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Optimization of Porosity and Water Absorption Behaviour of Coconut Fiber-Calabash Ash Hybrid Epoxy Composites for Automotive Dashboard Application

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Abstract: This study investigates the porosity and water absorption behaviour of coconut fiber–calabash ash reinforced polymer composites developed as potential materials for automotive dashboard applications. The research addresses the challenge of minimizing internal void formation and moisture susceptibility commonly associated with natural fiber reinforced composites. The objective of the study was to evaluate the influence of epoxy–hardener ratio, coconut fiber content, and calabash ash particulate loading on porosity formation and water absorption characteristics.A Box–Behnken experimental design was employed to systematically analyze the effects of these processing parameters. Treated coconut fibers and finely sieved calabash ash were incorporated into an epoxy matrix through a dispersion technique, after which composite specimens were fabricated and cured under controlled conditions. Porosity was determined using theoretical and experimental density relationships, while water absorption behaviour was evaluated following ASTM D570 procedures. Statistical analysis using ANOVA revealed that the epoxy–hardener ratio exerted the most significant influence on porosity, followed by calabash ash and coconut fiber content. The optimized composite formulation consisting of a 9.5:1.5 epoxy–hardener ratio, 7 wt.% calabash ash, and 4 wt.% coconut fiber produced low average porosity (1.467%) and moderate water absorption (1.313%).The findings demonstrate that controlled hybrid reinforcement of coconut fiber and calabash ash significantly enhances structural compactness while limiting moisture uptake.

Keywords: Natural fiber composites, Coconut fiber reinforcement, Calabash ash particulate, Polymer matrix composites, Porosity analysis, Water absorption behaviour, Hybrid bio–composites, Sustainable automotive materials.

I. INTRODUCTION

The increasing demand for lightweight, high-performance, and sustainable materials in the automotive industry has driven research toward alternatives to conventional petroleum-based polymers used in components such as dashboards. Although materials like ABS and polypropylene offer good mechanical and thermal properties, their environmental impact and reliance on non-renewable resources remain major concerns [1][2]This has encouraged the development of bio-based and waste-derived composites with lower ecological footprints.

Natural fiber reinforced polymer composites have emerged as viable substitutes due to their renewability, low density, and cost-effectiveness. Fibers such as coconut, flax, jute, and sisal improve mechanical performance while supporting sustainability goals [3][4][5] Among them, coconut fiber is particularly attractive because of its high lignin content, toughness, and availability as agricultural waste, with studies showing that surface treatments improve fiber–matrix bonding and overall mechanical properties [6]][7][8]

In addition, agricultural waste ashes such as calabash ash have gained attention as mineral fillers that enhance stiffness, hardness, thermal stability, and flame resistance due to their high oxide content [9][10]. The hybridization of natural fibers with such mineral fillers offers synergistic improvements in strength, durability, and moisture resistance compared to single-reinforcement systems [11][12] although challenges such as porosity, moisture absorption, and poor interfacial bonding still limit performance [13][14]15]

Porosity and water absorption are critical performance indicators, as they directly affect mechanical integrity, dimensional stability, and long-term durability. These properties are influenced by processing conditions such as fiber loading, filler content, curing behavior, and epoxy-to-hardener ratio, making optimization essential for performance improvement. Standard testing methods such as ASTM D570 are commonly used to evaluate moisture uptake in such systems.

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Recent industrial trends confirm the growing use of natural fiber composites in automotive interior applications, including dashboards and door panels, driven by weight reduction and sustainability requirements [16][17]. In this context, combining coconut fiber with calabash ash in an epoxy matrix provides a sustainable hybrid composite system aimed at improving mechanical performance, reducing porosity, and enhancing moisture resistance for automotive dashboard applications while supporting environmental sustainability objectives.

II. METHODOLOGY

A. Materials

The composites were fabricated using coconut fiber, calabash ash particulate, epoxy resin, and a curing hardener. Coconut fiber served as the main reinforcement due to its low density and good mechanical properties, while calabash ash acted as a filler to improve stiffness and dimensional stability. The epoxy resin functioned as the matrix, binding the materials and facilitating load transfer. All materials were prepared under controlled laboratory conditions to ensure consistency and reproducibility.

B. Porosity and Water Absorption Characterization

Water absorption was evaluated using ASTM D570 by oven-drying specimens, recording their initial weights, and immersing them in distilled water at room temperature for 24 and 48 hours. After immersion, samples were reweighed to determine percentage water uptake, allowing assessment of moisture resistance and dimensional stability across different composite formulations.

