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Modeling and Optimization of Thermal Transfer and Mechanical Properties of Bio-composite Using Response Surface Methodology

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ABSTRACT

In recent years, scientists have begun to search for more sustainable biomaterials. Although many studies have been conducted on different fiber-reinforced composites, much remains to be done. Using environmentally friendly composite materials for building insulation is a practical solution to reduce energy consumption. In this study, an advanced statistical approach using JMP software was adopted to manage a complex problem involving multiple parameters. This method was applied to optimize the thermal insulation characteristics of a bio-composite. By following a precisely designed experimental program. the study focuses on analyzing the impact of varying concentrations of date palm fibers (DPF) on the thermal properties of the material. The tested samples contained between 0% and 30% DPF. with a fiber length set at 7 mm. The findings of this study clearly illustrate that the thermal conductivity of the bio-composite decreases with an increase in the percentage of DPF. This phenomenon occurs because the incorporation of fibers into the composite enhances the porosity within the matrix. consequently, reducing its density. Thus. these results underscore the advantageous effect of DPF on the insulation properties of the material.

1. INTRODUCTION

The quest for scientific progress often exploits the power of digital simulations, a tool that allows researchers to apply a multitude of laws to observe and analyses phenomena likely to be of paramount importance in diagnostics [1-3]. Using this statistical technique, researchers can evaluate multiple factors simultaneously, rather than just one factor at a time. While some molecules are difficult to diagnose, others are simple but extremely reactive; Experimental designs allow scientists to adapt their studies to the unique properties of each molecule and refine their formulations [4-6]. Despite the increased volume of data output, this process is simple thanks to JMP' comprehensive visualization features, which are as essential for analyzing experimental designs as they are for attracting new users to use the software [7-10].

It facilitates a comprehensive evaluation of the primary and interactive influences of the independent variables, termed as 'factors xi', on the outcome variables, referred to as 'responses' [11, 12]. Nehdi and Summer [13] explored the potential of using waste materials as cement replacements in mortar. Their experiment with a full factorial design showed these replacements affect both strength and durability. Belkad et al. [14] investigated the impact of waste marble powder (MP) on eco-efficient mortars by partially replacing cement, utilizing a full factorial design method. Results demonstrate significant effects of MP content and particle fineness on compressive strength and water absorption, with optimized rates and fineness reducing disposal hazards. In the field of materials science, the integration of plant fibers into composite materials has become a major area of research. Pioneering studies, such as those carried out by Benaniba et al. [15], looked at the impact of these fibers on the properties of composite materials. An essential aspect in the design of thermal insulation materials for buildings is their thermal conductivity [16, 17]. The main goal here is to reduce this property to improve insulation efficiency. A thorough knowledge of the thermal conductivity of materials is crucial, not only to optimize processing conditions but also to analyze heat transport during practical applications, as highlighted in the literature [18-20]. Recent research has also increasingly focused on the internal applications of these materials, particularly in interior construction work. Studies by Lahouioui et al. [21], explored the use of biomaterials for interior insulation and wall panels, demonstrating their potential to improve the energy efficiency and environmental sustainability of buildings [22-24]. These surveys highlight the significant energy savings and improved environmental performance that can be achieved in residential and commercial buildings through the application of sustainable and environmentally friendly materials [25]. The study distinguishes itself by integrating the comprehensive factorial design method to investigate various engineering properties (such as compressive strength, flexural strength, and thermal conductivity) of eco-composites based on plant fibers, specifically date palm fibers, considering two pertinent factors: content and length. To the best of knowledge, few studies have combined statistical methods to explore engineering properties in this manner. Thus, the modeling provides technologists with mathematical equations to predict the behavior of eco-mortars based on date palm fiber.

2. EXPERIMENT METHODS

2.1 Materials

This study utilizes composite materials made from date palm fibers (DPF), sand, and cement. The Algerian-produced Portland cement and Bousaada-Algerian sand each possess distinct properties. Initially, the DPFs, sourced from the Ouargla oasis, were contaminated with dust due to environmental exposure. To address this, the fibers were immersed in a 1% sodium hydroxide (NaOH) solution for one hour at 100℃ and then dried at 40℃ in an oven. To optimize the composite's mechanical properties, DPFs with a diameter less than 0.7 mm were cut into two specific lengths (3 mm and 7 mm). This selection not only enhances strength and stiffness through efficient load transfer but also prioritizes ease of processing and ensures a uniform composite structure. Finally, the chosen sand boasts a wide particle size distribution, reaching a maximum diameter of 5 mm and exhibiting a coarse texture (Figure 1).

