

Effect of particle size and amount of nonmetallic PCB materials on the mechanical properties of rHDPE/PCB composites

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Abstract

Composites based on recycled high density polyethylene (rHDPE) and nonmetallic printed circuit board (PCB) waste were made through melt compounding and compression molding. In this study, the chemical compositions of the nonmetallic PCB material were determined via XRF and it was confirmed that it contains predominantly 72.7% of glass fiber materials which improve the mechanical performances of the rHDPE matrix. The main aim of this study is to determine the effect of different particle sizes and loadings of nonmetallic PCB on mechanical properties of rHDPE/PCB composite. The results indicated that mechanical properties of composites were excellent when nonmetallic materials with particle size from 0.09 to 0.15 mm and adding amount was 30 wt%. Microscopic images revealed that nonmetallic particles with the size of 0.07-0.09 mm and 0.09-0.15 mm contained majority of single glass fibers whereas, bigger particle sizes of 0.15-0.3 mm and 0.3-0.5 mm, contained glass fibers in the form of bundles and large resin sheet.

Keywords: Nonmetallic printed circuit board, particle size, mechanical properties, chemical compositions, morphology

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INTRODUCTION

Malaysia produces a large amount of waste from electronic waste (E-waste). According to United Nations Environment Programme (UNEP, 2007), electrical and electronic equipment or components that are destined for recycling or recovery or disposal are considered as E-waste. The examples of E-waste are such as used television, motherboard, printed circuit board (PCB), waste of integrated circuit, and others. These wastes exist in a complex situation in terms of materials, design, components and original equipment manufacturing process.

The growth of electrical and electronic industries in Malaysia has increased 13% from year 2000 to 2008 (Sohaili, Muniyandi, & Mohamad, 2012). Department of Environmental (DOE, 2009), in their inventory report stated that the amount of E-waste will be increasing by an average of 14% annually and by the year of 2020, a total of 1.17 billion units or 21.38 million tons of E-waste will be generated. It is estimated a cumulative total of 403.59 million units of waste from electrical and electronic equipment have been generated in year 2008 and total of 31.3 million units has been discarded in the same year (Sohaili et al., 2012). In developed country such as China, Japan and Malaysia, the production of electrical and electronic equipment is growing rapidly.

The disposal, storage, management, and environmental pollution have become a big problem with the increased E-waste. Government and private sectors should take the initiative to reuse E-waste without giving adverse effect to the environment. However, E-waste is

considered not safe to be reuse because it is categorized as scheduled waste. Based on Department of Environmental (DOE, 2010), E-waste is categorized as scheduled waste because it contains some contaminants that can be potentially hazardous, if improperly handled. For example, printed circuit boards contain heavy metals such as nickel, chromium, tin, lead, copper, brominated flame retardants and cathode ray tubes (CRTs) containing lead oxide.

A few studies have been done in the past to find the possibility of reusing this type of waste. It is therefore, the main concern of this study is to recycle the nonmetallic PCB waste in a safe and environmentally sound manner by preparing composites made from nonmetallic PCB and recycled HDPE (rHDPE). Through this study, the most effective particle size and loading amount of nonmetallic PCB to optimize the performances of the composites will be identified.

LITERATURE REVIEW

Management of hazardous waste in Malaysia

The control of toxic and hazardous waste disposal has been implemented through the provisions contained in clause 51 of the Environmental Quality Act 1974. In this provision, the law was designed to prohibit or control the discharge of materials such as toxic and hazardous waste to the environment. Based on (Norazlina, 2010), the purpose of this act is to prescribe the method of waste management to avoid the environmental pollution.

The Department of Environment (DOE) is responsible for the enforcement of these rules. However, DOE is the only law

enforcement agency rather than an organization that is providing and managing landfills. Therefore, the task of detailed planning, construction and operation of disposal sites should actually be implemented by other parties such as local authorities and the private sector in collaboration with the DOE. The consolidation of wastes management system is important for industrial countries to ensure cleanliness and environmental safety is assured.

Theng (2008) conducted a study on waste management in Malaysia. The findings indicate that the junkshops, recycling centres and scrap collectors play an important role in bridging the gap between the waste generators and recyclers, by collecting E-wastes generated from various sources and sending these to E-waste recyclers. Currently there are 20 full recovery facilities and 132 partial recovery facilities licensed by DOE in Malaysia. All of the recovery facilities are owned by private companies (DOE, 2012). These plants play a role to collect E-wastes from various middlemen, collectors and recycling centres. Materials such as plastics and metals will be recycled at these plants. Besides that, these recycling plants also extract precious metals such as gold, platinum, silver and lead from the circuit boards of the E-wastes. After recycling process, the reusable parts such as precious metals are shipped back to the market for reuse, while toxic parts such as nonmetallic printed circuit board (PCBs) are sent to Kualiti Alam Sdn Bhd for disposal.

In Malaysia, Kualiti Alam Sdn Bhd was built to address management problems of scheduled waste. Kualiti Alam Sdn Bhd is a center established by the Waste Management Center (WMC) in Bukit Nanas Negeri Sembilan. Nonmetallic PCBs from E-wastes which are categorized as scheduled wastes in Malaysia will be transported by licensed contractors to be disposed off in the centralized scheduled waste treatment and disposal facility in Kualiti Alam Sdn Bhd (Theng, 2008). WMC also provides treatment for scheduled wastes listed in the Environmental Quality (Scheduled Waste) Regulations 1989. The laboratories available in WMC are like burning plant, physical or chemical treatment plant, solidification or stabilization and landfill (Rabitah, 2000).

