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Unlocking energy efficiency: Experimental investigation of bamboo fibre reinforced briquettes as sustainable solution with enhanced thermal resistance

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ABSTRACT

Energy consumption data reveals that buildings account for 40 % of overall energy usage. Without urgent intervention, this figure is poised to escalate alongside population growth, exacerbating the dependence on fossil fuels for energy production. Addressing this pressing issue demands effective measures to curtail energy consumption in buildings, a realm where research on bamboo's thermal performance still needs to be improved. This study fills a critical gap by investigating the integration of bamboo fibre in the briquettes, known for their high heat transfer coefficient (U-value). Leveraging the innovative coheating test method, the research pioneers an unexplored avenue to evaluate thermal performance. This novel approach distinguishes the study as a unique and original endeavour in the field. The findings demonstrate significant thermal enhancements by substituting bamboo fibre: 2 %, 4 %, and 6 % bamboo additions yield U-values of 4.698 W/m^2K, 3.94 W/m^2K, and 2.77 W/m^2K, respectively. Notably, the 6 % bamboo-reinforced briquette showcases a remarkable 49.9 % improvement in thermal resistance compared to conventional counterparts. This study marks a pioneering effort towards achieving energy efficiency through sustainable materials in designing low/zero carbon buildings. By showcasing the potential of bamboo as a thermal insulator, the research illuminates a promising path for future construction practices. Embracing such innovations is paramount in mitigating the environmental impact and securing a sustainable future.

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1. Introduction

Recent economic turmoil, dwindling availability of non-renewable energy resources, and the escalating global population density have sparked growing apprehension within the building industry regarding energy consumption and its associated challenges [1]. Indeed, only few issues are as critical or demand immediate attention as the sustainability of buildings in the quest for a sustainable future [2]. Whether towering skyscrapers or quaint residences, the structures, inhabited epitomise both safe spaces, the shelter, and the environmental footprint (ecological impact) [3]. Nonetheless, it is noteworthy that 30–40 % of global energy usage is solely allocated to buildings [4,5]. Despite its role in bolstering economic growth in response to population expansion [6], the construction sector faces severe scrutiny for its significant contribution to global warming, excessive water consumption, generation of solid waste, environmental pollution (including the reduction of green spaces), and depletion of natural resources, encouraging the consumption of fossil fuels to meet energy demands, ultimately resulting in environmental degradation [7,8] by the limitation of current renewable energy sources to meet global energy demands [9], activities such as fossil fuel combustion, transportation, and building construction exacerbate CO_2 emissions, erratic weather patterns, and adverse impacts on human health. Consequently, amidst these escalating threats and challenges, an urgent imperative for energy-efficient initiatives arises. In the pursuit of enhancing energy efficiency within buildings, insulation emerges as a crucial tactic for sustaining comfortable indoor temperatures over extended periods while reducing energy usage to a minimum. In addition to this, Fig. 1 summarises the other pros of the use of insulation.

Recognising the prevalent energy loss points in the existing building stock, the exterior façade emerges as a predominant contributor, accounting for approximately 40 % of energy losses--. Therefore, substantial interventions targeting the building envelope stand poised to significantly alleviate the financial burdens on building occupants [10–12]. This intervention is relevant to both existing and forthcoming building structures--. While various methodologies exist to shield building envelopes from adverse weather conditions, the adoption of bamboo presents itself as a compelling alternative due to its inherent sustainability, low carbon footprint, prolonged lifespan, natural abundance, and benign impact on human health [13,14].

Bamboo stands as one of the most ancient and adaptable construction materials, boasting a rich history of over 2000 years of widespread utilisation in countries like China and Japan [15]. With a diverse array of 1250 species across 75 genera, bamboo is known for its rapid growth [16], maturing in just three to five years [17]. They have garnered attention due to their numerous advantages, including low density [18], improved thermal retention [19], ease of processing [20], high strength [21], cost-effectiveness [22], lightweight structure [23], excellent thermal properties [24], broad applicability [25], minimal greenhouse gas emissions [26], minimal environmental impact compared to other materials [27], biodegradability [28], and commendable mechanical characteristics [29]. Beyond construction, bamboo finds application in various domains such as woodwork, furniture, paper production, textiles, and even food [30]. Additionally, bamboo is recognised for its effective carbon dioxide absorption, distinguishing it from non-renewable materials [31]. More recently, bamboo fibres have also been incorporated to improve the physical characteristics of materials based on cement [32,33]. Besides, their thermal conductivity (k-value) is below 0.082 W/mK, making them suitable for applications in building insulation [34].

Al-Rukaibawi et al. [35] undertake a research study employing numerical simulation techniques with the objective of enhancing the performance of four specific building designs, aligning with the Hungarian government's ambition to attain zero-energy buildings by the year 2030. This research examines various building envelope options, including the original steel-bamboo structure used as a reference, an upgraded steel-bamboo design, brick, and a blend of bamboo and EPS for the building shells. For the upgraded steel-bamboo building layer, mineral wool insulation is incorporated, and the exterior is shielded by two layers of bamboo, along with multiple layers, including cement mortar. As a result of this investigation, the reference design exhibits a thermal transmittance of 0.649 W/m^{2}K, whilst the improved bamboo-steel design manages to lower it significantly to 0.235 W/m^{2}K for the external walls, sig-

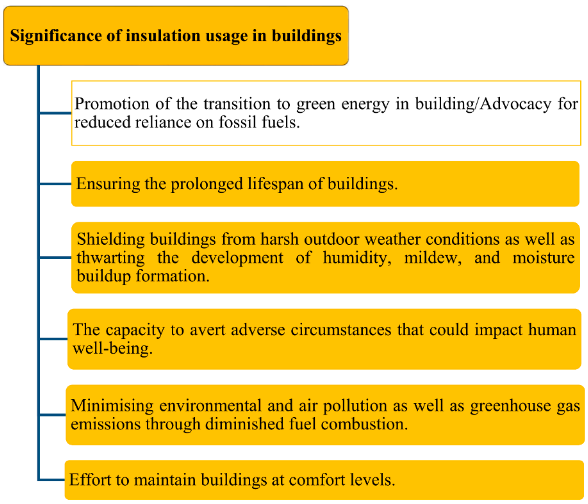

Fig. 1. The importance of using insulation in buildings.

