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Development of New Bio-Based Building Materials by Utilising Manufacturing Waste

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Abstract **– Over the last decade, research has increasingly focused on reducing the use of natural resources and improving waste management in the construction industry. Various possibilities exist for reducing waste in this sector, ranging from using waste as filler materials to developing new binders and building materials. This study focuses on the development of bio-based building materials using waste from the manufacturing of wood-wool cement boards. The binder and filler materials were obtained from the manufacturing waste and used in this research. The developed materials were tested for their visual appearance, macrostructure, material density, thermal conductivity coefficient and compressive strength. The results showed promising data for the self-bearing bio-based building materials, which had similar thermal properties to other bio-based materials and could be used as thermal insulation materials with a thermal conductivity coefficient of 0.0827–0.1172 W/(mK). The material density of the developed bio-based composites was found to be 430–617 kg/m³. By incorporating manufacturing waste into the production process of bio-based building materials, it becomes evident that overall waste from manufacturing plants can be significantly reduced, and the sustainability aspect of wood-cement board manufacturers can be enhanced.**

Keywords **– Waste recycling; circular economy; wood-wool cement boards; bio-based building materials; thermal insulation.**

1. INTRODUCTION

Cement has been a crucial building material in the construction industry for centuries, owing to its ability to bind building materials together and provide structural strength and stability. However, cement production is a significant contributor to carbon dioxide emissions, responsible for 8 % of all carbon dioxide emissions produced annually and profoundly impacts the environment [1]. Sustainable alternatives to traditional cement-based building materials are being developed to address these concerns. The construction industry generates approximately a third of the world's waste [2], including concrete, brick, and wood, which can be repurposed to produce new construction materials [3]. The utilisation of manufacturing waste in the production of construction materials can yield several benefits,

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including decreased reliance on virgin raw materials, reduced greenhouse gas emissions from waste disposal, and mitigation of the construction industry's environmental impact [4], [5].

Using recycled cement in building materials has received significant attention in recent years as the construction industry seeks to become more sustainable and reduce its environmental impact [6]. Cement production is a significant source of greenhouse gas emissions, and using recycled cement can help reduce the construction industry's carbon footprint. Reusing cement-based materials, such as concrete, can also help conserve natural resources [7] and reduce the construction industry's waste [8]. To address these issues, reactivating cement has gained traction to reduce waste and make the construction industry more sustainable [9]. Reactivating cement involves using leftover or waste cement in new construction projects instead of producing new cement from raw materials, thereby reducing the construction industry's carbon footprint, conserving natural resources, and minimising waste [10], [11]. There are several options for recycling cement and concrete, including using them as aggregates [12], [13] in new concrete production, using them as binders [9], [14], [15], and using them as raw materials in the production of blended cement [16]–[19].

Bio-based building materials refer to construction elements derived from renewable biological resources, such as plants, agricultural byproducts, or waste materials from natural sources [20]. These materials are distinguished by their environmentally sustainable nature, as they harness the inherent properties of organic substances to create resilient and eco-friendly structures [21]. Using bio-based building materials aligns with the global shift towards sustainable practices in the construction industry, aiming to reduce the environmental impact associated with traditional construction materials and methods [22].

Bio-based building materials have recently witnessed a remarkable evolution, marked by significant trends, achievements, and innovations. One notable trend is the increasing utilisation of waste materials from various industries, such as agricultural residues, forestry byproducts, and post-consumer waste, as feedstocks for bio-based materials [20], and this mitigates the environmental impact of these waste streams and reduces reliance on traditional, resource-intensive building materials. Achievements in bio-based building materials have included the development of high-performance composites, such as bio-based polymers [23] and engineered wood products, which exhibit impressive structural properties while being environmentally sustainable [24], [25]. Moreover, innovations have centred around enhancing bio-based materials' durability and fire resistance, addressing critical challenges that have historically limited their adoption in construction [26].

Wood wool-cement boards are composite materials made of wood fibres (in the form of wood wool) and cement, mixed with water, and pressed into a board form. The manufacturing process of wood wool-cement boards involves several steps, including preparing the wood wool, mixing the wood wool with cement and water, and pressing the mixture into boards. This process generates a significant amount of waste, including wood wool fibres and cement dust. The study utilises waste generated during the manufacturing process of wood wool-cement boards from two different waste streams (Fig. 1).