Figure 1. Date palm fiber with a length equal to 7 mm (DPF7)

2.2 Measurement methods

For this investigation, eco-friendly composite materials were prepared by combining various weight percentages of date palm fibers (DPF) with a specific type of cement. This cement, prompt Portland cement (CPJ-CEM II/A 42.5) from the LAFARGE factory in M'sila, Algeria, was chosen for its lower environmental impact. It contains less clinker and incorporates limestone fillers, reducing its polluting effect. The DPF content varied between 6% and 30% to analyze a broad range of material compositions and their performance. This selection allowed us to assess the influence of fiber concentration on mechanical strength, thermal properties, and other aspects. We aimed to strike a balance between achieving optimal performance and cost-effectiveness for industrial applications. Additionally, these concentrations align with current industry practices, facilitating comparison with prior research and potential future uses.

The preparation process involved meticulous mixing. First, DPF, cement, and sand were dry-mixed in a rotating mixer for 5 minutes at 40 rpm to ensure uniform distribution. Water was then gradually added, followed by another 5 minutes of mixing. The resulting mixture was swiftly transferred to molds (40 mm × 40 mm × 160 mm) to minimize water evaporation. After setting in open air for 24 hours, the samples remained in the molds for air-drying (48 hours) before demolding and undergoing a 28-day curing period, adhering to the EN 196-1 standard [26].

To evaluate the performance of this optimized eco-mortar, we measured key properties after the 28-day curing period. These properties included density, mechanical strength, and thermal conductivity. Density was determined using the mass and dimensions of 40 mm cubic samples, following ASTM C905 specifications [27]. Compression strength was measured according to ASTM C349-14 guidelines [28], using triplicate 40 mm cubes loaded at a rate of 5 mm/min on a 400 kN capacity machine. Finally, a transient plane source (TPS) 2500 device was employed to assess the thermal conductivity of 40 mm × 40 mm × 160 mm samples [29].

2.3 Factorial design methodology in statistical analysis

This study employed a factorial design, a powerful statistical method for optimizing experiments. It allows researchers to efficiently evaluate the individual effects (main effects) and combined effects (interactions) of multiple variables (factors) on a desired outcome (response). This approach is well-established in scientific literature [30, 31]. A full factorial design enables the creation of mathematical models, optimization of processing conditions, and exploration of how different factors influence each other [32].

In this investigation, a factorial design was used to analyze the physical, mechanical, and thermal properties of mortars. The focus was on understanding how the percentage of palm fibers and their length within the mixture affect properties like compressive and flexural strength, density, and thermal conductivity. The influence of these factors, both individually and in combination, was assessed using a statistical technique called Analysis of Variance (ANOVA) [33]. Specialized software (JMP16) then aided in interpreting the extensive data.

The researchers opted for a full factorial design because it offers a systematic approach. This method allows for evaluating the impact of individual factors and their interactions on the measured responses, while minimizing the number of experiments needed. This efficiency helps to optimize the research process.

To understand how factors like palm fiber content and length influence the material's compressive strength, density, and thermal conductivity (responses), a two-step process was followed:

Identifying factors and building a model: First, the key factors influencing these responses were identified. Then, a mathematical model was developed to predict the response values based on these factors. This involved using ANOVA to determine the individual contribution of each factor to the measured responses.

Creating response maps: Using the mathematical models, contour plots (iso-response curves) were generated. These plots visually represent how the responses (e.g., strength, density) change in response to variations in the factors (fiber content and length).

Equation for prediction: We employed a second-order factorial equation with a two-factor interaction to forecast the responses. This equation is represented as:

$$Y = \beta_0 + \beta_1 A + \beta_2 B + \beta_{12} AB$$

Y: Predicted response value

$s\beta_0$: Constant term (offset)

A and B: Independent factors (where A represents fiber concentration and B represents fiber length)

β_1 and β_2: Coefficients for the linear effects of factors A and β

β_{12}: Coefficient for the interaction effect between two factors

3. RESULT AND DISCUSSIONS

3.1 Thermal conductivity

The various plots derived from analyzing the 28-day thermal conductivity results, which take into account the factors of date palm fiber concentration Φ (%) and fiber length L (mm), are depicted in Figure 2.