nifying an impressive improvement of almost 64 %. Given these findings, this study holds promise in terms of fulfilling the Hungarian government's targeted objectives. Li et al. [36] conduct a combined research involving both practical experimentation and mathematical analysis to evaluate the thermal performance of a prefabricated house featuring an innovative light steel-bamboo wall structure. The choice of a prefabricated house is motivated by the Chinese government's encouragement of such structures, which are believed to offer energy savings and contribute to the proliferation of green buildings. In this study, the performance of the prefabricated house is compared to that of a typical reinforced concrete house. To enhance thermal insulation, the wall structure is modified with the inclusion of cement mortar, expanded polystyrene, bamboo plywood, C-type steel, and mineral wool to fill gaps in the building shell. The outcomes reveal that, during the hottest hours of summer months, the indoor thermal performance of the building remains lower compared to the reinforced concrete wall. Additionally, there is a notable improvement in the U-value, resulting in energy consumption reductions ranging from virtually 26.1 %–48.4 % during winter. Consequently, this study sheds light on the significant potential for applying steel-bamboo walls in residential buildings in regions characterised by hot summers and cold winters. Yu et al. [37] comprehensively assess the energy consumption and carbon emissions throughout the entire lifespan of a bamboo-structured residential building in China. They incorporate contemporary insulation technologies, like vacuum insulation panels between two facades. Their research results indicate that bamboo-structured buildings outperform typical brick-concrete buildings regarding energy efficiency and carbon footprint, as they demand lower energy usage and produce fewer CO_2 emissions. Dweik et al. [38] are presently engaged in a research study aimed at tackling issues associated with concrete. Their focus is on investigating how non-recyclable ground melamine formaldehyde (MF) thermoset plastic waste can be used as an alternative to sand in mortar mixtures, particularly for its thermal insulation properties. The study involves replacing sand with these waste materials, with proportions varying from 0 % to 60 %. Throughout the experiment, diverse samples featuring different MF percentages are positioned within an insulation block that includes a heated plate. The primary objective is to evaluate heat transfer in these samples by creating holes at three specific points from the top and placing thermometers in those locations. The findings reveal that as the MF percentage increases, there is an improvement in the insulation capabilities of the material. Notably, the sample containing 30 % MF shows a substantial temperature decrease of approximately 60 % in comparison to the control sample. Huang et al. [39] perform a simulation investigation centred on Moso bamboo's heat and moisture transfer characteristics. In their research, they employ four variations of bamboo panels encased within polypropylene foam, with the exterior layer being shielded by aluminium foil. The simulation study encompasses temperatures between −40 ˚C and 100 ˚C, along with humidity levels from 10 % to 98 %. The study's outcomes bring about the conclusion that the outer layer of these panels can effectively manage moisture dynamics, while the inner layer demonstrates notable thermal insulation performance. Quan et al. [30] execute research that explores the influence of altering the fibre content and length by incorporating both natural bamboo and basalt fibres into autoclaved aerated concrete. Table 1 and Table 2 provide an overview of the study's collected data. According to the acquired data, it is apparent that concrete samples containing 0.4 % natural bamboo fibre verify approximately 11 % better k-value performance in terms of concrete samples with an equivalent quantity of basalt fibre. Besides, the most excellent k-value is observed when the fibre length is 12 mm for both types, contributing to k-values of 0.142 W/mK for basalt fibre and 0.156 W/mK for natural bamboo fibre.

Cuce et al. [40] run a research endeavour aimed at reducing heat loss within a space by introducing a novel insulation plaster, with varying thicknesses, onto the primary building material, briquettes. The objective is to contribute to the development of green buildings. In this study, thicknesses of 1-1, 2-1, and 2-2 cm are employed, with conventional briquettes serving as a reference. For instance, "1-1" indicates that a 1 cm thickness of insulation plaster is coated to both the front and back surfaces of the briquette. A co-

Table 1
The range of k-values and the impact of adding fibre to it [30].

Material Fibres	Contents (%)	Enhancement (%)
Natural Bamboo	0.1	4.75
	0.2	8.44
	0.3	15.01
	0.4	20.37
Basalt	0.1	2.64
	0.2	5.66
	0.3	6.94
	0.4	9.79

Table 2
The scope of k-values and the influence of length on it [30].

	Length (mm)	Improvement (%)
Natural Bamboo	3	12.74
	6	15.01
	9	16.58
	12	19.54
Basalt	3	5.2
	6	6.94
	9	8.39
	12	9

