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IDENTIFICATION OF OPTIMAL BAMBOO FIBER CONTENT TO ENHANCE IMPACT RESISTANCE OF REINFORCED CONCRETE

Vega Aditama
Corresponding author
Assistant Professor*
Department of Civil Engineering
Institut Teknologi Nasional Malang
Bendungan Sigura-gura str., 2, Malang, Indonesia, 65145
E-mail: vegaaditama@gmail.com
Sri Murni Dewi
Professor*
Ari Wibowo
Associate Professor*
Ming Narto Wijaya
Assistant Professor*
*Department of Civil Engineering
Universitas Brawijaya
Veteran str., 10-11, Malang, East Java, Indonesia, 65145

This research focuses on the impact resistance of reinforced concrete enhanced with bamboo fibers, aiming to evaluate the influence of varying bamboo fiber content on impact energy, deflection, and impact force. Reinforced concrete beams were prepared with bamboo fiber contents of 1.25%, 2.5%, and 3.75%, representing a range of low to high volume fractions. The primary objective was to examine how bamboo fiber addition improves the concrete's mechanical performance under repeated impact loads and to determine the optimal fiber dosage for structural efficiency. The results indicate that the incorporation of bamboo fibers significantly reduces both maximum deflection and peak impact force. Notably, the 1.25% fiber content exhibited the highest increase in the Toughness Modulus (MoT), reflecting superior energy absorption capacity. Conversely, higher fiber contents (2.5% and 3.75%) led to a noticeable decline in MoT values, likely due to poor fiber dispersion and agglomeration effects. Graphical analysis of polynomial regression curves revealed that although bamboo fiber generally enhances energy absorption, each energy parameter exhibits a different trend. Released energy shows a moderately increasing trend with higher fiber content, but with high variability at elevated percentages, indicating inconsistency. Absorbed energy displays minor and inconsistent fluctuations across all fiber contents, suggesting limited fiber influence. In contrast, deformation energy peaked at 1.25% fiber content and declined sharply beyond 2.5%, implying that excessive fiber reduces the material's deformation ability. These findings confirm that bamboo fibers are a viable, sustainable additive to improve the impact resistance of concrete

Keywords: reinforced concrete, bamboo fibers, impact resistance, Toughness Modulus, impact force, deflection reduction

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1. Introduction

In the modern construction industry, the challenges faced by building materials, particularly reinforced concrete, are becoming increasingly complex. The ability to withstand dynamic loads, such as impact loads, has emerged as a critical issue that requires in-depth attention. Research on enhancing concrete with bamboo fibers has surfaced as a highly relevant topic, given the superior mechanical properties of bamboo fibers and their sustainability as an environmentally friendly resource [1, 2]. However, it is essential to emphasize that the relevance of this topic lies not only in the proposed innovations but also in the urgent need to improve structural resilience in the face of evolving challenges.

The argument underpinning the importance of this research is that many concrete structures today remain vulnerable to damage from impact loads, which can lead to significant structural failures [3, 4]. Despite various previous studies, there are still gaps in understanding how variations in bamboo fiber content can affect the performance of concrete under impact conditions. This indicates that the topic is not only relevant but also urgently requires further investigation to provide practical solutions that can be applied in the design of safer and more efficient structures.

Furthermore, if it is not reassess the relevance of this topic, it is possible to risk overlooking the potential innovations that could arise from this research. In a context where science and technology continue to advance, it is crucial to ensure that the research conducted focuses not only on theoretical aspects but also on practical applications that can yield tangible benefits for the construction industry [5, 6]. Therefore, a thorough literature analysis is necessary to identify existing achievements and the aspects of this problem that still require further research.

Thus, research dedicated to the application of bamboo fiber in reinforced concrete remains highly relevant. Considering the structural demands of modern construction and the urgency of sustainability, continued exploration in this area is expected to contribute both to scientific advancement and to the development of safer, more resilient, and environmentally conscious building practices. These studies will not only enrich academic knowledge but also provide practical solutions that can be implemented in future construction projects.

2. Literature review and problem statement

The paper [2] presents the results of research indicating that the incorporation of bamboo fibers can enhance the compressive strength of concrete while reducing crack width. However, there are unresolved issues related to the long-term durability of bamboo-reinforced concrete under various environmental conditions. The reason for this may be objective difficulties associated with conducting comprehensive studies on the performance of bamboo fibers over time, which makes relevant research impractical.

The paper [1] show that bamboo fibers can improve the impact resistance of concrete, highlighting their ability to absorb energy during impact. Yet, the study does not address the specific mechanisms by which varying fiber contents influence energy absorption capacity. A way to overcome these difficulties can be through targeted research that establishes guidelines for effective bamboo fiber integration. This approach was used in the study by [7], which explored the integration of natural fibers in composite materials; however, it lacked a focused examination of bamboo fibers specifically.

The paper [3] emphasizes the vulnerability of concrete structures to impact loads, which can lead to catastrophic failures. While this research provides a solid foundation for understanding the problem, it does not explore the potential of bamboo fibers as a solution. This oversight indicates a need for further studies that specifically investigate the impact resistance of bamboo-reinforced concrete.

The paper [4] provide insights into the dynamic response of reinforced concrete structures under impact loading. Their findings suggest that fiber inclusion can significantly alter structural responses, yet they do not delve into the optimal ratios of bamboo fibers that maximize performance. This gap underscores the necessity for research focused on determining the ideal fiber content for enhanced impact resistance.

The paper [5, 6] reinforce the importance of bamboo as a sustainable reinforcement material, noting its ability to reduce the environmental impact of concrete production. However, the existing literature lacks a thorough examination of the cost-effectiveness and practical applications of bamboo-reinforced concrete in real-world scenarios. This presents an opportunity for research that not only investigates the mechanical properties of bamboo fibers but also evaluates their economic viability in construction.

The research [8] conducted experiments on the mechanical properties of bamboo fiber-reinforced concrete, revealing that the addition of bamboo fibers can enhance tensile strength and ductility. However, the study does not explore the long-term effects of bamboo fibers on the durability of concrete, particularly under varying environmental conditions. This limitation indicates a need for further investigation into the longevity of bamboo-reinforced concrete.

Despite the advancements in understanding the benefits of bamboo fibers in concrete, several critical issues remain unresolved. The primary concerns include:

– optimal fiber content.

There is insufficient data on the ideal percentage of bamboo fiber that maximizes the mechanical properties of concrete while minimizing potential drawbacks, such as workability and uniformity of the mix;

– impact resistance mechanisms.

The specific mechanisms by which bamboo fibers enhance the impact resistance of concrete are not well understood, particularly in relation to varying fiber lengths and orientations;

– economic viability.

