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Optimizing the Flexural Behavior of Bamboo Reinforced Concrete Beams Containing Cassava Peel Ash using Response Surface Methodology

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Abstract

The growing concern to reduce global warming has necessitated the use of more eco-friendly materials in construction. The study is focused on the utilization of cassava peel ash as supplementary cementitious material and bamboo as reinforcement in concrete beams. The response surface methodology approach was explored to determine the effect of simultaneously varying the cassava peel ash content, bamboo size, beam length, and beam depth on the flexural strength and strain of beams. An analysis of variance was carried out on experimentally obtained results to determine the accuracy of the obtained models and the contributions made by the linear interaction and quadratic terms on flexural strength and flexural strain. The coefficient of determination obtained for RSM models showed a good correlation between all predicted and experimentally obtained results. The optimum conditions obtained for bamboo-reinforced concrete containing cassava peel ash were 3% cassava peel ash, 16 mm bamboo diameter, 500 mm beam length, and 150 mm beam depth. The predicted flexural strengths were 11.85, 14.34, and 14.95 N/mm^2 and flexural strains of 0.64, 0.67, and 0.91 for 28 days, 56 days, and 90 days, respectively. To validate the model prediction, a laboratory experiment was conducted using the optimum mix design proportion. From the results obtained, it was observed that the experimental results were close to those predicted by the models. These models can be efficiently used for simulating the flexural behavior of bamboo-reinforced concrete beams.

Keywords: Cassava Peel Ash; Bamboo; Response Surface Methodology; Flexural Strength; Flexural Strain.

1. Introduction

Concrete is one of the most popular man-made materials used for different construction purposes. It has good compressive strength but low tensile strength and can be produced in various sizes and shapes [1]. This deficiency of concrete in terms of tensile strength is taken care of by the introduction of reinforcement steel or other fiber materials. Concrete has undergone several evolutions and will continue to evolve as long as new inventions and materials are discovered. The changes concrete undergoes range from its constituent materials to its mixing strength, applications, and maintenance, especially as sustainability is now a key issue in concrete production. The manufacturing process of

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steel and cement is characterized by the emission of CO_2, and according to Mali & Datta [2], the production of a ton of steel emits about 1.83 tons of CO_2. This is one of the major disadvantages of conventional construction materials. It is therefore important to focus on ways to make concrete production more sustainable [3–5]. Timber is one of the alternative materials available for use in the construction industry that can promote environmental sustainability and green technology. It is a naturally occurring material with several species. Bamboo, a unique species of timber, is used as reinforcement in concrete [6, 7]. This is being advocated based on research findings, especially when there is a need to erect low-cost green buildings [4, 8, 9]. Similarly, the ever-increasing cost of steel and the need for alternative eco-friendly materials have led to the use of bamboo [10]. Bamboo fits into this category due to its considerable tensile strength and renewable nature. Bamboo has become a reliable replacement for steel in structural elements [11]. Previous studies by Premkumar & Vasugi [12] and Qaiser et al. [8] have identified bamboo to be suitable for rural construction where steel reinforcement is not affordable. Siddika et al. [13] have reported a reduction in construction costs ranging between 10 to 20% with the use of bamboo as reinforcement in place of steel. For the purpose of economy, the use of bamboo as reinforcement provides a strength-cost ratio that is nine times less than that of steel. The tensile strength of bamboo has been investigated and was found to be as high as 370 N/mm^2 [14]. With this, bamboo is gradually becoming a viable replacement for steel in tensile loading applications, and this is aided by the higher ratio of tensile strength to unit weight of bamboo, which is six times higher than that of steel [2, 15].

Another drive for sustainability is the adoption of various types of waste in concrete [16-18]. The addition of recycled waste materials as supplementary cementitious materials (SCM) in concrete production affects different concrete properties compared to that of normal concrete. The use of SCMs in suitable proportions in concrete is increasingly becoming inevitable as they provide technical, economic and environmental advantages [19, 20]. These advantages result from the reduction in clinker consumption and enhanced utilization of agricultural/industrial by-products [21]. In recent times, the attention of researchers has been drawn to cassava peel ash (CPA) due to its abundant availability in many parts of the world including Asia and Africa. Cassava peels (CP) are obtained from the peeling of cassava tubers and it makes up twenty to thirty-five per cent of the tuber mostly during the process of manually removing the peels [23]. The generation of CP rose to about twelve million tons in the year 2020 [22]. The unethical disposal of cassava peels which is resulted from under-exploitation and lack of adequate means to manage them has become a challenge and this caused serious environmental pollution. In view of the foregoing, the search for a better way of management has become critical. The result obtained from Cassava peels calcined at 700 ℃ for ninety minutes showed high pozzolanic potentials, meeting the minimum requirements of seventy per cent combined oxide of silicon, aluminium and iron [24].

Haryanto et al. [25] investigated the structural behavior of bamboo-reinforced concrete slabs with different reinforcement sizes under concentrated loads. It was observed that the ultimate load-carrying capacity was significantly influenced by the reinforcement size. From the results obtained, it was concluded that bamboo can be a suitable alternative for steel reinforcement. However, it was recommended that further studies be carried out to examine this opportunity. Dey & Chetta [9] studied the flexural behavior of bamboo-reinforced concrete beams with different fractional properties and observed that bamboo-reinforced concrete increased with an increase in curing days and reinforcement size when compared to smaller reinforcement sizes and shorter curing days. The study recommended the determination of an optimum reinforcement size to prevent uncertainty in design. Mali & Datta [2] have carried out an experimental evaluation of the bamboo-reinforced concrete beam. This study has identified that it is difficult to predict the behavior of beam-reinforced concrete beams. The current study will predict and optimize the flexural behavior of bamboo-reinforced concrete beams with different dimensions and reinforcement sizes using the Response Surface Methodology (RSM) approach.

The ability to provide a computer-simulated mathematical model that satisfactorily relates both CPA content, bamboo size, and specimen geometry with the desired response will enhance structural safety and provide eco-friendly reinforced concrete. RSM has been used for numerous studies in engineering and other disciplines. RSM establishes a relationship between experimental conditions and the outcome of the experiments using a minimal number of experiments. In addition, it provides improved processing for the optimization of input parameters to obtain the best output [26, 27]. RSM can be used to improve the performance of this composite material by providing mathematical models for desired responses. This study uses the numerical optimization and desirability approach in RSM for predicting and optimizing the flexural strength and minimizing the flexural strain of bamboo-reinforced concrete containing CPA. The study explores the influence of four variables, such as percentage of cement replaced with CPA, bamboo size (reinforcement size), beam depth, and length, in evaluating the flexural behavior of bamboo-reinforced concrete beams. The study will promote the use of bamboo as a choice material for reinforcing concrete. This provides an opportunity for increased cultivation of the plant since the growing process of bamboo culm absorbs CO_2 and can help provide a sustainable environment.

2. Experimental Programme, Material and Procedure

The process flowchart from the collection of materials to the testing and analysis of results for the BRC is presented in Figure 1.

