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Thermal, physical and mechanical properties of surface overlaid bark-based insulation panels

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Abstract

In terms of reduced energy consumption and simultaneously promoting woody biomass sustainability, researchers are seeking energy-efficient materials, originating from forestry and agricultural residues, for application in the building sector. In this study, bark-based panels overlaid on both surfaces with three different fibreglass types and two types of paper sheets were evaluated for potential utilization as thermal insulation panels. The proposed panels were then characterized regarding their thermal conductivity, physical, and mechanical properties such as density, water absorption, thickness swelling, surface soundness, bending strength and modulus of elasticity. It was found that thermal conductivity values ranged from 0.067 to 0.074 W/(m K) for all the produced panels. As suggested from the results, fibreglass overlays exhibited improved performance compared to paper sheet overlaying. In addition, the fibreglass overlaid bark-based panels displayed promising characteristics as insulation materials. Finally, fibreglass woven fabric was found to be more beneficial than the mesh and mat fibreglass types.

1 Introduction

Buildings are reported to consume 40% of the EU's total energy demand and produce about 35% of greenhouse emissions. Therefore, in the background of meeting EU directives and targets on minimizing energy consumption and internal greenhouse gases, effective thermal insulation materials could endow this attainment. Concerning this purpose, i.e. the improvement of energy efficiency of existing and new buildings, this could be achieved either by enhancing the thermal performance of building envelopes such as walls, roofs and floors or by adopting efficient installations for heating, cooling electricity etc. (Pavel and Blagoeva 2018; Schiavoni et al. 2016).

Besides the increasing request for high thermal performance and 'near-zero-energy' consumption buildings, recent emerging trends and issues in the area of sustainable development and low environmental impact require the utilization of bio-based related materials rather than conventional ones such as mineral wool or petro-chemical based insulation mats (Torres-Rivas et al. 2018). Thermal insulation panels

made of biomass, also referred to as 'bio-insulations', have been increasing rapidly due to their availability as renewable, low-cost and eco-friendly materials. So far, several agricultural residues and forest wastes including wheat, rice, corn or date palm residues, wood shavings, cotton stalks, cork, recycled paper or other plant-based fibres such as reed, oil palm, sansevieria, flax, kenaf, cattail and hemp fibres (Asdrubali et al. 2015; Liu et al. 2017) have been investigated as alternative sustainable materials to attain insulation panels.

Each year, a significant amount of millions of tons of bark generated during wood processing is produced globally, emanating as a residual woody biomass in sawmills and wood-based industries (Aydin et al. 2017). The increasing research and development needs of introducing value added products made of wood waste materials have prompted many research efforts on the usage of bark residues besides burning them as energy fuel (Tudor et al. 2018). Researchers have focused their targets on the application of bark as adhesive additives, in pharmaceutical companies as well as in the manufacturing of various wood-based boards incorporating bark (Pásztory et al. 2016).

During 1960s, Martin (1963) investigated the thermal properties of bark specimens obtained from three pines and seven hardwood species by a heat probe method. According to this author, the bark displayed better thermal conductivity values

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compared to similar density wood samples. Lately, it has been investigated whether bark could be used as feedstock material to supply the insulation panels manufacturing industries. Kain et al. (2013, 2014) manufactured and tested insulation panels obtained from various softwood bark species for relatively low density boards (< 500 kg/m^3). In like manner, Pásztory et al. (2017) examined the bark of black locust (*Robinia pseudoacacia*) trees as raw material for thermal insulation purposes.

One of the essential limitations on the exploitation of bark particles by wood industry is the resulting weakness of the mechanical properties of the manufactured wood-based panels or composites. A potential solution to overcome this issue could be the reinforcement of bark particle boards with common synthetic polymer fibres such as glass fibres. Inceptive research trials on fibreglass reinforced engineered wood products, started in the 1960s, with investigations focused on the bending properties of wood-fibreglass composite beams by Wangaard (1964) and Biblis (1965). Since then, fibreglass has been used by many researchers as external bonding, internal bonding, or near surface bonding reinforcement to increase the flexural stiffness and strength of wood composites. Such reinforced wood composites include MDF boards (Cai 2006), plywood (Biblis and Carino 2000; Mitzner 1973), laminated strand lumber (Moradpour et al. 2018), laminated veneer lumber (Bal 2014) and glulam timbers (Osmannezhad et al. 2014).

Both glass fibres and paper have been employed as insulation materials due to their low thermal conductivity values. The thermal conductivity of glass wool and paper are reported as 0.058 W/(m K) (Cao et al. 2015) and 0.06 W/(m K) (Bøhmer 2001) under standard temperature (25 °C) and atmospheric pressure, respectively. However, the thermal conductivity of paper varies upon the paper sheet density, filler content, nature of the fibres, measuring methods and ambient conditions (Lavrykov and Ramarao 2012).

