



Basalt grid reinforcement of lightweight plywood

Marcus Cordier¹ · Carsten Mai¹

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Abstract

By using basalt fibre grids as a reinforcing material, lightweight plywood with improved bending properties could be produced by using low density hardwood veneers and phenol-formaldehyde (PF) adhesives. The improvement in flexural strength would allow it to be used in a wider range of load-bearing applications. In this study, acrylate-coated basalt fibre grids with a grammage of 200 g m^{-2} and uncoated basalt fibre grids with a grammage of 116 g m^{-2} were inserted into the outer glue joints of five-layer lime (*Tilia cordata*) plywood as reinforcement. The plywood was bonded with two formulations of PF adhesive. The evaluation of the mechanical properties showed increases for the modulus of rupture (MOR) and the modulus of elasticity (MOE). The increase in MOR was up to 25% in the parallel direction of the top layers and up to 49% in the perpendicular direction of the top layers for plywood reinforced with the acrylate-coated basalt fibre grid compared to the unreinforced reference in a raw density-adjusted comparison. After treatment to evaluate moisture resistance under cyclic test conditions (MR), the reinforced plywoods exhibited similar bending strength to the unreinforced reference after standardised climate conditioning. At the same time, the addition of coated basalt fibre grid had no effect on surface soundness (SS). Therefore, the use of coated basalt grid as a reinforcing material could be a good way to produce high-strength plywood using low-density hardwood veneers.

1 Introduction

The worldwide demand of wood and wood-based products is continuously increasing and requires resource-efficient solutions in view of the increasing scarcity of resources.

Among wood-based products, the global demand for plywood is steadily increasing (Held et al. 2022). In addition to the demand for plywood, the general demand for wood is increasing worldwide (Held et al. 2022). One option to meet the growing overall demand for wood is the increased utilisation of hardwoods (Teischinger 2017). Fast-growing hardwood species are suitable for meeting the growing demand for plywood, particularly for lightweight, low-density plywood (Adi et al. 2014). These species can be harvested from plantations or mixed stands. A common characteristic of these fast-growing hardwood species is their low raw density

(Ieşavs et al. 2021), which offers both advantages and disadvantages in the processing of the wood into plywood and in its subsequent use. A major disadvantage of using low-density wood species for plywood production is that the achievable density-dependent properties of the plywood, such as bending strength, are also limited. To compensate for this disadvantage, and to obtain the advantages of a comparably lightweight material, plywood can be reinforced with fibre material. The reinforcement of plywood with various fibre materials has already been analysed in several studies (Jorda et al. 2021; Auriga et al. 2020; Li et al. 2020; Saal et al. 2024). The materials analysed include carbon fibre and glass fibre for example (Liu and Guan 2019; Bal et al. 2015). All of these fibre materials suffer from specific disadvantages, which make them less appropriate for the reinforcement of lightweight plywood. To be suitable as a reinforcement material for lightweight plywood, a fibre material must meet several requirements: First, it must fulfil the required mechanical properties. Second, it needs to be available in sufficient quantity. Third, its costs must be reasonable in relation to the overall expense. Fourth, it should be producible from natural raw materials in a chemically unmodified or unaltered, natural form. Fifth, it must not be hazardous waste for disposal at the end of the product life cycle.

✉ Marcus Cordier
marcus.cordier@uni-goettingen.de
Carsten Mai
cmai@gwdg.de

¹ Department of Wood Biology and Wood Products,
University of Goettingen, Buesgenweg 4, 37077 Goettingen,
Germany

Basalt fibres are attractive as a reinforcement material for plywood because they meet these requirements. Their mechanical properties make them suitable for use as a reinforcement material in composite materials such as plywood (Shubhra et al. 2011; Bauer et al. 2018). Basalt, the most common magmatic rock type in the Earth's crust, is widely available in large quantities (Grotzinger and Jordan 2017). It is therefore readily accessible for utilisation in various applications. Compared to glass and carbon fibres, the costs for basalt fibres are lower, which means that basalt fibres can be used more cost-effectively (Kessler et al. 2015, 2016). Basalt fibres can be produced from natural basalt rock without altering of its natural chemical form. As a result, basalt fibres produce no waste and have a comparatively low environmental impact (Huang 2009).

The positive effect for basalt grid as a reinforcement material for wood-based panels without significantly increasing the density, has been confirmed for particleboards and oriented strand boards (Kramár et al. 2020; Mayer and Mai 2024). For glued laminated beams with reduced mechanical properties, basalt fibres have been shown to be an effective structural reinforcement (Wdowiak-Postulak 2021; Wdowiak-Postulak et al. 2023). Positive effects have also been confirmed for basalt fibres as a reinforcement material for plywood and laminated veneer lumber using epoxy and polyvinyl acetate as an adhesive system (Núñez-Decap et al. 2022; Rescalvo et al. 2023). The reinforcement of plywood with pre-stressed basalt fibres in a phenol-formaldehyde (PF) adhesive matrix between veneer sheets has been demonstrated for the production of plywood (Lohmus et al. 2021).

PF adhesives are among the most important adhesives for the industrial production of plywood, due to their high durability, bonding properties, and resistance to moisture and heat (Ross 2021). The combination of basalt fibre grids with PF adhesive as a reinforcing material for lightweight plywood has received limited investigation.

The objective of this study was to demonstrate the effect of basalt grid reinforcement in combination with PF adhesive on lightweight plywood made from hardwood veneers with densities up to 400 kg m^{-3} . Plywood with a raw density of up to 650 kg m^{-3} was produced and analysed for this purpose. In order to assess the suitability of basalt fibre grids to reinforce lightweight plywood, it was necessary to confirm that basalt fibre enhance the mechanical-technological properties such as bending strength and impact resistance, while only slightly increasing the density of the plywood.

In order to evaluate the basalt grid insertion, the five mechanical-technological properties of bending strength, moisture resistance under cyclic test conditions for bending strength, impact bending strength (toughness), surface soundness and X-ray density profile of the plywood boards

were investigated and compared to reference boards without basalt grid insertion.

This research contributes to the growing global demand for plywood for structural applications by enhancing the mechanical-technological properties of lightweight plywood was made from fast-growing hardwood species with low raw densities, basalt grid and PF adhesive.

2 Materials and methods

2.1 Raw materials and plywood production

Five-layer plywood with a density below 650 kg m^{-3} was produced from 2 mm-thick rotary-cut veneers of small-leaved lime (*Tilia cordata*), hereafter referred to as 'lime'.

Two types of basalt fibre grids were used as reinforcing material for the plywood. The first type, subsequently referred to as 'Basalt uncoated', made from uncoated basalt fibre rovings (Deutsche Basalt Faser GmbH, Sangerhausen, Germany). This basalt fibre rovings were then processed using a double-plier weaving machine to create a leno weave pattern (Fraunhofer Institute for Wood Research, Wilhelm-Klauditz-Institut WKI, Braunschweig, Germany). The weft threads had a weight of 300 tex and the warp threads had a weight of 600 tex. The surface of the uncoated basalt fibre grid was uncoated. The second type of basalt fibre grid, subsequently referred to as 'Geogrid 200' (Deutsche Basalt Faser GmbH, Sangerhausen, Germany), was the commercial product 'Geogrid 200-9x9'. Geogrid 200 consisted of weft threads with a weight of 750 tex and warp threads with a weight of 720 tex. The surface of the Geogrid 200 was coated with acrylate (Deutsche Basalt Faser GmbH). The uncoated basalt grid had a grammage of 116 g m^{-2} , while the Geogrid 200 had a grammage of 200 g m^{-2} . Both basalt fibre grids had a mesh size of $9 \text{ mm} \times 9 \text{ mm}$.

