Effect of Climatic Variations and Mechanical Stress on the Strength of Epoxy-Wood Joints

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The influence of changing climatic conditions was studied relative to strength parameters—tensile strength, modulus of elasticity, and internal cohesion—of joints between hardened epoxy casting resin and solid wood. Samples were exposed to various climatic conditions, including ageing simulation under normal conditions (25 °C, 30% humidity), and extreme conditions (50 °C, 90% humidity). The study also examined the impact of incorporating oak wood dust (0.05% by weight) as a bio-based additive into the epoxy matrix. Chemical resistance of the cured resin—with and without the additive—was evaluated using a modified Buchholz indentation test following exposure to a toluene–naphtha–ethanol solvent mixture. Moisture content was assessed. Alternating climatic conditions significantly impacted the strength parameters, with extreme temperatures and humidity levels reducing joint integrity. Mechanical stress further exacerbated this deterioration, underscoring the importance of environmental considerations in applying resin-wood composites. Furthermore, the addition of oak wood dust improved the chemical resistance of the epoxy resin, suggesting enhanced durability and interfacial bonding. Visual inspection of post-failure specimens revealed a higher prevalence of cohesive wood failures in oak, indicating superior bonding compared to meranti. These findings offer insights for appropriate use of epoxy–wood joints in furniture applications conditions.

INTRODUCTION

Using epoxy resin for joining wood is becoming increasingly common in the furniture industry (Pizzi 2006). This material offers numerous advantages, including exceptional resistance to mechanical stress and chemical degradation. It also possesses remarkable thermal stability, cohesive strength, and electrical insulation properties that remain constant over a wide range of temperature. However, the effects of climatic conditions on the strength properties of epoxy resin joints remain underexplored and require further research (Dallaev *et al.* 2023). The production of quality furniture parts requires joints that are resistant to external factors, particularly fluctuations in climatic conditions. Although most studies have examined the properties of epoxy resin and solid wood separately, research on the effect of climatic variations on the strength parameters of epoxy-casting resin and solid wood joint is lacking. Wang *et al*. (2018) focused on the mechanical properties of epoxy resin under different application conditions. Bomba *et al*.

(2014) analysed the strength of solid wood joints under different humidity conditions. However, there has been a need for studies on the effect of climatic variations on the strength parameters of epoxy-casting resin and solid wood joints. There is evidence that humidity and temperature fluctuations can significantly influence the curing process of cast materials and negatively affect the internal structure of the polymer (Gonzalez *et al.* 2017). Improper storage of material components can lead to their degradation, causing changes in properties both during curing and in the final product. In addition, these materials are sensitive to ambient conditions, which can cause modifications to their dielectric properties, accelerate degradation, and induce dimensional changes in the polymer, leading to internal stresses and crack formation. Changes in the crystallinity of the polymer can then affect its aging process and facilitate the diffusion of ozone and oxygen into the material (Gonzalez *et al.* 2017; Nizin *et al.* 2021). Zhao *et al*. (2022) investigated the behaviour of epoxy resin and wood when exposed to different temperature and humidity conditions. These studies have contributed to understanding of the different components of joints, but the integrating these findings into a comprehensive understanding of epoxy casting resin and solid wood remains underexplored. This may be attributed to the relatively recent emergence of epoxy casting resin and solid wood combinations as a trend in modern joinery. However, as the trend of using these joints in large manufacturing plants is becoming more widespread, the pressure to thoroughly investigate them and understand their strength parameters is increasing.

Another reason to evaluate the joint properties is for the modification of epoxy resins using various methods (*e.g.,* addition of fillers, pigments, and plasticizers) to improve toughness, flame retardancy, and thermal stability. Studies not only have focused on the improvement of epoxy resins for casting, but also on promoting sustainability and efficient waste treatment (Mohan 2013). For example, a recent study investigated the modification of epoxy polymer systems using carbon fibers obtained by recycling hemp fibers, opening up previously unexplored possibilities (Szewczak and Szelag 2019). Cost-effectiveness and the development of affordable fillers also play a key role in maintaining the desired properties (Szewczak and Szelag 2019; Bartoli *et al.* 2022).

This study aimed to address this gap by systematically evaluating the mechanical strength and chemical resistance of these joints under controlled climatic exposures. Additionally, the study investigated the effect of incorporating oak wood dust additives on the chemical resistance of the epoxy matrix. The findings from this research will contribute to the optimization of material selection and bonding practices in furniture manufacturing. Moreover, the results will support the development of more durable and environmentally resilient designs, ultimately aiding designers, engineers, and manufacturers in producing higher-quality wood products.

