercial availability are of different area densities, and fibre/matrix ratio was kept similar, composites prepared were of different thicknesses. However, the nonwoven webs used for PP and PLA were prepared in the lab, their area density was kept similar for one set of fabric composites. Hence, the effect of matrix type on the fire/mechanical properties of a particular reinforcing fabric – composite can be directly evaluated. However, to study the effect of reinforcing fabric, the mechanical property parameters had to be normalised with regards to fibre volume fraction and selected fire performance parameters to densities and thicknesses of the samples as discussed in the following sections.

3.1 Mechanical properties of the fibre reinforced composites

3.1.1. Tensile properties

Typical stress versus strain curves of PP and PLA composites are shown in Fig. 2, from which the tensile modulus and strength values were calculated and reported in Table 2. As shown in Table 2, the PLA laminate had higher tensile modulus and strength as compared to the PP, which has also been reported by other researchers [20-22]. The incorporation of reinforcing fabrics improved the tensile properties of PP and PLA. It may be observed from Fig. 2 that the stress-strain curves initially showed linear relationship in the elastic range when the composites behaved as a homogeneous material with the fibres and matrix experiencing the same strain. From this first linear part initial modulus was calculated and presented in Table 2. Above the first elastic range the slope of the curve changed due to partial decoupling of the stress and strain in the matrix and fibre, followed by a small non-linear deformation prior to failure. In jute/PP and sisal/PP the change of slope from initial elastic stage (moduli = 3.7 and 4.9 GPa, respectively, Table 2) occurred at ~ 10 MPa and the moduli reduced to 2.7 - 2.9 GPa, and onset of non-linear deformation occurred at ~ 33 -38 MPa with a complete failure occurring at 45 – 52 MPa (Table 2). In glass/PP the change of slope from initial elastic stage (modulus = 9.8 GPa) occurred at ~ 30 MPa, reducing the modulus to 6.2 GPa; the onset of non-linear

deformation started at ~ 150 MPa with failure at 140 MPa . In case of PLA composites while the change of slope in glass/PLA after the initial elastic range was at ~ 30 MPa, which is similar to that in glass/PP, in jute/PP and sisal/PP it occurred at ~ 20 MPa, which is higher than in respective PP composites, indicating better adhesion of natural fibres with PLA as compared to PP. In all PLA composites the deformation was very less compared to respective PP composites, leading to clean fracture. Since the area densities of reinforcing fabrics and the thicknesses of the laminates were different in each sample type, the tensile parameters were normalised to 40% fibre volume fraction (FVF) as:

$$E_{Normalised} = \frac{E_{Absolute}}{FVF} * 40$$

The glass fibre, as expected was the most effective reinforcement for PP composite, followed by sisal and jute, respectively. This trend could be explained by the tensile properties of the reinforcing fabrics, as tensile properties are fibre dependent. The mechanical properties of glass fibres are much higher (initial modulus = 50 - 100 GPa) than natural fibres [4, 7, 23], hence their resulting laminates could perform better than those from natural fibres. In comparison between tensile properties of natural fibre reinforced PP composites, sisal fabric was the best reinforcement compared to jute fabric as can be seen in Fig. 2. This is due to the mechanical properties of sisal fabric, 0.26 N/Tex and 1.14 N/Tex of specific modulus in 0° and 90° respectively, was higher than jute as shown in Table 3.

In PLA composites tensile strength values with different reinforcements showed similar trend as for respective PP composites, Fig. 2. The normalised initial tensile moduli of jute (9.0 GPa) and sisal composites (9.9 GPa) were comparable to those of glass composites (9.8 GPa). Glass reinforced PLA composites showed the highest normalised tensile modulus followed by sisal and jute reinforced composites respectively. This behaviour could be related to better fibre-matrix adhesion in PLA composites compared to respective PP composites, demonstrated by SEM images of the fractured surfaces of the composite laminates after tensile tests in Fig. 3. It is well known that in composites, the tensile properties are affected not only by the properties of the reinforcing fibres/fabrics but also by the interfacial adhesion between the reinforcing fibre and the polymer matrix [4, 22]. Better fibre-matrix adhesion gives better load-transfer between fibre reinforcement and matrix resulting in a better mechanical performance [24, 25]. In jute/PP and sisal/PP fibres pulled out, holes developed due to fibre pull out can be clearly seen in Fig. 3 (a, b). In PLA composites there was slightly better interfacial adhesion as fibre pull-out was less and clean fracture occurred, fractured fibres can be seen in Fig. 3 (c, d). This can be explained by the difference in chemical structures of each component. Jute and sisal are cellulosic fibres containing hydroxyl group on the surface [7], therefore their compatibility with non-polar polymer such as PP is poor. On the other hand PLA is an aliphatic ester

polymer and contains oxygen atoms in its structure, therefore it is considered as more polar polymer compared to PP and hence can provide better interfacial adhesion towards jute and sisal fibres.

