A Review on Potential Reuse of Recovered Nonmetallic Printed Circuit Board Waste

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Abstract
In recent years there has been increasing concern about the growing volume of end of life electronics and the fact that much of it is consigned to landfill without any attempt being made to recycle the nonmetallic materials it contains. The production of electric and electronic equipment (EEE) is growing rapidly in most developed countries such as in China, Cambodia, India, Thailand and also in Malaysia. Waste of electric and electronic equipment (WEEE) is significantly increasing. A large amount of nonmetallic materials in printed circuit board (PCBs) are disposed of by combustion and disposal in landfill as the main method for treating nonmetals in PCBs, but it may cause secondary pollution and resource wasting. This paper presents a review on the reclamation and reuse of nonmetallic materials recovered from waste PCBs. The recovered nonmetals were used to make models, construction materials and composite boards. The PCB nonmetal products have better mechanical characteristics and durability than traditional materials and fillers. Products derived from PCB waste processing have been brought into industrial production. The study shows that PCB nonmetals can be reused in profitable and environmentally friendly ways.

Keywords: printed circuit board, nonmetallic, recovery, reuse, precious metals

INTRODUCTION
Based on the notification on scheduled waste received by the DOE Malaysia, a total of 1705308 metric tonnes of SW were generated in 2009 as compared to 1304898 metric tonnes in 2008 (Department of Environment, 2009) which reported an increase of 30.7%. Electronic/Electrical Industry has contributed 196808.64 metric tonnes which was 11.54% of the total quantity of scheduled waste generated by industry in the year 2009 in Malaysia. It is also being predicted by Department of Environmental (2009) in their inventory report that the amount of Waste of Electric and Electronic Equipment(WEEE) will increase by an average of 14% annually and by year of 2020, a total 1.17 billion units or 21.38 million tons of WEEE will be generated. Printed circuit board (PCB) is one of the most common components inside EEE at which without it, those electric and electronic instruments cannot function properly (Huang et al., 2009 and Lee et al., 2004). PCBs form about 3% by weight of the total amount of electronic scrap (Bernardes et al., 1997). The process of reusing recovered metals from PCBs is already quite mature. However the recovered nonmetallic materials are not widely reused. PCBs contain 70% to 80% nonmetals with the main nonmetallic ingredients being of glass fibers, epoxy resins and bromized flame retardant. Traditionally, most of these materials have been directly landfilled or incinerated (Jianzhi et al., 2004). The value of metals contained in waste PCBs is economic incentives for the recyclers. Recyclers use different methods to reclaim metals with high purity, which can be sold at a high price. However, nonmetallic materials are generated inevitably. The amount of nonmetallic materials is enormous, but economic value of nonmetallic materials is very low. Recyclers incur additional expenses when handling and disposing of nonmetallic materials. PCBs recyclers have to pay expensive fee when nonmetallic materials are sent for treatment and disposal, reducing the recycler’s net revenue. In contrast, using nonmetallic materials to produce new products from the nonmetallic materials in PCBs can save large amount of treating fee and generate economic value. In Malaysia and most of the developing countries, there is still no suitable process that being used to recover, reuse or recycle this nonmetallic PCBs. However, in developed countries like China, nonmetallic PCBs has been used to produce products such as nonmetallic plate (NMP) (Guo et al., 2008), composite boards (Mou et al., 2007), and other products that is proven capable to generate economic value. The objective of this paper is to present a review of few potential reuses of recovered nonmetallic PCBs so that the technology reviewed here can be applied in Malaysia to produce a cost effective method in utilizing nonmetallic PCBs waste that also have multipurpose usage. This can also overcome the environmental pollution associated with the recycling of PCBs and adopt a more sustainable approach to the problems associated with
end of life electronics. Lastly it can also help in promoting a better and proper management of PCBs waste in Malaysia and enhanced the cleaner technology by introducing new approach in recycling nonmetallic PCBs waste.