EXPERIMENTAL

Materials

Two wood species, oak (*Quercus* spp.) and meranti (*Shorea* spp.), were selected for this investigation due to their differing anatomical structures and widespread use in joinery and furniture manufacturing (Table 1). The materials were delivered with initial moisture contents of 11.3% for oak and 13.5% for meranti, consistent with standard conditions for seasoned timber. The adhesive system used was VEROPAL UV Plus 100 epoxy casting resin, supplied by SYNPO, a.s. As per manufacturer's specifications, the

resin and hardener were combined in a weight ratio of 100:40. The formulation allowed for a working time of up to three hours at 25 °C, with a minimum curing period of three days and full curing recommended within five days. The manufacturer-reported thermal resistance of the cured system was up to 40 °C.

To assess the influence of bio-based fillers on the performance of the adhesive joint, oak wood dust was incorporated into selected resin formulations at a concentration of 0.05% by weight. This was based on its compatibility with the wood–epoxy interface and its potential to enhance chemical resistance.

The extreme conditions (50 °C, 90% RH) used in this study reflect boundary values encountered in poorly ventilated or sun-exposed residential zones, as supported by IEC 60068-2-78 and related climate simulation literature (Künzel 1995; International Electrotechnical Commission, 2012). Samples were exposed to various climatic conditions, including ageing simulation consisting of 30 cycles. Each cycle included 1 h at -30 °C, 15 min at 25 °C, and 1 h at 50 °C).

Table 1. Comparison of Oak and Meranti Wood Properties Relevant to Adhesive Bonding

Property	Oak (*Quercus* spp.)	Meranti (*Shorea* spp.)	References
Wood Type	Temperate hardwood	Tropical hardwood	Pizzi and Mittal (2011)
Density (kg/m³)	670–750	420–640	Máchová *et al.* (2019); Rindler *et al.* (2019)
Grain Structure	Uniform, closed grain	Heterogeneous, open grain	Pizzi and Mittal (2011)
Porosity	Low to moderate	High	Frihart (2003); Pizzi and Mittal (2011)
Extractive Content	Low	High	Rindler *et al.* (2019)
Bonding Performance	High and consistent	Moderate to variable	Frihart (2003)

Tensile Testing

For the tensile strength tests, specimens were prepared with final dimensions of $10 \times 20 \times 90$ mm, incorporating an epoxy resin joint section measuring $10 \times 20 \times 10$ mm, in accordance with the requirements of ČSN EN 205 (2017) and ČSN EN 1465 (2009) (Fig. 1).
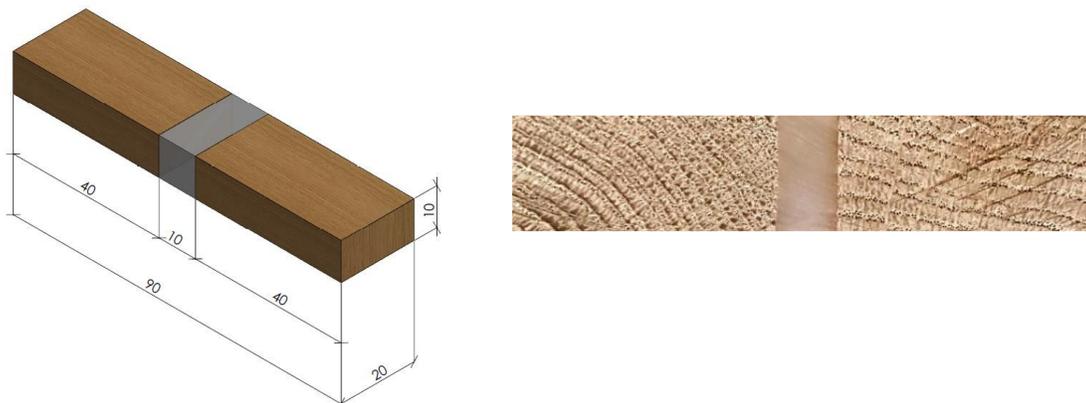

Fig. 1. Illustration for tensile strength test (dimensions given in mm) (own archive)

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A total of 30 specimens were fabricated for each wood species (oak and meranti) to ensure statistical robustness. Wood sections were first rough-cut to 25 × 45 × 850 mm and then machined down to 20 × 40 × 850 mm. These cuts were made so that the future bonded joint would be in a tangential section along its entire length to ensure greater consistency. Each section was further halved to produce two parts measuring 20 × 40 × 420 mm followed by storage for 21 days in an air-conditioning chamber at 25 °C and 30% humidity. Bonding surfaces were sanded to a final thickness of 20 mm using P60 and P80 grit sandpaper, followed by thorough removal of dust.