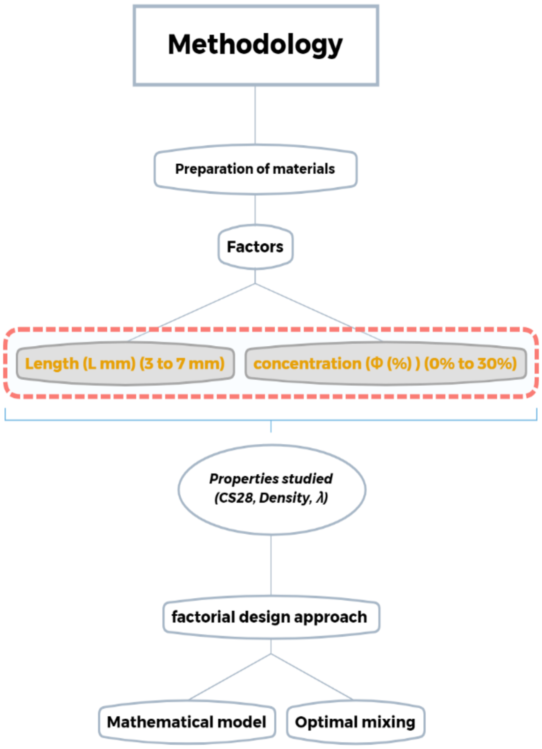
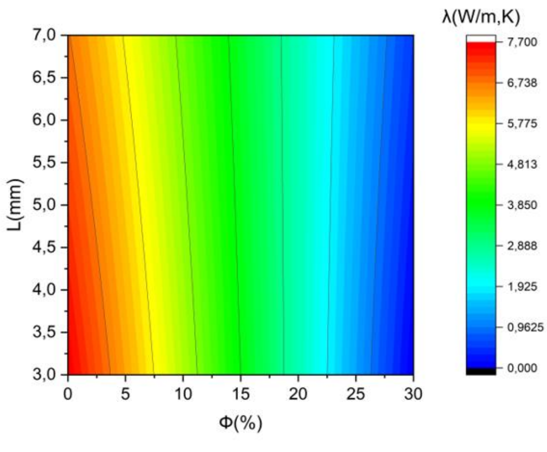
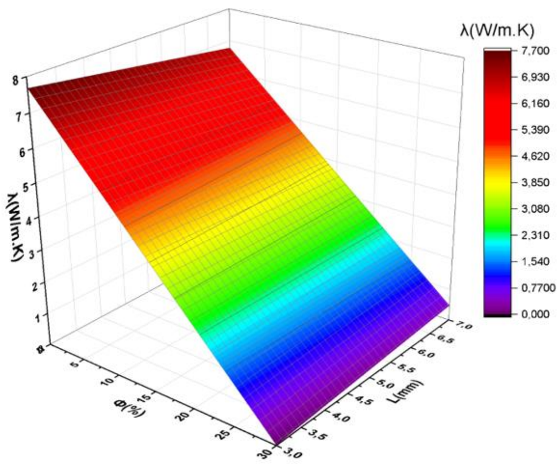


Figure 2. Flowchart illustrating the primary phases of the research



(a) Linear Iso response curve



(b) Surface Iso response curve

Figure 3. Thermal conductivity variation in function of the date palm length L (mm) and the concentration Φ (%)

The Figure 3(a) and (b) respectively displays the iso-response curve and areas for the thermal conductivity at 28 days of biomaterials produced with different DPF concentrations Φ (%) and fiber lengths (L mm). These results indicate a reduction in thermal conductivity from 7 to 0.5 W/m.k when the DPF concentration increases from Φ = 2.5% to Φ = 27%. This decline is expected, given that the fibers exhibit lowers thermal conductivity than the cementitious matrix, as demonstrated by Raut and Gomez [34] and Möller et al. [35]. In addition, the integration of fibers into the composite helps to increase the porosity within the matrix, thereby reducing its density. Additionally, it was observed that increasing the fiber length slightly improves the thermal conductivity of the biomaterial.