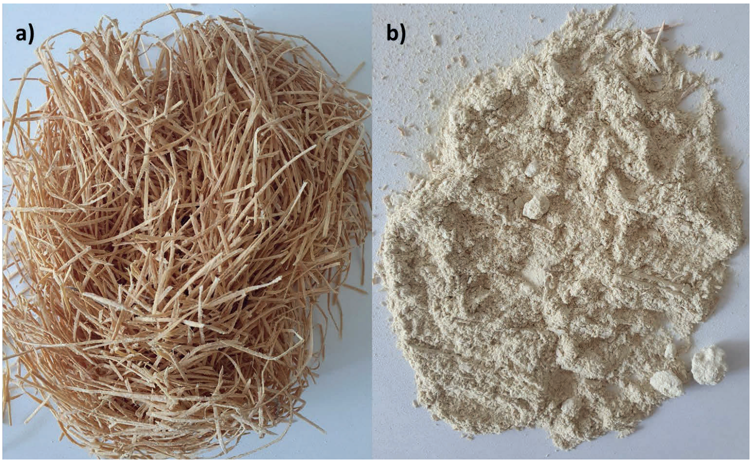

Fig. 1. The visual appearance of manufacturing waste streams: a) filler; b) fine fraction.

The first waste stream originates before the wood-wool and cement mix is pressed into boards. Some material falls off the production line; quality-wise, it is not usable to produce the boards. This waste stream is used as a filler for the proposed bio-based material in this study.

The second waste stream originates when the boards have been cured and go through the quality assessment phase, where the surface area is sanded and checked for discolouration, larger cement conglomerates and mechanical defects. The main problem with the fine fraction of manufacturing waste is that its lightweight nature can easily spread as dust particles throughout a landfill, contaminating the surrounding environment. To counter that, the dust that forms during the sanding process is vacuumed to a storage location near the plant so it may settle and not contaminate the environment.

Recycling and incorporating the processing waste into other applications would be more cost-effective than disposing of it in a landfill because it is made of the same materials as the primary manufacturing product. This study explores the possibility of using a previously developed binder [9], [14] and filler from a manufacturing waste stream to make building materials. The new binder would be an environmentally friendly alternative to traditional cement, as it is a manufacturing waste and can reduce the manufacturer's carbon footprint. The building materials would incorporate the developed binder and other waste stream materials used as filler material. This research can significantly contribute to sustainable building materials and a lasting positive environmental impact.

2. Materials and Methods

2.1. Raw materials

The wood wool-cement board manufacturing waste was collected from a local manufacturing plant and used as a raw material to produce a new bio-based building material. This study used the manufacturing waste's fine fraction of partially hydrated cement and wood fibres as the binder material subjected to reactivation. The waste fine fraction was sieved through a 0.2 mm sieve and then milled in a vibratory mill for 20 minutes to break up the conglomerates that contained unhydrated cement particles, allowing them to bind with water and form new hydration products (Fig. 2). The reactivation by mechanical treatment has been proven [28] in a different study. After reactivation, the binder showed a compressive strength of 1.6 MPa on the 28th day.

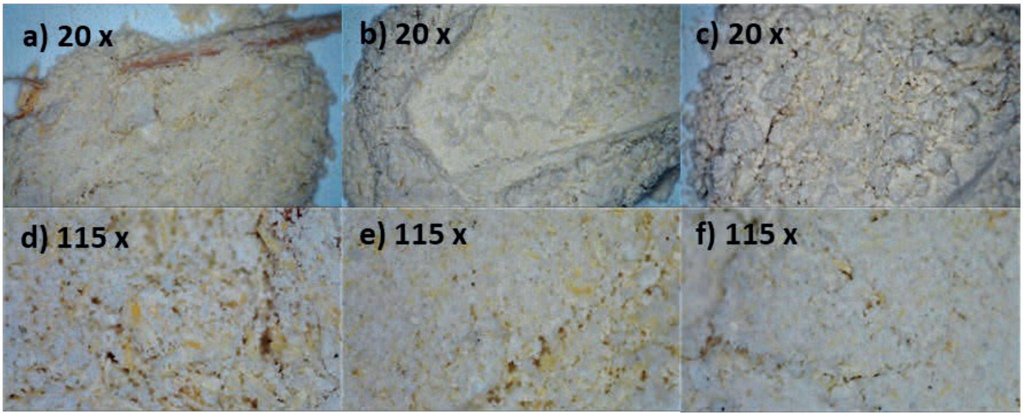

Fig. 2. The visual appearance of manufacturing waste fine fraction at different magnifications: a) and d) raw; b) and e) sifted; c) and f) sifted and milled.