Porosity was also determined by comparing theoretical density (rule of mixtures) with experimental density obtained from mass–volume measurements using geometric methods or Archimedes' principle. The difference between these values represents void content, which directly affects water absorption, strength, and overall durability of the composites.

C. Experimental Design

A Box–Behnken design as seen in table 1 was used to study the effects of epoxy-to-hardener ratio (8:1, 10:1, 12:1), coconut fiber content, and calabash ash content on composite performance. Each factor was tested at three levels (low, medium, high), corresponding to coded values of −1, 0, and +1. This approach enabled efficient evaluation of linear, quadratic, and interaction effects while minimizing the number of experiments.

Table 1 Decoded Varied Parameters

Factor 1 (A: E&H) %w		Factor 2 (B: C.P) %w		Factor 3 (C: C.F) %w	
` Coded	Real	Coded	Real	`Coded	Real
-1	8:1	-1	3	-1	3
0	10:1	0	6	0	6
1	12:1	1	9	1	9

D. Result and Data Analysis

Table 1**:** ANOVA for porosity and Water absorption

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	10.84	9	1.20	31.81	< 0.0001	significant
A-E&H	4.81	1	4.81	126.92	< 0.0001	
B-C.P	2.00	1	2.00	52.83	0.0002	
C-C.F	2.00	1	2.00	52.83	0.0002	
AB	0.0100	1	0.0100	0.2642	0.6231	
AC	0.3600	1	0.3600	9.51	0.0177	
BC	0.3600	1	0.3600	9.51	0.0177	
A²	0.0105	1	0.0105	0.2781	0.6143	
B²	1.05	1	1.05	27.81	0.0012	
C²	0.1684	1	0.1684	4.45	0.0729	
Residual	0.2650	7	0.0379			

Lack of Fit	0.1650	3	0.0550	2.20	0.2306	not significant
Pure Error	0.1000	4	0.0250			
Cor Total	11.10	16				

ANOVA for Water Absorption

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	11.05	9	1.23	27.06	0.0001	significant
A-E&H	5.28	1	5.28	116.44	< 0.0001	
B-C.P	2.00	1	2.00	44.09	0.0003	
C-C.F	1.90	1	1.90	41.92	0.0003	
AB	0.0225	1	0.0225	0.4961	0.5040	
AC	0.2500	1	0.2500	5.51	0.0513	
BC	0.4225	1	0.4225	9.31	0.0185	
A^2	0.0000	1	0.0000	0.0000	1.0000	
B^2	0.9500	1	0.9500	20.94	0.0026	
C^2	0.1684	1	0.1684	3.71	0.0953	
Residual	0.3175	7	0.0454			

The ANOVA results for both porosity and water absorption models in table 1 and 2 indicate that the regression models are highly significant and reliable in predicting the responses. For porosity, the model is highly significant ($F = 31.81$, $p < 0.0001$), showing that epoxy–hardener ratio (A), calabash ash content (B), and coconut fiber content (C) all significantly influence void formation, with A having the strongest effect. Similarly, the water absorption model is also highly significant ($F = 27.06$, $p = 0.0001$), confirming that A, B, and C strongly affect moisture uptake. In addition, the water absorption model shows that the BC interaction and the quadratic term B^2 are significant, while AB is not significant and AC is marginal. Both models exhibit small residual errors and non-significant lack of fit, confirming good adequacy, statistical validity, and reliability in describing the behavior of the composites.[18]

E. Interaction effect of varied parameters on Porosity and Water absorption

The mathematical models for porosity and water absorption in equation 1 and 2 describe the influence of factors A, B, and C on composite behavior. For porosity, the intercept (+1.70) represents the baseline condition, and all factors increase porosity, with A having the strongest effect. Interaction effects vary, where AB slightly reduces porosity, AC increases it, and BC reduces it, while the quadratic term B^2 shows the most significant nonlinear influence. For water absorption, the intercept (+1.90) defines the baseline, and all factors also increase absorption, with A being the most influential. Interaction effects are mixed, with AB being negligible, AC slightly increasing absorption, and BC reducing it, while B^2 shows strong curvature effects and C^2 contributes moderately. Overall, both responses are mainly governed by factor A and the nonlinear effect of factor B, with additional modifications from interaction and quadratic terms.

