Optimization of the second phase morphology and content effect to impact resistance of epoxy resin composite

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Abstract. The increasingly widespread use of composite materials for structural materials forces composite materials to have superior mechanical properties, one of which is impact strength. The material's impact strength was determined by calculating the impact energy obtained from the impact test. Many things impact the strength of composite materials. Many studies have been conducted on the mechanical properties of composite materials. However, the above research has not investigated the influence of the morphology of the second phase on the mechanical properties of resin composite materials. The morphology of the second phase used as reinforcement in composite materials can be particles, short fibers, or continuous fibers. The shape (morphology) of the second phase affects the impact strength of the composite material. Therefore, this study was intended to examine the effect of the morphology of Coir Coconut fiber as the second phase (reinforcement) combined with the percentage of its content in epoxy resin matrix composite on the impact strength, as well as to determine the optimum morphology and the percentage of the second phase. The study was designed using the full factorial. Furthermore, the data on the impact strength of the specimens were analyzed to obtain a regression model for the relationship between the morphology of the second phase and the percentage of the content of the second phase on the impact strength. With this regression model, it is possible to predict the impact strength of various morphological forms of the second phase and optimize the optimum content of the second phase.

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1 Introduction

1.1 Research background

The use of composite materials extends beyond those that cannot bear loads and includes structural materials designed to withstand various types of loading in automotive, marine, and aerospace components [1]. These loads can be static, dynamic (fluctuating), or impact. To assess a material's ability to handle these loads, laboratory tests are typically conducted to measure its mechanical properties. Static load resistance is often evaluated through tensile strength testing, dynamic load resistance is assessed using fatigue tests, and impact load resistance is determined through impact tests. As a result, researchers worldwide have extensively studied the mechanical properties of composite materials. For example, research has focused on the impact of Polysilazane on the densification and mechanical properties of Sicf/Sic composites [2], as well as on improving the mechanical properties and in-vitro degradation of chitosan-pristine graphene nanocomposites. This study showed that adding 0.2 to 0.4% wt. of pristine graphene enhanced chitosan's tensile strength and stiffness, particularly when combined with glycerol [3]. Numerous studies have also been conducted on natural fiber-reinforced composites, such as investigations into the mechanical performance of matrix natural fiber composites [4], the effect of chemical and heat treatments on the tensile strength, crystallinity, and surface morphology of Kenaf fibers [5], and the mechanical, damping, and chemical resistance properties of banana fiber hybrid composites [6]. Other research has examined the mechanical performance and resistance of mortar reinforced with treated fibers [7] and the energy dissipation and thermal response of Lontar Borassus Flabellifer fiber composites under dynamic tensile testing [8]. Additional studies have explored the effect of oil palm fiber percentage on the fatigue life of axial load resin matrix composites [9].

Coconut coir is a natural fiber that remains largely underutilized, often ending up as waste. Despite being abundantly available due to the widespread use of coconuts for various daily needs, particularly cooking, much of this fiber is discarded. In rural areas, coconut coir waste is less of an issue, as local communities repurpose it for activities such as broom-making or using it as an alternative to firewood. However, coconut husk is seldom used in urban areas, contributing to city waste problems. This highlights the urgent need to explore and promote using coconut coir as a reinforcement material in composite products, which could help address waste management challenges, especially in urban environments. While some studies have investigated its potential, such as using coconut coir-based carbon (CCC) to improve iron content through a carbothermic process, research in this area remains limited. Therefore, further exploration into using coconut coir in composite materials is essential.

Natural fibers strengthen polymers in polymer matrix composite materials designed to achieve combination properties that exceed the properties of fibers or polymers. Compared to fiberglass, natural fibers are more cost-effective and have lower density. However, the disadvantages of using natural fibers include lower fire resistance, limited processing temperatures, lower durability, mismatch between fiber and polymer matrix, low moisture resistance, tendency to form aggregates during processing variations in quality and price, and difficulty in using raw materials that are already established [11]. In developing countries, natural fiber composites such as wood substitutes attract more attention as a substitute for building materials [12].

A review of the manufacturing process of natural fiber-reinforced polymer composites has been conducted. They conclude that natural fiber material has contributed to being environmentally friendly and low-cost compared to synthetic fibers. Hence, natural fiber polymer composites can be developed and discovered in aerospace, automotive, and construction industry applications using a suitable manufacturing process via the type of natural fibers available [13].