Visualizing the data in Figure 4(a) and (b) respectively would help understand whether the effects are additive (simply adding up the individual effects of length and concentration) or synergistic (where the combined effect is greater or less to the sum of individual effects).

Based on these results, it is evident that date palm fiber concentration Φ (%) exerts a significantly greater effect on the results than DPF length. Additionally, the intersection of the two lines on the graph indicates a substantial interaction between the DPF concentration Φ (%) and length L (mm) factors. The mathematical model describing thermal conductivity as a function of DPF length L (mm) and concentration (Φ %) is expressed as follows:

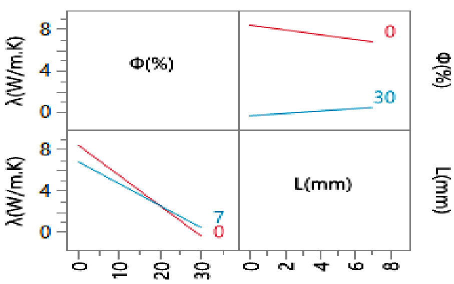
$$\lambda = 3.828 - 3.757\left(\frac{\Phi(\%)-15}{15}\right) - 0.194\left(\frac{L(mm)-3.5}{3.5}\right) + 0.602\left(\frac{\Phi(\%)-15}{15}\right)\left(\frac{L(mm)-3.5}{3.5}\right) \quad (1)$$

In a fictive professional comparison, the current results derived from the integration of date palm fibers notably differ from those reported by Romanovskiy and Bakatovich [36]. where the addition of flax fibers revealed no effect of fiber length on thermal conductivity. Additionally, our advanced mathematical model, which incorporates interaction terms between fiber concentration and length, represents a significant advancement compared to one-dimensional models such as that proposed by Liu et al. [37]. Meanwhile, while Shah et al. [38]. Documented a direct increase in thermal conductivity with bamboo fiber length, our observations suggest a more nuanced influence of fiber length, highlighting the behavioral specificity of date palm fibers within thermal composites.

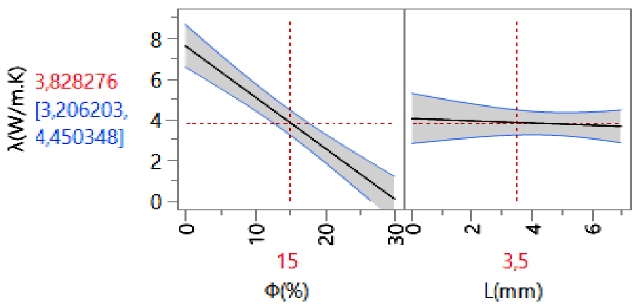
3.2 Density

The density plays a crucial role in assessing the porosity and evaluating the durability of the biomaterial. Various graphs, derived from the analysis of the 28-day density results, consider factors such as the concentration of date palm fiber, denoted by Φ (%), and the fiber length, represented by L (mm).

Figure 5(a) and (b) respectively, illustrates the iso-response curves and surfaces for the density of mortars with varying date palm fiber (DPF) concentrations Φ (%) and lengths L(mm). The results indicate a decrease in density from ρ=1751 kg/m^3 to ρ=746 kg/m^3 as the DPF concentration increases from Φ=2.5% to Φ=27%. This reduction is anticipated, as the fibers introduce additional porosity into the biomaterial.

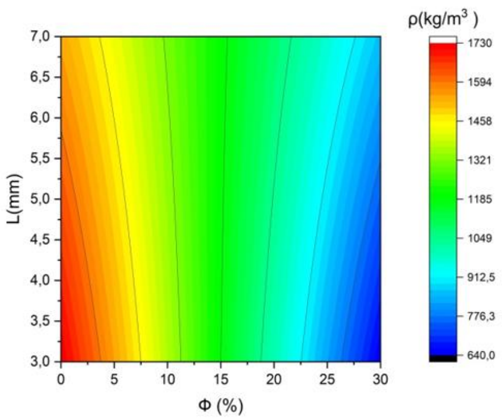


(a)