3.1.2. Flexural properties

The flexural test was performed in the elastic region, from which modulus values were calculated and given in Table 2. The flexural modulus of PLA (1.8 GPa) was much higher than that of PP (0.6 GPa). The effect of different reinforcements on the properties of the laminates could also be observed as the reinforcing fabrics with higher mechanical performance generally provided better flexural properties in the fabric reinforced PP and PLA composites, Table 2, where the normalised values to 40% FVF are also given for a more realistic comparison due to different area densities of the reinforcing fabrics. It must though be noted that flexural properties are not conventionally normalised because these are significantly influenced by the matrix compared to textile properties, which are dominated by the reinforcement. Trends for normalised values were similar to those seen for tensile properties, while the absolute values were less in the former. Glass and sisal fabric reinforced PP composites had similar normalised flexural modulus, about (4.0-4.3 GPa), which was higher than that of jute (3.6 GPa) reinforced PP composites. Similarly glass and sisal reinforced PLA composites had similar normalised flexural modulus (7.6 GPa), which was higher than of jute/PLA (6.7 GPa) composite. The higher flexural properties of PLA than PP composites are also supported by the literature [22].

3.1.3. Impact properties

The load-central displacement curves of PP and PLA composites subjected to 2 J impact are shown in Fig. 4. This energy level was set by pretesting on trial samples of jute and sisal composites so not to cause excessive surface damage. Since the sample thicknesses of jute, sisal and glass composites were very different and considering that the impact test results cannot be normalised to a particular FVF, a direct comparison with each other are not possible. Thin samples bend and crack in lower layers, whereas thicker samples are stiffer and hence have more contact on the surface during impact, causing surface damage. Hence, here the effect of matrix type on impact behaviour of composites with a particular reinforcing fabric has been evaluated.

On comparing PP and PLA composites, the behaviour was very different as seen from Fig. 4, where the load – displacement curves of PP composites were very smooth. The curves of PLA composites while have higher peak loads, they indicated cracks / interface debonds, shown by the undulating behaviour of the curves near the peak loads. The curves for glass composites however, were smooth, which is expected as 2 J energy for glass composites is very low to cause damage, moreover these

composites have very high FVF than respective PP and PLA composites (Table 1). These results show that while tensile and flexural properties of PLA composites were better those of respective PP, their impact responses were lower (Fig.4). This is due to brittle nature of PLA, widely reported in literature [22].

3.2. Fire performance of composites

3.2.1. Limiting oxygen index

The LOI values of PP, PLA polymers and their composites are given in Table 4. LOI is the minimum concentration of oxygen in a mixture of oxygen and nitrogen that will just support flaming combustion of a material. A low LOI for PP (17.4%) showed that PP was very flammable compared to PLA (LOI = 20%). It is interesting to observe that addition of natural fibres increased the LOI of PP, whereas slightly decreased in PLA. This is due to flammability of the flax and sisal (LOI = ~ 20.9 - 21.0 %), which was more than that of PP, but similar to PLA. All PLA samples (polymer and composites), have slightly higher LOI values than those of respective PP polymer/composites. The LOI though depends upon the sample size and in particular thickness, there is no direct relationship between them considering also the heterogeneity of these samples. Hence, the values cannot be normalised. For a better comparison between samples of similar thicknesses (produced from fabrics of similar area densities), these are grouped together in Table 4.

3.2.2. Flame spread

All samples failed UL-94 test as they were completely burnt. To get some meaningful data from this test, rate of flame spread of the neat polymers and composites was studied by recording times taken to reach 50 (T₁) and 100 mm (T₂) marks in both horizontal and vertical orientation, and the results are presented in Table 4. In the horizontal mode PP sample melted and burned with flaming drips. The dripping was very fast and it was difficult to count the number of drops. In vertical test, rate of burning was much faster and dripping was less compared to the horizontal as the samples burned more easily. In PLA polymer, the dripping was much less and slow compared to PP and the sample burned more steadily. Fabric reinforcement in both polymers reduced their burning rates, except for sisal, which is because of the thinness of the samples. Thin samples burn more easily than thicker samples. All polymer and composite samples burned slowly in horizontal mode compared to the vertical mode, which is as expected. All fibres also helped in stopping melt dripping of PP and PLA.