Electric and electronic waste

Based on (He *et al.*, 2006) the discarded and end-of-life electrical and electronic products are called as electrical and electronic waste (E-waste). E-waste comprises of wastes generated from used electronic devices and household appliances which are not fit for their original intended use and are destined for recovery, recycling or disposal. Electrical and electronic products are including computers, equipment for Information and Communication Technology (ICT), home appliances, audio and video products and all of their peripherals (Li, Lu, Guo, Xu, & Zhou, 2007; Rajesh, 2008).. According to (Martin, 1997), E-waste contain over 1000 different substances, many of which are toxic and potentially hazardous to environment and human health, if these are not handled in an environmentally sound manner.

With referring to the Environmental Quality Act 1974, E-waste is defined as waste of used electrical and electronic assemblies. E-waste is categorized as scheduled wastes under the code of SW 110 of First schedule of the Environmental Quality (Scheduled Waste) Regulation 2005. Under this regulation, the SW 110 waste are defined as wastes from the electrical and electronic assemblies containing components such as accumulators, mercury, glass from cathode-ray tube and other activated glass or polychlorinated biphenyl-capacitors, or contaminated with cadmium, lead, nickel, chromium, copper, manganese or silver.

According to (Rajesh, 2008; Torretta, Ragazzi, Istrate, & Rada, 2013), E-waste has been categorized into three main categories which are large household appliances, IT and telecom, and consumer equipment. Refrigerator and washing machine represent large household appliances, personal computer, monitor and laptop represent IT and telecom, while televisions represent consumer equipment. Based on (Brigden, Labunska, Santillo, & Allsopp, 2005) each of E-waste items has been classified with respect to twenty-six common components, which could be found in them. These components form the building blocks of each item and therefore they are readily identifiable and removable. These components are metal,

motor, ferrous, non-ferrous metals, cooling, plastic, insulation, glass, rubber, wiring, batteries, and printed circuit board.

The development of technology and industry have encouraged the replacement of electric and electronic equipment. In addition, this condition also cause the user to have a much wider choice to get better and cheaper electrical and electronic equipment. This has contributed, and resulting the increasing of E-waste. Without proper management, E-waste will cause environmental contamination and may also have adverse effects on human health. This is because most of the electronic waste contain valuable elements, that are simply stripped away from the waste, and the residue is simply dumped or burned away. E-waste have more of a raw material than junk. If these wastes are managed properly, they could be a huge source of revenue.

Printed circuit boards

Circuit boards are essential electronic components. A printed circuit board (PCB) is used to connect electronic components without the need for conventional cables. The large amount of material used in circuit boards and the presence of high levels of pollutants make their recycling and disposal very problematic.. PCBs are in fact the generalized term representing the platform upon which microelectronic components such as semiconductor chips and capacitors are mounted. They are used to support the electronic components as well as to connect them using conductive pathways, tracks or signal traces etched from copper sheets laminated onto them. In literature, a PCB is also referred to as a printed wiring board (PWB) or etched wiring board. A PCB populated with electronic components is also known as a printed circuit assembly (PCBA). In this study the term PCB is used in place of PCBA unless otherwise stated. PCB is categorized as one of the component of E-waste. PCB is a piece of plastic material on which electronic components can be mounted for mechanical support. PCBs is also defined as an electrically interconnects all the components by means supports of a pattern of metal tracks on its outer surfaces and sometimes on inner layers (Rakesh, 2008). PCBs are used to connect electronic components without the need for conventional cables. Circuit boards are estimated to make up about 3% of the electronic scrap (Scarlett, 1984). PCBs normally consist of a substrate onto which components have been soldered. (Martin, 1997) stated that, the components of waste PCBs can be divided into metallic fractions (MFs) and non-metallic fractions (NMFs) or non-conducting substrate or laminate, conductive circuits printed on or inside the substrate, and mounted components.

Compositions of PCB

PCBs are estimated to make up about 3% of the electronic scrap. The materials used in PCBs are listed in Table 1.

Guo, *et al.* (2008) stated that, PCBs forms about 3% by weight of the total amount of E-waste. Generally, waste PCBs contains approximately 30% metals and 70% nonmetals (Goosey & Kellner, 2003; Guo *et al.*, 2008). According to study conducted by (Veit *et al.*, 2005), they found out that PCBs scrap generally contains approximately 40% metals, 30% organic and 30% ceramics. The nonmetallic materials of PCBs consist of thermoset resins and reinforcing materials (Hall & Williams, 2007; Perrin, Clerc, Leroy, Lopez-Cuesta, & Bergeret, 2008). An organic material of PCBs usually consists of plastic. Plastics often contain flame retardants and paper. Plastic is made up from various types such as C-H-O and halogenated polymers. Sometimes Nylon and polyurethane are also used in the PCBs, but only in small amounts. PCB structure contains large quantities of base metals. Among the metals that exist in the PCBs are such as Cu, Fe, Al and Sn, rare and precious metals such as Tn, gallium, platinum, Ag, silver, and palladium. In addition, hazardous metals such as Cr, Pb, Be, Hg and Cd also present in PCBs. These metals are very harmful to the environment and also to human health if not managed in the right way. While ceramic element that exists in the PCBs are Si, Al, alkaline earth oxides, barium titanate and mica.

Table 1 Materials used in PCBs (Brodersen et al, 1994).

Type	Percentage by Mass	Materials
Metallic materials	25-30%	Main components: copper, iron, nickel, tin Other metals: lead, silver, manganese, gold, chromium, cadmium, platinum, beryllium
Organic non-metallic materials	20-25%	Thermoplastics, flame-protected duroplasts
Inorganic non-metallic materials	40-55%	Glass, ceramics

Metals

According to (Hino *et al.*, 2009), the PCBs contained approximately 30% of metallic materials such as Cu and Fe, approximately 25% of organic resin materials containing elements such as C and H, and approximately 30% of glass materials used as resin reinforcing fibers. From studies that have been conducted by (Guo *et al.*, 2008) as well as (Goosey & Kellner, 2003), revealed that in term of metals the Cu, had the highest content at 14.6 mass%, followed by Sn at 5.62 mass%, Fe at 4.79 mass%, Pb at 2.96 mass%, Ni at 1.65 mass%, and Cr at 0.35 mass%. While in terms of the precious metal composition, Au, Ag, and Pd were found at concentrations of 450, 200, and 220 ppm, respectively. In terms of the nonmetal compositions, Br was found at a content of 5.07 mass%. Sb was found at a content of 0.45 mass%, and is also being used in PCBs nonmetal because it has a flame-retardant efficacy through combination with a halide flame-retardant. For inorganic glass fiber materials, SiO₂ was found at a content of 24.7 mass%, followed by Al₂O₃ at 6.20 mass%, CaO at 3.36 mass%, and MgO at 0.081 mass%, and BaO at 0.0022 mass%.