The cost implications of using bamboo fibers as a reinforcement material in concrete have not been adequately addressed, raising questions about the practicality of its widespread adoption in the construction industry.

The reason for these unresolved issues may stem from objective difficulties associated with conducting comprehensive studies on bamboo fiber properties, the fundamental impossibility of achieving uniform distribution in concrete mixes, and the cost factors involved in sourcing and processing bamboo fibers. These challenges make relevant research on bamboo-reinforced concrete not only necessary but also urgent.

A way to overcome these difficulties can be through the development of standardized testing methods and guidelines for the incorporation of bamboo fibers in concrete. This approach has been utilized in studies such as those by [3], which explored the integration of natural fibers in composite materials; however, these studies often lack a focused examination of bamboo fibers specifically, indicating a gap in the literature.

Therefore, while existing studies have acknowledged the potential of bamboo fibers in concrete applications, significant research gaps remain particularly in determining optimal fiber content, understanding impact resistance mechanisms, and evaluating cost-effectiveness. These gaps highlight the need for continued investigation into the behavior of bamboo fiber-reinforced concrete under dynamic loading conditions. All this allows to assert that it is expedient to conduct a study on fill the existing gaps in knowledge and provide practical solutions for enhancing the performance of concrete structures through the use of sustainable materials.

3. The aim and objectives of the study

The aim of the study is to identifying the effects of bamboo fiber reinforcement on the mechanical properties of reinforced concrete, particularly focusing on its modulus of toughness, deflection under impact loads, and overall impact resistance.

To achieve this aim, the following objectives are accomplished:

– to determine how the addition of bamboo fibers in reinforced concrete affects the modulus of toughness (MoT);

– to analyze the distinct effects of bamboo fiber content on released energy, crack formation energy, and deformation energy in fiber-reinforced concrete.

4. Material and methods

4. 1. Object and hypothesis of the study

The object of this study is reinforced concrete beams reinforced with bamboo fibers at varying proportions of 1.25%, 2.5%, and 3.75% by weight of cement. These variations were selected to evaluate the influence of bamboo fiber content on the beams' performance when subjected to impact loading. The primary focus is to analyze the mechanical response particularly deflection, energy absorption, and cracking behavior of the fiber-reinforced specimens under dynamic loads. The objective is to identify the optimal fiber dosage that provides improved impact resistance and energy dissipation.

The main hypothesis of the study is that the incorporation of bamboo fibers enhances the impact resistance and modulus of toughness of reinforced concrete, with moderate fiber content (around 1.25%) expected to yield the most favorable results. It is assumed that all mixtures are homogenously mixed, fibers are uniformly dispersed, and specimens are consistently cured under standard laboratory conditions. The study adopts several simplifications by excluding long-term durability factors, environmental influences, and field condition variability. These assumptions and simplifications are necessary to focus the analysis on the direct mechanical effects of bamboo fiber content under controlled impact conditions.

4. 2. Theoretical methods

The research began with a theoretical framework based on existing literature regarding the mechanical properties of concrete and the reinforcing effects of bamboo fibers. Theoretical models were developed to predict the behavior of bamboo-reinforced concrete under impact loading conditions. Key equations governing the mechanical properties, such as compressive strength and tensile strength, were derived from established principles in material science and structural engineering:

– the modulus of elasticity for bamboo-reinforced concrete was calculated using the rule of mixtures, which considers the contributions of both the concrete matrix and the bamboo fibers;

– theoretical models were formulated to estimate the energy absorption capacity of the concrete mixtures based on the percentage of bamboo fibers incorporated. These models were designed to account for the non-linear behavior of materials under dynamic loading.

4. 3. Experimental setup

Before conducting the tests, a comprehensive experimental setup was established:

a) materials.

The primary materials for this study included Ordinary Portland Cement (OPC), fine aggregates (sand), coarse aggregates (gravel), and bamboo fibers sourced from local suppliers. The bamboo fibers underwent a treatment process involving immersion in a sodium hydroxide (NaOH) solution to enhance their bonding characteristics with the concrete matrix;

b) concrete mix design.

A series of concrete mixtures were prepared, varying the bamboo fiber content at 1.25%, 2.5%, and 3.75% by weight of cement. A control mix without bamboo fibers was also created for comparative analysis;

c) sample preparation.

Concrete samples were cast in standard Molds measuring 10 × 20 × 125 cm. The samples were cured under controlled conditions at a temperature of 20°C and 60% relative humidity for a period of 28 days to ensure optimal hydration and strength development.

4. 4. Testing conditions

To evaluate the performance of the prepared concrete samples, two categories of tests were carried out under controlled conditions:

a) impact testing.

The impact resistance of the concrete samples was evaluated using a pendulum impact testing apparatus. The pendulum was released from predetermined angles of 30°, 60°, and 90°, allowing for the assessment of energy absorption and deformation characteristics of the samples upon impact;

b) mechanical property testing.

Compressive strength tests were conducted in accordance with ASTM C39 standards, while tensile strength was evaluated using ASTM C496 methods. Each test was performed on three samples per mix to ensure statistical reliability.

4. 5. Software and hardware

Data acquisition and analysis were supported by appropriate software tools and measurement equipment used throughout the testing process:

a) software.

Data analysis was performed using MATLAB (R2021b – United states) for statistical evaluation and graphical representation of the results;

b) hardware.

The experimental setup included a pendulum impact testing machine, strain gauges for measuring deformation, and accelerometers to capture dynamic responses during impact testing. The testing apparatus was calibrated to ensure accurate measurements of force and displacement.

4. 6. Validation of proposed solutions

The proposed theoretical models and experimental methodologies were validated through a series of comparative analyses with existing literature on bamboo-reinforced concrete. The adequacy of the models was assessed by examining the correlation between theoretical predictions and empirical findings, ensuring that the models accurately represent the behavior of bamboo fibers in concrete under impact conditions.

Model validation: the results from the MATLAB simulations were compared with experimental data to confirm the reliability of the theoretical models. Sensitivity analyses were conducted to evaluate the influence of varying parameters, such as fiber length and content, on the overall performance of the concrete mixtures.

The specimen for impact testing model is presented in Fig. 1.

The object of this study is a reinforced concrete beam strengthened with bamboo fibers. This study focuses on the performance analysis of reinforced concrete beams subjected to impact loads, to evaluate the effect of bamboo fiber addition on deflection, reinforcement strain, crack area, and energy dissipation. The concrete beams used in this study have dimensions of 10 × 20 × 125 cm. Composition of the specimens is presented in Table 1.

The variations used consist of two main parameters: the bamboo fiber ratio and the impact angle. For the bamboo fiber ratio, three levels of variation are applied, namely 1.25%, 2.5%, and 3.75% of the weight of the cement, aimed at evaluating the effect of bamboo fiber addition on the performance of reinforced concrete beams under impact loads. Additionally, the impact angles were also varied into three levels, namely 30°, 60°, and 90°, to analyze how different impact angles affect deflection, reinforcement strain, crack area, and energy dissipation in the concrete specimens.