3.2.3. Cone calorimetry

Both PP, PLA polymers and composites were also tested by a cone calorimeter at 35 kW/m² heat flux. Heat release rate, mass loss and smoke release rate vs time curves are shown in Fig. 6 and derived

results are presented in Table 5. Both PP and PLA polymer samples ignited between 28 – 30 sec. PP showed peak heat release rate (PHRR) 1699 kW/m² and total heat release (THR) 95.4 MJ/m². For PLA the values were much lower, PHRR = 663 kW/m² and THR= 49.8 MJ/m². The effective heat of combustion of PLA (18.2 MJ/kg) was also much lower than for PP (42.9 MJ/kg). PLA, however, produced negligible smoke compared to PP as shown in Table 5. This shows that although PLA is combustible, it poses less of a fire hazard as it releases less heat and smoke during combustion. Since smoke is mainly composed of unburnt carbon, the lower smoke production in PLA can be explained based on its chemical structure with much lower carbon content (50% by mass) compared to that in PP (90% by mass). Moreover, in PLA, two of the carbon atoms in the repeat unit are already partly oxidized (C-O and C=O, respectively), hence less smoke is produced.

The cone calorimetric behaviour of samples is also dependent on their thicknesses [26] hence, samples of similar thicknesses (produced from fabrics of similar area densities) are grouped together in Table 5. In Figs. 5 and 6, HRR, mass loss and rate of smoke release (RSR) vs time curves for all samples of each type of matrix are shown. All fibres had minimal effect on time-to ignition (TTI) of PP or PLA matrix. This can be explained by the fact that the polymeric matrix on the composite surface is exposed and ignites first on exposure to an ignition source. All types of reinforcement reduced the PHRR of PP from 1699 kW/m² to 506 – 680 kW/m², which is 60-70% reduction. From all these fibres, glass displayed the greatest reduction, followed by jute and then sisal. This trend is as expected from the flammability of glass versus natural fibres. However, the total heat release (THR) increased for all natural fibres. The low value of THR shown by sisal/PP composite is due to its lesser thickness than other samples (Table 5). Thermally and physically thin samples ignite early, burn for shorter time and produce less total heat release compared to thermally and physically thick samples which burn slowly but for a longer time [26, 27]. Thermally thin means that the heat wave penetration depth is less than the physical depth in the sample [26, 28]. Natural fibre-reinforced composites burned slowly but for a longer time, producing more total heat and smoke. In the case of PLA composites, glass fibres helped in reducing the PHRR by 58% in comparison to PLA polymer, jute by 40% and sisal by 18%. This reduction is much less than that seen for PP composites. THR for Jute/PLA sample was increased, whereas smoke production in all samples was minimal.

On comparing the results for PP and PLA composites, the difference between any one type of fibre containing composites was similar to that seen for the two matrices in Fig. 6. While it is difficult to normalise these results because of so many variables (all fabrics are of different area densities and resulting samples are of different thicknesses), to compare the effect of different fibre types, selected cone parameters (PHRR and THR) were normalised w.r.t density (PHRR or THR/density of

composite). The results presented as specific PHRR ((kW.m / kg) and specific THR ((MJ.m / kg) are shown in Fig. 7. The trends in specific PHRR (Fig. 7) are similar to those seen in Table 5, sisal composites showing higher specific PHRR and lower THR compared to jute composites.

Conclusions

This work has shown that woven-nonwoven technology can be used to prepare natural-synthetic fibrous preforms, the composites prepared from which had good mechanical properties. The mechanical properties though can be further improved by using fibre surface treatments and/or compatibilisers for better fibre-matrix adhesion, which will be focus of the future work. Natural fibre reinforcement also helped in reducing flammability of PP and PLA composites and particularly melt dripping of thermoplastic matrices. Among PP and PLA composites, PLA showed better tensile and flexural properties, while their impact properties were inferior to PP composites. PLA composites were also less flammable and produced lesser smoke compared to respective PP composites. Both jute and sisal composites however, had inferior mechanical and flammability properties than their glass counterparts. For their usage in automotive, marine, aerospace or construction sectors, they will have to pass commercial fire tests, for which some sort of flame retardant treatments are required.

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Captions to Tables

Table 1. Composition and physical properties of the composites

Table 2. Mechanical properties of the PP, PLA polymers and composites

Table 3. Mechanical properties of the reinforcing fabrics

Table 4. LOI and UL-94 results for PP, PLA polymers and composites

Table 5. Cone calorimetric results of PP, PLA polymers and composites at 35kW/m^2 external heat flux.