Non-Metallic Fractions

Based on (Scarlett, 1984), nonmetallic fractions are called nonmetals, nonmetallic materials, glass fiber resin powder (GR powder), glass nonmetals, and epoxy resin compounds. The two main types of base laminate or nonmetallic fractions used are phenolic paper and epoxy glass (Dalrymple *et al.*, 2007). As stated by the American NEMA (National Electrical Manufacturers Association), Flame Retardant (FR-2) phenolic paper is known as FR-2 and epoxy glass is FR-4.

FR-2 is the grade specified for synthetic resin bonded paper where a composite material was widely used to build low-end consumer electronic equipment. The FR-2 is used mainly for non through-plated boards for the domestic and simpler industrial markets. The main advantages of FR-2 over FR-4 in these areas are its lower cost and the ease with which it can be punched. However, the electrical properties of FR-2 are inferior to those of FR-4 and its higher moisture absorption makes it unsuitable for plated-through hole work (Stevens & Goosey, 2008). Besides that, the mechanical strength of FR-2 is less than that of FR-4. FR-2 are distinguishable from FR-4 by their color, which is usually a deep purple, brown or black (Martin, 1997).

While FR-4 is the grade for circuit boards made of woven fiberglass cloth with an epoxy resin binder that is flame resistant (self-extinguishing). According to (LaDou, 2006), FR-4 is most commonly used as an electrical insulator due to their zero water absorption and considerable mechanical strength. Besides that, FR-4 offer better dimensional stability than FR-2, but neither material is truly stable.

FR-4 with chopped strand glass reinforcement can be used where properties such as moisture absorption are critical, and better electrical properties are required than can be achieved with a FR-2 (Joseph, 2006; Gary, 2009). However, they are not widely used and most of their possible uses are met by epoxy or woven glass laminates which are readily available and has better electrical properties and strength. FR-4 are available, but are used only in special cases where a FR-2 would have inadequate properties but the paper base considered desirable. Based on (Martin, 1997) the usual colors for FR-4 are pale, translucent green or brown. Rigid laminates for specialized applications are available on base materials such as irradiated polyethylene, melamine, triazine, polysulphone, silicone and polyimide resins, some of which may be reinforced.

The typical constituents of a FR-4 laminate are listed in Table 2 and are discussed in detail in the subsequent sections. Each of these constituents is important in its own, and in combination they determine the properties of the laminates.

Table 2. Typical constituents of FR-4 laminates (Weil and Levchik, 2004).

Constituent	Major function	Example material
Reinforcement	Provides mechanical strength and electrical properties	Woven glass (E-grade) fiber
Coupling agent	Bonds inorganic glass with organic resin and transfers stresses across the matrix	Organosilanes
Resin	Acts as a binder and load transferring agent	Epoxy (DGEBA)
Curing agent	Enhances linear/cross polymerization in the resin	Dicyandiamide (DICY), Phenol novolac (phenolic)
Flame retardant	Reduces flammability of the material	Silica
Accelerators	Increases reaction rate, reduces curing temperature, controls cross-link density	Imidazole, organophosphine

METHODOLOGY/MATERIALS

Materials

Recycled high density polyethylene (rHDPE)

rHDPE used in this work was supplied by Metahub Industries Sdn Bhd, Johor. The recycled HDPE is from post-industrial HDPE pipe waste. The HDPE pipe was recovered and shredded into small flakes with 8-10 mm sizes.

Nonmetallic printed circuit boards (PCBs) waste

The nonmetallic PCB (Figure 1) used as a filler material in this work was an industrial solid-waste byproduct from PCB recovery process obtained from METAHUB Industries Sdn Bhd (Johor, Malaysia). This was in the form of powder and without electronic elements.

Preparation of nonmetallic PCBs

For sample preparation, nonmetallic PCBs were taken from electronic waste recycling plant. The waste nonmetallic PCBs used in this study are without electronic elements. A stack of five sieves with hole widths from 0.5 to 0.07 mm were selected. The PCBs were sieved to remove impurities and manually sieved according to BS 812 sieve test: Part 103: Section 1 (BSI, 1989). The specimens were agitated for 20 minutes and the nonmetallic PCBs collected on each sieve were weighed to calculate the particle size distribution. The component of nonmetallic PCB materials is shown in Table 3.

Table 3 Component of nonmetallic PCBs materials.

Sieve size (mm)	Cumulative Percent Retained (%)
0.5-0.3	18
0.3-0.15	32
0.15-0.09	25
0.09-0.07	14.3
<0.07	10.7

Compounding and preparation of composites

Blends of rHDPE and nonmetallic PCBs were premixed in sealed containers and shaken manually. The rHDPE and the nonmetallic PCBs were dried at 80°C for 24 hours prior to compounding and were compounded using Brabender Plasticoder PL 2000 counter-rotating twin-screw extruder. The barrel temperature profile adopted during compounding was 210°C at the feed section, decreasing to 200°C at the die head with fixed screw rotation speed at 50 rpm. The extruded

materials were thermoformed by hot press machine into mechanical properties testing specimens with operating temperature of 200°C with 15 minutes of preheat and another 10 minutes for compression, followed by cooling process at room temperature for 5 minutes before removing it from the mold.