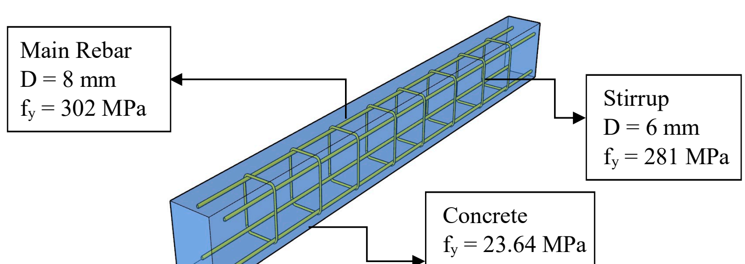


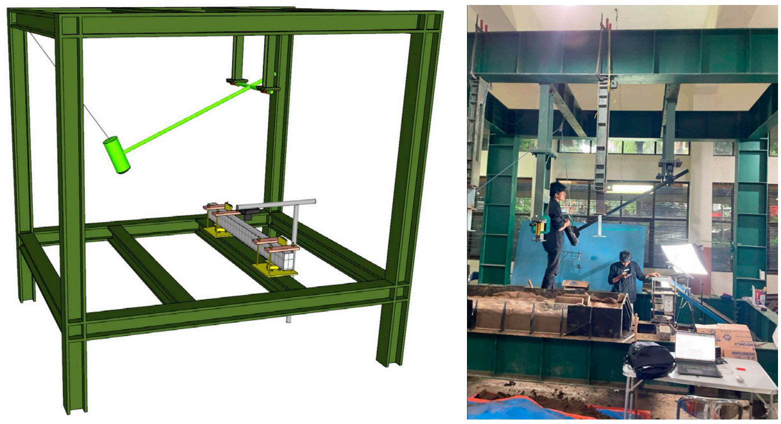
Fig. 1. Specimen for impact testing

Tested with an impact load and concrete impact testing equipment model is presented in Fig. 2, 3.

Fig. 2 shows the pendulum device used for testing the impact strength of concrete. This study uses concrete with varying bamboo fiber content, which is installed as shown in the picture. The pendulum is released with varying angles of inclination [9], causing it to strike the middle of the concrete, resulting in damage to it, as shown in Fig. 3.

Fig. 3 illustrates that the test beam is placed in the correct and proper position, secured so that the beam does not fall or shift when the pendulum strikes the middle of the beam, resulting in cracks as per the research plan. The procedure for preparing and testing the specimens is illustrated in Fig. 4, which shows the casting of test specimens with bamboo fiber addition, curing process, and impact testing.

Fig. 4 illustrates the sequence of experiments starting with the processing and assembly of the reinforcement for the preparation of the test specimen; The next step is the casting of the test specimens using a concrete mix added with bamboo fibers, followed by the preparation of the Molds/formwork for the specimens. First, a slump test is conducted to ensure the consistency of the concrete mix, followed by the casting process of the test specimen. The specimens that have dried/hardened then undergo a curing process to achieve the desired strength. After the curing process is completed, the impact test is conducted, which aims to evaluate the specimen's resistance to cracking.



a *b*

Fig. 2. Pendulum device used for impact testing of concrete specimens: *a* – frame for load testing model; *b* – construction and equipment setup in structural laboratory

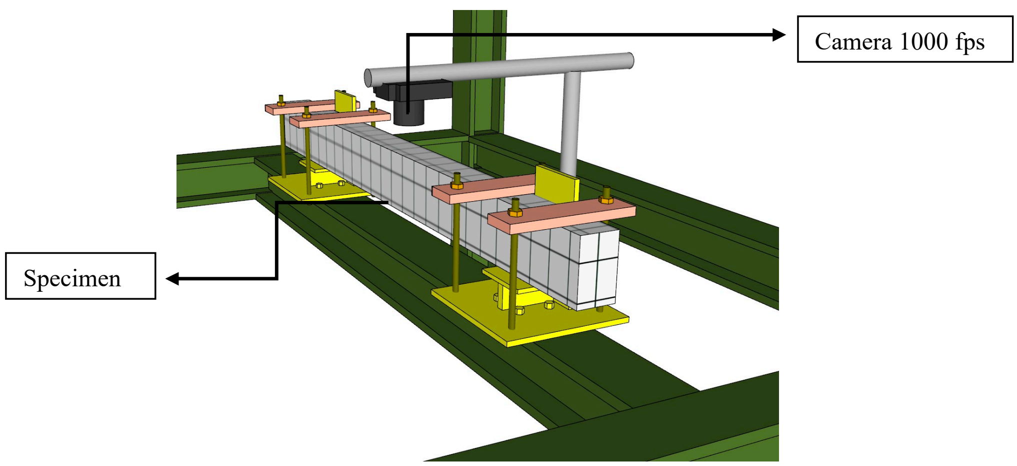


Fig. 3. Modelling the placement of test specimens on the impact testing machine

Fig. 4. Schematic of casting test specimens with bamboo fiber addition and impact testing

Table 1

Composition of the test specimens

Type of test object	Size (cm)	Ratio of bamboo fiber weight to cement weight	Impact angle	Code
Concrete beam	10 × 20 × 125	Bamboo fiber 1.25%	30°	A-30
Concrete beam	10 × 20 × 125	Bamboo fiber 1.25%	60°	A-60
Concrete beam	10 × 20 × 125	Bamboo fiber 1.25%	90°	A-90
Concrete beam	10 × 20 × 125	Bamboo fiber 2.5%	30°	B-30
Concrete beam	10 × 20 × 125	Bamboo fiber 2.5%	60°	B-60
Concrete beam	10 × 20 × 125	Bamboo fiber 2.5%	90°	B-90
Concrete beam	10 × 20 × 125	Bamboo fiber 3.75%	30°	C-30
Concrete beam	10 × 20 × 125	Bamboo fiber 3.75%	60°	C-60
Concrete beam	10 × 20 × 125	Bamboo fiber 3.75%	90°	C-90
Concrete beam	10 × 20 × 125	Plain concrete	30°	N-30
Concrete beam	10 × 20 × 125	Plain concrete	60°	N-60
Concrete beam	10 × 20 × 125	Plain concrete	90°	N-90

This section provides a comprehensive overview of the methodology employed in the research, detailing the materials, experimental conditions, and validation processes. The next section will present the research results, discussing the implications of the findings in relation to the objectives set forth in this study.