The adhesive used was a mixture of two commercially available PF adhesives (Hexion GmbH, Iserlohn, Germany), formulated in two different compositions. The first adhesive mixture (formulation 1) comprised 42% Bakelite® PF 2453 HW, 34% Bakelite® PF 2451 HW B and 10% water. The solids content of this adhesive mixture was 36%. The second adhesive mixture (formulation 2), consisting of Bakelite® PF 2453 HW, Bakelite® PF 2451 HW B, water, chalk powder and flour from kernel shells was prepared in an industrial setting mixing ratio. Taking into account the insoluble additives, this formulation yielded a solids content of 53%.

The plywood consisted of five layers of veneer, bonded together with the grain directions of the adjacent veneers perpendicular. To reinforce the plywood boards, basalt fibre grids were inserted into the adhesive joint beneath the top veneer layers on both sides. For both adhesive

formulations, the adhesive mixture was applied to one side of the veneer using a roller until the surface of the veneers was completely coated. The average application quantity for the first adhesive mixture was 184 g m^{-2} , while for the second adhesive mixture it was 156 g m^{-2} . After the veneers were coated with adhesive, they were stacked for further processing.

The stacked veneers underwent pressing at $125\text{ }^{\circ}\text{C}$ for 10 min at a specific pressure of 1 N mm^{-2} , using the hot-press LAP-40 (Gottfried Joos GmbH & Co. KG, Pfalzgrafenweiler, Germany). The dimensions of the plywood boards were $500\text{ mm} \times 500\text{ mm}$ with a nominal thickness of 9 mm.

After hot pressing, the boards were allowed to cool down for 24 h and then cut into specimens for further testing. Prior to further testing, the specimens were conditioned at $20\text{ }^{\circ}\text{C}$ and 65% relative humidity until mass constancy was achieved. The density of the specimens was then determined in accordance with EN 323 (1993).

Microscopic images of selected representative specimens for surface soundness were taken using a 3D reflected-light-microscope (VHX-7000, KEYENCE Corporation, Osaka, Japan).

2.2 Material testing

A total of five variants of plywood were assessed. For each variant, five boards were produced and tested (Table 1). Five key properties of the plywood boards were evaluated:

Bending strength (static and dynamic), moisture resistance under cyclic test conditions, impact bending strength, surface soundness, and X-ray density profile (Table 2).

The bending strength under static load was assessed according to EN 310 (1993), which includes evaluating the modulus of rupture (MOR) and the modulus of elasticity (MOE). This assessment was conducted using a ZwickRoell universal testing machine (ZwickRoell GmbH & Co. KG, Ulm, Germany) equipped with a 10kN load cell. To enhance the comparability of the individual plywood variants and to evaluate the resulting reinforcement effect, selected results were normalised to a theoretical density of 600 kg m^{-3} , assuming a proportional ratio.

The moisture resistance under cyclic test conditions (MR) was assessed for the bending strength under static load in accordance with EN 321 (2002). Subsequently, bending tests were conducted as described earlier to determine the MOR and MOE according to EN 310 (1993). This test was only conducted for the reinforced plywood variants.

The impact bending strength (IBS), denoted by ω , was assessed using unnotched specimens, following DIN 52189 (1981). A modified specimen size of nominal $150\text{ mm} \times 10\text{ mm} \times 10\text{ mm}$ (length $\times$ width $\times$ height) was used, ensuring that the height of the test specimens corresponded to the thickness of the plywood boards. The specimens were randomly selected from the boards, irrespective of the position and amount of the reinforcement material among them, taking into account the nominal mesh size of the basalt grids at $9\text{ mm} \times 9\text{ mm}$ and the nominal width of the specimens of 10

Table 1 Variants of plywood boards produced and tested: Five boards ($n=5$) were manufactured and tested for each plywood variant

Plywood variant	Wood Species	Reinforcement Material	Adhesive mixture
PF_Additives	Lime	None	Bakelite 2451/2453, additives, water
PF	Lime	None	Bakelite 2451/2453, water
PF_Additives_Basalt uncoated	Lime	Basalt uncoated	Bakelite 2451/2453, additives, water
PF_Additives_Geogrid 200	Lime	Geogrid 200	Bakelite 2451/2453, additives, water
PF_Geogrid 200	Lime	Geogrid 200	Bakelite 2451/2453, water

Table 2 Variants of plywood boards tested for modulus of rupture (MOR), modulus of elasticity (MOE), moisture resistance under cyclic test conditions (MR), impact bending strength (IBS), surface soundness (SS) and X-ray density profiling (X-ray D)

Plywood variant	MOR/MOE		MR		IBS		SS	X-ray D
		⊥		⊥		⊥		
PF_Additives	10	10	10	10	20	20	20	10
PF	10	10	10	10	20	20	20	10
PF_Additives_Basalt uncoated	10	10	10	10	20	20	20	10
PF_Additives_Geogrid 200	10	10	10	10	20	20	20	10
PF_Geogrid 200	10	10	10	10	20	20	20	10

Corresponding specimen sizes n for conducted material tests

Material tests were conducted both parallel (||) and perpendicular (⊥) to the grain direction of the top layers. The specified specimen sizes n refer to the total number of specimens from five plywood boards per variant

mm. The support span was 115 mm and the open span was 105 mm. The dynamic impulse was transmitted to the specimens using the pendulum machine Resil Impactor (CEAST GmbH, Martinsried, Germany), equipped with a pendulum hammer delivering an energy of 15J. The specimens were positioned on two abutments to ensure a perpendicular force application in relation to the top layers. The testing was conducted both in the longitudinal direction of the grain of the top layers and perpendicular to it. IBS (kJ m^{-2}) was calculated from the recorded energy, ω (J), according to Eq. 1.

$$\omega = (1000 \times W)/(w \times h) \quad (1)$$

The testing machine concurrently measured the total energy (J), which describes the bending work to the maximum force, and the maximum force $F_{\max}$ (N), which was utilised to calculate the dynamic bending strength (DBS). DBS (N mm^{-2}), denoted as σ_B , was calculated according to Eq. 2 specified in DIN 52186 (1978).

$$\sigma_B = (3 \times F_{\max} \times l)/(2 \times w \times h^2) \quad (2)$$

The surface soundness (SS) was evaluated using a modified procedure based on the guidelines of EN 311 (2002). The cutting depth was set to 2.2 mm to ensure that the adhesive joint containing the reinforcement material was completely cut. The assessment was conducted using a ZwickRoell universal testing machine (ZwickRoell GmbH & Co. KG, Ulm, Germany) equipped with a 10kN load cell.

X-ray density profiling (X-ray D) was conducted using a GreCon Densityprofiler (Fagus-GreCon Gerten GmbH & Co. KG, Alfeld, Germany). The density was measured at a feeding rate of 0.1 mm s^{-1} , with an applied voltage of 32.686kV and an electric current of 525 μA .

