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RESEARCH

Assessing thermal-mechanical properties of wood powder cellulose-based composites for 3D-printed architectural components

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Abstract
The construction industry is a major contributor to global CO_2 emissions, necessitating sustainable alternatives for building materials. Additive manufacturing (AM) using wood-based composites offers an eco-friendly solution for thermal insulation applications. This study explores the thermal and mechanical properties of wood powder–carboxymethyl cellulose composites fabricated via liquid deposition modeling (LDM). Six formulations incorporating industrial wood waste from beech and oak, with varied particle sizes, were developed to evaluate their extrudability, structural stability, and insulation efficiency. Material characterization included thermal conductivity testing via the transient plane source method and compressive strength assessment following ISO standards. Results indicate that particle size and wood species significantly influence material properties. Finer wood particles yielded higher compressive strength, whereas coarser particles exhibited lower conductivity, enhancing insulation performance. The best-performing formulation (B2: beech wood, medium particle size) demonstrated a balanced thermal conductivity of 0.188 W/m·K and compressive strength of 3 MPa. To assess large-scale buildability, a 3D-printed block component (200 × 350 × 220 mm) was fabricated. A refined formulation with reduced water improved print stability, demonstrating the viability of LDM for producing rigid, lightweight insulation blocks. This research establishes a foundational understanding of AM wood composites for thermal insulation, offering insights into material formulation, printability, and structural behavior. The findings underscore the potential of bio-based AM in sustainable construction, paving the way for scalable applications of wood waste in energy-efficient building systems. Future work will focus on optimizing binder composition, refining printing strategies, and exploring reinforcement techniques to enhance mechanical properties while maintaining thermal efficiency.

Keywords Additive manufacturing · Liquid deposition modeling · Thermal conductivity · Compressive strength · Recycled wood waste · Bio composites · Sustainable architecture

Introduction

The building and construction sector is responsible for approximately 37% of global energy and process-related CO_2 emissions, with building operations accounting for around 27% and the production of building materials contributing an additional 10% [1]. Insulating materials, such as mineral wool, expanded polystyrene, extruded polystyrene, and polyurethane with ranging thermal conductivity of 0.030–0.046 W/m.K, play a vital role in energy efficiency by maintaining stable indoor temperatures with reduced energy consumption [2]. However, these materials are often petroleum-based, posing challenges for disposal and contributing to higher CO_2 emissions. In this context, adopting low-carbon insulation could reduce CO_2 emissions from material production by over 80% [3]. The market for bio-based insulation is expected to grow, reaching 2.3 billion euros by 2032, with an annual growth rate of 3% per year [4]. A promising bio-based insulation material is wood-based insulation that is influenced by the manufacturing process, binder content and the natural structure of wood

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[5, 6]. Strategies such as selecting lower density wood, smaller particle sizes, and lowering forming pressures have proven effective in achieving lower thermal conductivities [7, 8]. These strategies create small voids within the structure, increasing the complexity of the heat transfer path and thereby reducing thermal conductivity.

Additive Manufacturing (AM), still a relatively new and underexplored field in the building and construction sector, holds significant potential for contributing to energy efficiency initiatives [9, 10]. AM competes with traditional production methods by enabling complex designs with reduced tooling costs, optimized performance, minimal material wastage, a lower carbon footprint, and customizable geometries, making it a promising technology for sustainable construction [11, 12, 13].

Wood waste, including sawdust from various industrial processes, is an emerging material in the context of AM. Wood-based AM has demonstrated that it can recreate several physical properties of wood such as compressive, acoustic and insulative performance [14, 15, 16]. Wood combined with a binder creates an extrudable wood-based material that can be deposited layer by layer [17, 18]. Wood powders mixed with polymers, extrudable at plastic melting temperatures using Fused Filament Fabrication (FFF) or Fused Deposition Method (FDM), achieve good structural properties albeit at lower wood percentages, typically between 5 and 20%. In contrast, methods such as layer-by-layer binding, Direct Ink Writing (DIW), and Liquid Deposition Modeling (LDM) can incorporate higher wood percentages, from 60 to 100%, effectively leveraging more wood properties and increasing wood biomass usage. LDM is a promising method for AM that predominantly uses wood [19]. To achieve sustainability, bio-based binders such as clay, gypsum, methyl cellulose, and Carboxymethyl cellulose (CMC) have been explored and cellulose-based binders mixed with wood powder have shown promising printability, exhibiting physical behaviors like wood in the final components [17, 18]. However, physical properties such as thermal performance attributed to wood remain underexplored in LDM printing. Additionally, challenges associated with large-scale printing persist, including significant post-drying shrinkage, deformation and the need for efficient tool paths [20].

In response, this paper evaluates sustainable construction materials using wood waste for thermal and structural efficiency by exploring the use of 3D printing techniques, specifically LDM. These materials were developed using industrial wood waste combined with natural binders, specifically CMC, to ensure recyclability. The study focused on optimizing the composition of these materials by investigating the influence of different wood types and particle sizes on their thermal conductivity and mechanical strength, providing insights into how variations in material formulations affect both the insulation capabilities and the structural performance of printed models. In addition, the development of a large-scale block component, measuring 200 mm high, 360 mm wide, and 220 mm deep, was 3D printed to assess the material's buildability and potential for applications in the architecture and construction sectors.

As a contribution to the field of sustainable building materials, this demonstration offers insights into how scalable, eco-friendly wood-based composites can be used as thermal insulation components. The study not only explores new possibilities for material formulation but also investigates how these materials can be effectively used in 3D printing, making them applicable to real-world construction needs.

Background

Bio-based insulation and wood as insulation material

Bio-based insulation materials, derived from renewable biological sources, are gaining popularity in the construction industry due to their sustainability and environmental benefits. Ajabli et al. reviewed various eco-friendly insulation materials used for indoor comfort in buildings, highlighting cellulose, hemp, flax, and wood fibers as viable alternatives to traditional insulation like fiberglass or foam [21]. These materials offer renewable and environmentally responsible solutions for thermal insulation.

The UN Environment Programme, discussed the role of sustainable building materials, including wood-based products, in reducing the environmental footprint of construction [1]. Wood waste, a byproduct of primary wood processing (e.g., sawdust), has been widely explored as an insulation material [5, 6, 22, 23]. Cetiner and Shea investigated the potential of wood waste as an alternative thermal insulation material, demonstrating that processed wood waste such as fiber boards or wood chips retains low thermal conductivity and good hygroscopic properties, making it a viable insulation option [6].

Jelle investigated the thermal performance of different insulation materials and emphasized that wood, due to its cellular structure, effectively traps air, reducing heat transfer and enhancing insulation properties [2]. The study also noted that wood-based insulation materials, such as wood fiber boards and wood wool, provide additional benefits such as sound insulation and moisture regulation. Similarly, Mawardi et al. investigated panels made from oil palm wood waste, confirming their potential as bio-insulation materials [24]. Additionally, the effect of wood species and particle size distribution on mechanical and thermal properties has been explored in multiple studies. Delviawan et al. investigated wood–plastic composites using pine wood powder with particle sizes ranging from 90 to 250 µm, finding that mechanical strength increased as the particle size decreased up to a threshold of 90 µm [25]. Furthermore, Oluyamo et al. examined the impact of wood type and particle size on the thermal conductivity of wood waste-based insulation. Their findings indicate that these factors significantly influence the insulation properties compared to bulk wood material [7].

These studies reinforce the idea that repurposing wood waste for insulation and structural requires examination at the material selection and processing level leveraging the sustainability of waste streams.