Captions to Figures

Fig. 1. Schematic of preparation of a) preform base fabric and b) composite laminates

Fig. 2. Tensile properties of the PP (a) and PLA (b) composites

Fig. 3. SEM images of the fractured surface of tensile tested specimens at two different magnifications of a) jute/PP, b) sisal/ PP, c) jute/PLA and d) sisal/PLA

Fig. 4. Load- central displacement curves in impact mode for a) Jute and b) sisal – PP and PLA composites

Fig. 5. Heat release rate and mass loss vs time curves of PP, PLA polymers and composites

Fig. 6. Smoke release rate vs time curves of PP and PLA polymers and composites

Fig. 7. Specific peak heat release rate and specific total heat release of PP and PLA composites tested at 35kW/m^2 external heat flux

Table 1. Composition and physical properties of the composites

Sample	Area density of reinforcing fabric (g/m ²)	Mass fraction Fibre/polymer (%)	Fibre vol. fraction (%)	Thickness (mm)
PP	-			2.7
PLA	-			2.5
Jute/PP	174	42/58	31	3.2
Sisal/PP	62	41/59	30	1.3
Glass/PP	280	72/28	48	3.8
Jute/PLA	174	39/61	36	3.0
Sisal/PLA	62	34/66	31	1.3
Glass/PLA	280	74/26	59	3.8

Table 2. Mechanical properties of the PP, PLA polymers and composites

Sample	Tensile properties			Flexural Mod.* (GPa)	
	Initial Tensile Mod. (GPa)		Tensile strength (MPa)	Absolute value	Normalised to 40% FVF
	Absolute value	Normalised to 40% FVF			
PP	1.0 ±0.1		24.2 ±2.3	0.6 ±0.1	
PLA	2.9 ±0.1		43.3 ±2.8	1.8 ±0.2	
Jute/PP	3.7 ±0.2	4.8 ±0.2	45.4 ±3.3	2.6 ±0.4	3.6 ±0.4
Sisal/PP	4.9 ±0.2	6.5 ±0.2	52.7 ±5.2	3.2 ±0.3	4.3 ±0.3
Glass/PP	9.8 ±0.3	8.2 ±0.3	140.7 ±12.5	4.8 ±0.3	4.0 ±0.3
Jute/PLA	8.1 ±0.1	9.0 ±0.1	69.3 ±3.8	6.0 ±0.4	6.7 ±0.4
Sisal/PLA	7.7 ±0.1	9.9 ±0.1	64.1 ±2.8	5.9 ±0.4	7.6 ±0.4
Glass/PLA	14.4 ±0.4	9.8 ±0.4	182.2 ±12.9	11.2 ±0.3	7.6 ±0.3

*= Values in parentheses and italics are normalised to 40% FVF

Table 3. Mechanical properties of the reinforcing fabrics

Fabrics	Tenacity (N/Text)		Breaking Extension (%)		Specific Modulus (N/Text)	
	0°	90°	0°	90°	0°	90°
Jute Fabric	0.04±0.00	0.04±0.00	4.1±0.3	3.3±0.3	0.08±0.00	0.05±0.00
Sisal Fabric	0.10±0.01	0.13±0.00	5.8±0.3	2.4±0.3	0.26±0.01	1.14±0.08

Table 4. LOI and UL-94 results for PP, PLA polymers and composites

Sample	LOI (%)	UL-94 rating	Horizontal burn		Vertical burn	
			Burn rate (mm/min)	No. of melt drops	Burn rate (mm/min)	No. of melt drops
PP	17.4	Fail	46±2	~1000	176±47	~600
PLA	20.0	Fail	43±2	388	137±21	194
Jute/PP	18.7	Fail	27±1	0	123±19	0
Jute/PLA	19.8	Fail	28±17	0	85±4	0
Sisal/PP	18.7	Fail	47±1	0	205±25	0
Sisal/PLA	19.4	Fail	47±2	0	176±25	0
Glass/PP	*	Fail	16±0	0	128±14	0
Glass/PLA	*	Fail	25±2	0	123±11	0

* = Test not performed

Table 5. Cone calorimetric results of PP, PLA polymers and composites at 35kW/m² external heat flux.

Sample	TTI (s)	FO (s)	PHRR (kW/m ²)	THR (MJ/m ²)	EHC (MJ/kg)	Smoke (m ² /m ²)	Char (%)
PP	30	160	1699	95.4	42.9	1302	0
PLA	28	180	663	49.8	18.2	0.7	3.0
Jute/PP	33	290	675	95.5	31.7	1121	3.3
Jute/PLA	38	300	393	60.7	16.1	0.9	4.4
Sisal/PP	25	140	680	43.1	30.6	532	3.2
Sisal/PLA	27	120	542	28.1	15.9	1.2	3.3
Glass/PP	25	260	506	79.7	38.1	1308	50.9
Glass/PLA	27	280	275	46.4	16.6	0.1	43.9

