

OPTIMIZATION OF FABRICATION PARAMETERS OF POLYPROPYLEN COMPOSITE AND SILICA SAND POWDER USING MOLTEN MIXING METHOD

TỐI ƯU THÔNG SỐ CHẾ TẠO VẬT LIỆU COMPOZIT POLYPROPYLEN VÀ BỘT CÁT SILICA BẰNG PHƯƠNG PHÁP TRỘN NÓNG CHẢY

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ABSTRACT

The optimization of parameters in the screw extruder setup is crucial for enhancing productivity, quality, and cost-effectiveness in the production of final products. In the manufacturing of Polypropylene (PP) thermoplastic with silica sand filler (BCSi), parameters such as temperature, heating time, and screw speed are pivotal in determining the properties of PP/BCSi composite materials. This study focuses on evaluating the effectiveness of surface response analysis methodology in experimental design, modeling, and optimizing manufacturing conditions for the properties of PP/BCSi composite materials. Parameters including mixing temperature, mixing time, and screw speed have been carefully selected to optimize technological factors in material fabrication. Employing the surface response methodology with Box-Behnken experimental design to optimize manufacturing conditions, Shore D hardness, impact strength, tensile strength, and elongation at break serve as objective functions for the optimization process. Statistical modeling results indicate significant correlations, with corresponding high coefficients of determination (R^2) of 0.9912, 0.9975, 0.9990 and 0.9981 for Shore D hardness, impact strength, tensile strength, and elongation at break, respectively. Under the optimal conditions of PP/BCSi material fabrication at 190°C, mixing time of 5 minutes, and screw speed of 50 rounds per minute, experimental objective function values align closely with predictions, with errors less than 5% for each response, indicating the suitability of experimental data and theoretical models. From the research findings, it can be concluded that the surface response methodology with the Box-Behnken design is an effective approach for determining the optimal conditions for manufacturing PP/BCSi composite materials.

Keywords: Optimization, Surface reaction method, Box-Behnken, Poly propylen (PP), PP/BCSi polymer composite.

TÓM TẮT

Cài đặt các thông số tối ưu của máy đùn trục vít đóng vai trò quan trọng trong việc tối ưu hóa năng suất, chất lượng và chi phí trong sản xuất của các sản phẩm cuối cùng. Trong sản xuất nhựa nhiệt dẻo Poly propylen (PP) với chất độn bột cát silica (BCSi), các thông số như nhiệt độ, thời gian gia nhiệt và tốc độ trục vít đều mang tính quyết định đối với các tính chất của vật liệu compozit PP/BCSi. Nghiên cứu này tập trung vào việc đánh giá khả năng của phương pháp phân tích phản ứng bề mặt trong thiết kế thử nghiệm, mô hình hóa và tối ưu hóa điều kiện chế tạo để tính chất của vật liệu compozit PP/BCSi. Các tham số gồm nhiệt độ trộn, thời gian trộn và tốc độ trục vít đã được lựa chọn để tối ưu hóa các yếu tố công nghệ trong chế tạo vật liệu. Sử dụng phương pháp phản ứng bề mặt với thiết kế thí nghiệm theo mô hình Box-Behnken để tối ưu hóa điều kiện chế tạo vật liệu. Độ cứng Shore D, độ bền va đập, độ bền kéo và độ giãn dài khi đứt là hàm mục tiêu cho quá trình tối ưu hóa. Kết quả mô hình thống kê cho thấy tất cả các phản ứng đều có ý nghĩa, với các hệ số tương ứng cao (R^2) lần lượt là 0,9912; 0,9975; 0,9998; 0,9981 cho độ cứng Shore D, độ bền va đập, độ bền kéo và độ giãn dài khi đứt. Dưới điều kiện tối ưu chế tạo vật liệu PP/BCSi ở 190°C, thời gian trộn 5 phút và tốc độ trục vít 50 vòng, các giá trị thí nghiệm hàm mục tiêu lần lượt là 74,58; 27,826; 24,05 và 415,32. Những giá trị này gần với giá trị dự đoán, sai số đều nhỏ hơn 5% cho mỗi phản hồi cho thấy sự phù hợp của dữ liệu thí nghiệm và các mô hình lý thuyết. Từ kết quả nghiên cứu, có thể kết luận phương pháp phản ứng bề mặt với mô hình Box-Behnken là phương pháp hiệu quả để xác định điều kiện tối ưu chế tạo vật liệu compozit PP/BCSi.

Từ khóa: Tối ưu hóa, phương pháp phản ứng bề mặt, Box-Behnken, Poly propylen (PP), Compozit PP/BCSi.

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1. INTRODUCTION

Polypropylene (PP) is one of the most widely used thermoplastics and a fast-growing commodity plastic in today's polymer market [1]. PP has excellent properties such as good heat resistance, chemical resistance and reusability. However, the impact strength, toughness, and low melting temperature lead to limitations in the use of PP in engineering. To improve its disadvantages and expand its application in other fields, it can be done in many ways such as increasing the molecular weight by copolymer synthesis between PP and PS PMMA or adding some inorganic particles (silica, carbon nanotubes,...) into PP [2, 3]. Adding inorganic particles into PP plastic is an effective way to enhance some of its mechanical properties. Previous studies on composite material fabrication often did not include the optimal combination of variables to achieve optimal material performance. In this study, PP/BCSi composite materials were manufactured using the heat-mixing method with screw extrusion [4].

Composite material manufacturing parameters such as temperature, time, screw speed,... have a significant impact on the mechanical properties of the product. To establish suitable conditions for manufacturing composite materials to obtain products with good application-oriented properties, careful selection of manufacturing parameters is necessary. The traditional approach considers one factor the dependent variable while keeping the other factors constant. Experiments are then repeated with different factors as the dependent variable each time. However, this method and approach is time-consuming, expensive, and does not yield reasonable results suitable for many experimental settings [5-9]. The PP/BCSi samples were manufactured with different parameters such as mixing temperature, mixing time and screw speed. The Box - Behnken design via response surface has been used experimentally to determine the influence of manufacturing parameters on hardness, impact toughness, elongation at break and tensile strength of PP/BCSi composite. Anova analysis results show that all three parameters significantly affect the physical and mechanical properties of PP/BCSi composites. In this study, we determined the optimal parameters to manufacture PP/BCSi composite materials with good mechanical properties, and created a mathematical model that can predict the change in mechanical properties of the material within the surveyed parameters.