Mechanical testing

Tensile test was carried out according to ASTM D638 using an EZ 20KN LLYORD under ambient conditions. The crosshead speed for 50 mm min⁻¹ was used for testing. Flexural test was done according to ASTM D790 by EZ 20KN LLYORD universal testing machine under ambient conditions. The crosshead speed of 3 mm min⁻¹ was used with a support span of 100 mm. Izod impact test was carried out on notched impact specimens, by using a Toyoseiki (Tokyo, Japan) impact testing machine according to ASTM 256 under ambient conditions. All the samples were notched using an automatic notching machine prior to testing. Five specimens of each formulation were tested and the average values reported.

Morphological study

The instrument used for this test is a Philips XL 40 Scanning Electron Microscopy and SEM EDAX AMRAY model. In this experiment, 1.0 cm x 1.0 cm samples were prepared and made into sheets with a flat and smooth surface. To get a smooth surface, the samples were coated with gold. Samples were coated with gold for 105 seconds in Automatic Coating Machine to improve conductivity and protect the sample from dust. The prepared samples were then stacked on a clean stud with tape conductor. The studs were then inserted into the machine that was maintained in vacuum condition. The structure of samples were detected and analyzed by SEM-EDAX. The analysis was done by selecting the appropriate focus, magnification range, working distance, and other suitable parameters for the required results.

RESULTS AND FINDINGS

Microstructure of nonmetallic PCB waste

The sample was analyzed using Scanning Electron Microscope test (SEM) to determine the pattern of microstructure surface, size and particles arrangement of nonmetallic PCB powder. It is obvious that nonmetallic PCB powder contained predominantly glass fibers, with majority of fibers being encapsulated in thermosetting resin as shown in Figure 1. While, some of the thermosetting resins are stuck on the surface of the glass fibers. It can also be observed that nonmetallic PCBs generally have rough surface with elongated shape and sharp structure.

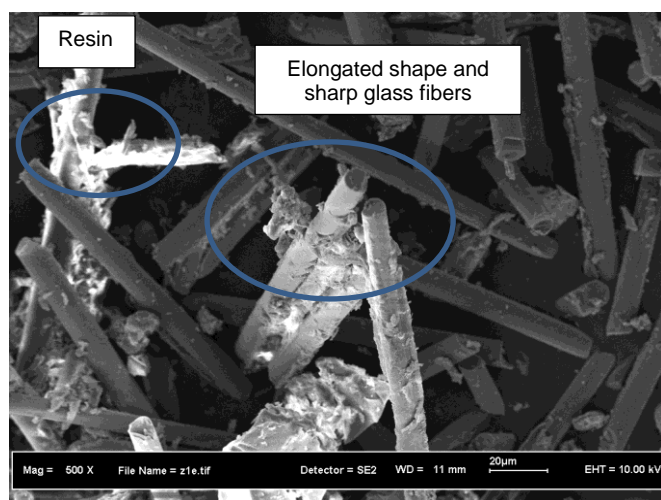


Fig. 1 SEM micrograph of nonmetallic PCB sample.

Chemical composition analysis of nonmetallic PCBs

Analysis of data obtained from X-ray Fluorescence Spectrometry (XRF) test can be used to find out the chemical elements in

nonmetallic PCBs. Epoxy resin, glass fibers and small concentration of metals were detected in the nonmetallic PCB sample (Table 4). Approximately, 72.7% content of nonmetallic PCB materials come from glass fiber materials such as SiO₂, Al₂O₃, CaO, MgO, BaO, Na₂O, and SrO, 6.7% of metallic materials such as CuO, SnO₂, and Fe₂O₃, and 6.5% of organic resin material containing Br. Glass fiber materials, SiO₂ was found at the highest content of mass which was 43.2%, followed by CaO 19% and Al₂O₃ 9.2%. While, metallic materials, CuO was found at 5.83%, followed by Fe₂O₃ with 0.77% of mass. Other elements found in nonmetallic PCBs were TiO₂, SO₃, K₂O, Na₂O, SrO, Cl, P₂O₅, SnO₂, ZrO₂, ZnO, As₂O₃, NiO, and PbO existed only in small amounts which were in the range of 0.44% to 5 ppm. The results obtained above are accordance with a few previous studies, which stated that C, O, Al₂O₃, SiO₂, CaO, Cu and Br are the main content in glass fiber reinforced epoxy resin (Goosey & Kellner, 2003; Guo *et al.*, 2008; Hino *et al.*, 2009). Therefore, it can be concluded that majority of the nonmetallic PCB content comes from glass fibers reinforced epoxy resin.

Table 4 Chemical composition of nonmetallic PCB.

Elements	Percentage (%)	Elements	Percentage (%)
CaO	18.98	MnO	-
SiO ₂	43.24	TiO ₂	0.44
Al ₂ O ₃	9.17	P ₂ O ₅	0.06
SO ₃	0.33	Sb ₂ O ₃	-
Br	6.53	SrO	0.14
CuO	5.83	ZrO ₂	0.02
BaO	0.50	ZnO	0.02
Fe ₂ O ₃	0.77	As ₂ O ₃	0.01
Na ₂ O	0.14	Cr ₂ O ₃	-
Cl	0.06	MoO ₃	-
SnO ₂	0.05	Rb ₂ O	-
MgO	0.52	NiO	77ppm
K ₂ O	0.16	PbO	5ppm

Mechanical properties of composites with different particle sizes of nonmetallic PCB

Filler particle size is intimately associated with the mechanical behaviours of composites due to its influence on the degree of contact between filler particles with polymer matrix. Therefore, study has been conducted to determine the most effective and suitable size of nonmetallic PCB particle to optimize the performances of the composites. The composite composition was fixed at 30 wt% nonmetallic PCB powder and 70 wt% rHDPE matrix, and particle sizes were chosen as 0.07-0.09 mm, 0.09-0.15 mm, 0.15-0.3 mm and 0.3-0.5mm, respectively.

