Development of natural fibre reinforced polystyrene (NFRP) composites: Impact resistance study

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Abstract. The prevalent global issue on environmental pollution and the growing desire for polymer based composite materials has given rise to increasing research in the production of composite containing natural organic fillers or fibres and recycled plastic [1]. This study describes the optimization of impact strength of plastic composites developed from polystyrene and natural fibre wastes(sawdust and rice husk) using 3-level-factorial-design via hand lay-up method studying the effect of filler concentration (15 – 45 %), filler size (20 – 100 µm) and alkaline treatment concentration (2 – 6 %) on the impact strength of polystyrene fibre reinforced composite. Models were developed using response surface methodology to predict impact strength of the composite as a function of the process variables investigated. The optimization of the process parameters show that the optimum condition for obtaining high impact strength are 15% filler concentration, 100 µm filler size and 4% alkaline (NaOH) concentration in saw dust filled composite while a filler concentration of 15%, filler size of 31µm and an alkaline concentration of 2% for the rice husk filled composite. The recycled polystyrene in combination with wood dust and rice husk has produced a polymer composite with moderate impact strength applicable in various applications.

Key words: Design parameters, response surface methodology, rice husk, sawdust, plastic composite optimisation

1. Introduction
The prevalent global issue on environmental pollution and the growing desire for polymer based composite materials has giving rise to increasing research in the production of composite containing natural fillers or fibres and recycled plastic [1]. This class of composite is otherwise called natural fiber-reinforced composite (NFRC). The growing interest in NFRC materials is as a result of the advantages it possess when compared to metal alloys [2] which are: ease of recycling and biodegradability [3], light weight, low cost, high specific strength and modulus, etc [4]. These informed their wide applications as an effective substitute for non-biodegradable polymers. Also, when compared to inorganic-mineral
reinforced composite, NFRC are less abrasive and can easily be disposed at the end of their life cycle either by recovery of their calorific value in a furnace or by composting [5].

The production of NFRC with natural biomass wastes like wood dust and rice husk RH fibers is an established technology [6, 7]. Wood dust and RH fibers can easily be obtained cheaply from saw and rice mill wastes and used after proper sieving [8]. Wood dust and RH fibers have a history of being used only to lower the density and cost of plastic articles, but have been found recently to also enhance the mechanical properties of these plastic articles [9]. Using wood dust and RH fibers to produce fiber-reinforced composites, the stiffness and other mechanical properties of the composite can be effectively improved and provide mechanical properties comparable to those of glass fiber-reinforced composites [10].

However, researches on NFRC are revealing new routes on constituents’ formulations to allow the manufacturing of new composites with optimal properties for unique applications [11]. Appreciable numbers of literatures have been documented on the production of wood fiber-reinforced plastic composites with special emphasis on optimal mechanical properties. These include: Mechanical properties of wood waste reinforced polymer matrix composites [12], optimization of mechanical properties of epoxy based wood dust reinforced green composite using Taguchi method [1], optimization of process parameter for sawdust/Recycle polyethylene composites, optimization of the tensile and flexural strength of a wood-PET composite, experimental investigation and Taguchi optimization of drilling properties on Teak wood reinforced epoxy resin [13], mechanical behavior of natural material (orange peel) reinforced polyester composite [14]; optimization of design parameters for achieving highest impact strength of rice straw based polymer composite using Taguchi method [15]; experimental study of mechanical and physical properties of jute/wood plastic composite; effect of the particle size on mechanical properties of particulate natural composite materials [16]; Effect of surface treatment on mechanical properties of natural fiber reinforced composites [17]. However, at this time there is no article published on the optimization studies of the Natural Fibre Reinforced Polystyrene Composites produced with solvated polystyrene as the matrix.

With specific emphasis to optimization of mechanical properties of solvated polystyrene wood dust, the use of response surface methodology (central composite design) has been scarcely documented. However, few works documented have shown that the use of response surface methodology (RSM) is a useful tool for the optimization of mechanical properties of polymer composites using different natural organic fillers.

2. Material and Methods

2.1. Preparation of natural fibre particulates

Two different kinds of natural fibre particulates from different solid waste sources (Table 1) and of no competitive usage were obtained and dried in oven for 18 hours at 40°C so as to remove free water present in it. The samples were sawdust and rice husk. The dried samples were graded to obtain the powder of varying sizes based on the experimental design.

| S/No | Natural Fibres | Source | Preparation Process          |
|------|----------------|--------|------------------------------|
| 1    | Sawdust        | Sawmill| Drying and Sieving           |
| 2    | Rice Husk      | Rice Mill| Drying and Sieving         |
2.2. Experimental Design Using Response Surface Methodology

Production of NFRP composite was optimized using response surface methodology (RSM) (A 3-factor experiment) to study the effect of resin composition (%), filler size (µm) and NaOH treatment effect on the mechanical properties of the polymer composite. With reference to resin composition, the upper composition level was set at 45% and the lower level will be set at 15%; filler size (mesh size) are 20 and 100 for low and high level respectively; the amount of NaOH solution for fibre treatment are 2% and 6% for the low and higher level respectively. A total number of 36 experimental runs were projected as indicated in Table 2.

