https://doi.org/10.3311/PPci.42126

Periodica Polytechnica Civil Engineering, 70(1), pp. 232–243, 2026

Enhancing Mechanical Performance of Hemp Fiber-reinforced Cementitious Composites

Experimental and Numerical Investigations Using RSM

Samir Deghboudj[1,2*], Wafia Boukhedena[1,3], Meriem Benzarti Miladi[4], Hamid Satha[5]

[1] Mines Laboratory, Echahid Cheikh Larbi Tebessi University, P. O. B. 42, 12002 Tebessa, Algeria
[2] Department of Mechanical Engineering, Faculty of Sciences and Technology, Echahid Cheikh Larbi Tebessi University, P. O. B. 42, 12002 Tebessa, Algeria
[3] Department of Materials Science, Faculty of Exact Sciences and Natural and Life Sciences, Echahid Cheikh Larbi Tebessi University, P. O. B. 42, 12002 Tebessa, Algeria
[4] Laboratory of Textile Physics and Mechanics, University of Haute-Alsace, 11 Alfred Werner Street, 68093 Mulhouse Cedex, France
[5] LSPN Laboratory, University 8 May 1945 Guelma, P. O. B. 401, 24000 Guelma, Algeria
* Corresponding author, e-mail: samir.deghboudj@univ-tebessa.dz

Received: 03 September 2025, Accepted: 03 February 2026, Published online: 25 February 2026

Abstract

Over the past decade, cement-based composites incorporating natural fibers have emerged as promising alternatives to conventional building materials due to their environmental benefits. The current trend in sustainable construction highlights the growing interest in bio-composites, particularly mortars reinforced with vegetable fibers, which combine technical efficiency with ecological responsibility. Compared to conventional mortars, these bio-composites reduce environmental impact, improve energy efficiency through their low density, and offer enhanced crack resistance and durability under flexural stresses. Hemp fibers, with their complex internal structure and mechanical resilience, are particularly suited for reinforcing cementitious matrices. This study examines the integration of hemp fibers into cement-based composites, aiming to enhance their mechanical performance for construction use. The fibers underwent alkali treatment with different concentrations of sodium hydroxide (NaOH) and were prepared in various lengths before being blended into the mortar. A design of experiments using Response Surface Methodology (RSM) was employed to evaluate the influence of these variables on compressive and flexural strength, tested after 28 days of curing. The outcomes were analyzed through Analysis of Variance (ANOVA) to identify optimal conditions. Additionally, a predictive model was developed to describe the behavior of the composites under varying treatment parameters. This research offers practical insights into the sustainable development of fiber-reinforced cementitious materials and highlights strategies for optimizing their mechanical performance using natural reinforcements.

Keywords

hemp fiber, biocomposite, mechanical behavior, mortar, optimization, Response Surface Methodology (RSM)

1 Introduction

Cementitious composite materials reinforced with vegetable fibers have garnered considerable attention in recent years due to their potential to offer sustainable and environmentally friendly alternatives to conventional construction materials. These bio-composites exhibit promising mechanical properties particularly improved compressive and flexural strengths that make them suitable for various structural applications. A thorough understanding of their behavior under bending and compressive loads is essential to evaluate their structural performance and long-term durability [1, 2]. The selection of fibers for cementitious composites is primarily based on key mechanical characteristics such as tensile strength, modulus of elasticity, elongation at break, and the bonding capacity with the cementitious matrix [3]. Numerous studies have investigated the mechanical performance of fiber- reinforced cementitious composites, with a particular focus on the relationships between flexural strength, compressive strength, fiber dosage, and shrinkage behavior [4, 5]. It is well established that unreinforced cementitious materials possess high compressive strength but exhibit poor resistance to tensile and flexural stresses. The incorporation of vegetable fibers effectively addresses these weaknesses by enhancing both tensile and flexural performance, thus

Cite this article as: Deghboudj, S., Boukhedena, W., Benzarti Miladi, M., Satha, H. "Enhancing Mechanical Performance of Hemp Fiber-reinforced Cementitious Composites: Experimental and Numerical Investigations Using RSM", Periodica Polytechnica Civil Engineering, 70(1), pp. 232–243, 2026. https://doi.org/10.3311/PPci.42126

increasing the applicability of such composites in load bearing structures [6, 7]. In line with the global transition toward sustainable construction, the use of bio-composites reinforced with natural fibers has become an active research trend. Compared to conventional mortars, which are characterized by a high carbon footprint and brittle behavior, vegetable fiber-reinforced mortars provide multiple benefits. They improve ductility, reduce crack propagation, and increase energy absorption capacity while simultaneously contributing to resource valorization and waste minimization. Furthermore, the use of renewable, biodegradable, and low-cost fibers aligns with the principles of circular economy and eco-efficiency, offering innovative pathways to reduce the environmental impact of construction materials. As such, bio-composites represent not only a promising structural material but also a strategic solution to meet the dual challenge of performance and sustainability in modern construction [8, 9]. This study aims to develop and evaluate cementitious composites reinforced with hemp fibers, focusing on their mechanical response under flexural and compressive stresses. The research places particular emphasis on the effects of fiber treatment, specifically alkaline treatment using sodium hydroxide (NaOH) as well as on fiber content and length. The influence of these parameters on the composite's mechanical behavior is explored to determine optimal performance conditions [10]. The findings of this work will contribute to the advancement of sustainable building materials by offering practical insights into the mechanical behavior, durability, and optimization of hemp fiber-reinforced composites. This study enriches the growing body of knowledge surrounding the structural performance of cement-based bio-composites, and is expected to benefit engineers, researchers, and stakeholders engaged in the promotion of sustainable construction practices [1, 2, 5]. The research methodology combines both experimental and numerical approaches and is structured into three main parts. The first part presents a detailed description of the raw materials, including hemp fibers and the cementitious matrix, followed by the chemical treatment process using varying concentrations of NaOH and the preparation of the bio-composites based on an experimental design utilizing Response Surface Methodology (RSM). Flexural and compressive tests performed after 28 days of curing are also described. The second part explores the experimental design framework used to analyze and interpret the influence of different parameters on composite performance. Finally, the third part presents an in-depth analysis of experimental data obtained from three-point bending and compression tests. An Analysis of Variance (ANOVA) is conducted to identify the most influential parameters fiber length, NaOH concentration, and fiber volume that optimize the mechanical behavior of the bio-composites.