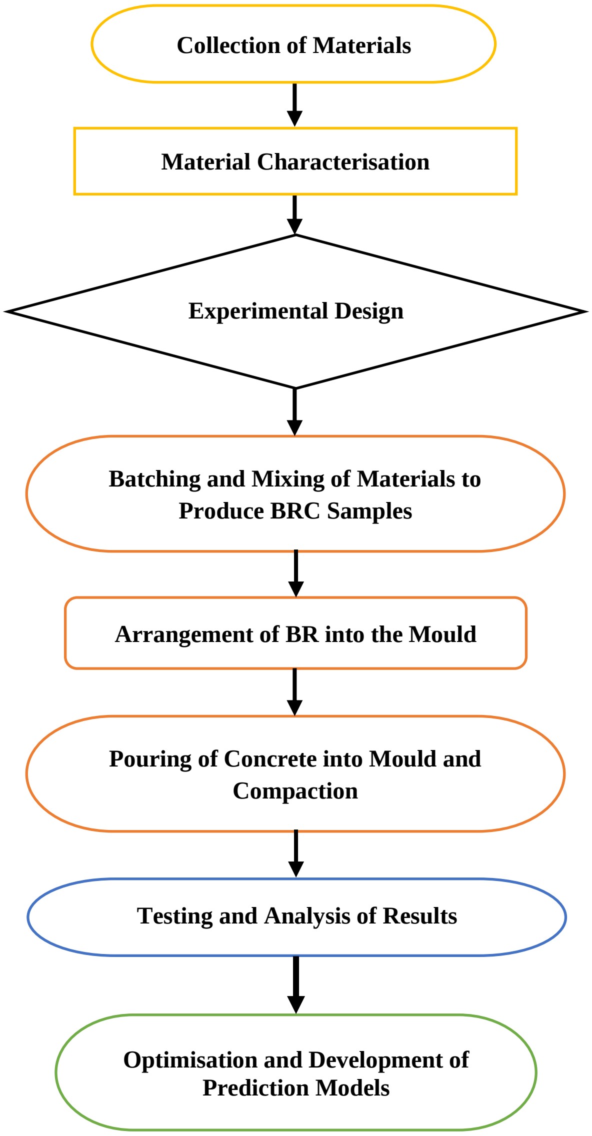

Figure 1. BRC production, testing and analysis flowchart

2.1. Experimental Programme

The tests were carried out using a Box-Behnken Design (BBD) with four components at three levels, as shown in Table 1. The percentage of CPA ash replacement, bamboo diameter, bamboo size, and beam size were chosen as the input factors (independent variables) for the design of the experiment. $N = 2k(k-1) + C_o$ is the number of experiments required to produce BBD (where k is the number of factors and Co is the number of central points). The BBD produced 29 experimental runs containing five central points. The percentage CPA replacement for cement was 0, 10, and 20%; the bamboo size considered was 12 mm, 14 mm, and 16 mm; and the beam size varied from a depth of 150–250 mm and length of 400–600 mm. The variation in beam depth provides three different arrangements of reinforcement with a cover of 25 mm. A uniform stirrup made of bamboo with a 12 mm diameter at a spacing of 75 mm was used. The geometrical details of the beams are presented in Figure 2.

Table 1. Experimental Design Layout

Test No	Ash (%)	Bamboo diameter (mm)	Beam size	
			Depth (mm)	Length (mm)
1	10	14	200	500
2	10	14	200	500
3	10	14	200	500
4	10	14	150	400
5	10	14	250	400
6	20	12	200	500
7	10	12	200	400

8	10	12	150	500
9	10	14	250	600
10	10	14	200	500
11	10	16	200	600
12	10	14	150	600
13	10	12	250	500
14	10	16	200	400
15	0	12	200	500
16	0	14	200	600
17	20	14	200	600
18	10	16	150	500
19	10	12	200	600
20	20	14	150	500
21	10	16	250	500
22	20	16	200	500
23	0	14	200	400
24	20	14	250	500
25	0	14	150	500
26	0	14	250	500
27	20	14	200	400
28	0	16	200	500
29	10	14	200	500

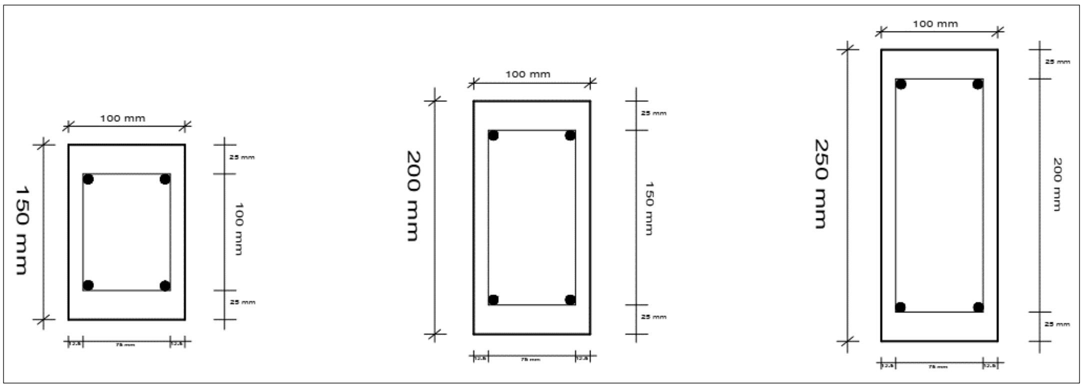

Figure 2. Geometrical details of the beam

2.2. Material Collection and Characterization

2.2.1. Cassava Peel Ash

The cassava peel ash was produced by first collecting the cassava peels from Landmark University farms in Kwara State, Nigeria. The peels were sun-dried and calcined at 800 °C for two hours using a Thermolyne furnace. The ash was then sieved and further pulverized with a ball milling machine to the required particle size, which was finer than sieve number 200 (75 µm). X-Ray fluorescence analysis was carried out on the CPA sample to determine its chemical composition. The test was performed following ASTM D5381-93 guidelines to determine the compounds present in the CPA. The main compounds identified include SiO_2, Al_2O_2, Fe_2O_2, etc. The chemical composition of CPA is presented in Table 2.

Table 2. XRF analysis test on CPA

Chemical composition	SiO_2	Al_2O_3	Fe_2O_3	K_2O	CaO	SO_2	P_2O_5	Ag_2O	MgO	Y_2O_3	Nb_2O_5	Cl	TiO_2	Na_2O	V_2O_5
CPA	39.26	16.98	14.76	4.36	5.03	4.54	4.88	1.58	2.42	1.57	1.58	1.05	1.39	0.30	0.29

2.2.2. Aggregates

The fine aggregate used was river sand with a specific gravity of 2.67 and 5.48% moisture content; the coarse aggregate was a siliceous granitic material with a specific gravity of 2.93 and an aggregate crushing value of 9.51%. The physicomechanical properties of the aggregates are presented in Table 3. The sieve analysis for the CPA and the aggregates used are in Figure 3.

Table 3. Physical and mechanical properties of aggregates

S/N	Parameters	Values obtained
Fine aggregates		
1	Specific Gravity	2.67
2	Moisture Content (%)	5.48
3	Silt/Clay Content (%)	7.10
4	Bulk Density (kg/m^3)	1749.33
Coarse aggregates		
1	Aggregate crushing value	9.51
2	Specific gravity	2.93
3	Bulk density (kg/m^3)	1737.3
4	Aggregate impact value	10.11
5	Flakiness Index	26.2
6	Elongation Index	26.7