The overall objective of this study was twofold, (i) to examine the fiberglass and paper overlaying reinforcement effect on the mechanical performance of the bark-based boards and (ii) to evaluate the suitability of producing fibreglass and paper sheet overlaid bark-based boards as insulation panels in building construction. Therefore, the suggested bark-based panels were investigated in terms of thermal, mechanical and physical properties in this work. Furthermore, the effect of glass fibre reinforced polymer (GFRP) compared to paper sheet overlays on the properties of bark-based panels employing epoxy and UF as adhesives were further assessed and discussed.

2 Materials and methods

2.1 Materials

Poplar (*Populus sp.)* bark slabs without separation of inner- and outer- bark, were peeled off from poplar trees at a local sawmill in Sopron, Hungary. After debarking, their moisture content was reduced to below 20% preceding to size reduction and following chopping into particles using a hammer mill equipped with 8-mm screening holes. The collected bark particles were dried up until a final moisture content of 6–9% was reached. Bark particles ranging from 0.5 up to 8 mm were selected as raw materials for the core layers in the insulation panel manufacturing.

For this study, three main commercial forms of fibreglass, i.e. fibreglass mesh (GFRP1), fibreglass mat (GFRP2) and fibreglass woven fabric (GFRP3) were used as surface layers in the analysis of the proposed panels (Fig. 1). The GFRP images were obtained with a Hitachi S3400 scanning electron microscope (SEM). Non-coated specimens were scanned under vacuum pressure of 70 Pa and an accelerating voltage of 15 kV.

Two types of paper sheets, one thicker double layer recycled paper (P1) and a thinner thermomechanical pulp (TMP) coated paper (P2) were bonded with urea–formaldehyde resin and pressed on both sides of the developed bark-based insulation panels. Their main properties, grammage (g) and tensile index (TI), were examined according to TAPPI T 410 (1998) and TAPPI T 494 (1996) standards, respectively (Table 1). The wetting behaviour of the paper sheet surfaces was characterized according to TAPPI T458 (2004) using a 68–76 PocketGoniometer PGX + model. Static measurements of contact angles (CA) and immersional wetting calculations (ΔG_i) were carried out with distilled water and DIM (3,3′-Diindolylmethane).

2.2 Bark-based insulation panels production

Four precent urea–formaldehyde resin DUKOL Ostrava s.r.o. (Kronores CB 1104 D) was used for the production of core-layer bark-based panels. Aqueous solution (35%) of ammonium sulfate as hardener (3% solid content) was added as a catalyst. The bark particles were mixed with the resin system in a laboratory blender for 5 min to ensure homogeneous mixture. Thereafter, the resin-bark particles mixture was formed into a wood frame mould; the mixture was manually pre-compacted and then the frame was removed.

Bark based insulation panels with a size of 500 mm × 500 mm, a nominal thickness of 20 mm and a target density of 350 kg/m^3 were produced using a laboratory hot press (Siempelkamp). The pressing time was 18 s per final thickness in millimetre, and the temperature of the plates was 180 °C. The initial pressure of the plates was 2.86 MPa, which was reduced after 120 s–2 MPa, and after 240 s–1.15 MPa to reduce the vapour pressure.

