EVALUATING THE MECHANICAL PROPERTIES OF COMMINGLED WASTE PLASTICS: A MIXTURE STUDY

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ABSTRACT

The study presented demonstrates the modeling of a commingled waste plastics blend. The approach is based on statistically designed mixture experiments and regression analysis. Through the evaluation of a specific array of test points, mathematical models and response surface plots were developed which describe the degree of influence and relationship of the formulation variables.

INTRODUCTION

A major challenge to the recycling of plastics waste is the utilization of mixed polymers. Physical and economic limitations often make separation of these materials impractical. Under suitable processing conditions, composite materials of desirable engineering properties may be created from mixed and/or contaminated polymers. However, little published work has modeled the effects of formulation and processing variables on the performance of various recycled blends. This has limited opportunities to optimize and predict end product performance. This has, in turn, restricted the ability of engineers to design and produce high value products. To investigate the practicability of modeling the mechanical properties of waste stream plastics, experiments were developed. These studies evaluated major components of the plastics waste stream, including recycled polyethylene (PE), polypropylene (PP) and polystyrene (PS).

MIXTURE DESIGNS

Statistically designed experiments encompass a wide range of strategies and techniques. Mixture experiments, which involve blends of materials, are somewhat unique in their design and analysis. In a mixture, the component's levels always sum to 100%. This imposes a special set of constraints on the design, since the controlled variables are no longer completely independent. Those familiar with regression analysis will recognize this violates the important assumption of independence among the "independent" variables. Fortunately, this does not present a serious barrier to analysis and several options exist for analysis of the data [1–3].

A classical designed experiment involving factorial arrangements of three variables (i.e., A, B and C) may be geometrically presented as a cube, with each variable represented by a different dimension (Fig. 1). An experiment to model these variables would explore and map this three-dimensional space. In a mixture design, the special constraint $A + B + C = 100\%$ reduces the design by one dimension (i.e., from a three-dimensional cube to a two-dimensional plane). The only region satis-

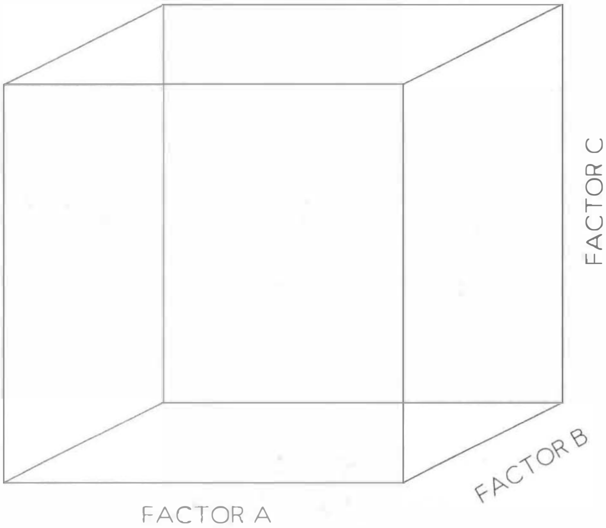

FIG. 1 THREE FACTOR DESIGN SPACE

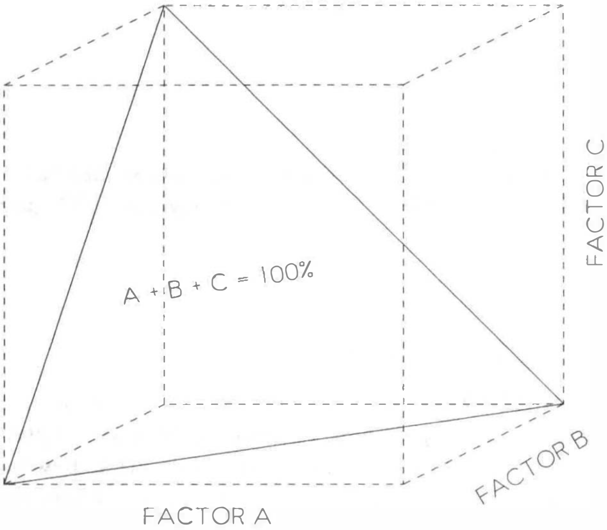

FIG. 2 MIXTURE CONSTRAINT PLANE

fying the 100% constraint is a triangular plane within the original cube space (Fig. 2). Three component mixture designs are therefore graphically represented by a triangular plane or surface, where each apex is a different component at its 100% level (Fig. 3). The experiments discussed in this paper used a three-component mixture design as their basic unit.