For mould preparation, a sealant was applied to prevent leakage at the bonding interface. The two wood parts were positioned in the mould and secured. A wood hardener was then applied to enhance adhesion, after which the epoxy casting resin was poured into the joint cavity. The specimens were allowed to cure for a minimum of three days at 25 °C and approximately 40% relative humidity, after which they were demoulded and left to mature under ambient conditions for an additional ten days. Finally, the composite blocks were cut into individual test specimens (10 × 20 × 90 mm) and conditioned before mechanical testing. This fabrication method ensured consistent adhesive layer quality and reproducible specimen geometry across all test samples.

Tensile strength measurements were conducted using a universal testing machine INSTRON 3365, following the protocols outlined in ČSN EN 205 (2017) and ČSN EN 1465 (2009), which specify procedures for testing adhesive bonds in wood. The tensile shear strength (τ_t) parallel to the grain was calculated using the following equation,

$$\tau_t = \frac{F_{max}}{l*b} \, [\text{MPa}] \tag{1}$$

where τ_t is the tensile shear strength (MPa), F_{max} is the maximum force at the point of failure (N), l is the length of the bonded (shearing) surface (mm), and b is the width of the bonded surface (mm).

Before testing, both the wooden and epoxy portions of each specimen were individually remeasured to ensure dimensional accuracy. These precise measurements were used in the calculation of the actual shear area for each test, thereby enhancing result reliability. During testing, specimens were mounted in the grips of the testing machine such that the clamps were positioned as close as possible to the epoxy joint without exerting direct pressure on the adhesive interface (Fig. 2). This ensured that the measured force reflected the true performance of the bonded region under tensile loading conditions.
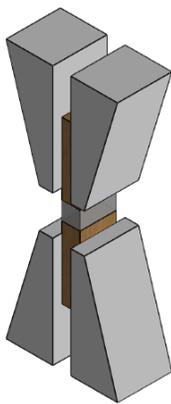

Fig. 2. Specimen clamped in machine (own archive)

Impact Bending Strength

Test specimens for the impact strength test were prepared in the same way as those for the tensile strength test, with the exception of their size (Fig. 3). The dimensions of the specimens were adjusted to 10 x 10 x 90 mm as proscribed in ČSN EN ISO 179-1 (2023). The dimensions of the epoxy casting resin part were 10 x 10 x 10 mm. The same number of specimens were prepared as for the tensile strength test.
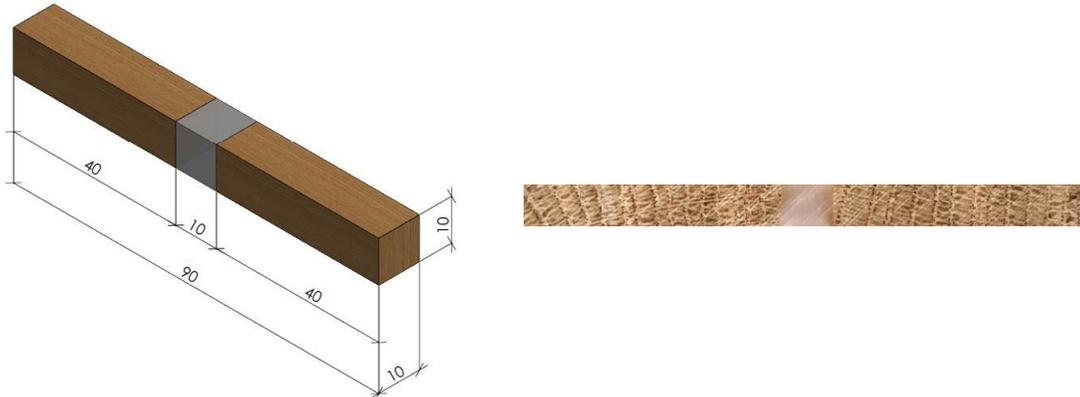

Fig. 3. Illustration of test specimens for the impact strength test (dimensions given in mm) (own archive)

