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Advancing Timber for the Future Built Environment

NATURAL EXPOSURE COMPARISON OF TIMBER JOINTS BONDED WITH POLYURETHANE ADHESIVE IN TWO CLIMATIC CONDITIONS

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ABSTRACT: The increased use of engineered wood in the built environment is attracting much attention because of the significant sustainable attributes. The formation of high quality reliable structural adhesive bonds is essential during the manufacture of such products. This research examines and compares the performance of bonded European beech and Radiata pine subject to natural weathering, comparing untreated, preservative treated and mineralized wood. Bonded joints were naturally weathered in Slovenia and New Zealand, respectively. The fracture energy was evaluated through Mode I fracture tests using the double cantilever beam arrangement at various ageing stages. FTIR analysis was conducted to assess chemical changes in the adhesives and wood substrate. The research provides insights into the interactions between ageing, wood species, and adhesive performance, enhancing timber structures sustainability.

KEYWORDS: Durability, Weathering, Climate, Adhesive bond, Mode I fracture testing

1 – INTRODUCTION

Timber engineering has advanced significantly in recent times, driven by the demand for sustainable building materials. The formation of quality adhesive bonding is essential to maintain the structural integrity of engineered wood-based products. Polyurethane (PUR) adhesives are a class of adhesives that have favourable characteristics given their mechanical properties, versatility, and manufacturing benefits [1]. Since timber structures can be exposed to weathering, it is essential to understand the effects of such external conditions on the products and materials. Wood must, in general, be protected from moisture and water accumulation, but design or erecting errors can lead to water build-up. Combined with UV radiation, this can alter the wood and the adhesive bond. Various pressure treatment systems are used worldwide in different countries where chemicals are forced deep into the fibres. Examples are alkaline copper quaternary, copper azole, and chromated copper arsenate (CCA). Due to health concerns relating to the latter, its use is restricted in many countries, but in New Zealand, it remains the primary treatment for exterior used timber because of its economic advantages and effectiveness. Globally, micronized copper-based alternatives like micronized copper azole (MCA) are gaining popularity. However, there is limited technical information on their compatibility with adhesives and the durability of treated joints [2]. As an alternative to commonly used preservation techniques, a novel method of wood treatment called mineralisation has been developed recently where wood is impregnated with a solution of calcium acetoacetate, which is then converted to calcium carbonate during post-treatment [3].

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2 – BACKGROUND

Currently in Slovenia, the majority of structural timber comprises from spruce and in New Zealand the softwood market is dominated by plantation of Radiata pine. In Europe, the use of beech has attracted considerable attention, not only due to its superior mechanical properties - highly favorable for structural applications - but also because it is increasingly replacing spruce at its natural growing sites. Some challenges with the species, however resulting from the higher shrinkage and swelling, pose challenges in passing structural adhesive quality control tests. The process of mineralisation has shown promise in reducing beech's susceptibility to decay, yet comprehensive tests validating its improved dimensional stability and bonding performance are still lacking.

In the standard tests for structural adhesives (EN 302-1), various ageing procedures of the bond are described, primarily focusing on the effects of water and temperature. However, tests that assess the ageing of adhesive bonds in a natural environment are relatively scarce. A study on PUR adhesive by [4] found no notable strength reductions after five years of natural ageing (specimens were cut from glued beech wood boards that were exposed to weathering). However, a significant reduction in beech wood density was observed after 48 months of ageing. A similar study, but using fracture energy tests on specimens cut from glulam, was conducted in [5], where no significant influence of the ageing process on adhesion was observed.

The influence of artificial ageing on PUR adhesive bonds was investigated in [6]. Tensile tests (not in accordance with EN 302-1) revealed that UV exposure significantly degraded the chemical composition of the PUR film, but only affected its surface. As a result, only minor reductions in the mechanical properties of the glued joint were observed. On the other hand, artificial weathering that included cycles of UV exposure and water spray significantly impacted the mechanical properties of the wood, causing it to (micro) crack and resulting in a reduction in mechanical properties. The wood failure percentage near 100 % revealed that the bond area was not significantly affected.

Table 1: Overview of conducted tests with specimens properties.