heating test is employed to collect data. The study's outcomes reveal that, compared to conventional briquettes, the 1-1, 2-1, and 2-2 thicknesses exhibit efficiency improvements of 22.5 %, 36.4 %, and 47.9 %, respectively. In accordance with the significant insights derived in alignment with the study's objectives, it is evident that this novel insulation plaster, characterised by its cost-effectiveness and substantial benefits, holds promise for future low/zero carbon housing initiatives. Cuce et al. [41] initiates an innovative research endeavour focusing on various glass products to mitigate this loss associated with windows, which significantly contribute to the heat loss in buildings. The experimental approach employed in this study is the coheating test method, revealing that the technology under examination demonstrates a fivefold improvement in thermal insulation compared to commonly utilised double-glazing technology, thereby offering a promising avenue for potential energy consumption reduction. Ahmed et al. [42] conduct a study aimed at mitigating waste clay brick pollution and repurposing this waste material. In this research, they create samples by incorporating waste clay bricks in two distinct methods. The first approach includes incorporating clay brick waste powder as a partial substitute for Metakaolin at levels of 10 %, 15 %, and 20 % by weight. Meanwhile, the second method involves crafting samples that include a blend of crushed clay brick waste aggregate, replacing 10 %, 20 %, and 30 % by volume of natural coarse aggregate. The outcomes of the study reveal significant improvements in thermal insulation when compared to samples without the addition of waste clay bricks. Specifically, the samples prepared with 10 %, 15 %, and 20 % replacement exhibit thermal insulation enhancements of approximately 43 %, 45 %, and 46.27 %, respectively. Conversely, samples with natural coarse aggregate replacements of 10 %, 20 %, and 30 % experience even more significant thermal improvements, measuring 43.44 %, 46.02 %, and 54.07 %, separately. Charai et al. [43] use varying amounts of hemp fibre to enhance the thermal performance of the patch. As a result, they achieve a 31 % increase in thermal performance and a 24.5 % diminishment in density with a 6 % fibre ratio. Lv et al. [44] attempt an investigation involving the utilisation of cross-laminated bamboo C/LB walls and C/LB-EPS composite in varying wall thicknesses and configurations, organised into different groups, with a focus on evaluating its impact on heat transfer. The research involves subjecting samples to testing using a double-sided protected hot plate. The findings from the experiments reveal that thermal insulation performance improves with increasing thickness. However, it is observed that different wall configurations exhibit relatively limited variations in thermal insulation effectiveness when they have the same C/LB wall thickness. Notably, the samples containing the C/LB-EPS composite display the most superior thermal performance. Jusoh et al. [45] prepare an experimental investigation to assess the k-value of two distinct bamboo varieties, Akar and Semantan. They conduct tests by applying heat flow in both perpendicular and parallel directions to the prepared samples. To prevent any alterations in their physical properties, mainly due to potential burning, the temperature is carefully maintained below 40 W. The study's outcomes, summarising the results, are presented in Table 3 below.

Wang et al. [46] engage in a study highlighting the growing significance of utilising engineered bamboo composites in light-frame constructions. This application addresses the existing gap in thermal insulation performance in such structures. Specifically, a wall structure comprising four distinct layers is chosen, and the outcomes are derived using a hot plate apparatus. Based on the test outcomes, the wall configuration offering the most robust insulation resistance is found to be the one featuring 9 mm bamboo, 140 mm glubam, and 140 mm rock wool. This configuration yields an experimental insulation value of approximately 0.308 W/m^{2}K. The graphical representations of the samples categorised by wall type are depicted in Fig. 2.

Table 3
Thermal conductivity measurements achieved by directing heat flow perpendicular and parallel to various bamboo types [45].

	Thermal conductivity (W/mK)	
Bamboo type	**Parallel**	**Perpendicular**
Akar	0.35	0.29
Semantan	0.49	0.24

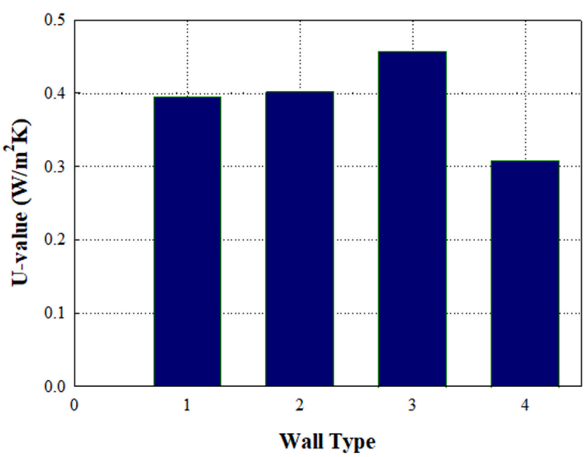

Fig. 2. U-values corresponding to different wall types derived from the test data [46].

Vieira et al. [47] carry out a study in a specific area, incorporating one, two, and three layers of bamboo into a house wall. They utilise numerical and simulation methods to enhance the thermal performance of the tested wall. The investigation aims to leverage bamboo's internal structure to reduce thermal resistance and minimise heat losses. The research takes place in a residential house located in Guayaquil, Ecuador, where the indoor-outdoor temperature difference is maintained at around 15 °C. The thermal properties of bamboo are defined as follows: a k-value of 0.175 W/mK, a density of 600 kg/m^3, and a specific heat of 1491 J/kgK. Based on the data, the findings indicate that a two-row bamboo configuration yields a highly suitable U-value. However, considering the presence of thermal bridges, it is suggested that a three-row configuration would be more appropriate. In Table 4, The U-values for the different bamboo layer configurations are presented [38].

The issue of effective thermal insulation in buildings remains an ongoing challenge. However, various countries are implementing precautionary measures, and researchers are actively addressing this concern through continuous studies to improve thermal insulation. Bamboo, though, has encountered some challenges in this regard. Despite a growing trend in the last decade suggesting that bamboo could be effectively utilised for its thermal and mechanical properties, research in this area still needs to be completed. The originality of this study lies in its approach to increasing thermal efficiency by converting bamboo, known for its heat retention properties, into fibres and then using these fibres in the production of briquettes, which are usually recognised for their poor thermal resistance characteristics. This aspect has not yet been addressed in the literature to date. Additionally, there are no studies specifically targeting the thermal performance analysis of bamboo and incorporating the coheating test method adopted in addressing this issue. Therefore, this study offers an innovative perspective. As a consequence of these, this study concentrates on assessing the thermal performance of bamboo fibre replacements at 2 %, 4 %, and 6 % levels, evenly distributed during the standard briquette casting process. Traditional briquettes are employed alongside these samples to underscore their thermal mending capabilities. The performance analysis is carried out in a controlled laboratory setting using a hot box that offers excellent insulation, preventing any heat leakage. To establish a temperature difference between the interior and exterior surfaces of the samples inside the hot box, the laboratory environment is cooled using air conditioning, whilst the hot box's internal environment is heated using an electric heater. Temperature measurements are observed through T-type thermocouples placed on both the inner and outer surfaces of the samples, and the results are meticulously recorded. Additionally, a susceptible sensor is employed for measuring heat flux. In this research, the goal of this study is to demonstrate enhanced thermal performance in briquettes containing bamboo when compared to conventional briquettes. This improvement is achieved by replacing different proportions of bamboo in the standard mortar typically used in briquette production, with the traditional briquettes already having low thermal resistance.