Additive manufacturing in construction and with wood biomass

AM has brought significant advancements to the construction industry by enabling the fabrication of complex and customized structures with high precision and minimal material waste, thereby reducing construction errors [11]. Extrusion-based and powder-based methods are recognized as the most promising for large-scale applications among various AM techniques, including binder jetting, material extrusion, direct energy deposition, sheet lamination, powder bed fusion, and vat photopolymerization [11]. The thermal and structural properties of the 3D printed structures can be optimized by geometry and materials. For example, Dziura et al. investigated the effect of internal geometries in additively manufactured building blocks to enhance thermal insulation [26]. Rangel et al. investigated cork as inclusion to improve thermal efficiency of 3D printed mortar by introducing porosity [27]. This underscores, how inclusion of higher percentage of biomass, which is high in natural porosity, or inversely lower binder ratios (assuming binder has high thermal conductivity), along with insulative geometries in AM may help develop highly insulative components.

Among various biomass types used in 3D printing, wood has recently emerged as a dominant material printed using various techniques such as FDM/FFF, DIW, binder jetting, LDM to name a few [28]. For successful extrusion in AM, wood must first be ground into a powder and suspended in an interface that can flow out of the nozzle. FDM and DIW both rely on fine particles due to small nozzle sizes. Bahar et al. explored FDM of wood-PLA composite containing 30% pine wood, achieving thermal conductivities in the range of 0.04 to 0.07 W/m·K using infill based geometries [29]. Additionally, Kam et al. examined DIW and Direct Cryo Writing (DCW) techniques with different wood species mixed with cellulose nanocrystals and xanthan gum as binders, resulting in thermal conductivities between 0.05 and 0.085 W/m·K [13]. Henke and Treml were the first to print wood chips of 0.8–2 mm size to fabricate wood composites using non synthetic binders such as methyl cellulose, concrete and gypsum using layer by layer binder deposition like method however were limited to maximum 2.5 mm layer height [30]. It can be noted that, FDM, DIW and DCW benefit from high-resolution printing which can highly control insulation properties through geometry, however DIW and DCW remain limited in scalability for large scale printing. Also, FDM while promising for large scale buildup, limits its wood content to 40% reducing the advantages of wood properties, and relies on energy-intensive synthetic materials [31].

LDM enables higher wood content, up to 90% using bio-based binders like methyl cellulose and starch, reducing energy consumption and dependence on synthetic resins as studied in the works by Rosenthal et al. [17, 32]. These studies employed larger particle sizes (up to ~500 µm) than FDM with cellulose based binders, along with larger nozzle diameters and greater layer heights, which makes LDM a promising approach for large-scale 3D printing. While in LDM with wood buildability remains a challenge due to high water content, it was also found that using larger wood particles in LDM resulted in reduced mechanical strength (limited to 5 MPa with biobased binders), but increased permeability, facilitating faster drying and improved buildability. This supports the idea of using larger wood particle sizes for large-scale 3D printing of rigid, non-structural, insulating components.

Despite these insights, the effects of wood percentage, wood species, and particle size in the specific context of LDM remain insufficiently explored for physical and especially thermal properties. Further research is required to establish correlations between material parameters and structural performance in large-scale additive manufacturing applications.

The objective of the study was to reveal the potential of using LDM of wood composites to build rigid insulative components in the building sector for which the local control of the thermal properties is ensured by the choice of wood type and wood particle size. The study employs CMC as the binder for it's already explored properties for LDM, and because of its natural origin, biodegradability and proven reusability [20, 33, 34].

In the study, the mechanical and thermal properties of wood-CMC composites for LDM are analyzed, focusing on utilizing wood waste as a raw material for applications in the building sector. A key hypothesis of this research is that the composite's thermal and mechanical properties can be tailored at the source by selecting specific wood types and particle sizes. Additionally, the printing of wood particles may present unique properties which may influence the final properties of the component. It can also be hypothesized that while the mechanical performance of wood-CMC composites might be low relative to load bearing material, this would not contradict their effectiveness as thermal insulators, as insulation materials do not necessarily require comparable mechanical strength [35]. Furthermore, exploring the scalability of wood-CMC composites for 3D printing rigid insulation applications in the architecture and construction sectors could enhance the sustainability of various building systems by utilizing bio-based materials and promoting environmentally responsible material and manufacturing practices.

Materials and methods

This study systematically explores the influence of wood type, particle size, and formulation ratios on the thermal and mechanical properties of wood-CMC composites for 3D printing. The research was structured into three key phases as illustrated in Fig. 1: (1) developing classified Wood-CMC composites for LDM, (2) evaluating dried and hardened properties such as particle distribution, thermal conductivity, and compressive strength, and (3) selecting an optimized formulation for fabricating a large-scale block to assess buildability. Six different formulations, using beech and oak wood with varying particle sizes, were tested to analyze their influence on printability, structural stability, and insulation efficiency. Correlations between material composition, thermal conductivity, and compressive strength were made aiding in the formulation of bio-composites optimized for large-scale additive manufacturing applications.

Materials

Composites tested in the research were fabricated using two types of wood powders: Beech and Oak. The wood, procured in the form of shavings, were selected based on their availability in local industries, Beech (Fagus sylvatica) known for density and machining for furniture and flooring industry and Oak (Quercus Robur) for sturdy, mechanical strength.

Wood powder was further classified into three particle size ranges to develop 6 formulations for the study as shown in Table 1. Beech and Oak wood shavings was procured in dry state and stored at ambient room conditions. Each wood sawdust shavings were ground into wood powder using a Ninja® Nutri-Blender Pro with Auto-iQ®, model BN40 [36] in the small batches of 2/3rd the container capacity in 60 s auto mode. The ground wood was manually sifted for 5 min using a sifting column with three sections having 1200-micron, 800- micron and 400-micron mesh. In total six wood powder ranges were prepared, three for each wood type, classified into <400 microns, 400–800 microns and 800–1200 microns (Fig. 2). These ranges were chosen based on having fine, medium and coarse particle sizes as described in previous works with wood 3D printing [19].

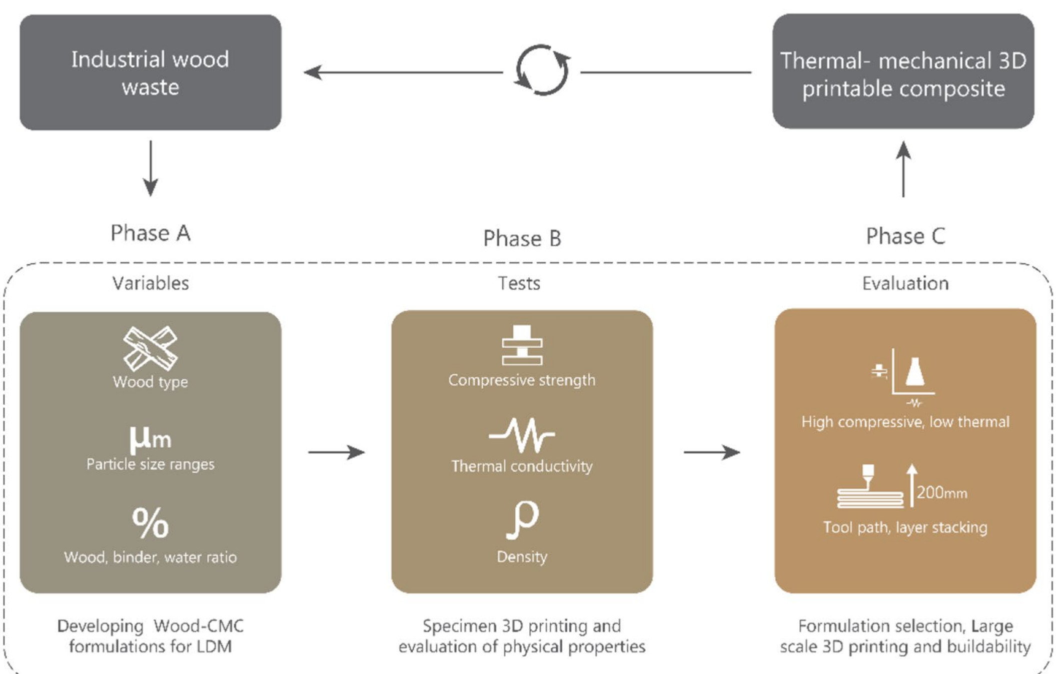

Fig. 1 Schematic roadmap of the research three-phased experiment setup

Table 1 Properties of the wood composite materials tested

Wood powder	Formulation code	Properties of wood powder		Wood-CMC-water ratio (by wt.)
		Size (microns)	Density (g/cm^3)	
Beech wood powder	B1	<400	0.68	2:1:7.75
	B2	400–800		
	B3	800–1200		
Oak wood powder	O1	<400	0.64	
	O2	400–800		
	O3	800–1200		