2.3. Composite Fabrication

The composites were produced using the facilities available at the Chemical Engineering Laboratory, University of Ilorin. Manual mixing method and hand lay-up technique were used for the composite production. The composites were prepared based on the experimental design. The waste polymer materials (polystyrene) were dissolved in a petroleum solvent at room temperature to form polystyrene based resin (PBR) as previously documented [18]. Based on RSM design matrix, a calculated amount of PBR and fillers were measured and mix together thoroughly in a container at low speed for 10 minutes until the mixture becomes uniform and tacky. The mixture of the matrix material will then be poured into the mold with dimension 20 cm x 8 cm x 1 cm to obtain the polymer composite which will be allowed to cure for 7 days at room temperature. The cured polymer composite were cut into different dimensions for mechanical property tests.

2.4. Impact Testing of Composite Samples

The impact tests were conducted using an unnotched Izod impact machine according to the ASTM standard method [19] (ASTM D256; ISO 180). The composite sample having thickness 3.2 mm with 10mm cross-section and 64 mm long is clamped into the pendulum impact test fixture with the notched side facing the striking edge of the pendulum. The pendulum is released and allowed to strike through the composite and the force consumed in breaking the composite sample is calculated [20, 21]

2.5. Optimization of Impact Strength Using Desirability Method

Desirability method of optimization is a method employed to evaluate the input variables for optimization of multiple responses [22]. The condition of each response is selected based on its significance by selecting a maximum, minimum or a target value of specification. The Design Expert software is a tool that allows input variables and responses to be changed in order to obtain the greatest overall desirability. The input variables are selected within their experimental ranges while only the responses are adjusted. The adjustment is subject to expertise and engineering knowledge. The software can also rate the response on a 1 to 10 scale and show its importance using a five-point scale system. Thus, a response becomes maximize when it approached a desirable specification.

3. Results and discussion

3.1. Impact Strength

The results of the 36 experimental runs for the impact strength of the two NFRP composite produced are presented in Table 2, the two types are wood dust reinforced polystyrene composite (WPC) and rice husk reinforced polystyrene composite (RPC) respectively. The three process variables in this study are filler concentration, filler size and alkaline (NaOH) treatment concentration. The impact strength for wood dust reinforced polystyrene composite ranged from 70 J/m² to 75.5 J/m² while the impact strength for rice husk reinforced polystyrene composite ranged from 69 J/m² to 78.5 J/m². The highest impact strength for wood
dust reinforced polystyrene composite was 75.5 J/m$^2$ under process condition of 15% filler concentration, 100 µm filler size and 4% NaOH concentration while the highest impact strength for rice husk reinforced polystyrene composite was 78.5 J/m$^2$ under process condition of 15% filler concentration, 60 µm filler size and 0% NaOH concentration.

The behaviour of a composite material is explained on the basis of the combined behaviour of the reinforcing element, PBR matrix, and the fiber/matrix interface. To attain superior mechanical properties the interfacial adhesion should be strong [17], thus, a filler concentration of 15% gives a stronger interfacial adhesion which results into higher impact strength as seen in the result obtained. Also, the finer the filler, the better the interfacial adhesion. In the case of wood dust reinforced polystyrene composite, the alkaline treatment of the wood dust at 4% of NaOH gives rise to a better interfacial adhesion between the polymeric matrix and the filler which results to an increase in the impact strength of the composite while the alkaline treatment of the rice husk does not show a significant effect on the interfacial adhesion and hence does not significantly contribute to the impact strength of the composite.

Table 2. The responses of the parameters used in central composite design

| Run | Filler concentration (%) | Filler Size (µm) | NaOH concentration (% Solution) | Impact Strength (WPC) (J/m$^2$) | Impact Strength (RPC) (J/m$^2$) |
|-----|--------------------------|-----------------|-------------------------------|-----------------------------|-------------------------------|
| 1   | 30                       | 100             | 2                             | 70                          | 71                            |
| 2   | 30                       | 60              | 2                             | 72                          | 69                            |
| 3   | 15                       | 60              | 2                             | 74                          | 74                            |
| 4   | 15                       | 100             | 2                             | 71.5                        | 72                            |
| 5   | 30                       | 60              | 4                             | 73                          | 70.5                          |
| 6   | 30                       | 100             | 4                             | 70                          | 70                            |
| 7   | 15                       | 60              | 4                             | 74                          | 71                            |
| 8   | 15                       | 100             | 4                             | 75.5                        | 70                            |
| 9   | 15                       | 60              | 6                             | 73                          | 72                            |
| 10  | 30                       | 60              | 6                             | 72                          | 70                            |
| 11  | 15                       | 100             | 6                             | 73.5                        | 69                            |
| 12  | 30                       | 100             | 6                             | 70                          | 71                            |
| 13  | 30                       | 20              | 2                             | 75                          | 73                            |
| 14  | 15                       | 20              | 2                             | 71.5                        | 71                            |
| 15  | 30                       | 20              | 4                             | 75                          | 69.5                          |
| 16  | 15                       | 20              | 4                             | 74.5                        | 71                            |
| 17  | 30                       | 20              | 6                             | 73                          | 70.5                          |
| 18  | 15                       | 20              | 6                             | 71                          | 70.5                          |
| 19  | 15                       | 60              | 0                             | 72                          | 78.5                          |
| 20  | 15                       | 100             | 0                             | 72                          | 71                            |
| 21  | 15                       | 20              | 0                             | 73.5                        | 72                            |
### 3.1.1. Effect of Interactive Parameters on Impact Strength