The effect of different nonmetallic PCB particle sizes on impact strength of rHDPE/PCB composites is illustrated in Figure 2. It can be observed that, the impact strength decreased with increasing in nonmetallic PCB particle size. Initially, when the particle size ranging from 0.07-0.09 mm, the impact strength was 42.5 J/m. When the particle size increased to 0.09-0.15 mm, the impact strength started to decrease slightly by about 5%. The impact strength continued to decrease with increasing nonmetallic particle size, and at particle size of 0.3-0.5mm, the impact strength dropped drastically by about 28.5%.

The same pattern as impact strength was observed for tensile strength (Figure 3), whereby the tensile strength decreased with increasing nonmetallic PCB particle size. When the particle size was 0.07-0.09 mm, the tensile strengths recorded at 6.78 MPa. At particle size of 0.09-0.15 mm, there was no significant changes seen in the tensile strength. However, beyond 0.15 mm, the tensile strength dropped drastically and at particle size of 0.3-0.5 mm, it decreased by about 50% compared to particle size of 0.07-0.09 mm.

While, as can be seen in Figure 4, flexural strength achieved highest value of 12.44 MPa with addition of 0.07-0.09 mm nonmetallic PCB particle size. The flexural strength decreased slightly with further increases of particle sizes from 0.09 to 0.3 mm. However, at particle size of 0.3-0.5 mm, flexural strength decreased drastically by about 31%. This indicates that, adding larger particle size does not favour the mechanical performances of the composites.

A balance of stiffness and toughness is one of the main target as far as mechanical properties are concerned. Therefore, Figures 5 illustrates the effect of different particle sizes on stiffness and toughness of rHDPE/PCB composites. It is proposed that the optimum nonmetallic PCB particle size with balanced mechanical properties is 0.07-0.09 mm with flexural modulus of 16.41 GPa and impact strength of 42.5 J/m (Figure 5).

Overall, it can be noted that the increasing of particle size affected the mechanical properties causing it to decrease. Mechanical properties of composite materials with particle size less than 0.15mm somewhat showed better performances compared to larger particle sizes of 0.15 mm -0.3 mm. Particle size from 0.07-0.09 mm showed the best mechanical properties. While, particle size from 0.15-0.3 mm, the mechanical properties worsened and dropped drastically. This can be rationalized that, smaller particle size presented the bigger specific surface area, which caused the bigger infiltration area of contact between rHDPE matrix and filler particles and vice versa.

Figure 6 shows the microscopic images of nonmetallic PCB material with different particle sizes. Nonmetallic materials with particle sizes of 0.07-0.09 mm and 0.09-0.15 mm contained predominantly single glass fibers (Figure 6a and b). Whereas, fiber in the form of bundles and large resin sheets were seen in particles with bigger sizes of 0.15-0.3 mm and 0.3-0.5 mm (Figure 6c and d).

Particle size distribution of nonmetallic materials in rHDPE matrix can be seen in Figure 7. Nonmetallic particles from 0.07-0.09 mm and 0.09-0.15 mm contained mostly single glass fibers (Figure 7a and b) with majority of the glass fibers being encapsulated in rHDPE matrix and voids were not easily generated. Smaller size nonmetallic particles showed good adhesion between the filler and polymer matrix as the glass fibers were homogeneously dispersed in the matrix. Moreover, small filler size will aid the polymer matrix to flow into the voids and fill the gaps among the fillers thus, providing a good mechanical bonding. Filler agglomeration was obviously seen in bigger particle sizes (0.15-0.3 mm and 0.3-0.5 mm) with deep voids generated near the glass fibers (Figure 7c and d). The glass fibers were in the form of bundles and only some of the polymer matrix were coated on the surface of glass fibers. The presence of voids can affect the performances of the composites severely. Inner structures of rHDPE/PCB composites with fine nonmetallic materials are seen better than those of the composites with large nonmetallic materials. This observation was also inconformity with the result of mechanical properties.

This can be rationalized by the fact that, during the mixing and molding process, smaller sizes nonmetallic materials were able to be covered with rHDPE polymer matrix and flowed into the pores between the fillers. However, when the particle size of nonmetallic PCB materials was too big, the polymer matrix just spread out the surfaces of the fillers and did not fill the gaps/voids completely as can be seen in Figure 9c and d. Apart from that, phase separation was also clearly seen whereby, the nonmetallic materials did not mix well with the rHDPE matrix indicating bonding problem as the large nonmetallic PCB materials showed poor adhesion with the rHDPE matrix (Muniyandi, Sohaili, & Hassan, 2016).

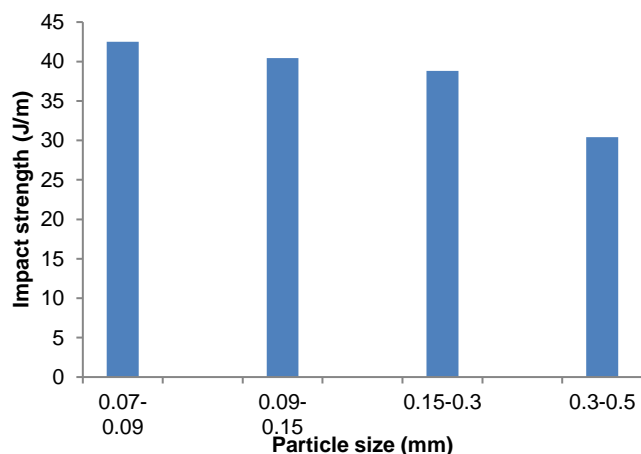


Fig. 2 Impact strength of different nonmetallic PCB particle sizes.