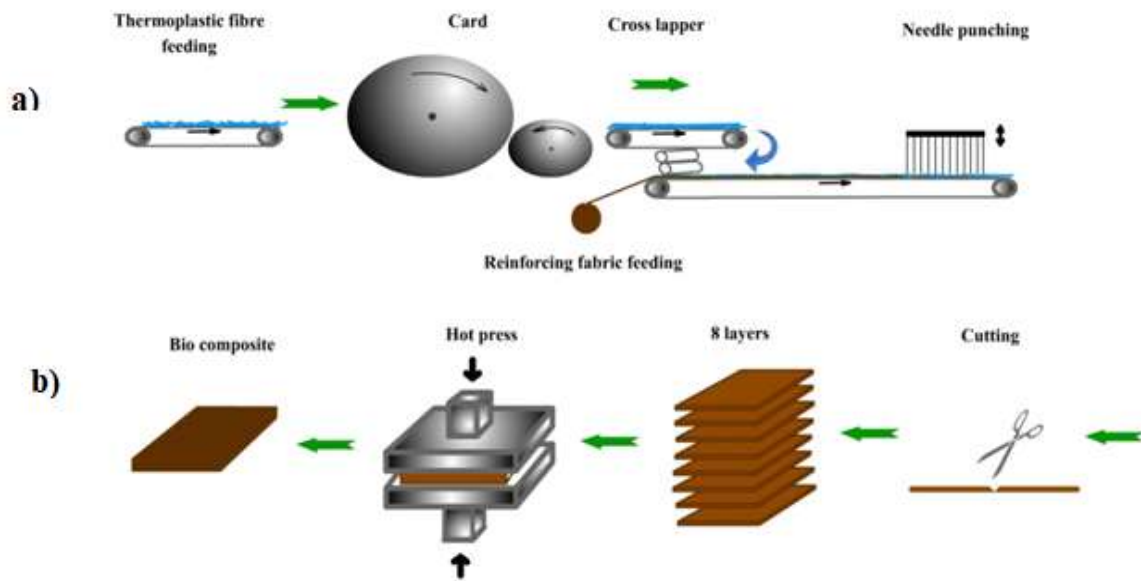


Fig. 1. Schematic of preparation of a) preform base fabric and b) composite laminates