2. EXPERIMENTAL

2.1. Materials

Polypropylene (PP) plastic is used in granular form, the commercial product (Singapore) has a density of 0.903 g/cm³, flow index of 20g/min at 146°C.

Silica sand powder (BCSi) commercial product (Vietnam) has SiO₂ content 99.0 - 99.8%, Fe₂O₃ ≤ 0.03% with size 5µm.

2.2. Manufacturing methods and analysis of mechanical properties of composite materials

Box - Behnken design is an engineering response surface approach used in experimental design. In this study, the technological parameters investigated include mixing temperature (°C, A), screw speed (rpm, B), mixing time (minutes, C). Using advanced mathematical and statistical methods, the response surface approach investigates the possible influencing factors of several variables. The different technological conditions of the experiment are presented in Table 1. Design Expert software was used as the data statistical analysis tool.

Table 1. Technical parameters used in experiments

Specifications	Technological conditions		
	1	2	3
Temperature/°C (A)	180	190	200
Screw speed/ rpm (B)	40	50	60
Mixing time/ min (C)	4	5	6

To investigate the influence of technological parameters on the material fabrication process, 15 different experiments were performed (Table 2) and evaluated based on many different methods.

Table 2. Experimental design runs

Run No.	Temperature/°C (A)	Screw speed/rpm (B)	Mixing time/min (C)
1	190	50	5
2	190	40	6
3	190	50	5
4	190	50	5
5	190	60	6
6	180	60	5
7	200	50	6
8	180	50	4
9	180	40	5
10	200	50	4
11	190	40	4
12	190	60	4
13	200	40	5
14	180	50	6
15	200	60	5

The obtained PP/BCSi composite samples were determined for physical and mechanical properties such as shore hardness D (ASTM D785-08), impact strength (ISO standard), tensile strength and elongation when rupture (ASTM D638M-93/89). The results of analyzing the mechanical properties of PP/BCSi material according to each test run are presented in Table 3.

Table 3. Results of experiments performed under different technological conditions

No.	Temperature/ °C (A)	Screw speed/ rpm (B)	Mixing time/ min (C)	Impact resistance (kJ/m ²)	Shore D hardness	Tensile strength (MPa)	Elongation after fracture (%)
1	190	50	5	74.59	27.83	24	414.63
2	190	40	6	72.83	25.73	21.68	413.79
3	190	50	5	74.59	27.83	24	414.57
4	190	50	5	74.59	27.83	24	414.57
5	190	60	6	71.87	25.73	23.04	410.94
6	180	60	5	63.16	24.64	22.05	409.85
7	200	50	6	71.51	22.89	21.03	401.03
8	180	50	4	67.04	26.76	22.97	407.81
9	180	40	5	65.79	26.85	21.45	406.84
10	200	50	4	62.07	21.34	19.54	398.21
11	190	40	4	63.98	27.38	20.71	409.95
12	190	60	4	72.83	25.17	21.47	411.97
13	200	40	5	62.15	21.54	17.94	400.17
14	180	50	6	62.86	24.38	23.87	408.55
15	200	60	5	68.87	22.63	19.32	398.88

2.3. Manufacturing methods and analysis of mechanical properties of composite materials

The PP/BCSi composite material was produced using the melt mixing method on the Haake Rheomixer internal mixing equipment, with a mass ratio of PP to BCSi set at 7:3. Technical parameters for manufacturing PP/BCSi materials are adjusted according to Table 2. PP/BCSi composite material samples were determined for physical and mechanical properties such as shore hardness D (ASTM D785-08), impact strength (ISO standard), tensile strength and elongation at break (ASTM D638M-93/89). The results of analyzing the mechanical properties of PP/BCSi material according to each test run are presented in Table 3.

2.4. Statistical analysis of experimental results

Variance analysis, computational analysis, model determination, response surface analysis and optimization are all performed on the results obtained from experimental data. Anova is an objective decision-making tool based on statistics, evaluated by regression coefficients, F values, P values, R correlation coefficients.

3. RESULTS AND DISCUSSION

3.1. Experimental results

Experimental results on the mechanical properties of PP/BCSi material of each test run according to the experimental design (Table 2) are presented in Table 3.

3.2. Analyze the influence of technological parameters on the basic properties of PP/BCSi materials

Data from 15 experiments were analyzed to evaluate the influence of technological factors such as temperature, screw speed and mixing time on the properties of PP/BCSi

composite materials. ANOVA results on Shore D hardness, impact strength, tensile strength and elongation at break performed with 95% confidence level and 5% significance level are presented in Tables 4 - 7.

Table 4. Anova results for Shore D hardness

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	338.12	9	37.57	62.75	0.0001	significant
A- Temperature	4.13	1	4.13	6.90	0.0467	
B- Screw speed	17.94	1	17.94	29.96	0.0028	
C- Mixing time	21.62	1	21.62	36.10	0.0018	
AB	21.86	1	21.86	36.50	0.0018	
AC	46.38	1	46.38	77.46	0.0003	
BC	24.06	1	24.06	40.18	0.0014	
A ²	183.65	1	183.65	306.73	< 0.0001	
B ²	23.92	1	23.92	39.94	0.0015	
C ²	10.27	1	10.27	17.15	0.0090	
Lack of Fit	2.99	3	0.9979			
R ²	0.9912					
Adjusted R ²	0.9754					
Adeq Precision	20.6558					

The results in Table 4 show that the model is considered significant with a P value less than 0.05 and a larger F value indicating that a change in process parameters will produce a significant change in properties. Mechanics of PP/BCSi composite materials. Process parameters with P values less than 0.05 indicate that the model parameters significantly influence the response in the design space. In this case A, B,

C, AB, AC, BC, A², B², C² are important model terms. Meanwhile, the influence of the time parameter (C) is not significant (p value > 0.05). Therefore, it can be concluded that mixing temperature (A) and screw speed (B) have individual effects in the fabrication of PP/BCSi composites. Cross interactions (AB, AC, BC) and square interactions (A², B², C²) have a significant influence on the Shore D hardness of PP/BCSi composite materials. This model can be used to navigate the design space.