To examine the effect of external fibreglass reinforcement, each fibreglass type mat was overlaid on the top and bottom faces of the bark-based panels after hot pressing. The assembled GFRP structures were then bonded on core layers
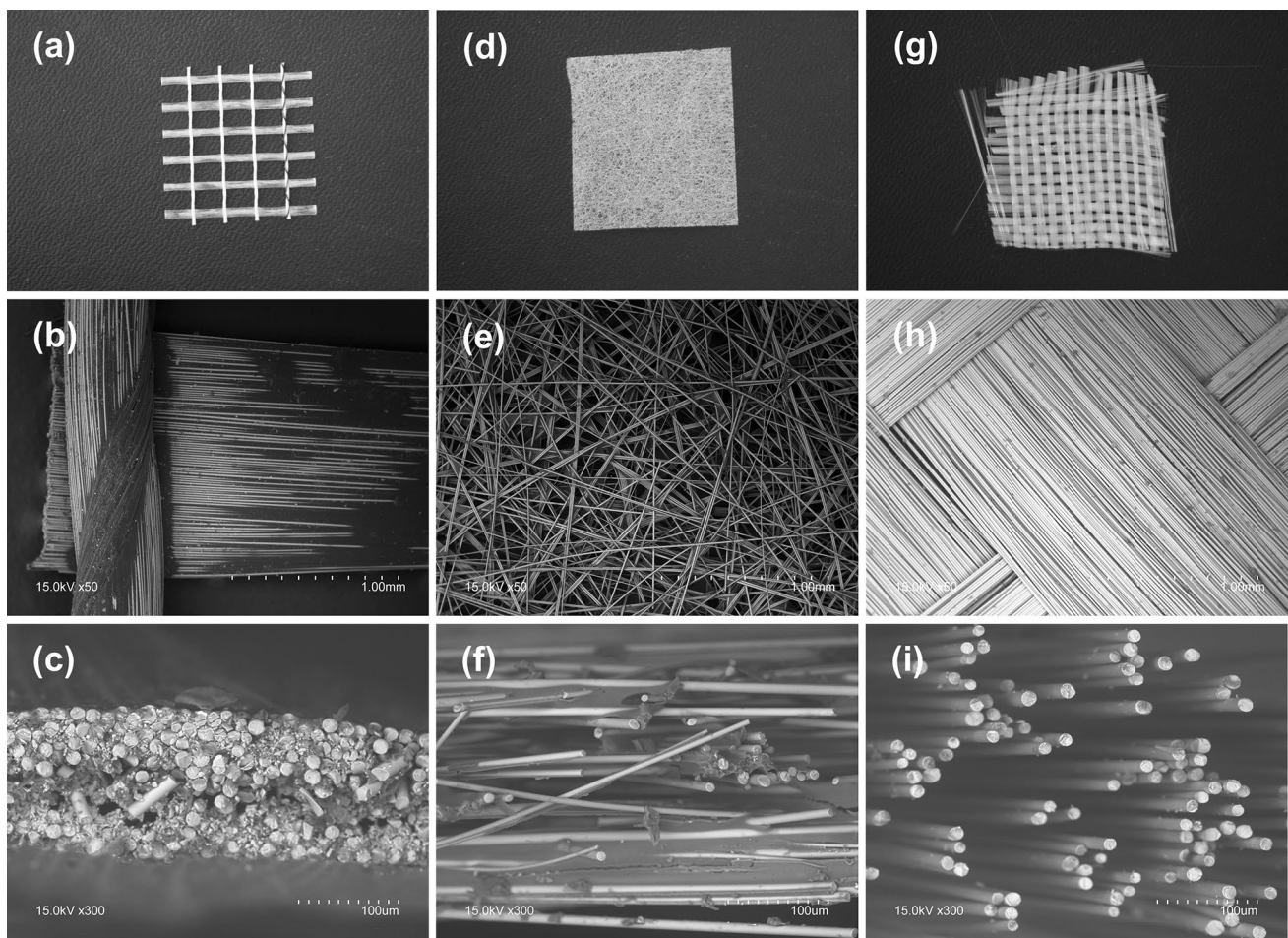
Fig. 1 Macroscopic images of GFRP1 (**a**), GFRP2 (**d**) and GFRP3 (**g**). In the second and third row, the surface can be seen; scale bar 1.00 mm (**b**, **e**, **h**) and cross-section; scale bar 100 um (**c**, **f**, **i**) SEM images of GFRP1, GFRP2 and GFRP3, respectively

Table 1 Sheet thickness and main properties of the paper sheets used in the research, according to TAPPI standards

	Sheet thickness (µm)	Sheet grammage (g/m²)	MD tensile index (Nm/g)	CD tensile index (Nm/g)	CA (°)		ΔG_i (mJ m^{-2})	
					Upper	Glued	Upper	Glued
P1	278	194	60.19	22.28	109.8	71.4	24.66	− 23.22
P2	116	88.6	53.62	30.32	96.5	113.9	8.24	29.49

MD machine direction, *CD* cross direction

using a 2 K epoxy resin (Elan-tech EC 152; W152 HR) to form the panel. The epoxy-based adhesive was brushed onto the surface of bark panel and GFRP layers. The GFRP material which was equal in length to the panel dimensions, was glued onto it using a roller. After the hand lay-up process, bonding and simultaneous curing of fibreglass overlays to the core layer was made in a press under a pressure of approximately 2 bar and ambient temperature for 24 h.

Paper overlaid insulation panels were prepared in a one-step process, since paper sheets were hot pressed simultaneously to form mat layer of bark particles. Paper sheets were applied to the bottom and upper surface during the manual

formation of panel. Identical UF resin mixture as used in the bark particles, was spread on the surface of the papers using a brush before they were heat compressed. Before applying the overlaid sheets to the boards, dirt and dust were removed from the surface by using air.

For comparison purpose, only bark-based panels as control used as the core layer, were also investigated. At the end, a total of eighteen panels, three for each type were manufactured for the implementation of the measurements. Prior to testing, all panels were stored in a climate chamber at 20 °C and 65% relative humidity (RH) until an equilibrium moisture content was reached, which resulted in an

average moisture content ranging from 7.29 to 9.12%. The final appearance of the overlaid panels is illustrated in Fig. 2.

