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Influence of Millet Husks on the Physical, Mechanical and Thermal Performance of a Lightweight Bio-Based Concrete

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Abstract: In the context of transitioning toward more sustainable construction materials, this study explores the impact of incorporating millet husks as an alternative to sand on the physical, mechanical, and thermal performance of lightweight concrete. Through a mixture design approach, five formulations were selected and thoroughly characterized. The analysis of iso-response curves enabled an in-depth assessment of the cross-effects between formulation parameters and their interactions on the final properties of the material. The results show that integrating millet husks leads to a significant reduction in density, reaching up to 21%, while maintaining notable mechanical performance. A balanced formulation of sand and fibers achieved a maximum compressive strength of 12.11 MPa, demonstrating that, under specific conditions, plant fibers actively contribute to the structural integrity of the composite. In tensile strength, the positive influence of fibers is even more pronounced, with a maximum resistance of 8.62 MPa, highlighting their role in enhancing material cohesion. From a thermal perspective, millet husks reduce both thermal conductivity and effusivity, thereby limiting heat transfer and accumulation within the composite. Iso-response curve analysis reveals that these effects are directly linked to the proportions of the constituents and that achieving an optimal balance between sand, fibers, and cement is key to maximizing performance. These findings demonstrate that the adopted approach allows moving beyond conventional substitution methods by identifying optimal configurations for the design of lightweight bio-based concretes that are both strong and insulating, thereby confirming the potential of millet husks in developing lightweight concretes suitable for sustainable construction applications.

Key words: Lightweight bio-based materials, plant fibers, mixture design, iso-response analysis, formulation optimization, mineral aggregate substitution.

1. Introduction

The global production of construction materials accounts for a significant share of greenhouse gas emissions, primarily through the extraction and processing of natural resources such as cement and sand. Given these environmental challenges, research is increasingly focused on more sustainable alternatives that involve the use of agricultural waste in concrete and mortar to reduce the carbon footprint and limit the exploitation of non-renewable resources. Among these alternatives, the incorporation of bio-based materials and plant aggregates into concrete and mortar formulations presents a promising approach. Several studies have shown that plant fibers and lightweight agricultural aggregates, such as hemp, rice husk, wood, straw, and flax, can improve thermal performance while reducing the material's density [1-9].

The use of RHA (rice husk ash) as a partial cement substitute is well documented in the literature. This

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ash, rich in amorphous silica, acts as a pozzolanic material that enhances the mechanical performance and durability of concrete and mortar by partially replacing the hydraulic binder. Several studies indicate that this substitution optimizes the material's microstructure, increases its strength, and reduces its permeability [10-12]. In parallel, plant fibers and aggregates derived from agricultural waste can be utilized to lighten formulations while imparting insulating properties to the final material [13]. However, incorporating bio-based aggregates presents challenges related to their high porosity and compatibility with the cement matrix, necessitating pretreatments or formulation adjustments [14].

This study aims to valorize two local agricultural wastes: RHA as a pozzolanic cement substitute and millet husks as a sand replacement. Given that sand is becoming an increasingly scarce and costly resource due to extraction and transportation constraints, replacing it with abundant agricultural waste represents a viable alternative. However, fully substituting sand with plant aggregates can significantly alter the material's microstructure, affecting both its mechanical strength and thermal properties [3].

One of the major challenges in designing bio-based materials lies in the formulation and optimization of mixtures. Most existing studies rely on empirical approaches, where the constituent proportions are adjusted based on experimental results, limiting a thorough analysis of each parameter's effect on the final properties. In contrast, approaches based on experimental design and statistical methods allow for the simultaneous study of multiple variables and the optimization of formulations in a more rigorous manner [15].

In this context, the objective of this study is to evaluate the influence of replacing sand with millet husks on the physical, mechanical, and thermal performance of a bio-based mortar. The study seeks to better understand the interactions between these components while identifying an optimized formulation that maximizes carbon footprint reduction without compromising the performance required for construction applications.

2. Materials and Methods

2.1 Materials

2.1.1 RHA

The rice husk used in this study was sourced from a local processing plant in Benin. The RHA was obtained by calcining the husks at 600 °C for 2 h [16].

The chemical composition of the RHA used in this study is summarized in Table 1.

2.1.2 Millet Husks

Millet husks are abundant agricultural residues collected after the threshing process (Fig. 1). They represent approximately 20%-25% of the harvested millet and constitute a lightweight material that can be used as a substitute for mineral aggregates.

The physical properties of the millet husks used in this study are summarized in Table 2.

The particle size distribution is represented by the granulometric curve in Fig. 2.

2.1.3 Sand

The sand used in this study is a fine lagoon sand with a fineness modulus of 1.83. Its granulometry is represented by the particle size distribution curve in Fig. 3.

Table 1 Chemical composition of RHA.

Elements	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	Cr_2O_3	Mn_2O_3	F	P_2O_5	Cl	LOI (Loss On Ignition)
Proportion	86.46	1.27	0.59	2.64	0.47	0.25	0.06	1.37	0.01	0.11	0.04	0.36	0.01	6.35

Table 2 Physical properties of millet husks used in this study.

Absolute density (kg/m³)	Bulk density (kg/m³)	Water absorption (%)
344.82 ± 1.23	30.13 ± 0.34	76.08 ± 0.67

Fig. 1 Millet husks used in this study.