The impact strength of the epoxy–wood joints was evaluated using a CEAST 9050 impact pendulum, following the guidelines of ČSN EN ISO 179-1 (2023). The impact bending strength (AW) was calculated using the following formula,

$$A_w = \frac{Q}{b * h} \ [\text{kJ} \cdot \text{m}^{-2}] \qquad (2)$$

where A_W is the impact bending strength (kJ · m^{-2}), Q is the energy expended to damage the test specimen (kJ), b is the width of the specimen (m), and h is the height (thickness) of the specimen (m).
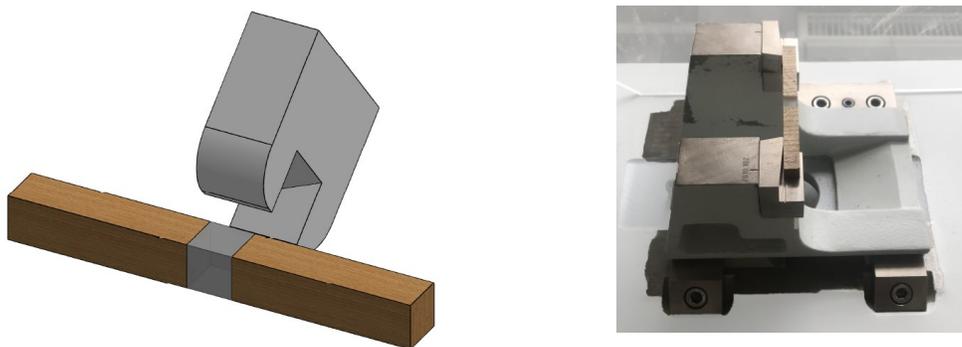

Fig. 4. Test of the impact strength (own archive)

As in the previous test, all the tested specimens were remeasured before testing. The specimens were attached to the machine, as shown in Fig. 4. The pendulum hammer was configured to strike the central region of the specimen, specifically targeting the epoxy joint area, to evaluate the response of the adhesive layer under dynamic loading. This ensured that the impact was applied directly to the investigated part of the sample.

Chemical Resistance Test (Conversion Quality Assessment)

The test specimens for the conversion quality test were designed so that measurements could be carried out efficiently based on the principles of ČSN EN ISO 2815 (2003). Samples were cast with dimensions of Ø 80 x 12 mm. One group of the samples consisted only of epoxy resin and hardener mixed in the correct ratio and to the other part of the samples was added an additive in the form of wood dust in the mass ratio of 0,05 % of the total mass.

The chemical resistance of the cured epoxy resin was assessed using a modified Buchholz indentation method, following the ČSN EN ISO 2815 (2003) standard for coatings. To simulate exposure to aggressive solvents, a mixture of toluene, naphtha, and ethanol (in a 1:1:1 volume ratio) was applied to the resin surfaces.

For each test, filter papers (400 g/m²) were soaked in the solvent mixture for 30 seconds and then placed on the surface of the cured resin. To minimize the evaporation of volatile components and ensure uniform exposure, the soaked papers were covered with a non-absorbent barrier. After 20 min, the papers were removed and the surfaces gently cleaned. Surface indentation was then measured using a Buchholz hardness tester to evaluate the depth of penetration.

Indentation measurements were taken immediately after exposure, as well as 24 h and 7 days later. These intervals enabled evaluation of both immediate and delayed chemical effects. Tests were performed on samples both with and without the addition of oak wood dust (0.05 wt%) to determine the influence of bio-based micro-fillers on chemical resistance.

Moisture Content

Samples were prepared in accordance with ČSN EN 322 (1993) with dimensions of 30 x 20 x 20 mm. This method is based on gravimetric analysis before and after oven drying. Each sample was weighed in its initial (undried) state to determine the wet mass (mw). Subsequently, the specimens were oven-dried at $103 \pm 2\ °C$ until a constant mass was achieved, after which the dry mass (m_o) was recorded. The moisture content (w) was calculated as follows,

$$w = \frac{m_w - m_0}{m_0} * 100 \qquad (3)$$

where w is the moisture content in percent (%), m_w is the mass of the undried sample (g), and m_0 is the weight of the oven-dried sample (g).