Table 5. Anova results on impact strength

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	72.25	9	8.03	225.52	< 0.0001	significant
A- Temperature	25.31	1	25.31	711.10	< 0.0001	
B- Screw speed	1.39	1	1.39	38.94	0.0015	
C- Mixing time	0.4608	1	0.4608	12.95	0.0156	
AB	2.72	1	2.72	76.49	0.0003	
AC	3.86	1	3.86	108.48	0.0001	
BC	1.22	1	1.22	34.30	0.0021	
A ²	34.07	1	34.07	957.07	< 0.0001	
B ²	2.84	1	2.84	79.87	0.0003	
C ²	3.33	1	3.33	93.62	0.0002	
Lack of Fit	0.1780	3	0.0593			
R ²	0.9975					
Adjusted R ²	0.9931					
Adeq Precision	42.2521					

Table 5 shows that the cases A, B, C, AB, AC, BC, A², B², C² are important model terms. Meanwhile, the influence of single parameter screw speed (B) time (C) and cross parameter (AB, AC) is not important (p value > 0.05). Therefore, it can be concluded that mixing temperature (A), cross interactions AC, BC and square interactions A², B², C² have a significant influence on the impact strength of PP/BCSi composite materials. This model can be used to navigate the design space.

Table 6. Anova results on tensile strength

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	49.95	9	5.55	5163.06	< 0.0001	significant
A- Temperature	19.56	1	19.56	18197.69	< 0.0001	
B- Screw speed	2.10	1	2.10	1954.65	< 0.0001	
C- Mixing time	3.04	1	3.04	2826.15	< 0.0001	
AB	0.1521	1	0.1521	141.49	< 0.0001	
AC	0.0870	1	0.0870	80.95	0.0003	
BC	0.0900	1	0.0900	83.72	0.0003	
A ²	12.52	1	12.52	11644.34	< 0.0001	
B ²	14.31	1	14.31	13312.84	< 0.0001	
C ²	0.3463	1	0.3463	322.14	< 0.0001	
R ²	0.9998					
Adjusted R ²	0.9996					
Adeq Precision	227.1612					

From Table 6 it can be seen that the cases A, B, C, AB, AC, BC, A², B², C² are important model terms. Meanwhile, the effect of cross interaction (AB, AC, BC) is not significant (p value > 0.05). From there, it can be concluded that the single interactions of mixing temperature (A), screw speed (B), mixing time (C) and square interactions (A², B², C²) have a significant influence. to the tensile strength of PP/BCSi composite material. This model can be used to navigate the design space.

Table 7. Anova results on elongation at break

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	484.91	9	53.88	293.03	< 0.0001	significant
A- Temperature	151.03	1	151.03	821.43	< 0.0001	
B- Screw speed	0.0990	1	0.0990	0.5385	0.4960	
C- Mixing time	5.07	1	5.07	27.59	0.0033	
AB	4.62	1	4.62	25.14	0.0041	
AC	1.08	1	1.08	5.88	0.0597	
BC	5.93	1	5.93	32.25	0.0024	
A ²	313.11	1	313.11	1702.94	< 0.0001	
B ²	7.72	1	7.72	42.00	0.0013	
C ²	8.10	1	8.10	44.06	0.0012	
Lack of Fit	0.9169	3	0.3056	254.70	0.0039	significant
R ²	0.9981					
Adjusted R ²	0.9947					
Adeq Precision	46.7032					

Table 7 shows that the cases A, C, AB, BC, A², B², C² are important model terms. Meanwhile, the influence of screw speed parameter (B), cross interaction AC, BC is not important (p value > 0.05). Therefore, it can be concluded that mixing temperature (A), mixing time (C) have individual effects in the fabrication of PP/BCSi composite materials, AB cross interactions and square interactions have a significant influence. refers to the elongation at break of PP/BCSi composite material. This model can be used to navigate the design space.

3.3. Mathematical modeling and graph analysis

From the data in Anova and applying set regression analysis on experimental data, the proposed suitable quadratic polynomials are:

$$\begin{aligned}
 \text{Shore D hardness} = & 74.59 + 0.7187*A + 1.50*B + 1.64*C \\
 & + 2.34*AB + 3.41*AC - 2.45*BC \\
 & - 7.05*A^2 - 2.54*B^2 - 1.67*C^2 \quad (1)
 \end{aligned}$$

$$\begin{aligned}
 \text{Impact strength} = & 27.83 - 1.78*A - 0.4163*B - 0.2400*C \\
 & + 0.8250*AB + 0.9825*AC + 0.5525*BC \\
 & - 3.04*A^2 - 0.8775*B^2 - 0.9500*C^2 \quad (2)
 \end{aligned}$$

$$\begin{aligned}
 \text{Tensile strength} = & 24.00 - 1.56*A + 0.5125*B + 0.6163*C \\
 & + 0.1950*AB + 0.1475*AC + 0.1500*BC \\
 & - 1.84*A^2 - 1.97*B^2 - 0.3063*C^2 \quad (3)
 \end{aligned}$$

$$\begin{aligned}
 \text{Elongation at break} = & 414.59 - 4.35*A + 0.1112*B + 0.7963*C \\
 & - 1.07*AB + 0.5200*AC - 1.22*BC \\
 & - 9.21*A^2 - 1.45*B^2 - 1.48*C^2 \quad (4)
 \end{aligned}$$

Quadratic equation models were developed for output variables such as Shore D hardness, impact strength, tensile strength, elongation at break evaluated by F test. From Table 4 - 7 the values The p-value for each model is less than 0.05, showing that the overall models are statistically significant for analyzing influencing factors. This assertion is very consistent with the large correlation coefficient R^2 for the corresponding models. The models have a high degree of fit to highly variable data and are therefore likely to be representative of the experimental results. The residuals follow a normal distribution, generally falling within a tight least squares line with no reasonable outliers, and all the data are within limits and there is no unusual structure in the model.

Normal probability plot of residuals for Shore D hardness, impact strength, tensile strength and elongation at break are presented in Figures 1a-d.