2.3 Measurements

2.3.1 Thermal properties

Thermal conductivity was measured across the thickness of the panel under a heat flow meter by using a custom-made, certified hot-plate apparatus. The thermal conductivity was calculated under steady state conditions by measuring the heat flux, as described by Fourier's law, according to the following equation:

$$\lambda = \frac{d \cdot \phi_q}{\Delta T} \tag{1}$$

where λ is the thermal conductivity measured in watts per meter kelvin (W/m K), Φ_q is the heat flux (W/m^2), ΔT is the temperature difference across the specimen (K) and d is the thickness of the specimen (m). Heat flow was measured in the 120×120 mm midrange of the sample, whilst the full size of the specimens was 500×500 mm. To ensure heat flux parallel to the panel surface, additional 150 mm side insulation was used and the measurement was started after having the steady state conditions. The temperature difference between the hot and cold plate was set to 10 °C and the mean temperature was 10 °C. For each panel type, thermal conductivity test was carried out on three specimens.

2.3.2 Physical properties

Bulk density (ρ) was measured on the same samples used for the mechanical tests, according to European standard EN 323 (1993). The density of each panel was individually measured at current moisture content at time of mechanical bending test.

Dimensional stability of the specimens regarding thickness swelling (TS) and water absorption (WA) after immersion in water for 2 and 24 h was calculated as suggested by the European standard EN 317 (1993). Twelve specimens with 50 mm by 50 mm dimensions were weighed and their thicknesses were measured with a level of accuracy of 0.01 g and 0.1 mm, respectively.

2.3.3 Mechanical properties

The standard mechanical properties of the obtained bark-based panels were characterized using a universal testing machine Instron 5506. The characteristic flexural properties, i.e. bending strength (modulus of rupture, MOR) and modulus of elasticity (MOE) were determined using European standard EN 310 (1993). In addition, surface soundness (SS) tests were conducted to assess the quality of bonding between the overlaid mats and bark-based core layer (EN 311 1993). The specimens were prepared from different areas of the board and cut according to EN 326-1 (1994).

2.4 Statistical analysis

To assess the influence of overlaid GFRP and paper mat reinforcements on the bark-based panel properties, one-way ANOVA statistical analysis was performed using the Statistica13 software. All data were checked for normality (Shapiro–Wilk test) and homogeneity of variance (Levene's test). Post hoc tests were conducted with Tukey's HSD test method.

3 Results and discussion

3.1 Thermal conductivity

The thermal conductivity values of the overlaid bark-based panels, presented in Table 2, were calculated in the range of 0.067–0.074 W/(m K), depending on the overlaying type. The proposed poplar bark-based panels (control and overlaid) can be characterized as an intermediate thermal performance mat as classified by Asdrubali et al. (2015). These values are in agreement with thermal conductivity values referenced in the literature for bark or other wood composite panels of similar densities and thicknesses. For instance, the thermal conductivity of larch (*Larix decidua*) bark panels reported by Kain et al. (2014) ranged from 0.069 to 0.093 W/(m K) depending on the panel's density. Likewise, Pásztory et al. (2017) reported that the thermal conductivity of panels made of black locust (*Robinia pseudoacacia*) was 0.0651 W/(m K). In addition, the thermal conductivity of low density
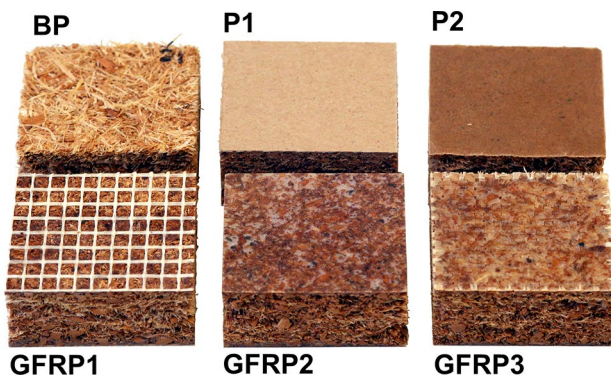

Fig. 2 Sample specimens (dimensions 50 mm × 50 mm × 20 mm) of experimentally produced panels

Table 2 Results of thermal, physical and mechanical properties of the bark-based panels overlaid with paper mats