Location	Material	Treatment Type	(Natural) Ageing Duration (months)	Test Type	Dimensions (mm) (w x h x l)	No. of Specimens
Slovenia	European beech (Fagus sylvatica)	Untreated, Mineralized	1, 3, 6 No ageing for mineralized specimens	Lap shear (EN 302-1)	20 x 10 x 150	15 / 30 per ageing period
Slovenia	European beech (Fagus sylvatica)	Surface preparation variations	No ageing	Fracture energy evaluation	20 x 20 x 200	10 per surface type
Slovenia	Beech offcuts	/	3, 10	FTIR analysis	/	/
Slovenia	PUR adhesive	/	1, 3, 10, 12	FTIR analysis	20 x 5 x 70	/
New Zealand	Radiata pine (Pinus radiata)	Untreated, CCA, MCA treatments	3, 6, 9, 12	Fracture energy evaluation – solid and bonded specimens	20 x 38 x 200	12 per treatment / ageing period
New Zealand	PUR adhesive layer	Untreated, CCA, MCA treatments	Artificial ageing	FTIR analysis	/	/

Table 2: PUR adhesive properties and bonding conditions. All adhesives used are qualified as Type 1 and considered suitable for exterior exposure (Service Class 3).

Location	Adhesive	Viscosity (mPas)	Density (kg/m^3)	Solid content (%)	Spread – one sided (g/m^2)	Assembly time (min)	Press time (min)	Pressure (MPa)
Slovenia	PUR	24000	1160	100	160	30	75	1
New Zealand	PUR 1	24000	1160	100	180	30	200	1
New Zealand	PUR 2	1050	1150	99,5	250	60	150	1

The wood failure percentage of the bond when bonding beech wood was not correlated to higher or lower strength of the joint in beech wood [7], [8]; therefore, adhesive properties could contribute a more significant role when bonding beech wood compared to bonding traditionally used species in the industry.

3 – RESEARCH OVERVIEW

A range of experimental tests were conducted to examine the characteristics and fracture energy of adhesively bonded wood joints after being subject to ageing exposure. Specific information and variables in the test programme are presented in Table 1. The properties of the PUR adhesives and manufacturing conditions are presented in Table 2.

4 – EXPERIMENTAL SETUP

Untreated and preservative-treated specimens were exposed to natural weathering in Slovenia (Fig. 1) and New Zealand (Fig. 2). European beech was used in Slovenia, while Radiata pine was used in New Zealand. The mineralization of wood was conducted in Slovenia.

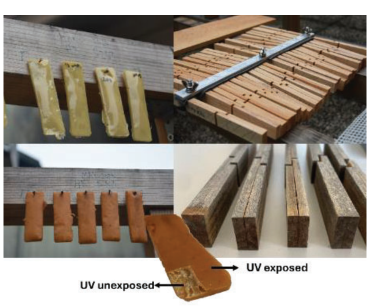

Figure 1: Weathering of PUR adhesive in Slovenia and lap shear test specimens.

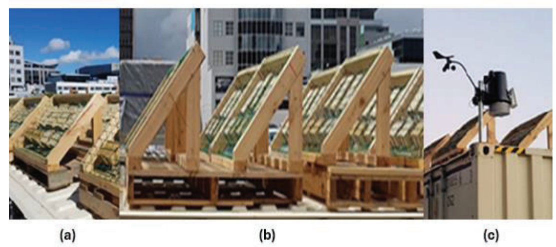

Figure 2: Natural weathering arrangements in New Zealand (a) Weather rack angle view (b) Weather rack side view (c) Elevated weather station.

Preservative treatments such as CCA and MCA were assessed in the test programmes initiated in New Zealand [9].

The fracture energy of Radiata pine specimens (Fig. 3) was evaluated after 3, 6, 9, and 12 months of ageing . Crack length propagation during testing was monitored (Fig. 4).