EXPERIMENTAL PROCEDURE

The overall investigation was composed of two major phases. Phase 1 included evaluation of both formulation and processing variables on a Killion 31.75-mm single screw extruder. The formulation work was replicated across both virgin and recycled resins. Phase 2 expanded the formulation work on a 50-mm Davis–Standard single screw extruder. All studies evaluated blends of PE, PP and PS. This paper concentrates on the formulation work of Phase 2.

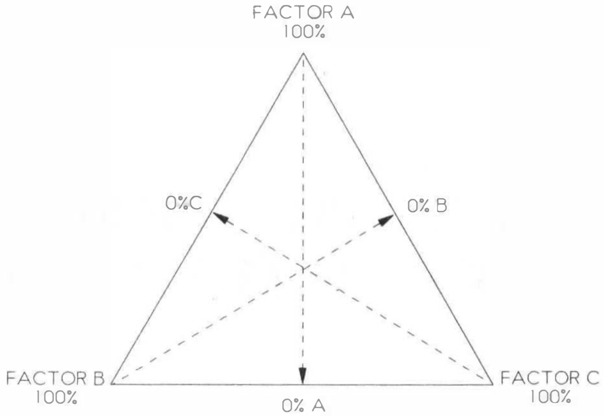

FIG. 3 3 COMPONENT MIXTURE

The Phase 1 experiment included replication of the basic mixture design across three extruder screw speed treatments (30, 70 and 110 rpm). Results of this work were discussed by Engelmann et al. [4].

Recycled resin material for Phase 2 was obtained from a variety of post-consumer sources. Within each resin type, several sources were utilized so that each resin represented a general mix of available grades. No cleaning or drying of the materials was performed. All materials were ground and combined into the 10 unique blends required by the design. No special additives or compatibilizers were used in the experiment.

In this experiment, the samples were first extruded. The 50-mm Davis–Standard extruder was equipped with an olefin mixing screw. The samples were then compression molded to achieve the desired final form. A 45-metric ton Dake compression molder and a cast Ampco bronze alloy mold were used to mold the extrudate into test plaques. The mold was a simple flash-type and utilized water cooling. The mold produced a product with a thickness of 3.175 mm, the standard for the subsequent ASTM tests. Samples were cut from the compression molded extrudate and tested for tensile strength (ASTM D638), izod impact strength (ASTM D256) and flexural modulus (ASTM D790). The tensile strength test draws or elongates the sample to its "break" point on a stress/strain curve. Tensile strength is the load at break divided by the original cross-sectional area. Izod impact strength measures the