PCB Compositions
No one shows more interests than waste (PCB) in the recycling field of WEEE. PCBs are platforms on which integrated circuits and other electronic devices and connections are installed. In general, waste PCBs contains approximately 30% metals and 70% nonmetals (Guo et al., 2008, Goosy and Kellner, 2002). The material presents in PCB can be further categorized in three groups that are organic, metals, and ceramics. Organic materials in PCB are mainly composed of plastics with contents of flame-retardants and paper. The type of plastics is predominantly C-H-O and halogenated polymers. Nylon and polyurethane are also used sometime in smaller amounts. Metals in PCBs consist of a large amount of base metals such as copper, iron, aluminium and tin, rare and precious metals like tantalum, gallium, platinum, gold, silver, and palladium. Precious metals are metals that have high economic value due to their rarity. Hazardous metals such as chromium, lead, beryllium, mercury and cadmium are also present. These hazardous metals are metals with properties that make them potentially harmful and toxic to health and environment. Ceramics present in the PCB are primarily silica and alumina. Other ceramic materials include alkaline earth oxides, mica and barium titanate. Metals are sent to recovery operations. However, significant quantities of nonmetals in PCBs present an especially difficult challenge for recycling because it mainly consist of resins and glass fibers which cannot be remelted or reformed because of their network structure (Mou et al., 2004). PCBs also contain large amount of solder, Cu and Ni along with Fe and precious metals. Approximately 90% of the most valuable materials in most scrap boards of PCB are in the gold and palladium content.

Recycling Technologies of Printed Circuit Boards Waste
PCB recycling process usually divided into three stages which are pretreatment stage, shredding/separation and physical/chemical recycling. As illustrated in Fig.1, PCB recycling generally starts from the pretreatment stage whereby an optional composition analysis and disassembly of the reusable and toxic parts will be carried out. Through shredding and separation process, PCB boards are reduced into small sized particles and can be separated by various separation methods such as physical or chemical refining process. In physical recycling process, magnetic separators, low intensity drum separators are widely used for the recovery of ferromagnetic metals from non-ferrous metals and other non magnetic wastes. While, Electric conductivity bases separation such as Eddy current separation (Rem, 1999 and Lungu, 2005), Corona electrostatic separation (Iuga et al., 1998) are used to separate materials of different electric conductivity such as non ferrous metals from inert materials. (Veit at al., 2005, Cui and Forssberg, 2003). This Eddy current separation technology is also used to recover metals, which consists of approximately 28% by weight of a typical PCB scrap (Jianzhi et al., 2004). Other than that, Density based separation of particles (Cui and Forssberg, 2003) such as sink-float separation (Zhang and Forssberg, 1999) is also used to separate metal from nonmetallic materials in PCB scraps. Hence, it can be said that, physical recycling reported a great potential and a promising recycling method without environmental pollution, lesser investment, operation cost and low energy cost (Wen Xuefeng, 2005). However, the separation between the metallic and nonmetallic materials in PCB waste has to be enhanced. Typical chemical recycling process consists of pyrolysis process (Menad et al., 1998) and gasification process (Cui and Zhang, 2008). Pyrolysis actually degrades the organic part of the PCB waste, making the process of separating and recycling the organic, metallic and glass fibre in PCB much easier. One of the main ingredients in PCB scrap, resin is originally produced from crude oil and can be thermally cracked into fuels or petrochemicals. So, it can be seen that, pyrolysis is an economical and environmentally sound resource recovery alternative to treat PCB scraps (Chien et al., 2000). Recycling of metallic fractions in PCB can be done through metallurgical recovery. It has been recently reviewed by Cui (2008) and underlines three approaches which are pyrometallurgy, hydrometallurgy and biometallurgy. Traditionally, pyrometallurgy technology has been used for recovery of precious metals from WEEE to upgrade the mechanical separation which cannot efficiently recover precious metals. However, pyrometallurgical processing has its own limitation. It results in a limited upgrading of the metal value and hydrometallurgical techniques or electrochemical processing are required for refining. Hydro metallurgical processes are mainly used for recycling of the metallic ferrous materials in PCB where the extraction of the metal content is profitable (Bernandes et al., 1997). Jianzhi et. al (2004) has reported in their studies that different hydrometallurgical processes can be used depending on the substrate material (ceramic, glass, or polymer). They also stated that, for nonmetallic substrates, metals are recovered from substrates by the process of leaching in the resulting solution. While for metallic substrates, electrochemical processing can be used to recover metals. Thus, a pure metal recovered can be sold without any further processing while the remaining nonmetallic substrates still need to be treated thermally prior reusing or dumping in
landfills. Hydrometallurgical method is also said to be more exact, more predictable and more easily controlled compared to pyrometallurgical processing. Biometallurgy has been used for recovery of precious metals and copper from ore for many years (Ehrlich, 2007 and Rohwerder et al., 2003) but biometallurgy used for recycling waste PCBs is still in its infancy. Biotechnology is one of the most promising technologies in metallurgical processing. This is mainly because microbes have the ability to bind metal ions present in the external environment at the cell surface or to transport them into the cell for various intracellular functions. This interaction could promotes selective or non selective in recovery of metals. But this technology is still under development.