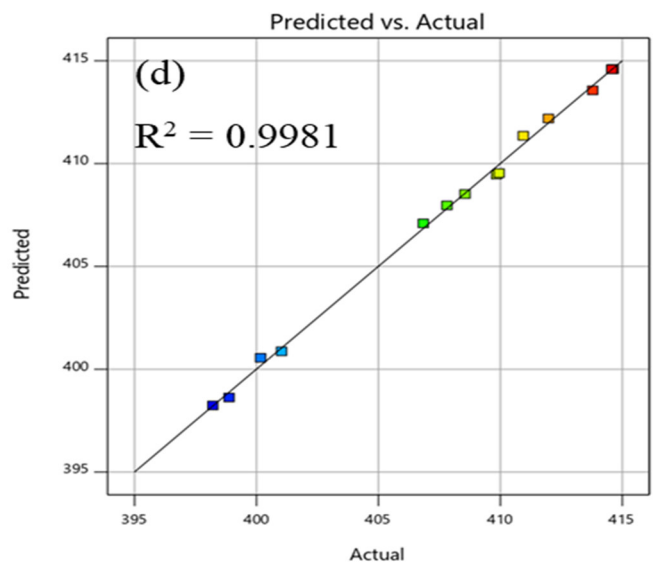
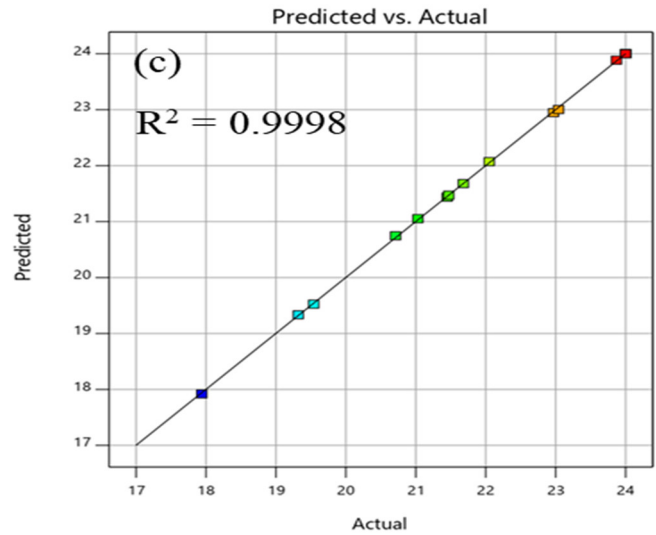
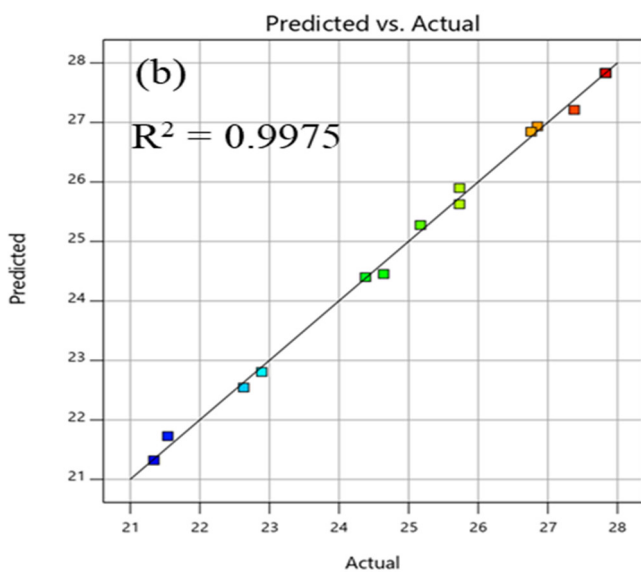
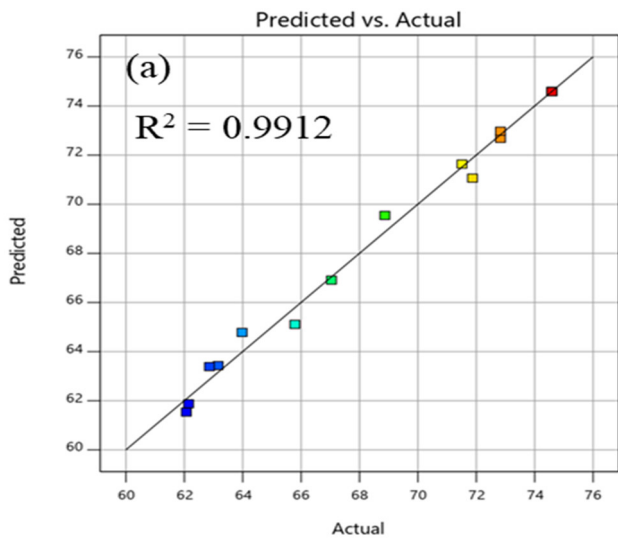
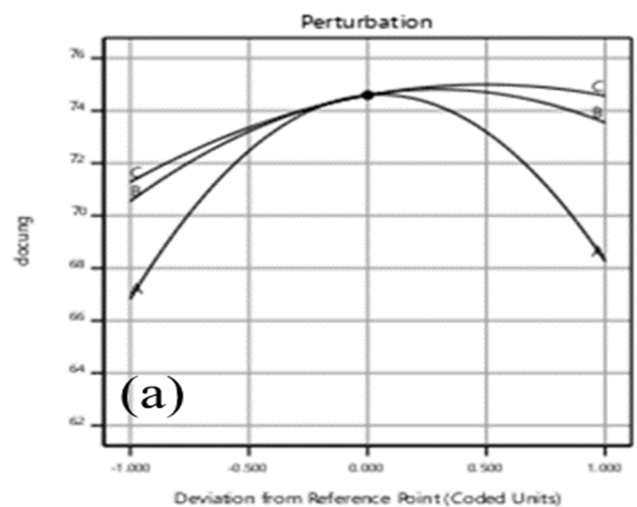


Figure 1. Normal probability plot of residuals for Shore hardness D (a), impact strength (b), tensile strength (c) and elongation at break (d)

Perturbation curves of Shore D hardness, impact toughness, tensile strength and elongation at break are presented in Fig. 2a-d.