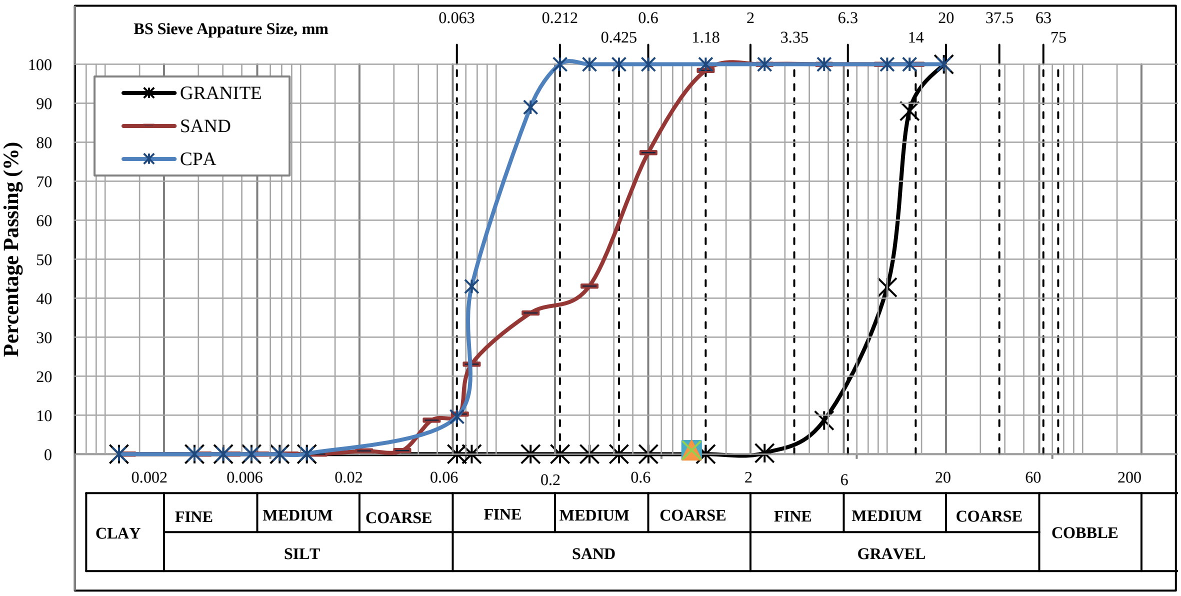

Figure 3. Graduation curve for materials

2.2.3. Bamboo

Bamboo used as reinforcement in this study was collected from a local farm in Ute, Ifon local government area of Ondo State. After cutting, the bamboo culms were sun-dried for a minimum period of 15 days before being processed to the required sizes at the Landmark University wood workshop using the lathe turning and planning machine. A water absorption test was carried out on the bamboo reinforcement before and after bitumen coating to determine the effectiveness of bitumen coating against water ingress into the bamboo. The test was done in accordance with [28]. Firstly, the weight of each coated bamboo stick was taken after which they were fully immersed in a bucket of water. The weight of each of the sticks was taken and recorded for 2hrs, 4hrs, 6hrs, 8hrs, and 24hrs, respectively. Also, a tensile strength test was carried out based on ASTM D2915 [29] standards on the bamboo strips used as replacements for steel to determine their tensile strength. The average tensile strengths obtained for 12 mm, 14 mm, and 16 mm diameters were 128.21 N/mm^2, 114.98 N/mm^2, and 122.64 N/mm^2, respectively. It was done at the Strength of Material Laboratory, Mechanical Engineering Department of Landmark University. The tensile strength testing process is shown in Figure 4.

Figure 4. Tensile testing of bamboo

2.3. Test Procedure

2.3.1. Mixing and Specimen Preparation

The mixing process involves mixing the constituent materials proportionally as presented in Table 4. The required percentage replacement of cement with CPA for each experimental run is determined by Table 1. A slump test was carried out following British Standard 1881-104 [30] guidelines to determine the workability of each concrete mix. The total number of specimens cast was 261. The specimens produced were demolded after 24 hours and cured in water by immersion.

Table 4. Concrete mix proportion

S/N	Material	Composition (kg/m^3)
1	Cement	675
2	Coarse aggregate	660
3	Fine aggregate	990
4	Water	412.5

2.3.2. Mechanical Strength Testing (Flexural Strength and Strain)

The flexural strength of concrete, also referred to as the modulus of rupture, is a function of the highest load that may be applied to concrete in bending. The rectangular beams were employed in this test, and the center point loading method was adopted according to the BS EN 12390-5:2009 standard. During the test, the development of the first fracture and subsequent cracking up to failure were thoroughly monitored. Once the specimen failed, the maximum load shown on the display was recorded, and then the crack widths at different locations on the beam and their distance between the crack line and the nearest support were measured. The flexural strength and flexural strain in BRC samples were estimated using Equations 1 and 2, respectively. A sample of a bamboo-reinforced concrete beam under flexural loading is shown in Figure 5. Flexural strain was measured as the nominal fractional change in the length of the concrete beam specimen's outer surface at mid-span when the largest strain occurs [28].

$$\text{Flexural strength, } f_s = \frac{3PL}{2bd^2} \tag{1}$$

where f_s is flexural strength (N/mm^2), P is maximum load (N), L is distance between supporting rollers (mm), b is width of beam (mm), and d is depth of beam (mm).

$$\text{Flexural strain} = \frac{6CWD}{L^2} \tag{2}$$

where CW is crack width, D is depth of beam, and L is length of beam.

Figure 5. A bamboo reinforced concrete beam under flexural loading

3. Optimization of BRC Mixed Design using RSM

The Response Surface Methodology is a powerful analytical tool for the optimization of input and output parameters in any experimental design [26, 31–33]. Various components that operate concurrently are fitted to a quadratic function in RSM. RSM outperforms the ‘one factor at a time’ method, which is slow and ignores the interrelationships between factors [34]. For changing levels of direct variables on output/response, RSM incorporates the use of linear, reaction, and quadratic terms, which is necessary for good optimization. It investigates the link between the response and the factors as well as determines the factors' influence on the process [35]. RSM has cutting-edge strategies for dealing with complex experimental designs. It can primarily be used in situations where specific characteristics have a substantial role in predicting a system's behavior [36]. Experiment design, modeling, and optimization are the three main processes [37]. RSM can be used to locate reaction surfaces and develop a ready-to-use mix design for producing concrete that meets certain requirements [26, 27, 38, 39], and it has been used in many previous similar experimental studies. For example, Alsanusi & Bentaher [40] used it to forecast the compressive strength of traditional concrete and discovered the impact of mixed elements on concrete strength.

4. Results and Discussion

The experimental test result is presented in Table 5. From Table 5, the flexural strength of BRC samples increased with concrete age from 28 to 90 days, and all the input parameters, including % CPA replacements, bamboo size, and beam dimensions, were seen to contribute to the attained flexural strength and strain of BRC samples. For flexural strain, it reduces with concrete age, and similar to flexural strength, all input parameters significantly contributed to the attained BRC beam flexural strain.

Table 5. Experimental test results of BRC beams' flexural strength and strain

Test No.	Cassava peel ash (mm)	Bamboo size (mm)	Beam Length (mm)	Beam Depth (mm)	length/depth ratio (l/d)	28 days Flexural Strength	56 days Flexural Strength	90 days Flexural Strength	28 days Flexural Strain	56 days Flexural Strain	90 days Flexural Strain
1	10	14	500	200	2.50	9.6	10.8	11.6	2.974	0.688	0.48
2	10	14	500	200	2.50	9.2	9.8	10.2	3.122	0.88	0.64
3	10	14	500	200	2.50	9.9	10.3	10.8	3.228	0.768	0.72
4	10	14	400	150	2.67	11.4	13.4	14.2	8.409	2.25	1.238
5	10	14	400	250	1.60	3.1	3.5	3.7	11.855	4.625	3.281
6	20	12	500	200	2.50	5.4	6.6	7.1	0.888	1.104	1.344
7	10	12	400	200	2.00	7.9	9.2	9.5	11.261	3.775	3.075
8	10	12	500	150	3.33	9.1	9.3	9.9	2.558	2.089	1.26
9	10	14	600	250	2.40	4.3	9.4	9.6	3.708	2.222	1.625
10	10	14	500	200	2.50	8.9	9.2	9.6	0.535	1.008	0.912
11	10	16	600	200	3.00	14.6	15.2	15.6	2.835	0.922	0.867
12	10	14	600	150	4.00	9.3	14	15	1.125	0.575	0.5
13	10	12	500	250	2.00	4.7	5.4	5.7	3.864	1.7	1.86
14	10	16	400	200	2.00	7.5	8	8.3	8.029	2.9	2.625
15	0	12	500	200	2.50	11	12.2	12.8	3.379	1.584	1.008
16	0	14	600	200	3.00	13.9	15.6	16.3	4.333	0.578	0.433
17	20	14	600	200	3.00	11.1	11.8	12.4	0.355	1.089	0.933
18	10	16	500	150	3.33	12.3	14.9	15.5	1.89	1.164	0.972
19	10	12	600	200	3.00	10.1	11.3	11.6	2.07	1.4	1.133
20	20	14	500	150	3.33	8.3	8.3	9.3	1.634	1.38	1.044
21	10	16	500	250	2.00	5.9	7.1	7.4	4.689	1.94	1.44
22	20	16	500	200	2.50	5.3	6	6.8	4.874	1.92	1.584
23	0	14	400	200	2.00	5.1	5.6	6.1	2.775	2.47	2.025
24	20	14	500	250	2.00	6.2	6.5	6.9	1.821	1.86	1.5
25	0	14	500	150	3.33	10.1	12.5	14.1	2.124	0.936	0.9
26	0	14	500	250	2.00	6.8	10.6	12.2	4.77	1.5	1.14
27	20	14	400	200	2.00	4.6	5.7	6.6	4.361	2.45	1.8
28	0	16	500	200	2.50	8.3	9.8	10.2	0.624	1.232	0.96
29	10	14	500	200	2.50	9.2	9.9	11.1	1.404	1.376	1.248

The effect of variations in beam dimensions on the flexural strength of BRC beams was analyzed through regression analysis. The BRC beams length/depth ratio was estimated, and it was found that flexural strength generally increased with increasing l/d ratio. After 90 days, BRC samples with high l/d above 3.0 have high flexural strength values, with the highest attained for sample 16 (l/d =3, f_s = 16.2 N/mm^2), while samples with low l/d values below 2.0 have low flexural strength values, with the least recorded for sample 5 (l/d = 1.6, f_s = 3.7 N/mm^2). Similarly, the flexural strain was observed to reduce as the l/d ratio increased, with the least flexural strain observed at a l/d of 3.33. The results of the regression analysis of BRC against flexural strength and strain against l/d ratio are shown in Figure 6. Since all the input parameters influence the flexural strength and strain of BRC, it is therefore important to determine the optimum condition for the input parameters to achieve enhanced flexural strength and reduced strain using the numerical optimization technique of response surface methodology.