All statistical analyses were performed using base R (version 4.2.2, R Core Team, 2022) and RStudio (version 2024.09.0+375, Posit PBC, Boston, Massachusetts). Descriptive statistical methods were employed to summarise and present the data, with particular emphasis on graphical representations that provide insights into data distribution. Boxplots were generated to visually represent the distribution of numerical data and provide a comprehensive overview of key statistical

parameters. The horizontal solid line within each boxplot represents the median value of the dataset. Unlike the mean, the median offers a robust measure of central tendency that is less sensitive to extreme outliers. The box itself encompasses the interquartile range (IQR), spanning from the first quartile (25th percentile) to the third quartile (75th percentile), which contains the middle 50% of the data. Whiskers extending from the box represent the data range beyond the IQR, typically extending to 1.5 times the IQR from the box edges. Any data points beyond these whiskers are plotted as individual points and identified as potential outliers. The position of the median line within the box provides insights into data symmetry. A centrally positioned line suggests a symmetrical distribution, while an off-centre line indicates skewness in the dataset. Utilising base R's core statistical functions for data manipulation and visualisation, the statistical methods focused on descriptive statistics. For each dataset, these descriptive statistics were calculated to include the median, interquartile range, minimum and maximum values, mean (where appropriate), and standard deviation. This approach ensures a thorough examination of the data's statistical properties, complementing the visual representations provided by boxplots.

3 Results and discussion

3.1 Mechanical-technological properties

The mean modulus of rupture (MOR) parallel to the grain of the top layers varied between 70 N mm^{-2} for the unreinforced 'PF_Additives' variant and 91 N mm^{-2} for the reinforced 'PF_Additives_Geogrid 200' variant (variants shown in Table 1). The respective mean MOR perpendicular to the grain of the top layers varied between 31 N mm^{-2} for the unreinforced 'PF' and 55 N mm^{-2} for the reinforced 'PF_Additives_Geogrid 200' variant. The mean density of the specimens was up to 9.2% higher due to basalt reinforcement compared to the reference (Fig. 1, Table 3).

Based on the actual material densities, the insertion of Geogrid 200 resulted in a mean MOR increase of approximately 30% in the parallel direction and 60% in the

Table 3 Mean values $\pm$ standard deviations of plywood modulus of rupture (MOR), modulus of elasticity (MOE) and density measured parallel and perpendicular to the grain of the top layers ($n = 10$)

Plywood variant	Density ρ (kg m^{-3})	MOR $f_{\max}$		MOE $E_{\max}$	
		(N mm^{-2})	(N mm^{-2})	(N mm^{-2})	(N mm^{-2})
			$\perp$		$\perp$
PF_Additives	587 ± 13	67 ± 5	34 ± 1	8281 ± 582	2723 ± 85
PF	606 ± 25	73 ± 15	31 ± 14	7134 ± 3620	2463 ± 953
PF_Additives_Basalt uncoated	592 ± 9	75 ± 4	38 ± 3	8479 ± 494	3014 ± 127
PF_Additives_Geogrid 200	638 ± 10	91 ± 4	55 ± 5	9142 ± 208	3614 ± 213
PF_Geogrid 200	641 ± 17	90 ± 4	54 ± 4	9307 ± 427	3700 ± 167

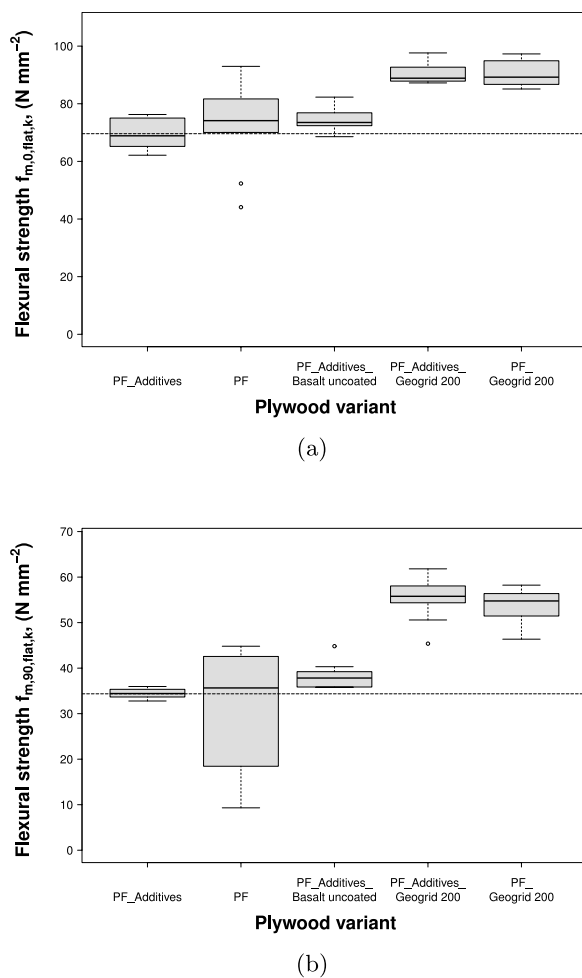


Fig. 1 Modulus of rupture (MOR) of plywood variants measured parallel (a) and perpendicular (b) to the grain of the top layers. Each boxplot represents 10 measurements (5 boards $\times$ 2 specimens). The dashed horizontal line marks the mean value of the 'PF_Additives' reference

perpendicular direction compared to the unreinforced references. If the strengths were normalised to theoretical density of 600 kg m^{-3} , the reinforcement yielded an MOR increase of approximately 25% in the parallel direction and 49% in the perpendicular direction of the top layers. The scatter of the results was higher for the plywood variants bonded with PF adhesive without additives (formulation 1) than for variants glued with PF adhesive combined with additives (formulation 2). The insertion of uncoated basalt grid only marginally increased the MOR of the plywood.

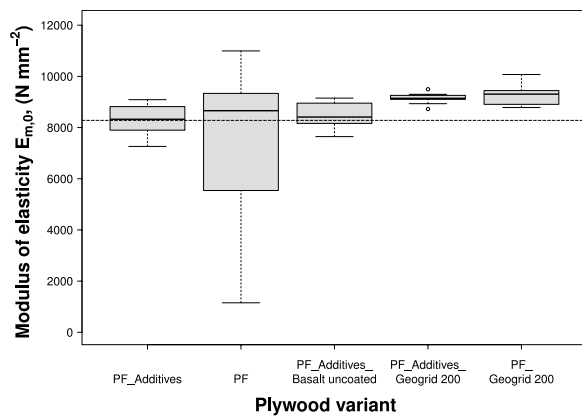
The increase in MOR resulting from the reinforcement with Geogrid 200 can be attributed to the higher density near the surface, a finding supported by X-ray D profiling results. Due to its high tensile strength, the basalt grid can absorb tensile stress occurring on the tensile side of the specimen under bending load conditions. The comparatively lower effect on MOR caused by the uncoated basalt reinforcement