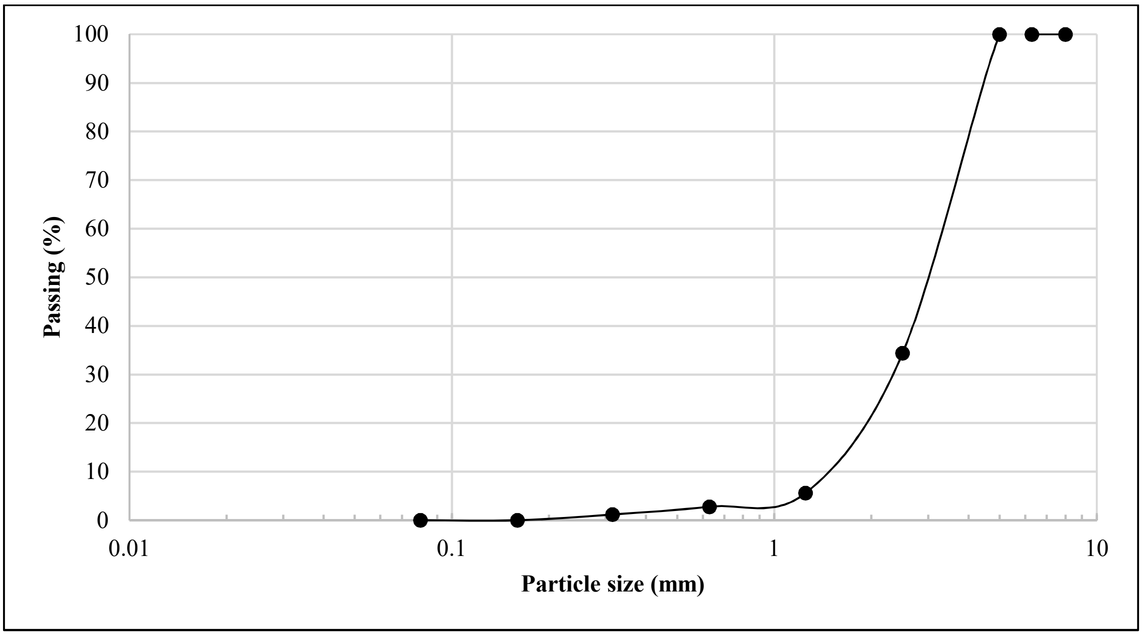


Fig. 2 Granulometric curve of millet husks.

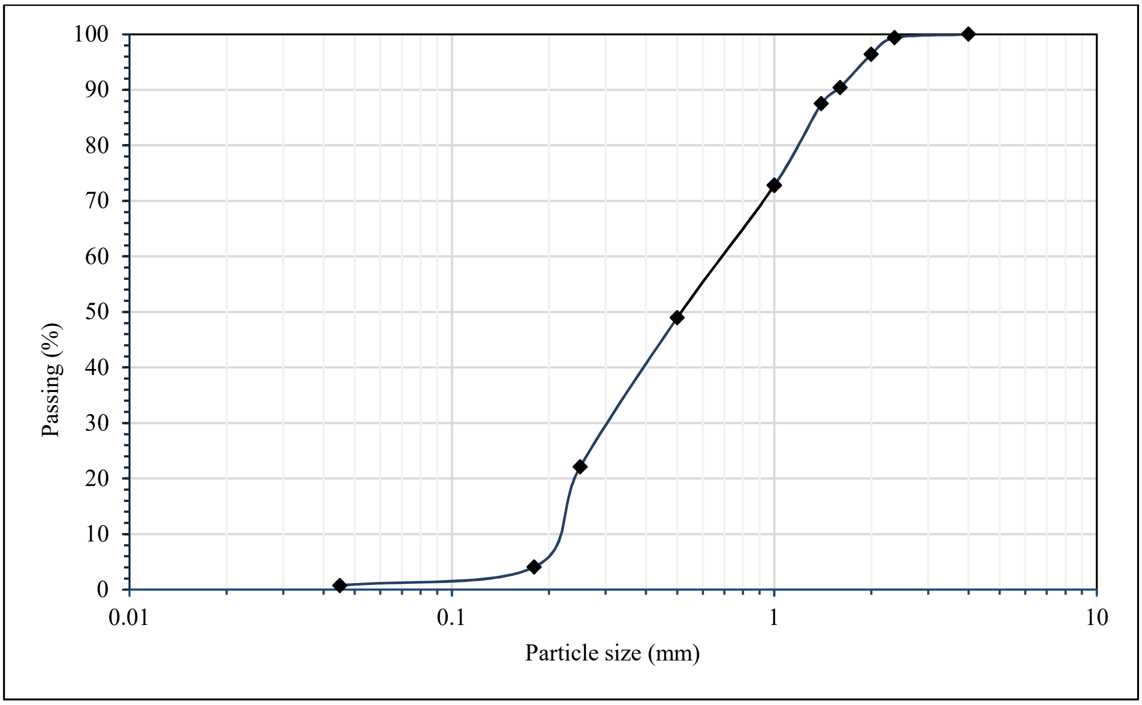


Fig. 3 Granulometric curve of the sand used in this study.

2.2 Concrete Mix Design

The formulation method adopted in this study is based on experimental design, particularly mixture designs, which allow optimizing the composition of the material by reducing the number of experiments while accounting for interactions between factors. The formulations were generated using MINITAB software, based on the lower and upper levels of the studied factors.

The lower and upper levels of the factors considered in this study are presented in Table 3.

From these levels, the tested formulations are detailed in Table 4.

2.3 Concrete Implementation

The implementation of the composite followed a rigorous methodology to ensure proper homogeneity of the mixture and reproducibility of the tests. The millet husks were first pre-soaked for 24 h to limit their water absorption during mixing. After this step, they were drained and spread on a sieve to remove excess water before being incorporated into the mixture.