2 Materials and methods

2.1 Hemp fiber

In this study, industrial hemp (*Cannabis sativa*), a member of the Cannabinaceae family, was used as the reinforcing fiber [11, 12]. Industrial hemp is an annual plant with a stem that typically reaches a height of 2 to 4 meters and a diameter of 1 to 3 cm, depending on the variety and growing conditions [13, 14]. The stem is generally hollow, fluted, and sparsely branched [11]. The morphological characteristics of the plant, particularly its vegetative structure, may vary significantly depending on the species and environmental factors [15, 16]. Hemp fiber exhibits high tensile strength and stiffness, making it a promising candidate for reinforcement in composite materials. Its mechanical performance is often comparable to that of glass fibers, while offering the added advantages of biodegradability and renewability [17]. Under optimal conditions, hemp is typically ready for harvest within two to three months after sowing [18–20].

2.2 Cementitious matrix

This research was supported by the cement company located in Tebessa, Algeria, which also provided the cement used in this study. The product complies with the Algerian standard NA 442:2013 [21] and is classified as Portland Composite Cement (CEM II/A-M (P-L) 42.5 R). The technical characteristics of the cement, as defined by Algerian standard NA 234:2018 [22], are detailed in Table 1 [23].

Table 1 Technical specifications of Portland Composite Cement (CEM II/A-M (P-L) 42.5 R) [23]

	Expiry in days	Measures
Bending resistance MPa	02 days	4.7
	07 days	6.3
	28 days	7.02
Compressive resistance MPa	02 days	23.3
	07 days	37.8
	28 days	48.2

2.3 Preparation of the bio-composite

2.3.1 Fiber preparation

Natural fibers are increasingly used in composite materials due to their cost-effectiveness, low density, and biodegradability. Compared to synthetic fibers such as glass fibers, hemp fibers generally exhibit lower stiffness but offer significant advantages in terms of sustainability, renewability, and reduced environmental impact. While glass fiber-reinforced mortars often achieve higher compressive strengths, natural fibers provide improved crack-bridging capacity and ductility, making them attractive for eco-efficient construction applications. However, their main drawbacks lie in the poor interfacial compatibility with cementitious matrices and their relatively high moisture absorption capacity [24]. To overcome these limitations, chemical treatments are commonly employed to modify the surface properties of the fibers [25]. While these treatments aim to improve the mechanical strength of the fibers, they can also significantly influence the interfacial bonding between the fiber and the matrix [26]. Alkali treatment using sodium hydroxide (NaOH) has been shown to reduce water absorption and enhance the mechanical properties of fiber-reinforced composites [27]. In this study, NaOH solutions were prepared at three concentrations: 2%, 3%, and 4%. To achieve these concentrations, 1000 mL of distilled water were mixed with 20 g, 30 g, and 40 g of NaOH, respectively. A total of approximately 300 g of hemp fibers was divided into three equal portions. Each portion was immersed in one of the NaOH solutions for 24 hours at room temperature. This treatment softens the fibers and facilitates the removal of non-cellulosic compounds such as waxes, pectins, lignin, and hemicelluloses, which otherwise impair the fiber-matrix bond. After the immersion period, the fibers were removed from the alkaline solution and thoroughly rinsed with clear water to eliminate any residual chemicals or impurities that could negatively affect adhesion with the cementitious matrix. The washed fibers were then oven-dried at 60 °C for 6 hours. Once dried, they were cut into various lengths and stored in sealed bags to prevent moisture reabsorption from the ambient air.

2.3.2 Preparation of samples

The samples were manufactured and prepared in accordance with a reference mortar (control) specified by European Standard CEN EN 196-1:2016 [28]. The control mortar comprised a cement, sand, and water ratio of 1:3:0.5, with 450 ± 2 g of cement, 1350 ± 5 g of sand, and 225 ± 1 ml of water. Fibers with varying volumetric percentages (1%, 1.5%, and 2%), treated with different alkaline concentrations (2%, 3%, and 4%) and cut to lengths of 1, 3, and 5 mm, were incorporated into the mixture, adjusting the sand weight accordingly. The selected ranges of fiber length (1–5 mm), NaOH concentration (2–4%), and fiber volume fraction (1–2%) were determined based on previous studies reported in the literature and practical considerations related to workability and fiber dispersion. Alkali concentrations within this range are commonly used to enhance fiber-matrix adhesion without causing excessive degradation of the fiber structure. Similarly, short fiber lengths were selected to ensure adequate dispersion in the cementitious matrix, while fiber contents above 2% were avoided to limit porosity and loss of compactness. The fibers were mixed manually and gradually over five minutes to ensure uniform dispersion. Although manual mixing may introduce some degree of variability in fiber distribution, a controlled and progressive mixing procedure was applied to minimize heterogeneity. The low coefficients of variation obtained for both flexural and compressive strengths indicate that the experimental repeatability remained within acceptable limits. The mixture was then poured into steel molds measuring 40 × 40 × 160 mm^3 (Fig. 1).

Using a shock table, 60 blows were applied in two phases to eliminate air bubbles (Fig. 2).

The specimens were placed in a humid room at 20 °C and 90.5% humidity for 24 hours (Fig. 3).

Fig. 1 Steel prismatic mold (40 × 40 × 160 mm^3)

Fig. 2 Steel mold positioned on the shock table

Fig. 3 Specimens in humid chamber (20 °C, 90.5% RH)

After demolding, they were cured in water for 28 days before testing. Following European Standard CEN EN 196-1:2016 [28], compressive strength tests and three-point bending tests were conducted. Each specimen type, was tested at least three times for both compression and bending. The tests were performed at room temperature using a universal ToniPrax 1543 machine with a 10 kN load cell at a speed of 2 mm/min. Results were collected using testXpert software [29]. This work aims to study the influence of the parameters mentioned above on the development of mortars and to extract the impact on the behavior of the material in compressive and bending strength. A strategy of elaboration experiments has been developed using Design-Expert software [30], as reported in Table 2, to reduce the number of trials as much as feasible and enable the development of bio-mortars at the lowest possible experimental expense.