As beech wood is a dimensionally unstable species and highly prone to decay and warping, only lap shear tests according to EN 302-1 of bonded beech wood were naturally aged for 1, 3, and 6 months (Fig. 3). 15 specimens for each ageing period were prepared. Additionally, mineralized beech wood specimens were tested to assess bonding characteristics after mineralization. To evaluate the fracture properties of unaged beech wood, specimens with different surface preparation methods were prepared, including planed surfaces, sanded surfaces, and the use of primer prior to adhesive bonding. Surfaces were sanded after thickness planing and cleaned of dust before bonding. Water-based

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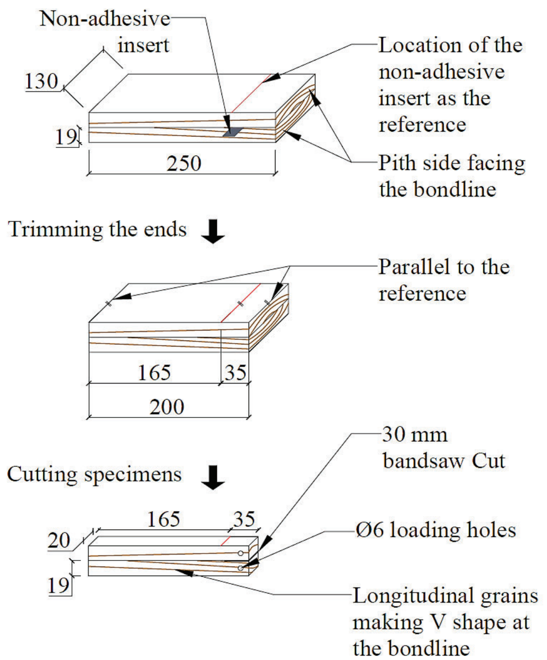

Figure 3: Manufacture of Mode I glued laminated wood specimens in New Zealand. Dimensions are given in mm.

primer solution was applied per the manufacturer's instructions, and pressing time was doubled as recommended. Since no literature on gluing mineralized wood could not be found, more specimens (30) were prepared to have a better overview of results of bonding characteristics.

In New Zealand, the manufacture of Mode I fracture specimens followed a glulam-type approach, as illustrated in Fig. 3. Two bonded laminates were assembled and later cut into individual test pieces. The surface of the laminated boards was planed to provide a clean bonding surface, and the pith side was oriented toward the bond line. The longitudinal grain was arranged in a V-shape at the bond line and toward the uncracked end. A non-adhesive insert was placed at the bond interface to ensure that the applied force would focus on the bond line at the start of the test. All four sides of the manufactured specimens were trimmed to create clean surfaces, ensuring uniform exposure during the ageing process.

For chemical analysis, beech wood offcuts from lap shear tests were exposed and analyzed after 3 and 10 months. For the PUR adhesive, specimens were prepared in a mold, allowed to cure, and then exposed to natural ageing on a stand. Chemical analysis was conducted on the surface where visible degradation could be observed (UV-exposed) and inside the cured adhesive sample

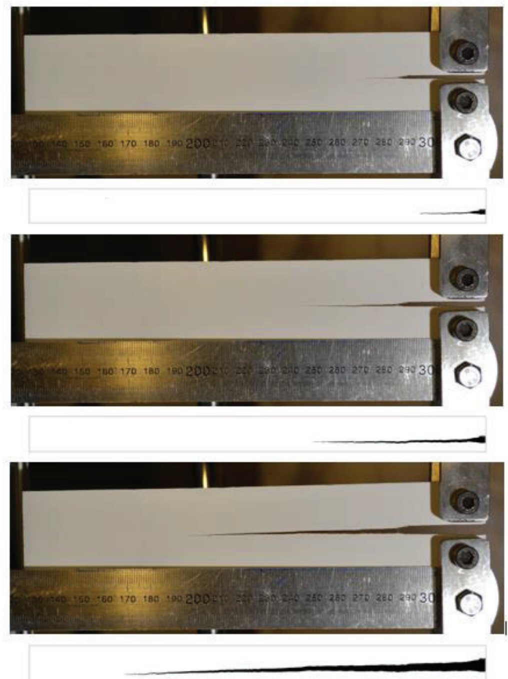
Figure 4: Crack length propagation and determination during Mode I testing in New Zealand.

where no visible degradation was observed (UV-unexposed) (Fig. 1). Adhesive specimens were exposed on a stand for 12 months, with chemical composition results evaluated after 1, 3, 10, and 12 months.

FTIR (Fourier transform infrared spectroscopy) analysis of artificially aged PUR adhesive bondlines was performed by removing the adhesive layer from the bondline after artificial ageing. FTIR analysis was conducted on the aged gluelines of block-glued MCA and CCA treated and untreated Pinus radiata with two PUR adhesives. Ageing regimes involved exposure of the specimens to an environment in which constant long-term high humidity was present and specimens were examined at intervals.