can be explained by its lower grammage compared to Geogrid 200. Additionally, the lack of a protective coating makes the mesh susceptible to thread displacement during handling. As a result, the mesh threads may partially be displaced, leading to a loss of orientation among the adhesive joints and a subsequent reduction in bending load uptake. The results further indicate that coating the basalt fibre surface increases the adhesion of the PF adhesive, thereby enhancing the reinforcing effect. These results highlight the importance of sufficient grammage and suggest that appropriate coating is likely beneficial for the effectiveness of basalt reinforcement in plywood bonded with PF adhesive. Investigations into the surface modification of basalt fibres as a reinforcing material in wood-based boards seem to substantiate this observation (Mayer et al. 2024). The study, which examined various coatings on basalt fibres using scanning electron microscopy combined with energy-dispersive X-ray spectroscopy, has shown that the quality of the coating affects the reinforcement effect. The findings indicate that when basalt fibres are surface modified by coating, both the individual strengths of the filaments and the matrix (coating) are important, but the shear strength of the interface between the fibre and matrix is also a significant factor. The authors also pointed out that additional factors contributing to the failure of fibre-matrix composites can apply to coated fibres. A more detailed investigation is necessary to precisely delineate the singular and combined impacts of these variables on the strengthening effect of the plywood caused by the basalt fibres. In addition, it is essential to ascertain the edgewise bending strength of reinforced plywood, which is a critical material characteristic for engineering applications (Wang et al. 2022).

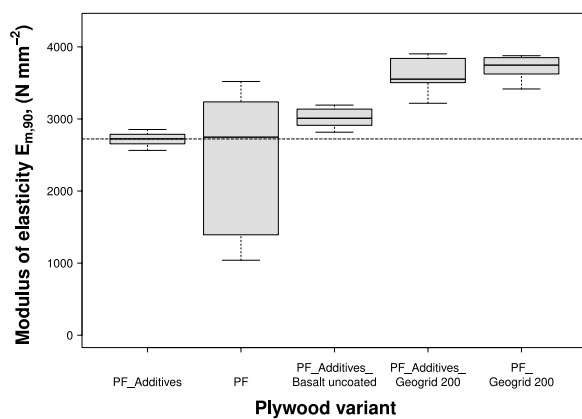
The mean modulus of elasticity (MOE) of the plywoods varied between 7134 N mm^{-2} for the unreinforced reference 'PF', for which no additives were used, (formulation 1), and 9307 N mm^{-2} for the 'PF_Geogrid 200' variant parallel to the grain of the top layers. Perpendicular to the grain direction of the top layers, the mean MOE ranged from 2463 to 3700 N mm^{-2} (Fig. 2, Table 3).

There was a greater increase in MOE with the insertion of Geogrid 200 compared to the uncoated basalt grid, both parallel and perpendicular to the grain of the top layers. In particular, the MOE was more significantly affected by the insertion of the reinforcement materials perpendicular to the grain of the top layers than parallel to the grain of the top layers.

Similar to the MOR, the greater reinforcement effect of Geogrid 200 compared to the uncoated basalt grid can be attributed to the higher proportion of mass per area due to its 72% higher grammage. The higher reinforcing effect observed in the perpendicular direction of the top layers may be due to the characteristics of the wood veneers.



(a)



(b)

Fig. 2 Modulus of elasticity (MOE) of plywood variants measured parallel (a) and perpendicular (b) to the grain of the top layers. Each boxplot represents 10 measurements (5 boards $\times$ 2 specimens). The dashed horizontal line marks the mean value of the 'PF_Additives' reference

Wood exhibits significantly greater bending strength in the direction parallel to the fibre orientation. This is primarily due to the anatomical structure of the wood and the arrangement of the fibres (Hankinson 1921).

The force-deformation diagram of representative specimens of the plywood variants assessed shows that those reinforced by Geogrid 200 can undergo a greater degree of deformation and withstand a greater force before breaking than the reference specimens (Fig. 3).

The deformation (mm) of the plywood reinforced with Geogrid 200 was approximately 22% greater than that of the unreinforced references, and required approximately 220N more force to be absorbed within the linear elastic deformation range. This results in an approximately 1.8 fold increase in the area of linear elastic deformation due to the basalt grid reinforcement. Additionally, the applied force prior fracture was approximately 400N higher.

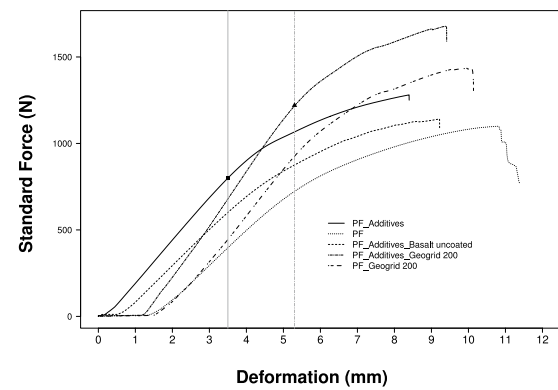


Fig. 3 Force-deformation graphs of representative specimens from plywood variants, parallel to the grain of the top layers. The vertical lines mark the boundaries of the areas of linear elastic deformation

The results show an increase in the elastic area due to the Geogrid 200 reinforcement compared to the references, which corresponds to the higher MOE shown above.

The mean values for MOR in the test for moisture resistance under cyclic conditions (MR) ranged from 36 N mm⁻² for the 'PF_Geogrid 200' variant to 78 N mm⁻² for the 'PF_Additives_Geogrid 200' variant parallel to the grain of the top layers (Table 4). Perpendicular to the grain of the top layers, the mean values for MOR varied between 34 N mm⁻² for the 'PF_Geogrid 200' variant and 37 N mm⁻² for the 'PF_Additives_Basalt uncoated' variant.

The mean values for MOE after cyclic testing ranged from 4935 N mm⁻² for the 'PF_Geogrid 200' variant to 8731 N mm⁻² for the 'PF_Additives_Geogrid 200' variant parallel to the grain of the top layers. Perpendicular to the grain of the top layers, the mean MOE values after the cyclic test fluctuate between 2770 N mm⁻² ('PF_Additives_Basalt uncoated') and 3394 N mm⁻² ('PF_Additives_Geogrid 200'; Table 4). The 'PF_Geogrid 200' variant, bonded with the PF adhesive mixture without additives (formulation 1), showed a significantly higher delamination rate ($\parallel$ 20%; $\perp$ 80%) of the specimens, lower results for MOR and MOE (Table 4), and a higher mass loss during the cyclic test (Table 5) compared to the variants bonded with the PF adhesive and additive-containing mixture (formulation 2).