3 Response Surface Methodology (RSM)

Response Surface Methodology (RSM) involves a collection of mathematical and statistical approaches designed to fit empirical models to data gathered from structured experiments. Initially developed by Box and Wilson, RSM has been widely and effectively applied across various scientific fields [31, 32]. The methodology offers several benefits, including the precise prediction of response models, the creation of robust models with minimal experimental data, the evaluation of interaction effects among factors, and the identification of optimal responses [33, 34]. In RSM, regression analysis is combined with statistical techniques to interpret the experimental data comprehensively and predict the relationships between a dependent variable (response of interest, y) and multiple independent variables (input or control variables, x_1 through x_k) [35]. This approach to experimental design is characterized by a restricted calculation range. The factor levels are indicated by the codes (−1) and (+1), representing the minimum and maximum values, respectively, with the midpoint denoted as (0) [36]. It should be noted that the regression models developed using Response Surface Methodology are valid within the experimental domain defined by the investigated ranges of fiber length, NaOH concentration, and fiber volume fraction. Although the models demonstrate excellent predictive accuracy within this domain, extrapolation beyond the tested parameter ranges is not recommended, as the response behavior outside the experimental space may differ significantly. In this investigation, bending and compression tests on a bio-composite consisting of cement mortar reinforced with hemp fibers were conducted using the parameters listed in Table 3. Utilizing Response Surface Methodology (RSM), the parameters for the experimental design included fiber length (A), percentage of NaOH (B), and volumetric fiber fraction (C). The Central Composite Design (CCD) was employed in this study. RSM facilitates the creation of regression models that can evaluate the effects of different variables and their levels on the mechanical properties, specifically bending and compressive breaking stresses [31, 32, 36]. In this study, a fitting analysis indicated that a cubic function model would be appropriate. The third-order polynomial equation utilized to fit the experimental data and identify the significant model terms is expressed as follows:

Table 2 Central Composite Design (decoded matrix) showing factors (*A*, *B*, and *C*) and experimentally obtained responses (Y_1 and Y_2)

N°	Factor 1 (*A*) Fiber's length	Factor 2 (*B*) NaOH (%)	Factor 3 (*C*) Fibers (%)	Response 1 (Y_1) Bending break stress (MPa)	Response 2 (Y_2) Compression break stress (MPa)
1*	3	3	1.5	6.30	36.08
2	3	3	2	6.62	36.33
3	1	2	2	5.80	35.40
4	1	4	2	6.73	43.90
5	1	2	1	6.71	40.13
6	3	4	1.5	6.25	36.83
7	3	3	1	6.52	41.37
8	5	3	1.5	6.25	36.77
9	1	4	1	6.76	40.17
10	5	2	2	4.94	31.83
11*	3	3	1.5	6.30	36.08
12	5	4	2	5.39	29.90
13	5	2	1	7.08	42.80
14	3	2	1.5	5.81	36.83
15	1	3	1.5	6.44	38.13
16*	3	3	1.5	6.30	36.08
17	5	4	1	7.06	44.13

* Three points in the center of the model

Table 3 Fit summary of the two statistical models (bending stress and compressive stress)

Test type	Source	SD	R^2	Adjusted	Predicted	PRESS	Observation
Bending							
	Linear	0.42	0.5499	0.4461	0.0732	4.72	
	2FI	0.32	0.8043	0.6868	0.3313	3.41	
	Quadratic	0.32	0.8621	0.6847	−0.1886	6.05	
	Cubic	0.012	0.9999	0.9995	0.8616	0.70	Suggested
Compression							
	Linear	3.10	0.4879	0.3697	−0.1688	285.14	
	2FI	1.95	0.8446	0.7514	−0.3546	330.47	
	Quadratic	1.79	0.9081	0.7899	−0.8101	441.60	
	Cubic	0.82	0.9918	0.9561	−12.059	3185.95	Suggested

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i=1}^{k} \beta_{iii} x_i^3 + \sum_{i<j}^{k} \beta_{ij} x_i x_j + \sum_{i<j}^{k} \beta_{iij} x_i^2 x_j \sum_{i<j}^{k} \beta_{ijj} x_i x_j^2 \sum_{i<j<k}^{k} \beta_{ijk} x_i x_j x_k . \quad (1)$$

The response variable (y) corresponds to the bending and compression strengths. The β_0 denotes the intercept term; x_i, x_j, and x_k are the independent variables; and β_i, β_{ii}, and β_{iii} are the coefficients of the linear, quadratic, and cubic terms, respectively. The β_{ij} represents the two-factor interaction between variables i and j, β_{iij} and β_{ijj} denote interactions between quadratic and linear terms, and β_{ijk} represents the three-factor interaction. The study investigates the influence of these parameters on mortar development and evaluates their effects on compressive and bending strengths. Experimental planning was carried out using Response Surface Methodology (RSM) with a Central Composite Design (CCD) implemented in Design-Expert software [30]. The experimental matrices are presented in Table 2 (decoded factors).

4 Analysis of variance (ANOVA) and regression modeling

In compliance with the pre-established experimental design, the cementitious composite manufactured with hemp fiber-reinforced mortar was subjected to experimental bending and compression tests. Using the polynomial regression models detailed in Table 3, which include linear, two-factor interaction (2FI), quadratic, and cubic equations, the responses (bending and compression stresses) were individually analyzed. A preliminary analysis indicated a preference for the cubic model for this study. These models underwent statistical evaluation to identify the most influential variables impacting the mechanical properties of the bio-fiber-reinforced mortar. This study employed a Central Composite Design, which facilitated the development of a test campaign comprising 17 tests, including three points corresponding to the model's center. The number of trials ranged from 1 to 17. Mathematical models were constructed to depict the responses of bending stresses (Y_1) and compression stresses (Y_2) as functions of the independent variables A, B, and C. These predictive models, respectively for bending and compression, were derived from the results of experimental trials conducted on the samples and expressed in terms of decoded variables in Eq. (2) and Eq. (3):

$$\begin{aligned} Y_1 &= 11.68 - 3.21A + 0.33B - 6.26C + 0.4AB \\ &+ 1.73AC + 0.49BC + 0.52A^2 - 0.14B^2 + 1.02C^2 \\ &- 0.05ABC - 0.01A^2B - 0.32A^2C - 0.05AB^2 \end{aligned} \tag{2}$$

$$\begin{aligned} Y_2 &= 69.59 - 0.96A - 6.03B - 37.18C \\ &+ 1.63AB + 1.37AC + 5.69BC + 7.64C^2 - 1.46ABC. \end{aligned} \tag{3}$$

