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SECURING SUPERIOR PROPERTIES OF COMPOSITE (PP+ WF) THROUGH CENTRAL COMPOSITE DESIGN

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Abstract. Due to numerous attractive properties, use of composites is in increasing trend. Efforts are being made to develop new composites securing their useful properties at optimum level for more demanding applications. The purpose of this project is to optimize the mechanical properties of composite (polypropylene + wood fiber) using Central Composite Design (CCD) technique. Accordingly experiments were conducted to develop mathematical models in terms of three process parameters - composition (percentage of PP and wood fiber), injection pressure (bar), and time (second) for functional characteristics such as tensile strength and water absorption. Design expert software was used for convenience to carry out the analysis with a view to identifying the optimum level of the processing parameters for securing the desirable properties of the composite.

INTRODUCTION

Polymer matrix composites (PMC) have become a substitution material mainly to metallic components for wider applications in automobile, aerospace, civil structures, sport equipment, electronics and others for their light weight and high specific strength. The volume and scope of PMC applications have grown steadily and it has become a material of choice in the 21st century. However, further development activities are still being undertaken to deploy its tremendously attractive properties. Though usage of thermosetting resins is common as matrix in PMC, thermoplastic wood fiber composites also have received considerable attention. The reasons are that the thermoplastic nature of the composites allows them to be processed using traditional manufacturing methods and the environmental friendliness leaving a scope of recycling the products or resultant wastes at the end of useful life. Additionally, PMC is relatively easier to design, fabricate and repair the structures as endorsed by Kalpakjian & Schamid (2006). Reinforced plastic structures do not have only high specific strength and stiffness, but also have improved fatigue resistance, greater toughness, and higher creep resistance.

In shaping the behavior of PMC, the role of matrix materials is very significant. According to Mazumdar (2002) the matrix must bind the fiber together and transfer the load to the fiber and as a result the propagation of crack in the fiber slows down. Moreover, a good surface finish with protection of fibers from mechanical wear and chemical assault can also be achieved. Although wood fiber would decrease the overall cost, it was not used to improve the properties of the products widely. A major issue in achieving true reinforcement for wood plastic composite is due to the inherent incompatibility between the hydrophilic fibers and the hydrophobic polymers which results in poor adhesion leading to poor ability to transfer stress from the matrix to the reinforcing fibers (Yihua Cui et al., 2007). Selection of right coupling agents is vital in order to improve the adhesion between wood fiber and matrix. Variation in fiber orientation can result in unexpected behavior of the material and should be taken into considerations in the quality assessment of the material (Blanc et al., 2004). Wood fiber in thermoplastics is valuable due to their renewability, favorable strength/weight ratio, low hardness, abrasiveness, etc. as stated by Bledzki et al. (2004). PMC products can be manufactured in different routes, among which Injection Molding is a widely used process. Influence of injection molding parameters on tensile strength of pure Polypropylene (PP) was studied by M F M Ehsan (2008). The effect of the processing parameters on tensile strength and Young's modulus of elasticity was not found to be significant. However, the extent of effect is different for a composite. Influence of the processing parameters (weight percent of wood fiber in the composite, injection pressure and time) was investigated to derive models for the functional properties of the PMC of (PP+WF),

EXPERIMENTAL DETAILS

The study is based on an established approach ensuring lower number of experimental conditions according to which samples were prepared and tested. Samples of composites with polypropylene (PP) and WF were prepared by using Ray-ran Test Sample Injection Molding machine. A five weight percent of maleic anhydride-grafted polypropylene was added as a coupling agent to improve the adhesion between WF and PP.