Compared to the mean values for MOR obtained in the three-point bending test with specimens conditioned to normal climate, the results after cyclic treatment showed a mean loss of 2.6% for the 'PF_Additives_Basalt uncoated' variant, 14.3% for the 'PF_Additives_Geogrid 200' variant, and 60% for the 'PF_Geogrid 200' variant (Tables 3 and 4). Notably, only eight of the specimens of the latter variant passed the entire test cycle before delamination occurred. Parallel to the grain of the top layers, the average decreases were 2.6% for the 'PF_Additives_Basalt uncoated' variant, 14.5% for the 'PF_Additives_Geogrid 200' variant, and 37% for the

Table 4 Mean values $\pm$ standard deviations of plywood modulus of rupture (MOR) and modulus of elasticity (MOE) measured parallel and perpendicular to the grain of the top layers after completing the moisture resistance (MR) treatment cycle according to EN 321 (2002) ($n = 10$, 5 boards $\times$ 2 specimens)

Plywood variant	Density ρ (kg m ⁻³)	MOR $f_{\max}$		MOE $E_{\max}$	
		(N mm ⁻²)	(N mm ⁻²)	(N mm ⁻²)	(N mm ⁻²)
			⊥		⊥
PF_Additives_Basalt uncoated	529 $\pm$ 11	73 $\pm$ 7	37 $\pm$ 10	8080 $\pm$ 622	2770 $\pm$ 383
PF_Additives_Geogrid 200	586 $\pm$ 13	78 $\pm$ 7	47 $\pm$ 4	8731 $\pm$ 632	3394 $\pm$ 232
PF_Geogrid 200	560 $\pm$ 15	36 $\pm$ 14 ¹	34 $\pm$ 12 ²	4935 $\pm$ 2959 ¹	2910 $\pm$ 71 ²
1 Non-delaminated and tested specimens after the third cycle: $n = 8$					
2 Non-delaminated and tested specimens after the third cycle: $n = 2$					

Table 5 Mean values $\pm$ standard deviations of plywood density ρ measured before and after completing the treatment cycle for moisture resistance (MR) for non-delaminated specimens (n)

Plywood variant	Density ρ			Specimens	
	before	after	lossrate	n	
	(kg m ⁻³)	(kg m ⁻³)	(%)		⊥
PF_Additives_Basalt uncoated	583 $\pm$ 12	529 $\pm$ 11	9.3 $\pm$ 1.2	10	10
PF_Additives_Geogrid 200	633 $\pm$ 9	584 $\pm$ 13	7.5 $\pm$ 1.8	10	10
PF_Geogrid 200	639 $\pm$ 17	564 $\pm$ 15	11 $\pm$ 3.6	8	2

two specimens of the 'PF_Geogrid 200' variant that did not delaminate.

Regarding MOE, the mean decrease compared to values of specimens tested conditioned to normal climate, parallel to the grain of the top layers were 4.7% for the 'PF_Additives_Basalt uncoated' variant, 4.5% for the 'PF_Additives_Geogrid 200' variant, and 47% for the specimens of the 'PF_Geogrid 200' variant that did not delaminate. Perpendicular to the grain of the top layers, the decrease was 8.0% for the 'PF_Additives_Basalt uncoated' variant, 6.0% for the 'PF_Additives_Geogrid 200' variant, and 21.4% for the specimens of the variant 'PF_Geogrid 200' that did not delaminate.

The decrease in MOE and MOR was accompanied by a decrease in density during the cyclic test (Table 5).

The results of MOR and MOE testing under cyclic wetting conditions for MR reveal two key findings. Overall, basalt grid reinforced plywood can withstand intense swelling and shrinking loads, as well as temperature changes, resulting in bending properties equivalent to those of unreinforced plywood conditioned under normal climate and tested in a three-point bending test. In particular, the resistance to delamination and the resulting bending strength after cyclic testing are mainly influenced by the PF adhesive mixture used. It is therefore essential to adapt the adhesive formulation to meet the specific requirements. Most delamination of the 'PF_Geogrid 200' variant occurred in the outer adhesive

joints containing the basalt grid. Due to the right-angled arrangement of the veneers, opposing forces are generated during the cyclic test, which stress the bonding. The isotropic basalt inlay might not conform to the movements of the anisotropic wood veneers and may therefore promote shear fracture. The higher mass loss of the specimens bonded with the additives-free adhesive mixture (formulation 1) might further intensify this effect.

The impact bending strength (IBS, ω) of the plywood variants varied between 6.1 kJ m⁻² and 12.6 kJ m⁻² parallel to the grain of the top layers, and 5.3 kJ m⁻² and 11.4 kJ m⁻² perpendicular to the grain of the top layers (Fig. 4). The 'PF_Additives_Geogrid 200' variant exhibited the highest mean IBS, observed both parallel and perpendicular to the grain of the top layers.

The insertion of Geogrid 200 significantly increased the IBS compared to the unreinforced references. This increase occurred regardless of the adhesive mixture used. In contrast, the insertion of uncoated basalt fibre grid did not effectively increase the IBS, neither parallel nor perpendicular to the grain of the top layers (Fig. 4). However, the dispersion of IBS in the reinforced plywood variants was higher than in the unreinforced references. The IBS of the 'PF_Additives' reference variant, as well as the reinforced 'PF_Additives_Geogrid 200' variant, were higher than those of the variants bonded with PF adhesive without additives. In addition, the reinforced variants bonded with PF adhesive with additives (formulation 2) exhibited slightly lower dispersion IBS values than the variants bonded with PF adhesive alone (formulation 1).

This finding underscores the effectiveness of incorporating Geogrid 200 in enhancing the structural integrity of the PF-bonded plywood. Such reinforcement proves beneficial in different orientations relative to the grain, suggesting its robust performance in various load-bearing scenarios. The increased dispersion observed in the results for the reinforced variants, compared to the references can be attributed to the variable proportion and positioning of the basalt grid among the specimens. This variation results from the random selection of the specimens from the boards and thus the different distribution of the mass or volume and position of the reinforcing material in the specimens.

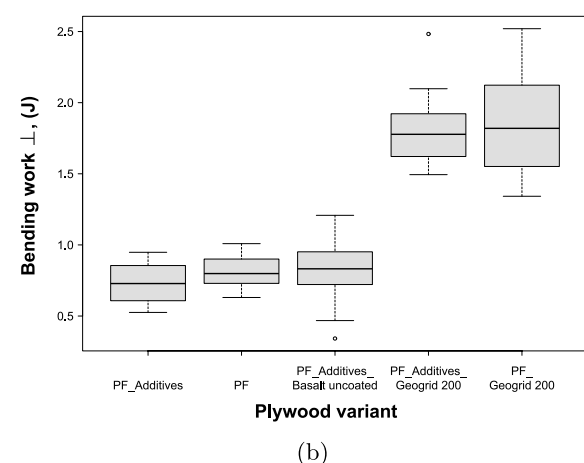
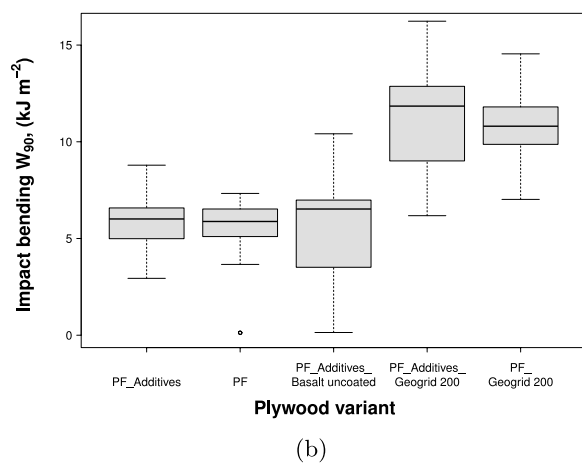
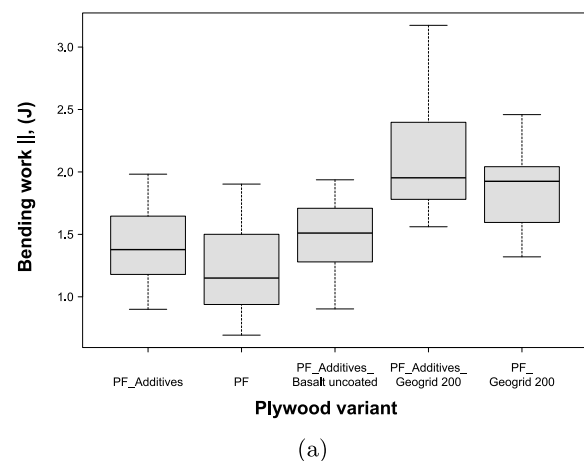
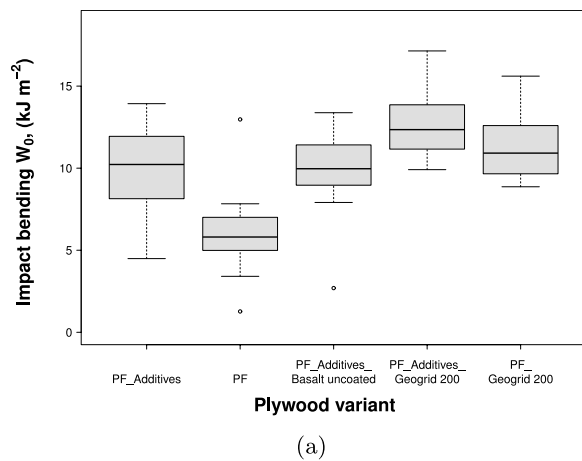