$$\text{Porosity} = 1.70 + 0.7750\,A + 0.5000\,B + 0.5000\,C - 0.0500\,AB + 0.3000\,AC - 0.3000\,BC + 0.0500\,A^2 + 0.5000\,B^2 + 0.2000\,C^2 \quad \text{Equ…1}$$

$$\text{Water Absorption} = 1.90 + 0.8125A + 0.5000B + 0.4875C - 0.0750AB + 0.2500AC - 0.3250BC + 0.0000A^2 + 0.4750B^2 + 0.2000C^2 \quad \text{Equ….. 2}$$

The perturbation and contour plot in figure 2 and 3 indicates the effect of coded variables (–1 to +1) on predicted porosity, which ranges from about 0% to 4%, with a baseline value of approximately 1.7% at the center point. Factor A has the strongest positive influence, showing a near-linear increase in porosity, followed by Factor B with a moderate increasing effect. Factor C has only a slight impact. Overall, Factor A is the dominant contributor to porosity, while Factor B has a secondary effect and Factor C is minimal. Therefore, controlling Factor A is most important for reducing porosity and improving composite quality.

The perturbation and 3D surface plots collectively illustrate in figure 3 and 4 respectively the effects of factors A, B, and C on water absorption in the composite. The perturbation plot shows that water absorption ranges from about 1.0% to 3.0%, with a baseline of approximately 1.8%, and identifies Factor A as the dominant contributor, followed by Factor B, while Factor C has a minimal effect.

In contrast, the 3D surface plot reveals the interactive effect of Factors A and B (with C held constant), showing that water absorption increases from about 1% to 3.7% as both factors rise. The curved surface indicates a strong interaction between A and B, with experimental points closely matching predicted values, confirming good model reliability. Overall, both plots consistently show that minimizing Factors A and B is essential for reducing water absorption and improving the composite's moisture resistance.