The mixing was carried out according to a precise sequence. Water was first introduced into the mixer, followed by cement and RHA. After 30 s of slow-speed mixing, the millet husks and sand were gradually added over an additional 30 s period. The mixer was then accelerated to high speed, and the mixing continued for another 30 s. A pause of 1 min 30 s was taken to manually scrape any mortar adhering to the walls of the mixing bowl. Finally, a high-speed mixing cycle of 60 s was applied to ensure a homogeneous mixture.

The specimens were prepared using 4 × 4 × 16 cm^3 molds for mechanical tests and 4 × 4 × 5 cm^3 molds for thermal tests. The inner surfaces of the molds were coated with oil to facilitate demolding after setting. The mortar was manually compacted before being left to set.

After 24 h, the specimens were demolded and stored in the open air in the laboratory, where they were kept for 28 days before undergoing characterization tests.

Table 3 Lower and upper levels of the studied factors.

Factors	Low level (-1)	High level (+1)
Cement + RHA (g)	1,253	1,373
Millet husks (g)	0	120
Sand (g)	0	120
Water (g)	627	747

Table 4 Composite formulations with millet husks generated using MINITAB software.

Reference	Cement + RHA (g)	Sand (g)	Millet husks (g)	Water (g)
F1	1,253	60	0	687
F2	1,275	40	40	645
F3	1,293	0	40	667
F4	1,292	0	60	648
F5	1,313	0	0	687
F6	1,253	60	60	627
F7	1,283	30	30	657
F8	1,268	15	15	702
F9	1,313	60	0	627
F10	1,268	15	75	642
F11	1,293	40	40	627
F12	1,253	0	120	627
F13	1,253	120	0	627
F14	1,253	0	0	747
F15	1,328	15	15	642
F16	1,290	60	10	640
F17	1,283	75	15	627
F18	1,373	0	0	627
F19	1,253	0	60	687

The thermal parameters were determined using the hot-wire method, which provides a fast and reliable measurement by applying a heat flux and analyzing the temperature evolution within the material.

3. Results and Discussions

The experimental results obtained are summarized in Table 5, which presents the physical, mechanical, and thermal characteristics of the selected formulations.

3.1 Density

The density measured for the different formulations ranges from 1.351 g/cm³ (F12) to 1.727 g/cm³ (F6). Two main trends emerge:

- Increasing the millet husk content reduces density, as the fibers have a lower density than cement and sand. For example, F12 (120 g of millet husks, 0 g of sand) exhibits the lowest density (1.351 g/cm³).
- Adding sand increases density, as observed when transitioning from F12 (no sand) to F6 (60 g of sand), where the density increases to 1.727 g/cm³.

These observations align with previous research findings [17, 18], which indicate that plant fibers generally reduce the density of cementitious composites.

Fig. 4 presents ternary diagrams illustrating the iso-density curves by keeping one factor constant (water, millet husks, sand, or cement). Each colored zone corresponds to a range of density values (from light green for lower density to dark green for higher density).

Table 5 Summary of measured parameters.

Formulation	Cement + RHA (g)	Sand (g)	Millet husks (g)	Water (g)	Density (g/cm³)	Tensile strength (MPa)	Compressive strength (MPa)	Thermal conductivity (W/m·K)	Thermal effusivity (W.s^(1/2)/m²·K)
F2	1,275	40	40	645	1.555	5.113	10.661	0.28	785.78
F4	1,292	0	60	648	1.531	7.763	11.160	0.27	590.14
F6	1,253	60	60	627	1.727	8.625	12.113	0.39	792.97
F10	1,268	15	75	642	1.490	8.075	10.054	0.22	633.38
F12	1,253	0	120	627	1.351	6.425	7.554	0.29	656.24