Reuse of Recovered Nonmetallic Materials from Waste PCBs

The recovered nonmetallic material has been used in several ways based on the physical characteristics of the nonmetallic powder. In this paper, a few potential reuses of recovered nonmetallic PCBs have been reviewed. Many previous applications have used the recovered nonmetallic materials as filler or for concrete and various framing materials. The recovered nonmetallic PCB powder is lighter than cement and sand, has finer granularity which makes the microstructure more reliable, and contains coarse glass fibers which could improve mechanical strength of the materials. Yokoma and Iji (1995) have carried out many studying works on recycling glass fiber and resin powder taken from PCBs. In their studies, nonmetals reclaimed from waste PCBs could be as fillers for other products, such as construction materials, decorating agent, adhesives and insulating materials.

Another study by Mou et al (2007) used six different percentages of recovered nonmetallic powder to make construction materials that were tested according to the China National Testing Method for Cement Mortar. The detailed compositions of the bricks made from the sand and PCB nonmetallic powder and the flexural and compressive strength of the modified and standard bricks are listed in Table 1. From the data in Table 1, it can be seen that sample R3 has the best flexural strength while sample R4 has the best compressive strength. Therefore, sample R3 or sample R4 or some composition of these two would give the best result. Muo et al (2007) also concluded from their studies that the reuse of recovered nonmetals of PCB as fillers to make construction materials is feasible but not very attractive since the improvements in the flexural and compressive strengths are quite limited with less than 10% when compared with the standard concrete (R1).

<table>
<thead>
<tr>
<th>Sample</th>
<th>Portland Cement (g)</th>
<th>Sand (g)</th>
<th>PCB nonmetals (g)</th>
<th>Water (ml)</th>
<th>Flexural strength (MPa)</th>
<th>Compressive strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>540</td>
<td>1351</td>
<td>0</td>
<td>238</td>
<td>8.30</td>
<td>0.43</td>
</tr>
<tr>
<td>R2</td>
<td>505</td>
<td>1199</td>
<td>63</td>
<td>222</td>
<td>8.18</td>
<td>0.43</td>
</tr>
<tr>
<td>R3</td>
<td>474</td>
<td>1066</td>
<td>118</td>
<td>208</td>
<td>8.76</td>
<td>0.44</td>
</tr>
<tr>
<td>R4</td>
<td>446</td>
<td>949</td>
<td>167</td>
<td>196</td>
<td>8.65</td>
<td>0.46</td>
</tr>
<tr>
<td>R5</td>
<td>422</td>
<td>844</td>
<td>211</td>
<td>186</td>
<td>8.03</td>
<td>0.35</td>
</tr>
<tr>
<td>R6</td>
<td>400</td>
<td>750</td>
<td>250</td>
<td>176</td>
<td>7.42</td>
<td>0.31</td>
</tr>
</tbody>
</table>

Source: Composition of brick material (Mou et al, 2007)