2. Material and method

Under this section, the aim is to articulate the procedural aspects of the study across distinct subheadings to readers. Initially, attention will be directed towards delineating the thermophysical properties of bamboo, a naturally occurring plant, and its insulative attributes. Subsequently, the methodology and measurements employed during briquette casting will be elucidated. Finally, an endeavour will be made to explicate the adoption of the coheating test as the primary method within the study.

2.1. Bamboo

Upon reviewing the literature pertaining to bamboo, it becomes evident that while there is a wealth of mechanical studies, thermal investigations are notably sparse. Consequently, there is a necessity for a thermophysical examination of bamboo. Nevertheless, a concise overview of the existing studies on this topic can be provided as follows. Bamboo demonstrates remarkable capabilities in heat insulation and protection due to its adaptable fibre structure, resulting in thermal conductivity as minimal as 0.30 W/mK [48]. Bartlett et al. conduct experiments on bamboo samples, suggesting that laminated bamboo exhibits nearly twice the thermal conductivity compared to timber, setting it apart from engineered wood which typically has a thermal conductivity of 0.14 W/mK [49]. Additionally, bamboo shows resilience to high temperatures, capable of withstanding up to 400 °C for a maximum duration of 20–30 min. Its low energy consumption attributes render bamboo valuable for diverse building applications, potentially replacing other industrially manufactured building materials due to its thermal stability. Fig. 3 depicts a representative image of the bamboo acquired during pre-grinding and utilised in the experiment.

2.2. Briquette casting

Prior to commencing the briquette casting, the primary objective of the study entails determining the weights of materials requisite for crafting bamboo-compatible briquettes across varying weight percentages. Concurrently, procurement of the briquette-making materials—cement, fine aggregate, and coarse aggregate—is initiated. A pivotal aspect involves sieving the aggregates to ensure appropriate thickness, employing a screening process predicated on an 8 mm thickness standard. Subsequently, the predetermined quantities of materials are meticulously measured gram by gram using precise scales and deposited into suitable containers

Table 4
U-values for various arrangements of bamboo layers [47].

Layers	U-value (W/m^{2}K)
Individual Layer	2.07
Two Layers	1.40
Three Layers	0.66

Fig. 3. The depiction of bamboo intended for usage in the experiment.

alongside bamboo fibres. Following this, the amalgamation of ingredients in a mortar machine ensues, wherein materials are individually added in accordance with the designated bamboo fibre ratio to foster homogeneity prior to moulding. Water, measured to the prescribed weight, is gradually poured into the mixing mortar machine, facilitating cohesion among aggregates, cement, and water—the binding agents. Post thorough mixing to ensure uniform distribution, the inner surface of the briquette mould, conforming to predefined standards, is uniformly lubricated to avert potential adhesion issues during the curing process. Subsequently, the mould is affixed to a vibration machine, facilitating the pouring of the homogenised mortar mixture into the mould. The vibration machine's role is pivotal in ensuring optimal bonding of the mortar. Upon completion of this stage, the mould is placed in a controlled environment at room temperature, accompanied by periodic watering to deter cracking. Following adequate curing duration, the briquette is demoulded, thus yielding a test-ready specimen. This iterative process is replicated across varying bamboo weight ratios, resulting in the acquisition of four distinct samples, including one devoid of bamboo fibre substitution. Meanwhile, the mould is designed to produce briquettes with dimensions of 15 cm in depth, 15 cm in height, and 33 cm in length. The moulding of the briquette sample and its appearance when it is ready for testing are visualised in Fig. 4a and b, respectively.

The weights utilised in this study fluctuate according to the bamboo fibre weight ratio, as detailed in Table 5 provided below.

2.3. Coheating test method

The coheating test, a method integral to determining the U-value of a building, involves being able to get temperature differences between the interior and exterior environments of a structure or sample within a laboratory setting. This testing approach is initially pioneered by Leeds Beckett University in 2010 [50] and has since found application both in real-world building assessments and laboratory-based experiments. To ensure standardisation, the indoor environment is maintained at a comfortable 25 °C, often necessitat-

Fig. 4. ***a)*** *The sample at the stage of being prepared for testing,* ***b)*** *The ready state of the sample for testing.*

Table 5
Weight values determined based on bamboo fibre proportions.

	Fibre content (%)		
	2	4	6
Cement (g)	1190	1150	1150
Bamboo (g)	225.23	438.38	641.85
Fine aggregate (g)	2544	2416	2288
Coarse aggregate (g)	6392.5	6258.5	6124.5
Water (ml)	1135	1135	1135

ing the use of an electric heater for regulation, along with a fan for uniform air circulation. Meanwhile, the outdoor temperature should be at least 15 °C, creating a minimum 10 °C temperature difference crucial for test efficacy, typically achieved by conducting tests during winter months. While primarily assessing heat loss through external walls, the coheating test methodology can also be adapted to evaluate the thermal performance and air tightness of windows. Combining the coheating test with complementary methods such as thermal imaging and heat flow measurement enhances the study's accuracy and bolsters test reliability. Typically spanning 14–28 days, the duration of the coheating test can be expedited in laboratory settings to simulate real-world conditions efficiently. Hence, in this study, a 1 m^3 hot box is custom-designed, featuring airtight surfaces insulated with 4 cm thick XPS insulation material on each side to get the test in a laboratory medium. Fig. 5 observes a simulated version of the test area.