5. The results of research on the impact of bamboo fiber reinforcement on the mechanical properties of concrete

5. 1. Optimal volume of bamboo fibers for impact force reduction

The results of the impact tests with various bamboo fiber quantities on deflection and time at a 90° impact rotation angle are presented in Fig. 5.

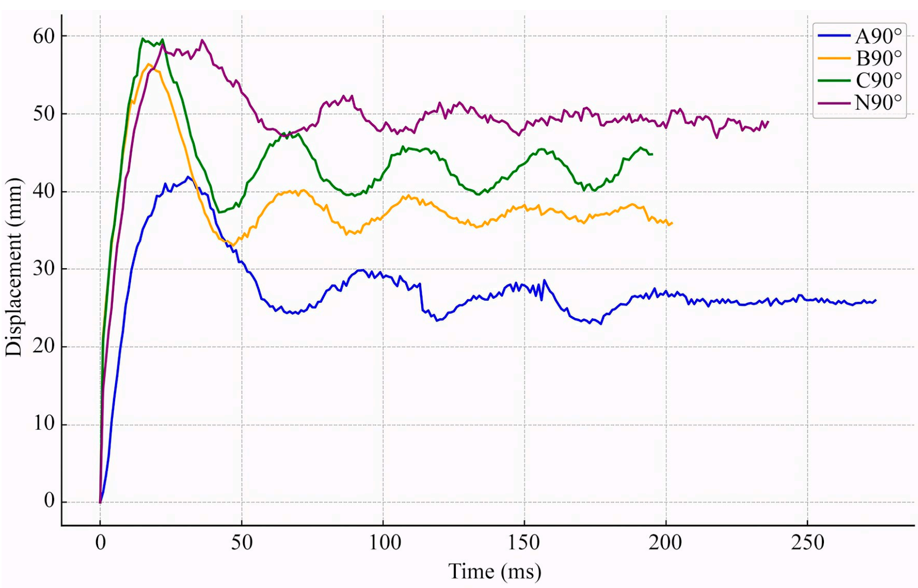


Fig. 5. The effect of bamboo fiber quantity on deflection and time at 90° angle

The results of the impact tests with various bamboo fiber quantities on deflection and time at a 90° impact rotation angle are presented in Fig. 5. It illustrates the maximum displacement observed for each test specimen, highlighting the differences in performance based on fiber content:

– fiberless concrete (N90°, purple), exhibits the highest maximum displacement of around 60 mm, indicating the greatest deformation. This suggests that fiberless concrete is more flexible but also more prone to cracking due to its inability to absorb impact energy;

– variation A90° (blue), displays the lowest maximum displacement of around 30–35 mm, indicating that the concrete with 1.25% fiber is stiffer and better at reducing deformation from impacts;

– variation B90° (yellow), has a maximum displacement of approximately 45 mm, indicating that the concrete with 2.5% fiber strikes a balance between flexibility and resistance to deflection;

– variation C90° (green), shows a maximum displacement of about 50 mm. Although lower than N90°, the concrete with 3.75% fiber effectively absorbs impact energy, resulting in more controlled deflection.

The addition of fibers to concrete enhances its impact resistance and reduces deformation, with varying degrees of flexibility and stiffness depending on the fiber content.

The results of the impact tests with various bamboo fiber quantities on deflection and time at a 90° impact rotation angle are presented in Fig. 6.

The results of the impact tests with various bamboo fiber quantities on deflection and time at a 60° impact rotation angle are presented in Fig. 6. This Fig. provides a visual representation of the maximum displacement for each test specimen at this angle:

– fiberless concrete (N60°, purple), exhibits the highest maximum displacement of around 45 mm, indicating the greatest deformation and increased vulnerability to cracking due to a lack of effective energy damping mechanisms;

– variation A60° (blue), displays the lowest maximum displacement of around 20 mm, indicating that the 1.25% fiber concrete is stiffer and experiences the least deformation compared to the other variations;

– variation B60° (yellow), shows a maximum displacement of about 40 mm, slightly lower than N60°, indicating that the 2.5% fiber concrete has better flexibility but still experiences significant deflection;

– variation C60° (green), has a maximum displacement of approximately 30 mm, demonstrating that the 3.75% fiber concrete is more effective in absorbing impact energy, thus reducing deflection.

The addition of fibers to concrete improves its impact resistance and reduces deformation, with varying effectiveness in energy damping and flexibility depending on the fiber content.

The results of the impact tests with various bamboo fiber quantities on deflection and time at a 90° impact rotation angle are presented in Fig. 7.