	Control	P1	P2	GFRP1	GFRP2	GFRP3
Physical properties						
ρ (kg/m^3)	336.80 ($\pm$22.95)	360.24 ($\pm$17.57)	353.06 ($\pm$14.67)	413.07 ($\pm$23.77)	395.69 ($\pm$18.66)	403.71 ($\pm$26.97)
EMC (%)	8.88 ($\pm$0.17)	9.12 ($\pm$0.15)	7.60 ($\pm$0.36)	7.29 ($\pm$0.28)	7.51 ($\pm$0.56)	7.64 ($\pm$0.23)
W (wt %) n=10	218.37 ($\pm$28.03)	159.32 ($\pm$6.98)	210.87 ($\pm$42.45)	147.03 ($\pm$24.04)	1($\pm$23.53)	1.83 ($\pm$22.96)
TS (%)	18.18 ($\pm$3.09)	12.39 ($\pm$0.86)	16.90 ($\pm$2.40)	13.76 ($\pm$2.90)	9.78 ($\pm$2.14)	9.63 ($\pm$1.37)
Thermal properties						
λ (W/m K)	0.067 ($\pm$0.004)	0.068 ($\pm$0.001)	0.067 ($\pm$0.004)	0.074 ($\pm$0.002)	0.068 ($\pm$0.001)	0.070 ($\pm$0.004)
Mechanical properties						
SS (N/mm^2) n=10	0.04 ($\pm$0.02)	0.12 ($\pm$0.07)	0.08 ($\pm$0.05)	0.16 ($\pm$0.06)	0.17 ($\pm$0.04)	0.23 ($\pm$0.10)
MOR (MPa) n=5	0.54 ($\pm$0.17)	2.12 ($\pm$0.18)	1.43 ($\pm$0.24)	2.54 ($\pm$0.81)	2.82 ($\pm$0.68)	4.45 ($\pm$1.98)
MOE (GPa)	0.28 ($\pm$0.08)	0.99 ($\pm$. 0.10)	0.66 ($\pm$. 0.06)	1.95 ($\pm$0.40)	1.36 ($\pm$0.19)	2.86 ($\pm$0.48)

Numbers in brackets represent standard deviation. For WA, TS and flexural properties (MOR and MOE) measurements, identical specimens were used

ρ bulk density, *EMC* equilibrium moisture content, *WA* water absorption after 24 h, *TS* swelling in thickness after immersion in water for 24 h, λ thermal conductivity, *SS* surface soundness, *MOR* flexural strength, *MOE* modulus of elasticity, *n* number of specimens per board

wooden mats, composed of wood shavings and kenaf fibres was estimated with 0.069 W/(m K) (Nakaya et al. 2016).

It is acknowledged that thermal conductivity is expected to increase proportionally to moisture content, temperature and density (Sonderegger and Niemz 2009; Troppová et al. 2015). Additionally, the wood-based panel manufacturing methods, wood-based materials and wood particle sizes, were also indicated as having a large impact on thermal conductivity (Sonderegger and Niemz 2012, 2009). As shown in Fig. 3, the thermal conductivity from all examined panels in this study was plotted as a linear function of density. Evidently, the higher the density of the overlaid bark-based panels, the higher was their thermal conductivity.

3.2 Physical properties

In this study, the core layer density of the panels was attempted to be kept identical in the range of 350 kg/m^3. Consequently, the increased and statistically higher density values observed on the overlaid panels can possibly be explained by the additional weight and thickness of the paper and fibreglass mats. The results of physical and mechanical properties of overlaid bark-based panels observed in this work are shown in Table 2.

As suggested by the results, control panels displayed high water absorption (217.89%) and thickness swelling (17.67%). In terms of reaction to water immersion (Fig. 4), statistical analysis showed that both thickness swelling and water absorption of P1 overlaid panels after 24 h were significantly lower than control (p < 0.05) bark-based panels. Likewise, these panels displayed better results on water absorption of P2 overlaid panels, whilst thickness swelling of recycled paper was also significantly lower than that
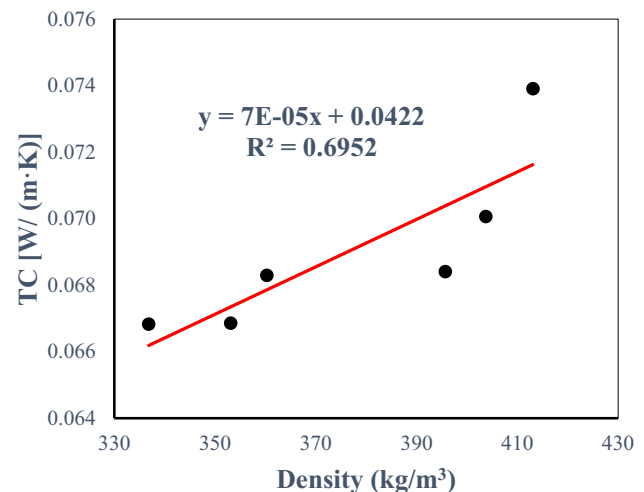
$$y = 7E\text{-}05x + 0.0422$$
$$R^2 = 0.6952$$

Fig. 3 Linear regression model between density and the thermal conductivity of overlaid bark-based panels (confidence level 95%)

of P1. However, the results showed that P2 type overlaid panels demonstrated the worst overall performance, including water immersion properties and mechanical behaviour.