Fig. 4 Impact bending strength (IBS) of plywood variants parallel (a) and perpendicular (b) to the grain of the top layers. Each boxplot represents 20 measurements (5 boards $\times$ 4 specimens)

The mean bending work up to the point at which the specimens failed ranged from 1.2J for the 'PF' variant to 2.1J for the 'PF_Additives_Geogrid 200' variant parallel to the grain of the top layers. Perpendicular to the grain of the top layers, the mean bending work ranged from 0.75J for the 'PF_Additives' variant to 1.84J for the 'PF_Additives-Geogrid 200' variant (Fig. 5).

The insertion of the uncoated basalt grid did not lead to a significant improvement in bending work, while the insertion of Geogrid 200 led to a significant increase. This increase was observed both parallel and perpendicular to the grain of the top layers and thus represented an improvement in both main directions. This improvement was achieved with both adhesive formulations. In the longitudinal direction, the improvement for both adhesive formulations was 50%, with the variants 'PF_Additives' compared to 'PF_Additives_Geogrid 200' and 'PF' compared to 'PF_Geogrid 200'. Perpendicular, the increase of bending work

Fig. 5 Bending work until failure in impact bending test of plywood variants parallel (a) and perpendicular (b) to the grain of the top layers. Each boxplot represents 20 measurements (5 boards $\times$ 4 specimens)

varied depending on the adhesive formulation. When using formulation 2, the increase in comparison between the variants 'PF_Additives' and 'PF_Additives_Geogrid 200' was 140%. For adhesive formulation 1, the increase between the 'PF' and 'PF_Geogrid 200' variants was 126%. Particularly in the perpendicular direction, the rates of increase largely corresponded to the increase in impact strength achieved by the insertion of Geogrid 200. The ratio of bending work to impact bending strength, calculated based on the mean values, was improved by the usage of adhesive formulation 2 containing the additives in combination with the 'Geogrid 200', from 0.14 to 0.16 in the longitudinal direction and from 0.12 to 0.15 in the perpendicular direction. The increase in the ratio means that the reinforced material is more flexible and less prone to fracture. It can absorb more energy before breaking (Figs. 4 and 5).

The increase in the ratio suggests that reinforced plywood tends to be more resistant to fracture, as it can absorb more

energy before breaking. These results are in line with the increase in impact bending strength (IBS) and emphasise that the insertion of Geogrid 200 significantly increased the bending work before failure of the plywood.

The mean dynamic bending strength (DBS, σ_B) of the plywood variants ranged from 55.5 N mm⁻² to 87 N mm⁻² parallel to the grain of the top layers. Perpendicular to the grain of the top layers, the mean DBS varied between 36.5 N mm⁻² and 59 N mm⁻². The 'PF_Additives_Geogrid 200' variant achieved the highest DBS of the plywood variants, both perpendicular and parallel to the grain (Fig. 6).

The mean DBS for the 'PF_Additives_Geogrid 200' variant exceeded that of the 'PF_Additives' reference variant by 24.3%, disregarding the actual density and considering the direction parallel to the grain of the top layers. The comparison disregarded the actual density and considered a calculated theoretical density of 600 kg m⁻³ instead. Parallel to the grain of the top layers, the mean DBS of the 'PF_Additives_Geogrid 200' variant was 5.4% higher than the mean DBS of the 'PF_Additives' reference. Perpendicular to the grain of the top layers, the increase in DBS of the 'PF_Additives' variant compared to the 'PF_Additives_Geogrid 200' variant was 47.5% based on the actual density and 27.6% based on calculated theoretical density of 600 kg m⁻³. The insertion of uncoated basalt in the 'PF_Additives_Basalt uncoated' variant did not result in any significant increase in the mean DBS compared to the 'PF_Additives' reference, neither parallel nor perpendicular to the grain of the top layers. Compared to the mean MOR values from the static three-point bending test parallel to the grain of the top layers, the mean DBS results for the reference variant 'PF_Additives' were almost the same, while the values for the reinforced variants were slightly lower in the dynamic test. Perpendicular to the grain of the top layers, the mean DBS values for all variants were slightly higher than the mean MOR values obtained from the static test.

The results of both the static and dynamic bending tests together confirm the beneficial effect of incorporating Geogrid 200 on the bending properties of the plywood. The enhancement is particularly noticeable in the perpendicular direction, indicating that the orientation of the basalt grid in relation to the weft and warp threads within the plywood board is of secondary importance. In addition, the reinforcement effect appears to be slightly more pronounced when combined with the PF adhesive mixture containing additives (formulation 2).

An additional observation was that the reinforced plywood specimens tested for IBS and DBS showed a markedly different damage pattern compared to the unreinforced references.

Despite the fracture, most of the reinforced specimens remained structurally held together by the basalt fibre reinforcement after failure. Consequently, the splintering under