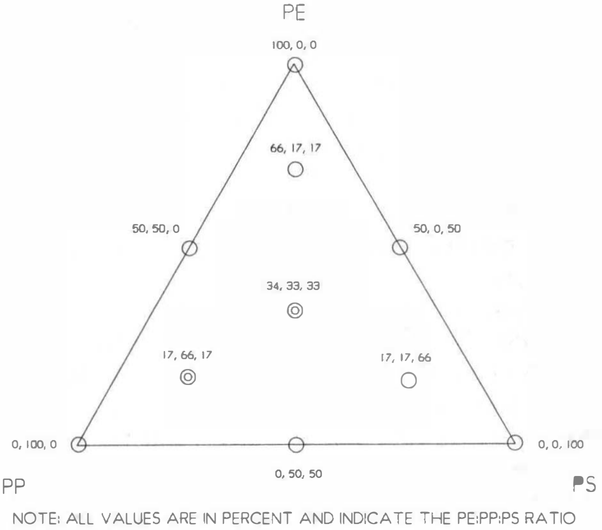

FIG. 4 PHASE 2 DESIGN

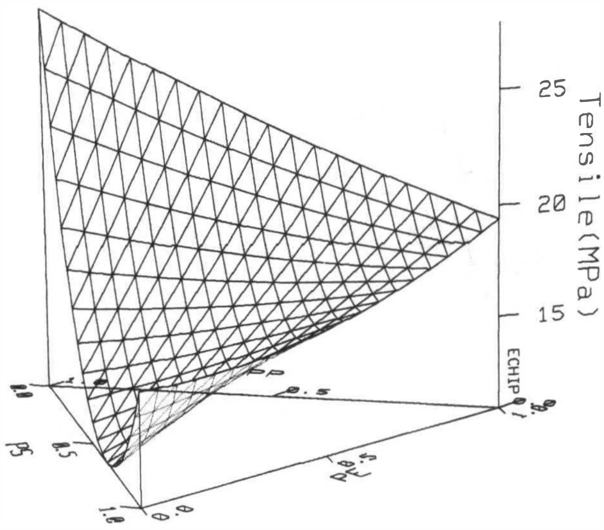

FIG. 5 TENSILE STRENGTH PLOT

toughness of a sample, or its ability to withstand a sharp blow, such as that from a hammer. Flexural modulus is a measure of the flexural strength or stiffness of a sample.

Ten unique blends and two replicates were processed during the experiment. The test points may be seen in Fig. 4. Blend order was randomized and PE purges were used between blends. A marker dye was used to identify transitions between runs. All processing conditions were held constant throughout the experiment. Approximately seven samples were collected and molded within each blend. Four to five samples per blend were tested for each ASTM procedure. Replicates were made of all dimensional measurements to control measurement error.

Study data were subsequently analyzed, by least-squares regression analysis. The software packages ECHIP and SAS were used for the analysis duties. Formulation models and graphs were developed from the regression equations.

RESULTS AND DISCUSSION

Quadratic or second order polynomial models were found to adequately explain variation in all mechanical properties evaluated. The generic model, suggested by Cox [2], was:

$$R = a_0 + a_1x_1 + a_2x_2 + a_3x_3 + a_{11}x_1^2 + a_{22}x_2^2$$
$$+ a_{33}x_3^2 + a_{12}x_1x_2 + a_{13}x_1x_3 + a_{23}x_2x_3$$

where:

R = response or dependent variable.
a_i = parameters of the model.
x_1 = PE
x_2 = PP
x_3 = PS

An alternate model, suggested by Scheffe [3] was also evaluated. This model was of the form:

$$R = a_1x_1 + a_2x_2 + a_3x_3 + a_{12}x_1x_2 + a_{13}x_1x_3$$
$$+ a_{23}x_2x_3 + a_{123}x_1x_2x_3$$

Both model types yielded similar results. All further discussion specifically relates to the former model. *R*-square values were 0.87, 0.84 and 0.92 for tensile, impact and flexural models, respectively. Fortunately, sample variation throughout the experimental region was relatively homogeneous. In general, results compared favorably to Phase 1 work by Engelmann et al. [4]. Since results are frequently difficult to interpret in the model form, response surface plots were developed to better understand the relationships. Three dimensional plots for tensile strength, izod impact and flexural modulus are presented in Figs. 5–7, respectively.

It was evident that specific combinations of the three resins significantly influenced mechanical performance of the product. The most notable feature is the nonlinearity present in the blending relationships of the three recycled plastics. Combining the resins does not result in simple linear changes in mechanical properties. In addition, prominent interactions between resins were observed.