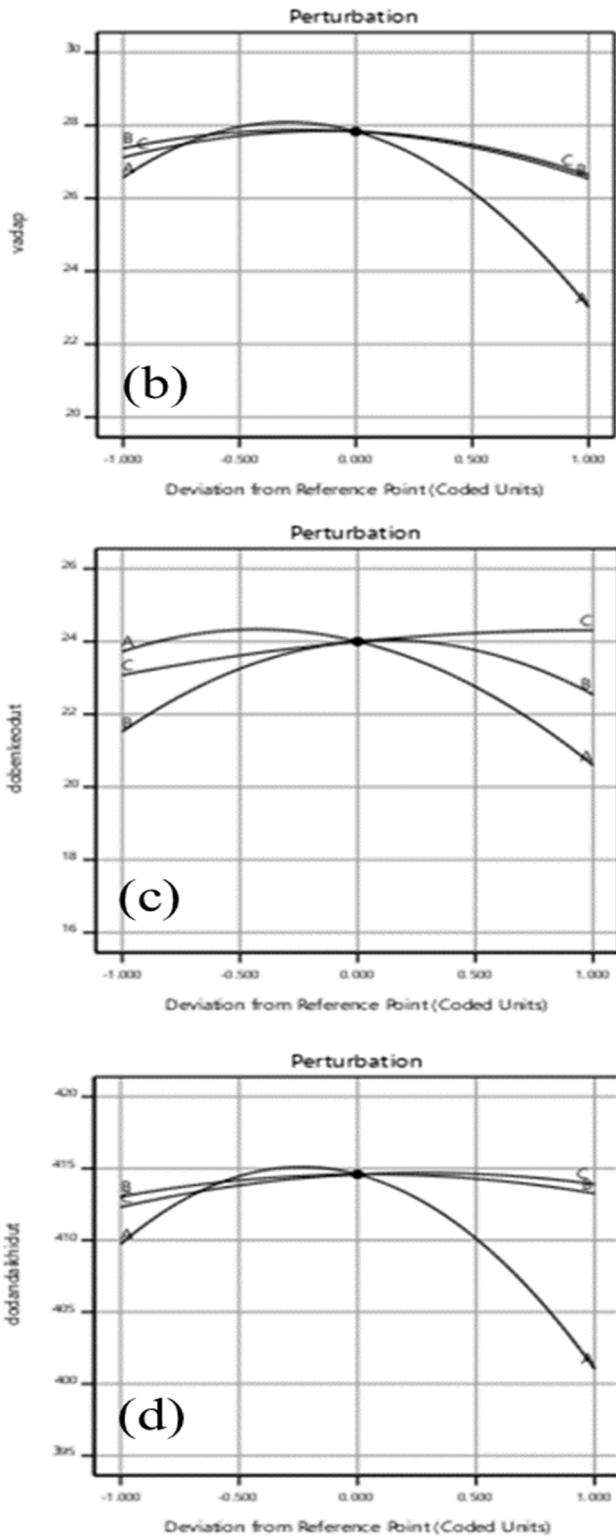


Figure 2. Perturbation diagram for Shore D toughness (a), impact toughness (b) tensile strength (c) and elongation at break (d)

According to the Shore D hardness results, Figure 2a shows that the coefficient A tends to increase from the minimum point (-1) to the center point (0) and then gradually decrease from the center point to the maximum point (+1). It is shown that for technological conditions

mixing temperatures from 180°C to 190°C lead to an increase in Shore D hardness of PP/BCSi composites. Meanwhile, coefficient B tends to increase gradually between points -1 and +1, describing the trend as positive linear. The coefficient C tends to increase from point -1 to the central point 0 and then gradually decrease to point +1.

Regarding impact intensity, Figure 2b shows that the coefficients A, B, C all tend to increase from point -1 to the central point 0 and then gradually decrease to point +1. This proves that increasing fabrication conditions is not favorable for the impact resistance of PP/BCSi composite materials.

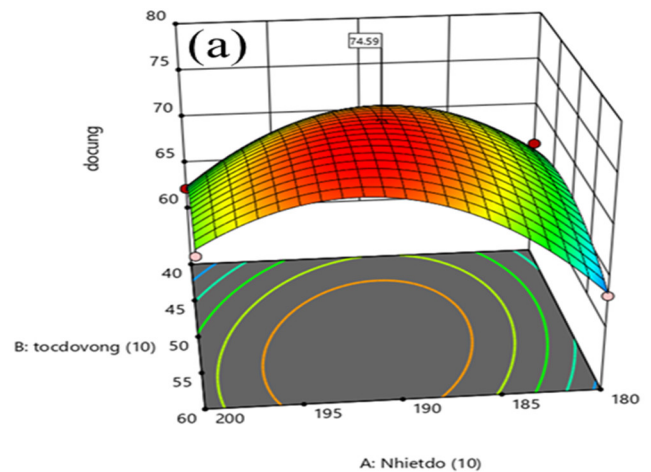
Figure 2c of the tensile strength shows that coefficient A also tends to increase from point -1 to the central point 0 and then decreases sharply when reaching point +1, while for coefficients B and C the trend increases more. from point -1 to center point 0, then increases slightly as it passes through 0 to point +1. This means that increasing the mixing temperature to 190°C improves the tensile strength of PP/BCSi material, in the temperature range of 190°C - 200°C is not favorable.

Similarly, the elongation at break in Figure 2d shows that the coefficient A tends to increase from point -1 to point -0.25 and then gradually decrease from point -0.25 to point +1. Coefficients B and C tend to increase slightly from point -1 to the central point 0 and then decrease slightly to point +1.

3.4. Analyze surface plots and contour plots

The predicted maximum and optimal values for Shore D hardness, impact strength, tensile strength, and elongation at break from testing can be determined using response surface equations. The relationship between the above properties and the interaction of related parameters is presented in the form of 3D surface plots and contour plots. Each 3D surface plot shown was created by keeping one element constant at the center point and varying the other elements within the experimental range.

The influence of the interaction between temperature, mixing time and screw speed on the Shore D hardness of PP/BCSi composites is presented in Figure 3a-c.



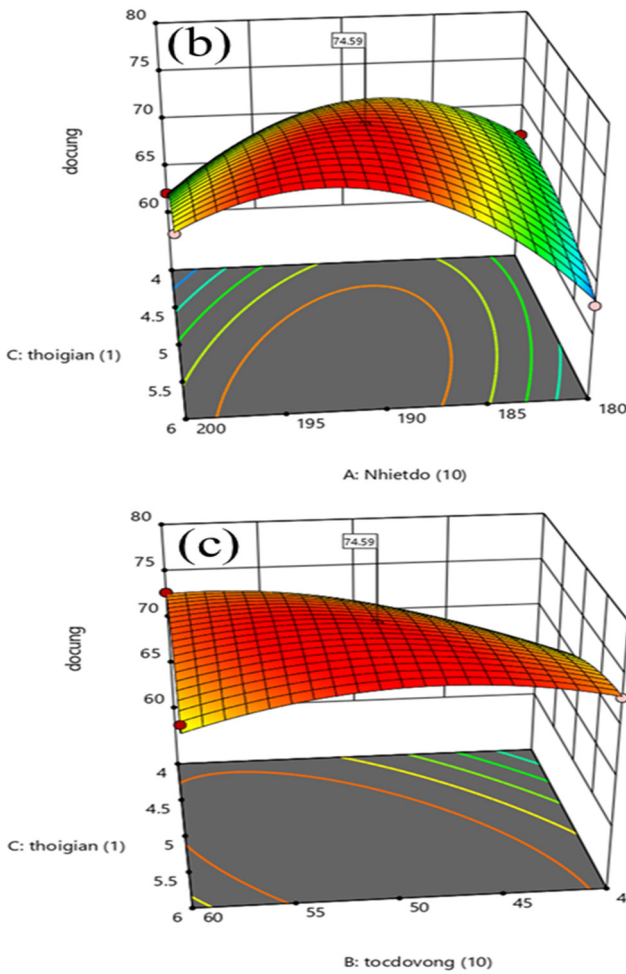


Figure 3. 3D response surface diagram showing the influence of the interaction between mixing temperature, screw speed and mixing time on Shore D hardness