An electric heater is placed inside the designed hot box to obtain a temperature difference, and a temperature control unit is placed to fix the temperature at the desired level. Then, the sample is placed in the appropriate area adjusted for the size of the briquette, and a highly sensitive heat flux and thermocouple are placed on its inner surface. Since the necessary measuring devices for the indoor environment are installed, the top is closed to zero. Subsequently, a thermocouple is placed on the external surface of the sample, and the air conditioning temperature of the external environment is adjusted to suit the internal environment. The other ends of the measurement devices are connected to data loggers, allowing data to be retrieved. When the system starts operating, air tightness is checked by applying a thermal imaging test, and according to this result, it is determined that an excellent seal is achieved. After the necessary operations are completed on the computer, the environment is left, and the data is retrieved. Control is achieved by downloading data at regular intervals, and this process takes approximately three days for each sample. Fig. 6a and **b** depict all the devices mentioned above and used during the test.

2.4. Uncertainty analysis

The overall uncertainty analysis can be done by using the following equation (Eqn. (1)) below [51].

$$Y_Q = \sqrt{\left(\frac{\partial Q}{\partial Z_1} \times Y_1\right)^2 + \left(\frac{\partial Q}{\partial Z_2} \times Y_2\right)^2 + \left(\frac{\partial Q}{\partial Z_3} \times Y_3\right)^2 + \ldots} \tag{1}$$

where, Q refers to the dimension to be assessed, Z informs that it is the factor influencing quantification, and Y is the detached factor uncertainty.

So as to calculate the uncertainty value, it is needed to evaluate some parameters like following,

$Used\ thermocouples'\ uncertainty\ value: 0.15,\ T_{indoor} = 25°C,\ T_{outdoor} = 14.5°C,\ \Delta T = 10.5°C,\ Uncertainty\ of\ utilised\ heat\ flux: 0.02.$

$$Q = U \times A \times \Delta T \cong 190\ W \tag{2}$$

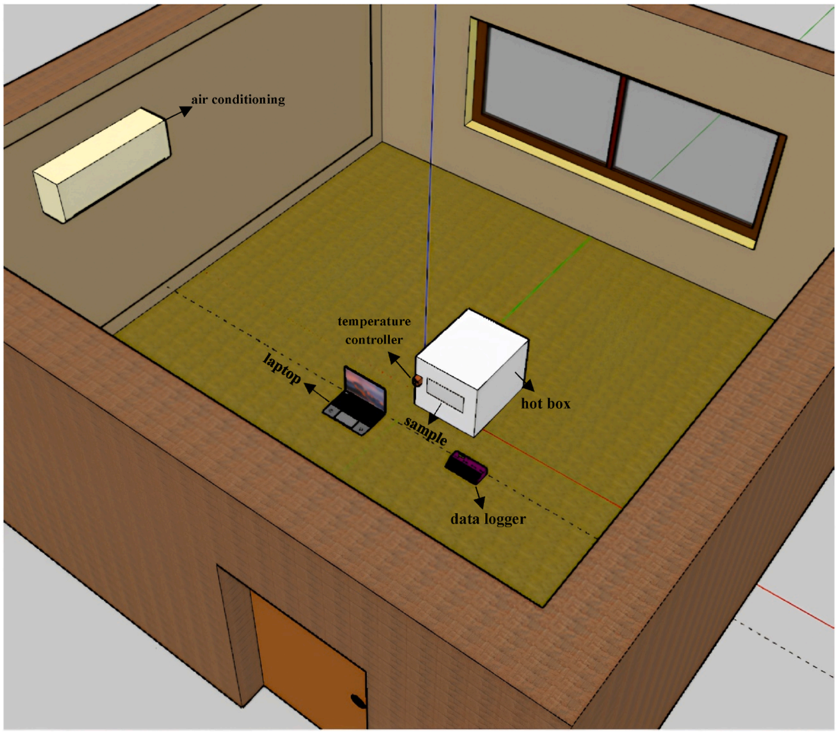

Fig. 5. Modelling the laboratory test environment.

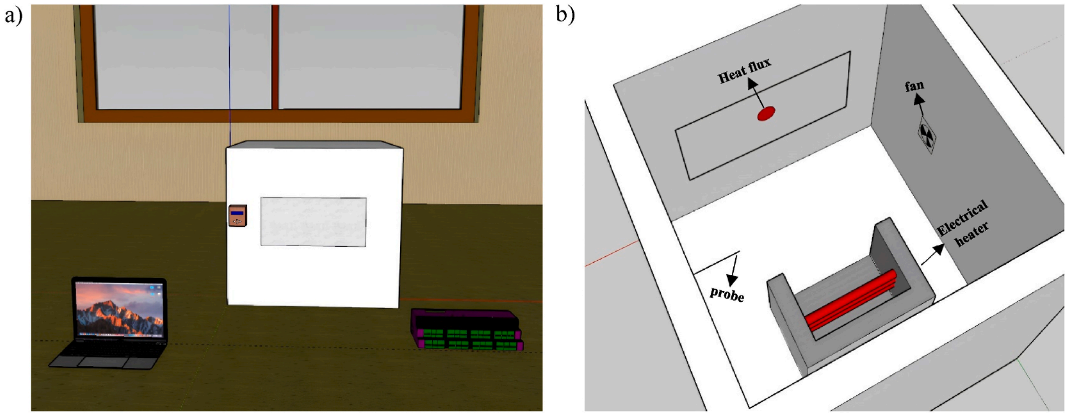

Fig. 6. a) Zoomed-in view of the devices employed in the experiment, **b)** Representation of the internal environment within the hot box.

$$H_{losses} = \frac{Q}{\Delta T}\left(\frac{W}{K}\right) \tag{3}$$

$$\frac{\partial H_{losses}}{\partial Q} = \frac{1}{\Delta T} = \frac{1}{10.5} = 0.095 \tag{4}$$

$$\frac{\partial H_{losses}}{\partial T} = -\frac{Q}{\Delta T^2} = -\frac{190}{10.5^2} = -1.723 \tag{5}$$

$$H = \frac{Q}{\Delta T} = \frac{190}{10.5} = 18.1 \tag{6}$$

$$\frac{Y_H}{H} = \frac{0.258}{18.1} \times 100 = 1.42\% \tag{7}$$

The overall uncertainty, determined to be 1.42 % in the worst-case scenario, falls within acceptable limits.