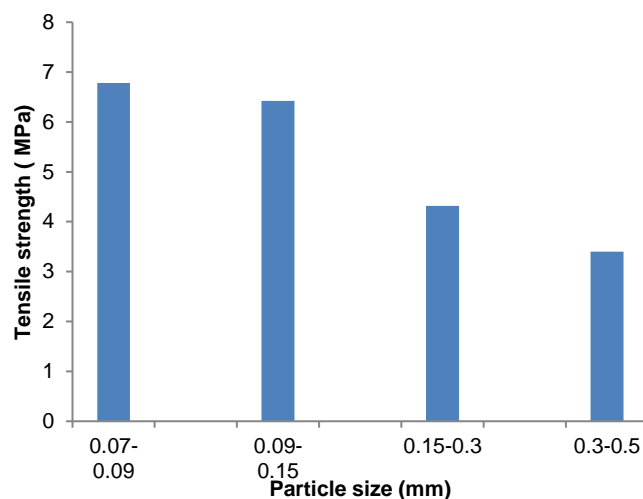


Fig. 3 Tensile strength of different nonmetallic PCB particle sizes.

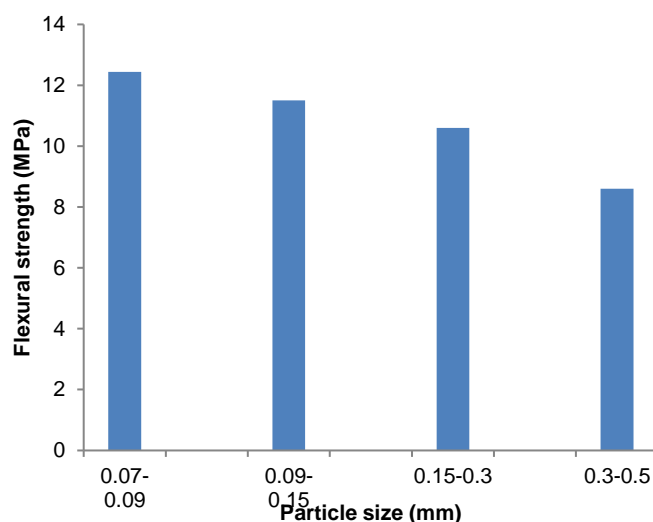


Fig. 4 Flexural strength of different nonmetallic PCB particle sizes.

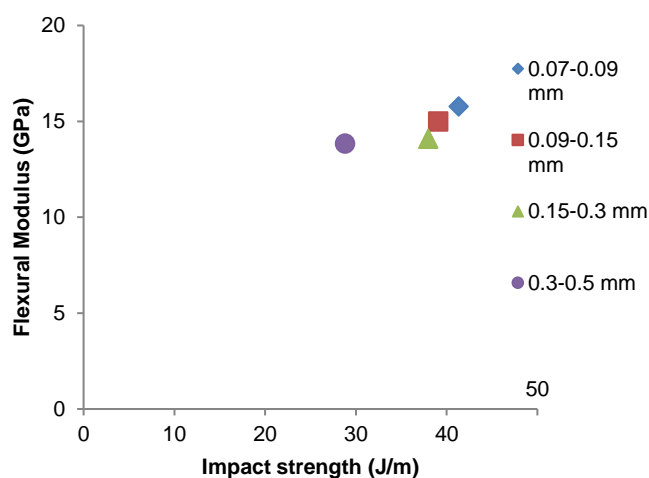


Fig. 5 Determination of balanced properties based on flexural modulus and impact strength of rHDPE/PCB composites with different nonmetallic PCB particle sizes.