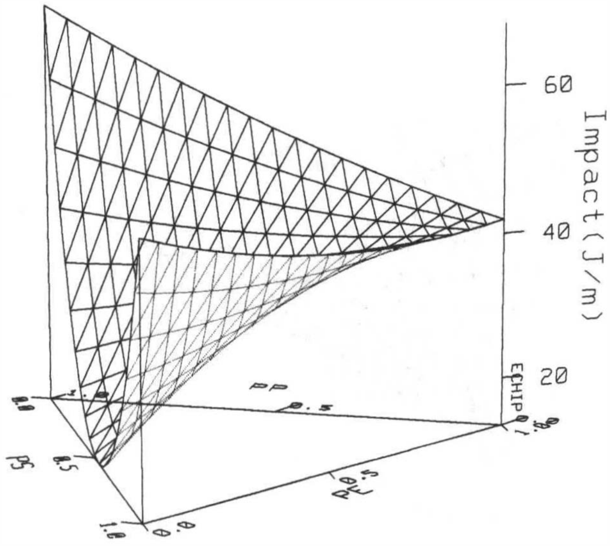

FIG. 6 IZOD IMPACT STRENGTH PLOT

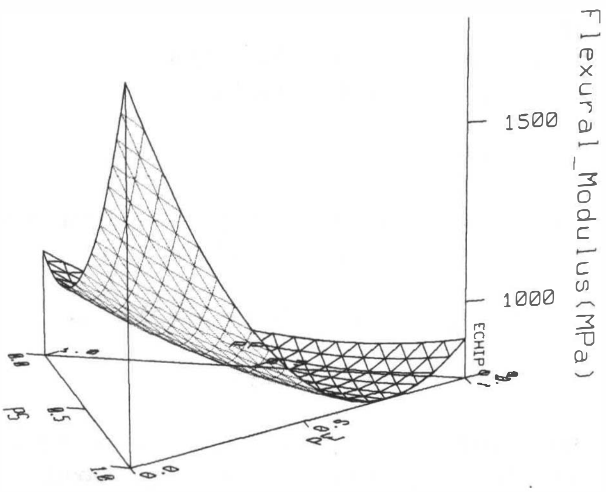

FIG. 7 FLEXURAL MODULUS PLOT

Analysis of the tensile strength data suggested all three resins had significant individual effects on blend performance. Linear effects were observed for PE and PS. Quadratic effects were observed for PP and PS. An interaction between PP and PS was also apparent. Blends composed primarily of intermediate levels of PP and PS demonstrated lower tensile performance, as compared to other blends.

Results for izod impact strength included significant PE and PS linear effects, PP and PS quadratic effects, and a PP*PS interaction. It is interesting to note the various formula management scenarios which can be evaluated from these data. For example, if PS is held to levels of about 30% or less, izod impact strength will not fall below 40 J/m as the PE : PP ratio is varied. Alternately, at higher levels of PS, dramatic changes in impact strength will result from variation in the PE : PP ratio. Another area of interest on the impact response surface is a "flat spot" in the plane centered around the 70% PE : 10% PP : 20% PS blend. In this region the blend may vary in composition by as much as 8% without appreciable variation in impact performance.

Analysis of the flexural modulus data indicated a linear PE effect, quadratic PE and PS effects, and a prominent interaction between PE and PS. Addition of PS to PE initially lowers the flexural modulus until the blend is about 30% PS, at which point the flexural modulus begins to rise rapidly. The level of PP had little or no effect on flexural modulus.

The response surface graphs also show that blends of these three plastics can have performance similar to, or even superior to that of individual "pure" resins. Blends may also be constructed which borrow characteristics from each of the individual resins. However, the response is often nonlinear and slight changes in blend composition can result in large performance changes. The mechanisms behind blend performance were not evaluated in this study. Work by Appelbaum et al. [5], Nosker et al. [6] and others has suggested the presence of beneficial heterogeneous phase morphology in some blends. Favorable performance of some commingled blends may owe more to mechanical bonding than chemical bonding.

CONCLUSIONS

Results of this study suggest designed experiments and statistical modeling have ready application for studying the performance of commingled resin blends. The resultant models and graphs can be used to develop a detailed understanding of both formulation and processing effects. This information may then be used to optimize and predict the mechanical properties of end products. The availability of performance and reliability data will provide the basis to develop higher value products from mixed waste plastics.

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