3. Results and discussion

The test begins by proving the accuracy of the coheating test method and the robustness of the casting method, which is one of the main focuses of this study, with the help of traditional briquettes obtained without bamboo fibre substitution. Accordingly, the data shows that a very close k-value is obtained with the classical briquettes from the previous study [40]. Based on this, the production method of the casting sample obtained has been correctly assigned. The graph for this data is clearly shown in Fig. 7.

The data, calculated in accordance with the coheating test method, which is the adopted test method for a total of 4 samples - conventional briquette, 2 % bamboo-reinforced briquette, 4 % bamboo substituted briquette, and finally, 6 % bamboo improved briquette sample - will be presented in order of lowest and highest values. Following this, the average data will be provided and subsequently graphed. Three parameters need to be presented: internal temperature, external temperature, and heat flux. Based on this, the

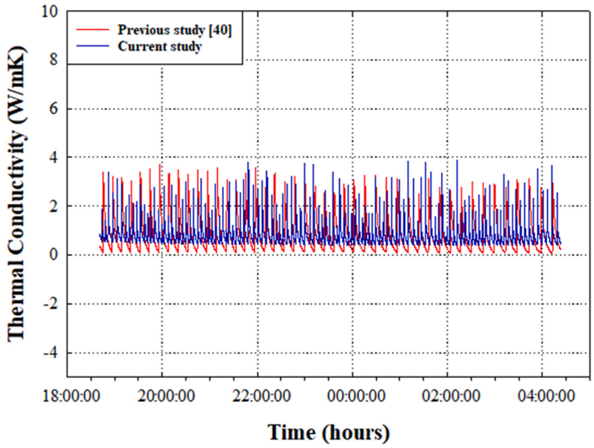

Fig. 7. Comparison of thermal conductivity coefficients: Prior study vs current study.

total U-value will be determined, revealing the thermal performance (insulation performance) of bamboo-infused briquettes with a high heat conduction coefficient. Firstly, data obtained from conventional briquettes indicate that the lowest and highest internal temperatures range between 25.701 and 27.507 °C, with an average of 26.28864 °C. Outside temperature readings range from a minimum of 15.657 °C to a maximum of 16.685 °C, with an average of 16.22224 °C.

Once the accuracy of the study is confirmed, further tests are conducted using briquettes with bamboo fibre substitution aimed at enhancing thermal performance. Consequently, for 2 % bamboo fibre briquettes, the range of internal temperature variation spans from 27.533738 to 23.197164 °C, with an average of 24.93186 °C. Additionally, external temperature fluctuations range from 16.76755 to 13.65911 °C, with an average of 14.92728 °C. Beyond temperature discrepancies, heat flux values are also examined. The minimum and maximum heat flux values recorded are 0.0323066507 and 2.02252074 $\frac{W}{m^2} \times 10^{-2}$, respectively, with a mean of 0.469965677 $\frac{W}{m^2} \times 10^{-2}$.

Upon obtaining these test results, the parameters essential for evaluating the thermal performance of another test sample, a 4 % bamboo fibre-reinforced briquette, are ensured into the computer employing a similar methodology. Subsequently, it is observed that the internal temperature alters from 27.14302 to 23.52354 °C, with an average of 23.98069 °C. Conversely, outdoor temperatures are between 15.17617 and 14.17605 °C, with an average of 14.18594 °C. Additionally, the heat flux values are documented as follows: the highest and lowest recorded values are 1.82234727 and 0.181135927 $\frac{W}{m^2} \times 10^{-2}$ respectively, with an average of 0.385538769 $\frac{W}{m^2} \times 10^{-2}$.

Ultimately, based on the test results obtained from the briquette sample with 6 % bamboo replacement, the internal temperature is from 28.77421 to 25.37536 °C, with an average of 26.4726 °C. Conversely, the variation in outside temperature is observed to range between 15.62938 and 14.15306 °C, averaging at 14.88522 °C. Most importantly, it has been demonstrated that the heat flux value ranges from 1.50724169 to 0.141029997 $\frac{W}{m^2} \times 10^{-2}$, with an average of 0.321250928 $\frac{W}{m^2} \times 10^{-2}$.

Overall, these findings are further elucidated through a comprehensive graphical representation available in Fig. 8.

Even without delving into the specifics of the U-value of bamboo, its thermal insulating properties are readily apparent. For instance, findings demonstrate that substituting bamboo at a 6 % concentration significantly enhances thermal resistance. Specifically, compared to samples reinforced with 4 % bamboo, the 6 % substitution exhibited approximately a 17 % increase in resistance, and when compared to those with 2 % bamboo reinforcement, it showed a 33 % enhancement in resistance.