Several studies have been conducted to investigate the impact strength of composite materials. One such study focused on epoxy matrix composites reinforced with vetiver fiber. The research revealed that the bending and impact strengths are reduced when the fiber volume fraction exceeds 20% [14].

Another study examined composite materials' impact strength with a polypropylene matrix and oil palm fiber reinforcement. The results showed that specimens with 10% fiber content exhibited the highest impact strength, outperforming those with 5% and 7% fiber content. Additionally, the study found that specimens with fiber lengths of 10 mm demonstrated the greatest impact strength compared to those with 5 mm and 7 mm fiber lengths [15].

Composite materials that are widely developed today are composite materials with a polymer matrix, such as polyethylene, polypropylene, resin, and so on. Along with these developments, research on improving the mechanical properties of composite materials remains a fascinating and seemingly endless research topic for many researchers [9,16,17].

A study in the form of a literature review on increasing the mechanical properties of natural fiber composites using water hyacinth fibers has been conducted. The results of that research prove that the water hyacinth plant has the potential to be used as reinforcement in the manufacture of natural fiber composites [18].

Research on the ability of natural fibers to increase the flexural compressive strength of construction materials has also been conducted. They have studied increasing concrete compressive strength and flexural strength with variations in adding pineapple leaf fiber. The results showed that the addition of pineapple leaf fiber to the concrete mixture with a percentage of 5% of the weight of cement in the concrete mixture, succeeded in increasing the maximum compressive strength reaching 267.00 kg / cm2, and the highest flexural strength value of 41.61 kg / cm^2 [19].

Investigating the impact of fiber weight percentage on the tensile and bending strength of coconut fiber polyester resin composites revealed that a 15% fiber weight percentage resulted in the highest tensile strength [20]. However, the studies mentioned above did not explore how the morphology of the second phase influences the properties of resin composite materials. Various forms of second-phase morphologies are used as reinforcements in composite materials, such as particles, short fibers, and continuous fibers, among others [21].

The shape (morphology) of the second phase in natural fiber composites is likely to affect their performance, even when the second phase is derived from the same material [21]. Changes in fiber morphology can alter the adhesion strength to the matrix, and the second-phase morphology also influences stress concentration. Spherical second-phase particles generally cause minimal stress concentration on their surface, whereas sharp-edged particles lead to stress concentrations at their points, potentially generating internal residual stresses. If residual stress is kept within certain limits, it can enhance the material's strength. However, excessive residual stress can result in a brittle material that is prone to breaking. Therefore, it is essential to study the morphology and percentage of the second phase (coconut husk) to determine the optimal combination for achieving the best mechanical properties. This research aims to investigate how the morphology of the second phase affects the composite's mechanical properties, aiming to optimize the composite material's performance.

The first objective of this study was to use a full factorial design to obtain a regression model of the impact strength of the fiber reinforcement epoxy resin composite material with 3 contents and 3 forms of coir coconut fiber morphology.

Another objective of this research is to determine the optimum value of the impact strength of the fiber reinforcement epoxy resin composite material from 3 contents and 3 morphological forms of coconut fiber, using the differential equation of regression model.

The Coir coconut fiber as the second phase was used in this study consists of short Fiber with 10 mm length (Second Phase of Short Fiber, SPSF), coconut husk particles (Second phase of Powder, SPP), and coir charcoal ash (Second phase of Charcoal Ash, SPCA), This study evaluated the mechanical properties of samples using Charpy Impact test according to ISO 179-1: 2010 [22]. The experiments in this study were designed using Full factorial and analyzed to generate a regression model of impact strength of composite material with 3 different morphology and 3 different content.

2 Methods

This section outlines the research to assess the impact of coconut coir morphology and the proportion of the second-phase content on the impact strength of fiber-reinforced epoxy resin composites. The goal is to determine the optimal impact strength by analyzing the regression model results, considering various coconut coir morphological shapes.

2.1 Experimental Process

The research started with preparing the second-phase material in three forms: 10mm short fiber, powder, and charcoal ash. Each material was mixed with epoxy resin at three concentration levels: 2%, 4%, and 6%. A hardener was added in the same proportion as the resin, and the mixture was poured into molds for impact test specimens. The specimens were left in the mold for 24 hours to dry and harden fully. Afterward, the specimens were removed for visual inspection and dimension measurements before impact testing.The impact test results were used to calculate the impact strength of the specimen for analysis later. Then the impact strength regression model was generated for each type of the second-phase morphology. The process was started from a linear regression model and then check whether the model generated is significant, as seen from the R^2 value. The process will be stopped when R^2 higher than 0.95. If R^2 is less than 0.95, This process is repeted by increase the regression order for one level before regenerating the new model, and so on until the regression model is generated for order 3. Usually, if R2 for order 3 still does not reach 0.95, the model generating process is stopped. Because it is likely that if it is continued, R^2 will not reach 0.95. So, the established model is the model with the highest R^2 from the simulation that has been done.