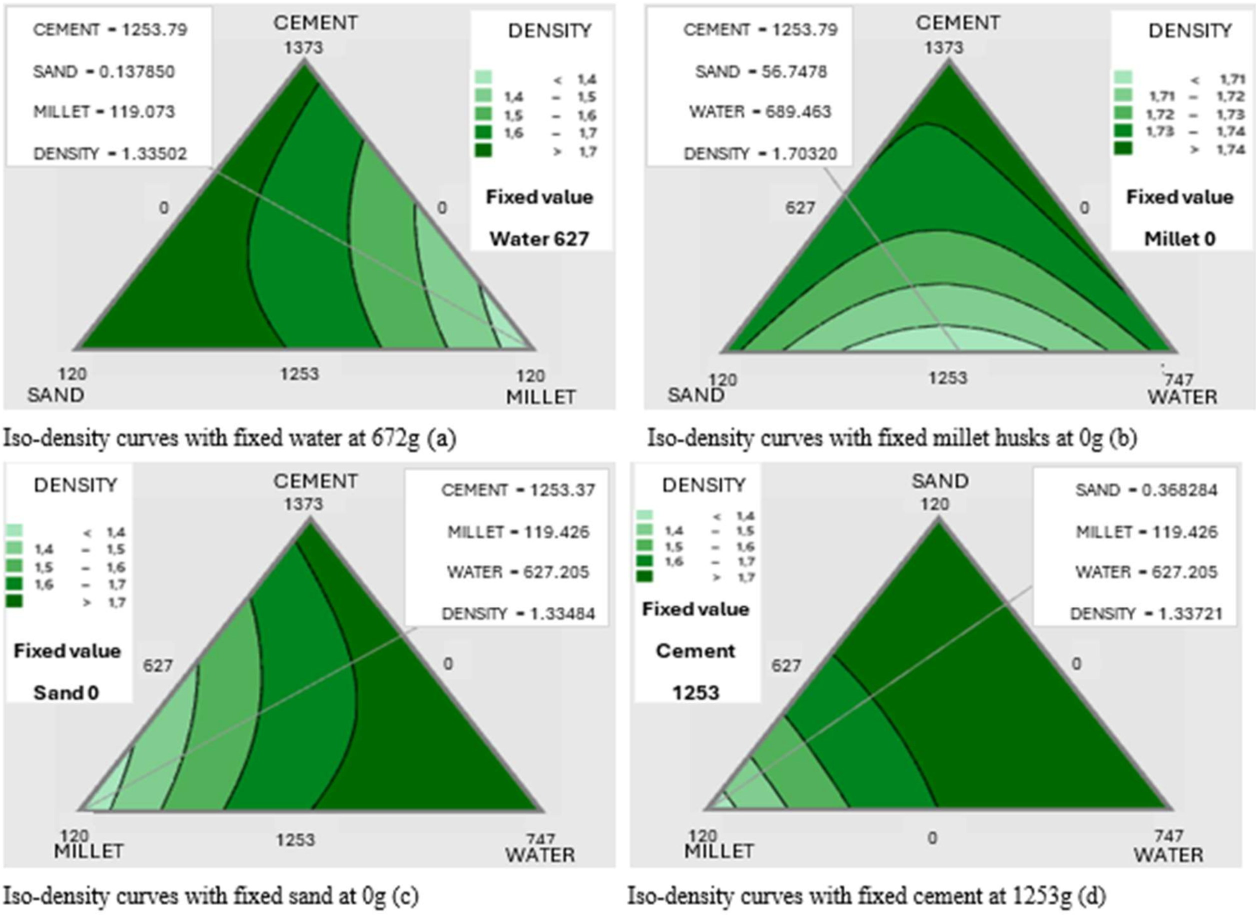


Fig. 4 Iso-density curves of millet husk lightweight concrete.

- Fig. 4a: Water maintained at 672 g

Increasing sand content raises the density, while the incorporation of millet husks lowers it. Since the fibers have a low density, they lighten the composite, whereas the heavier sand increases density.

- Fig. 4b: Millet husks maintained at 0 g

The absence of fibers results in higher density values, dominated by the proportions of cement and sand. As sand content increases, density rises.

- Fig. 4c: Sand maintained at 0 g

A marked decrease in density is observed as the proportion of millet husks increases, since the fibers replace dense sand, reducing the overall density.

- Fig. 4d: Cement maintained at 1,253 g

In this configuration, water, sand, and millet husks influence density in different ways depending on their individual densities. A low sand content and high fiber content lead to a lighter composite, whereas an increase in sand or water can raise density.

Overall, these curves confirm that adding millet husks reduces density, while incorporating sand significantly increases it. The optimal density reduction points occur when fiber content is maximized and sand content is minimized.

3.2 Compressive Strength

Table 5 shows that the compressive strength varies from 7.554 MPa (F12) to 12.113 MPa (F6). Two key trends emerge:

- Increase in compressive strength with sand content

Moving from F12 (0 g of sand, 7.554 MPa) to F6 (60 g of sand, 12.113 MPa), a significant increase in strength is observed. The addition of sand, which is denser and fills voids more effectively, enhances the compactness of the composite and improves its strength.

- Reduction in compressive strength with high millet husk content

F12, containing 120 g of millet husks and no sand, exhibits the lowest strength (7.554 MPa). The fibers, occupying a large volume and creating voids, reduce the compactness of the material and negatively impact its compressive strength. A moderate fiber content, combined with a certain amount of sand, can help optimize mechanical performance.

Fig. 5 presents the iso-compression curves, keeping one factor constant per plot. Each shade of green or blue represents a range of compressive strengths (from lowest to highest values).

- Effect of water fixed at 627 g (Fig. 5a)

When water is held constant, increasing both sand and millet husks together leads to a maximum compressive strength of 10.61 MPa. Millet husks enhance material cohesion up to a certain limit, beyond which their effect becomes negative due to increased porosity. A balanced proportion of sand and fibers is necessary for optimal strength.

- Effect of millet husks fixed at 0 g (Fig. 5b)

Without millet husk fibers, maximum compressive strength reaches only 7.70 MPa, significantly lower than in other configurations. The reduction in strength suggests that fibers contribute positively, likely by improving internal adhesion and reducing crack propagation. Increasing sand enhances strength, but excess sand leads to cohesion loss.

- Effect of sand fixed at 0 g (Fig. 5c)

Without sand, the composite still achieves a notable compressive strength of 10.2383 MPa with 62.4094 g of fibers and increased cement (1,310.57 g). This result indicates that fibers, in the absence of sand, help maintain structural cohesion, though they require additional cement compensation. However, excess fibers reduce compactness and gradually decrease strength.

- Effect of cement fixed at 1,253 g (Fig. 5d)

With constant cement content, the best compressive strength (10.6241 MPa) is achieved with 57.5692 g of sand and 62.4094 g of fibers. Increasing sand initially improves strength, but excessive amounts cause strength reduction. A similar trend is observed for millet husks: a moderate fiber content improves strength, but beyond 60 g, excessive porosity weakens performance.

The cross-analysis of iso-compression curves highlights the structural role of millet husk fibers. Contrary to common assumptions, fibers do not systematically reduce compressive strength. When well-dosed (~60 g), they enhance material cohesion, particularly in sand-free formulations. This is evident from the 10.2 MPa compressive strength achieved using only cement and fibers. In contrast, without fibers, the maximum strength remains limited to 7.7 MPa, proving their importance. Fibers act as a stabilizing agent, reducing cracking and enhancing stress distribution. However, excessive fiber content (> 60 g) increases porosity and weakens strength.