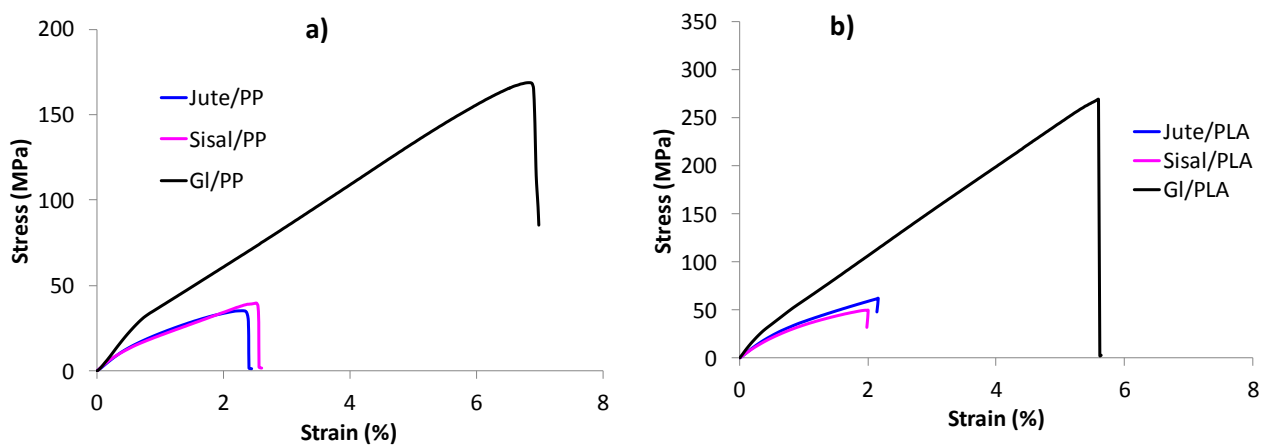


Fig. 2. Tensile properties of the PP (a) and PLA (b) composites

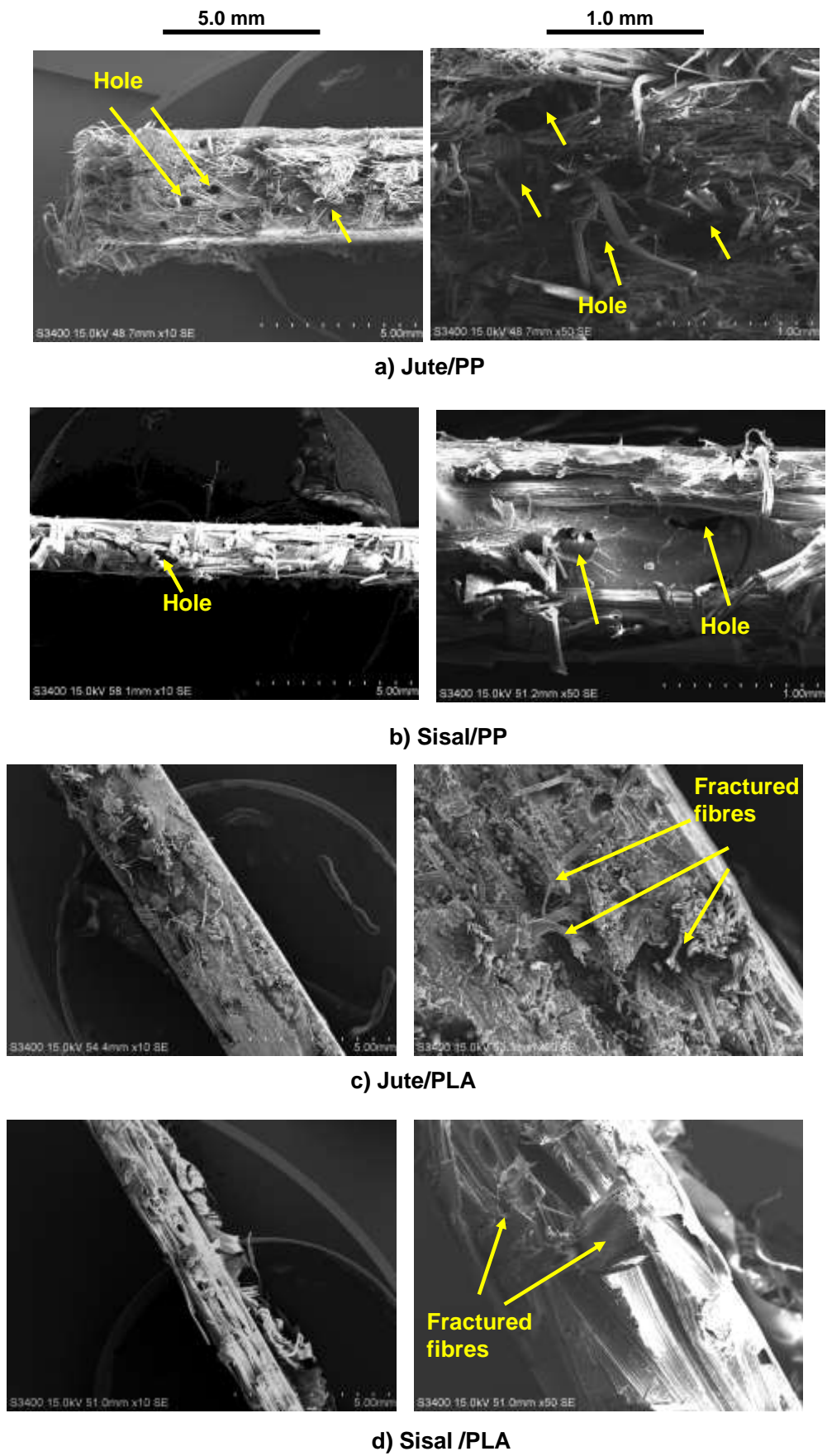


Fig. 3. SEM images of the fractured surface of tensile tested specimens at two different magnifications of a) jute/PP, b) sisal/ PP, c) jute/PLA and d) sisal/PLA