Visual Inspection of Joint Quality

Following mechanical testing, all specimens were subjected to visual inspection to assess the mode and extent of joint failure. The primary objective was to differentiate between adhesive failures—occurring at the interface between the epoxy resin and the wood—and cohesive failures, which take place within the bulk of the resin or the wood substrate. The inspection methodology was adapted from Frihart (2003). Specimens were evaluated under uniform diffuse lighting without magnification to maintain consistency and avoid observational bias. Failure surfaces were classified into three distinct categories: (i) adhesive failure, defined as a clean separation between the resin and wood, typically indicating insufficient adhesion; (ii) cohesive failure in resin, characterized by fracture within the cured epoxy layer, suggestive of brittle behavior or material degradation; and (iii) cohesive failure in wood, identified by rupture through the wood fibers with visible

resin remnants, indicating strong interfacial bonding. To document the observations systematically, representative specimens were photographed, and failure types were recorded immediately after testing to ensure accurate classification and reproducibility.

Statistical Analysis

STATISTICA 13 software (TIBCO Inc., USA) was used to analyse the data. The data were analysed using a one-way analysis of variance (ANOVA). Duncan's test was performed to verify the results with a 95% confidence level.

RESULTS AND DISCUSSION

Tensile Strength

The tensile strength of the epoxy resin-wood joints was evaluated in different climatic conditions.
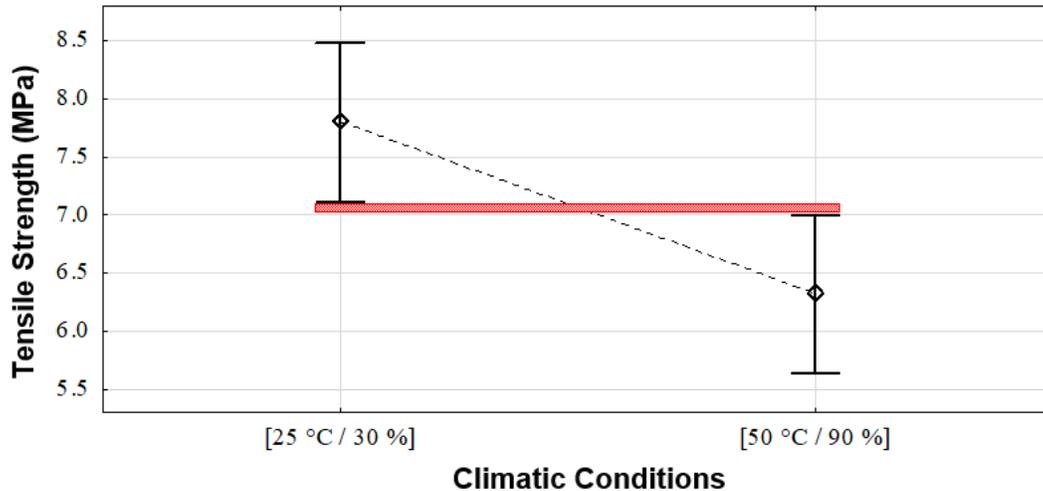

Fig. 5. Graph of 95% confidence interval of the measured ultimate tensile strength of meranti
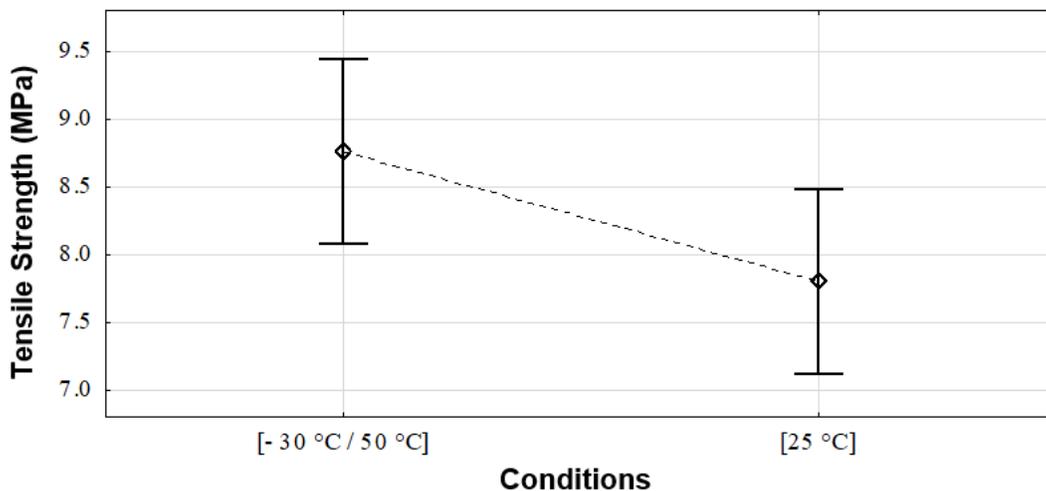