Sand has a reinforcing effect up to a threshold (~57 g), beyond which cohesion loss occurs. Cement also plays a key role, but excessive amounts cannot fully compensate for an imbalanced formulation.

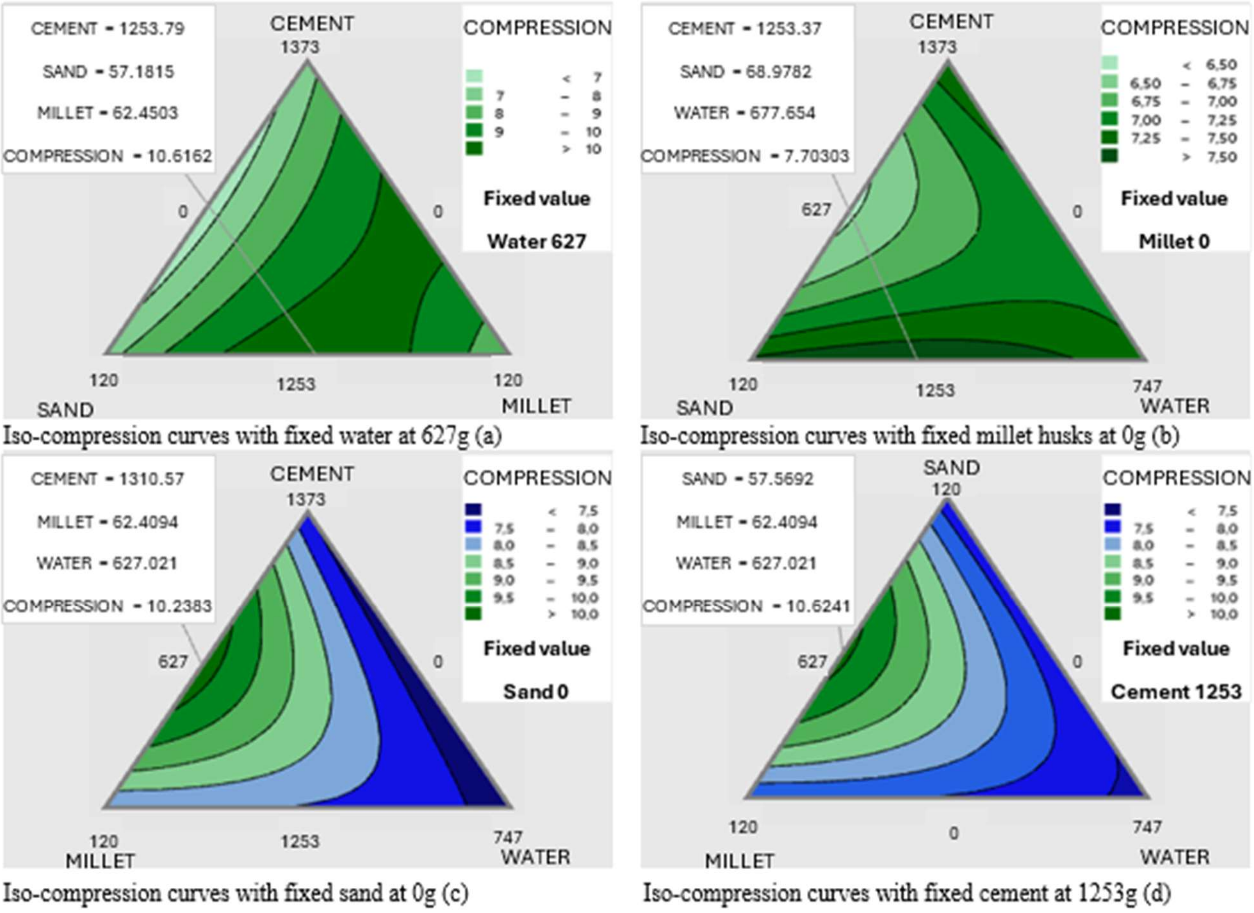


Fig. 5 Iso-compression curves of millet husk lightweight concrete.

These results demonstrate that millet husks can enhance the compressive strength of cement-based composites, but only when their proportions are carefully optimized in relation to the other components.

3.3 Tensile Strength

The iso-response curves in Fig. 6 allow for an evaluation of the effect of each parameter on tensile strength.

- Effect of Cement

The curves indicate that when cement content is maintained at 1,253 g (Fig. 6d), tensile strength ranges from 5 MPa to 7.6 MPa. Notably, the highest strengths are achieved when millet husk content is significant. Increasing cement alone does not guarantee improved tensile strength, confirming that fibers play a structural role in the material.

- Effect of Sand

When sand is maintained at 0 g (Fig. 6c), the maximum tensile strength reaches 7.18 MPa, showing that fibers can partially compensate for the absence of sand. However, formulations including sand exhibit better overall performance.

- Effect of Millet Husks

Millet husks significantly improve tensile strength. When fiber content is fixed at 0 g (Fig. 6b), the maximum tensile strength drops to 5.17 MPa, which is much lower than values obtained with fiber-rich formulations. This confirms that millet husks act as structural reinforcement by limiting crack propagation.

- Effect of water

When water content is fixed at 627 g (Fig. 6a), the maximum tensile strength reaches 7.68 MPa. A gradual decrease in strength is observed with excess water, which aligns with the weakening effect of excessive water on cement-fiber bonding.