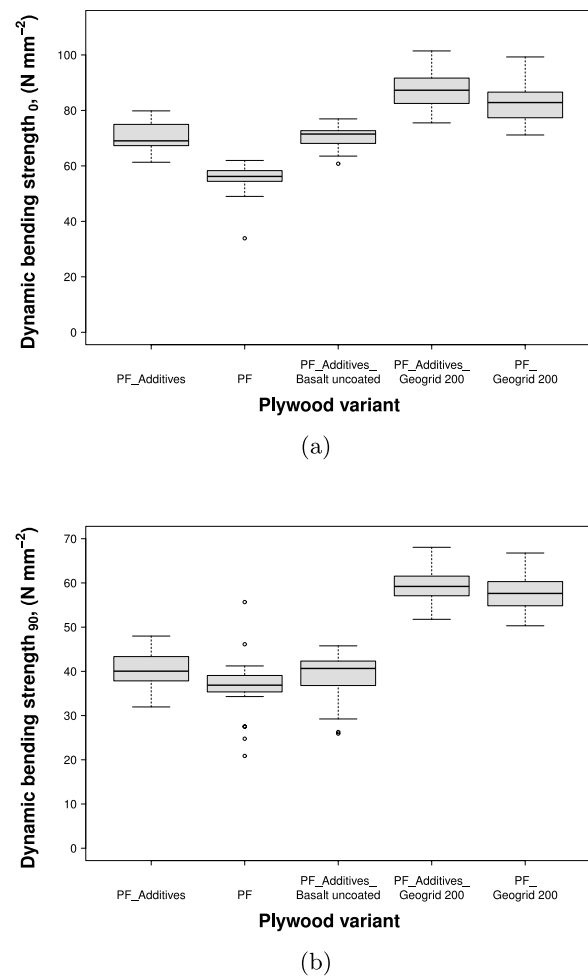


Fig. 6 Dynamic bending strength (DBS) of plywood variants parallel (a) and perpendicular (b) to the grain of the top layers. Each boxplot represents 20 measurements (5 boards × 4 specimens)

dynamic loading was reduced compared to the reference specimens.

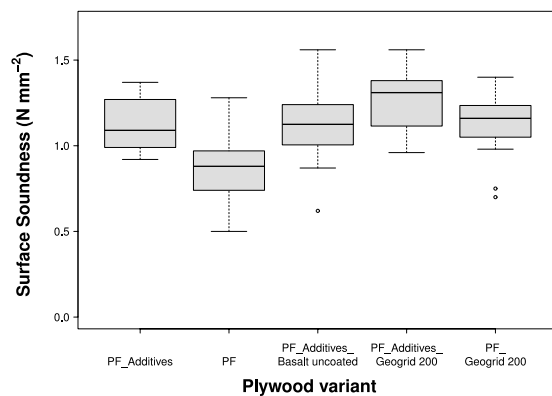
This observation indicates that the insertion of basalt fibre fabrics not only results in an immediate increase in flexural strength, but also provides an additional safety factor in the event of failure under dynamic loading.

The median value of the surface soundness (SS) was similar for all plywood variants, typically around 1.1 N mm⁻², with a slightly higher median of 1.3 N mm⁻² for the 'PF_Additives_Geogrid 200' variant (Fig. 7). However, the plywood variants exhibited different failure proportions regarding the several adhesive joints and a different proportion of wood failure (Figs. 7 to 9, Table 6). Both types of basalt grid showed effective bonding to the wood in the areas tested (Fig. 8).

These results and subsequent microscopic image analysis (Fig. 9) showed no negative effect of the basalt grid insertion on the quality of the plywood bonding. The images

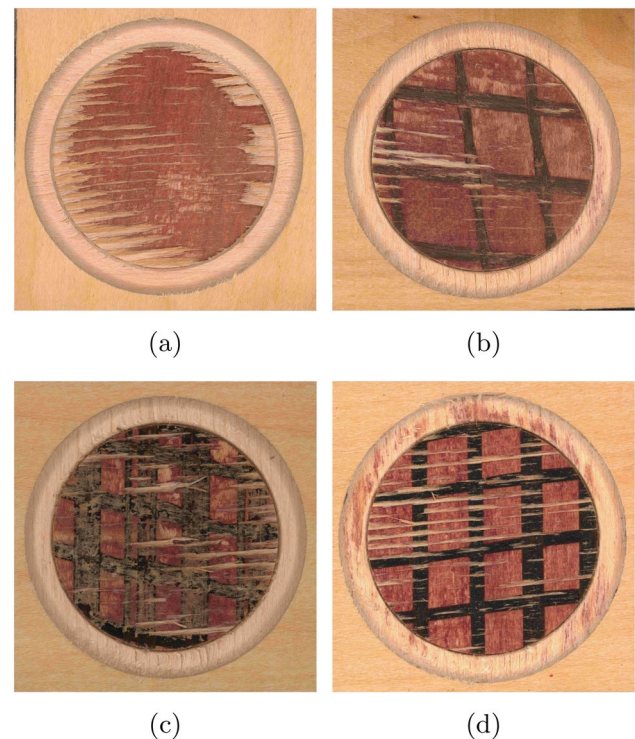
Table 6 Median values of surface soundness (SS) and proportion of failure according to EN 321 (2002) for plywood ($n = 20$)

Plywood variant	Density ρ (kg m ⁻³)	SS (N mm ⁻²)	Proportion of failure	
			(%)	(%)
			Outer (reinforced) Adhesive joint	Second Adhesive joint
PF_Additives	490 ± 9	1.14	30	70
PF	610 ± 36	0.85	100	0
PF_Additives_Basalt uncoated	490 ± 9	1.13	90	10
PF_Additives_Geogrid 200	546 ± 12	1.31	35	65
PF_Geogrid 200	539 ± 11	1.16	55	45

**Fig. 7** Surface soundness (SS) of plywood variants. Each boxplot represents 20 measurements (5 boards × 4 specimens)

demonstrated that both the Geogrid 200 and the uncoated basalt fibre grid were well bonded to the veneers when using the adhesive mixture with additives (formulation 1). The measured SS values for the 'PF_Additives_Geogrid 200' variant were comparable to those for the 'PF_Additives' reference, as were the failure proportions observed for both the outer and second adhesive joints. However, for the 'PF_Additives_Basalt uncoated' variant, the failure rate was higher in the outer adhesive joint containing the reinforcement material than in the second adhesive joint.

The SS results provide two important insights into the quality of the bonding and the influence of the basalt grid reinforcement on it. Firstly, the minimal deviations in the median and mean values between the plywood variants indicate that the bonding quality of reinforced plywood is not consistently negatively affected compared to the reference. Secondly, although several specimens failed at the second adhesive joint, which does not contain basalt grid reinforcement, there were no significant differences to the results of the specimens that failed in the reinforced adhesive joints. Thus, no detrimental effect of the basalt fibre insertion on the quality of the material bond can be demonstrated. One possible reason for the good bond between the two reinforcement materials is the better physical interlocking of the

**Fig. 8** Representative material failure of the plywood variants observed after surface soundness testing: (a) 'PF_Additives', (b) 'PF_Basalt uncoated', (c) 'PF_Additives_Geogrid 200', (d) 'PF_Geogrid 200'. 'PF' omitted due to optical similarity with 'PF_Additives' (a). Panoramic images captured at 4420 × objective magnification

adhesive matrix with the uncoated basalt fibres compared to the better surface adhesion of the adhesive to the coated Geogrid 200 (Fig. 10).

Density profiling revealed that insertion of the basalt reinforcement materials led to a localised increase of the bond area in density of approximately 550 kg m⁻³ in the vicinity of the outer adhesive joints. In general, the density of the four adhesive joints was higher than that of the five veneer layers (Fig. 11).