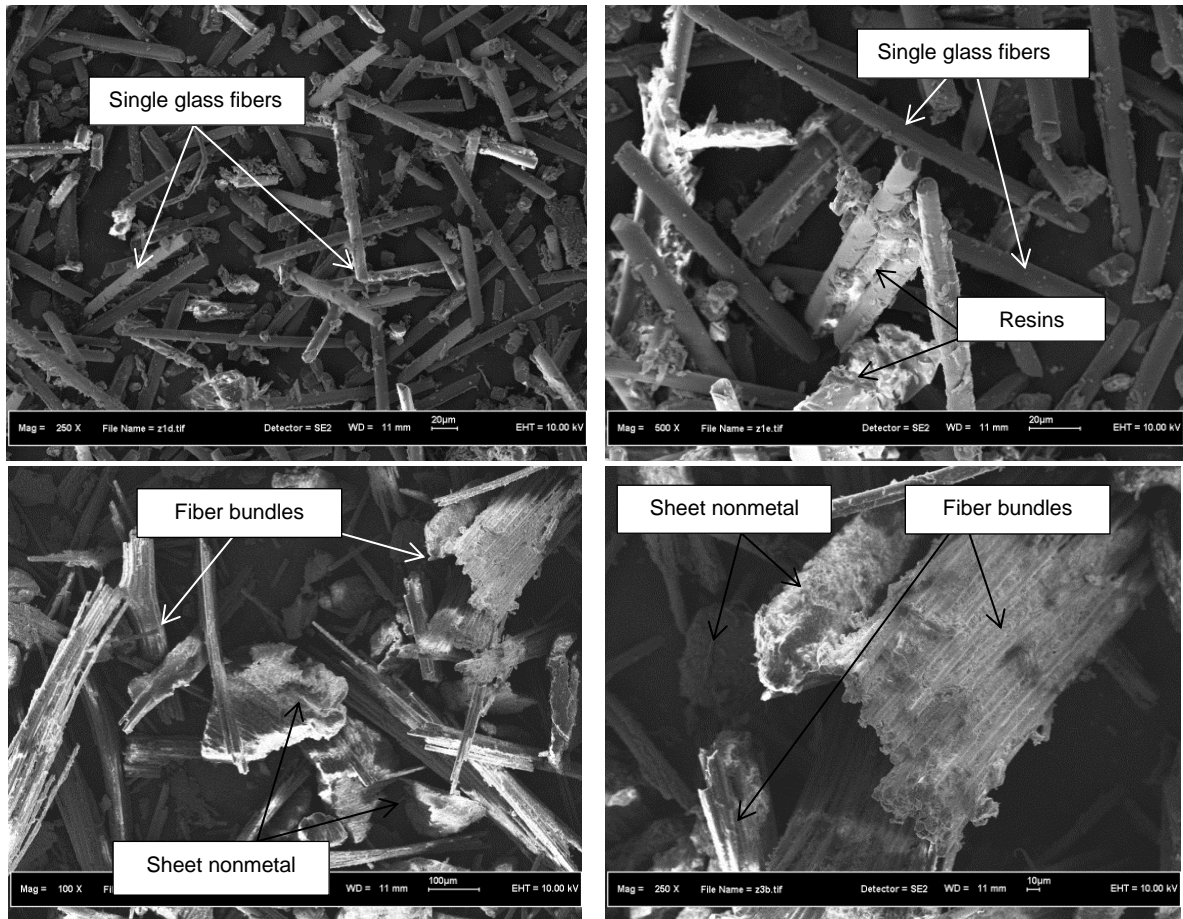


Fig. 6 Micrographs of nonmetallic materials with different particle sizes: (a) 0.07-0.09 mm; (b) 0.09-0.15 mm; (c) 0.15-0.3 mm; (d) 0.3-0.5 mm.

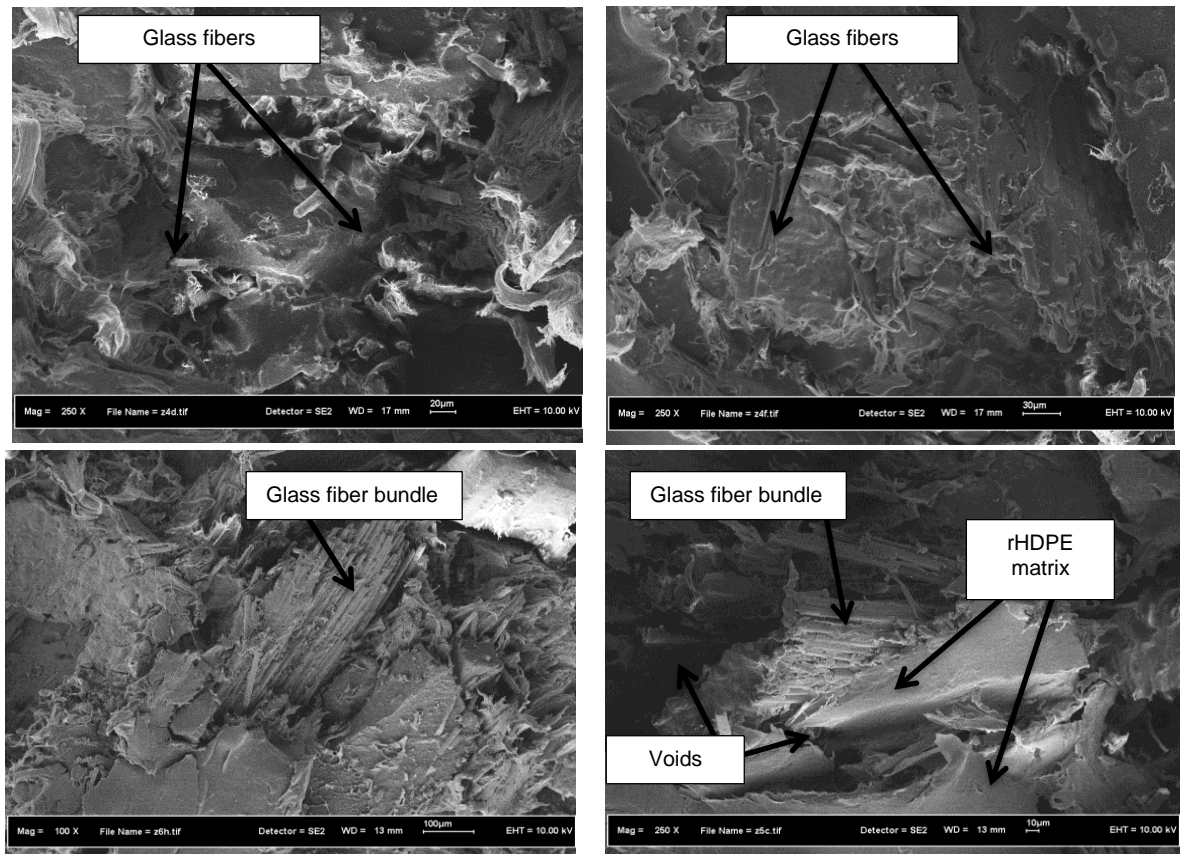


Fig. 7 The inner structure between filler and matrix in the rHDPE/PCB (70/30) composites with different particles sizes of nonmetallic materials: (a) 0.07-0.09 mm; (b) 0.09-0.15 mm; (c) 0.15-0.3 mm; (d) 0.3-0.5 mm.

Effects of different amount of nonmetallic PCB content on the mechanical properties of rHDPE/PCB composites

Particle size of 0.07-0.09 mm showed the best mechanical properties in the previous section, therefore, it was chosen to further study the effects of amount of nonmetallic powder on the mechanical properties of rHDPE/PCB composites. The nonmetallic powder was added to the rHDPE matrix at weight fractions of 10, 30 and 50 wt%. The composites were tested for its impact strength, tensile properties and flexural properties.

There is significant decrease in impact strength by about 19% compared to the neat unfilled rHDPE matrix with incorporation of 10 wt% nonmetallic PCB content (Figure 8). The impact strength continued to decrease slightly with further incorporation of nonmetallic PCB at content of 30 wt% and 50 wt%. The decreasing trend in impact strength implies that the mobility of polymer chain will be reduced with increasing in filler content, thus restricting its movement.