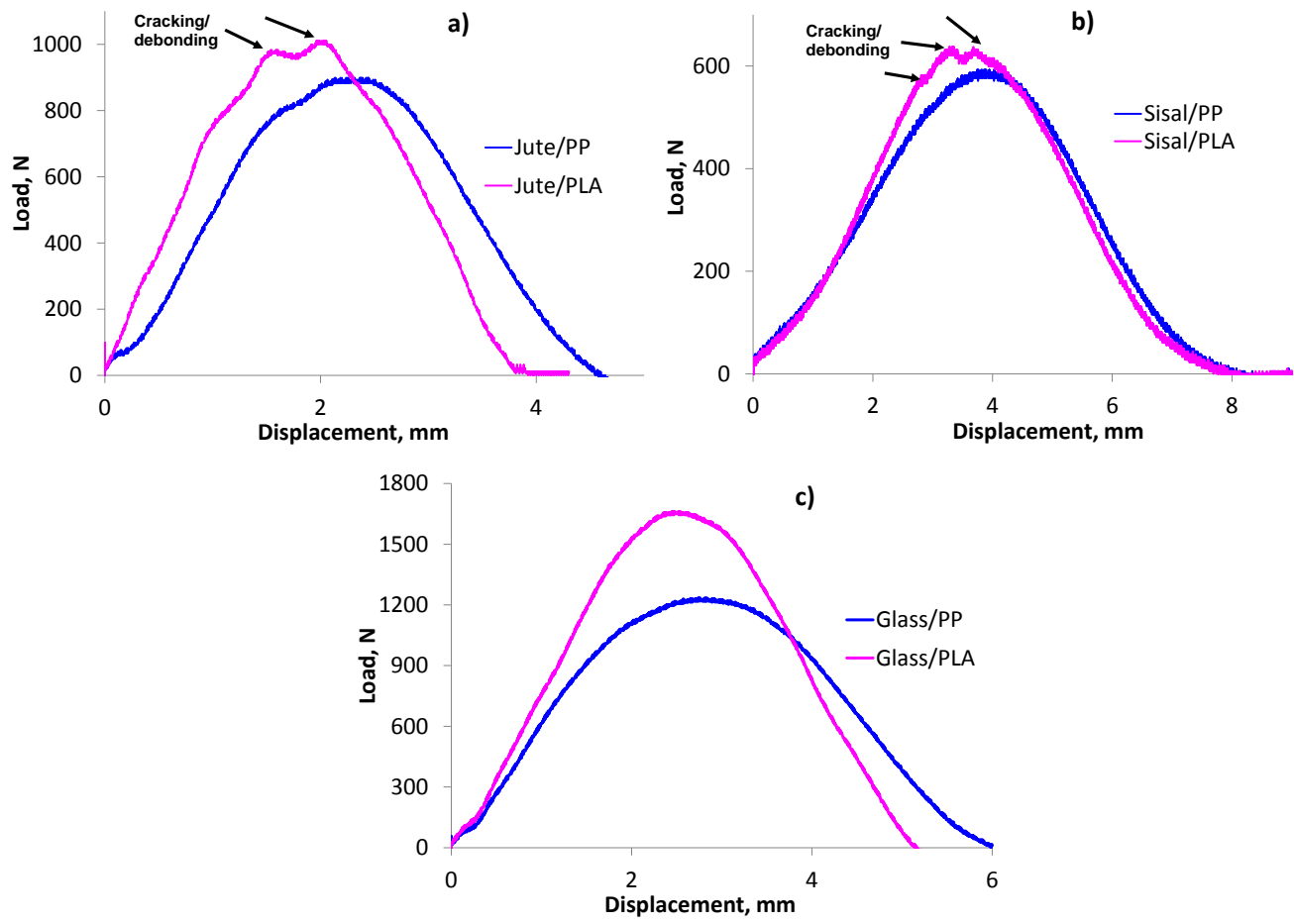


Fig. 4. Load- central displacement curves in impact mode for a) Jute, b) sisal and c) glass – PP and PLA composites

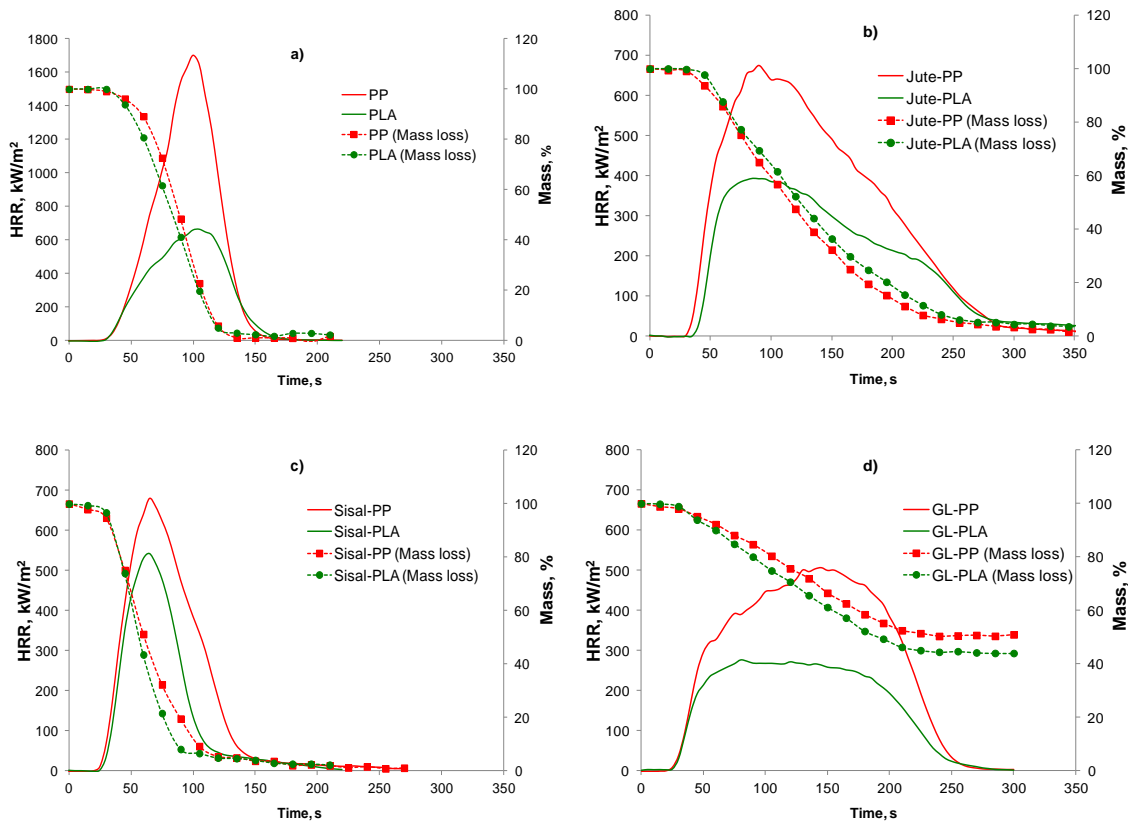


Fig. 5. Heat release rate and mass loss vs time curves of PP, PLA polymers and composites