The filler used in the study is spruce wood fibres ranging 5–200 mm in length, 1–1.5 mm in width and 0.5–0.8 mm in thickness. The average bulk density is 250 kg/m^3. The fibres are coated in hydrated cement from the manufacturing process. Most of the fibres have been separated one from the other, except for small patches of fibres that have clumped together. The filler material is checked before the sample preparation to avoid these hardened patches of material for a more homogenous structure. The visual appearance of the material can be observed in Fig. 3.

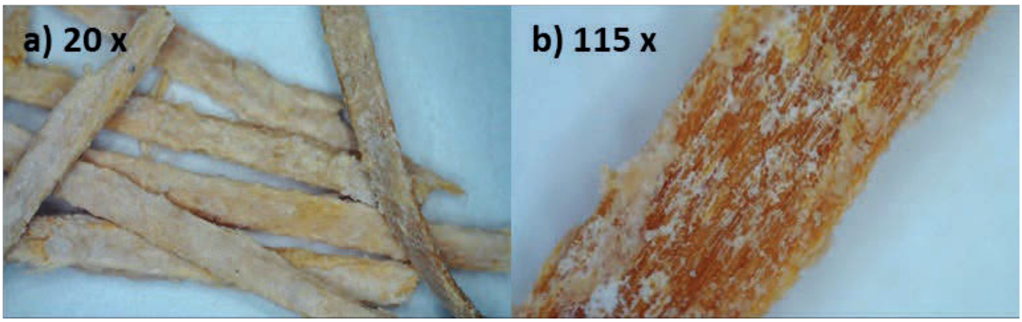

Fig. 3. The visual appearance of the filler material at different magnifications.

2.2. Mixture design and sample preparation

Three compositions of bio-based building materials were made with varying binder content. The mixture design is compiled in Table 1.

TABLE 1. MIXTURE DESIGN IN MASS PARTS OF THE DEVELOPED BIO-BASED BUILDING MATERIALS

Sample	Binder		Filler	
	Manufacturing waste fine fraction	**water**	**Dry**	**Water for wetting***
P1	10	7	10	1
P2	5	3.5		
P3	3	2.1		

*The filler was moistened before mixing so that the filler did not absorb the water intended for the binder

The water of a mass part of 1 of the filler was mixed to wet the surface for easier mixing of the binder. Water with filler was mixed manually for 3 minutes to ensure all the fibres were wet. Based on the sample made, a different mass of binder was gradually added (10, 5, 3 mass parts of the filler) to the filler while mixing it, resulting in a homogeneous coating of the fibres. Afterwards, the water necessary for the binder was added to the mix. For each composition, a W/B ratio of 0.7 was used. Then, the mixture was remixed to form a homogenous composition in oiled forms of dimensions 35×35×10 cm.

A plate was put on top after the mixture had been formed to ensure pressure and a smoother surface structure. An initial pressure of 571 Pa was added to the samples to ensure better bonding between the binder and the wood fibers. Initial pressure was carried out for 60 seconds, after which a weight was added to ensure a pressure of 65 Pa to the samples as a secondary pressurization as they cured. Samples were demolded after seven days, wrapped with plastic film and cured for 21 days to guarantee a minimal humidity loss for the rest of the curing process. After the curing process of 28 days, the plastic film was removed, and the samples were cured in room conditions.

2.3. Characterisation techniques

The macrostructure of the samples was taken with a Veho HDMI Dual Vision Digital Scope at magnifications of 20 and 115 times, respectively.

Thermal conductivity was tested according to ISO 8301 standard using Linseis HFM 200 with a temperature range of −30 to +70 °C, thermal conductivity ranges between 0.005 to 0.5 W/(mK), and the sensor are 100×100 mm. The specimens were conditioned to a moisture content average of 6±1 % before testing.