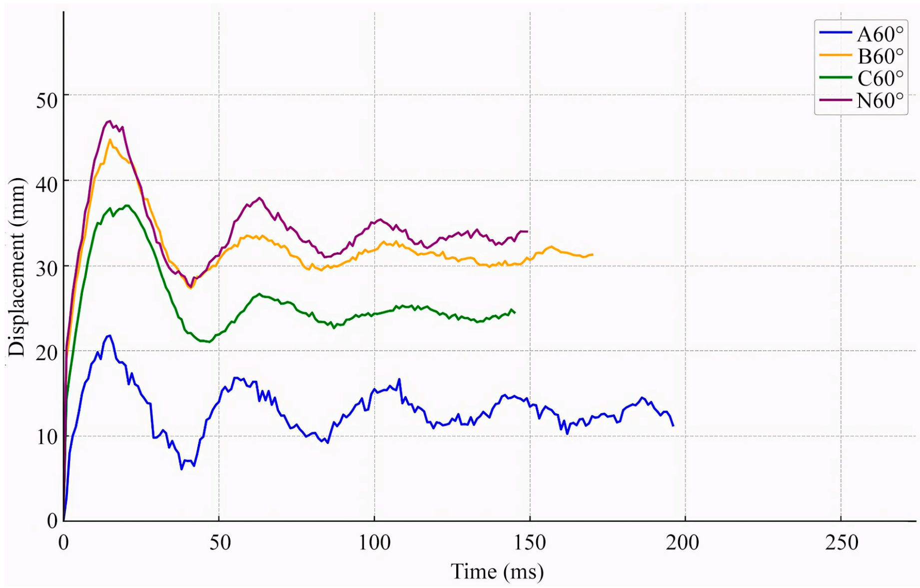


Fig. 6. The effect of bamboo fiber quantity on deflection and time at 60° angle

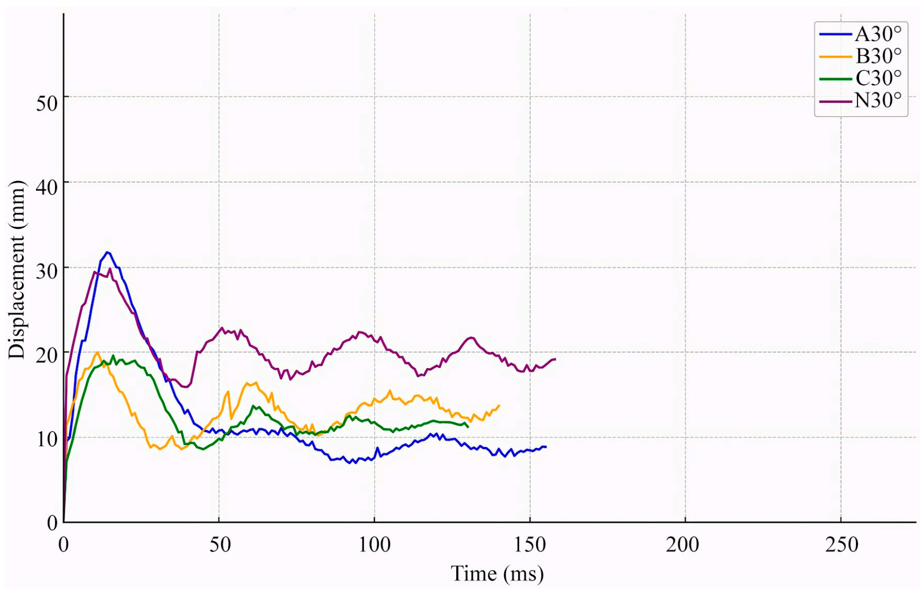


Fig. 7. The Effect of bamboo fiber quantity on deflection and time at 30° angle

The results of the impact tests with various bamboo fiber quantities on deflection and time at a 30° impact rotation angle are presented in Fig. 7. Fig. 7 illustrates the maximum displacement for each test specimen at this angle:

– fiberless concrete (N30°, purple): exhibits the highest maximum displacement of around 28–30 mm, indicating the greatest deformation and increased vulnerability to cracking due to a lack of impact energy damping mechanisms;

– variation A30° (blue): also shows high displacement of about 30 mm but experiences a rapid decrease after the first peak, indicating that the 1.25% fiber concrete is stiffer yet still undergoes significant deformation at the onset of impact;

– variation B30° (yellow): has a maximum displacement of approximately 17 mm, demonstrating that the 2.5% fiber concrete is better at absorbing impact energy compared to A30° and N30°;

– variation C30° (green): displays the lowest maximum displacement of around 14 mm, indicating that the 3.75% fiber concrete has the best capability to absorb impact energy and reduce deformation.

The incorporation of fibers in concrete significantly enhances its ability to absorb impact energy and reduce deformation, with greater effectiveness observed at higher fiber content.

After the impact test, the concrete specimen is immersed in white-colored paint to enhance the visibility of crack patterns formed due to the impact. This immersion process aims to make cracks on both the surface and within the concrete structure more discernible, allowing for more accurate analysis. Once the paint has dried, the specimen undergoes a splitting process by applying pressure until it separates into two parts. This method allows for a clearer and more detailed observation of the crack areas on the cross-section as shown in Fig. 8.

The next step is to perform a quantitative analysis of the crack area using the Image Region Analyzer in MATLAB software. This process begins with capturing images of the painted crack cross-section, followed by image segmentation to separate the crack areas from the concrete background. Using thresholding and edge detection techniques, the crack boundaries are digitally identified. Subsequently, geometric features such as crack area, shape, and crack distribution are measured using image analysis functions.

The data obtained from MATLAB enables a more objective and accurate evaluation of concrete damage due to impact. This analysis also helps in understanding the extent to which the material can absorb impact energy and how crack distribution develops within the concrete structure.

For further analysis, a linear regression model is applied using the function, which allows researchers to evaluate the effect of fiber content on the absorbed energy and obtain regression coefficients that indicate the extent of change in the dependent variable when the fiber content increases. After all analyses are completed, the results can be exported back to the desired format using the function so that the processed data can be used to compile reports and scientific publications, providing a clear picture of the effectiveness of adding bamboo fibers in enhancing the impact resistance of reinforced concrete.

The results of the analysis using MATLAB show the crack area ratios for each test specimen, as summarized in Table 2. This table provides a quantitative assessment of the crack areas observed in each specimen after impact testing.

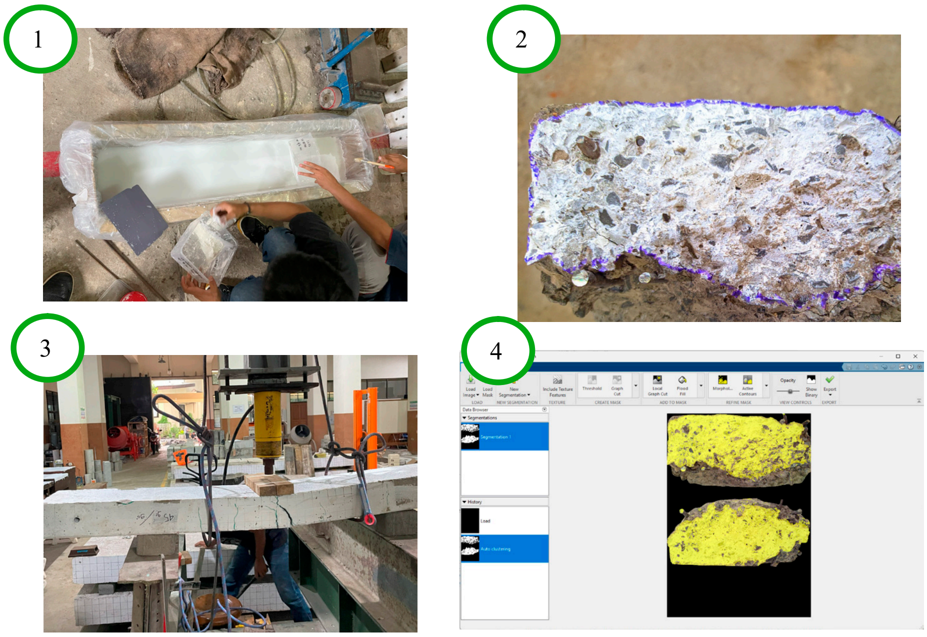


Fig. 8. Experimental procedures: 1 — specimen immersed in white paint; 2 — load testing of the specimen; 3 — cutting of test specimen after impact load; 4 — crack analysis of concrete after impact testing

Table 2

Result of crack area based on MATLAB

No.	Test specimens	Total area experiencing (pixel)	Crack area ratio to concrete cross-section
1	S1-30	221.08	9%
2	S1-60	1,976.14	79%
3	S1-90	2,233.54	89%
4	S2-30	443.97	18%
5	S2-60	2,202.23	88%
6	S2-90	2,305.17	92%
7	S3-30	42.65	2%
8	S3-60	1,607.39	64%
9	S3-90	1,972.87	79%
10	N-30	119.54	5%
11	N-60	1,457.22	58%
12	N-90	1,436.82	57%

Overall, the analysis results using MATLAB support the hypothesis that the addition of bamboo fibers enhances the impact resistance of reinforced concrete, providing strong empirical evidence for the recommendation of using bamboo fibers in concrete mixtures.