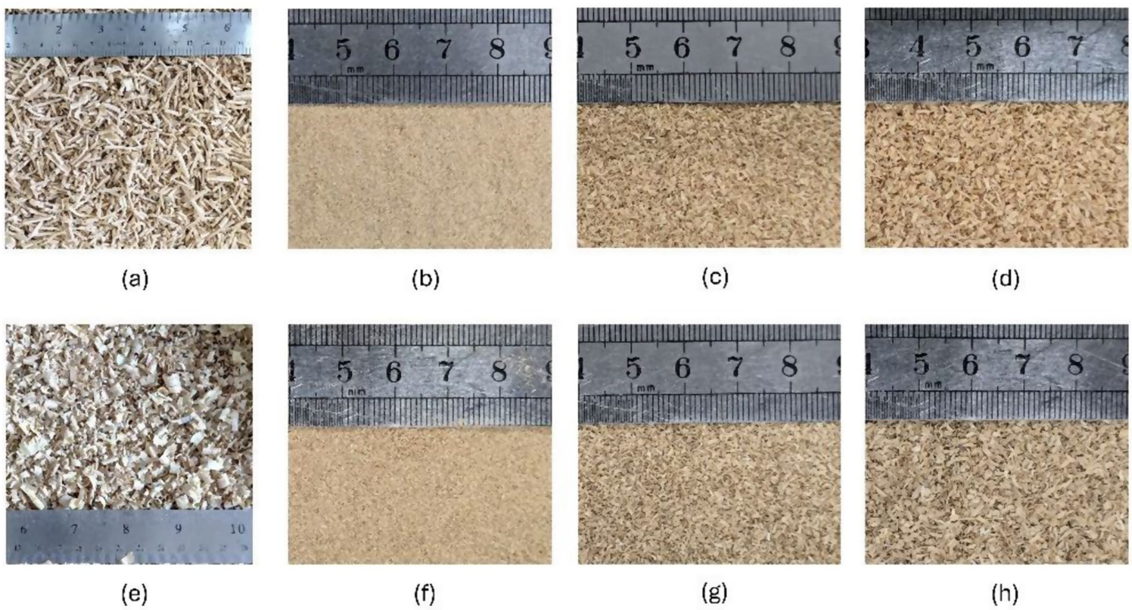

Fig. 2 Initial sawdust of beech (**a**) and oak (**e**); Wood powder derived from beech (**b**, **c**, **d**) and oak (**f**, **g**, **h**), corresponding to B1, B2, B3, and O1, O2, O3, respectively

ASEL TY 300 (Aciselsan, Turkey) [37], a technical-grade sodium carboxymethyl cellulose (Na-CMC), was used as a binder and interface. It appeared as a white to cream-colored powder or granule with a CMC content of 60±2% (dry basis), DS of 0.7–0.8, pH of 8–11 (1% sol.), viscosity of 300–600 cP (2% sol., Brookfield, 20 °C), and max. moisture content of 15%. Na-CMC is known for its stable composition for storage, for not forming lumps too easily, and for its ease of dissolving in water at room temperature. Tap water at room temperature was used as the base for the formulations.

Initial explorations were done in smaller batches to optimize the Wood/CMC ratio to increase wood content across all the particle size ranges. Wood/CMC ratios of 4:1, 3:1 and 2:1 by weight were tested for developing a homogeneous paste. Water requirement was different across particle sizes and wood types ranging between 7 and 7.75. The highest value of optimized water amount was chosen to achieve homogeneous paste with standard ratios throughout the formulations.

For the specimen fabrication, all the formulations mixes were prepared using the same wood to binder to water ratios as 2:1:7.75. This ensured wood type and particle sizes are particularly investigated.

Material preparation was carried out in two phases. In the first phase, the wood powder and CMC powder, in 2:1 weight ratio, were dry mixed in a pan for 1 min to achieve a homogeneous, lump-free mixture. The mixture was then transferred to a planetary mixer for further processing. In the second phase, water was added in batches of 1/3 of the total weight, in 3 cycles, until a clay-like homogeneous paste was formed. This ensured uniform consistency of the mix. In total the six materials were prepared with the same wood to CMC ratios by weight. The formulation was named O1, O2, O3 and B1, B2, B3 for fine, medium and coarse size particles, and for Oak and Beech respectively (Table 1). Owing to CMC's gelling time, the material was given a resting time of 15–20 min before it was kneaded again to be loaded into the 3D printer extrusion tank.

Fig. 3 Wood-CMC wet paste formed into lumps before loading (B1 formulation)

Table 2 Printing parameters for specimen fabrication

Nozzle diameter	Layer height	Print Speed	Extrusion width	Extrusion pressure
16 mm	3 mm	500 mm/min	~25 mm	4.5-5 bar

Material properties of wet mixture

The rheological properties of the clay like mixture for 3D printing were evaluated manually through observation and tactile manipulation. The wood CMC wet mix shows a viscoelastic behavior due to CMC's properties [33]. The mixture was assessed for its resistance to cracking and adhesion to evaluate homogeneity and optimal water content. Every lump was manually kneaded for the water and CMC to homogeneously spread into the viscoelastic solid mixture (Fig. 3).

Fabrication of 3D printed specimens

To develop specimen for each formulation, a single tool path describing a free wall geometry of 150 mm length and 80 mm height were fabricated using the printing parameters shown in Table 2. The tool path was designed in Rhinoceros 8 using the Grasshopper plugin, using the generative tool path facilitated by the Droid v2.0.8 plugin ("Droid − 3d Print Slicer and Path Plotter," 2018 [38] A delta type AM setup was used to print the specimen. The setup involved the Delta wasp 40100 LDM 3D printer assembled with an Extruder XL 3.0 and a 3 L tank. A custom extrusion nozzle was designed with a 16 mm output diameter and 3D printed using PLA (Fig. 4, Image 1). The pressure at the source was 9 to 11 bar which was regulated by the pressure valve maintained at a constant 4.5-5 bar pressure to extrude the material for uniform layer thickness.

A sturdy mesh base was used to print, serving as a transport tray and enabling ventilation for the base of the print during the drying process.