While, for tensile properties (Figure 9), interestingly, Young's modulus increased with increasing in nonmetallic PCB contents from 0 to 50 wt%. However, with incorporation of 10 wt% nonmetallic PCB, tensile strength decreased at initial part but began to achieve constant value with increasing in nonmetallic PCB contents. Overall, with incorporation of 50 wt% nonmetallic PCB, the Young's modulus of the composite increased by about 275%, while tensile strength has reduced by about 15% compared to the unfilled rHDPE matrix.

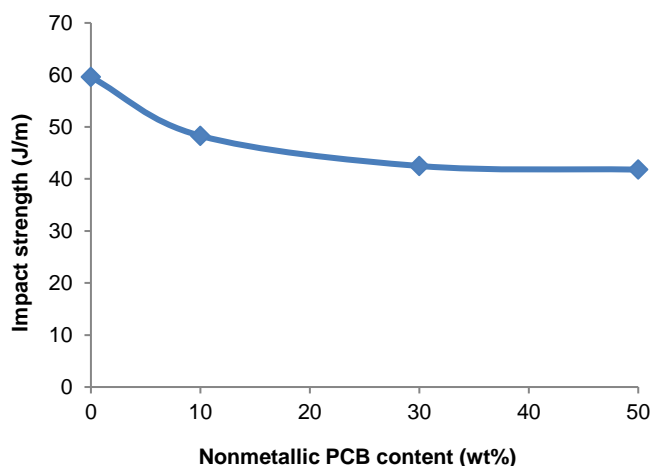


Fig. 8 Effect of different contents of nonmetallic PCB on impact strength.

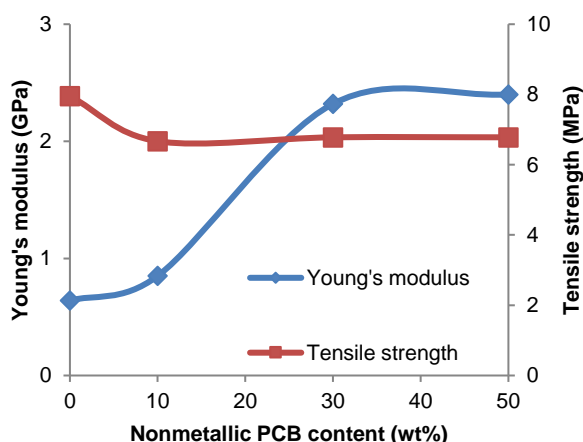


Fig. 9 Effect of different contents of nonmetallic PCB on tensile properties.

The incorporation of rigid filler reinforcement such as nonmetallic PCB in this case into polymer matrix is making it to become more

stiffer, thus increase in modulus. Apart from that, less effective adhesion of rHDPE matrix towards nonmetallic PCB particles could be one of the factor possibly contributed to the low tensile strength compared to the unfilled neat rHDPE matrix (Muniyandi, Sohaili, & Hassan, 2013). In contrast, increasing in nonmetallic PCB contents from 0 to 50 wt% had caused improvements in flexural modulus and strength. The flexural modulus has increased by about 135% with increasing of nonmetallic PCB contents from 10 to 50 wt%, while the flexural strength increased by about 35% with further incorporation of 50 wt% nonmetallic PCB (Figure 10). The increasing trend in flexural properties is expected since, with such millions of glass fibers and good compatibility between the nonmetallic PCBs and rHDPE matrix (Muniyandi *et al.*, 2013). There are mass excellent supporting bodies and appropriate interfacial adhesives are formed between the particles and matrix (Zheng, Shen, Cai, Ma, & Xing, 2009).

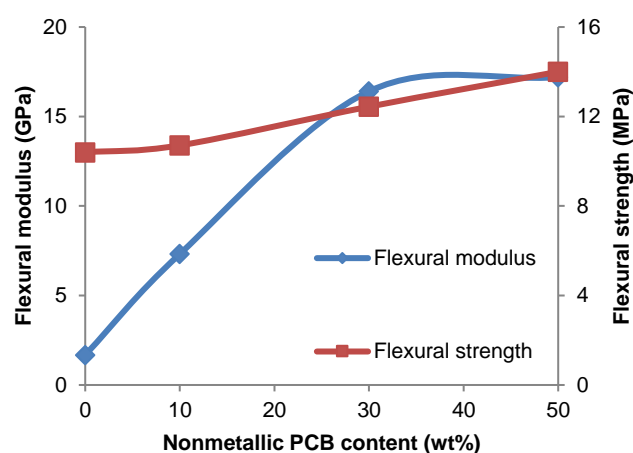


Fig. 10 Effect of different contents of nonmetallic PCB on flexural properties.

CONCLUSION

Nonmetallic materials obtained from PCBs recovery process are suitable and could be used as filler material in rHDPE matrix in production of composite material. The effect of different particle sizes of nonmetallic PCBs on mechanical properties of composites have been studied and it has been proven that smaller size of nonmetallic PCB material as filler contributed to better performances in terms of mechanical properties than larger size. The optimum mechanical properties was obtained from composites with particle size ranging from 0.07 to 0.15 mm. Microscopic observation also revealed that when nonmetallic PCBs with smaller size particles are used, the polymer matrix can encapsulate the nonmetallic materials entirely and voids were not easily generated. Therefore, mechanical properties of rHDPE/PCB composites with fine nonmetallic materials are seen better than those of the composites with large nonmetallic materials. The effects of nonmetallic PCB amount on the mechanical properties were studied and concluded that the composite with nonmetallic PCB loading of 30 wt% showed the excellent mechanical properties. Thus, this research has successfully developed a new potential reuse of recovered nonmetallic materials of PCBs and HDPE plastic waste. From environmental point of view, recycling of these wastes are being attempted in order to reduce its harmful effects on the environment. In fact, due to ever increasing environmental concerns and disposal costs, reuse and recycling the nonmetallic fractions from PCB wastes are considered as the best treatment practices and can generate economy too by commercializing the products made from the rHDPE and PCB composites.

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