Central Composite Design (CCD) of Response Surface Methodology (RSM) was adopted to design the experiments so that the results or responses could be analyzed in a systematic way. Initially the ranges of the three chosen parameters (weight percent of wood fiber (WF) in the composite, injection pressure and injection time) with the low (1.5, 4, 4), central (2.3, 5.5,5) and high (4.0, 7, 6) levels were selected. The parametric values can be expressed in the coded form using logarithmic scale with the central level as zero, and extreme values as ±√2 or ± 1.414. The three coded variables representing the composition of PP and wood fiber (WF), the injection pressure (bar) and time (second). The values of the coded variables can be obtained with following transformation:

$$\text{Coded Variable} = \frac{\ln X_i - \ln(\text{central})}{\ln(\max) - \ln(\text{central})}$$

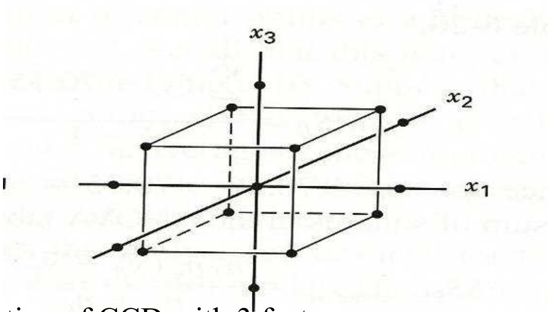

Figure 1: Geometric representation of CCD with 3 factors

The coded variable allows an experimenter to investigate the relative importance of the design factors or parameters. For this study the experiments were extended to develop the second-order model by adding six augmented points to the factorial design. Depending on the realistic level of the parameters, an augmented length of ±√2 was chosen as shown in Figure 1. Therefore, the variables are to lie within a range of $-\sqrt{2} \leq X \leq +\sqrt{2}$ and the corresponding actual values are shown in Table 1.

Table 1: Values of the input parameters with five levels in actual and coded form

Coded variable	**Lowest - 1.414**	**Low -1**	**Center 0**	**High +1**	**Highest +1.414**
X_1: Composition (PP:WF)	1.05	1.32	2.30	4.00	5.03
X_2: Injection Pressure (bar)	3.90	4.32	5.50	7.00	7.70
X_3: Injection Time (sec)	3.86	4.17	5.00	6.00	6.47

Using the Central Composite Design (CCD) algorithm, a total of 15 runs with five center runs was identified as shown in Table 3. Design Expert software was used to map the experimental runs. The five center runs were carried out to observe if there was any variance as the replication was carried out randomly.

Sample Preparation

Test specimens were prepared by using extrusion and injection molding. Initially extrusion process was carried out to get the composite pellets upon mixing the polypropylene and wood fiber according to the composition of weight percentage as mapped by the design of experiment as in Figure 1 with numerical values in Table 2. In extrusion a solid plastic (also called a resin), usually in the form of beads or pellets, was continuously fed to heated chamber and carried along by a feed screw. The melted composite was forced through an opening/die. Then, it was cooled with an air-blast or water cooling system. Test specimens of composites with polypropylene (PP) and wood fiber were prepared by using Ray-ran Test Sample Injection Molding machine.

Characterization of the Composite

Among the various functional characteristics of composite, tests were confined to determine the tensile strength, elongation to fracture and water absorption. Test specimens of dog-bone-shape were stretched at a particular rate to a point beyond its yield stress. The ultimate tensile strength was recorded as the maximum stress before a necking took place. Percent elongation of the specimens was calculated as the ratio of the difference of the length upon fracture and the original length divided by the original length. Water absorption was determined following the requirements of the ASTM D57 method. The composite samples were soaked in distilled water. At a regular interval of time, each sample was removed from the water tank, dried by wiping with blotting paper and subsequently weighed to determine water uptake. The water absorption was calculated as the weight difference. Water can be absorbed in three main areas of the composite - the lumen, the cell wall and also the gaps between WF and PP, especially when the adhesion is weak between the interfaces. For this experiment, a time interval of six days was chosen and three samples were prepared for each experimental run. The average value of water absorption was taken.

RESULTS AND DISCUSSION

The experimental results are also presented in Table 2. Water absorption was found to be the lowest at run condition 11 and highest ultimate strength was achieved at run 12.