Each print was dried using a two-phase protocol, air drying in room conditions and hot air drying. Air drying was done for 4 days at the temperature of 21 ± 3ºC and relative humidity of 60 ± 5%. A setup was created with two mini table fans placed at the top and the bottom of the specimen to keep constant airflow on all the surfaces promoting even drying. In the second phase, the hardened specimens were hot air dried with a dehydrator for 10 h at the temperature of 50ºC. Post drying, the dried specimens were extracted from the fully dried 3D printed wall (Fig. 4, Image b, i) as per the

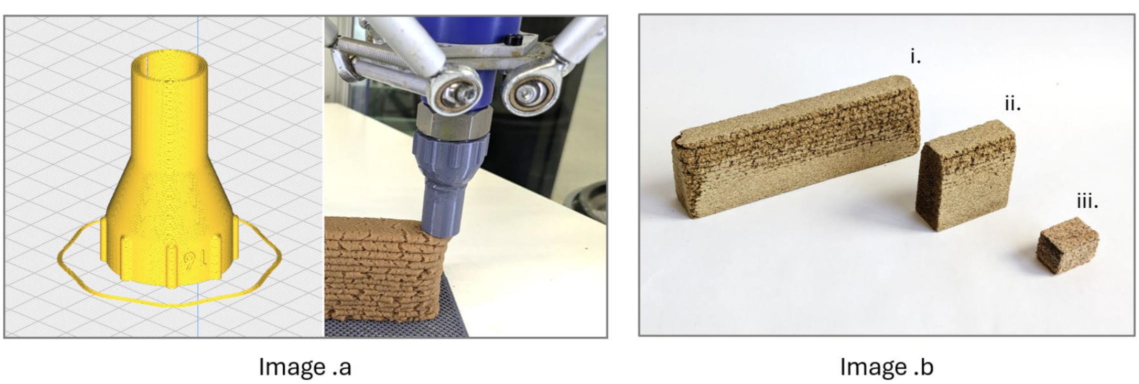

Fig. 4 Image **a**: Custom 3D-printed nozzle designed for specimen fabrication. Image **b**: Specimen extraction process in progress: **a**. Partially sanded specimen being prepared for thermal conductivity testing. **b**. Specimen being prepared for compressive testing

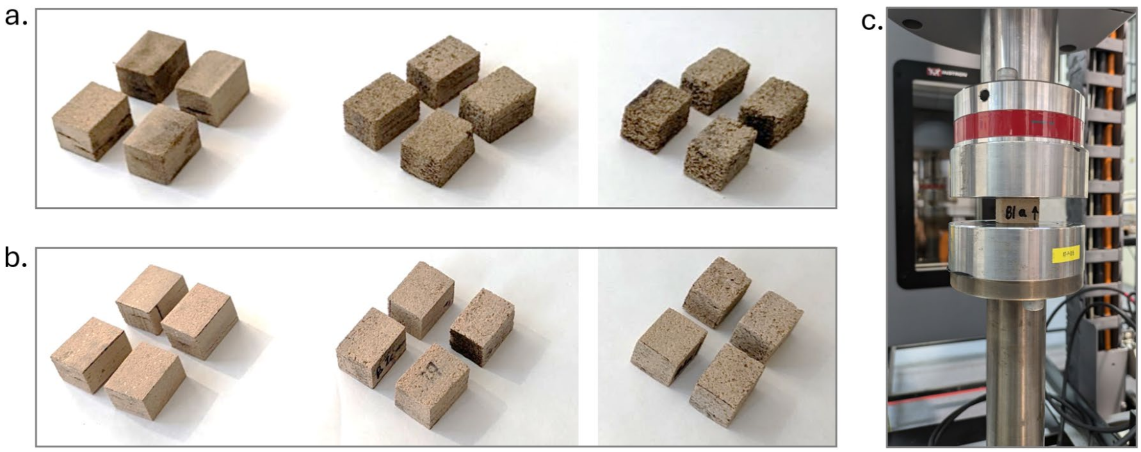

Fig. 5 Specimens for compressive tests **a**.: Oak wood composites and **b**. beech wood composites. **c**. compressive test setup Instron ElectroPuls® E10000 Linear-Torsion press

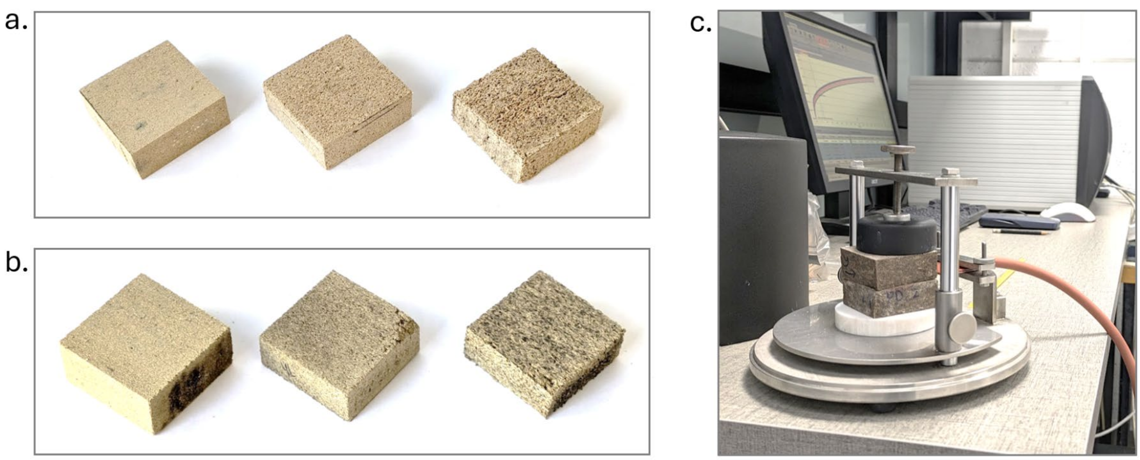

Fig. 6 Specimens for thermal tests (**a**) beech wood composites (**b**) Oak wood composites, (**c**) Hot Disk TPS setup for thermal conductivity tests

compressive (Fig. 4, Image b, iii) and thermal conductivity (Fig. 4, Image b, ii) test standards, and further sanded to achieve smooth parallel surfaces.

Mechanical and thermal performance of dried 3D printed specimens

The compression test was conducted on four specimens measuring 18 × 27 × 18 mm (Fig. 5, a & b), following ISO 13061-5:2020 [35], chosen for its suitability in evaluating small wood specimens. The test was performed using an Instron ElectroPuls® E10000 Linear-Torsion press, capable of exerting up to 10 kN (Fig. 5).

Thermal conductivity was assessed using an extracted pair of square prisms (50 × 50 × 15 mm) for each formulation in accordance with the Transient Plane Source (TPS) method as per ISO 22007-2:2022 [36] using TPS 2500 S® model of Hotdisk®. The sensor used for the test was Kapton insulated sensor number 8563 with a radius of 9.9 mm (Fig. 6). The TPS method was selected due to its availability, accuracy, and reliability in measuring the thermal properties of wood composites. Studies have confirmed its effectiveness across varying moisture levels and temperatures [37, 38]. Each test went through five cycles of test and standard deviation was assessed.

Each extracted sample of square prisms was weighed to measure their apparent density. All specimens were conditioned and tested at approximately 60% relative humidity under ambient temperature conditions.

Design and fabrication of block component

To assess the buildability and customization potential of the proposed wood composite formulation for large-scale 3D printing in architectural and construction applications, two test blocks were designed and fabricated as potential wall segments. The block dimensions were kept 200 mm in height, 350 mm in width, and 220 mm in depth. These dimensions were chosen to fit within the constraints of the Wasp Delta 40,100 3D printer, which has a 400 mm diameter print bed.

The first block design incorporated a combination of single-walled and double-walled structures. One of the walls incorporated a negative cantilever and a staggered infill pattern (Fig. 7), which was employed to imitate long heat-bridging paths aiming to enhance the thermal insulation properties. The single wall paths varied in length from 35 to 70 mm to evaluate how the formulation performed in buildability. The tool path geometry was designed using Rhinoceros 3D software, with the custom slicing performed through the Grasshopper plugin to develop a continuous tool path per layer. The nozzle diameter for extrusion was 6 mm, and a layer height of 3.2 mm was used for both blocks and extrusion pressure 4.5-5 bar.