From Figure 3a, it can be seen that the effect of temperature and mixing time on Shore D hardness. When increasing the temperature to 190°C, the mixing time increases to 5 minutes, Shore D hardness increases, this value tends to decrease with continued use. Continue increasing the temperature to 200°C, mixing time to 6 minutes because at this condition PP begins to decompose. The Shore D hardness affected by mixing time and screw speed is shown in Figure 3b and mixing temperature and screw speed are shown in Figure 3c. The viscosity of the system depends on temperature and it affects the properties of PP/BCSi composites. At low temperatures of 180°C, the viscosity of the system is low, BCSi has low mobility in the melt, causing segregation, agglomeration and coagulation. Fabrication conditions for PP/BCSi composite materials at 190°C, 5 minutes mixing time and 50 rpm screw speed resulted in materials with Shore D hardness reaching the highest value seen from the 3D model.

The influence of the interaction between temperature, mixing time and screw speed on the impact strength of PP/BCSi composites is presented in Figure 4a-c.

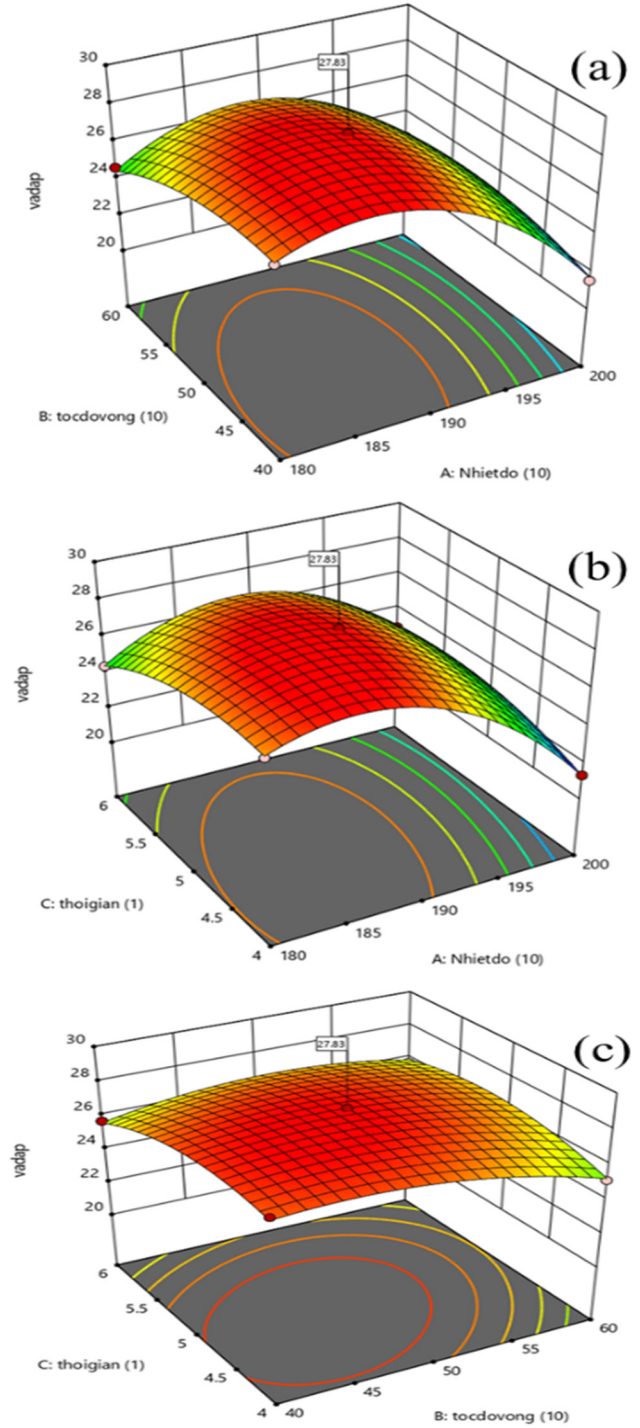


Figure 4. 3D response surface diagram showing the influence of the interaction between mixing temperature, screw speed and mixing time on impact strength

Figures 4a, 4b, 4c show that the impact strength of PP/BCSi composite material is increased during the process of increasing the mixing temperature to 190°C, mixing time of 5 minutes and screw speed of 50 revolutions, if continued to increase. With temperature and mixing time, the impact resistance of the material tends to decrease. Two factors, temperature and mixing time, greatly affect the impact strength of PP/BCSi composites.

The influence of the interaction between temperature, mixing time and screw speed on the elongation at break of PP/BCSi composites is presented in Figure 5a-c.