The compressive and flexural strength of the bio-based building materials was tested at 0.5 mm/min using Zwick Z100 universal testing equipment (ZwickRoell, Kennesaw, GA, USA) according to BS EN 12390-3 standard [27]. The compressive strength was measured in two directions, and samples were tested parallel and perpendicular to the forming direction (3 samples for each direction). For parallel direction, an ultimate load was used to calculate compressive strength. A load of 10 % of the sample's height was used for perpendicular direction. The flexural strength was measured in 1 direction – perpendicular to the forming direction for 3 parallel samples to account for variability.

3. Results

Developed bio-based building materials were characterised by their visual appearance, macrostructure, material density and thermal conductivity.

3.1. Visual appearance and macrostructure of the bio-based building materials

Visual appearance of the bio-based building materials can be seen in Fig. 4.

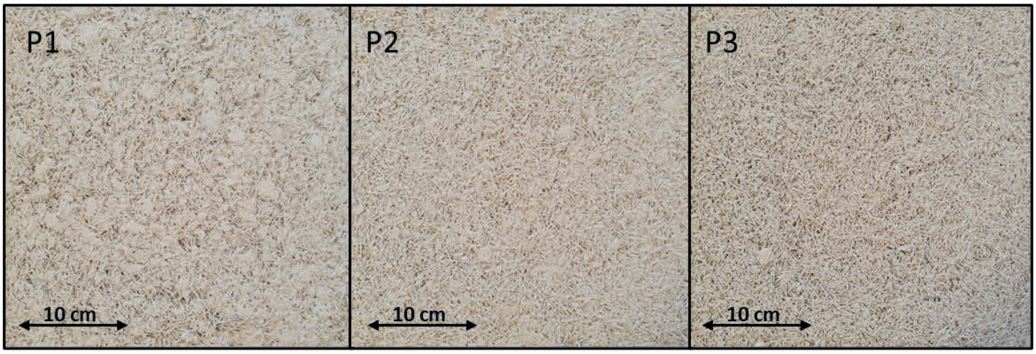

Fig. 4. The visual appearance of the developed bio-based building materials.

It can be seen that the P1 sample has a lot of larger patches of binder clumping together and making the visual look not homogenous. A more homogenous sample was obtained by lowering the binder amount with the intention of leaving larger voids filled with binder. Decreasing the binder amount further allows more voids to be observed, and the material's structure becomes brittle.

Looking at the macrostructure of all the samples (Fig. 5), note the considerable difference between the samples.

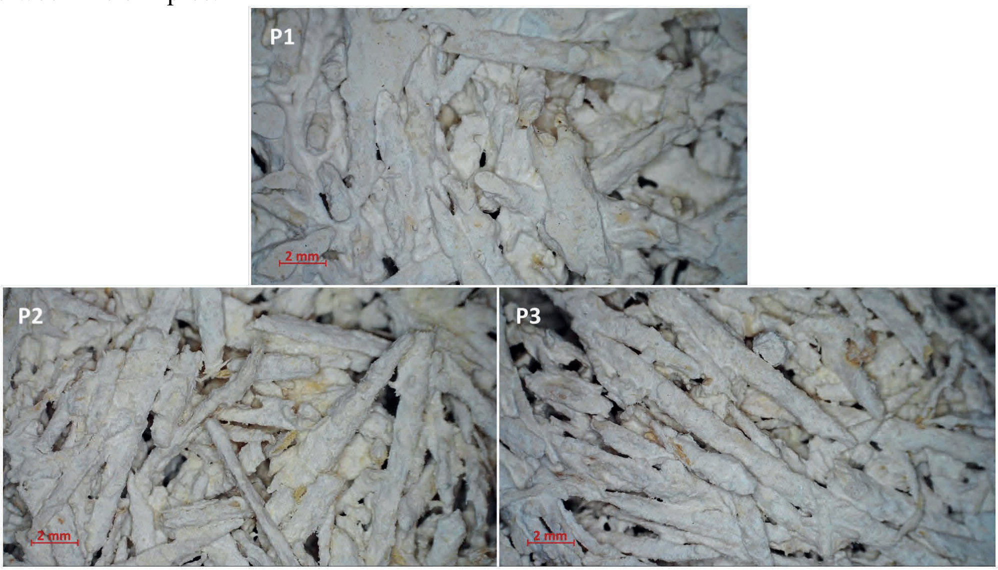

Fig. 5. The macrostructure of the developed bio-based building materials.