5. 2. Evaluation of the modulus of toughness (MoT)

The measurement of energy in this study was conducted to evaluate the modulus of toughness (MoT) of reinforced concrete incorporating bamboo fibers. The total energy applied to the specimen was calculated using the formula

$$E_{total} = m \times g \times h, \quad (1)$$

where m represents the mass of the pendulum, g – the acceleration due to gravity (9.81 m/s^2), and h – the height from which the pendulum is dropped. Subsequently, the energy released during the impact was calculated using the formula

$$E_{released} = 4\pi\xi \times E_{total}, \quad (2)$$

while the energy absorbed can be determined by subtracting the released energy from the total energy, expressed as

$$E_{absorbed} = E_{total} - E_{released}. \quad (3)$$

The modulus of toughness (MoT) is calculated using the formula

$$MoT = \frac{E_{deformed}}{V}, \quad (4)$$

where $E_{deformed}$ – the energy absorbed and V – the volume of the specimen that has undergone deformation. The results of the tests indicate that different fiber variations significantly affect the total energy, released energy, and absorbed energy. The results of this calculation can be found in Table 3.

The analysis results show that total energy (E_{total}) increases with the impact rotation angle, with specimen A rising from 110.4 J at 30° to 824.04 J at 90°. Specimen B exhibits better energy absorption efficiency at a 60° angle compared to specimen A, attributed to its higher bamboo fiber content, while specimen A is more susceptible to cracking, with E_{crack} at 605.78 J versus 549.10 J for specimen B. This vulnerability highlights the necessity of incorporating bamboo fibers into the concrete mix to improve impact resistance and mitigate structural damage risks. The following results are tabulated in Table 4 and illustrated in Fig. 9.

Table 3

Results of the energy analysis calculations

Test specimens	Impact rotation angle (°)	E_{total} (J)	$E_{released}$ (J)	$E_{absorbed}$ (J)	E_{crack} (J)	$E_{deformation}$ (J)
A	30	110.4	22.18	88.22	15.88	72.34
A	60	412.02	96.98	315.04	277.23	37.81
A	90	824.04	165.58	658.46	605.78	52.68
B	30	110.4	21.51	88.89	1.79	87.11
B	60	412.02	81.78	330.24	211.35	118.89
B	90	824.04	127.71	696.33	549.10	147.23
C	30	110.4	25.97	84.43	7.60	76.83
C	60	412.02	105.84	306.18	241.88	64.30
C	90	824.04	175.81	648.23	577.93	70.30
N	30	110.4	21.52	88.88	1.78	87.10
N	60	412.02	80.30	331.72	212.30	119.42
N	90	824.04	160.61	663.43	524.11	139.32

Table 4

Results of energy analysis calculations

Test specimens	$E_{deformation}$ (J)	MoT (J/m^3)
A	86.44	3,601.67
A	103.69	4,320.42
A	134.35	5,597.92
B	81.29	3,387.08
B	47.64	1,985.00
B	68.40	2,850.00
C	68.55	2,856.25
C	28.95	1,206.25
C	42.45	1,768.75
N	87.09	3,628.75
N	119.42	2780
N	114.33	4,763.75

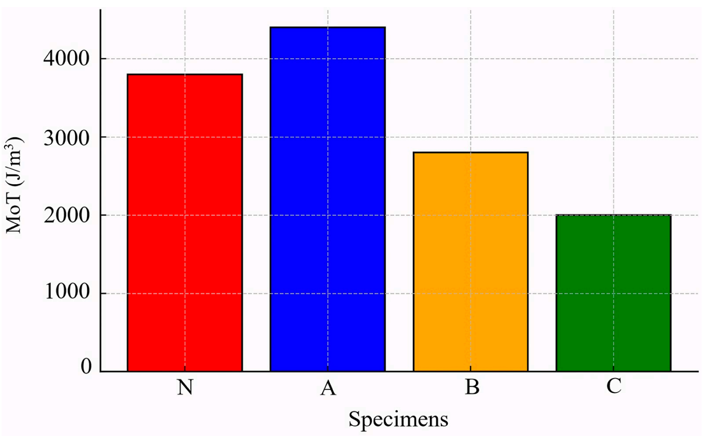


Fig. 9. Average toughness modulus graph based on specimen variations

From Fig. 9, specimen variation A has the highest average modulus of elasticity, approximately 4600 J/m^2, while specimen variation C has the lowest average modulus, around 2000 J/m^2. Specimen variations N and B show relatively high modulus values that are not significantly different from each other, but still lower than A. Overall, the graph indicates that specimen A performs the best in terms of modulus of elasticity, while specimen C performs the worst. The multiple regression model used has the following general form

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_1^2 + \\ + \beta_4 X_2^2 + \beta_5 \left(X_1 X_2 \right) + \varepsilon. \quad (5)$$

The regression model is utilized to analyze the effect of independent variables on the dependent variables [10], namely absorption energy [11], fracture energy, or deformation energy. In equation (5), Y represents the dependent variable, while X_1 and X_2 are the fiber content (%) and impact energy Total Energy, (E_{total}), respectively. The coefficient β_0 serves as the intercept or constant term, while β_1 and β_2 are linear coefficients that indicate the direct influence of fiber content and impact energy on Y. The coefficients β_3 and β_4 capture the nonlinear effects of fiber content and impact energy through quadratic components, while β_5 describes the interaction between fiber content and impact energy in influencing Y. Finally, ε is the error term that reflects the variability not explained by the model.

The following Fig. 10 illustrates the relationship between fiber content and fracture energy.

Overall, Fig. 10 indicates that crack energy in concrete initially decreases until reaching a fiber content of approximately 1.5% and then increases as fiber content continues to rise. The scattered experimental data points suggest variability, indicating that the effect of fiber addition on crack energy is not consistently significant across the tested samples.

To further explore the relationship between fiber content and energy absorption.

Fig. 11 shows that absorbed energy tends to slightly decrease as fiber content increases, with only minimal variation in the trendline. The data points range from approximately 90 J to 650 J across all fiber content levels (0% to 3.75%), indicating high variability and no clear pattern of improvement due to fiber addition.

These results suggest that fiber content has minimal and inconsistent influence on the absorbed energy of the concrete under impact loading.

To further explore the relationship between fiber content and energy absorption.

