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Improving mechanical properties of recycled polypropylene-based composites using Taguchi and ANOVA techniques

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Abstract

This study was aimed at optimising the composition of recycled plastic based composite for improving mechanical performance. The fractions of virgin polypropylene (vPP), talcum powder (talc) and maleic anhydride grafted polypropylene (MAPP) were selected as controllable factors. Taguchi L9 (3^3) orthogonal array (OA) was applied as an experimental design tool. Compositions were prepared by extrusion and injection moulding. The performance was measured and expressed in signal to noise (S/N) ratio. The S/N ratios were investigated by the Taguchi coupled analysis of variance (ANOVA) to determine optimal condition. The effectiveness and efficiency of the proposed approach was demonstrated through confirmation tests.

Keywords: Recycled polypropylene; Mechanical property; Taguchi method; Analysis of variation; Signal to noise ratio

1. Introduction

Under the concept of circular economy, it is more economic and environmental to use recycled plastics to replace virgin plastics, especially for materials of enormous consumption, such as polypropylene (PP) [2]. Also, extending the use of recycled materials could promote the recycling rate [2]. But, recycled PP (rPP) tend to have inferior performance during manufacturing process when compared with virgin materials [1,2], the applications of rPP are thereby limited [2,3,4]. With the addition of fillers, recycled polymer matrix composites (RPMCs) with desirable properties can be produced [2,3,4], and some of them are even better than virgin materials [2].Talcum powder (talc) is one of the most used reinforcing fillers used for promoting the performance of rPP [2,5,6,7,8]. Talc not only enables to improve both the thermal and mechanical properties of rPP [2,5], but also facilitates the production by reducing and homogenizing the molding shrinkage [6]. Also, talc has a positive stabilising effect on the mechanical properties of PP composites [7,8]. The stabilising effect of talc addition is highly depended on the interfaces between the talc and the PP matrix [9]. Further, there are some tradeoffs in rPP/talc composites, as tensile and flexural properties increased with addition of talc while impact properties deteriorated [2,8]. Thus, formula analysis, design and optimisation of rPP/talc composite are required to extend its application.

Nomenclature

AEV	Accumulated explained variation
ANOVA	Analysis of variance
DF	Degree of freedom
EV	Explained variation
FM	Flexural modulus
FS	Flexural strength
GRA	Grey relational analysis
HCA	Hierarchical clustering analysis
MAPP	Maleic anhydride grafted polypropylene
MS	Mean of square
MFI	Melt flow index
OA	Orthogonal array

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PP	Polypropylene
PC	Principle component
PCA	Principle component analysis
PCE	Principal component estimate
RPMC	Recycled polymer matrix composite
rPP	Recycled polypropylene
RSM	Response surface methodology
SEM	Scanning electronic microscopy
S/N	Signal to noise
SS	Sum of square
SEBS	Styrene-ethylene-butylene-styrene
Talc	Talcum powder
TM	Tensile modulus
TS	Tensile strength
vPP	Virgin polypropylene

Formula design of polymeric composites has attracted an increasing attention during recent years, and several approaches have been developed to optimise the composition of PP composites for improving multiple properties [8,10,11,12,13,26]. Leu et al used experimental design to obtain the optimal levels of the selected components in an arranged sequence [10]. Homkhiew et al adapted a D-optimal mixture experimental design in modelling of mechanical characteristics of wood flour filled RPMCs [11]. Ayaz et al used Taguchi method combined with grey relational analysis (GRA) to determine the optimal composition of PP/LLDPE/TiO_2/SEBS composites for improving impact and flexural strength [12]. Taguchi optimisation approach was also adapted by Porras et al for improving tensile properties of biocomposites [26]. Ghasemi et al designed experiments according to response surface methodology (RSM) to optimise the fractions of talc, MAPP and exfoliated graphene nanoplatelets (xGnPs) [13]. In our previous work, hierarchical clustering analysis (HCA) and principal component estimate (PCE) was used to obtain cheapest rPP composites which met the technical requirements of automobile parts [8].

The literature review shows research on formula design for rPP composites is limited [8,11]. Adapting rPP into manufacturing could increase the recycling rate of plastic waste [4,14], and the composition optimisation can be thereby considered to be the first crucial step [8]. Taguchi method and analysis of variance (ANOVA) were applied for this purpose. Taguchi method coupled with ANOVA has been extensively applied in optimising manufacturing procedures of plastic products [15,16,17,18,19,20,21], only limited applications were found in formula design [11,26]. In this study, vPP, talc and MAPP were selected as the controllable factors, and experimental design was based on a Taguchi L9 (3^3) OA. The aim of using Taguchi OA is to reduce the number of initial composition trials without sacrificing comparability of controllable factors [22]. Compared with other formula optimisation approaches [8,10,12,13], the trials used in Taguchi method are minimal [11,26]. The tested mechanical properties were expressed in form of signal to noise (S/N) ratios, and the effect of each component was analysed. Due to the single response controlling capacity of Taguchi method [12] and [19], the tested mechanical properties were transformed to a series of scores using principal component analysis (PCA). The optimal formula was hence obtained via analysing PCA socres and was later verified through confirmation tests.

2. Experimental

2.1. Materials

The rPP pellets used in this study was purchased from Tianqiang Recycling Co., Ltd., Shanghai, China, and have a density of 0.91 g cm^{-3} and a melt flow index (MFI, at 230 °C under a load of 2.16 kg according to ISO1133-1:2011) of 2.47 g/10 min. An injection grade of PP homo-polymer with trade mark of H1500, produced by LG Chem Co., Ltd., Republic of Korea, was used as vPP in the matrix resin. The density and MFI are 0.9 g cm^{-3} and 10.97 g/10 min, respectively. The coupling agent - maleic anhydride grafted polypropylene (MAPP) used in this study is bought from Nanjing Deba Chemical Co.,Ltd, has a density of 0.9 g cm-3 and a MFI of 88.67 g/10 min. Talc used in this study is purchased from Ningbo Haike, a local supplier, has an average particle size of 12.5 µm and a density of 2.75 g cm^{-3}.

2.2. Design of Compositions

The 3 selected components - vPP (wt.%), talc (wt.%) and MAPP (wt.%) and their levels are shown in Table 1. The full factorial design requires 3^3=27 possible combinations of tests to evaluate the effects of the selected components, while only a total of 9 experiments required in a Taguchi L9 (3^3) OA, as shown in Table 2. A significant reduction in the number of trials has been achieved when compared with previously proposed formula optimisation methods [10,11,13].

Table 1. Selected components (vPP, talc and MAPP) and their levels.

Components	Level 1	Level 2	Level 3
vPP (wt.%)	20	40	60
talc (wt.%)	5	10	20
MAPP (wt.%)	0	2.5	5

Table 2. Designed compositions based upon Taguchi L9 (3^3) OA.

Trial No	vPP (wt.%)	talc (wt.%)	MAPP (wt.%)
1	20	5	0
2	20	10	2.5
3	20	20	5
4	40	5	2.5
5	40	10	5
6	40	20	0
7	60	5	5
8	60	10	0
9	60	20	2.5

2.3. Sample Preparation

After drying in an oven at 75ºC for 12 h and mixing in a high-speed mixer for 3 min, all materials were compounded by a KRSHJ-20 co-rotating twin-screw extruder, whose screw