Based on the examination of the printing outcomes of the first block, a second block was designed and fabricated using fine-tuned material ratios to improve buildability. The cantilever design was removed, the toolpath overlap was increased, a double outer wall was added, keeping the overall build dimensions of (200 mm x 350 mm x 220 mm consistent to the first block. The same printing parameters were maintained and the material was extruded at 6.5 bar pressure.

Both blocks were measured immediately after printing and again after a 14-day drying period. These measurements provided insights into the structural integrity and dimensional stability of the printed components as the moisture content decreased during drying. The shrinkage, and any deformations observed during the drying process were recorded for further analysis.

Results and discussion

The experimental results from the three research phases revealed significant findings regarding the influence of wood type, particle size, and formulation ratios on the thermal and mechanical properties of wood-CMC composites developed for LDM printing. These findings, in correlation to the 3D printing buildability challenges of large-scale block components from the developed composites, will be discussed in the following sections.

Mixture development and printability

The first phase of material development focused on maximizing wood content and optimizing CMC and water ratios to develop an extrudable mix across different particle sizes of beech and oak wood. CMC/wood ratios 1:4, 1:3,1:2 was explored. The water ratio required to ensure a homogeneous, clay-like paste ranged between 7 and 7.5. The second phase focused on material preparation of the formulation mix of

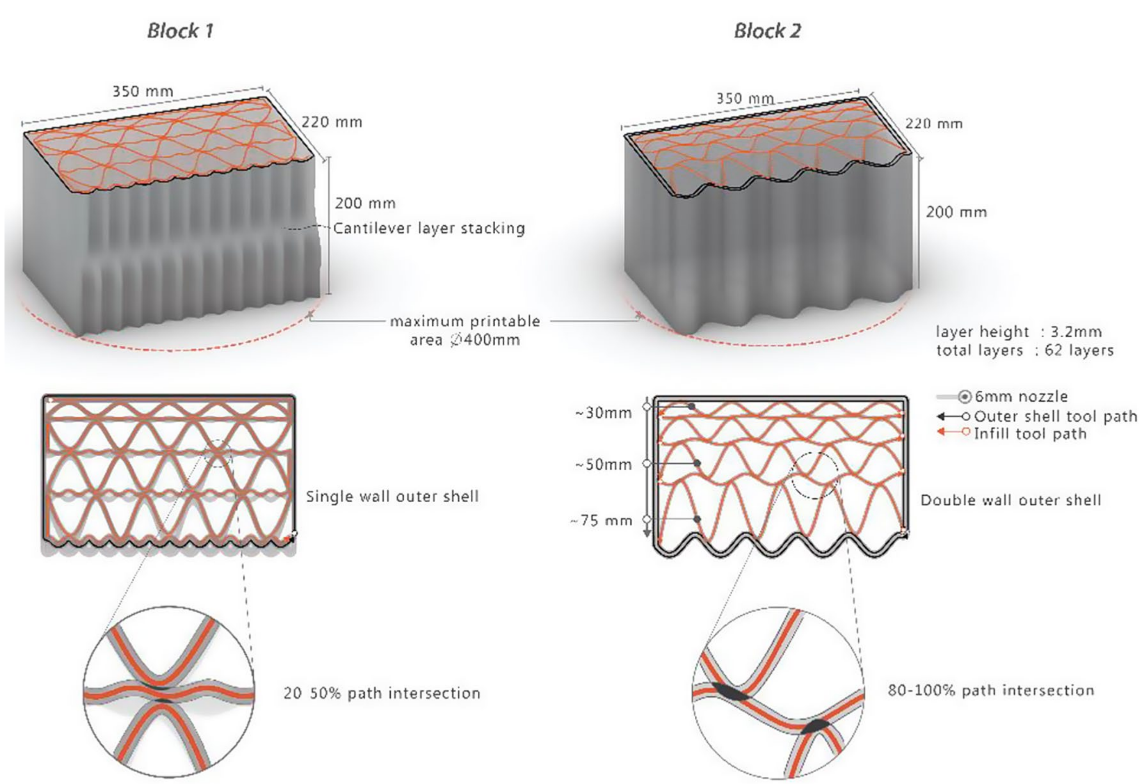

Fig. 7 Design schematics of large-scale 3D printed test blocks as a potential wall segment

wood/CMC/Water at ratio 2:1:7.75 and checking printability. This ratio was achieved for coarse particle size which was standardized for all the mixes for further printing of specimens, ensuring only wood type and particle size are the parameters for further evaluation.

In the first phase, CMC/wood ratio 1:4 rendered a non-homogeneous crumbly mix for all the particles leading to wood particle separation from the CMC gel on material manipulation. While medium and fine particles achieved optimal homogeneity at around 1:3 ratio. 1:2 ratio was optimal for all the particle sizes. Smaller particles required less CMC and water to form an extrudable paste, while coarser particles experienced binder separation under high-pressure extrusion when excessive CMC was added. Water demand remained similar for both beech and oak, with beech requiring slightly less (~1% difference). It was revealed that both wood and CMC absorb significant amounts of water and may also be particle size dependent but extrudability is primarily governed by the viscosity of the Water-CMC gel interface, the ability of wood particles to move within the interface and the extrusion pressure. Water availability for paste formation depends on the residual water after absorption by wood particles. Water absorption and extrusion characteristics of Wood-CMC composites are influenced by particle size, surface area, and water distribution. Larger particles required more water for extrudability due to their granular structure, which may have hindered uniform paste formation.

In the second phase, while all the particle sizes were found easily extrudable, the workability of the mix was found to be sensitive to time. For example, Beech formulations benefited from a 15–20-minute resting period to achieve optimal workability. This may be attributed to the swelling time for wood particles which is species dependent and CMC. The order of mixing the wood and CMC to water may also contribute towards change of water and CMC ratios in the mixture. Previous work with Wood-CMC printing used much higher water/binder ratio [20] which may be due to CMC's dynamic viscosity or cP value. Higher viscosity grades of CMC tend to retain more water due to their increased molecular weight and higher degree of substitution, affecting the rheological properties and extrudability of the paste [39].

Influence of wood particle size on thermal conductivity and compressive strength

The test results for density, thermal conductivity, and compressive strength of the specimens are summarized in Table 3.For all tested formulations, a decrease in particle size corresponded to an increase in thermal conductivity. The highest thermal conductivity values were observed in B1 (0.218 W/m·K) and O1 (0.188 W/m·K), while the lowest were recorded for B3 (0.175 W/m·K) and O3 (0.14 W/m·K) for Beech and Oak, respectively. A similar trend was noted in compressive strength measurements. Among the tested specimens, B1 exhibited the highest compressive strength at 4.1 MPa, whereas O3 had the lowest at 0.6 MPa. These results align with findings by Rosenthal et al. [17] on the limitation of compressive strength of wood composites up to 5 MPa with bio-based binders. These findings highlight the significant effect of particle size on thermal conductivity, corroborating the results reported by Oluyamo et al. [7]. Furthermore, the measured thermal conductivity values were lower than the bulk thermal conductivity reported for Beech (0.2365 W/m·K) and Oak (0.2582 W/m·K) by Yapici et. al [40]. The formulations containing fine particle sizes exhibited the highest standard deviation, followed by coarse particles, with the lowest observed in medium-sized particles. This variability may be attributed to the formation of minor internal cracks in the fine particle formulations and the non-uniform particle rearrangement in the coarse particle formulations. Compressive testing of all specimens demonstrated only vertical deformation, indicating high material porosity and horizontal fibre directionality influenced by the printing process..