2.2. Tools and materials

The tools used in this research are as follows:

1. Mould for preparing the impact specimens
2. Impact test equipment for plastic/polymer materials.

Materials used in this study are:

1. Epoxy resin EPR174 and hardener V-140.
2. Dry coir coconut fiber.

2.3 Specimens preparation

Coconut coir fibers were washed with water and dried under sunlight until fully dried. After cleaning, the fibers were divided into three groups. The first group was cut into 10mm lengths to create short fibers for SPSF. The second group was crushed in a blender to form a powder (SPP). The third group was burned to produce ash (SPCA).

Table 1. Full Factorial experimental Design for 2 factors with 3 level [23].

No.	Second Phase Morphology (X_1)	Second Phase Content (%) (X_2)
1	1	2
2	1	4
3	1	6
4	2	2
5	2	4
6	2	6
7	3	2
8	3	4
9	3	6

Remarks: Second Phase Morphology: 1= Powder, 2= Short Fiber, 3= Charcoal Ash

Specimen manufacturing is carried out according to ISO 179-1: 2010 standards [22] as shown in Fig. 1.

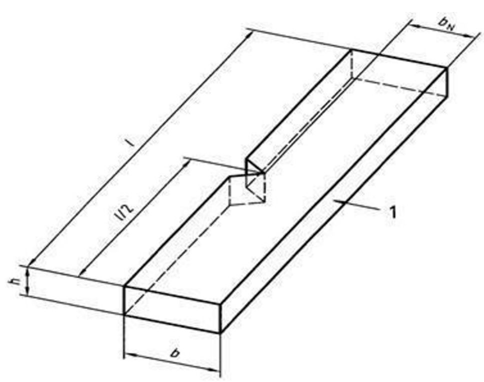

Fig. 1: The Charpy impact specimen dimension according to ISO 179 standard, type no.1, B notch type [22].

There were 2 factors studied i.e.: The morphology and the content of the second phase as follows:

1. Morphology of the second phase: short fiber, powder, and Charcoal ash.
2. Content of the second phase: 2%, 4%, and 6% weight.

The study followed a full factorial design, consists of 3 factors with 3 level for each factor, resulting in 9 sample type combinations (3 x 3), with each combination 5 samples prepared, a total 45 samples. The samples were prepared as follows:

1. Fiber (10mm length) with 2%, 4%, and 6% weight content.
2. Coconut husk powder with 2%, 4%, and 6% weight content.
3. Coir coconut charcoal ash with 2%, 4%, and 6% weight content.

The preparation involved pouring resin into a container, mixing it with the coconut husk, powder, or ash as per the designated content, and stirring to ensure even distribution. A hardener was then added and mixed, the mixture was poured into molds, and the specimens were removed after hardening.

2.4 Testing and Characterization

Impact testing was conducted using specialized equipment for polymer and composite materials at the Mechanical Engineering Laboratory of the University of Mercu Buana.

The test measured the impact energy of all specimens, and these values were subsequently used to calculate the impact strength for each specimen and the average impact strength for each condition. The results were then presented in graphical form to derive a regression equation that describes the relationship between the percentage content of the second-phase material and the impact strength for each morphological type of the second phase.

The regression model, derived from the research data, is a mathematical equation including independent and dependent variables. This model allows the independent variable's simulation to predict the dependent variable's corresponding value. In this study, the independent variable is the percentage weight of the second-phase content for each morphology, while the dependent variable is the impact strength. Using the regression model, it becomes possible to simulate the required fiber content needed to achieve a specific impact strength value for each type of second-phase morphology.

2.5 Modeling

The responses investigated for the linear regression model for Impact Strength for specimens can be correlated with the Second phase content (x), with the following general equation:

$$Y_j = b_{ij}\, x^k + \ldots + b_{2j}\, x^2 + b_{1j}\, x + b_{0j} \quad (1)$$

Where, i = 0, 1, 2, . .., i, until the best R^2 was obtained

j = 1 for Short fiber, j = 2 for Charcoal ash, and j = 3 for Powder

k = degrees of regression model, whereas k = 1, 2, , . .., i, until the best R^2 was obtained.