Table 2 Designed levels of the three processing parameters in coded and actual forms

Run no.	Location in exp design (CCD)	Input Variables						Responses		
		Coded form			Actual form					
		X_1	X_2	X_3	Com'n PP:WF	Inj Pr (bar)	Inj Tim (s)	UTS (MPa)	Elong. (%)	Water abs,mg
1	Factorial	+1	+1	-1	4.00	7.00	4.17	29.83	1.52	23
2	Factorial	+1	-1	+1	4.00	4.32	6.00	28.96	1.75	20
3	Factorial	-1	+1	+1	1.32	7.00	6.00	35.99	1.60	67
4	Factorial	-1	-1	-1	1.32	4.32	4.17	--	--	83
5	Center	0	0	0	2.30	5.50	5.00	40.59	2.14	27
6	Center	0	0	0	2.30	5.50	5.00	39.22	2.14	53
7	Center	0	0	0	2.30	5.50	5.00	38.89	2.01	53
8	Center	0	0	0	2.30	5.50	5.00	39.52	1.97	50
9	Center	0	0	0	2.30	5.50	5.00	38.13	2.02	37
10	Axial	$-\sqrt{2}$	0	0	1.05	5.50	5.00	--	--	83
11	Axial	$+\sqrt{2}$	0	0	5.03	5.50	5.00	31.74	2.16	10
12	Axial	0	$-\sqrt{2}$	0	2.30	3.90	5.00	41.02	1.88	37
13	Axial	0	$+\sqrt{2}$	0	2.30	7.70	5.00	36.23	1.99	57
14	Axial	0	0	$-\sqrt{2}$	2.30	5.50	3.86	35.86	1.66	27
15	Axial	0	0	$+\sqrt{2}$	2.30	5.50	6.47	39.30	2.09	40

The models for ultimate strength, percent elongation at fracture and water absorption were developed by using design expert software and the concept of RSM as presented in Table 3. Responses for run number 4 and 10 were ignored in the analysis as at those two run conditions samples could not be produced. Relatively low injection pressure and time for run number 4, and high percentage of wood fiber for run number 10 are attributed to result in partial filling of the cavity. The adequacy of the developed models was verified by analysis of variance (ANOVA) for a 95% confidence interval and all the three models were found to be significant.

Table 3: Developed Models for UTS, elongation and water absorption of the composite

Ultimate Tensile Strength (MPa) $= 343.36 - 60.97X_1 - 43.37X_2 - 44.70X_3 + 5.400X_1X_2 + 5.74X_1X_3 + 5.94X_2X_3$
Percent elongation $= 30.87 - 6.00X_1 - 3.97X_2 - 4.63X_3 + 0.48X_1X_2 + 0.69X_1X_3 + 0.58X_2X_3$
Water absorption $= 0.081 - 0.017X_1 + 1.668E\text{-}003X_2 - 4.245E\text{-}004X_3$

It is clear from the above mathematical model for UTS, the main effect of the individual parameter is negative whereas the interactive effects of the parameters have positive impact and increase the ultimate strength of the composite. Similar trend is observed for percent elongation. Higher composition has the maximum level of negative impact whereas injection pressure has the lowest. The interactive effects are in favor of increased elongation making the composite ductile in nature. Water absorption model reveals that higher composition and injection time are to lower the absorption whereas the injection pressure contributes slightly in the phenomenon of water absorption. In the context of multi-criteria optimization, a desirability level of 96.6% is achievable for the UTS of 41.02 MPa, percent elongation at fracture of 2.98% and water absorption of 17mg. The optimum values of the three combinations of process parameters (composition of the raw materials, injection pressure and injection time) are also identifiable to ensure the desired outcome.

CONCLUSION

The experimental results and the developed models indicate that not only the fiber fraction but also the process parameters affect the behavior of the composites. Higher injection pressure and injection time can improve UTS and percent elongation at fracture. However, water absorption of PMC is affected by fraction of fiber present in the composite. Higher wood fraction would result in more water absorption as it acts as an absorbent. Hence a superior composite in terms of mechanical properties is possible to be attained by optimization of the three processing parameters through RSM and the derived models can be reliably used to predict the functional properties of the composite in terms of the processing parameters at least within experimental limits.

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