Compared to Air Crete, which exhibits a thermal conductivity range of approximately 0.1–0.15 W/m·K and a compressive strength typically ranging from 0.5 to 3 MPa, the wood composite materials show comparable thermal insulation potential while offering enhanced mechanical performance in formulations such as B2.

Table 3 Specimen density, thermal conductivity and compressive strength of formulations

Specimen Name	Average Density (g/cm^3) at 60% RH)	Thermal Conductivity (W/m·K) at 60% RH (average of test 5 cycles)	Compressive Strength (MPa) at 10% Strain (average of 4 specimens)
B1	0.601	0.218 ± 0.004	4.1 ± 2.19
B2	0.545	0.188 ± 0.001	3 ± 0.05
B3	0.437	0.175 ± 0.001	1.2 ± 0.31
O1	0.509	0.150 ± 0.002	1 ± 0.18
O2	0.459	0.141 ± 0.001	1.6 ± 0.11
O3	0.455	0.140 ± 0.002	0.6 ± 0.2

This suggests that wood composite materials can serve as alternative for non-structural building components where moderate insulation and compressive strength are required such as for making wall panels, insulation blocks, and partition systems. Given that the required thermal conductivity for insulation materials typically falls below 0.2 W/m·K, and non-structural load-bearing materials often require a compressive strength above 0.5 MPa, these composites seem promising for functional integration into sustainable construction practices.

Influence of wood type on thermal conductivity and compressive strength

Beech-based formulations overall exhibited higher compressive strength and thermal conductivity than Oak-based formulations. Highest being 4.1 Mpa and 0.218 W/m.K in Beech, and 1.6 Mpa and 0.150 W/m.K in Oak. This can be correlated with slightly higher bulk density of Beech 0.68 g/cm^3 than Oak 0.64 g/cm^3. The R-value (correlation coefficient) for the regression analysis between thermal conductivity and compressive strength is approximately 0.898. This indicates a strong positive correlation between the two variables in the bio-composite specimens (Fig. 8). This shows that the composites carry forward the physical properties of the wood used in it. The strong correlation ($R \approx 0.898$) between compressive strength and thermal conductivity aligns with trends seen in other wood-based composites [41]. Denser materials tend to transfer heat more efficiently because they have fewer air gaps and more solid contact. While this is beneficial for structural applications, it may be a drawback for insulation, where lower thermal conductivity is preferred. Other factors like moisture absorption, binder distribution, and how well the wood particles bond with the binder might also affect this relationship. Studying these aspects further could help in designing bio-composites that balance strength and insulation. Future research could explore ways to adjust these properties, such as modifying the material's structure, adding controlled porosity, or optimizing the binder composition for different needs.

Influence of particle distribution and orientation on thermal conductivity and compressive strength

Using optical microscopy, visual analysis of morphology and the microstructure at the cross section of samples was done. Particle distribution, voids and inter particle bonding were observed, which are the main characteristics that influence thermal and physical properties of the material. The microscopy images presented in Fig. 9 illustrate the presence of voids that increase as the particle size grows, which can be correlated with the thermal conductivity and compressive strength decrease. The particle distribution shows homogeneous layer bonding in all the particle sizes which explains material homogeneity during the print. Particles also exhibit an orientation in the direction of print, more evident in large particle size, which explains only vertical deformation in compression tests samples, may also contribute to anisotropic behavior in strengths. In the microscopic images in Fig. 10, fine and medium particle size samples show a microstructure composed of closed pores within wood particles and inter-particle voids that form open pores. The larger voids in coarse particles likely increased moisture permeability during drying, influencing drying deformations and overall dimensional stability. It can be assumed that a mix of large and small particles can be developed that can fill up the voids offering better packing ensuring better

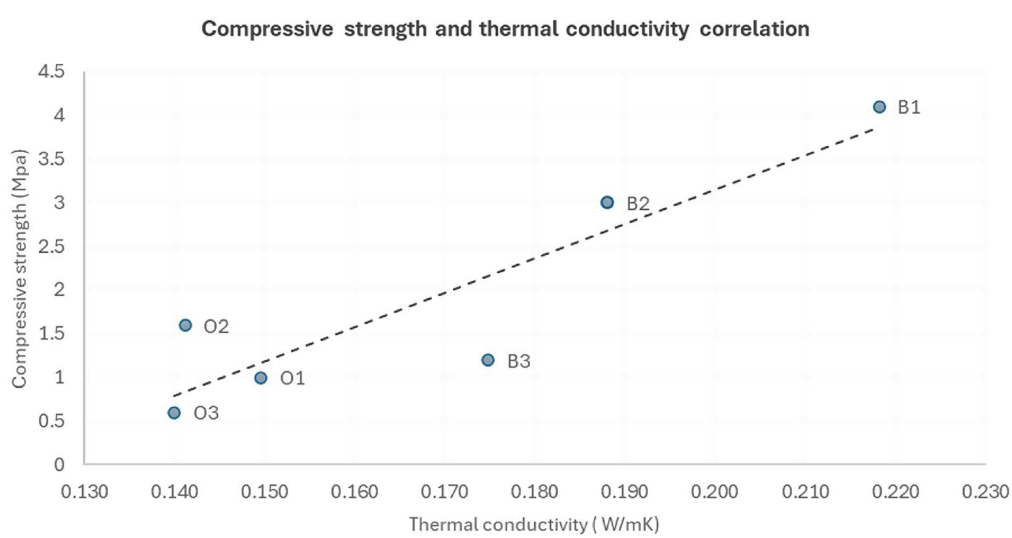

Fig. 8 Regression analysis between Thermal Conductivity and Compressive Strength of Wood Bio-Composite Specimens