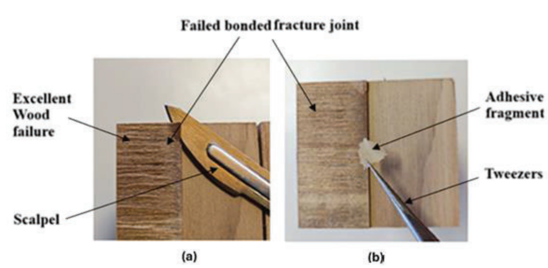

Figure 5: Preparation of FTIR adhesive specimens in New Zealand (a) Wood substrate cut adjacent to bond line (b) Extraction of adhesive fragment.

For FTIR analysis of bondlines after artificial ageing, cured PUR adhesive was carefully extracted from the bondline of tested specimens using a scalpel and tweezers to prevent contamination (Fig. 5). Measurements were performed with a Nicolet iS50 FTIR spectrometer over the spectral range of 650–4000 cm^{-1} at a resolution of 4 cm^{-1}, using a diamond ATR accessory. Samples were firmly pressed onto the ATR crystal surface using the built-in pressure mechanism. Spectral data, comprising 64 scans per sample, were collected and processed using OMNIC software. A background spectrum of 16 scans was recorded, and the ATR crystal was cleaned with ethanol before each measurement.

5 – RESULTS

5.1 MECHANICAL PROPERTIES OF BONDED RADIATA PINE

Fracture energy and bonding characteristics were evaluated through fracture energy and lap shear tests. The fracture energy release rate of untreated Radiata pine specimens was not significantly affected by ageing. In contrast, preservative-treated Radiata pine exhibited suboptimal bonding characteristics but showed no significant difference in fracture energy compared to untreated wood [2]. It is important to note that fracture energy tests were performed on specimens cut from larger boards, meaning the inner sections of the boards were not directly exposed to ageing effects. This form of ageing would therefore be more accurately referred to as partial weathering in comparison to the full weathering conducted in Slovenia. The energy release rate of naturally aged specimens was evaluated in Mode I, and no statistically significant difference was found when compared

to unaged bonded specimens for both untreated and preservative-treated wood. Among the adhesives tested, PUR generally, demonstrated the best performance, likely due to its ductile nature. Specifically, when bonding untreated, CCA-treated, and MCA-treated wood with PUR 2, the mean energy release rates - defined as the amount of energy required to propagate a crack per unit area of the bondline - were 115 %, 31 %, and 34 % higher, respectively, compared to solid unaged specimens. Testing of all naturally aged specimens bonded with PUR adhesive resulted in achieving very high wood failure percentages.

5.2 MECHANICAL PROPERTIES OF BONDED BEECH WOOD

The unaged beech fracture tests presented in Fig. 6 indicate that both sanding and primer application increase the specific fracture energy (SFE) compared to untreated surfaces. Primer-treated samples showed some wood failure, contributing to higher SFE. The planed samples (344 J/m²) align with literature values, such as the 360 J/m² found for spruce wood using the same method and adhesive [10] and little higher than found for beech wood in study from Amman (240 J/m²) [5]. The highest wood failure percentage (WFP) was visually estimated to be in primer-treated specimens. Sanded specimens showed significantly higher SFE, possibly due to the evaluation method focusing only the area under the curve. These specimens exhibited cohesive failure with visible adhesive residue, unlike other samples that showed adhesive failure, except for the primer-treated specimens with adherend failure. Results of lap shear tests on bonded beech wood presented in Fig. 7 show clear degradation and greater scatter of tensile shear strength after 3 months of natural ageing. Most specimens in the 6-month ageing regime could not withstand the conditions, so their results are not represented. It is worth mentioning that 3 specimens after 1 month and 2 specimens after 3 months failed without applying any load. The results of tensile shear strength of unaged beech wood are in line with what is reported in literature [7], [8], [11], [12] for planed surface, where the WFP percent varies. However, as stated in [8] no general correlation between WFP and tensile shear strength could be established (in the dry state) for beech wood and PUR adhesive.