P1 has the highest density, and the binder covers vast wood fibres. Separate voids can be seen, but the contact areas between the fibres are entirely covered with the binder. The P2 sample has some similarities with P1, with the binder covering almost all the fibres, but in P2, larger voids can be seen, and the contact zones are not entirely covered with the binder. In the P3 sample, the binder has covered only individual fibres, and the contact area between them is thin, significantly affecting the sample's strength. However, the gaps between the fibres are not filled with binder, which decreases thermal conductivity. During the inspection, individual wood fibres crumbled away from the sample because of the weak contact area between them.

3.2. Physical properties of the bio-based building materials

Physical properties were evaluated as the primary properties of the feasibility of this material. The properties looked at were material density and thermal conductivity and are compiled in Table 2.

TABLE 2. PHYSICAL PROPERTIES OF THE DEVELOPED BIO-BASED BUILDING MATERIALS

Sample	**Material density, kg/m^3**	**Thermal conductivity, W/(mK)**
P1	613	0.1172
P2	494	0.0934
P3	430	0.0827

The material density of the samples ranges 430–613 kg/m^3. This means that the materials have different degrees of added binder, as seen in Table 1, with P3 being the lightest and P1 being the densest. This information can be important when selecting materials for specific applications where density is critical, such as construction or insulation.

The thermal conductivity of the samples ranges 0.0827–0.1172 W/(mK). This parameter determines the rate at which heat flows through the material, and it is an important consideration when designing thermal insulation systems. The higher the thermal conductivity, the faster the heat will flow through the material, which means it will be less effective at insulating. The dependence of thermal conductivity on material density is visualised in Fig. 6.

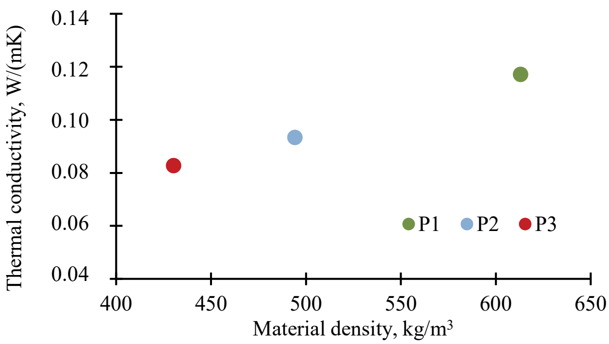

Fig. 6. Thermal conductivity dependence of material density.

A correlation between density and thermal conductivity can be seen in a study by Sahmenko [28], where many hempcrete samples were tested, differentiating the density and their thermal conductivity. It was found that even with different binders used, comparing that study to this study's developed materials, a conclusion can be drawn that these materials have lower thermal conductivity with the same density. Compressive strength, however, is lower than in Sahmenko studied hempcrete samples. A lower binder-to-filler ratio in this study could explain this.

3.3. Mechanical properties of the bio-based building material

The ultimate load-deformation graph can be seen in Fig. 7, from which the compressive strengths based on the formation direction were calculated. For the perpendicular direction testing, a critical load (marked by the end of the elastic zone) was used to calculate compressive strength as the sample started to delaminate as the deformation increased. For the parallel direction testing, a 10 % deformation was used for the calculations as the ultimate load increased with the increase of deformation. A marker was put on each representative graph as the point of value calculation.