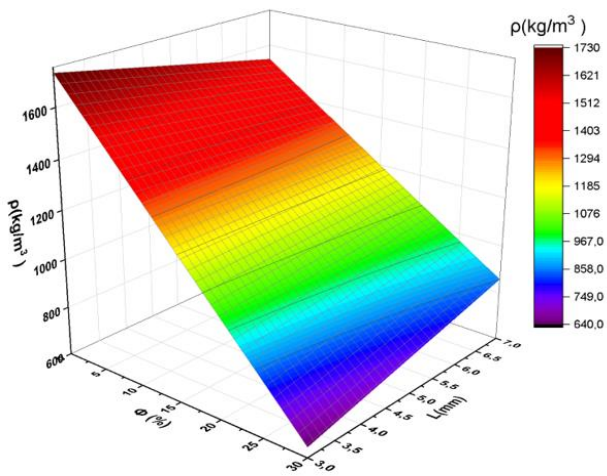


(b)

Figure 4. Thermal conductivity variation of the date palm fibers: (a) Degree of the DPF influence; (b) Interaction between the concentration Φ (%)

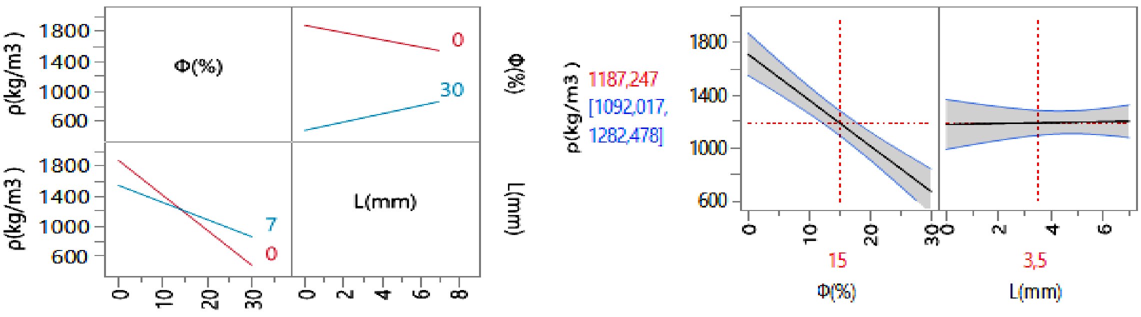


(a) Linear Iso response curve



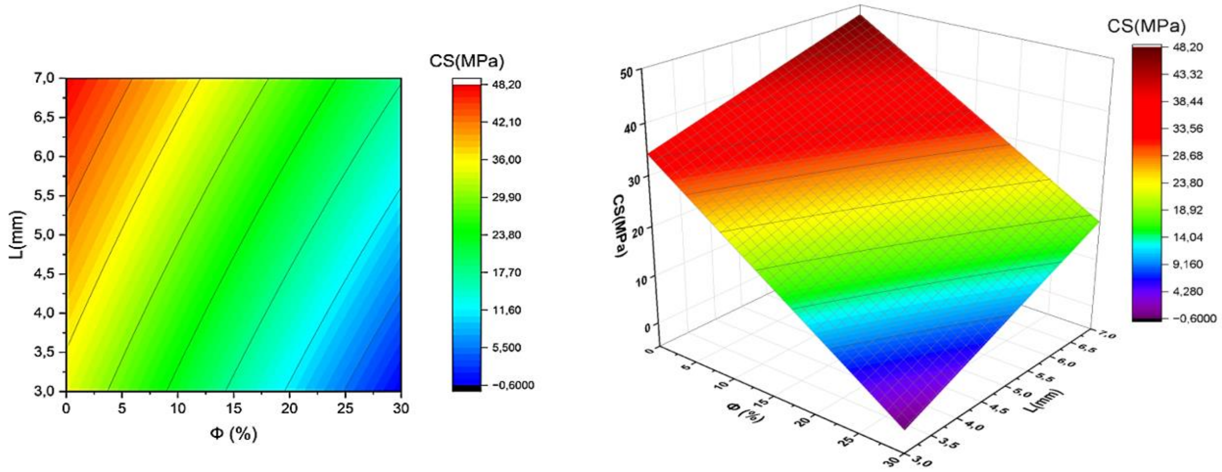
(b) Surface Iso response curve

Figure 5. Density variation in function of the date palm fiber length L(mm) and the concentration Φ (%)