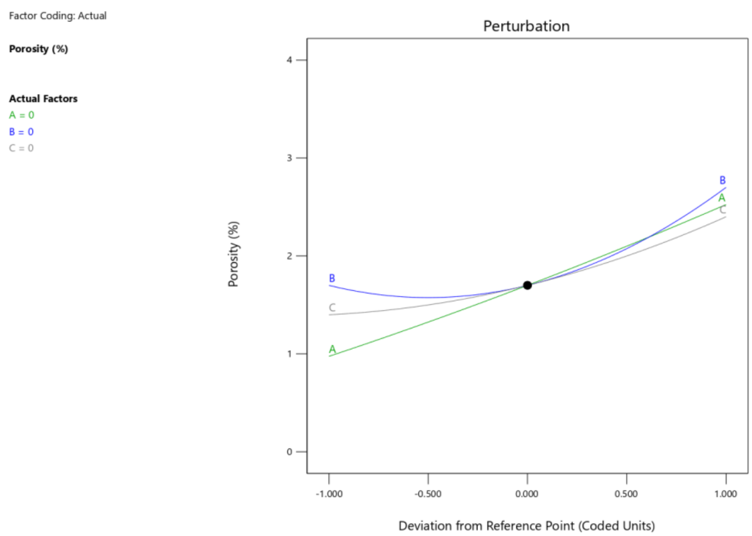

Figure 2 Perturbation plot on Porosity

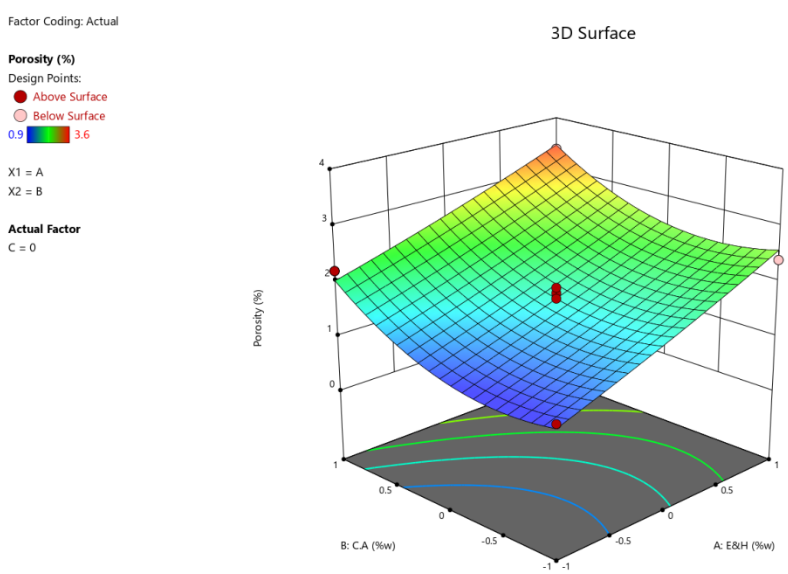

Figure 3 Contour Plot on Porosity property

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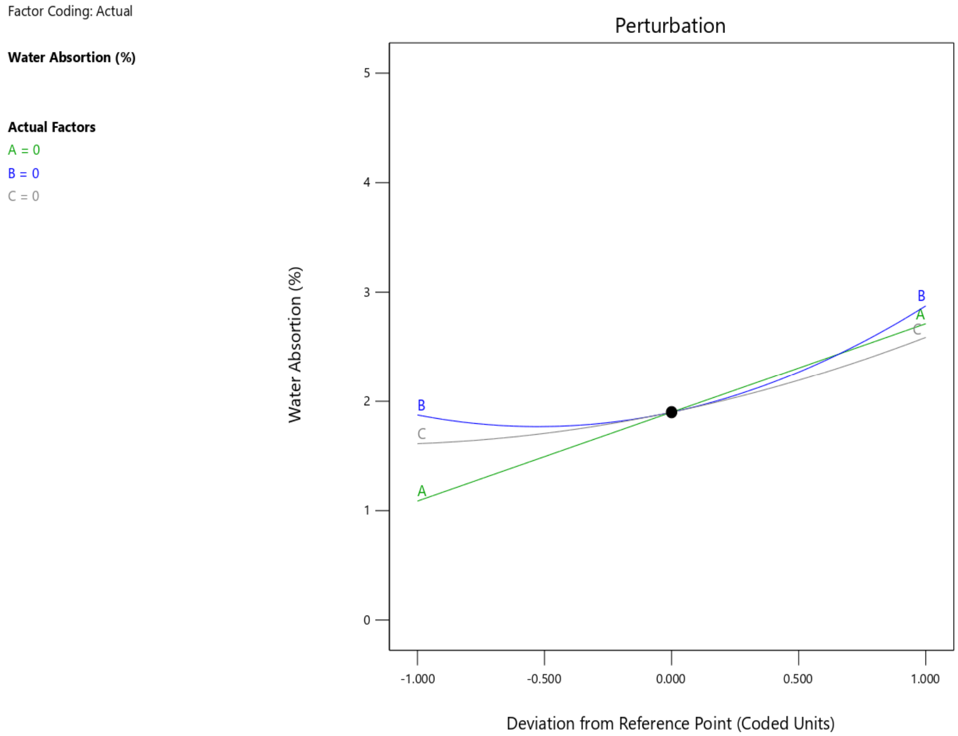
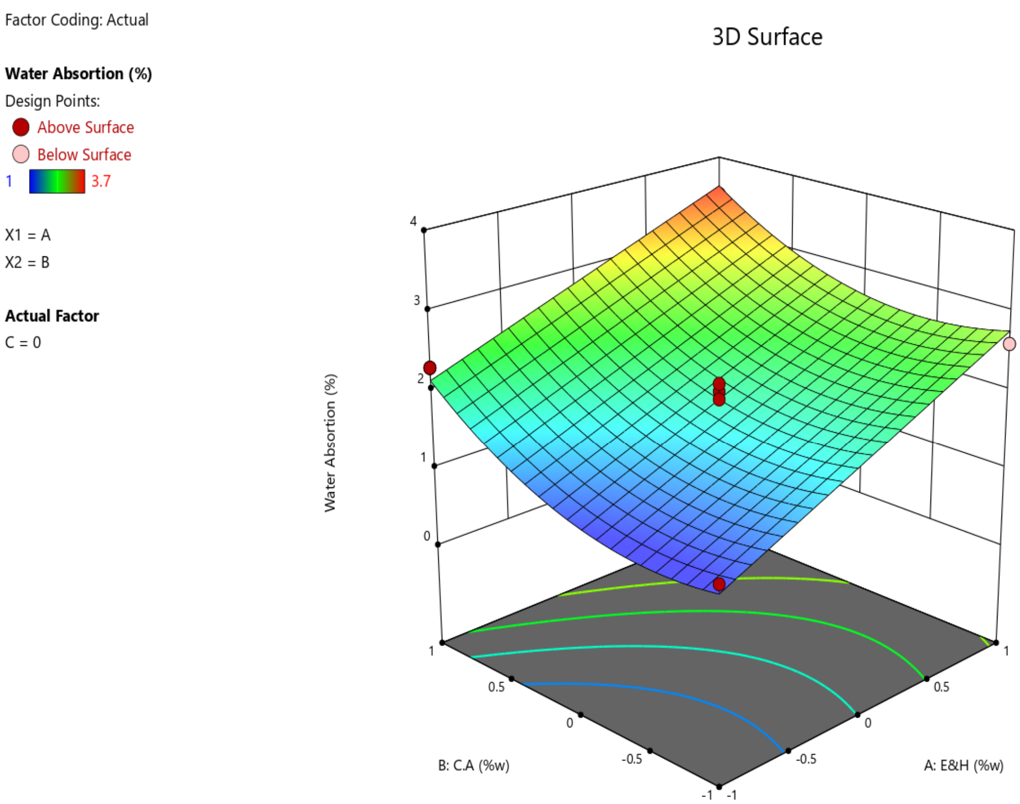