Fig. 6. Graph of 95% confidence interval of the measured ultimate tensile strength of meranti

As shown in Fig. 5, meranti–epoxy joints exhibited a noticeable decline in tensile strength when subjected to extreme environmental conditions (50 °C and 90% relative humidity). This reduction was statistically significant ($p = 0.013$), indicating that meranti joints are vulnerable to degradation under hygrothermal stress. Figure 6 further illustrates the distribution and variability in tensile strength measurements across different climate treatments for meranti, reinforcing this trend.

In contrast, Figs. 7 and 8 show that oak–epoxy joints demonstrated greater mechanical stability under the same extreme conditions. Although a slight reduction in strength was observed, it was not statistically significant. This suggests that oak provides a more robust bonding substrate under elevated temperature and humidity, which is likely due to its higher density and lower extractive content, which favor improved adhesive penetration and interfacial bonding (Frihart 2003; Pizzi and Mittal 2011). These findings are consistent with previous research showing that epoxy resins, while mechanically strong, are susceptible to moisture-induced degradation.
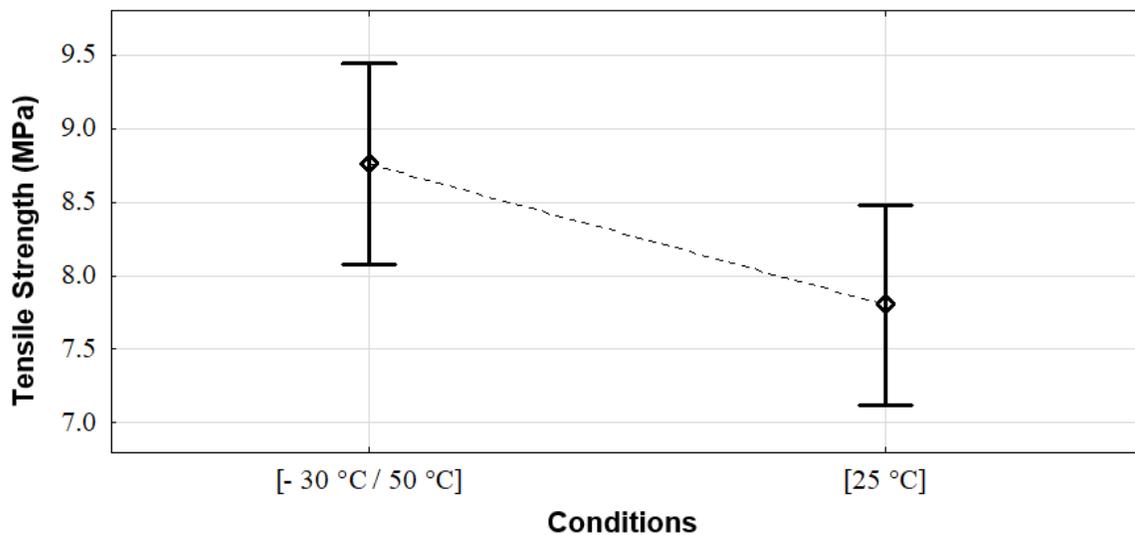

Fig. 7. Graph of 95% confidence interval of the measured ultimate tensile strength of meranti
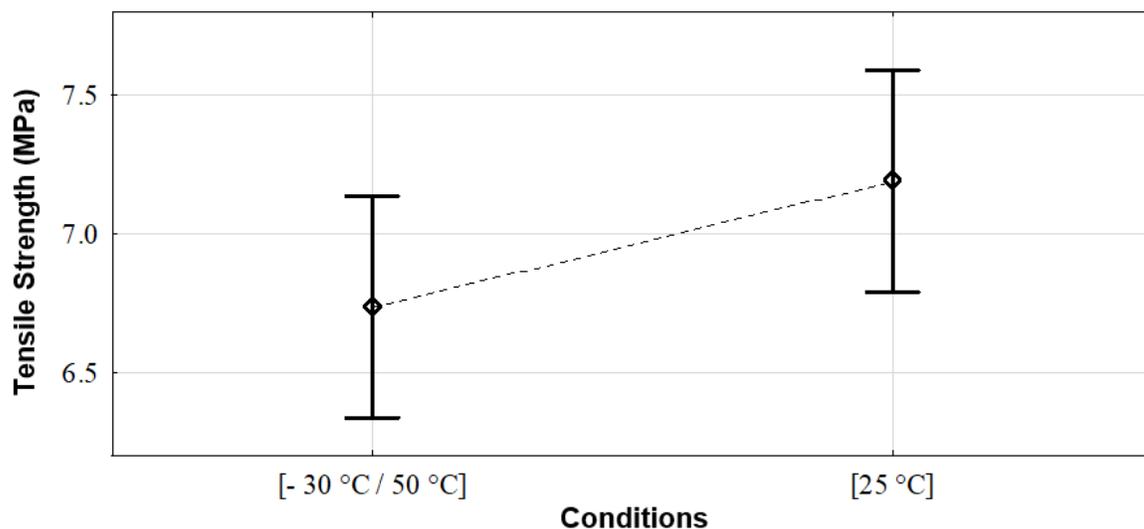

