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Performance evaluation for composites based on recycled polypropylene using principal component analysis and cluster analysis

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ABSTRACT

It is more economic and environmental-friendly to use recycled plastics in manufacturing, especially under the context of circular economy. Since there are many which formulae exist which improve the different properties of recycled plastics, there is a need to develop decision support tools for evaluating the materials based on multiple properties. In this study, principal component analysis (PCA) was used as a decision support tool to evaluate the performance of plastic composites based on multiple properties. Cluster analysis (CA) was used for classify those properties. The base materials were polypropylene (PP), including a virgin PP (vPP) which is currently used in automobile industry and recycled PP (rPP) recovered from mixed scrap plastics. Two primary fillers were talcum powder (talc) and glass fibre (GF) which are commonly used in the composites for manufacturing industry, maleic anhydride grafted polypropylene (MAPP) was used as compatibiliser. Two vPP-based industrial composites for making automobile parts were used as comparatives. The materials were blended using a twin screw extruder, pelletized, and injected moulded into ISO standard sample specimens for ISO standard mechanical tests. The properties tested were tensile strength, yield strength, flexural modulus, flexural strength, and impact strength. The experimental results revealed that both virgin and recycled plastics are improved by the addition of fillers, and some properties of recycled plastics are better than those of industrial composites. Based on the experimental results, the multiple tested mechanical properties and the composites were classified by CA. Evaluation was performed by PCA, and the scores of some rPP based composites are higher than vPP based composites and industrial materials.

1. Introduction

From an economic perspective, manufacturers of plastic parts want to use more recycled plastics to reduce production costs, because recycled plastics are cheaper. From environmental protection perspective, using recycled plastics could reduce greenhouse gas emission by approximately 80% (Makuta et al., 2000). The calculated carbon footprint of recycled plastics are lower than virgin materials, thus the proportion of recycled materials used in manufacturing should always be maximised (Dormer et al., 2013). Moreover, recycled plastics are recovered from the waste stream, which is considered as a renewable source of material, while virgin plastics are mainly made from fossil fuels which is non-renewable. Using recycled plastics in manufacturing industry fits the popular idea of circular economy, and become a common practice towards the full scope of socio-ecological sustainability (Lindahla et al., 2014).

Due to chemical and physical changes in the molecular structures, recycled plastics can have less desirable properties (such as rheological and mechanical properties) when compared to virgin material (Hemela and Cramer, 2002). Common practices for improving desired qualities of recycled plastics are to blend them with various fillers (Dintcheva et al., 1997). Talcum powder (talc) is one of those common fillers used for improving the performance of rPP (Long et al., 1995; Tall et al., 2001; Bahlouli et al., 2006). Bahlouli et al. (2006) promoted rPP by compounding with talcum powder and/or a virgin high-crystallinity PP, and the results of mechanical tests indicated that the composites can be used for demanding applications, such as automobile parts. Glass fibre (GF) has been commonly used as a reinforcing agent for polymers once developed

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(Marsh, 2006). When compared to carbon fibre, GF is much cheaper and significantly less brittle though it is not as strong as carbon fibre (Fu et al., 2000). Al Maadeed et al. (2012) added GF to palm wood flour/rPP composites, and used an extruder and an injection moulding machine to mix and prepare samples. The results shows that the tensile strength and Young's modulus of wood flour/rPP composites increased by addition of GF, as little as 5 wt% GF addition to wood flour/rPP increases the tensile strength by about 18% compared to the wood flour reinforcement alone. Maleic anhydride grafted polypropylene (MAPP) is one of the most common coupling agents used to improve the interactions between PP and their various fillers, especially for rPP and talc or GF (Tall et al., 2001; Serrano et al., 2014).

Current research mainly focus on reporting the changes in properties by formulation as those mentioned above, as only a limited number of researchers are looking into analysis properties and evaluation of materials for potential applications. An example of the existing research is Recycling Cycle of Materials (RCM), it is a tool that provides scientific/technical support in the selection of materials based on series of tests (Cândido et al., 2011). However, it only focus on certain types of materials with specific treatments, and lacks necessary analysis of interrelationships of different properties and is unable to handle multiple criteria evaluation. Thus, principal component analysis (PCA) and cluster analysis (CA) were introduced as decision making support tool to analyse the interrelationships between multiple properties of recycled plastic based composites, to sort the general patterns of compositions, and to perform quick evaluation on those materials. With proper analysis and evaluation procedure, the promoting effect of formulation is proved. Thus, the use of recycled plastics can be expanded, and plastic recycling rate can be improved which is beneficial to economy and environment (Karlsson and Luttropp, 2006; Luttropp and Lagerstedt, 2006).