The adequacy of the regression models was assessed at the 95% confidence level using ANOVA. Model significance was determined from the p-values, where values below 0.05 indicated a statistically significant effect on the response [37–39]. According to the ANOVA results, the models for bending (F = 2645.36) and compression (F = 41.68) were highly significant, with only a 0.01% probability of these results arising from noise [34, 40, 41]. For bending strength (Y_1), significant terms included main factors A, B, and C; interactions AB, BC, and AC; quadratic terms A^2, B^2, and C^2; and cubic effects ABC, A^2B, A^2C, and AB^2. For compression strength (Y_2), the significant terms were A, B, and C; interactions AB, AC, and BC; the quadratic term C^2; and the cubic effect ABC. The coefficients of determination were very high ($R^2 = 0.9999$ for bending, $R^2 = 0.9766$ for compression), indicating excellent model fit. Predicted and adjusted R^2 values were in good agreement for bending (predicted = 1.0000, adjusted = 0.8616, experimental $R^2 = 0.9995$), explaining 99.99% of the variability. For compression, predicted and adjusted R^2 values (0.9766 and 0.6872, respectively, with experimental $R^2 = 0.9531$) showed good predictive capability. The coefficient of variation (CV) values was well below the 15% acceptability threshold [18], at 0.19% for bending and 2.24% for compression, confirming the precision and reliability of the experimental data.

5 Results and discussion

5.1 Variation of mechanical performance

The experimental results derived from the Central Composite Design (CCD) clearly demonstrate that both bending strength (Y_1) and compressive strength (Y_2) of the hemp fiber-reinforced bio-composites are highly sensitive to the processing parameters, namely fiber length, NaOH concentration, and fiber content. The bending strength values were found to vary within a relatively narrow range (5.39–7.08 MPa), indicating that flexural performance is moderately influenced by the studied parameters (Fig. 4). This limited variation suggests that flexural behavior is mainly governed by fiber matrix interfacial bonding and fiber dispersion within the cementitious matrix, which were relatively stable under the experimental conditions. In contrast, compressive strength exhibited a much wider variation, ranging from 29.90 to 44.13 MPa (Fig. 4). This broader spread highlights the stronger dependence of compressive behavior on the quality of the cementitious matrix and its ability to transfer stresses effectively in the presence of fibers. While fibers tend to enhance tensile and flexural responses by bridging microcracks, their incorporation can sometimes disturb matrix homogeneity and increase porosity, which in turn reduces compressive capacity when fiber content or treatment is not optimized.

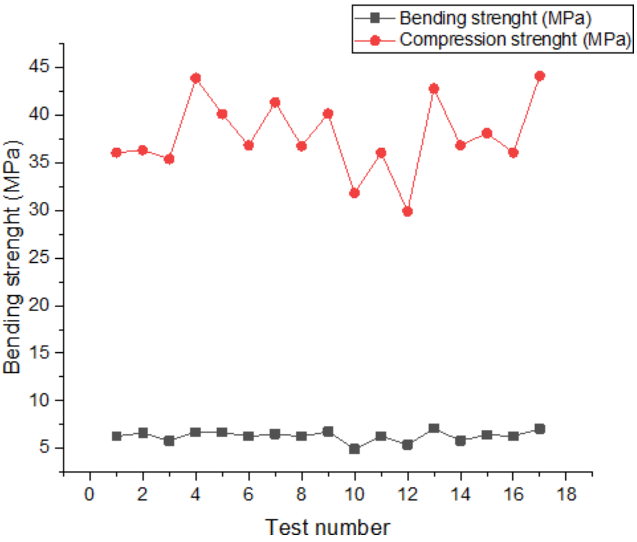

Fig. 4 Evolution of flexural and compressive strength across the 17 experimental tests

Overall, these findings emphasize that the optimization of processing parameters plays a more decisive role in improving compressive strength compared to bending strength. Nevertheless, the simultaneous improvement of both properties requires a balanced control of fiber dosage, surface treatment, and aspect ratio to ensure effective reinforcement without compromising matrix compactness.

5.2 Comparison with control mortar

The control mortar specimen, composed of plain cement mortar without fibers, exhibited a flexural strength of 7.02 MPa and a compressive strength of 48.2 MPa. When compared with the bio-composites, it is evident that the incorporation of hemp fibers induced two distinct effects on the mechanical response. For bending strength, the values of the reinforced composites (5.39–7.08 MPa) were very close to that of the control. In certain formulations, the flexural resistance approached or even slightly exceeded the control value (7.08 MPa vs. 7.02 MPa), confirming that fiber reinforcement can effectively bridge microcracks and sustain flexural loads. This behavior highlights the potential of hemp fibers to compensate for the inherent brittleness of the cement matrix. For compressive strength, however, a significant reduction was observed. While the control mortar reached 48.2 MPa, the reinforced composites ranged only between 29.90 and 44.13 MPa (Fig. 5). This decline can be attributed to the disturbance in matrix compactness and increased porosity induced by fiber incorporation. Although fibers improve tensile and flexural performance, they may act as flaws under compressive loading if their distribution, aspect ratio, or surface treatment is not optimized. These observations underline a key trade-off: the reinforcement with hemp fibers contributes positively to flexural performance but tends to reduce compressive capacity relative to plain mortar. Hence, optimization of fiber length, content, and chemical treatment is crucial to achieving a balanced enhancement of both mechanical properties.

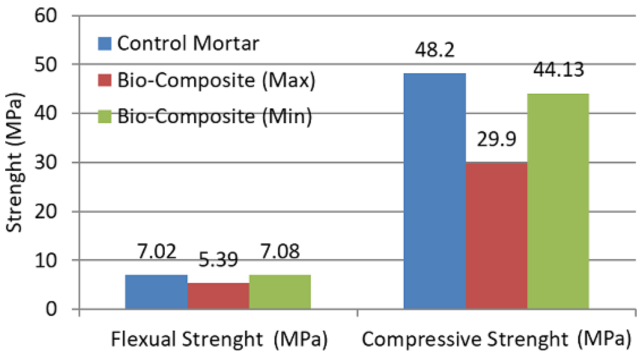

Fig. 5 Comparison of flexural and compressive strengths of the control mortar and hemp fiber-reinforced bio-composites (min-max range)

5.3 Identification of optimal combinations

Certain tests demonstrated remarkable improvements in both responses. For example, Test 17 achieved the highest compressive strength (44.13 MPa) with a bending strength of 7.06 MPa, suggesting a nearly optimal balance between the three factors. Similarly, Test 13 also exhibited high performance (7.08 MPa bending, 42.80 MPa compression), confirming that the appropriate selection of fiber treatment and dosage significantly enhances the overall performance of the composites. Conversely, Tests 10 and 12 reported the lowest strengths (4.94 and 5.39 MPa in bending; 31.83 and 29.90 MPa in compression, respectively). These results may be attributed to poor compatibility between fibers and matrix or to non-optimal fiber dosage and distribution.