Since there are three types of second-phase morphology used in this research, i.e.: Short fibre, Charcoal ash, and Powder, Equation (1) could be detailed as follows:

$$Y_1 = b_{ij}\, x^k + \ldots + b_{21}\, x^2 + b_{11}\, x + b_{01} \quad (2)$$

$$Y_2 = b_{ij}\, x^k + \ldots + b_{22}\, x^2 + b_{12}\, x_1 + b_{02} \quad (3)$$

$$Y_3 = b_{ij}\, x^k + \ldots + b_{23}\, x^2 + b_{13}\, x1\; b_{03} \quad (4)$$

Where, i = 0, 1, 2, . .., i, until the best R^2 was obtained

j = 1 for Short fiber, j = 2 for Charcoal ash, and j = 3 for Powder

k = degrees of regression model, whereas k = 1, 2, , . .., i, until the best R^2 was obtained.

3 Results and Discussion

The Charpy impact test provided the impact energy for each sample, which was subsequently used to calculate the impact strength of each specimen. Similar impact testing and impact strength calculations were performed on pure resin for comparison. A summary of the impact strength results is presented in Table 2.

Table 2. Impact Strength of the specimens in kJ/m²

NO	Composite sample Name	Second Phase Morphology	Impact strength (kJ/m²			
			Pure Resin	Content (2 %)	Content (4 %)	Content (6 %)
1	Short Fiber reinforced Resin Composita (SFRRC)	Short Fiber	1.07	7.15	7.69	6.81
2			2.09	6.61	6.74	7.59
3			1.48	4.59	6.90	7.56
4			0.67	6.85	7.40	7.75
5			1.54	6.49	6.90	4.10
6	Charcoal Ash reinforced Resin Composita (CARRC)	Charcoal Ash	1.07	5.79	6.35	3.88
7			2.09	6.22	3.90	4.88
8			1.48	6.24	4.90	6.03
9			0.67	6.41	4.85	3.69
10			1.54	6.21	5.06	5.01
11	Powder reinforced Resin Composita (PRRC)	Powder	1.07	4.37	4.98	4.78
12			2.09	7.61	3.98	5.08
13			1.48	6.39	6.26	3.68
14			0.67	6.39	7.48	6.22
15			1.54	4.00	6.23	6.27

As shown in Table 2, the impact strength of the composite material reinforced with coconut coir short fibers, coconut coir charcoal ash, and coconut coir powder increased significantly, with an improvement ranging from 300% to 500% compared to pure resin. The impact strength of the composite materials varied between 3.68 kJ/m² and 7.79 kJ/m², while the impact strength of pure resin ranged from 0.67 kJ/m² to 2.09 kJ/m². These Data were analyzed for obtaining the regression model of every type of the second phase morphology. The results are shown in Fig. 2, 4, and 5.

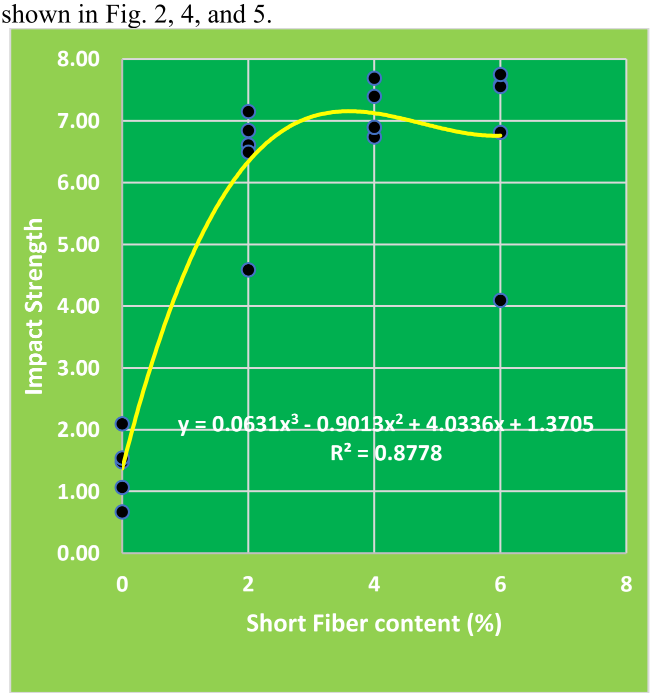

Fig. 2. The regression model and graph of the impact strength of SFRRC.

