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Composites: Part A

A parametric study of mechanical and flammability properties of biochar reinforced polypropylene composites

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ABSTRACT

A parametric study of biochar/wood/polypropylene (PP) composites has been conducted in order to evaluate the significant material factors that could affect the mechanical and flammability properties of the resulting composites. The presence/absence of coupling agent and wood, particle size of biochar and melt flow index of PP are the four factors investigated employing the Taguchi's design of experiment technique. Eight composite samples were manufactured by extrusion and injection moulding to be tested for their mechanical and flammability properties. Experimental results indicate that the presence of coupling agent and wood (in conjunction with biochar) play a critical role in achieving improved tensile and flexural properties. It is interesting to note that in terms of flammability properties, there does not appear to be much difference in the values of peak heat release rate amongst the composites, thus allowing the selection of the composition that would essentially be best suited for mechanical properties.

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1. Introduction

Organic waste mitigation is one of the major concerns of the 21st century as the carbon in the waste could exit as environmentally harmful carbon dioxide, volatile organic carbons, and leachates. The methane from the organic wastes could make up 20% of the total anthropogenic methane emissions and is also 23% more potent greenhouse gas than carbon dioxide [1]. Environmental degradation has urged scientists and environmentalists to identify multiple ways to recycle, reuse, and reduce waste in order to curb pollution and conserve energy, simultaneously. Pyrolysis is one such technology which can be used to convert organic wastes into useful products [2]. Biochar, a by–product of organic waste pyrolysis is a renewable material which has been extensively employed in agriculture and environmental management as a low cost carbon sequester and a natural adsorbent [3–5]. Its exceedingly stable honeycomb like carbonaceous structure with high surface area has ensured its use in soil amendment and remediation [6]. However, the aforementioned properties of biochar can be employed in other areas as well, in order to diversify its application potential. This has raised the motivation of using biochar as an additive/reinforce-

ment in composite materials in order to achieve improved mechanical and flammability/thermal properties. Biochar, when produced at high temperature (>500 °C), can exhibit numerous pores on its surface. Therefore, when biochar is added as reinforcement in polymeric composites, mechanical bonding/interlocking occurs between the porous biochar and the polymer, thus potentially enhancing the mechanical performance of the composite [7]. In addition, as identified in previous studies, biochar can possess high thermal stability (compared to wood and polypropylene) which might lead to enhanced flammability properties, when integrated in composites [8].

In recent times, several investigations have been undertaken to analyse the potential of biochar for fabrication purposes. Waste pine wood biochar made at 450 °C was used to manufacture wood and PP composites [9]. The study was focused on finding the most suitable loading rate of biochar to enhance the mechanical properties of composites. Elsewhere, hardwood derived biochar was used to make wood and PP composites, where again different amounts of biochar suitable to achieve certain properties were reported [10]. In another study biochar produced from several types of wastes (pine waste, poultry litter and sewage sludge) were used to manufacture composites which had enhanced mechanical and flammability properties compared to conventional wood plastic composite and neat polypropylene [7]. A comparative study to investigate the potential of plastic waste biochar (PWC), wood shavings biochar (WSC), and pine cone biochar (PCC) in the

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manufacturing of epoxy based composites was conducted by varying the loading levels of biochar between 5 and 30 wt% [11]. It was reported that for the PWC–epoxy composites, the tensile strength was highest at 15% filler concentration. However, for WSC–epoxy and PCC–epoxy composites, 25% filler concentration exhibited enhanced tensile properties. Most of the studies mentioned earlier have focussed mainly on the application of biochar in polymeric composites whose porosity was low, thus resulting in an overall lower surface area. However, biochar can be activated at higher temperatures resulting in improved surface area and pore volume which consequently, enhances its adsorptive capability. However, the activated biochar with high surface area has mostly been used in areas relating to remediation of contaminants, filtration and as anti-microbial agents [12,6]. Therefore, in order to impart versatility in the application of activated biochar, there is a need for identifying other possible areas of application. One such application area is to capitalize on the highly porous nature of activated biochar in fabrication of polymeric composites which is the basis of this current study.