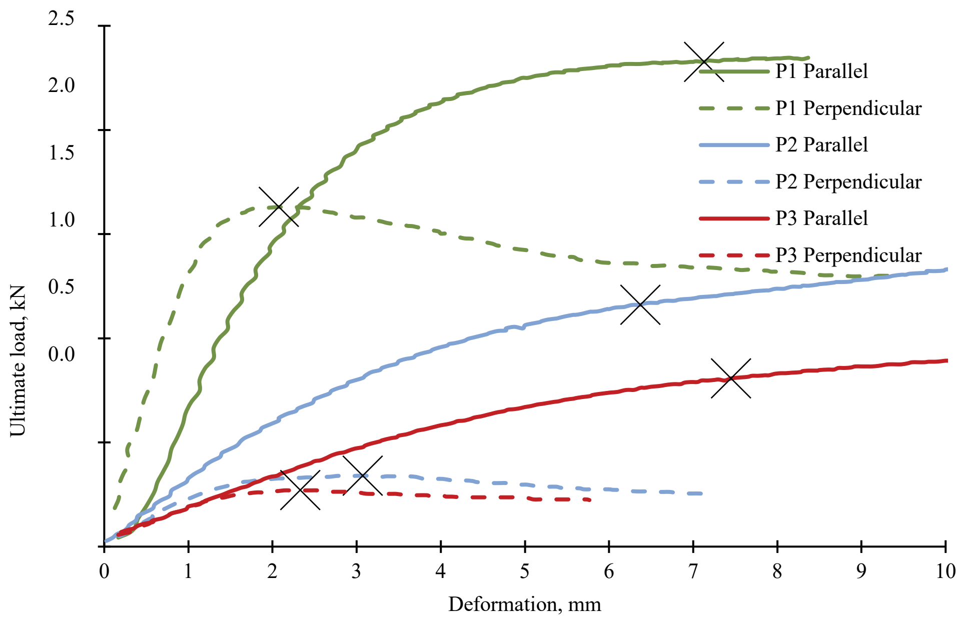

Fig. 7. Ultimate load-deformation graph for the developed bio-based building materials.

Based on the flexural and compressive strength values provided in Table 3, it can be concluded that the bio-based building material exhibits moderate to low strength characteristics. The flexural strength values range 60–236 kPa, indicating that the material is weak in resisting bending forces. The compressive strength values are also moderate, ranging 55–469 kPa, depending on the forming direction.

TABLE 3. MECHANICAL PROPERTIES OF THE DEVELOPED BIO-BASED BUILDING MATERIALS

Sample	Flexural strength, kPa	Compressive strength based on the forming direction, kPa	
		Parallel	Perpendicular
P1	236	469	330
P2	108	256	88
P3	60	177	55

Comparing the three developed bio-based building material prototypes, it can be seen that the highest values in both directions of compressive strength and flexural strength are for sample P1, reaching 236 kPa of flexural strength and 469 kPa and 330 kPa in parallel and perpendicular compressive strength, respectively. The lowest values were found for sample P3, which confirms that the lowest amount of binder used would result in lower flexural and compressive strength. P3 showed 60 kPa of flexural strength 177 kPa and 55 kPa of compressive strength in parallel and perpendicular directions. Further approving the hypothesis was the P2 sample reaching a flexural strength of 108 kPa. Compressive strength resulted in 256 kPa parallel and 88 kPa perpendicular based on the forming direction. The resulting material had unique properties compared to other bio-based building materials, and it showed promise for use in an envelope building material system as a middle layer replacing thermal insulation materials.

4. DISCUSSION

Based on their physical and mechanical properties, the developed bio-building materials could be used in non-load-bearing applications such as interior wall partitions, ceiling tiles, and insulation. Its moderate compressive strength could make it a viable option for low-stress construction projects. Additionally, its eco-friendly nature could make it attractive for sustainable construction practices.

The material could have potential applications in the construction industry, especially in building envelopes where thermal insulation and mechanical strength are critical. It could be suitable for insulation for walls, roofs, and floors in buildings, where it can help reduce heat transfer and maintain thermal comfort while providing adequate mechanical support. The approximate envelope system application is visualised in Fig. 8, where the developed bio-based building material could be used as a middle layer made of reactivated binder and recovered wood fibres.

Fig. 8. Approximate envelope system based on the developed bio-based building material.

It is worth noting that further testing and evaluation would be necessary to determine the material's suitability for specific applications. The material's properties and behaviour under different environmental conditions should also be considered before deciding on its use in construction projects.

Similarities can be drawn by analysing different bio-based building materials as thermal insulation materials. In research about hempcrete, a density of 150–500 kg/m^3 can be seen with the compressive strength and thermal conductivity being in the ranges of 150–552 kPa [29] and 0.056–0.102 W/(mK) [30], [31]. Flexural strength changed in the 130–200 kPa [32]. All the materials can be made with different compositions; thus, different properties can be gained.

A similar picture can be seen when comparing straw bale materials, with a density ranging from around 150 kg/m^3 [33] and thermal conductivity ranging from 0.052–0.06 W/(mK) [34].

Wood fibre insulation materials show increased flexural and compressive strength (910–1130 kPa and 1000–1200 kPa, respectively) to studies developed insulation material, which the orientation of the fibres can explain. Cross-orientated fibres can achieve higher strength values. Densities for wood fibre materials can vary between 250–500 kg/m^3 and achieve 0.069–0.093 W/(mK) [35].