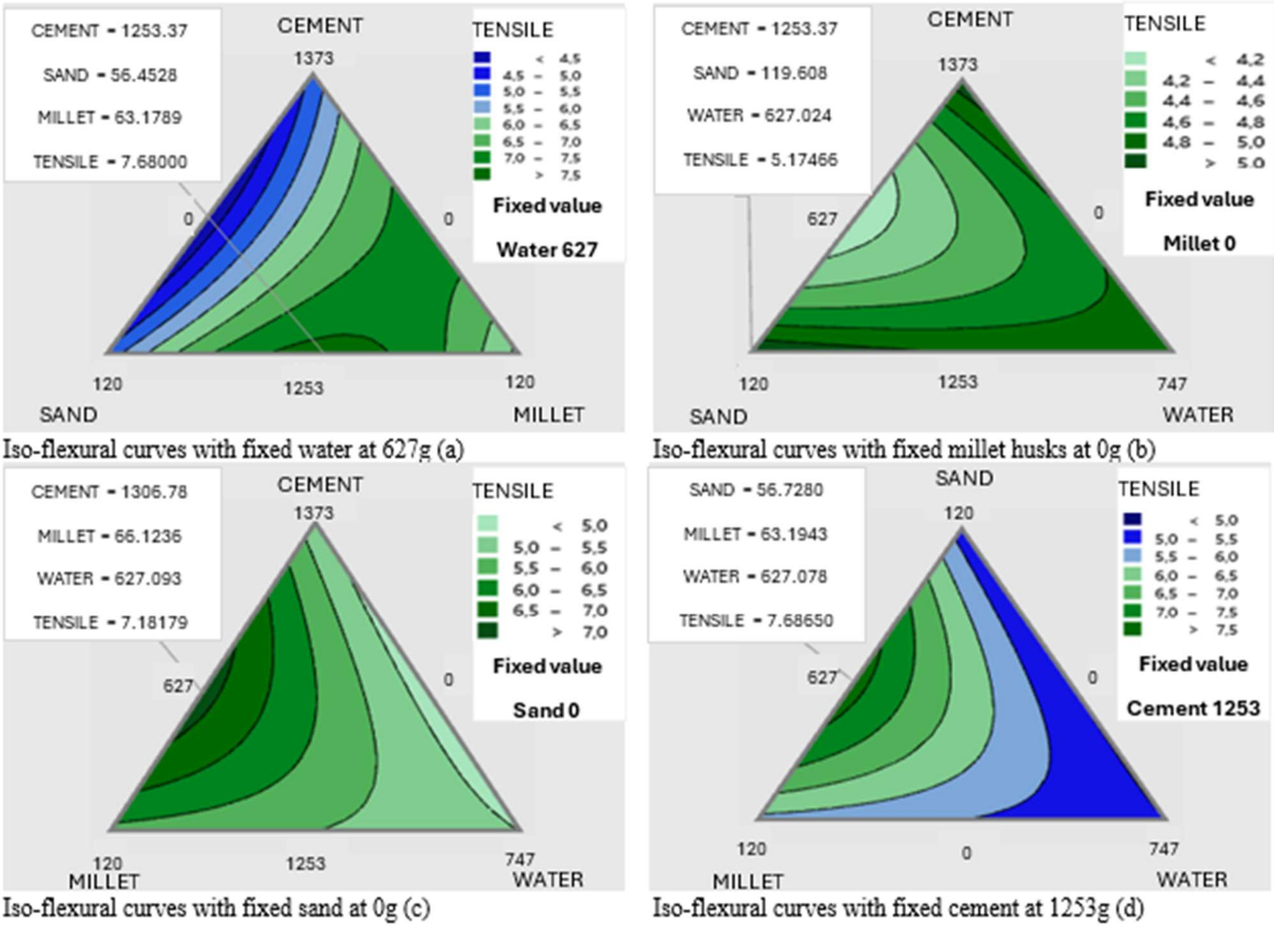


Fig. 6 Iso-flexural curves of millet husk lightweight concrete.

The results indicate that millet husk fibers significantly enhance tensile strength. The best performance is obtained for a balanced formulation of fibers and sand. A moderate cement content and an appropriate water-to-cement ratio are essential to ensure good fiber adhesion to the cement matrix. The iso-curves confirm these observations, demonstrating that fibers play a key role in improving the composite's tensile strength.

3.4 Thermal Conductivity

The iso-curves in Fig. 7 illustrate the influence of different parameters on thermal conductivity.

- Effect of Cement

Increasing cement content notably impacts thermal conductivity. Comparing the curves, it is observed that as cement content increases, thermal conductivity follows a slightly increasing trend. The curve in Fig. 7d, where cement is fixed at 1,253 g, exhibits lower conductivity values compared to other configurations. However, for higher cement proportions (Figs. 7a, 7b, and 7c), thermal conductivity slightly increases, likely due to cement's density.

- Effect of Sand

Adding sand also influences thermal conductivity. Comparing Fig. 7c (sand fixed at 0 g) with other curves, an increase in sand content leads to higher thermal conductivity. This is particularly evident in the dark green-to-blue zones in Fig. 7c, which indicate lower values. Sand, being a dense mineral material, enhances the composite's compactness and increases thermal conductivity.

- Effect of Millet Husks

Millet husks play a major role in reducing thermal conductivity. Comparing Fig. 7b (0 g of millet husks) with Fig. 7c (higher fiber content), it is clear that incorporating millet husks lowers thermal conductivity values. This is due to the fibrous and porous nature of millet husks, which trap air and reduce heat transfer. The darker blue areas in Fig. 7c indicate better thermal insulation in fiber-rich formulations.