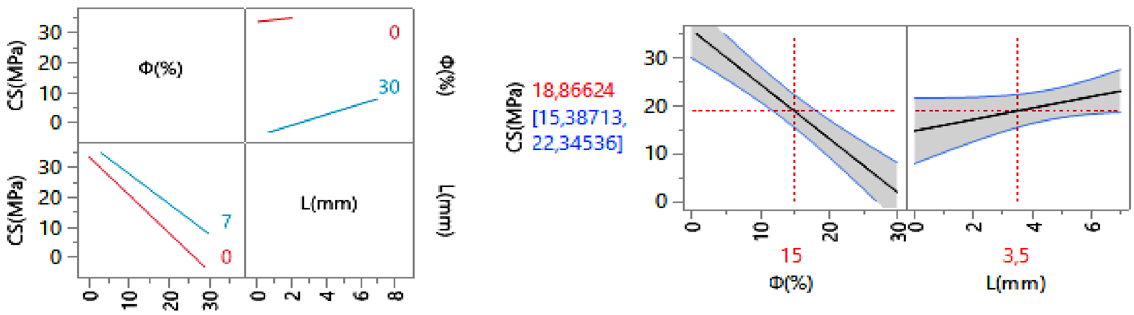
(a) (b)

Figure 6. Density variation of the biomaterial: (a) Degree of the DPF influence; (b) Interaction between the concentration Φ (%) and the length L (mm) of the date palm fibers



(a) Linear Iso response curve (b) Surface Iso response curve

Figure 7. Effect of the DPF on the compressive strength



(a) (b)

Figure 8. Compressive strength variation of the date palm fibers: (a) Degree of the DPF influence; (b) Interaction between the concentration Φ (%) and the length L (mm)

As documented by Raut and Gomez [34] and Möller et al. [35], the density diminishes correspondingly. Furthermore, it is observed that an increase in the length of the DPF slightly elevates the density of the biomaterial in question. Bahja et al. [39] showed that the addition of 4% sisal fibers by cement mass resulted in a decrease in its density and an increase in its porosity.

The Figure 6(a) and 6(b) demonstrates the impact of date palm fiber (DPF) length and concentration on biomaterial density variation, respectively, as well as the interaction between these two factors to influence the observed responses. The analysis reveals that the effect of density is considerably greater than that of DPF length. This is highlighted by two intersecting lines, indicating a strong interaction between the concentration Φ (%) and the length L (mm) of the date palm fiber. The model designed to predict the density of the biomaterial, from the length L (mm) and the concentration Φ (%) of the DPF, is structured as follows:

$$\rho = 1187.24 - 518.41.\left(\frac{\Phi(\%)-15}{15}\right) + 11.94.\left(\frac{L(mm)-3.5}{3.5}\right) + 177.84.\left(\frac{\Phi(\%)-15}{15}\right).\left(\frac{L(mm)-3.5}{3.5}\right) \quad (2)$$

3.3 Compressive strength

Figure 7(a) and 7(b) displays various plots derived from the analysis of 28-day compressive strength results (RC), considering the factors of date palm fiber concentration Φ (%)

and length L (mm). These results show a decrease in compressive strength from 36 MPa to 1.4 MPa as the DPF concentration increases from Φ = 2.5% to Φ = 27%. Additionally, it has been found that an increase in fiber length leads to enhanced mortar resistance. Specifically, the biomaterial containing 5% DPF with a length of L = 7 mm demonstrates a 30% improvement in resistance compared to a biomaterial of the same DPF concentration but with a length of L= 3 mm. Furthermore, this increase in strength is attributed to the rough surface of the fibers, which enhances their interaction with the matrix, as indicated by Da Silva et al. [40] and Jia et al. [41]. Belkadi et al. [42]. demonstrated that date palm fibers slightly decrease compressive strength.

Figure 8(a) and 8(b) respectively, illustrates the significant impact of date palm fiber (DPF) concentration Φ (%) on compressive strength (Cs) and its correlation with DPF length along the x-axis. The interaction between fiber length L (mm) and concentration Φ (%) of date palm fiber on compressive strength. These findings reveal two intersecting lines that underscore the strong interplay between the two factors, Φ and L. These results offer fresh insights into the pivotal role of fiber length in predicting compressive strength. Engineers must consider this factor to optimize the mechanical properties of the produced biomaterial. The model proposed for the prediction of compressive strength as a function of the date palm fibers length L (mm) and the fibers concentration Φ (%) is written as follows:

$$Cs = 20.26 + 1.2\,(L - 5) + 1.02\,(\Phi - 15) + 0.037\,(L - 5)(\Phi - 15) \tag{3}$$

3.4 Analysis of variance

We used a statistical analysis called ANOVA to determine how much each factor (from Table 1) affects the different material properties we measured. The models we created to predict these effects are very accurate, with correlation coefficients between 0.91 and 0.98. This high correlation shows a strong connection between the actual results and what the models predicted. In other words, our models can reliably predict how fiber content changes the mechanical and physical properties of this biomaterial.