5.4 Influence of fiber treatment and content

The effect of alkaline treatment was found to be critical in enhancing adhesion between the fiber and the cementitious matrix. Proper NaOH concentrations contributed to the removal of amorphous components (lignin, hemicellulose), improving bonding and stress transfer. However, excessive treatment or inadequate fiber dispersion could lead to decreased performance, as reflected in lower strength values in some trials. Additionally, the fiber content played a dual role: while moderate fiber percentages improved crack bridging and tensile strength, excessive fiber volume may have induced fiber clustering and porosity, which negatively impacted compressive strength.

5.5 Statistical modeling and validation

The ANOVA results confirmed the high significance of the developed models. The cubic regression model was found to be the most suitable, with coefficients of determination $R^2 = 0.9999$ for bending and $R^2 = 0.9918$ for compression, demonstrating excellent agreement with experimental data. The predicted and adjusted R^2 values were also consistent, particularly for bending, where the model explained over 99% of the observed variability. The low coefficients of variation (CV = 0.19% for bending and 2.24% for compression) further validate the accuracy and reliability of the experimental campaign. Fig. 6 illustrates the correlation between the predicted and experimental

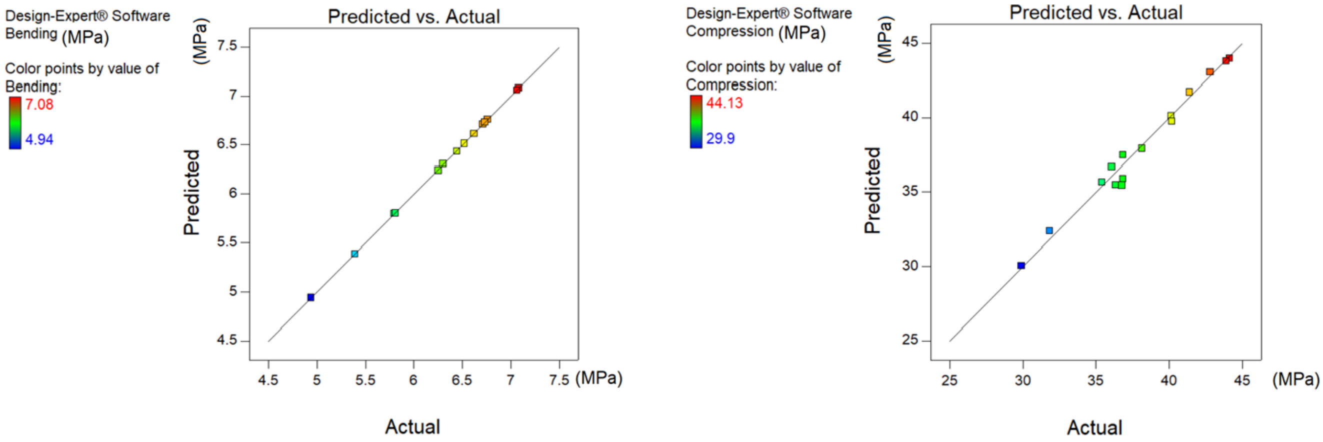

Fig. 6 Plots of predicted versus experimental values for bending and compression

values for compression and bending responses, respectively. These plots serve as a critical diagnostic tool for assessing the quality of the developed models. A close alignment of data points along the 45-degree diagonal line indicates a high degree of agreement between predicted and actual values, thereby demonstrating the reliability of the model. Moreover, the dispersion of the data points around the line of perfect agreement provides insight into the model's predictive accuracy. A narrow and symmetric distribution around this line suggests minimal systematic error and a good representation of the experimental data by the model. The coefficient of determination (R^2) values obtained for bending and compression are 0.9999 and 0.9918, respectively, indicating excellent model performance. The near-perfect (R^2) value for bending stress reveals an almost ideal fit, while the high (R^2) value for compression stress also confirms strong predictive capability, albeit with slightly more variability. These findings confirm that the linear regression models developed for both responses are statistically significant and capable of accurately capturing the underlying experimental trends.

5.6 Graphical representation of responses

The interpretation of the experimental data can be significantly enhanced through graphical representations, which provide a clearer understanding of the influence of the studied parameters on the mechanical behavior of hemp fiber-reinforced mortars. Several types of plots are recommended and discussed below.

5.6.1 Response surface plots

Three-dimensional response surface plots provide valuable insights into the combined effects of two experimental factors on mechanical strength, while keeping the third constant at its central value. For instance, plots of fiber length versus NaOH concentration reveal that moderate alkaline treatment coupled with intermediate fiber lengths generally favors flexural performance, while compressive strength tends to decrease when extreme values of either parameter are used. These surfaces visually confirm the statistical significance of factor interactions identified in the ANOVA analysis and help pinpoint the most favorable processing conditions.

- According to Table 2 the experimental trials clearly highlight a greater variability in compressive strength (≈ 30–44 MPa) compared to flexural strength (≈ 5.4–7.1 MPa). The highest values observed in the CCD campaign confirm two distinct zones of performance:
- Flexural strength (Y_1): a maximum of 7.08 MPa **at** $A = 5$ mm, $B = 2\%$, $C = 1\%$ (run #13), closely followed by 7.06 MPa **at** $A = 5$ mm, $B = 4\%$, $C = 1\%$ (run #17).
- Compressive strength (Y_2): the maximum value of 44.13 MPa was also achieved at $A = 5$ mm, $B = 4\%$, $C = 1\%$ (run #17).

These trends suggest that long fibers (A high) and a low fiber volume fraction ($C \approx 1\%$) are favorable for both properties, while the effect of alkaline treatment (B) appears more nuanced, acting as a tuning parameter.

The 3D surfaces (Fig. 7) at $C = 1\%$ illustrate:

- Y_1 (flexural strength): a clear ridge at high A (≈ 5 mm). The predicted optimum occurs for $B \approx 2.8$–3.2%, in good agreement with experimental maxima at $B = 2\%$ and 4%:
  - predicted at 5 mm, 2%, 1%: 7.12 MPa (close to measured 7.08 MPa).