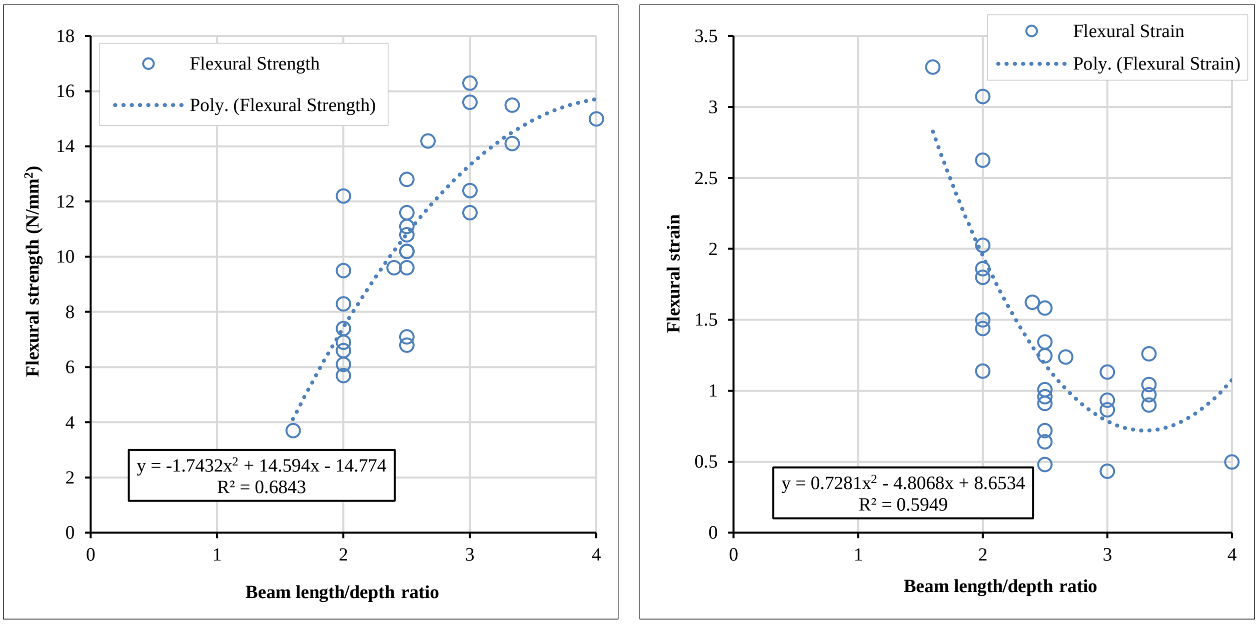

Figure 6. Flexural behavior of BRC with varying beam length/ ratio

4.1. Analysis of Variance (ANOVA)

To determine the contributions of the linear, interaction, and quadratic interactions of all input factors, an analysis of variance (ANOVA) was carried out. The student's t-test (p-value 0.05) was used to assess the statistically significant terms. Significant terms had p values less than 0.05, whereas inconsequential terms had p values greater than 0.05. The ANOVA results for flexural strength and flexural strain for concrete beams containing CPA and reinforced with bamboo are presented in Table 6. From Table 6, the six responses have model values less than 0.05, which indicates an efficient model. For flexural strength, it was observed that the linear terms A, B, and C were statistically insignificant, while the linear expression D was significant judging by the p-values obtained. Also, all the interactions and quadratic terms were insignificant for flexural strength. The aforementioned trend was observed at all curing ages (28, 56, and 90) considered.

This implies that beam depth is a major factor that influences flexural strength and should be adequately considered during the design of bamboo-reinforced concrete beams. Similarly, for flexural strain, the linear terms for A, B, and D are insignificant, and only linear expression C was significant for flexural strain judging by the p-values obtained, while quadratic term C^2 was significant for flexural strain at 28 days. However, at 56 days and 90 days, it was observed that the linear terms C and D as well as the quadratic terms B^2, C^2, and D^2 were significant with p values less than 0.05. This indicates that the influence of bamboo size, beam length, and beam depth becomes more significant on the flexural strain with an increase in test age. Furthermore, the coefficient of determination (R^2) was used to determine the influence of input variables on the desired response. According to Chaliha et al. [41], the level of model accuracy can be determined by R-squared. The values of R-squared at 28, 56, and 90 days are 0.714, 0.821, and 0.817 for flexural strength and 0.804, 0.876, and 0.868 for flexural strain, respectively. These high values show that the obtained model is in good agreement with the experimental results [42].

4.2. Analysis of Response Surface Plots

The 3D plots were used to assess the interactive relationship between the mix design parameters and the flexural strength and strain properties of bamboo-reinforced beams containing CPA. RSM has been used to generate 3D plots for all factors as displayed in Figures 7 to 9 for flexural strength and Figures 10 to 12 for flexural strain at 28, 56, and 90 days, respectively. The dependent responses' 3D plots were pinched as a function of two independent factors, with the third and fourth independent variables held at the midpoint. The 3D plots for CPA and beam size in Figures 7-a, 8-a, and 9-a show a gradual increase in flexural strength from 28 days to 90 days with reduced bamboo size and CPA content. The relationship between CPA and beam length shows that the flexural strength increases with increased beam length and a reduced percentage of CPA, as displayed in Figure 7-b.

A similar trend was observed in Figures 8-b and 9-b. As expected, the figures showed a progressive increase in flexural strength with increasing curing age. From Figures 7-c, 8-c, and 9-c, the influence of CPA content was negligible, while reduced beam depth was observed to positively influence the flexural strength as observed for all curing ages. Figures 7d, 8d, and 9d display the relationship between beam length and bamboo size for 28, 56, and 90 days, respectively. From these figures, it was observed that increasing beam length and reducing bamboo size can positively influence flexural strength. Figures 7-e, 8-e, and 9-e showed that reduced beam depth combined with increased bamboo size will increase flexural strength irrespective of the test age. However, Umeonyiagu et al. [43] carried out a study on bamboo-reinforced concrete for two sizes of beams, both comprising two sticks of 12 mm diameter. Beam depths of 150 and 200 mm were considered, and the flexural strengths observed were 5.93 and 6.57 N/mm^2, respectively.

A comparison between Karthikraja et al. [43] and the current study indicates that higher flexural strength can be obtained with an increase in bamboo size without an increase in beam depth. The choice of reduced beam depth with an increase in bamboo diameter will further promote sustainability in the construction industry. Another study by Govindan et al. [44] utilized 10 mm bamboo sticks as reinforcement both in the tension and compression zones for beams of uniform size; very low values of flexural strength were observed at 28 and 56 days. It is worth noting that bamboo sticks with higher diameters reinforced in the tension and compression zones can be used to improve flexural strength, as observed in the current study. Furthermore, a previous study by Dey & Chetia [9] also observed that the flexural strength of bamboo-reinforced concrete increased with an increase in curing days and reinforcement size when compared to smaller reinforcement sizes and shorter curing days. Another study by Mali & Datta [5] has also observed improved performance for bamboo-reinforced concrete slabs with flexural strength marginally better than mild steel-reinforced concrete slabs. The improved strength was attributed to the adequate bonding between the treated bamboo strip and concrete.