The graph illustrates a slight increase in released energy as the fiber content increases, as indicated by the upward trend in the fitted polynomial curve. Despite this trend, the data exhibit significant scatter, with values ranging from approximately 20 J to 180 J across all fiber content levels. Notable fluctuations are particularly evident at 2.5% and 3.75% fiber content. Nevertheless, the overall average released energy tends to improve slightly with the addition of bamboo fibers. These findings suggest that while fiber reinforcement may enhance energy release under impact, the response is inconsistent at higher fiber contents due to increased variability.

To further explore the relationship between fiber content and energy absorption.

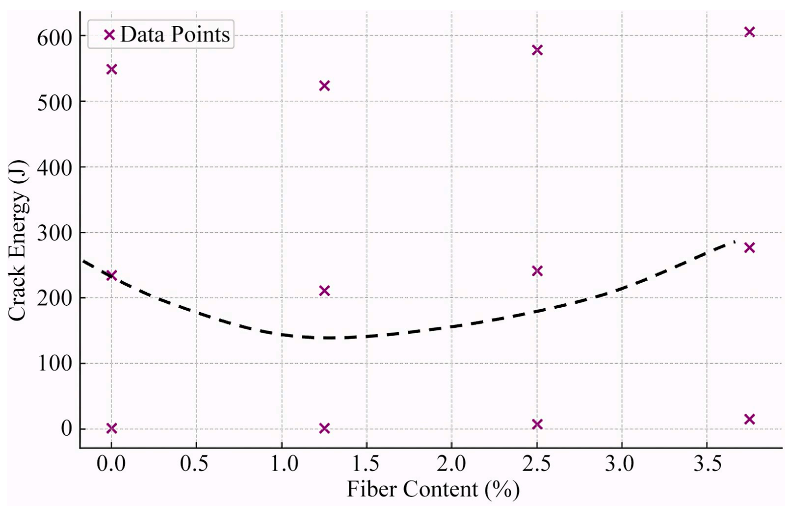


Fig. 10. Polynomial regression: crack energy vs fiber content

Fig. 13 shows that deformation energy increases with fiber content up to around 1.25%, after which it declines sharply as the fiber content continues to rise. Data points range from approximately 30 J to 130 J, with the highest values observed at 1.0–1.25% fiber content and the lowest values at 3.75%, indicating a parabolic trend. The fitted curve confirms that excessive fiber addition may reduce the material's ability to deform under impact. Deformation energy in concrete improves with moderate fiber content but significantly decreases when the fiber content exceeds 1.5%.

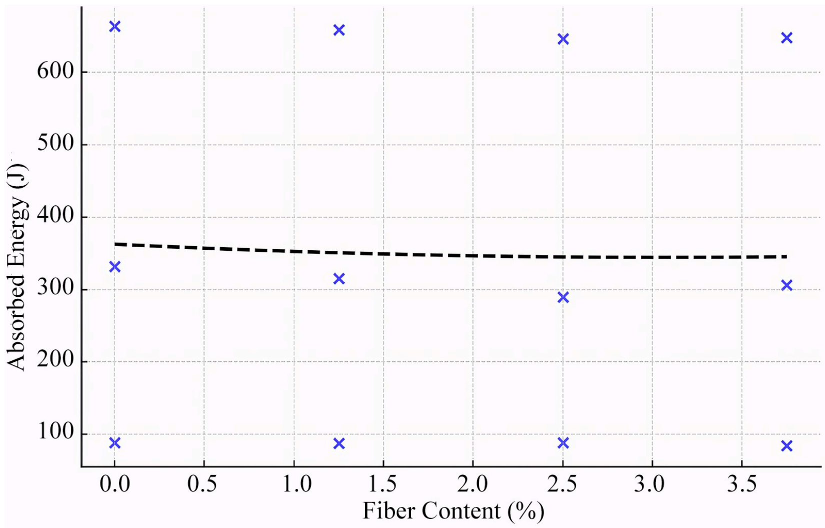


Fig. 11. Polynomial regression: absorbed energy vs fiber content

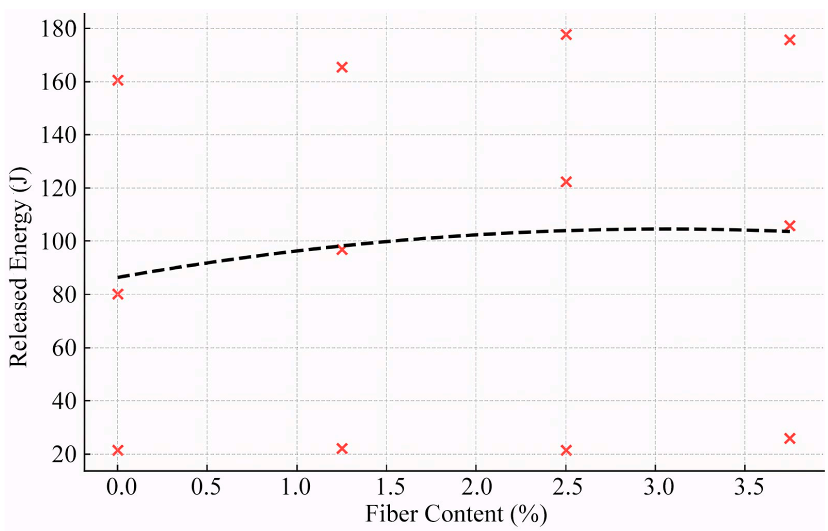


Fig. 12. Polynomial regression: released energy vs fiber content

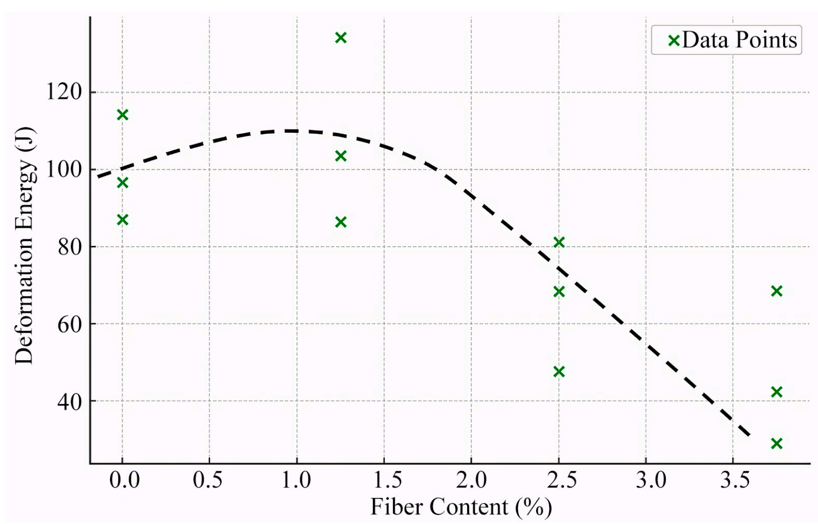


Fig. 13. Polynomial regression: deformation energy vs fiber content

Based on the overall energy analysis, fiber content affects different energy parameters in varying ways. Moderate fiber addition (around 1.0–1.5%) generally improves crack and deformation energy, while excessive amounts (≥ 2.5%) tend to reduce deformation capacity and introduce greater variability in the results. Overall, the optimal fiber content for enhancing energy performance under impact appears to lie in the moderate range, as higher percentages may lead to inconsistent or diminished benefits.