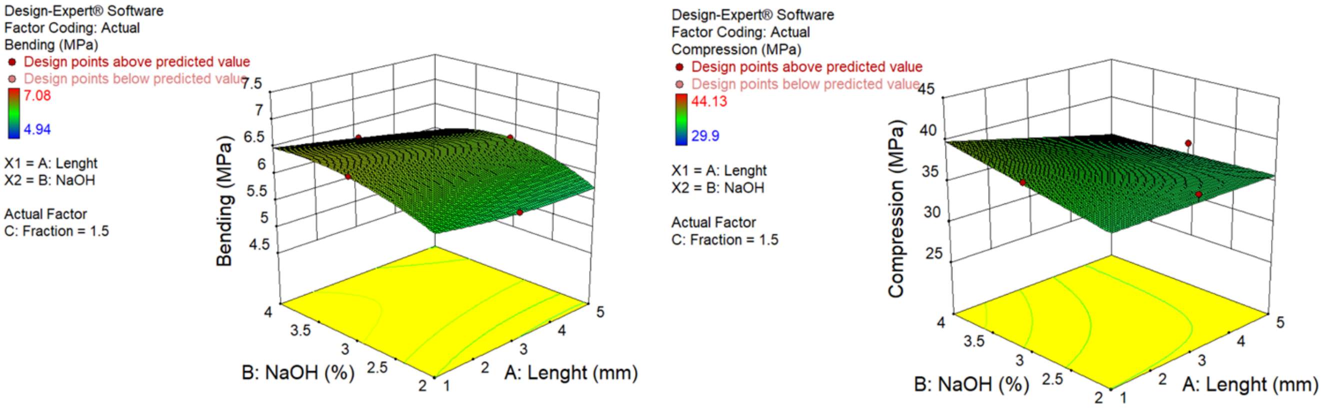

Fig. 7 3D response surface plot for the binary interaction (*A*-*B*) effect of the bio-composite manufacturing parameters on the bending and compression

- predicted at 5 mm, 3%, 1%: 7.49 MPa, suggesting a slightly higher flexural strength at $B \approx 3\%$, a condition not yet tested experimentally.
- Y_2 (compressive strength): a broad plateau for $A \approx 5$ mm, $B \approx 4\%$, $C = 1\%$, with a maximum of ≈ 44.1 MPa, consistent with the experimental peak at run #17 (44.13 MPa).

These plots confirm the antagonistic behavior of fiber content: while fibers enhance ductility and crack-bridging, excessive amounts reduce compactness, leading to strength loss. Moderate alkali treatment (≈ 3%) improves fiber-matrix adhesion without excessive degradation of fibers.

5.6.2 Contour plots

Contour plots offer a two-dimensional projection of the response surfaces, making it easier to delineate the regions of optimal mechanical performance. These plots are particularly useful to identify parameter ranges that simultaneously maximize bending and compressive strength. The two-dimensional contour plots derived from the response surface models (Fig. 8) provide complementary insight into the interaction effects between the studied parameters:

- Flexural strength (Y_1): The contour maps reveal an elongated elliptical ridge at high fiber length ($A \approx 5$ mm) combined with low fiber fraction ($C \approx 1\%$). The gradient is more pronounced along the *C*-axis, confirming that fiber dosage is the most influential factor. As *C* increases beyond ≈1.5%, the contours rapidly converge toward lower strengths, illustrating the detrimental effect of excessive fiber content. Conversely, the plots show that the effect of NaOH concentration (*B*) is less abrupt, forming broad contour regions between 2–4%, where flexural strength remains close to its maximum. This indicates that moderate alkaline treatment improves adhesion while maintaining fiber integrity.
- Compressive strength (Y_2): The compression contour plots display a wide plateau extending across the region $A \approx 5$ mm and $B \approx 3–4\%$ at $C = 1\%$. The contours here are more circular, showing reduced

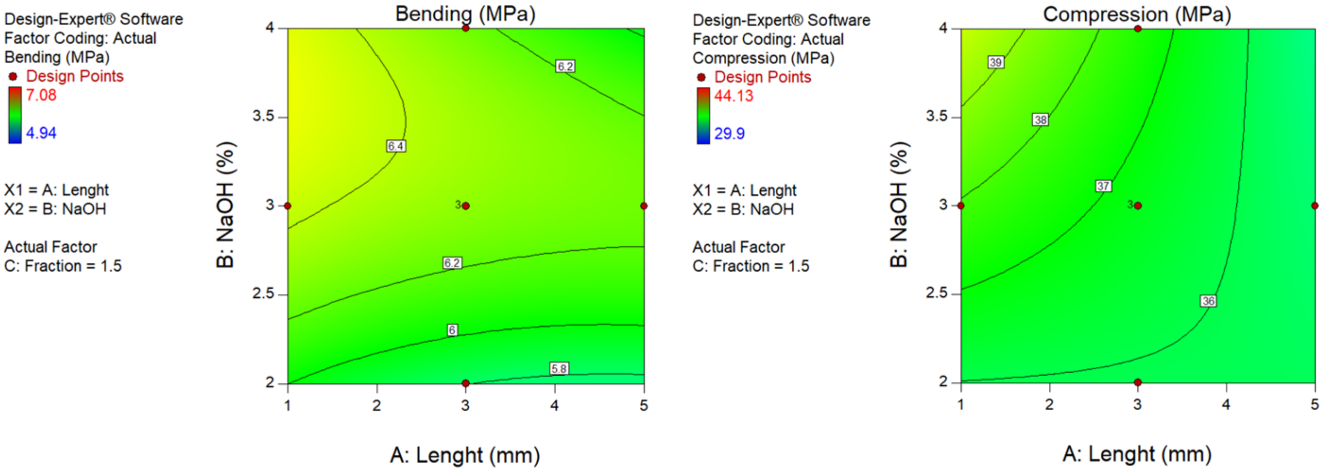

Fig. 8 2D contours plots for the binary interaction (*A*-*B*) effect of the bio-composite manufacturing parameters on the bending and compression

sensitivity to factor *B* compared with Y_1. However, a sharp drop is evident along the *C*-axis, again confirming that fiber volume is the limiting parameter. Notably, the compressive contours suggest that even slight increases in *C* beyond 1.3% lead to a steep reduction in strength, regardless of *A* or *B*.