Haryanto et al. [25] also observed that the strength of bamboo-reinforced concrete slabs was 18% less than that of steel-reinforced concrete slabs, while the ductility of both types of slabs was almost equivalent. The observations indicate the possibility of bamboo as a suitable alternative for steel reinforcement. From Figures 7-f, 8-f, and 9-f, the flexural strength increased progressively for all tested concrete ages with reduced beam length and depth. Figures 10-a, 11-a, and 12-a display the relationship between the percentage CPA and bamboo size for flexural strain at 28, 56, and 90 days, respectively.

From these figures, it was observed that increasing the content of CPA combined with an increase in bamboo size reduces the flexural strain. From Figures 10-b, 11-b, and 12-b, the influence of CPA content seems negligible, while an increase in beam length reduced the flexural strain. A similar trend of negligible influence of CPA content on flexural strain was observed in Figures 10-c, 11-c, and 12-c, while a reduction in beam depth tends to reduce the flexural strain. From Figures 10-d, 11-d, and 12-d, the increase in beam length reduces the flexural strain, while the effect of bamboo size seems negligible. A close look at Figures 10-f, 11-f, and 12-f indicates a slight reduction in flexural strain with reduced beam depth, while the variation in bamboo size seems negligible. From Figures 10-e, 11-e, and 12-e, it was observed that an increase in beam length reduced the flexural strain, while the effect of beam depth seemed negligible.

Table 6. ANOVA for experimental results

Source		Experimental Results																	
		28 days Flexural Strength (MPa)			28 days Flexural Strain (%)			56 days Flexural Strength (MPa)			56 days Flexural Strain (%)			90 days Flexural Strength (MPa)			90 days Flexural Strain (%)		
	DF	SS	F value	P value	SS	F value	P value	SS	F value	P value	SS	F value	P value	SS	F value	P value	SS	F value	P value
Model	14	168.77	2.49	0.0494	192.70	4.11	0.0062	232.73	4.59	0.0036	21.57	7.05	0.0004	250.40	4.45	0.0042	12.19	6.57	0.0006
A	1	1.14	0.2358	0.6348	3.32	0.9898	0.3367	1.96	0.5415	0.4740	0.0002	0.0008	0.9782	1.84	0.4582	0.5095	0.0040	0.0299	0.8653
B	1	1.69	0.3488	0.5642	3.56	1.06	0.3203	1.44	0.3965	0.5391	0.1593	0.7290	0.4076	1.47	0.3659	0.5549	0.0663	0.5001	0.4911
C	1	5.53	1.14	0.3029	88.31	26.34	0.0002	2.45	0.6755	0.4249	10.45	47.84	< 0.0001	4.02	0.9995	0.3344	5.25	39.62	< 0.0001
D	1	32.34	6.68	0.0216	5.04	1.50	0.2403	43.70	12.07	0.0037	1.22	5.56	0.0334	47.60	11.85	0.0040	1.23	9.28	0.0087
AB	1	1.69	0.3493	0.5639	11.36	3.39	0.0869	0.8100	0.2238	0.6435	0.3411	1.56	0.2320	1.32	0.3291	0.5753	0.0207	0.1564	0.6985
AC	1	1.32	0.2734	0.6093	7.74	2.31	0.1509	3.80	1.05	0.3228	0.0705	0.3226	0.5790	4.84	1.20	0.2909	0.1314	0.9911	0.3364
AD	1	0.3600	0.0744	0.7890	1.51	0.4510	0.5128	0.0025	0.0007	0.9794	0.0018	0.0081	0.9297	0.0625	0.0156	0.9025	0.0117	0.0880	0.7711
BC	1	6.00	1.24	0.2841	3.99	1.19	0.2935	6.50	1.80	0.2015	0.0394	0.1803	0.6775	6.76	1.68	0.2156	0.0085	0.0638	0.8042
BD	1	1.0000	0.2067	0.6563	0.5573	0.1662	0.6896	3.80	1.05	0.3228	0.3393	1.55	0.2331	3.80	0.9464	0.3472	0.0044	0.0329	0.8588
CD	1	2.72	0.5627	0.4656	0.1862	0.0555	0.8171	7.02	1.94	0.1854	0.1325	0.6064	0.4491	6.50	1.62	0.2240	0.2107	1.59	0.2281
A^2	1	4.65	0.9611	0.3436	7.29	2.18	0.1623	3.77	1.04	0.3247	0.0053	0.0241	0.8788	1.71	0.4254	0.5248	0.0002	0.0015	0.9694
B^2	1	0.0606	0.0125	0.9125	4.34	1.29	0.2745	0.5361	0.1481	0.7061	1.17	5.36	0.0363	2.06	0.5123	0.4859	1.18	8.90	0.0099
C^2	1	0.0001	0.0000	0.9970	43.41	12.95	0.0029	2.96	0.8164	0.3815	4.86	22.25	0.0003	1.62	0.4023	0.5362	2.35	17.75	0.0009
D^2	1	13.11	2.71	0.1220	6.53	1.95	0.1846	0.5838	0.1613	0.6941	1.55	7.09	0.0185	0.2005	0.0499	0.8264	0.4236	3.19	0.0055
Residual	14	67.73			46.93			50.68			3.061			56.25			1.86		
AP		6.4847			7.95			8.353			9.992			8.30			10.132		
SD		2.20			1.83			1.90			0.467			2.0			0.3641		
Mean		8.38			3.64			9.72			1.67			10.35			1.33		
R^2		0.714			0.804			0.821			0.876			0.8166			0.8679		

SS: Sum of squares; DF: Degree of freedom; SD: standard deviation; R2: Coefficient of determination; AP: Adequate precision. A = Cassava Peel Ash, B = Bamboo Size, C = Beam Length and D = Beam Depth.