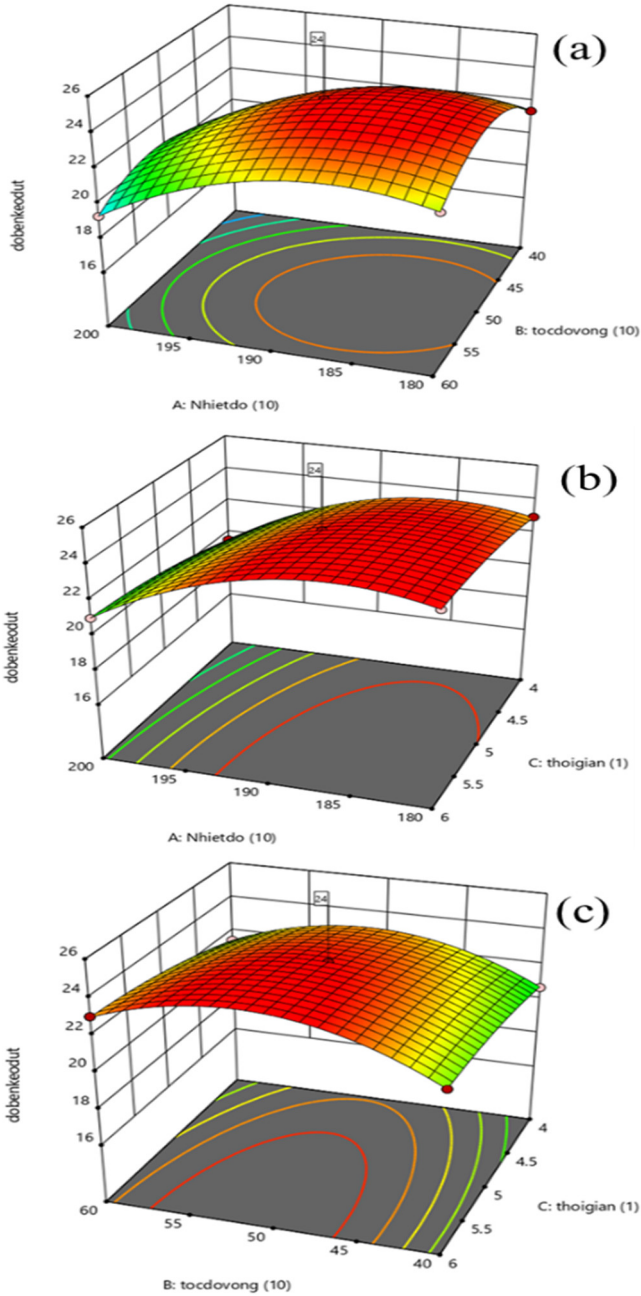


Figure 5. 3D response surface diagram showing the influence of the interaction between mixing temperature, screw speed and mixing time on elongation at break

Figure 5a depicts the effects of temperature and mixing time; Figure 5b depicts the contrast between mixing temperature and screw speed; Figure 4c depicts the effect of mixing time and screw speed on the elongation at break of the material. Observing Figures 5a, 5b shows that mixing temperature and mixing time greatly affect the elongation at break of the material. Figure 5c shows that the effects of mixing time and screw speed do not greatly affect the above properties of PP/BCSi composites.

The effects of the interaction between temperature, mixing time and screw speed on the tensile strength of PP/BCSi composites are presented in Figure 6a-c.

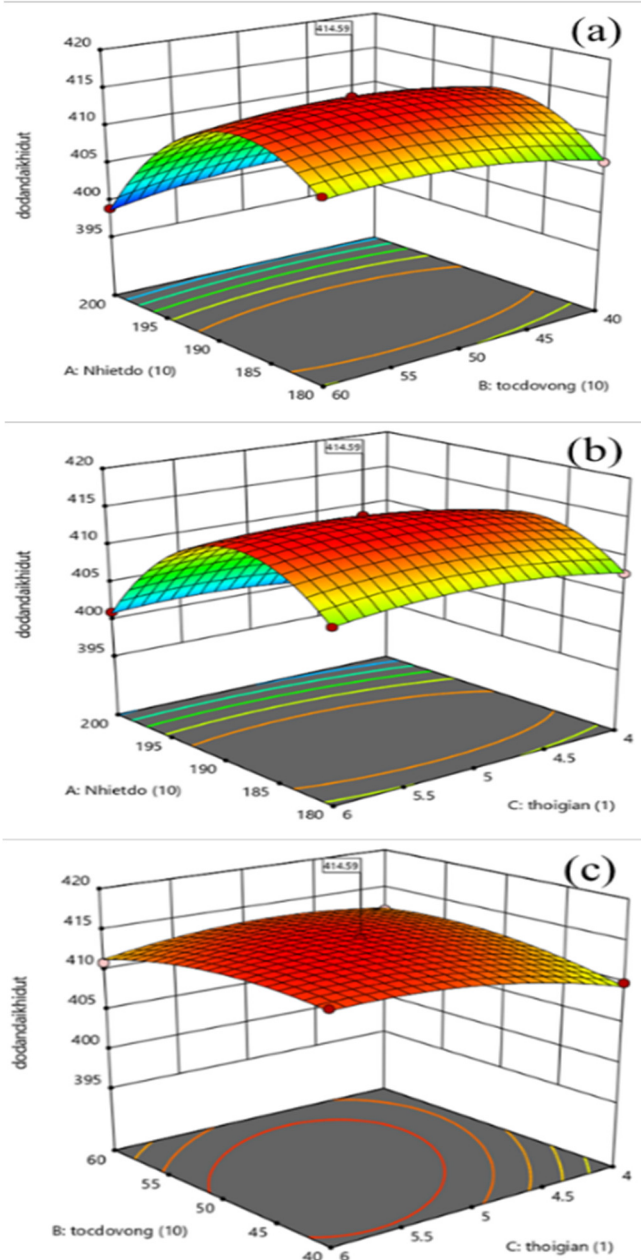


Figure 6. 3D response surface diagram showing the influence of the interaction between mixing temperature, screw speed and mixing time on tensile strength

Figure 6a-c shows that, when increasing the mixing temperature from 180°C to 190°C, the mixing time increases from 4 minutes to 5 minutes and the screw speed increases from 40 to 50rpm, the tensile strength tends to increase. However, the tensile strength begins to decrease as the manufacturing conditions for PP/BCSi materials continue to increase because as the temperature increases, the mixing time lengthens causing PP to decompose, the system viscosity increases and the BCSi particles have agglomeration phenomenon.