6 Conclusions

This study investigated the influence of hemp fiber length, alkaline treatment, and fiber volume fraction on the mechanical performance of hemp fiber-reinforced cementitious composites, combining an experimental campaign with statistical modeling through Response Surface Methodology (RSM). The results revealed that flexural strength exhibited only moderate variability (≈ 5.4–7.1 MPa), mainly governed by fiber-matrix adhesion and dispersion, while compressive strength displayed a broader range (≈ 30–44 MPa), underscoring its sensitivity to matrix compactness and porosity. Compared with the control mortar, the incorporation of hemp fibers maintained or slightly improved flexural strength but reduced compressive capacity, highlighting the trade-off between crack-bridging benefits and potential disturbance of matrix homogeneity. Optimal performance was achieved with fibers of 5 mm length, a NaOH concentration of 2–4%, and a fiber volume fraction of 1%, providing the best balance between tensile reinforcement efficiency and matrix compactness. The developed statistical models demonstrated excellent predictive accuracy ($R^2 = 0.9999$ for flexural strength and 0.9918 for compressive strength), further validated by the strong agreement between predicted and experimental results. Response surface and contour plots confirmed the critical role of fiber dosage and treatment intensity in defining performance windows and suggested that slightly higher flexural strength could be attained with NaOH treatment near 3%, a parameter that warrants further experimental validation. From a broader perspective, this work contributes to the advancement of sustainable construction by highlighting hemp fibers as an effective natural reinforcement for cementitious composites. The findings not only improve understanding of the mechanical behavior of plant fiber-based composites but also establish a robust methodological framework for optimizing their formulation. Future work should focus on long-term durability aspects such as shrinkage, creep, and resistance to aggressive environments. In addition, sustainability claims could be further strengthened through life cycle assessment (LCA) and carbon footprint analysis. The use of hybrid reinforcement systems may also be explored to overcome the reduction in compressive strength while maintaining the benefits of natural fibers. In summary, hemp fiber-reinforced cementitious composites demonstrate strong potential as eco-efficient construction materials. With careful optimization of fiber treatment and content, and by integrating durability assessment, sustainability metrics, and hybrid reinforcement strategies, these composites offer a promising pathway toward greener, more resilient, and scalable building solutions.

Acknowledgment

The authors would like to thank to the Directorate General for Scientific Research (DGRSDT) and the Ministry of Higher Education and Scientific Research (MESRS) for their support.

References

[1] Zollo, R. F. "Fiber-reinforced concrete: an overview after 30 years of development", Cement and Concrete Composites, 19(2), pp. 107–122, 1997. https://doi.org/10.1016/S0958-9465(96)00046-7

[2] da Silva Neto, J. T., Ribeiro Soares Junior, P. R., Reis, E. D., de Souza Maciel, P., Gomes, P. C. C., Gouveia, A. M. C., da Silva Bezerra, A. C. "Fiber-reinforced cementitious composites: recent advances and future perspectives on key properties for high-performance design", Discover Civil Engineering, 2(1), 65, 2025. https://doi.org/10.1007/s44290-025-00209-9

[3] Balagopal, V., Panicker, A. S., Arathy, M. S., Sandeep, S., Pillai, S. K. "Influence of fibers on the mechanical properties of cementitious composites - a review", Materials Today: Proceedings, 65, pp. 1846–1850, 2022. https://doi.org/10.1016/j.matpr.2022.05.023

[4] Li, V. C., Kanda, T. "Innovations Forum: Engineered cementitious composites for structural applications", Journal of Materials in Civil Engineering, 10(2), pp. 66–69, 1998. https://doi.org/10.1061/(ASCE)0899-1561(1998)10:2(66)

[5] Signorini, C., Nobili, A. "Durability of fibre-reinforced cementitious composites (FRCC) including recycled synthetic fibres and rubber aggregates", Applications in Engineering Science, 9, 100077, 2022. https://doi.org/10.1016/j.apples.2021.100077

[6] Kabir, M. M., Wang, H., Lau, K. T., Cardona, F. "Effects of chemical treatments on hemp fibre structure", Applied Surface Science, 276, pp. 13–23, 2013. https://doi.org/10.1016/j.apsusc.2013.02.086

[7] Ramakrishna, G., Sundararajan, T. "Studies on the durability of natural fibres and the effect of corroded fibres on the strength of mortar", Cement and Concrete Composites, 27(5), pp. 575–582, 2005. https://doi.org/10.1016/j.cemconcomp.2004.09.008

[8] Arvizu-Montes, A., Martinez-Echevarria, M. J. "Vegetable fibers in cement composites: a bibliometric analysis, current status, and future outlooks", Materials, 18(2), 333, 2025. https://doi.org/10.3390/ma18020333

[9] Ahmad, H., Chhipi-Shrestha, G., Hewage, K., Sadiq, R. "A comprehensive review on construction applications and life cycle sustainability of natural fiber biocomposites", Sustainability, 14(23), 15905, 2022. https://doi.org/10.3390/su142315905

[10] Bentur, A., Mindess, S. "Fiber reinforced cementitious composites", [e-book] CRC Press, 2006. ISBN 9780429177293 https://doi.org/10.1201/9781482267747

[11] Andre, C. M., Hausman, J.-F., Guerriero, G. "*Cannabis sativa*: The Plant of the Thousand and One Molecules", Frontiers in Plant Science, 7, 19, 2016. https://doi.org/10.3389/fpls.2016.00019

[12] Small, E., Cronquist, A. "A practical and natural taxonomy for Cannabis", Taxon, 25(4), pp. 405–435, 1976. https://doi.org/10.2307/1220524

[13] Tang, K., Struik, P. C., Yin, X., Thouminot, C., Bjelková, M., Stramkale, V., Amaducci, S. "Comparing hemp (*Cannabis sativa* L.) cultivars for dual-purpose production under contrasting environments", Industrial Crops and Products, 87, pp. 33–44, 2016. https://doi.org/10.1016/j.indcrop.2016.04.026

[14] Clarke, R. C., Merlin, M. D. "Cannabis: Evolution and Ethnobotany", University of California Press, 2013. ISBN 978-0-520-95457-1 [online] Available at: https://www.jstor.org/stable/10.1525/j.ctt3fh2f8

[15] Imran, A., Ahmad, M., Ali, A., Azhar, M., Syed, Q., Abidi, H. I., Hussain, S. "Hemp in History: An Evolutionary Perspective on its Types and Uses", Indus Journal of Bioscience Research, 3(5), pp. 67–74, 2025. https://doi.org/10.70749/ijbr.v3i5.1401

[16] Shahzad, A. "Hemp fiber and its composites - a review", Journal of Composite Materials, 46(8), pp. 973–986, 2011. https://doi.org/10.1177/0021998311413623