- Effect of Water

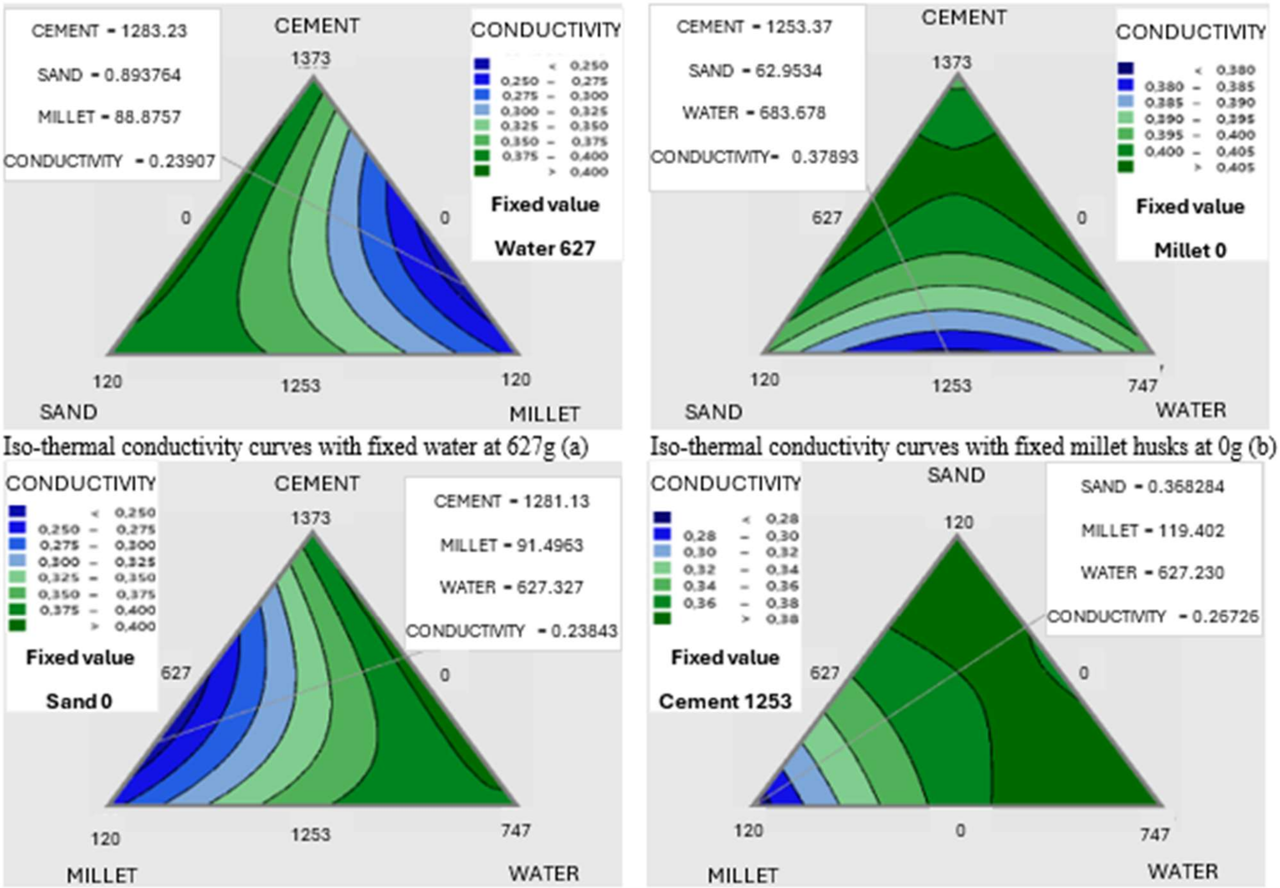
Water content also influences the material's thermal conductivity. Fig. 7a, where water is fixed at 627 g, shows lower values compared to formulations where water content varies. Lower water content enhances thermal insulation, while excess water can create uncontrolled porosity, increasing conductivity.

These findings confirm that plant fibers improve the material's thermal insulation properties, making these formulations suitable for applications requiring good thermal performance, as highlighted by several authors [3, 5, 19].

3.5 Thermal Effusivity

The iso-curves for thermal effusivity (Fig. 8) allow us to evaluate the influence of each parameter (cement, sand, millet husks, and water) on this thermal property of the material.

A cross-analysis of the four iso-curves shows that thermal effusivity is primarily controlled by the cement and sand content, which tend to increase this property. In contrast, millet husks act as an insulating agent and reduce thermal effusivity, due to their low density and porous nature. These results confirm that incorporating plant fibers into lightweight concrete helps limit its capacity to store and release heat, which can be an advantage for bioclimatic construction insulation applications.



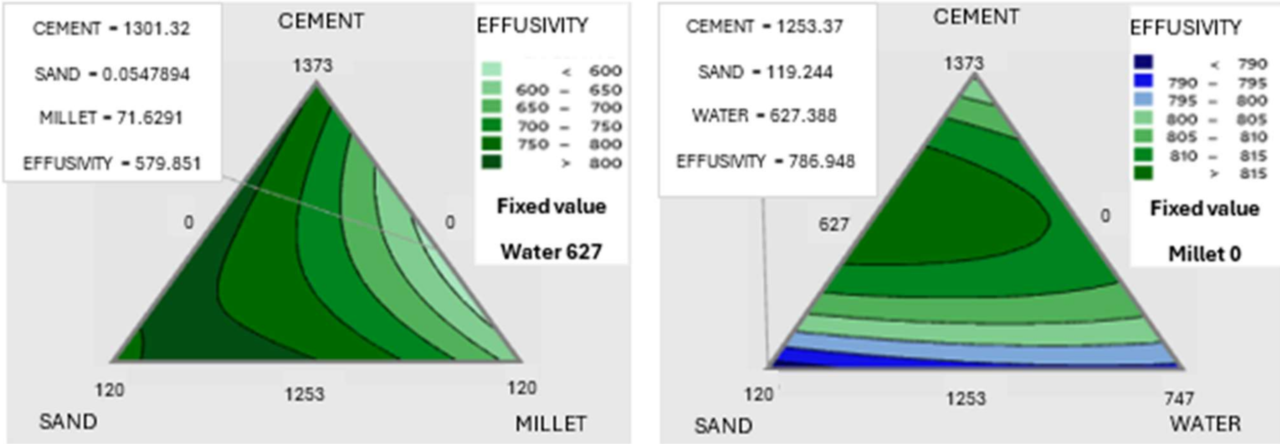
Iso-thermal conductivity curves with fixed water at 627g (a)