To further understand these relationships, we generated contour plots (iso-response curves) based on the models. Additionally, Table 2 presents a detailed breakdown of the ANOVA results, highlighting how significant each factor is for each property.

We also performed a Fisher's test to assess the overall significance of our models. This test revealed very high Fisher ratios (above 2.45) for compressive strength, indicating a strong influence of the factors on this property. Furthermore, all the models have probability values (p-values) below 5%, which confirms that at least one factor has a significant effect on each measured property.

Table 1. Effect test

	Model Term	**Estimation**	**Standard Error**	**t Ratio**	**Prob. > |t|**
CS_{28} (MPa)	Constante	18.866	1.471	12.82	<.0001*
	Φ (%) (0.30)	-17.035	2.102	-8.10	<.0001*
	L(mm) (0.7)	4.181	1.982	2.11	0.0729
	Φ (%) *L(mm)	2.010	2.688	0.75	0.4788
$\rho(\frac{kg}{m^3})$	Constante	1187.24	40.273	29.48	<.0001*
	Φ (%) (0.30)	-518.41	57.540	-9.01	<.0001*
	L(mm) (0.7)	11.948	54.265	0.22	0.8320
	Φ (%) *L(mm)	177.84	73.580	2.42	0.0463*
$\lambda(\frac{W}{m}.K)$	Constante	3.828	0.263	14.55	<.0001*
	Φ (%) (0.30)	-3.757	0.375	-10.00	<.0001*
	L(mm) (0.7)	-0.194	0.354	-0.55	0.5994
	Φ(%)*L(mm)	0.602	0.480	1.25	0.2500

Table 2. Analysis of variance (ANOVA) for derived models

	Source	**Degree of Freedom**	**Sum of Squares**	**Mean Square**	**F -Ratio**
CS_{28}	Model	3	1151.601	383.867	22.1704
	Error	7	121.201	17.314	**Prob. > F**
	Total	10	1272.802		0.0006*
$\rho(\frac{kg}{m^3})$	Model	3	1201811.3	400604	30.881
	Error	7	90807.5	12972	**Prob. > F**
	Total	10	1292618.8		0.0002*
$\lambda(\frac{W}{m}.K)$	Model	3	65.497	21.8326	39.441
	Error	7	3.8748	0.5535	**Prob. > F**
	Total	10	69.372		<.0001*

3.5 Correlation between experimental values and numerical values

Figure 9 illustrates the correlation between the experimental and numerical values of various mechanical and physical properties. Upon careful analysis of Figure 9, it becomes evident that a robust and meaningful correlation exists between the empirical and computational results. This correlation underscores the exceptional alignment of the numerical model with all investigated attributes, indicating a high degree of accuracy in predicting the material properties.

The correlation coefficient (R^2) obtained in the analysis ranges notably between 0.90 and 0.94. This high correlation coefficient confirms a strong agreement between the actual experimental data and the predictions made by the numerical model. Furthermore, the proximity of all data points to the mean line in the graph further enhances the reliability of the model. This indicates that the numerical model can effectively and reliably capture the characteristics of the various examined attributes, even under varied experimental conditions.

The outcomes depicted in Figure 9 are incredibly promising and signify the model's resilience in accurately forecasting the characteristics of the analyzed materials. The concordance observed between experimental and numerical outcomes further bolsters the trustworthiness of employing the model for material design and optimization purposes.

These findings hold significant implications for the field of repair materials research, as they provide a reliable framework for the development of innovative solutions and their practical implementation in real-world applications. By leveraging the predictive capabilities of the numerical model, researchers and practitioners can make informed decisions in material design and optimization, ultimately leading to enhanced performance and durability of repair materials in various applications.