Fig. 8. Graph of 95% confidence interval of the measured ultimate tensile strength of oak

Elevated humidity and temperature can lead to plasticization, microcrack formation, and a reduction in cross-link density in the polymer matrix, thereby compromising the adhesive bond (Zhou and Lucas 1999; Lettieri and Frigione 2012). In the present study, these effects were more evident in meranti joints, which experienced an average 33% reduction in tensile strength under extreme conditions compared to normal laboratory conditions.

Interestingly, no significant difference in tensile strength was observed between specimens exposed to alternating thermal cycles (−30 °C to +50 °C) and those maintained under normal conditions. This suggests that thermal cycling alone does not significantly impair joint integrity within the operational temperature range of the epoxy system. This observation supports the conclusions of Khoramishad *et al*. (2011), who found that moisture ingress, rather than temperature variation alone, is the dominant factor in adhesive bond degradation. Furthermore, a higher incidence of joint defects was noted in the meranti samples exposed to extreme conditions. These defects are likely attributable to meranti's more porous structure and higher extractives content, which can interfere with resin curing and weaken interfacial adhesion (Máchová *et al.* 2019). Such findings highlight the importance of wood species selection in the design of epoxy-bonded composites intended for environments with fluctuating or extreme climatic conditions. Figure 5 shows that extreme climatic conditions affect the tensile strength of the meranti joint. Subsequently measurements of the effect of changing conditions on the tensile strength of the joint did not show statistically significant changes.

Comparison of the Effect of Climatic Conditions in the Impact Strength Test

The impact strength test determined the resistance of the epoxy resin-solid wood joint to mechanical force. The test was performed on thirty samples, and the results are shown in Figs. 9 through 12.

As shown in Figs. 9 and 10, meranti–epoxy joints exhibited relatively stable impact strength values across all environmental exposures, including extreme conditions. Similarly, Figs. 11 and 12 demonstrate that the impact strength of oak–epoxy joints remained consistent regardless of climatic treatment. Statistical analysis confirmed the absence of significant differences across conditions for both wood species ($p = 0.298$), indicating that the impact performance of the joints was not significantly affected by elevated temperature or humidity.
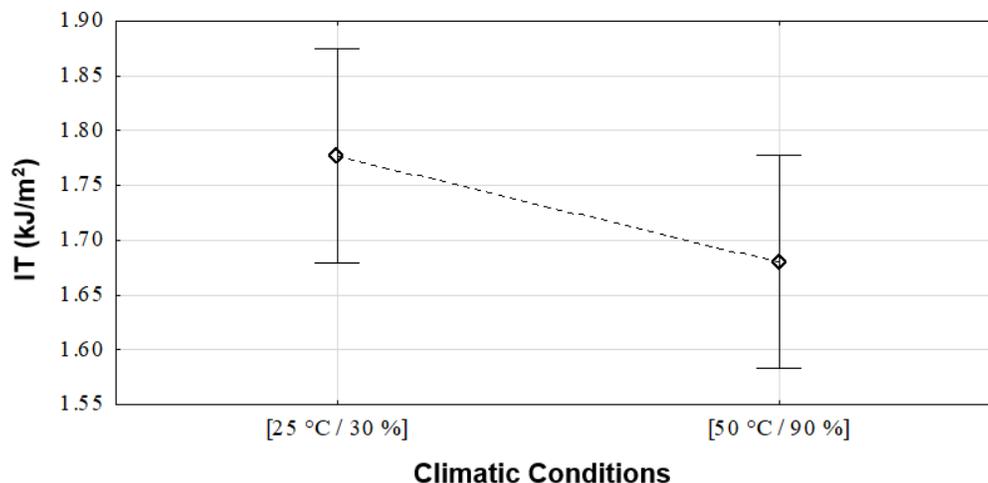