6. Discussion of experimental results on the impact of bamboo fiber reinforcement in concrete

The integration of bamboo fibers into concrete significantly affects the mechanical performance of the composite under impact loading, particularly in terms of deflection control and energy dissipation. Fig. 5–7 illustrate the deflection-time responses of concrete specimens subjected to impact at three angles: 30°, 60°, and 90°. Fiberless specimens (N-series) recorded the highest maximum deflections across all angles up to 60 mm at 90° suggesting a lack of resistance to impact-induced deformation and higher susceptibility to crack formation.

In contrast, specimens reinforced with 1.25% bamboo fiber (A-series) demonstrated notably reduced deflections around 30–35 mm at 90°, 20 mm at 60°, and a peak of 30 mm followed by rapid damping at 30°. These results indicate enhanced structural stiffness and the presence of internal fiber bridging those aids in dissipating impact energy. Variation B (2.5%) showed intermediate performance, while C-series (3.75%) exhibited a mix of effectiveness, particularly excelling at lower angles (30°) with the smallest deflection of approximately 14 mm.

The effectiveness of fiber reinforcement is further confirmed through visual crack analysis, conducted using MATLAB image segmentation techniques as shown in Fig. 8 and Table 2. Fiberless concrete specimens developed extensive cracking (e.g., N-90 with 57% crack area), reflecting their inability to control crack propagation under impact. Meanwhile, specimens A-90 and A-60 showed high crack area ratios of 89% and 79%, respectively, which, despite their low deflection, suggest internal concentration of stress that resulted in fracture initiation.

Interestingly, B- and C-series exhibited better energy distribution, as evidenced by lower crack area ratios at lower angles. For example, C30 recorded only a 2% crack area, the lowest among all specimens, indicating superior crack resistance and efficient energy dissipation in lower-impact conditions. This highlights that the relationship between fiber content and crack resistance is not linear and depends on the interaction between impact angle and fiber dispersion within the matrix.

The impact energy analysis in Table 3 provides insight into how each specimen responded to the dynamic load in terms of energy absorption, release, and deformation. Across all variations, total impact energy increased with the angle, reaching 824.04 J at 90°. Variation A absorbed 658.46 J at 90° but showed only 52.68 J of deformation energy, indicating a stiffer response. In contrast, B-series absorbed more energy (696.33 J) and displayed higher deformation energy (147.23 J), suggesting a more balanced and ductile performance.

Although C-series specimens maintained relatively high absorbed energy at 648.23 J, their deformation energy was significantly lower (70.30 J), indicating a trade-off between stiffness and ductility at higher fiber contents. Notably, the fiberless N-series specimens absorbed 663.43 J with deformation energy of 139.32 J, but this did not translate into improved toughness due to the absence of fiber bridging mechanisms and poor crack control.

The Modulus of Toughness (MoT), calculated and shown in Table 4 and Fig. 9, further clarifies the optimal fiber content for impact resistance. Variation A recorded the highest MoT values, reaching up to 5,597.92 J/m^3. Meanwhile, B-series had moderately high MoT values between 1,985.00 J/m^3 and 3,387.08 J/m^3. Variation C showed a decline in toughness, ranging between 1,206.25 J/m^3 and 2,856.25 J/m^3. These values indicate that 1.25% fiber content offers the best compromise between energy absorption and resistance to permanent deformation.

Polynomial regression analyses in Fig. 10–13 show nonlinear trends in energy-related parameters. Crack energy and deformation energy increased with fiber content up to 1.25%, then declined sharply beyond 2.5%. Absorbed energy and released energy displayed high data scatter at higher fiber percentages, which is attributed to poor fiber distribution, clumping, and lack of uniform bonding with the cement matrix. These inconsistencies underscore the challenges in using excessive natural fiber content without adequate dispersion techniques.

From a practical standpoint, these results suggest that bamboo fibers can serve as a sustainable reinforcement alternative in concrete, particularly in structural components exposed to dynamic or impact loads, such as protective barriers, bridge decks, and prefabricated floor systems. Optimal performance was consistently observed at a fiber content of 1.25%, where the concrete exhibited high toughness, controlled crack propagation, and efficient energy dissipation.

However, limitations must be acknowledged. All specimens were tested under controlled laboratory conditions with uniform curing, which may not represent field performance. Moreover, only three fiber content levels were tested, limiting the accuracy of the identified optimum. Variability in fiber size, orientation, and mixing technique may also contribute to data scatter. Therefore, further research should explore intermediate fiber levels (e.g., 1.5–2.0%), long-term durability, hybrid fiber systems, and improvements in fiber dispersion methods to enhance performance consistency.

7. Conclusions

1. The research indicates that the addition of bamboo fibers to reinforced concrete significantly affects the modulus of toughness (MoT). Specimen variation A (with a fiber content of 1.25%) shows the highest increase in toughness, with a MoT value reaching 3,601.67 J/m^3. Variation N (without fibers) has a MoT value of 3,628.75 J/m^3, while variations B (2.5% fiber) and C (3.75% fiber) show a decrease in MoT values, at 3,387.08 J/m^3 and 2,856.25 J/m^3, respectively. This indicates that at a certain fiber content, fiber-reinforced concrete can provide a positive contribution to impact resistance, but an excessive increase in fiber content may lead to a reduction in MoT values.

2. Graphical analysis of the polynomial regression curves revealed that while bamboo fiber addition generally improves energy absorption, the response of each energy parameter differs. Released energy shows a moderate increasing trend with fiber content but remains highly scattered, indicating inconsistency at higher fiber percentages. Absorbed energy, on the other hand, shows minimal and inconsistent variation across fiber contents, suggesting limited influence of fiber on this parameter. Meanwhile, deformation energy was observed to peak at moderate fiber content (around 1.25%) and decrease sharply beyond 2.5%, implying that excessive fiber addition can reduce the material's ability to deform under impact. Therefore, optimal fiber content should be carefully controlled to avoid excessive variability and ensure the effectiveness of fiber reinforcement.

Conflict of interest

The authors declare that they have no conflict of interest concerning this research, whether financial, personal, authorship, or otherwise, that could affect the research and its results presented in this paper.

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The study was performed without financial support.

Data availability

All data are available in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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