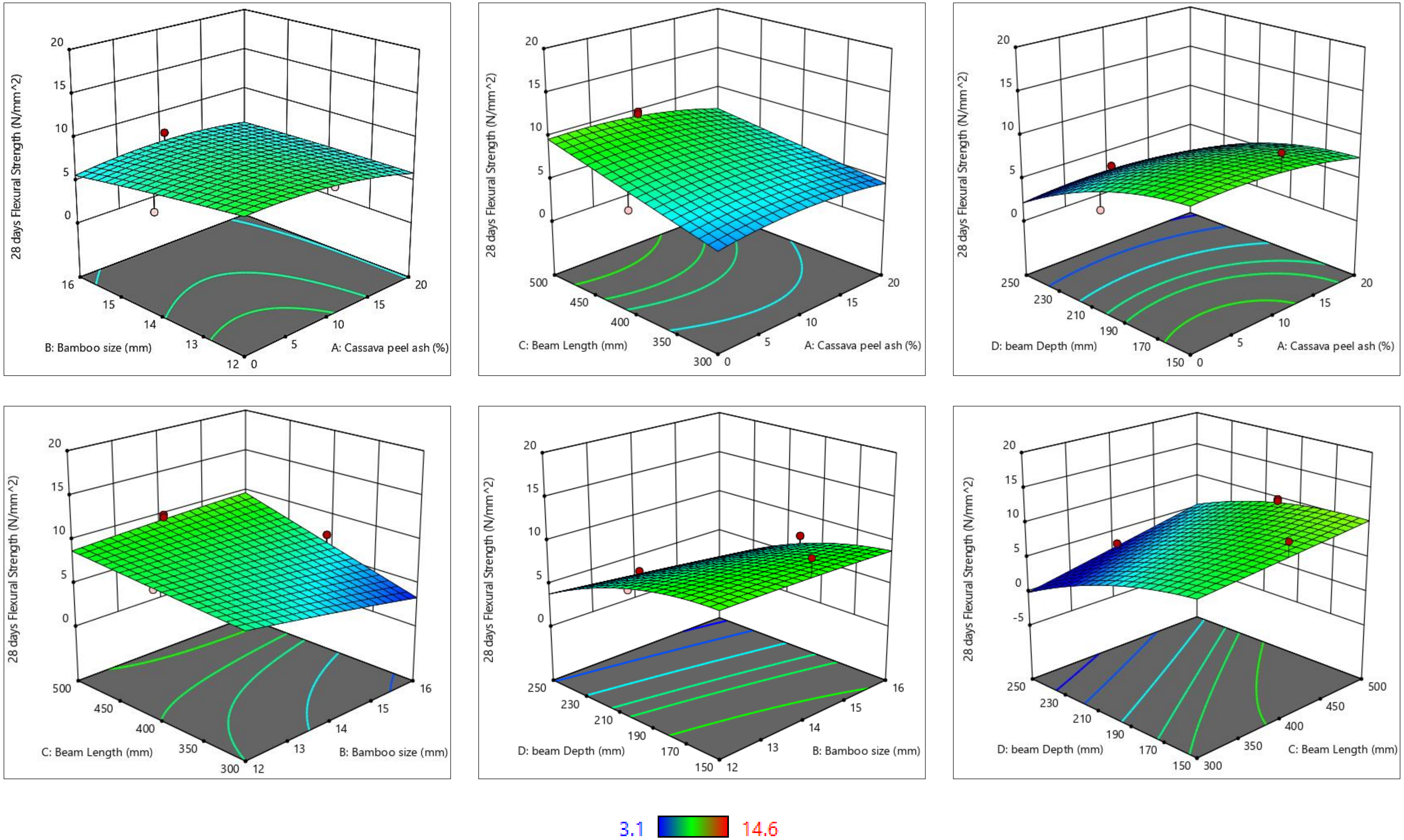

Figure 7. Response surface plots for Flexural strength at 28 days

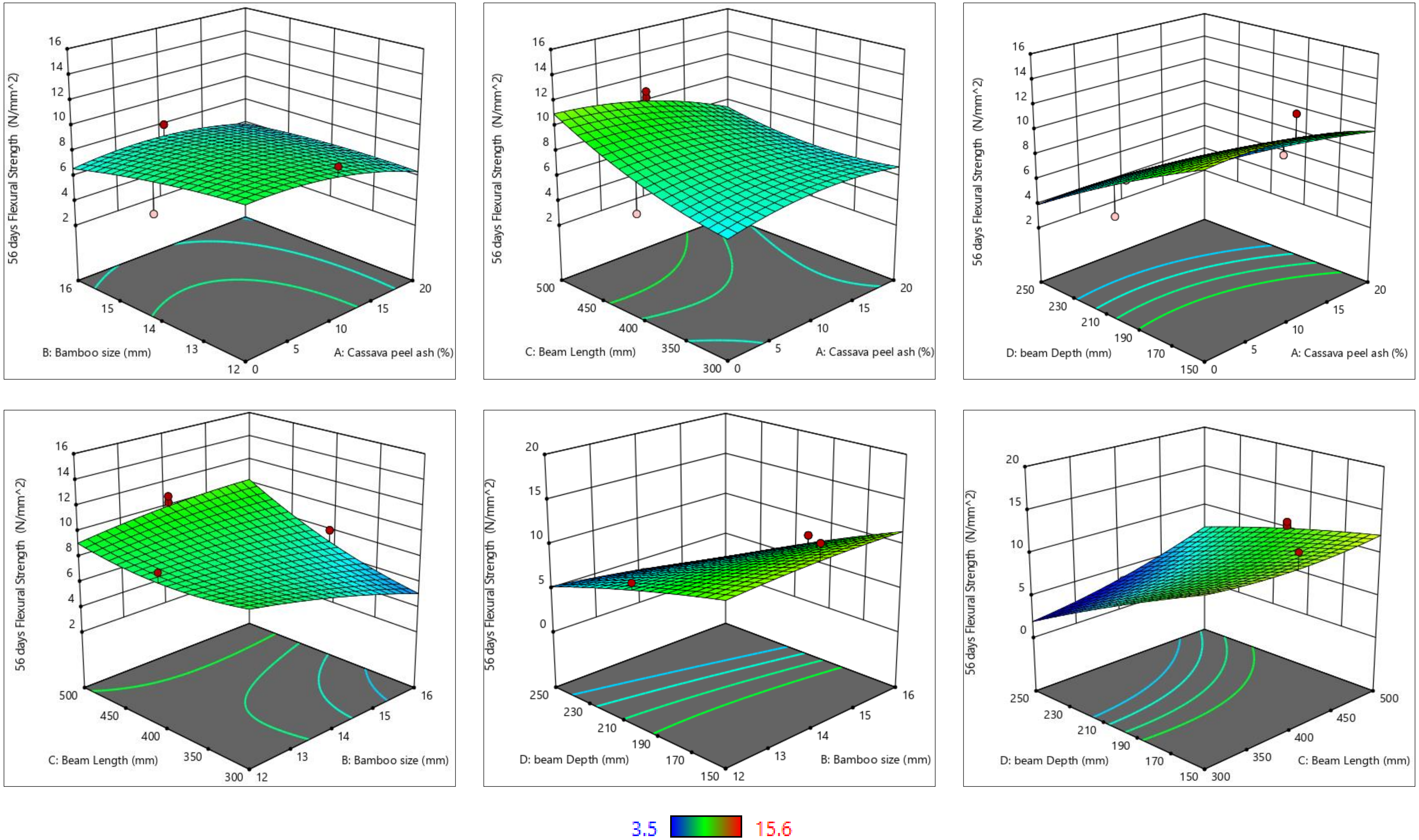

Figure 8. Response surface plots for Flexural strength at 56 days

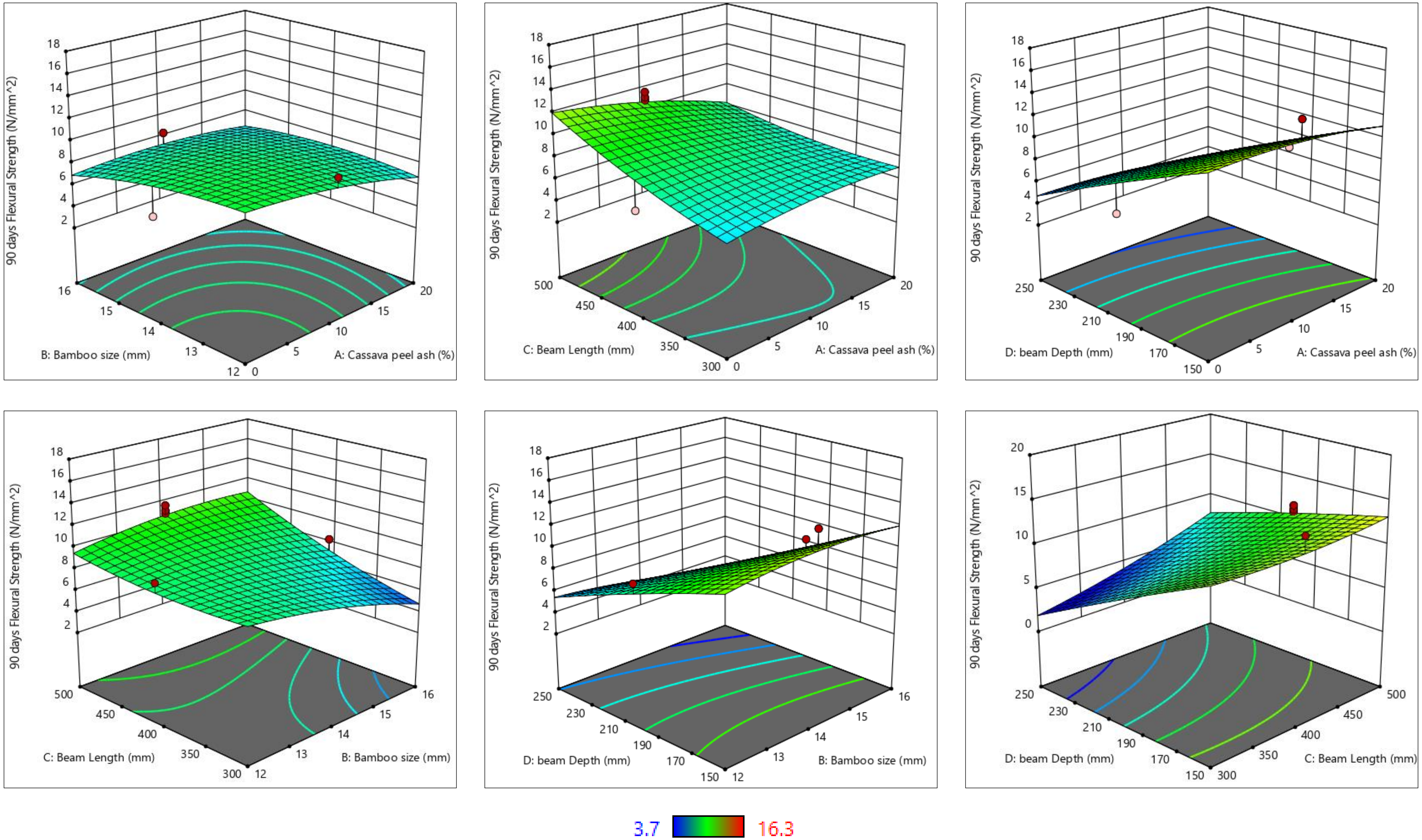

Figure 9. Response surface plots for Flexural strength at 90 days

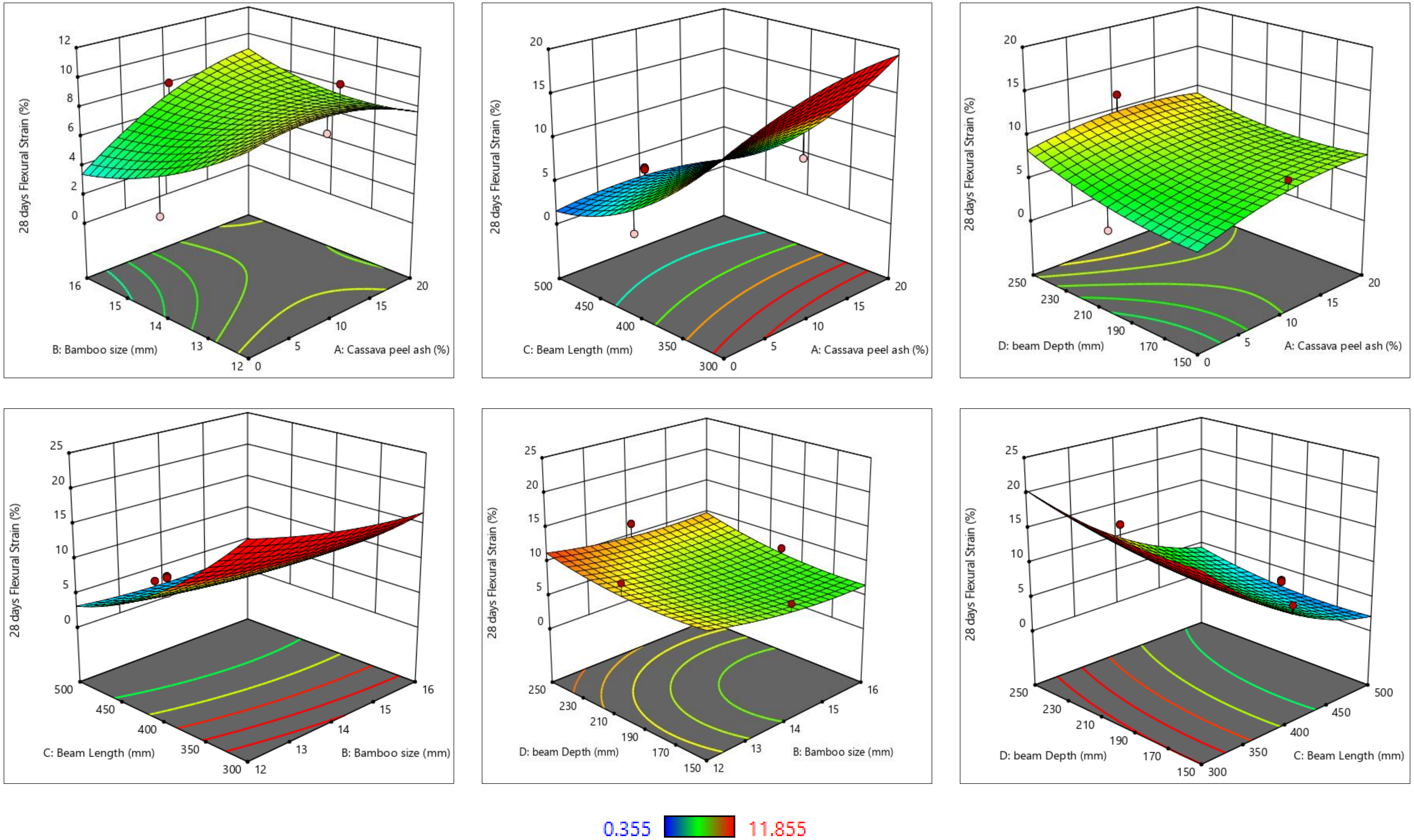

Figure 10. Response surface plots for Flexural strain at 28 days

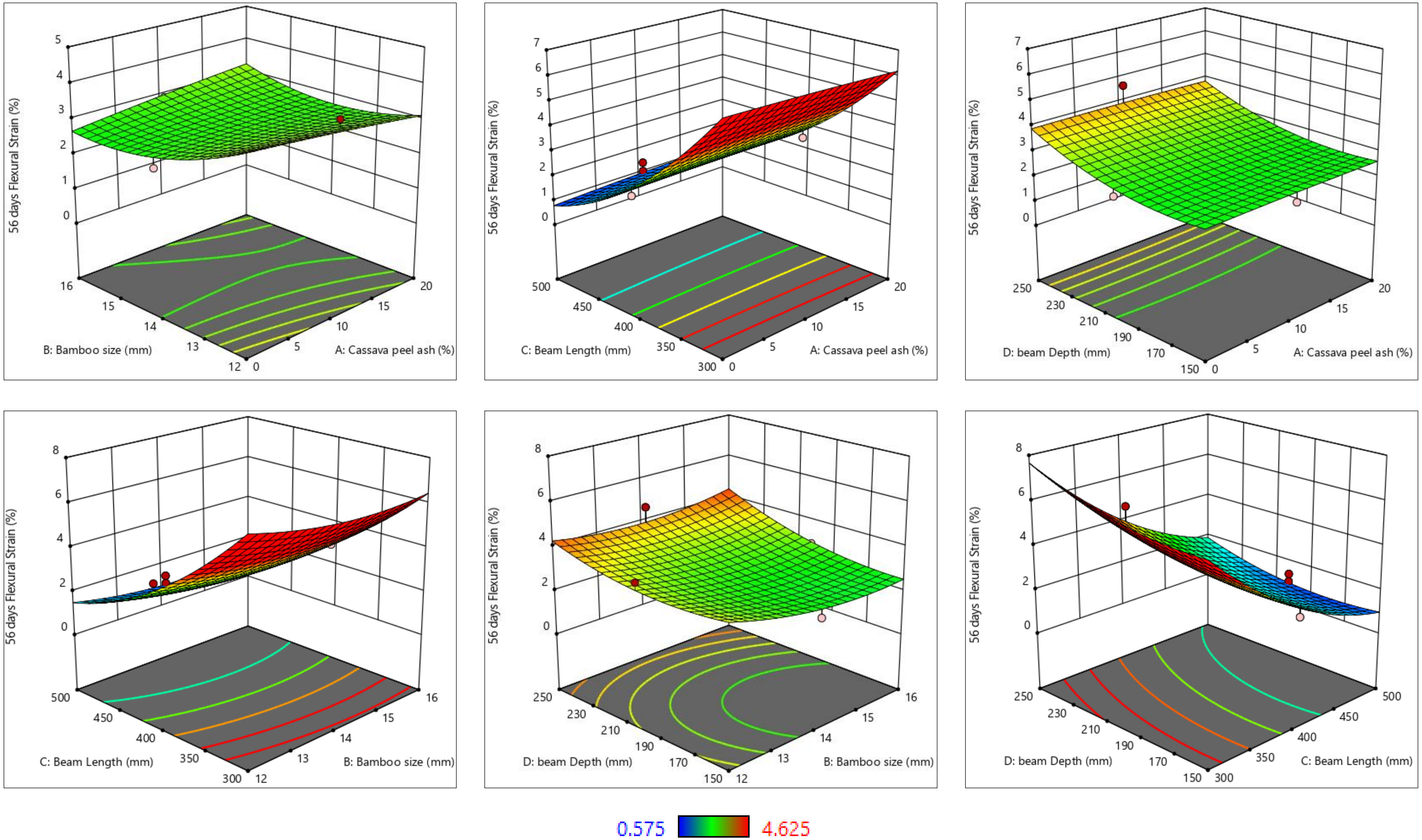

Figure 11. Response surface plots for Flexural strain at 56 days

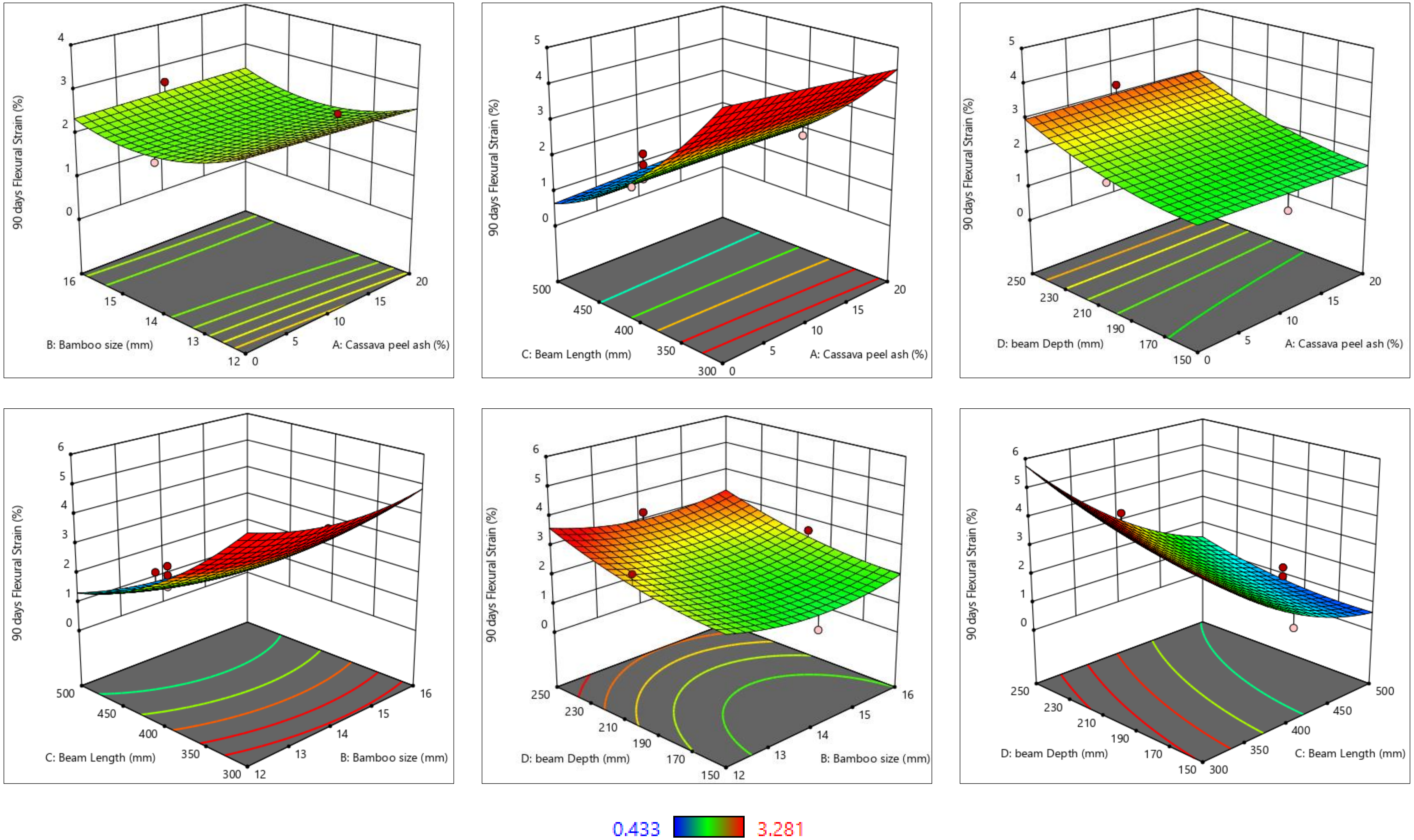

Figure 12. Response surface plots for Flexural strain at 90 days

4.3. Optimization and Validation

The optimal values for the independent variables (A, B, C, and D) were determined using the numerical optimization tool of RSM. This was achieved by setting the desired goal for each mix design parameter (A, B, C, and D) for BRC containing CPA as presented in Table 7. Flexural strength was defined as the maximum in order to attain the highest strength, while flexural strain was defined as the minimum for reduced crack propagation. The process involved interpolating factors within the range considered in the mix design to obtain desired outputs at a 95% confidence level. For validating the model predictions, a laboratory experiment was conducted using the optimum value of each mix design parameter. From the results obtained, it was observed that the experimental results were close to those predicted by the models. The absolute relative percent errors (PE) for BRC containing CPA were relatively low. From these PE values, it could be inferred that the model predicted the desired responses with good accuracy.