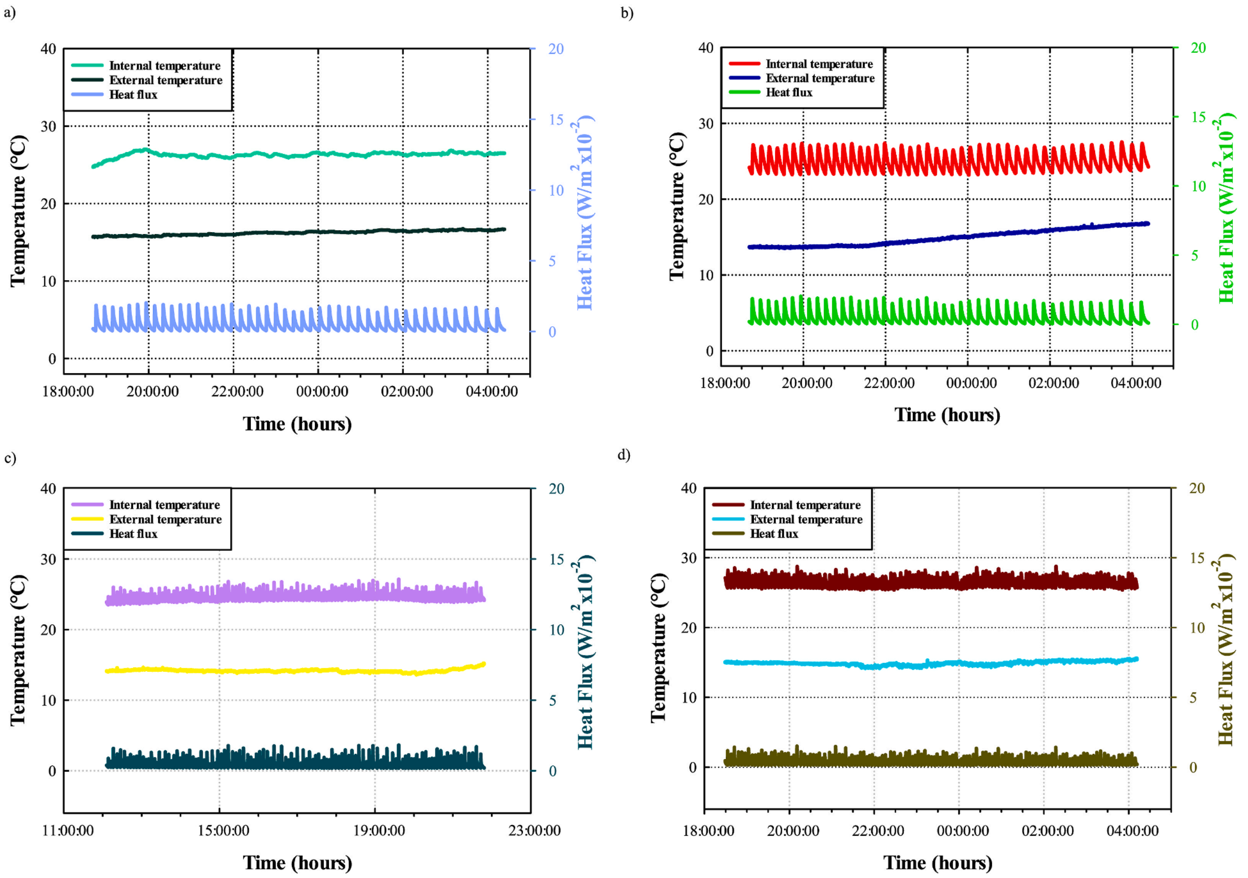

Fig. 8. Internal and external temperatures and heat flux values plotted for **a)** traditional briquette, **b)** 2 % bamboo reinforced briquette, **c)** 4 % bamboo improved briquette, **d)** bamboo strengthened bamboo.

The determination of the U-value, as planned through the coheating test method, is derived from the culmination of these gathered data. Consequently, the straightforward process involves dividing the heat flux by the difference between internal and external temperatures. This calculation leads to the determination of the U-value, thereby fulfilling the objectives of both the study and the coheating test method. Subsequently, if presented in the sequential order as delineated above, the traditional briquette exhibits a highest value of 13.75 W/m^2K, a lowest of 1.17 W/m^2K, and an average of 5.53 W/m^2K. In contrast, data from the briquette infused with 2 % bamboo indicate values of 31.456313 W/m^2K (highest), 0.232847 W/m^2K (lowest), and 4.698 W/m^2K (on average). Similarly, for the 4 % bamboo-reinforced briquette, values are recorded as highest 19.495579 W/m^2K, lowest 1.5136478 W/m^2K, and average 3.94 W/m^2K. Upon increasing the bamboo reinforcement to 6 %, a notably favourable outcome is achieved, with an average value of 2.77 W/m^2K, a highest of 10.308637 W/m^2K, and a lowest of 1.4470587 W/m^2K. The mean values of the samples are shown in Fig. 9 as well so as to prove the thermal performance of utilising bamboo for sustainable and low/zero carbon buildings in future.

Upon scrutinising the advancements in the U-value, as delineated by the data presented earlier and depicted in Fig. 9, the study unveils a profound revelation: bamboo, a quintessential exemplar of sustainable natural resources, augments the thermal resistance of briquettes, inherently characterised by modest thermal insulating properties. Evidently, as the proportion of bamboo fibres escalates, so does the magnitude of improvement. The discernible enhancement in thermal performance, elucidated by the empirical findings, showcases a remarkable escalation: introducing 6 % bamboo fibre in briquettes yields an approximate 41 % surge in resistance compared to the 2 % counterpart. However, with a doubling of the bamboo fibre ratio to 4 %, the observed thermal resistance of the 6 % variant registers at 30 %. This substantiates the substantial thermal performance contribution wielded by bamboo fibres, irrespective of their marginal differences in concentration. Furthermore, an unexpectedly substantial 49.9 % amplification in thermal characterisation, heralding a paradigm shift in sustainable insulation practices for between conventional and 6 % reinforced briquettes. Additionally, it has been noted that there is a 3 % enhancement in thermal efficiency compared to the 2.86 W/m^2K value recorded from the contemporary insulation plaster investigated in the prior study [40]. Moreover, Charai et al. [43] attain an approximately 31 % enhancement in thermal performance in their research employing 6 % hemp fibre, underscoring the effectiveness of this study with a similar ratio. The results have also proved the effectiveness of the coheating test method, which has been previously applied to the windows [52–57] and external walls [58–60] in different studies, and shown an excellent accordance with manufacturers' performance reports and real time monitoring data. The only issue with the coheating test method is the number of sensors or measurement units utilised in the tests as well as the accuracy of whole testing system. In this regard, within the present work, highly sensitive HF-P01 heat flux plates of Hukseflux company along with standardised T-type thermocouples have been utilised in the U-value analysis of bamboo fibre reinforced briquettes.