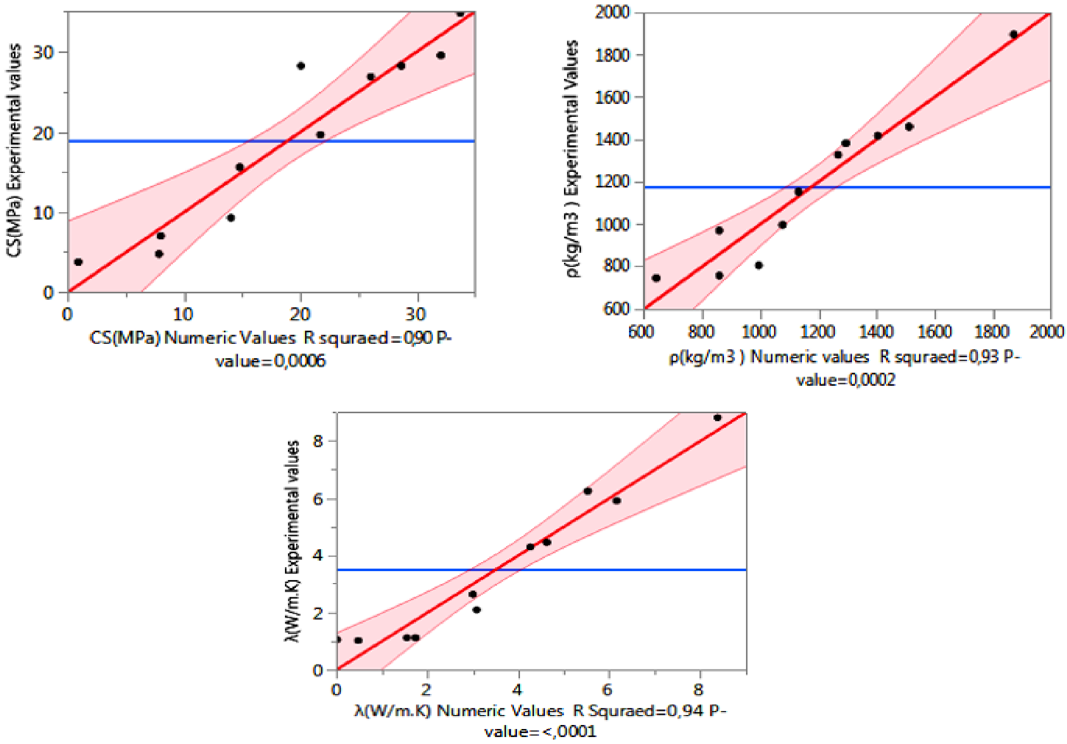


Figure 9. Correlation between actual and predicted values

4. CONCLUSIONS

In this study, we investigated the enhancement of thermal insulation in biocomposites, accompanied by a static modeling of the impact of various concentrations of date palm fibers (DPF) on the thermal and mechanical properties of the material. Our findings reveal:

- A significant decrease in thermal conductivity, from 7 to 0.5 W/m. k, as the DPF concentration rises from $\Phi = 2.5\%$ to $\Phi = 27\%$.
- A reduction in density from $\rho = 1751$ kg/m^3 to $\rho = 746$ kg/m^3, correlated with the increase in DPF concentration from $\Phi = 2.5\%$ to $\Phi = 27\%$.
- A decrease in compressive strength from 36 MPa to 1.4 MPa as the DPF concentration increases from $\Phi = 2.5\%$ to $\Phi = 27\%$. It was also observed that an increase in fiber length enhances the mortar's resistance.
- Mathematical equations have been developed to effectively predict the heat transfer as well as the mechanical and physical performance of bio-composites.
- This study bridges two current fields: numerical modelling based on experimental data and the use of ecological and efficient materials in the construction sector. It paves the way for researchers in applied mathematics in the construction field to improve or predict various material properties.

Furthermore, this work, which combines experimentation and modeling, allows materials technologists to develop a new ecological, economical, and efficient material. The modeling presented in this study aids in predicting and optimizing the mechanical, physical, and thermal performances of mortars based on plant fibers.

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NOMENCLATURE

DPF	date palm fiber
L	fiber length
ANOVA	variance analysis
Cs	compressive strength

Greek symbols

Φ	concentration of DPF
ρ	density
λ	thermal conductivity