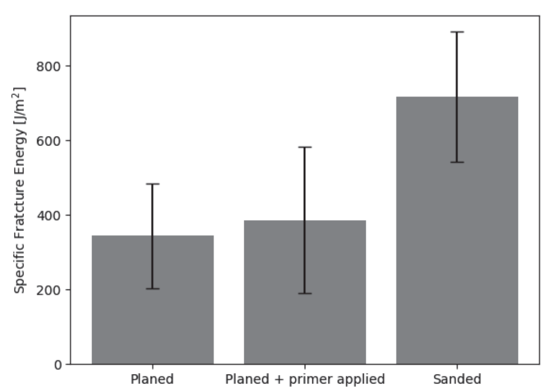

Figure 6: Specific fracture energy results of bonded beech wood with different surface preparation methods prior adhesive bonding.

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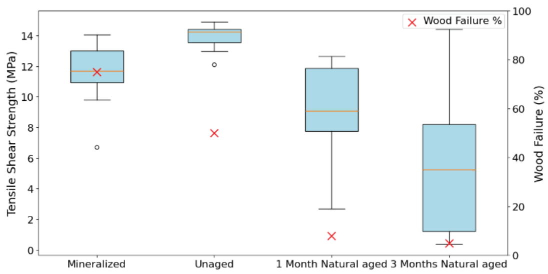

Figure 7: Results of lap shear test of mineralized bonded beech wood and native bonded beech wood specimens after 1 and 3 months of full weather exposure.

The tests indicate that natural ageing, with specimens fully exposed to weathering, quickly degrades the mechanical properties of the bond, as expected. Most of the degradation in strength likely occurred due to the shrinking and swelling of the beech wood. Once the bond started to delaminate, water and UV exposure further degraded the bond. Such openings in glulams are typically present [13], [14], [15] while delaminations over 60% of the cross section are considered a critical point where structural integrity may be at risk [16]. Therefore, protective design is effective in preventing such issues, especially in the case of potentially exposed elements or wood species that are more challenging to bond.

While mineralized beech wood was found to be more brittle in bending tests according to the literature, this brittleness could have resulted in a higher wood failure percentage and overall lower shear strength. More studies are needed to confirm the effect of mineralization on mechanical properties; however, as indicated by this test, bonding could be performed similarly to untreated beech wood in order to achieve sufficient bonding performance.

5.3 FTIR ANALYSIS – ARTIFICIAL AGEING

FTIR analysis of the polyurethane adhesive samples after artificial ageing, which was considered a more severe exposure than the natural ageing in New Zealand, revealed minimal chemical degradation under prolonged exposure to high temperature and humidity. The artificial ageing was considered more severe because considerably greater reductions in mechanical performance for fracture energy were determined in comparison to the fracture energy of natural aged specimens versus unaged specimens.

The integrity of the adhesive itself was then best assessed from FTIR of the accelerated ageing exposure. The characteristic peaks of the urethane bonds in the aged samples remain prominent and closely resemble those of the unaged samples, including NH stretching (3500 cm^{-1}), C=O stretching (1700 cm^{-1}), and C–O stretching (1234 cm^{-1}), indicating the adhesive's stability under these conditions (Fig. 8). However, upon closer examination of specific peak regions, a slight shift in the C–O peaks (1250–850 cm^{-1}) in Fig. 9 (a), and stretching of the C–H peaks (3050–2750 cm^{-1}) in Fig. 9 (b) can be observed, suggesting potential hydrolytic degradation [17]. The changes in the evaluated PUR adhesive formulations, did not directly correlate across different ageing stages. This finding meant that making definitive conclusions about chemical degradation was difficult to ascertain and confirmed results and findings for related accelerated ageing and examinations with FTIR in which there was no clear evidence to suggest that the PUR adhesive had undergrone any degradation.

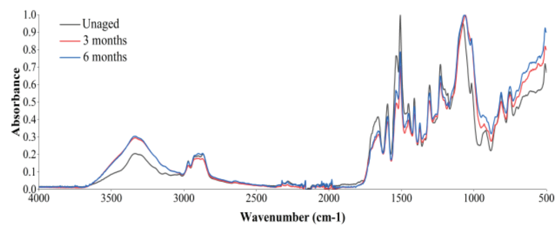

Figure 8: Representative FTIR spectra of PUR 2 bonded CCA preservative-treated samples.