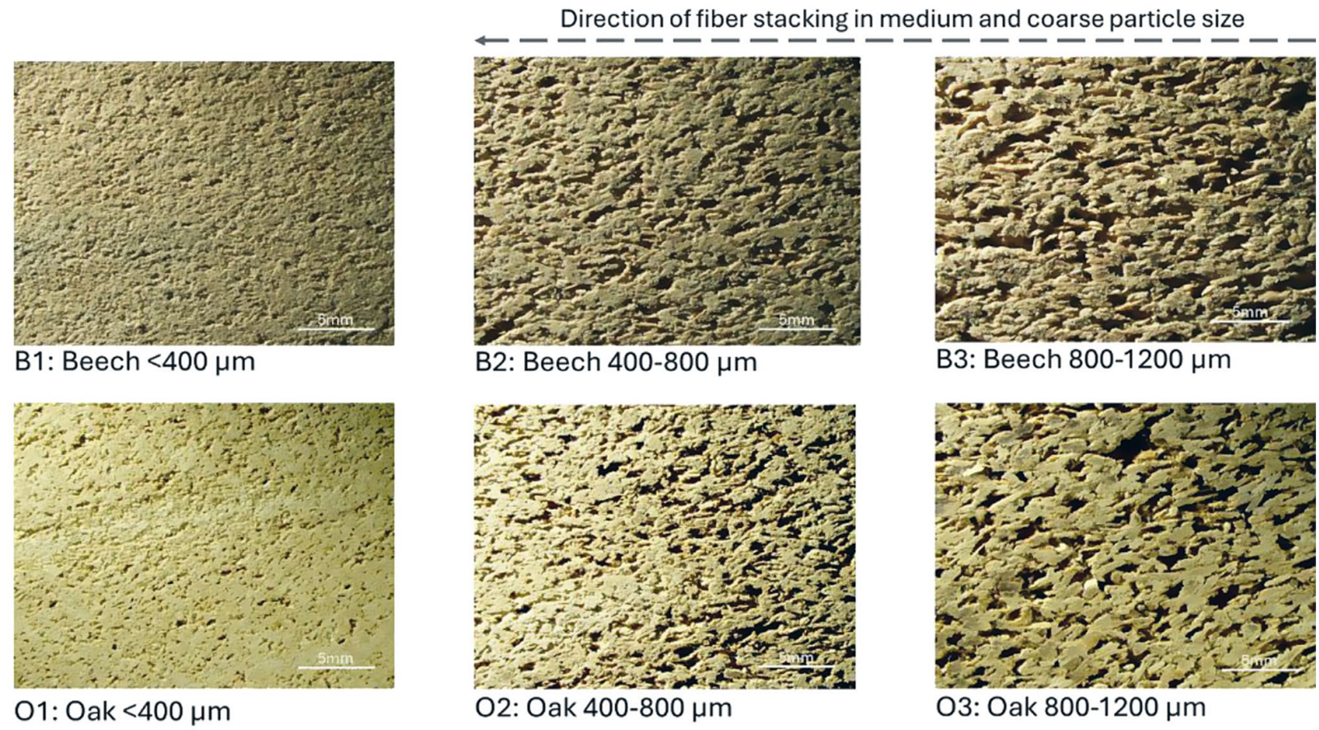

Fig. 9 Optical microscopy images showing the cross-section of dried 3D-printed oak and beech Wood-CMC specimens, highlighting particle distribution along the tool path

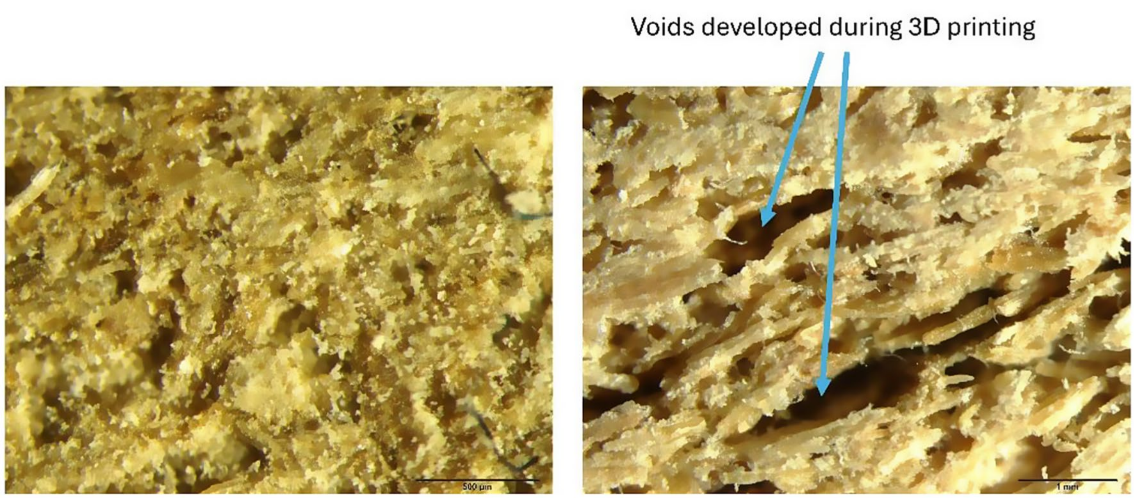

Fig. 10 Optical microscopy images revealing interaction between Wood particles and CMC, the voids formed and CMC film coating (left: B1 specimen, right: B2 specimen)

compressive properties, which may also help in buildability [17] and reduced drying deformations.

Thermal conductivity of CMC

This study faces uncertainty regarding the thermal conductivity of CMC within the dried composite. As the binder, CMC's thermal properties could impact the composite's overall conductivity, but precise data on its behavior in this form is lacking. To control this, the CMC content was kept constant across all formulations, allowing variations in performance to be mainly attributed to wood particle size and type. While CMC likely has lower thermal conductivity than wood [42], its interaction with different wood types may affect the composite's thermal behavior in ways not fully understood. Future research should focus on CMC's thermal properties in this specific context.

Buildability results of block component

In order to assess the buildability of the proposed wood composite formulation for large-scale 3D printing, two blocks were designed and fabricated as potential wall segment. Based on the results, the B2 formulation was selected for its balanced thermal conductivity, compressive strength, and low standard deviation to further assess its buildability for large-scale block components. The block dimensions were kept 200 mm in height, 350 mm in width, and 220 mm in depth. 6 mm nozzle diameter, 3.2 mm layer height were used as printing parameters to print both the blocks. The first block incorporated cantilever geometry on one of its sides and printed using original B2 formulation. The first block collapsed (Fig. 11, b1 and c1) likely due to bulking, which can be attributed to high water content in the mix and cantilever design. The material also showed pulling effect towards the center of the volume which may be due to central material bulking. The stability of the wet material may also be with regards to the reduced material overlap, and single wall reducing support for buildup. Using these observations block two was designed without cantilever geometry, double wall shell was incorporated along with higher overlapped tool paths. An improved formulation of B2 with reduced water with new ratios of wood/CMC/water as 2:1:7.1 was used which rendered a successful printed block (Fig. 11, a2). Higher extrusion pressure, up to 6.5 bar, was required to extrude the material. Post-printing, the structure exhibited significantly improved stability with negligible layer buckling. The observed deformations were primarily attributed to the material's viscoelasticity, water content, and top-layer loading. Adjustments to the material composition and tool path design mitigated, but did not fully eliminate, these effects. Tool path strategy significantly influenced stability of the walls. Single-path walls demonstrated poor layer adhesion and instability under increasing load, exacerbated by insufficient support from long infill lines.

When analyzed overall, single-path walls exhibited weak layer adhesion, leading to uncontrolled offsets and reduced stability under the weight of upper and peripheral structures. Additionally, infill lines provided insufficient support beyond critical length. In contrast, double-walled geometry demonstrated improved layer stacking, offering greater structural integrity for taller prints. The second block was self-standing when transported post-printing, however, was very sensitive to tilts and sudden jerks which might have triggered a collapse.

The wet material weighed 11.1 kg post printing. After 14 days of air drying, it hardened completely, the final weight was 5.2 kg, reflecting a 53% reduction from the wet weight and a 76% water loss, yielding a lightweight component (Fig. 12). An average shrinkage was of ~16.5% vertically and ~6–8% horizontally (Fig. 13). This aligns with the shrinkage ranges reported in previous studies [17, 20]. The horizontal shrinkage was higher on the top compared to bottom. This may be due to the higher weight on the lower particles due to rearrangement during printing and drying. Incomplete loss of water can be due to moisture retention