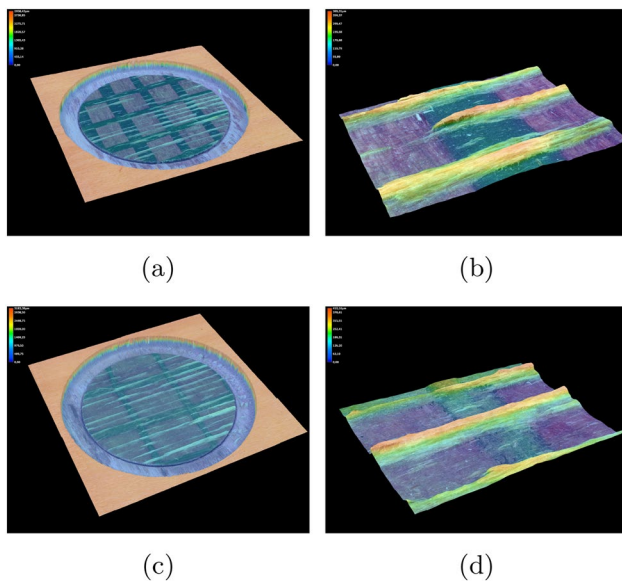


Fig. 9 Representative material failure of basalt grid reinforced adhesive joints observed during surface soundness testing. The colour mapping indicates the height in the 3D images: Blue indicates the lowest height and red the maximum height. Maximum height of 3200 μ m for a and b. Maximum height of 410 μ m for c and d. **a** 3D image of a specimen of 'PF_Geogrid 200' (20 $\times$ objective magnification), **b** Close-up image of wood failure on a specimen of 'PF_Geogrid 200' with height measurement of fragments (50 $\times$ objective magnification), **c** Close-up image of the contact area between wood fragments and basalt fibre grid of a specimen 'PF_Basalt uncoated' (20 $\times$ objective magnification), **d** height measurement of the wood fragments in contact with the basalt fibre grid of a specimen 'PF_Basalt uncoated' (50 $\times$ objective magnification)

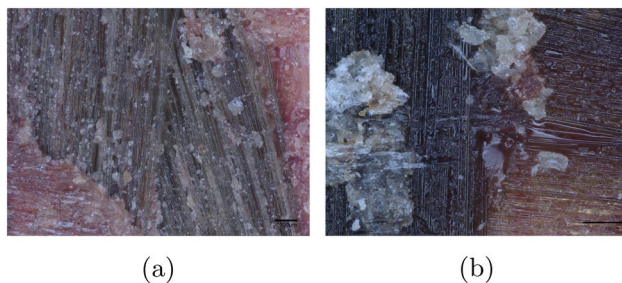


Fig. 10 Comparative analysis of PF (formulation 2) adhesion to basalt grid surfaces: **a** Uncoated basalt grid 'Basalt uncoated'. **b** Acrylate coated basalt grid 'Geogrid 200'. Panoramic images captured at 400 $\times$ objective magnification

Due to the reinforcement concentrated near the surface, the plywood boards reinforced in this manner exhibit a more pronounced U-shaped density profile than the unreinforced references. This phenomenon is generally associated with an enhancement in bending properties of the material.

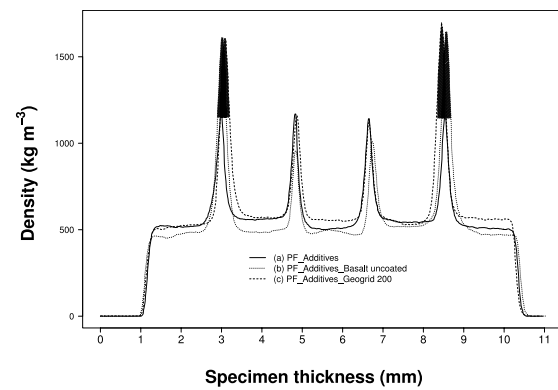


Fig. 11 Representative density profiles of plywood: **a** without basalt reinforcement grid ('PF_Additives'), **b** with uncoated basalt reinforcement grid ('PF_Additives_Basalt uncoated'), and **c** with Geogrid 200 as reinforcement material ('PF_Additives_Geogrid 200'). The hatched areas depict the density increments resulting from the insertion of the basalt grid, in comparison to the reference

The positioning of the reinforcement materials in the outer adhesive joints ensured the maximum possible distance from the neutral axis under bending stress. Combining the density profiles of the reinforced plywood variants with the results of static (MOR) and dynamic (DBS) bending tests, the chosen positioning of the reinforcing materials in the outer adhesive joints can be deemed appropriate for improving the bending properties of plywood. This finding is consistent with earlier studies that confirmed similar basalt fibre reinforcements in particle board and oriented strand board (Kramár et al. 2020; Mayer and Mai 2024). It was highlighted that positioning the fibres as close to the surface as possible yields the highest reinforcement effect for the wood-based material.

The results presented show that insertion of basalt fibre grids into low-density hardwood plywood can effectively enhance their strength properties. An acrylate coating on the basalt grid seems to enhance the effect. Given the widespread availability of low-density hardwood species and basalt, combined with the well-established and technologically straightforward process of producing plywood using PF adhesives, this method represents a promising approach to sustainable material utilisation. In further research, three critical areas warrant investigation: Firstly, in order improve the environmental sustainability of basalt-reinforced plywood, it is essential to investigate the potential of modified PF adhesives with reduced petroleum-based phenol content for use in combination with coated basalt grid reinforcement, alongside developing of resource-efficient recycling concepts. Secondly, achieving superior adhesion to the basalt surface requires a deeper understanding of the interaction between basalt fibre surfaces and PF-based adhesives. Future investigations

should focus on optimising the PF based adhesive mixture to ensure optimal bonding with the basalt surface. Thirdly, a comprehensive analysis of the material properties is essential. This includes a thorough examination of the quality of the bond using microscopic imaging techniques and taking into account shear tensile strength. In addition, detailed studies into the effects of the reinforcing material at different load-surface angles are crucial. Furthermore, the relationship between the proportion of basalt reinforcing material and of wood material as well as the interaction between the raw density of the wood and the reinforcement material applied should be investigated. Addressing these areas in further research can improve the understanding of basalt-reinforced plywood and facilitate its wider application in sustainable building practices.

4 Conclusion

Reinforcement of plywood with the acrylate-coated basalt grid Geogrid 200, with a grammage of 200 g m^{-2} , effectively enhances the bending properties under static and dynamic loading. Both adhesive formulations used in combination with Geogrid 200 result in plywood that shows a significant improvement in the assessed material parameters. Surface soundness tests indicate that the bonding performance is slightly affected by the insertion of the basalt grid, albeit resulting in a change in the failure mode, particularly in the adhesive joint. Microscopic examination of the failure areas reveals that adhesion between the wood and basalt surfaces takes place. The reinforced plywood has a higher load-bearing capacity in the linear elastic range and can absorb greater total bending loads before it breaks. However, the effect is notably less pronounced for the insertion of the uncoated basalt grid with a lower grammage (116 g m^{-2}). In conclusion, reinforcing PF-bonded plywood from low-density hardwood with basalt grids enhances strength properties, especially bending strength and impact bending strength. This approach holds great promise for optimising the resource-efficient use of low-density hardwood and basalt, particularly in light of the growing global demand for plywood.

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Author contributions Marcus Cordier: Conceptualisation, Methodology, Data curation, Analysis, Investigation, Writing—original draft preparation, Writing—review and editing. Carsten Mai: Conceptualisation, Methodology, Writing—review and editing, Supervision, Funding acquisition.

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Data availability Data generated in this study can be accessed from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors have no conflict of interest to declare that are relevant to the content of this article.

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