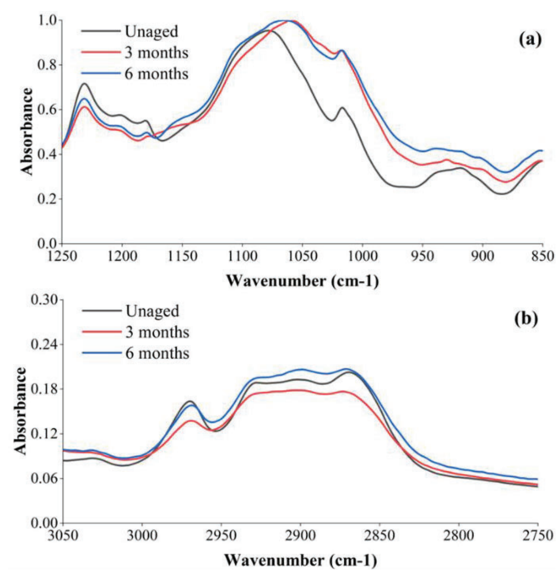

Figure 9: FTIR spectra of PUR 2 bonded CCA preservative-treated samples after constant long-term high temperature and humidity ageing (a) 850-1250 cm^{-1} (C–O) region (b) 2750-3050 cm^{-1} (C–H) region.

5.4 FTIR ANALYSIS – NATURAL AGEING

The absorbance peaks at 1593 cm^{-1}, 1503 cm^{-1}, and 1285 cm^{-1} in the graph represent significant chemical bonds in beech wood (Fig. 10). The 1593 cm^{-1} band is linked to aromatic ring vibrations, indicating lignin content. The 1503 cm^{-1} band relates to C=C stretching vibrations in aromatic rings, also connected to lignin. The 1285 cm^{-1} band is tied to C-O stretching vibrations in cellulose and hemicellulose as similar observed in [18], [19], [20]. Changes in these bands reveal alterations in the wood's chemical composition due to ageing and weathering. Ageing of wood was found to be more visible in the step from 3 to 10 months, while the differences between 0 and 3 months seem to be less significant. It is important to note that only the wood surface was analyzed in this study. For a more comprehensive understanding of ageing effects throughout the entire wood structure, future research should consider milling the specimens and applying techniques such as XRD or similar depth-profiling methods.

The FTIR results of the UV-unexposed parts of the adhesive indicate minimal or no chemical degradation throughout the 12-month natural weathering period (Fig. 11). The spectral bands associated with key functional groups remain relatively unchanged, suggesting that exposure to natural conditions without direct UV radiation does not significantly affect chemical structure of PUR adhesive.

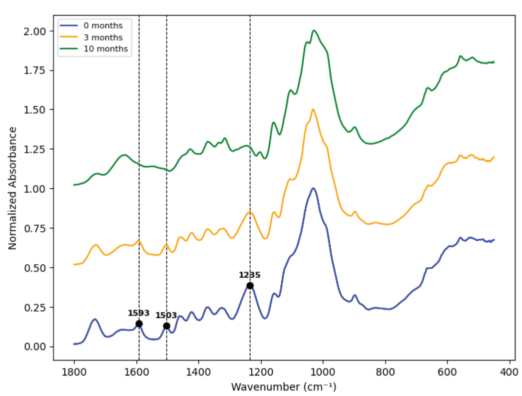

Figure 10: FTIR spectra of beech wood surface during 3 and 10 months of full weather eposure.

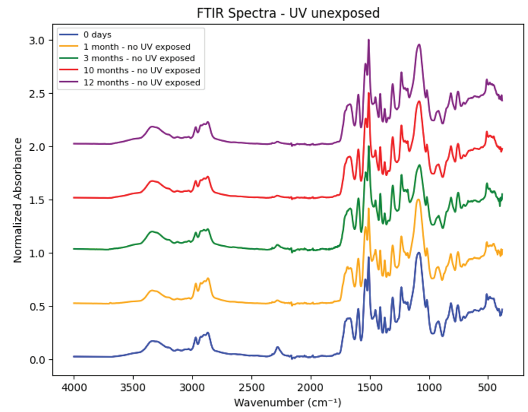

Figure 11: FTIR spectra of full weather unexposed part of adhesive, during 1, 3, 10 and 12 months of natural ageing.