4. Conclusion

In this groundbreaking study, the integration of sustainable, rational, and nature-endowed resources is pursued to address the pressing issue of low thermal resistance in briquettes, a primary contributor to escalating energy costs. Through the incorporation of varying proportions of bamboo fibre (2 %, 4 %, and 6 %), traditionally overlooked as a thermal insulator, into the briquette composition, a concerted effort is made to revolutionise conventional practices. With a dearth of thermal investigations focusing on bamboo within the existing literature, the study aims to bridge this gap by pioneering the adoption of the coheating test method to evaluate bamboo's thermal performance when utilised as a briquette component. As the inaugural endeavour of its kind, this study stands as a testament to the innovative potential inherent in leveraging sustainable materials like bamboo for thermal insulation purposes. It is noteworthy that conventional briquette samples are meticulously prepared for comparative analysis alongside experimental varia-

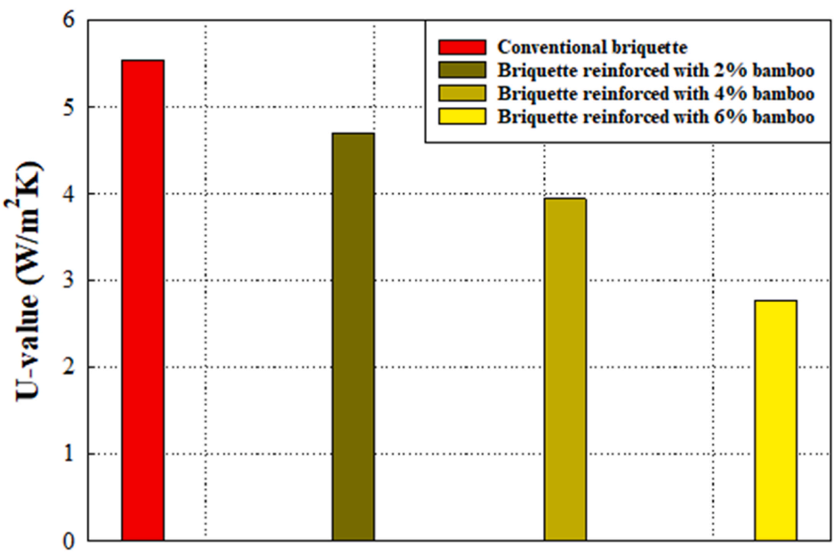

Fig. 9. Enhancements in thermal insulation characteristics of briquettes with bamboo fibre substitution.

tions incorporating bamboo fibre, affording a comprehensive understanding of the thermal enhancement achieved. In summary, this experimental inquiry underscores the following key findings and contributions:

- Whilst the conventional briquette yields a coefficient value of 5.53 W/m^{2}K, the inclusion of just 2 % bamboo fibre results in a marked decrease to 4.698 W/m^{2}K.
- The briquette containing 4 % bamboo fibre exhibits a coefficient of 3.94 W/m^{2}K, whereas the sample reinforced with 6 % bamboo achieves an even lower value of 2.77 W/m^{2}K.
- Upon examination of the sample ratios in light of the data presented, it becomes evident that the thermal performance of the briquette with 6 % bamboo addition surpasses that of the conventional briquette by an impressive 49.9 %. This significant improvement highlights bamboo's potential to reduce energy consumption in buildings, advancing energy efficiency in construction practices.
- In accordance with the previous study [40], the 6%-added bamboo sample demonstrates practically 3 % enhancement in thermal performance. Also, the study by Ref. [43], although the same fibre content is added like this study, the bamboo has great potential onto thermal resistance against the hemp fibre.
- Furthermore, it has been unveiled that the briquette sample with 6 % bamboo addition yields a thermal enhancement of 41 % and 30 % when compared to the samples containing 2 % and 4 % bamboo, respectively.
- The trend indicates a clear correlation between the amount of bamboo fibre in briquettes and improved thermal resistance.
- Bamboo fibre reinforced briquettes have a notable potential to achieve ideal built environment conditions in terms of thermal aspects [61]. In addition, the projections can be much more outstanding in case of integration with any type of renewable energy resource [62].

Overall, this pioneering study, which demonstrates significant enhancement in thermal resistance by substituting bamboo, holds immense significance for advancing sustainable and low/zero carbon housing design. The insights are poised to illuminate the potential of integrating sustainable materials like bamboo in construction practices, offering valuable guidance to architects, engineers, researchers, and stakeholders alike. By showcasing the feasibility and efficacy of bamboo as a thermal insulator, this study lays a solid foundation for future endeavours to foster environmentally-conscious building solutions. Collectively, these findings not only underscore the efficacy of bamboo as a sustainable solution for thermal insulation but also pave the way for further exploration and adoption of environmentally conscious materials in energy-efficient applications. In future studies, efforts will be made to find out the most optimum state in thermal performance by altering the sample size.

CRediT authorship contribution statement

Pinar Mert Cuce: Writing – original draft, Methodology, Formal analysis, Conceptualization. **Emre Alvur:** Writing – original draft, Software, Formal analysis. **Erdem Cuce:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization. **Saad Alshahrani:** Writing – review & editing, Funding acquisition. **Chander Prakash:** Writing – review & editing, Supervision. **Huseyin Tan:** Writing – review & editing, Methodology. **Ilker Ustabas:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare no conflict of interest.

Data availability

No data was used for the research described in the article.

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