They also mentioned in their report that, the replaced materials in the original concrete, the sand and cement, are cheaper and abundant, so the substitution will not give a good economic return. Therefore, current research on the use of recycled PCB nonmetallic materials as construction materials seek simply to find some use for the recycled material even it is a relatively small amount. Apart from that, Guo and Xu (2009), and Guo et al (2010) from Shanghai Jiao Tong University have also developed a technique to utilize the nonmetallic PCBs materials in production of Nonmetallic Plate (NMP). In their study, Unsaturated Polyester Resin (UPR) was used as the bonding agent (Guo, 2008) due to its low viscosity, fast cure, excellent chemical resistance, and low cost (Rebeiz, 1996). In their study, the content of nonmetallic PCBs and filler materials was kept at a constant value of about 60 wt%. The Cu particles and non-metallic PCBs after two-step crushing and electrostatic separating are shown in Fig. 2. The nonmetallic PCBs were added to the raw materials mixture at weight fractions of 0 to 40%. To complete the curing process of UPR, additives were added and tert-butyl perbenzoate (TBPB) was added as the initiators. The glass fibers used were 25mm length (Guo, 2008). Table 2 shows the raw materials of the NMP used in the study. The production process of NMP is shown in Fig. 3.

Fig. 2: Metallic fractions (a) and the Nonmetallic fractions (b) of pulverized waste PCBs (Guo et al., 2008)
The application of nonmetallic PCBs waste does not stop until here. Mou et al (2007) used the NMP to make composite boards. Composite boards are used extensively in many fields including automobiles, furniture, amusement equipment, and decorative materials. The main components used in this composite boards are as listed in Table 3. The most attractive aspect of making composite boards from PCB nonmetallic materials is the potential economic benefit because the recovery not only recycles waste PCBs but also earns a profit. In general it can be said that, products made from composite boards are high value products with large profit margins. A wide variety of products can be made from composite boards for various applications such as trays, kitchen utensils and so on. The most important and useful characteristics of the recovered nonmetallic material is their compatibility with the epoxy resin adhesive used to bind the filler and the fibers, so the nonmetallic PCB has better compatibility with the resin adhesive which suggests better moulding properties and mechanical strength (Mou et al., 2007). They used different proportions of nonmetallic PCB in their studies and compared it with the two typical materials used for making composite boards which are talc and silica powder. Their research showed that the outstanding characteristic of the nonmetallic material board is its flexural strength, which was enhanced by more than 50% for the 15% blending ratio when compared with talc. Therefore, they concluded that this characteristic is good for products that mainly bear bending stresses.

Moreover when compared with talc and silica powder, PCB nonmetals have three main advantages such as, coarser granularity, containing glass fiber and better compatibility with the binding agent used in making composite board. Coarser granularity and glass fiber may enhance the intensity.

Analysis of the mechanical properties conducted by Mou et al (2007) indicates that the nonmetallic PCB can best be used to make products which resulted in greater bending stresses because of its excellent flexural strength. The process used to make composite boards from the nonmetallic PCB was also used to make the other construction materials including walls, frames. Steel fiber concrete and glass fiber reinforced plastic (FRP) are two commonly used materials to make construction materials. The main advantages of these products made of PCB nonmetallic are lower in cost and better mechanical strength, especially the flexural strength. Moreover, these processes which make use of PCB nonmetallic materials is a better alternative rather than be sent to landfills. Nonmetallic PCBs are also used to replace wood flour in the production of wood plastic composites. In analogy, addition of nonmetallic PCB as reinforcing fillers in polypropylene has proven to be an effective way to enhance strength and rigidity with particles size between 0.178-0.104 mm (Guo et al, 2010). Modified silane coupling agent, could be successfully added in the composites as a substitute of traditional fillers.