Figure 3 Perturbation plot on Water absorption



Contour Plot on Water absorption

F. Optimization

Table 4 Optimal solution

No	E&H	C.P	C.F	Porosity	Water Absorption	Desirability	
1	9.5-1.5	7	4	1.168	1.323	0.728	Selected
2	9.5-1.5	7	4	1.197	1.325	0.728	
3	9.5-1.5	7	4	1.184	1.312	0.728	

Table 5 Validation Results

S/N	E&H	C.P	C.F	POROSITY	WATER ABSORPTION
1	9.5-1.5	7	4	1.423	1.212
2	9.5-1.5	7	4	1.511	1.412

The validation results in table 5confirm the reliability of the optimized composite formulation with E&H (9.5–1.5), calabash particulate (7), and coconut fiber (4). The two validation runs show consistent performance,. Porosity (1.423–1.511) and water absorption (1.212–1.412) remained low, reflecting a dense microstructure with good moisture resistance. The slight variations between runs from optimal solution in table 5 that demonstrated good reproducibility.

III. DISCUSSION OF FINDINGS

This study successfully developed and statistically validated regression models for predicting porosity and water absorption in coconut fiber–calabash ash reinforced polymer composites using ANOVA and response surface methodology. The results confirmed that both models are highly significant, with porosity ($F = 31.81$, $p < 0.0001$) and water absorption ($F = 27.06$, $p = 0.0001$), indicating strong predictive capability and reliable representation of the experimental data. The epoxy–hardener ratio (Factor A) consistently exhibited the most dominant influence on both responses, followed by calabash ash (Factor B) and coconut fiber (Factor C), demonstrating that matrix composition plays a critical role in controlling void formation and moisture uptake.Interaction and quadratic analyses revealed that the behavior of the composites is not purely linear. Significant interactions such as AC and BC for porosity, and BC for water absorption, indicate that combined effects of reinforcement and matrix constituents significantly influence material performance. The quadratic term B^2 was particularly important in both responses, confirming nonlinear behavior and the sensitivity of the system to calabash ash content at higher loading levels. In contrast, AB interaction was generally insignificant, and A^2 and C^2 showed minimal curvature effects.Graphical analyses from perturbation, contour, and 3D surface plots further supported the statistical findings, showing that Factor A is the primary driver of both porosity and water absorption, while Factor B contributes moderately and Factor C has a relatively minor effect. The surface response trends also confirmed strong interaction effects between A and B, particularly for water absorption, where simultaneous increases in both factors significantly elevated moisture uptake.The developed models demonstrated good adequacy, with low residual errors and non-significant lack of fit, confirming their reliability for prediction and optimization.The validation results in Table 5 confirm the reliability of the optimized composite formulation with E&H (9.5–1.5), calabash particulate (7), and coconut fiber (4). The two validation runs show consistent performance, with porosity (1.423–1.511) and water absorption (1.212–1.412) remaining low, reflecting a dense microstructure with good moisture resistance. The slight variations between runs from the optimal solution demonstrate good reproducibility, further confirming the stability and effectiveness of the optimized model parameters for achieving desirable composite performance.

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