[17] Pickering, K. L., Efendy, M. G. A., Le, T. M. "A review of recent developments in natural fibre composites and their mechanical performance", Composites Part A: Applied Science and Manufacturing, 83, pp. 98–112, 2016. https://doi.org/10.1016/j.compositesa.2015.08.038

[18] Karus, M., Vogt, D. "European hemp industry: Cultivation, processing and product lines", Euphytica, 140(1–2), pp. 7–12, 2004. https://doi.org/10.1007/s10681-004-4810-7

[19] Bócsa, I., Karus, M. "The Cultivation of Hemp: Botany, Varieties, Cultivation and Harvesting", Hemptech, 1998. ISBN 978-1886874039

[20] Bonini, S. A., Premoli, M., Tambaro, S., Kumar, A., Maccarinelli, G., Memo, M., Mastinu, A. "*Cannabis sativa*: A comprehensive ethnopharmacological review of a medicinal plant with a long history", Journal of Ethnopharmacology, 227, pp. 300–315, 2018. https://doi.org/10.1016/j.jep.2018.09.004

[21] IANOR "NA 442:2013 Ciment - Composition, spécifications et critères de conformité des ciments courants" (NA 442:2013 Cement - Composition, specifications and conformity criteria for common cements), Algerian Institute of Standardization, Algiers, Algeria, 2013. (in French)

[22] IANOR "NA 234:2018 Méthodes d'essais des ciments - Détermination des résistances mécaniques" (NA 234:2018 Methods of testing cement - Determination of strength), Algerian Institute of Standardization, Algiers, Algeria, 2018. (in French)

[23] Société des Ciments de Tébessa "Ciments produits" (Cement products), Industrial website of cement company, Algeria. [online] Available at: https://dz.kompass.com/c/societe-des-ciments-de-tebessa-spa/dz119139/ (in French)

[24] Neto, J., Queiroz, H., Aguiar, R., Lima, R., Cavalcanti, D., Banea, M. D. "A review of recent advances in hybrid natural fiber reinforced polymer composites", Journal of Renewable Materials, 10(3), pp. 561–589, 2022. https://doi.org/10.32604/jrm.2022.017434

[25] Saba, N., Jawaid, M., Alothman, O. Y., Paridah, M. T. "A review on dynamic mechanical properties of natural fibre reinforced polymer composites", Construction and Building Materials, 106, pp. 149–159, 2016. https://doi.org/10.1016/j.conbuildmat.2015.12.075

[26] Liao, Z., Hu, Y., Shen, Y., Chen, K., Qiu, C., Yang, J., Yang, L. "Investigation into the Reinforcement Modification of Natural Plant Fibers and the Sustainable Development of Thermoplastic Natural Plant Fiber Composites", Polymers, 16(24), 3568, 2024. https://doi.org/10.3390/polym16243568

[27] Islam, T., Chaion, M. H., Jalil, M. A., Rafi, A. S., Mushtari, F., Dhar, A. K., Hossain, S. "Advancements and challenges in natural fiber-reinforced hybrid composites: A comprehensive review", SPE Polymers, 5(4), pp. 481–506, 2024. https://doi.org/10.1002/pls2.10145

[28] CEN "CEN EN 196-1:2016 Methods of testing cement - Part 1: Determination of strength", European Committee for Standardization, Brussels, Belgium, 2016.

[29] ZwickRoell GmbH & Co. KG "testXpert® III, (Version 3.7)", 2021. [computer program] Available at: https://www.zwickroell.com/accessories/testxpert-testing-software/

[30] Stat-Ease Inc "Design-Expert®, (Version 13)", 2022. [computer program] Available at: https://www.statease.com/software/design-expert/

[31] Whitcomb, P. J., Anderson, M. J. "RSM Simplified: Optimizing Processes Using Response Surface Methods for Design of Experiments", [e-book] Productivity Press, 2004. ISBN 9780367806071 https://doi.org/10.4324/9780367806071

[32] Myers, R. H., Montgomery, D. C., Anderson-Cook, C. M. "Response Surface Methodology: Process and Product Optimization Using Designed Experiments", John Wiley & Sons, 2016. ISBN 978-1-118-91601-8

[33] Hurtado-Alonso, N., Manso-Morato, J., Revilla-Cuesta, V., Skaf, M., Ortega-López, V. "Optimization of cementitious mixes through response surface method: a systematic review", Archives of Civil and Mechanical Engineering, 25(1), 54, 2025. https://doi.org/10.1007/s43452-024-01112-3

[34] Montgomery, D. C. "Design and Analysis of Experiments", John Wiley & Sons, 2017. ISBN 9781119113478

[35] Goos, P., Jones, B. "Optimal Design of Experiments: A Case Study Approach", John Wiley & Sons, 2011. ISBN 9780470744611 https://doi.org/10.1002/9781119974017

[36] Bezerra, M. A., Santelli, R. E., Oliveira, E. P., Villar, L. S., Escaleira, L. A. "Response Surface Methodology (RSM) as a Tool for Optimization in Analytical Chemistry", Talanta, 76(5), pp. 965–977, 2008. https://doi.org/10.1016/j.talanta.2008.05.019

[37] Deghboudj, S., Boukhedena, W., Satha, H. "Optimization of Bending and Compressive Strength Behavior of *Agave americana* Fiber Reinforced Cementitious Composite Using Response Surface Methodology", Periodica Polytechnica Civil Engineering, 67(3), pp. 744–756, 2023. https://doi.org/10.3311/PPci.21696

[38] Labib, W. A. "Plant-based fibres in cement composites: A conceptual framework", Journal of Engineered Fibers and Fabrics, 17, 15589250221078922, 2022. https://doi.org/10.1177/15589250221078922

[39] Khan, M., Cao, M., Ai, H., Hussain, A. "Basalt fibers in modified whisker reinforced cementitious composites", Periodica Polytechnica Civil Engineering, 66(2), pp. 344–354, 2022. https://doi.org/10.3311/PPci.18965

[40] Felekoğlu, B. "Effects of loading conditions and specimen thickness on the flexural behavior of fiber-reinforced cementitious composites", Periodica Polytechnica Civil Engineering, 58(3), pp. 279–291, 2014. https://doi.org/10.3311/PPci.7486

[41] Mohamad Said, K. A., Mohamed Amin, M. A. "Overview on the response surface methodology (RSM) in extraction processes", Journal of Applied Science & Process Engineering, 2(1), pp. 8–17, 2015. https://doi.org/10.33736/jaspe.161.2015