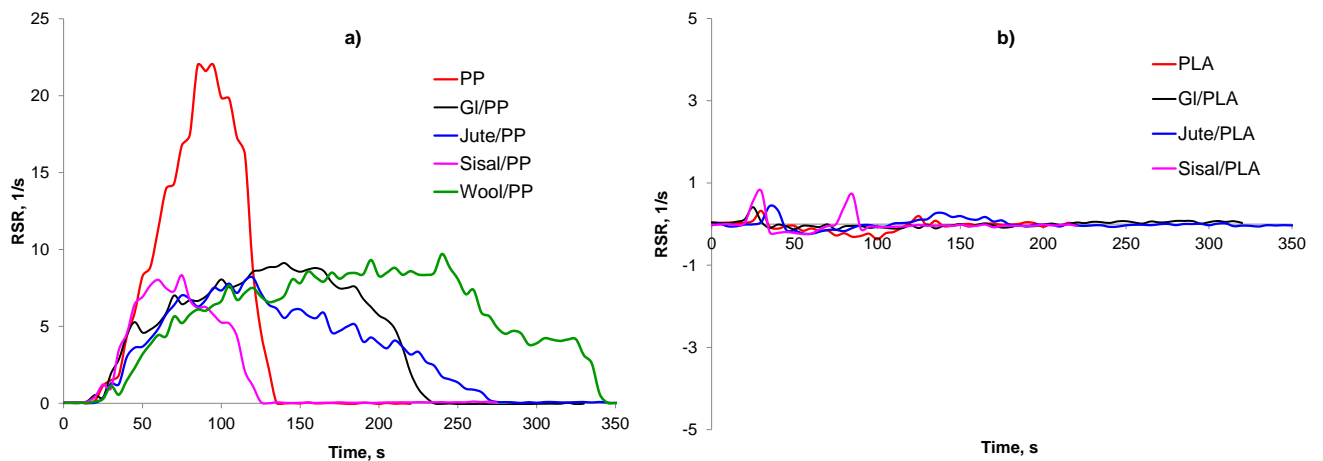


Fig. 6. Rate of smoke release (RSR) vs time curves of PP and PLA polymers and composites

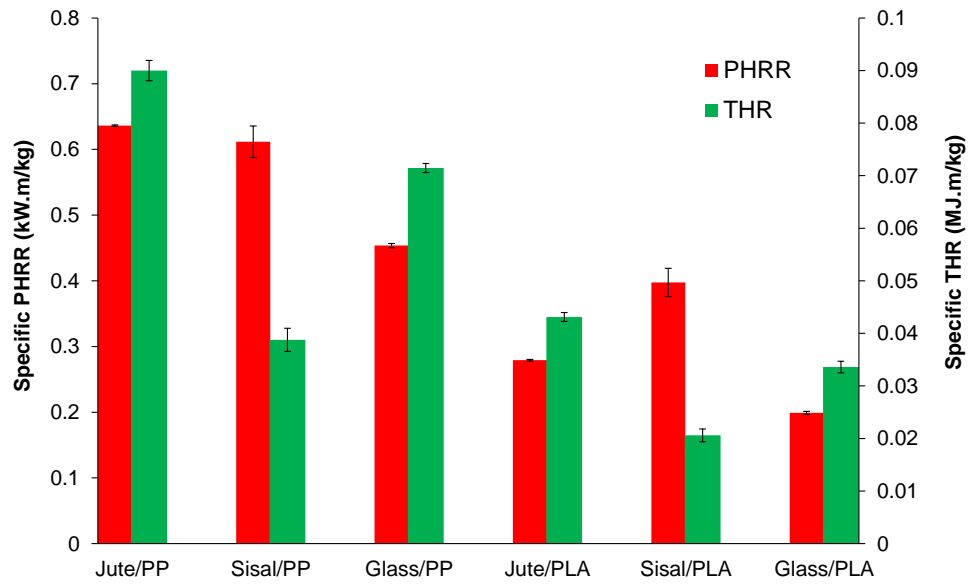


Fig. 7. Specific peak heat release rate and specific total heat release of PP and PLA composites tested at 35kW/m^2 external heat flux