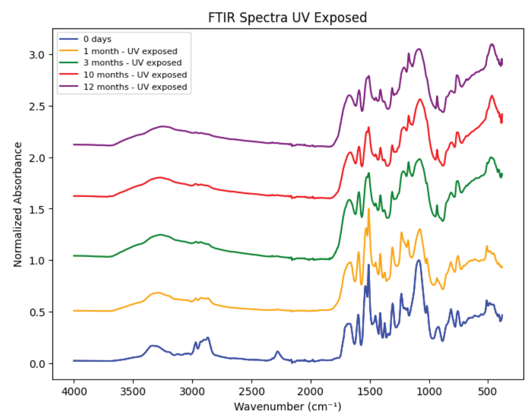

Figure 12: FTIR spectra of full weather exposed part of adhesive, during 1, 3, 10 and 12 months of natural ageing.

In contrast, the FTIR spectra of the UV-exposed portions of the adhesive demonstrate significant chemical alterations (Fig. 12). These changes are evident in the reduction of absorption intensities in specific spectral regions, particularly in the 2800–3000 cm^{-1} range, where C-H stretching vibrations in alkanes are present. Thisreduction indicates the degradation of aliphatic chains, likely due to photochemical oxidation processes initiated by UV radiation as similarly observed in [6]. Additionally, the spectral region from 1500 to 1800 cm^{-1}, which is commonly associated with carbonyl (C=O) stretching vibrations, shows notable variations. The increased intensity of these bands suggests the formation of oxidation products such as carboxyl and aldehyde groups, further confirming that UV exposure accelerates chemical degradation. However, bands within the 500–1500 cm^{-1} range remain relatively stable, indicating that the adhesive's structural components associated with C-O and C-N bonding are more resistant to UV-induced degradation.

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6 – CONCLUSION

This study investigated the natural weathering effects on polyurethane-bonded timber joints in two climatic conditions, focusing on European beech (Fagus sylvatica) and Radiata pine (Pinus radiata). The work on the topic also involved examination with accelerated ageing. The results highlighted the significant differences between natural and accelerated ageing approaches. While artificial ageing generally comprises of moisture cycling and/or exposure in high heat enivronments, natural exposure includes the combined influence of UV radiation, moisture variations, and biological factors, which can lead to complex degradation mechanisms.

Key findings indicate that the adhesive bond in Radiata pine remained relatively stable over time. However, the bonding to preservative treated wood demonstrated increased challenges and marginally reduced performance despite the PUR adhesive achieving high quality wood failure percentages. The PUR adhesive bonded joints also experienced higher fracture energy performance in general which was believed to be because of the lower elasticity of the adhesives and increased ductility which was consequently more forgiving at the bond interface during fracture initiation.

Swelling and shrinking cycles of beech contributed significantly to bond deterioration, ultimately accelerating adhesive failure. The FTIR analysis confirmed that the top layer of the adhesive undergoes substantial chemical changes under UV exposure, whereas the inner layers remain structurally intact. Only minor differences of adhesive chemical structure were observed after artificial ageing.

It is important to note that the tests in this study were conducted using a different methodology compared to some previous studies on bonded beech wood. This likely contributed to the greater differences observed in mechanical properties after ageing. Literature reports on similar tests with beech do not show such a significant reduction in mechanical performance, suggesting that test conditions, specimen preparation, and exposure methods play a crucial role in determining the durability of bonded joints. Moreover, the results were based on previously completed tests not originally intended for direct comparison, which limits the strength of conclusions but still allows for some general observations.

The study also provided insights into the effect of wood treatments on adhesive performance. Mineralized beech wood, despite its increased brittleness, showed bonding characteristics comparable to untreated beech. However, further research is needed to fully assess the long-term mechanical properties of mineralized wood in structural applications.

These findings underscore the importance of proper structural protection for timber elements exposed to the environment. Given the susceptibility of beech to weather-induced degradation, its use in bonded structural components requires careful consideration of protective measures, including surface treatments and design modifications to mitigate moisture ingress.

Future work should focus on fracture properties of weathered beech wood and weathering performance of (bonded) mineralized beech wood in further climates. Future work on bonding of preservative-treated wood should examine higher chemical concentrations and in-ground conditions while also examining the influence of changing the manufacturing parameters and examining the associated influence on the longevity of the bond quality.

7 – ACKNOWLEDGMENTS

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