The observed differences of the overlaid paper sheets can be explained by the structural characteristics of the investigated papers. These structural features (such as grammage, type of pulp, manufacturing conditions, additives and/or coating etc.) influence the penetration of UF resin, the quality of interphase bonding, the water uptake behaviour and therefore, indicating a strong overall effect on the performance of bark-based panels. This outcome is further enhanced by the discrepancy noticed between the paper sheets as well as their surfaces. The lower CA and negative ΔG_i values observed on the glued surface of recycled paper
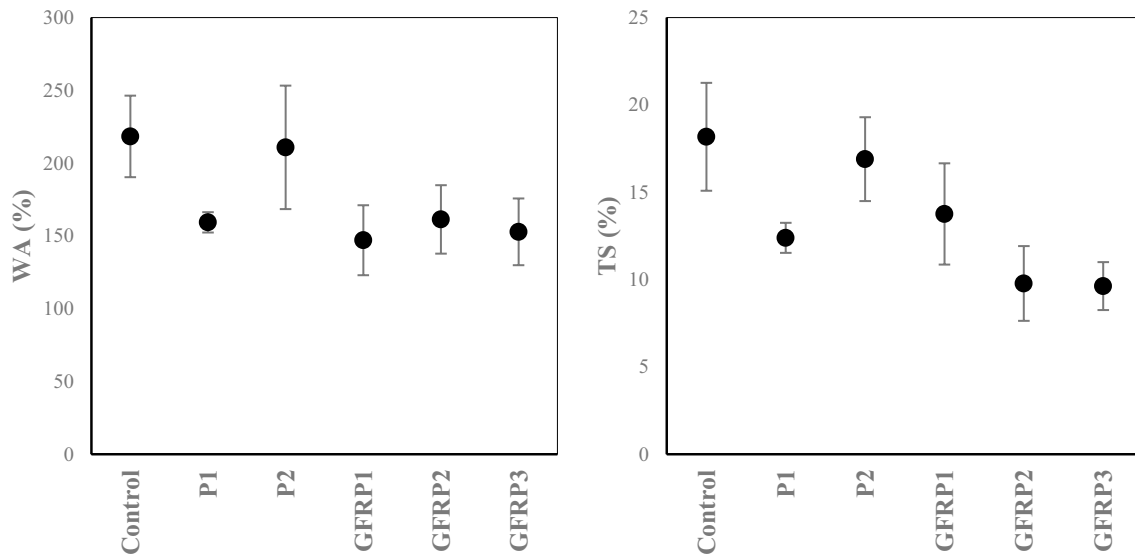
Fig. 4 Water absorption (WA) and thickness swelling (TS) percentages after 24 h water immersion dependent on paper and fibreglass type

indicate the most favourable wettability, in contrast to the higher CA and positive ΔG_i calculated for the remaining paper surfaces and the coated thermomechanical pulp.

On the contrary, application of fibreglass and epoxy resin bonding on the surfaces of bark-based panels, appeared to significantly minimize and restrain the magnitude of water absorption and thickness swelling (Fig. 4). Aside from their low thermal conductivity, glass fibres appear to have very high specific strength and sound absorption properties, are lightweight, and exhibit very good durability and water vapor resistance behaviour (Cao et al. 2015). Among these three fibreglass types, fibreglass woven fabric and mat revealed improved values compared to fibreglass mesh. The incorporation of GFRP2 and GFRP3 types led to a significant decrease in thickness swelling and water absorption up to 46.20–47.03% and 26.02–30.01%, respectively.

Even though bark is less hygroscopic than wood, water flux and humidity sorption and desorption behaviour of bark panels play an essential role in the heating energy consumption of buildings (Kain et al. 2018). Therefore, diffusion properties, usually expressed by the water vapour resistance factor (µ-value), are another important attribute of characterizing insulation materials. Like thermal conductivity, sorption behaviour and water diffusion of wood-based panels are influenced by several factors. Among these factors, panel density, moisture content (relative humidity) and temperature are the most crucial.

Sonderegger and Niemz (2009) investigated the water vapour resistance and diffusion coefficient values of several commercial wood-based panels with different densities and thicknesses. Results have shown that the water vapour resistance factor of the wood-based materials increased with increasing density and decreases with increasing moisture

content. Further, an influence of the coefficients of variation range on the values of water vapour flux was also revealed among the wood-based panels (such as OSB, plywood, coated and uncoated boards), due to the diverse particle sizes among the wood-based panels or the bonding interaction of the coated or overlaid boards.

Kain et al. (2018) concluded that the vapour flow through larch bark insulation panels was significantly influenced by the panel structure of void, and that the most important factor influencing the water vapour diffusion resistance was board density. According to these authors (Kain et al. 2018), the panel structure, in terms of particle orientation and particle size, proved to have a minor influence on the panel`s vapour permeability, which could be a result of low variation. However, fine particles presented a lower compression resistance compared to coarse ones and are possibly compressed more strongly during hot pressing, thus affecting the density of panels.