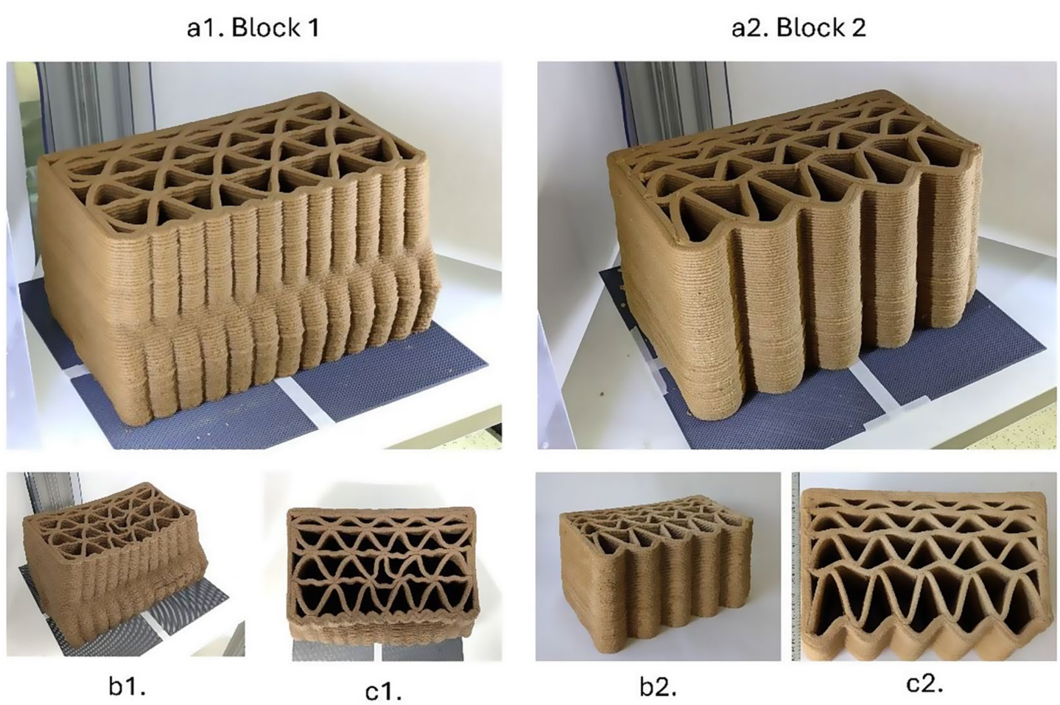

Fig. 11 Block post printing stages post printing wet state: **a1** and **a2**; post printing deformation **b1** and **c1**; **b2** and **c2** dried state

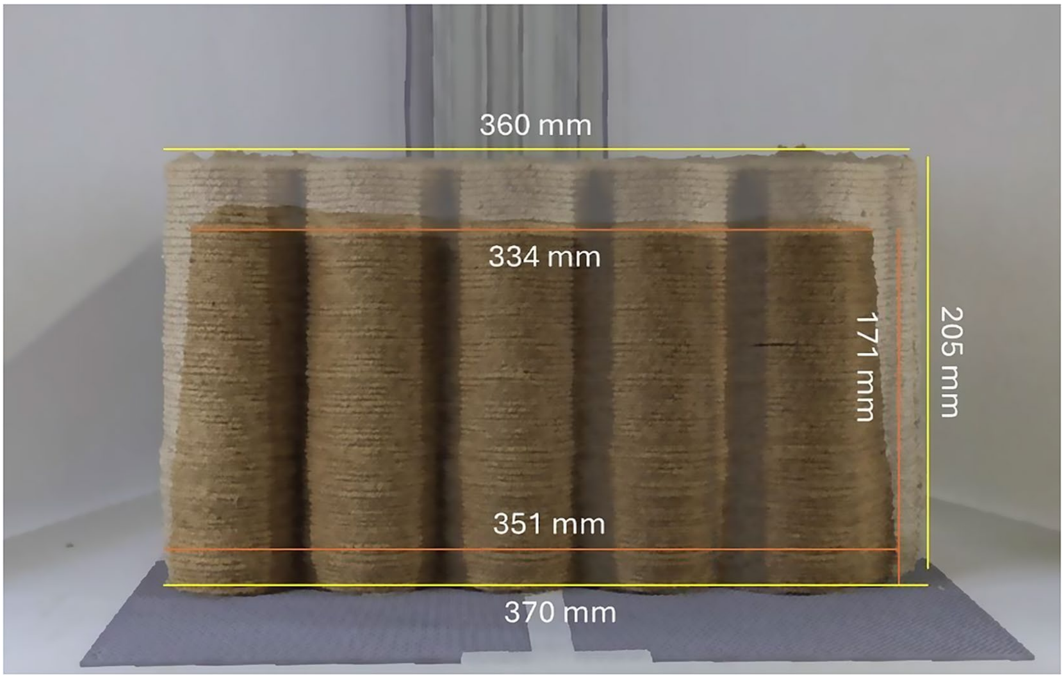

Fig. 12 Post drying deformations in the block are illustrated in comparison to the wet state

properties of wood and CMC, and the water locked in inside the wood particles due to slow drying. Methods like oven drying above degrees may trigger further water loss. These shrinkages in the context of large-scale components may affect the estimation of dimensionality of the final component which will need to be considered in the design and the formulation development of Wood-CMC composites.

These findings align with broader research on 3D printing of bio-composites, where shape fidelity and material stability are often limited by rheological properties and viscoelastic behavior during post-processing. Optimizing water content and refining tool path strategies are critical for enhancing the buildability in additive manufacturing. Further research into advanced layer deposition techniques and real-time adjustments to counteract viscoelastic deformation could improve performance and reliability in large-scale bio-composite printing.

The potential for introducing new architectural building components (e.g., blocks, paneling systems, partitions, and modular walls) using rigid wood-CMC printed composites, while still requiring further investigation, already exhibits a significant degree of consistency. This development holds promise for advancing sustainable construction practices by incorporating existing wood waste streams through 3D printing LDM technology, facilitating the scalability of customized, thermo-mechanically efficient structures, also exhibiting potential new expression for wood tectonics in architecture.

Conclusions and future perspectives

LDM with wood-based materials presents a promising approach for printing material with higher biomass, hence, to potentially leverage the physical properties of abundant biobased waste. The study presents the approaches in which formulations can be developed to enhance specific properties such as thermal conductivity and compressive strength by choosing species and optimizing particle size developed for LDM printing.

Limitations are also presented in relation to formulation development with relation to high amount of water that limits buildability and causes drying deformations for which alternative ideas are presented such as increasing permeability by combining different types of biomasses, reduction in water and enhancing the setup that increases extrusion pressure, leveraging tool path strategies for building supporting geometries and speeding- up curing during printing.

Compared to conventional materials, such as masonry or fiber-reinforced mud bricks (0.38 to 0.87 W/m·K) and Aircrete(0.1–0.15 W/m·K), the developed Wood-CMC composites showed better or comparable properties to be used as insulative components (0.14–0.21 W/m.K). These results underscore the potential of the wood-CMC composite as a viable sustainable material for future construction rigid insulation applications.

Future research should explore a wider range of wood species, particularly softwoods like pine, which are abundant as waste and may improve thermal insulation. Investigating

Fig. 13 Block 2 3D printed using wood-CMC Beech formulation as a potential large scale wall segment unit with customizable infill geometries represented by tool paths

wood type combinations and particle sizes could optimize thermal and mechanical performance. Additionally, refining water content is key to balancing buildability with lower extrusion pressures while ensuring structural stability. Optimizing toolpath strategies can further enhance buildability and structural integrity by introducing support structures for complex geometries during printing. Given the material's moisture retention, studies should assess its impact on long-term stability, thermal performance, and durability. Surface treatments or hydrophobic additives could help mitigate moisture absorption while preserving biodegradability.

In a broader context, this study provides a framework for developing 3D-printable wood waste composites as sustainable alternatives to synthetic materials. These composites can address current challenges in the construction sector related to traditional building materials while enabling the large-scale production of customized architectural components through LDM printing using recycled materials that meet structural and thermal insulation standards. Introducing high-performance bio-based materials empowers designers and architects to significantly broaden their material palette, offering sustainable alternatives that could potentially drive environmental impact and design innovation.

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Author contributions AJ, GA, and SB collaboratively contributed to the conceptualization and methodology of the study. AJ took on the roles of investigation, data curation, original draft writing, project administration, and visualization. GA and SB shared responsibilities in

formal analysis, as well as in reviewing and editing the manuscript. Additionally, GA and SB provided supervision, with SB also contributing resources and project management.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

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