PCA is first developed by Pearson (Pearson, 1901; Hotelling, 1933; Joliffe, 2002). It is a statistical procedure that converts a set of observations of possibly correlated variables into a set of values of linearly uncorrelated variables which are called principal components (PCs) (Joliffe, 2002). The selected number of PCs is less than or equal to the number of original variables. PCA is also considered as a data reduction procedure, and the selection accounts for as much of the variability in the data as possible (Joliffe, 2002). While cluster analysis characterizes similarities among samples by examining interpoint distances representing all possible sample pairs in high dimensional space, and yields two dimensional diagrams presenting similarities of samples called dendrograms (Sharaf et al., 1986). As statistical methods in exploratory data analysis and for making predictive models, both techniques have been applied in many fields such as environmental science (Zafiriou et al., 2012; Chen et al., 2015), geochemical study (Fadigas et al., 2010; dos Santos et al., 2010), analytic chemistry (Pontes et al., 2009), polymer science (Zhao et al., 2009a, 2009b), and manufacturing industry (Zeng et al., 2008; Park et al., 2015).

This study focuses on using CA and PCA techniques on classifying the relationship between multiple tested properties and evaluating PP based composites with addition of talc, GF and MAPP in different proportions. Mechanical properties were tested in accordance with respective ISO standards, and analysis was performed through utilising CA and PCA techniques. The experimental results were plotted and compared to two industrial use PP/talc composites. The effects of introducing talc and GF as fillers are discussed. The interrelationships of multiple mechanical properties of PP based composites and general composition patterns were sorted and plotted by CA, and the materials were evaluated by PCA. The economic advantage of recycled plastic composites was identified based on material costs combining PCA results. Through the use of CA and PCA, the understanding of rPP-based composites is improved, the quick evaluation method is established, and comparisons are made against industrial composites based on performance and material cost. The methods could be used as decision support tools in the early stage of product development for material evaluation and selection, which would increase environmental sustainability at the end of the product's useful life and expand the application of recycled plastics.

2. Experimental approach

2.1. Materials

The vPP material used in this work is a high grade homopolymer, denoted EPS30R, produced by Dushanzi Sinopec, and is used for automobile part production. The material was used as received and has an average particle size of 3 mm.

The rPP material used in this work is recovered from mixed scrap plastics, e.g. post-consumer crates, household devices, and used packages, as the poorer performance is expected from such mixed plastic scraps (Luijsterburg and Goossens, 2014). The material was used as received and has an average particle size of 3 mm.

Talc used in this work is bought from Ningbo Haike, a local supplier, has an average particle size of 12.5 μm and was used as received.

GF used in this work is bought from a local factory, which has an average length of 6 mm, a density of 2.5 g cm^{-3} and was used as received.

The coupling agent – MAPP used in this work is bought from Nanjing Deba Chemical Co., Ltd, has average particle size of 2.5 mm and was used as received.

There were two types of industrial use PP/talc composites in this study as comparatives. These plastics are mainly used in the automobile industry for producing dashboards and other interior trims. A5132TB12378L (denoted by Pret PP, its manufacturer's brand) is manufactured by Shanghai Pret Composites Co., Ltd, and is a PP copolymer with 20 wt.% talc as a filler, which has an average particle size of 3 mm. APO-4004HMB001 (denoted by Kinghfa PP, its manufacturer's brand) is manufactured by Shanghai Kingfa Science & Technology Co., Ltd, a type of PP copolymer with 40 wt.% talc as filler, whose average particle size is 3 mm. Both materials are bought directly from a factory of Ningbo Tokai Minth Automotive Parts Co., Ltd, and both materials were used as received.

The detailed groups of various proportions as shown in Table 1. Both vPP and rPP were started with no talc content (ash content tests are performed to verify that no talc in original rPP in later testing section), talc content was increased by 10% up to 40%, and MAPP content was kept to 1:4 to talc content in the various compositions. GF content was increased by 5% up to 20%, and MAPP content was kept at a 1:2 ratio to GF content in the various compositions. The selection of filler/MAPP ratio is based on empirical experience and literatures (Tall et al., 2001; Bahlouli et al., 2006; Serrano et al., 2014). The two types of industrial composites were used as comparatives.

Further, the improvement rate per loading (*IRPL*) was used to calculate the proportional ratio of performance' improvements of recycled composites comparing to the original performance of recycled plastics per 1% added filler loading, with the purpose to check the effectiveness of each filler.

2.2. Sampling

All materials were initially processed by an electrical mixer with speed of 60 rpm for 5 min according to proposed compositions in Table 1. Then mixed materials were blended by a Kangrun KRSHJ-