Wu and Suchsland (1996) examined the effect of moisture content and gradient of overlaid three-layer hardwood particleboards. Their results revealed that the particleboard core layer had a larger water diffusion coefficient than the face layers as a consequence of lower density and larger internal void volume of the core. Even more, they reported that the dominant moisture transfer mechanism in wood-based panels such as particleboard and fibreboard, may be water–vapor diffusion through air-filled pore spaces, while in solid wood bound water diffusion may play a more important role. In addition, wood and bark anatomical cell characteristics have been shown to influence sorption behaviour of wood and wood-based panels. For instance, Neimsuwan et al. (2008) indicated that earlywood of small loblolly pine had greater sorption rates and diffusion coefficients than latewood, while

Kain et al. (2018) cited an investigation in which the vapour diffusion through the periderm of hemlock was studied. According to the study findings, White (1979) indicated that the thin-walled periderm tissue sorbs water about three times slower and the thick-walled one thirty times slower than the wood xylem, as reported by Kain et al. (2018).

In this study, the processing parameters and conditions were identical. Therefore, it is believed the high levels of water absorption, which were observed, can be explained by the following reasons: (a) the low panel density, as well as the size and shape of internal panel voids; (b) poplar bark thicknesses (proportion of phloem and periderm) and intrinsic anatomical characteristics (cell types and dimensions), and (c) surface area, density and aspect ratio of bark particles. Thermal or chemical modification of particles or panels would improve their dimensional stability and hygroscopicity.

Besides bark hygroscopicity, absorption of water is assumed to have a major impact on the mechanical performance of gluelines between fiberglass overlays and epoxy resins and consequently on the mechanical performance of overlaid fiberglass bark panels. As water moves inside the wood, the gluelines might act as barriers that are potentially leading to local moistening (Wimmer et al. 2013) and water molecules can easily migrate into the adhesive and modify its chemical and physical properties (Maggana and Pissis 1999). The transport of moisture in epoxy resin systems in moist or humid environments is of great importance, since most epoxies absorb between 1 and 7 wt% moisture (Soles and Yee 2000). Yet, epoxy was selected as most appropriate for bonding fiberglass with bark. Experiments on the vapor sorption isotherms of common, cured wood adhesives showed an 18%, 22%, 10% and 3.5% moisture uptake of phenol-resorcinol–formaldehyde (PRF), melamine–formaldehyde (MUF), polyvinyl acetate (PVAc) and polyurethane (PU) films, respectively. Moreover, PRF and MUF were classified as slow absorbing adhesives with low diffusion coefficients, PU as medium absorbing adhesives and PVAc as fast absorbing (Wimmer et al. 2013).

3.3 Mechanical properties

The measured mechanical properties of the paper and fibreglass overlaid panels indicated very much alike tendencies to their physical properties (Table 2). The variations in static bending properties, i.e. flexural strength (MOR) and flexural modulus of elasticity (MOE), as well as surface soundness (SS) as a function of overlaid type are illustrated in Fig. 5. It was observed that the examined mechanical properties were significantly influenced by the type of overlaying material. Still, it can be reported that fibreglass overlaid panels

demonstrated improved values compared to paper overlaying sheets.

The observed differences among the overlaying GFRP and paper mats can be explained by the influence of the inherent properties of fibres itself, the volume fraction and orientation of adherent fibres to the matrix, the type of used resins in this research and their manufacturing processes. In the case of the two paper types bonded with UF resin on the bark-based boards, recycled paper sheet exhibited enhanced mechanical properties compared to the coated TMP paper sheet. Nevertheless, none of these paper sheets resulted in satisfying mechanical performance outcomes, same as their water absorption and thickness swelling values. On the contrary, in terms of the tested fibreglass types, fibreglass woven fabric exhibited the best mechanical behaviour regarding fibreglass mesh and mat reinforcements. However, similar mechanical properties were obtained for both fibreglass mesh and mat types.

More specifically, GFRP3 samples resulted in (i) the lowest thermal conductivity values, (ii) the lowest water immersion properties, and (iii) the highest mechanical properties of all the proposed panels. This may be due to the differences in the fibreglass type structures as determined by the porosity, the glass fibre diameter distribution and the resin applied to these polymeric materials. Based on SEM images, it is assumed by the authors, that glass fibres appear loose 'knitted' in the case of woven fabric with on indication of any resin, while in the other two types, there is an apparent existence of embedded resin through the glass fibers. Even more, it was found that the modulus of rupture of all fibreglass types was higher than the values required by the European standard EN 622-4 (2009), type SB. However, it was shown that fibreglass mesh could not satisfy the required thickness swelling values, which possibly can be explained by its grid sized net format.

The good mechanical performance of the fibreglass bark-based panels could be attributed to the good adhesion between GFRP and bark particles. As reported by Raftery et al. (2009a), epoxy adhesives are generally accepted as appropriate binder to form good quality GFRP-wood bonds in dry conditions. It was also noted that the integrity of the bond depends not only on the epoxy but also on bondline thickness and the glass fibre reinforcing type (Raftery et al. 2009b).