The regression model of SFRRC based on SPSF content is shown in Fig. 2 as follows:

$$Y_1 = 0.0631x^3 - 0.9013x^2 + 4.0336x + 1.3705 \quad (5)$$

Where: Y_1 = Impact strength of SFRRC (kJ/m2)
x = SPSF content (%)

The coefficient of determination (R^2) of this regression equation is 0.8778. It indicates that 87.78 % of SPSF affects the impact strength of SFRRC. In other words, the variation in the percentage of SPSF in SFRRC in this research is 87.78% able to explain variations in impact strength.

The highest impact strength for SFRRC is obtained by differentiating equation 5 and making it equal to zero to get the maximum and minimum Y_1, as follows:

$$Y_1 = 0.0631x^3 - 0.9013x^2 + 4.0336x + 1.3705$$
$$dY_1/dx = 0.1893x^2 - 1.8026x + 4.0336 \quad (6)$$
Y_1 will be Maximum or minimum when $dY_1/dx = 0$
$$0 = 0.1893x^2 - 1.8026x + 4.0336$$
$$x_1 = 5.9199$$
$$x_2 = 3.5994$$

Based on Fig. 2, can be seen that the maximum Y_1 is in the range of x between 3 and 4. So, it can be determined that the Y1 maximum is when $x = x_2 = 3.5994$. This means that the highest impact strength of SFRRC is obtained when the content of SPSF is 3.5994%.

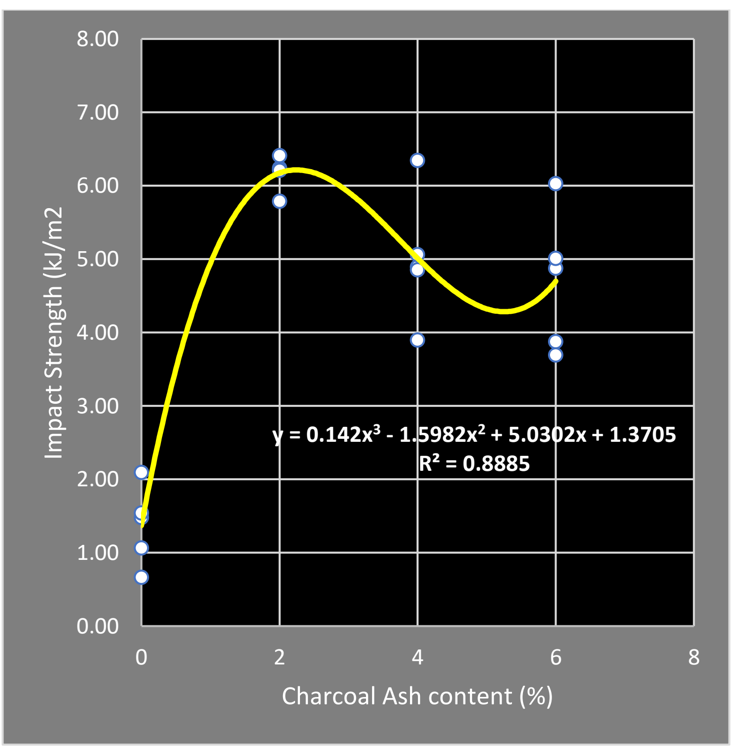

Fig. 3. The regression model of the impact strength of CARRC.

The regression model of CARRC based on SPCA content is shown in Fig. 2 as follows:

$$Y_2 = 0.142x^3 - 1.5982x^2 + 5.0302x + 1.3705 \quad (7)$$

Where: Y_2 = Impact strength CARRC (kJ/m2)
x = SPCA content (%)

The coefficient of determination (R^2) for this regression equation is 0.8885, which means that the percentage of SPCA influences 88.85% of the variation in the impact strength of CARRC. In other words, 88.85% of the variation in the SPCA content in CARRC can explain the changes in impact strength observed in this study.