In a polymeric composite, there are multiple constituents whose variation in the composition may affect the overall properties of the composite. Therefore it is required to identify the optimum level of various factors which contribute towards achieving the desirable properties, either mechanical or flammability. The properties of a biochar composite may depend on various processing and material factors. These factors affect the interfacial bonds, mechanical bonds, and particle dispersion within the polymer matrix, thus influencing the overall mechanical and flammability properties of the composite. Based on this, four material factors (i.e. coupling agent, polymer viscosity, particle size of biochar and presence/absence of wood) have been carefully selected for this present study which are most likely to impact the mechanical and flammability properties of biochar composites. It is well known that coupling agent (here maleic anhydride grafted polymer or MAPP) governs the interfacial adhesion between a non–polar polymer and a polar additive/reinforcement [13]. However, due to the dearth of functional groups on biochar's surface, it is possible that biochar may not take part in MAPP assisted adhesion with polypropylene. The viscosity of a polymer is often commercially defined by its melt flow index (MFI). Thus, it is hypothesised that a polypropylene with high MFI would be able to flow into the honeycomb like pores of biochar during processing with ease, creating beneficial mechanical bonding. Particle size of an additive is an important consideration as smaller particles although can disperse better under favourable conditions (positively correlated to better flammability properties), they tend to agglomerate at higher loading levels [14]. They also generate larger surface area of contact with the matrix if the surface texture is comparable to that of a large particle. The inclusion of wood (possessing functional groups) as an additional reinforcement might aid MAPP assisted adhesion with polypropylene, thus potentially improving the mechanical properties of the composite. However, it might be possible to have adequate mechanical bonding with biochar without wood. Therefore, in this study, each selected factor had two defined levels based on which composites were manufactured via twin–screw extrusion and injection moulding. Taguchi design of experiment (DoE) approach was adopted to generate an L_8 experimental layout. Mechanical, thermal and flammability properties of the composites were identified using the ASTM standard tests for tension and bending, thermogravimetry, differential scanning calorimetry, and cone calorimeter. The morphologies of the tensile fractured surfaces of each composite sample along with the microstructures of char residue after burning were evaluated using scanning electron microscopy (SEM). Analysis of variance (ANOVA) was performed to statistically determine the significant factors contributing towards the improvement of mechanical and ther-

mal/flammability properties. The novelty of the investigation can be highlighted by the fact that this is the first parametric study to involve biochar reinforced polymeric composites. A parametric analysis plays a vital role in order to recognise the effect of individual parameters as well as interactions. Furthermore, the factors pertaining to both mechanically sound and fire resistant biochar based composites are not available in the current literature. This study aims to enable the choice of most suitable material properties for a biochar based composite to optimize its mechanical and flammability properties.

2. Materials and methods

2.1. Materials

Activated biochar for the experiments was produced at Taupo Carbon Services, Taupo, New Zealand. The pine wood biochar was produced in two steps. Firstly, the pyrolysis of biomass was performed at 500 °C followed by high temperature activation at 900 °C. As has been shown in a previous study [7], the ash content of the biochar was about 13 wt% whereas the elemental carbon content was 82 wt%. The specific surface area was calculated to be 335 m²/g. The activated biochar was ground into two different particle sizes of 1000 μm and 50 μm using a Retsch Mill (Germany: Model SM 100; 230 V and 50 Hz). The particle size distribution was determined by Mastersizer 2000 (Malvern Instruments, UK; Version 5.60). Two grades of commercially available polypropylene (PP) with varying melt flow index (HP400 N with MFI of 11 g/10 min and HP400L with MFI of 5.5 g/10 min) were selected. PP and maleated anhydride polypropylene (MAPP Licocene 6452) used in this research were supplied by TCL Hunt and Clariant Ltd, respectively.

2.2. Manufacturing of composite samples

The blends for eight samples were made according to Table 1 using a Ferry Industries Inc. Plas. Mec. (US; Model: TRL/20/FV; 415 V and 50 Hz) high intensity mixer. A co-rotating Brabender® twin screw extruder was used for melt blending of mixed samples (Lab tech Engineering Company Ltd. Thailand; Model: LHFS1-271822; S/N 020). The screw rpm was set at 50 whereas the temperature profile was maintained in the range of 175–195 °C across the ten zones from barrel to die. This profile was chosen keeping in mind the melting temperature of PP which is around 165 °C and thermal degradation temperature of wood which is around 200 °C. The blended samples were fed at a constant rpm of 1.1 and the extruded material was collected at end of the conveyor belt. The extruded material was then pelletized by a palletizing mill (Lab tech Engineering Company Ltd. Thailand; Model: IZ-120; 0.9 kW). The pellets were oven dried at 70 °C for 24 h and then injection moulded (Dr. Boy, GMBH 53577, Neustadt, Germany) into dog bones and discs for their respective use in tensile/bending and flammability experiments. The temperature range in the barrel was 160–195 °C whereas the holding and the back pressure was set at 70 and 0.8 bars, respectively.

Table 1
Experimental parameters and levels.

Factors	Level	
	1	2
A: MAPP content	4%	0%
B: Particle size	1000 μm	50 μm
C: MFI of PP	11 g/10 min (HP400 N)	5.5 g/10 min (HP400L)
D: Wood content	30%	0%