Table 7. Optimum conditions achieved for BRC containing CPA

Parameters	Unit	Goal	Model prediction	Laboratory experiment	PE
A	%	In range	3	3	-
B	mm	In range	16	16	-
C	mm	In range	500	500	-
D	mm	In range	150	150	-
R1 at 28 days	N/mm^2	Maximum	11.45	11.85	3.375527426
R2 at 56 days	N/mm^2	Maximum	14.04	14.34	2.092050209
R3 at 90 days	N/mm^2	Maximum	14.78	14.95	1.137123746
R4 at 28 days	%	Minimum	0.633	0.64	1.09375
R5 at 56 days	%	Minimum	0.659	0.67	1.641791045
R6 at 90 days	%	Minimum	0.884	0.91	2.857142857

Note: Absolute relative percent error $(PE) = 1 - \frac{Value_{Predicted}}{Value_{Experiment}} \times 100$, R1 = Flexural strength, R2 = Flexural strain, A = Cassava peel ash, B = Bamboo size, C = Beam length and D = Beam depth

5. Conclusion

The proportions of CPA content, beam dimension, and bamboo reinforcement size used in the production of BRC influence its flexural behavior properties. ANOVA results revealed that the contributions made by the linear, interactive, and quadratic terms of all these input parameters on flexural strength and flexural strain are significant. Also, based on the coefficient of determination obtained from the RSM models, there was a good correlation between all predicted and experimentally obtained results, indicating that these models can be efficiently used for simulating flexural strength and strain.