As one of the plastic wastes to a certain extent, the non-metallic PCB can also be used with some effectiveness as a partial replacement of inorganic aggregates in concrete applications to decrease the dead weight of structures. According to Panyakapo and Panyakapo (2008), lightweight concrete is extensively used for the construction of interior and exterior walls of buildings for the case where the walls are not designed for lateral loads. In their recent study, they have used thermosetting plastic waste for lightweight concrete. The melamine waste, which is also a kind of thermosets used in PCBs was selected for application in the mixed design of concrete. They found that the ratio of cement, sand, fly ash, and melamine waste equal to 1.0:0.8:0.3:0.9 is an appropriate mix proportion. The results also showed

<table>
<thead>
<tr>
<th>Ingredients</th>
<th>Content (wt %)</th>
</tr>
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<tbody>
<tr>
<td>Nonmetallic fraction</td>
<td>0,10,20,30,40</td>
</tr>
<tr>
<td>CaCO₃</td>
<td>64,54,44,34,24</td>
</tr>
<tr>
<td>Unsaturated Polyester</td>
<td>18</td>
</tr>
<tr>
<td>Polystyrene</td>
<td>6</td>
</tr>
<tr>
<td>TBPB</td>
<td>0.2</td>
</tr>
<tr>
<td>Glass fiber</td>
<td>10</td>
</tr>
<tr>
<td>Zinc stearate</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 2: Raw Materials of the NMP

Source: (Guo: 2008)

<table>
<thead>
<tr>
<th>Ingredients</th>
<th>Ratio (wt %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass fiber cloth</td>
<td>30-45</td>
</tr>
<tr>
<td>Epoxy resin</td>
<td>35-40</td>
</tr>
<tr>
<td>Fillers</td>
<td>5</td>
</tr>
<tr>
<td>PCB nonmetals</td>
<td>15-30</td>
</tr>
</tbody>
</table>

Table 3: Main components in composite boards

Source: (Mou et al: 2007)
that compressive strength and dry density are 4.14N/mm² and 1395 kg/m³ respectively. It has been proven in their study that, this type of concrete meets most of the requirements for non-loading bearing lightweight concrete according to ASTM C129 Type II standard. Their study indicated that use of waste thermosts of PCB to produce lightweight concrete is a promising method. The nonmetallic PCBs waste is a mixture of waste thermosts, glass fibers and other components, therefore, it can replace the melamine waste to produce lightweight concrete.

Another study by Guo et al (2009) also indicated that, the glass fibres and resins powder contained in the non-metallic PCBs can also be used to strengthen the asphalt by composition effect. Adding of the nonmetallic PCBs to asphalt can also reduce the cost of asphalt whose usage amount is very large. This is because, it is more economic since the cost of the nonmetallic PCBs waste can be considered as zero because they are unwanted waste otherwise would be expensive if sent to disposal or treatment.

Pyrolysis of organic materials contained in PCBs leads to the formation of gases, oils and chars with can be used as chemical feedstocks or fuels (Williams and Hall, 2007). At present, there are some pilot studies on the recovery of metals from PCBs waste by pyrolysis in China. According to a report from Huazhong University of Science and Technology in China, pyrolysis was adopted to recover valuable materials from PCBs. The result indicated the liquid, gas, and solid were obtained (Sun et al., 2002 and Sun et al., 2003). The liquid products have high calorific values that might be recycled as fuel oils after simple treatment. However, pyrolysis is also highly dependent on equipment investments and the residues are a mixture of organic and various metals which need to be further separated.

CONCLUSIONS
This paper describes several potential methods for reusing recovered nonmetallic from waste PCBs. The nonmetallic PCB can be reused in construction materials, to make models, in composite boards, and in practical products. Although these applications are said better than landfills and incineration, but many improvements are still needed to futher study the potential reuse of this nonmetallic PCB waste into more profitable and practical use. From this review also, it can be seen that using recovered PCB nonmetallic material to make composite boards and related products will be effective solutions for recovering nonmetallic materials of waste PCBs and reduce resource wasting. Developing new techniques for reuse of recovered PCB nonmetals can also help in resolving the environmental pollution associated with the recycling of PCBs and the adopt a more sustainable approach to problems associated with end of life electronics.

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