However, in most of the cases, the results were associated with a high standard deviation, which demonstrates the degree of variation in the obtained properties of these specimens. This phenomenon can presumably be explained by the major difficulty in obtaining manually preformed pressed panels with a homogeneous distribution. Another possible reason for this observation might be the amount of the proportions of outer and inner bark and differences
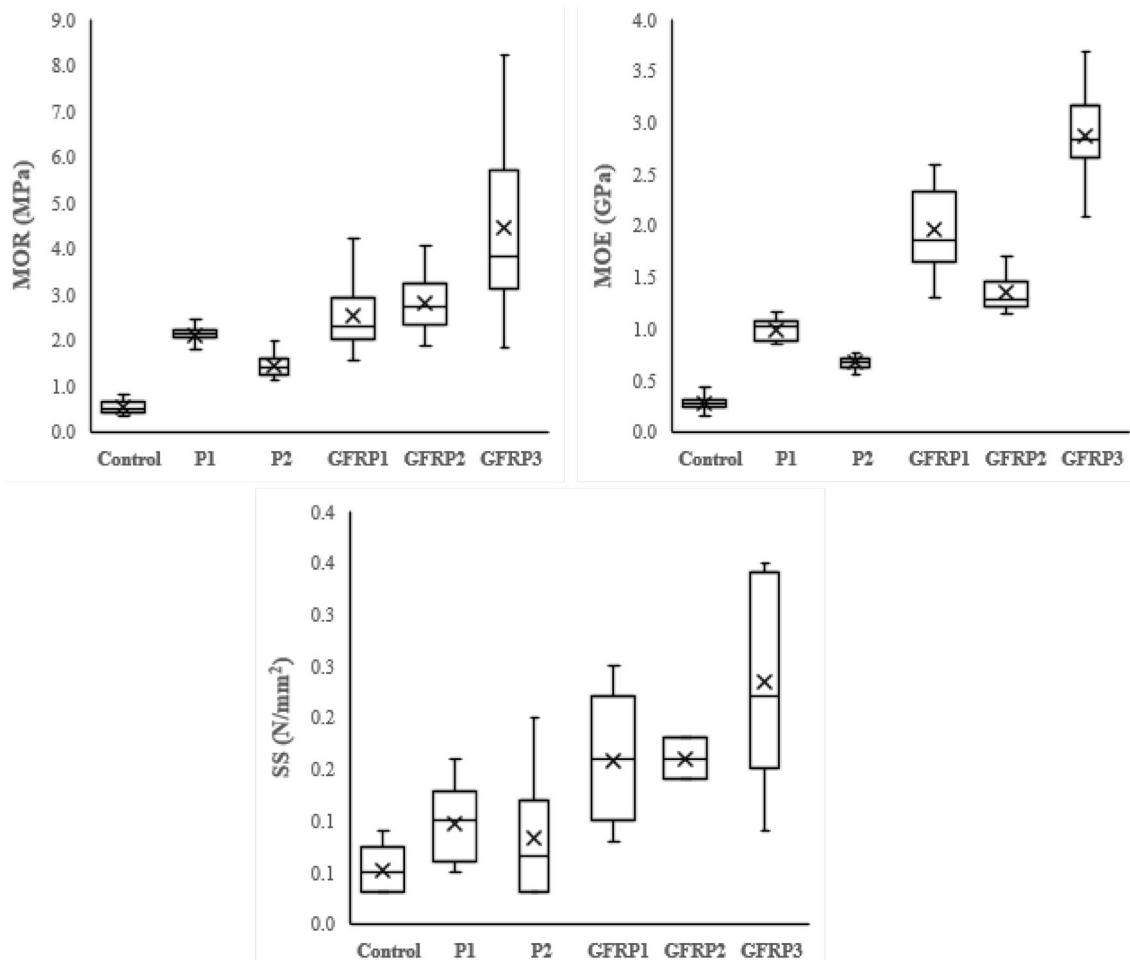
Fig. 5 Flexural strength (MOR), modulus of elasticity (MOE) and surface soundness (SS) of overlaid bark-based panels

in their cellular types and chemical compositions (Eberhard 2013).

4 Conclusion

The thermal, physical and mechanical properties of five overlaid bark-based panels were investigated in this work. Three fibreglass types and two paper sheets were used as exterior reinforcements to enhance the stiffness and strength of the bark-based core layers. Thermal conductivity is one of the most important properties for a thermal insulating material. The observed thermal conductivity values were found to be similar to literature values, and indicated an intermediate thermal performance. Consequently, these fibreglass type overlaid panels could potentially be used as insulating panels for thermal insulation of walls. Even more, the results have shown that fibreglass woven fabric and mat types could fulfil the values required by the European standard EN 622-4, type SB.

Nevertheless, further product development is required to evaluate the water sorption, fire and durability behaviour of the proposed insulation panels.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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