The analysis of the response surface plot for BRC input parameters showed a progressive increase in flexural strength with an increase in curing age. Similarly, the dimension configuration of a BRC beam affects its flexural behavior. The regression analysis of experimental results indicated that BRC beams with a high l/d ratio of about 3.0 have higher flexural strength and lower flexural strain values. While beams with lower l/d values below 2.0 have lower flexural strength and higher strain values.

The optimum condition obtained for BRC containing CPA was 3% CPA, 16 mm diameter for reinforcement, 500 mm for beam length, and 150 mm for beam depth to achieve flexural strengths of 11.85 N/mm^2, 14.34 N/mm^2, and 14.95 N/mm^2 and flexural strains of 0.64, 0.67, and 0.91 for 28, 56, and 90 days, respectively. The results of the validation laboratory experiments conducted at the optimum conditions were very close to those predicted by the models; this validates the optimum design conditions obtained for BRC in this study and their application for practical purposes.

6. Declarations

6.1. Author Contributions

Conceptualization, T.F.A. and O.J.A.; methodology, T.F.A., O.J.A., and E.K.A.; software, T.F.A. and O.E.B.; validation, T.F.A. and O.J.A.; formal analysis, T.F.A., O.J.A., and O.E.B. ; investigation, T.F.A. and O.J.A..; resources, M.A. and A.F.D.; data curation, T.F.A. and O.J.A.; writing—original draft preparation, T.F.A. and O.E.B.; writing—review and editing, T.F.A., O.E.B., and M.A.; visualization, T.F.A. and O.J.A.; supervision, T.F.A.; project administration, T.F.A.; funding acquisition, A.F.D. and M.A. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

6.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

6.4. Conflicts of Interest

The authors declare no conflict of interest.

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