Cork materials, on the other hand, can range from 300–400 kg/m^3 with flexural and compressive strength reaching up to 1000 kPa. Thermal conductivity for these materials ranges 0.068–0.100 W/(mK) [36]. The comparison between the developed material and previously mentioned materials can be seen in Fig. 9, where, based on the material density and thermal conductivity, the developed material P2 and P3 are comparable and competitive with commercially available bio-based materials. P1 has a slight increase in density and thermal conductivity, resulting in the material being on the worst part of comparison.

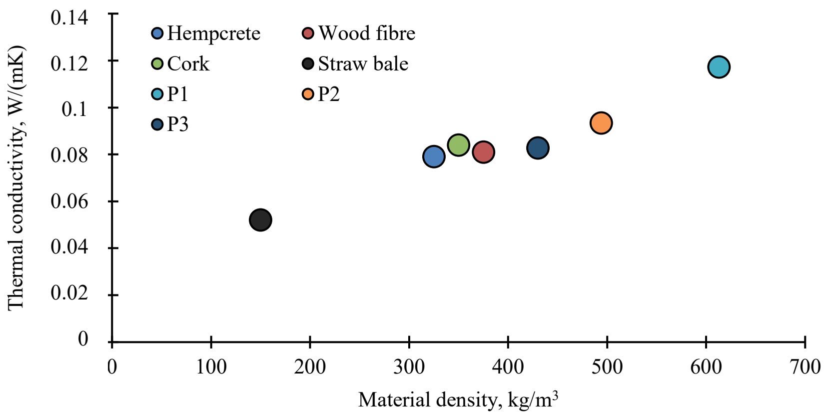

Fig. 9. Comparison between the developed and commercially available bio-based thermal insulation materials.

The thermal properties of bio-based building materials can vary depending on moisture content, density, and manufacturing processes. Therefore, these comparisons are only meant to provide a rough idea of how the samples compared to similar materials, and further studies may be necessary to make more specific comparisons.

Nevertheless, the developed bio-based building material is sustainable and environmentally friendly due to its bio-based nature. It may be suitable for non-load-bearing walls or interior partitions where high strength is not critical. The material's performance could be enhanced through reinforcement or composite fabrication, depending on the specific application. Therefore, it could be an attractive alternative to traditional building materials for those prioritising sustainable and eco-friendly solutions.

5. CONCLUSION

This study analysed the physical and mechanical properties of a bio-based fibre and cementitous binder material. The material was assessed based on its macrostructure, material density, thermal conductivity, and flexural and compressive strength in parallel and perpendicular forming directions.

The macrostructural analysis of three samples (P1, P2, and P3) in Fig. 5 reveals significant differences. P1 has the highest density, with the binder covering wood fibres extensively. P2 shows similarities but has larger voids and incomplete binder coverage in contact zones. In P3, the binder only covers individual fibres, resulting in thin contact areas and decreased thermal conductivity. Weak contact areas between fibres in P3 lead to fibre crumbling. Overall, density and binder distribution variations influence each sample's structural characteristics.

The results indicated that the material exhibited good thermal properties, such as low thermal conductivity, making it a potential use as a thermal insulator. The P3 sample had the lowest thermal conductivity coefficient, at 0.0827 W/(mK), while sample P1 achieved 0.1172 W/(mK) due to its higher binder-to-filler ratio.

In terms of mechanical properties, the material showed low to moderate flexural and compressive strength in both directions, indicating its potential use as a self-bearing material. The density of the material decreased as the binder addition decreased, ranging from 613 to 430 kg/m^3. Comparing flexural and compressive strength, sample P1 achieved the highest values, reaching 236 kPa in flexural strength and 469 kPa and 330 kPa in compressive strength in parallel and perpendicular forming directions, respectively. Sample P3 achieved the lowest strengths, reaching 60 kPa flexural strength, 177 kPa compressive strength in the parallel direction and 55 kPa in a perpendicular direction.

Comparing the material's properties to other bio-based building materials, such as straw bales, wood wool, and hempcrete, the analysis revealed that the material's thermal properties are similar to those of wood fibre. In contrast, its mechanical properties are similar to those of hempcrete.

In conclusion, the material has potential applications in the construction industry, particularly in building envelopes and insulation, where thermal insulation and mechanical strength are important factors. However, further research and testing are necessary to fully explore the material's potential applications.

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