#### 3.1.1.1. Effect of filler concentration and filler size on Impact Strength

Figures 1(a) and 1(b) show the response surface plot for the wood dust reinforced polystyrene composite and rice husk reinforced polystyrene composite demonstrating the effect of filler concentration and filler size on the impact strength of the composite. In Figure 1(a), the impact strength increases as the filler size increases while the impact strength decreases as the filler concentration increases. In Figure 1(b), the impact strength remain constant over a range of filler size (100 µm to 60 µm) and then starts decreasing at 45% filler concentration while the impact strength increases as the filler size increases at 15% filler concentration. The impact strength increases over a range of filler concentration (15% to 30%) and then starts decreasing as shown in Figure 1(b).

The combination of high filler size and high filler concentration caused a decrease in the wood reinforced polystyrene composite impact strength while rice husk reinforced polystyrene composite demonstrated an increase impact strength at a combination of high filler size and high filler concentration.
3.1.1.2. Effect of filler concentration and alkaline concentration on impact strength

Figures 2(a) and 2(b) show the response surface plot for the WPC and RPC demonstrating the effect of filler concentration and alkaline concentration on the impact strength of the composite. In Figure 2(a), the impact strength decreases as the filler concentration increases while the impact strength increases as the alkaline concentration decreases. In Figure 2(b), the impact strength decreases as the filler concentration increases at minimum alkaline concentration while the impact strength increases as the alkaline concentration decreases at minimum filler concentration.
3.1.1.3. Effect of Filler Size and Alkaline Concentration on Impact strength
Figures 3(a) and 3(b) show the response surface plot for WPC and RPC demonstrating the effect of filler size and alkaline concentration on the impact strength of the composite. In Figure 3(a), the impact strength increases significantly as the filler size increases at maximum alkaline concentration while the impact strength increases slightly over a range of alkaline concentration (2% to 4%) and then start decreasing as the alkaline concentration increases at minimum filler size. In Figure 3(b), an increase in the filler size gives a slight increase in the impact strength of the composite at minimum alkaline concentration while an increase in the alkaline concentration gives a decrease in the impact strength of the composite at minimum filler size.

Figure 3(a). Response surface plot for WPC

Figure 3(b). Response surface plot for RPC

3.2. Optimization
A useful approach for simultaneous optimization of multiple responses is to use a desirability function. To optimize the impact strength of polystyrene composite using an overall desirability function, it is important to formulate the specification for each of the factors and responses as shown in Table 3.

| Name               | Goal        | Lower Limit | Upper Limit | Lower Weight | Upper Weight | Importance | Desirability |
|--------------------|-------------|-------------|-------------|--------------|--------------|------------|--------------|
| A: Filler Concentration | is in range  | 15          | 45          | 1            | 1            | 3          | 1            |
| B: Filler Size     | is in range  | 20          | 100         | 1            | 1            | 3          | 1            |
| C: Alkaline Conc.  | is in range  | 2           | 6           | 1            | 1            | 3          | 1            |
| Impact Strength (WPC) | maximize    | 70          | 75.5        | 1            | 1            | 3          | 0.6413       |
| Impact Strength (RPC) | Maximize    | 69          | 78.5        | 1            | 1            | 3          | 0.3483       |
Figure 4 shows the overall desirability function applied to multiple responses simultaneously i.e WPC impact strength and RPC. The optimum overall desirability (D) of 47.3% was achieved with a filler concentration of 15%, filler size of 31µm and an alkaline concentration of 2%. This optimal point of the system attained by geometric mean maximization was calculated from the individual desirability (d) for each response, as shown in Table 3. Thus, the tensile strength for wood dust reinforced polystyrene composite and rice husk reinforced polystyrene composite are 73.53 J/m² and 72.31 J/m² respectively.

**Figure 4.** 3D response surface plot of desirability function applied to multiple responses

### 4. Conclusion

The effect of filler concentration, filler size and alkaline treatment concentration on the impact strength of polystyrene fibre reinforced composite (WPC and RPC) were examined. For both plastic composites, lower filler size and higher filler concentration give higher impact strength composites. The models obtained and the associated optimisation scheme revealed that filler size and concentration are sensitive factors that affect the impact strength of natural fibre plastic composites.

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