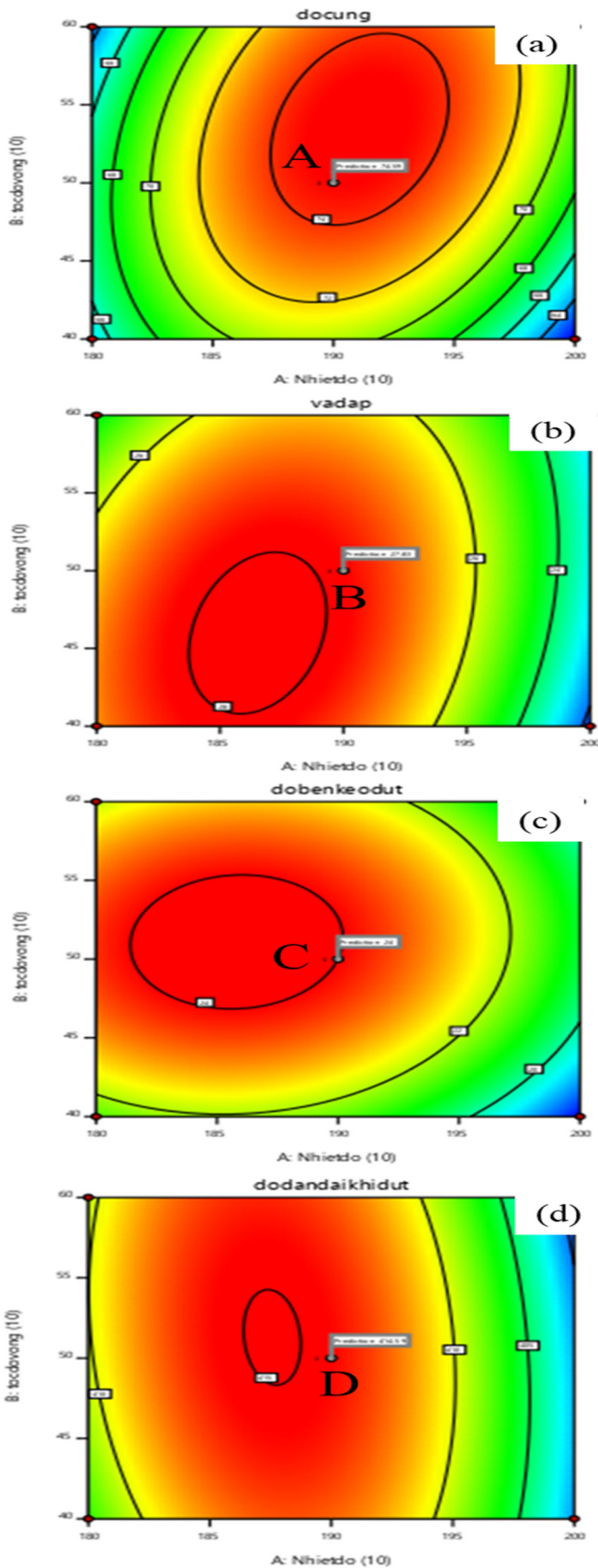


Figure 7. Diagram of the influence of parameters on Shore D hardness (a), impact strength (b), tensile strength (c) and elongation at break (d) of composite materials PP/BCSi

The influence of parameters on Shore D hardness (a), impact strength (b), tensile strength (c) and elongation at break (d) of PP/BCSi composite material is shown as The contour plot is presented in Figure 7.

The sections marked A, B, C, and D in the plots are regions where the combination of fabrication parameters yields a desired range of values for the responses.

3.5. Optimization of PP/BCSi composite fabrication process and validation

After Anova analysis, some technical solutions are presented in Table 8 and the results of validation tests with optimal PP/BCSi composite fabrication conditions are presented in Figure 8.

Among a number of technical solutions, in this study we choose the optimal conditions for forming PP/BCSi composite materials as solution number 2 to run confirmation tests.

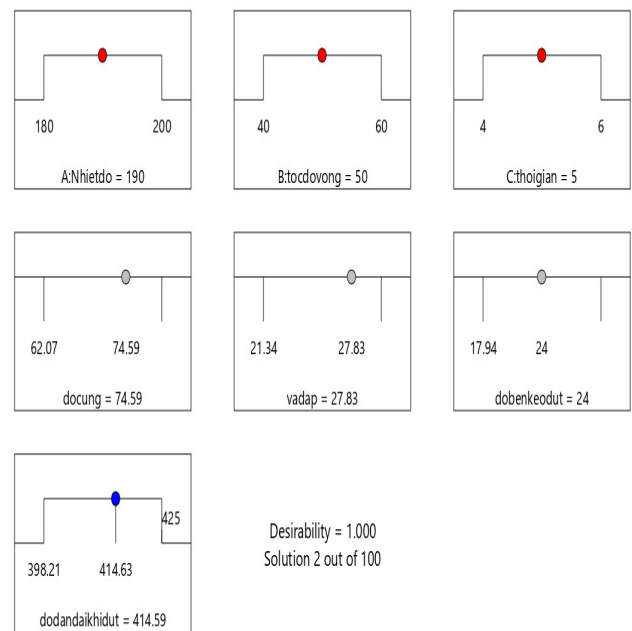


Figure 8. Optimum conditions and predicted mechanical properties of composite materials

The results of testing the optimal conditions when manufacturing PP/BCSi composite materials are presented in Table 9.

Model testing process and validation experiments were conducted at optimal composite fabrication conditions. The obtained experimental values show agreement between predicted and experimental results with error < 5%.

4. CONCLUSION

In this study, Anova analysis holds significant importance in the design of experiments, property analysis, modeling, and optimization of the mechanical properties of PP/BCSi composite material. The results of variance analysis show that three parameters mixing temperature, mixing time and screw speed significantly impact the physical and

Table 8. Some technical solutions to manufacture PP/BCSi composite materials with expected physical and mechanical properties

No	Temperature (°C)	Screw speed (rpm)	Mixing time (min)	Impact resistance (kJ/m ²)	Shore D hardness	Tensile strength (MPa)	Elongation after fracture (%)	Desirability	
1	192.534	52.174	4.161	71.825	26.321	22.724	411.196	1.000	
2	190.000	50.000	5.000	74.590	27.830	24.000	414.590	1.000	Selected
3	190.000	40.000	6.000	72.976	25.626	21.679	413.565	1.000	
4	200.000	50.000	4.000	61.540	21.321	19.525	398.239	1.000	
5	180.000	40.000	5.000	65.114	26.935	21.436	407.094	1.000	
6	200.000	60.000	5.000	69.546	22.545	19.334	398.626	1.000	
7	180.000	50.000	6.000	63.390	24.399	23.885	408.521	1.000	
8	190.000	60.000	4.000	72.684	25.274	21.471	412.195	1.000	
9	200.000	40.000	5.000	61.876	21.727	17.919	400.554	1.000	
10	190.000	40.000	4.000	64.784	27.211	20.746	409.538	1.000	

Table 9. Results of validation runs with optimal PP/BCSi composite material fabrication parameters

Temperature (°C)	Mixing time (min)	Screw speed (rpm)	Shore D hardness		Impact resistance (kJ/m ²)		Elongation after fracture (%)		Tensile strength (MPa)	
			Prediction	Reality	Prediction	Reality	Prediction	Reality	Prediction	Reality
190	5	50	74.59	74.58	27.830	27.826	414.59	415.32	24.00	24.05

mechanical properties of PP/BCSi composites. More over, the built model for each response parameter has been determined, has statistical significance and is suitable for use in predicting the mechanical properties of fabricated PP/BCSi composite materials.

The optimal conditions for manufacturing PP/BCSi composite materials are mixing temperature of 190°C, mixing time of 5 minutes and screw speed of 50rpm with properties of Shore D hardness 74.59, impact strength 27.83MPa, elongation at break 414.54% and tensile strength 24.00MPa. A model is justified when it is established by testing that produces results.

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