The highest impact strength for CARRC is obtained by differentiating equation 7 and making it equal to zero to get the maximum and minimum Y_2, as follows:

$$Y_2 = 0.142x^3 - 1.5982x^2 + 5.0302x + 1.3705$$
$$dY_2/dx = 0.426x^2 - 3.196x + 5.0302 \quad (8)$$
Y_2 will be Maximum or minimum when $dY_3/dx = 0$
$$0 = 0.426x^2 - 3.196x + 5.0302$$
$$x_1 = 5.2556$$
$$x_2 = 2.2467$$

Based on Fig. 4, can be seen that the maximum Y_2 is in the range of x between 2 and 4. So, it can be determined that the Y2 maximum is when $x = x_2 = 2.2467$. It means that the highest impact strength of CARRC would be obtained when the content of SPCA is 2.2467%.

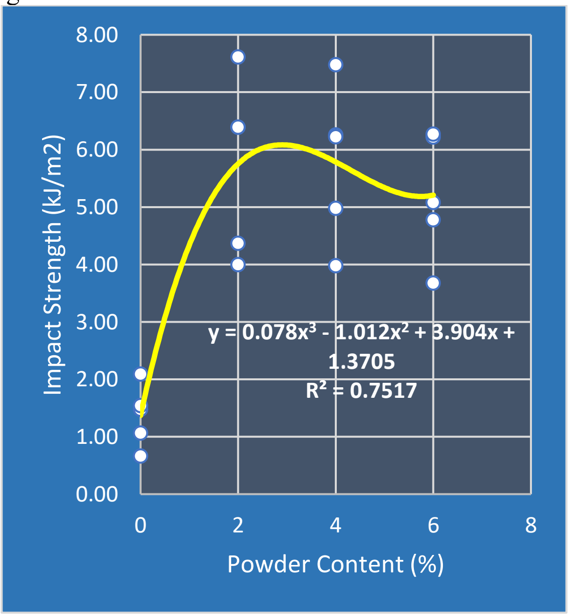

Fig. 4. The regression model of the impact strength of PRRC.

The regression model of PRRC based on the SPP content is shown in Fig.5 as follows:

$$Y_3 = 0.078x^3 - 1.012x^2 + 3.904x + 1.3705 \quad (9)$$

Where: Y_3 = Impact strength PRRC (kJ/m2)
x = SPP content (%)

The coefficient of determination (R^2) for this regression equation is 0.7517, meaning that the percentage of SPP influences 75.17% of the variation in the impact strength of PRRC. In other words, 75.17% of the variation in the SPP content in PRRC can account for the changes in impact strength observed in this study.

The highest impact strength for PRRC is obtained by differentiating equation 9 and making it equal to zero to get the maximum and minimum Y_3, as follows:

$$Y_3 = 0.078x^3 - 1.012x^2 + 3.904x + 1.3705$$
$$dY_3/dx = 0.234x^2 - 2.024x + 3.904 \quad (10)$$
Y_3 will be Maximum or minimum when $dY_3/dx = 0$
$$0 = 0.234x^2 - 2.024x + 3.904$$
$$x_1 = 5.7461$$
$$x_2 = 2.9035$$

Based on Fig. 4, can be seen that the maximum Y_3 is in the range of x between 2 and 4. So, it can be determined that the Y3 maximum is when $x = x_2 = 2.9035$. It means that the highest impact strength of PRRC would be obtained when the content of SPP is 2.9035%.

4 Conclusions

The conclusions obtained from this study are:

1. The full factorial design has been successfully used in this study to determine the effect of the content and morphology of the second phase on the impact strength of the coconut fiber-reinforced resin composite. The number of independent variables was 2 each of which consisted of 3 levels. the number of combinations based on the full factorial design was 9 combinations. From this study, the influence of each phase morphology is obtained as a form of a regression model. The regression model of SFRRC based on SPSF content is $Y_1 = 0.0631x^3 - 0.9013x^2 + 4.0336x + 1.3705$ with a coefficient of determination (R^2) of 0.8778. The regression model of CARRC based on SPCA content is $Y_2 = 0.142x^3 - 1.5982x^2 + 5.0302x + 1.3705$ with a coefficient of determination (R^2) of 0.8885. The regression model of PRRC based on the SPP content is $Y_3 = 0.078x^3 - 1.012x^2 + 3.904x + 1.3705$ with a coefficient of determination (R^2) of 0.7517
2. This research has also obtained the optimum second-phase content to produce the highest impact strength. By differentiating the regression model from each second phase morphology (SFRRC, CARRC, and PRRC), The optimum content of the second phase for SFRRC is 3.5994%, for CARRC is 2.2468%, and for PRRC is 2.9035.

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