Iso-thermal conductivity curves with fixed millet husks at 0g (b)

Iso-thermal conductivity curves with fixed sand at 0g (c)

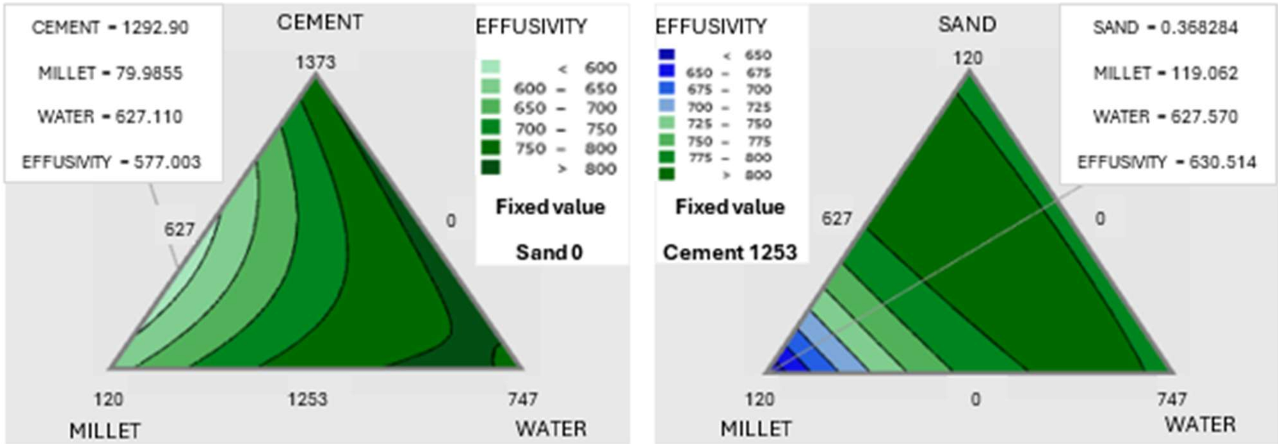
Iso-thermal conductivity curves with fixed cement at 1253g (d)

Fig. 7 Iso-thermal conductivity curves of millet husk lightweight concrete.



Iso-thermal effusivity curves with fixed water at 627g (a)

Iso-thermal effusivity curves with fixed millet husks at 0g (b)



Iso-thermal effusivity curves with fixed sand at 0g (c)

Iso-thermal effusivity curves with fixed cement at 1253g (d)

Fig. 8 Iso-thermal effusivity curves of millet husk lightweight concrete.

4. Conclusion

This study analyzed the influence of replacing sand with millet husks on the physical, mechanical, and thermal performance of a lightweight cementitious composite. The experimental approach, based on mixture design and iso-response curve analysis, provided an in-depth understanding of the interactions between different constituents and their impact on material properties.

The results show that incorporating millet husks significantly reduces density, confirming their role in lightening the composite. From a mechanical standpoint, millet husks do not merely act as fillers: when well-dosed, they improve tensile strength and can partially compensate for the absence of sand in certain configurations. Compressive strength is optimized when fibers are combined with a moderate proportion of sand, preventing excessive loss of compactness.

The thermal analysis highlights the benefits of these fibers for material insulation properties. The addition of millet husks reduces both thermal conductivity and effusivity, indicating better insulation capacity and lower heat storage capability. These findings confirm that integrating plant fibers not only reduces composite weight but also enhances its energy efficiency, demonstrating the potential of such composites for applications requiring a balance between lightweight properties, strength, and thermal insulation.

The iso-response curve analysis enabled the identification of optimal mixtures, providing a deeper understanding of the cross-effects of constituents on final performance. This approach goes beyond conventional substitution strategies by refining recommendations for a targeted use of bio-based materials.

Thus, this study highlights the potential of millet husks as a viable alternative to conventional aggregates, offering a compromise between mechanical strength and thermal performance for the design of lightweight and sustainable concretes.

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Author Contributions

Conceptualization and study design: V. Doko;

Data collection: S. Saloufou, E. Chabi;

Data analysis and interpretation: S. Saloufou, V. Doko, E. Chabi, E. Olodo;

Manuscript drafting: S. Saloufou, E. Chabi;

Critical manuscript review for intellectual content: S. Saloufou, V. Doko, E. Chabi, E. Olodo;

Final manuscript approval: S. Saloufou, V. Doko, E. Chabi, E. Olodo.

Conflicts of Interest

The authors declare that there are no conflicts of interest that could inappropriately influence, or be perceived to influence, the work reported in this manuscript.

Data and Code Availability

No additional datasets or code repositories are associated with this research.

Ethical Approval

Ethical approval was not required for this research as it did not involve human or animal subjects.

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