Fig. 9. Graph of 95% confidence interval of the measured impact strength of meranti
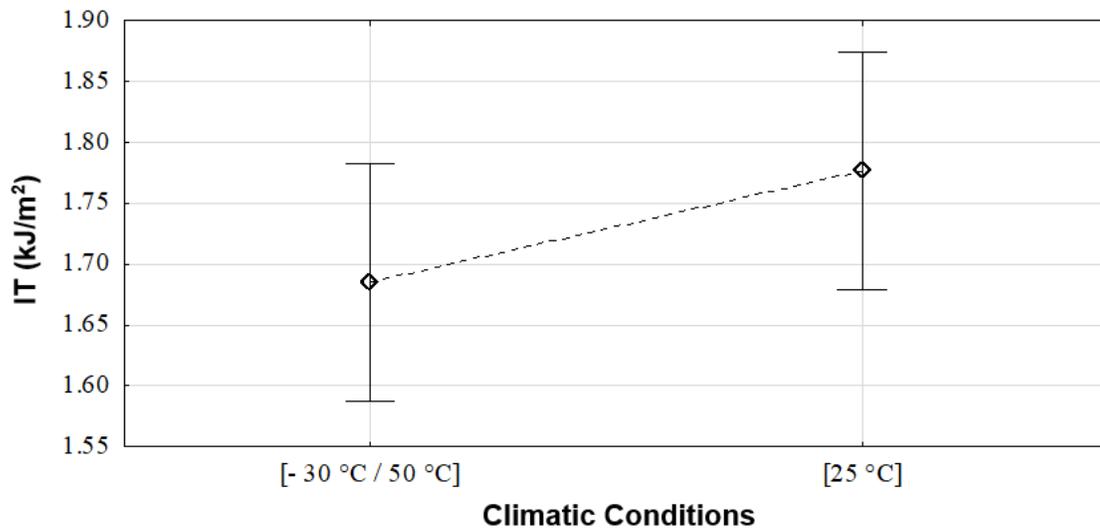
Fig. 10. Graph of 95% confidence interval of the measured impact strength of meranti
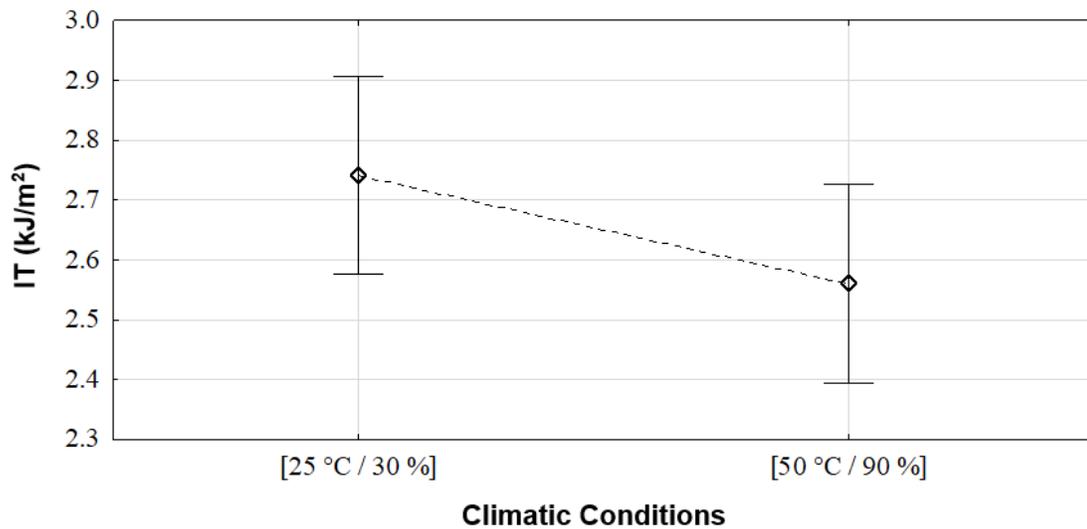

Fig. 11. Graph of 95% confidence interval of the measured impact strength of oak
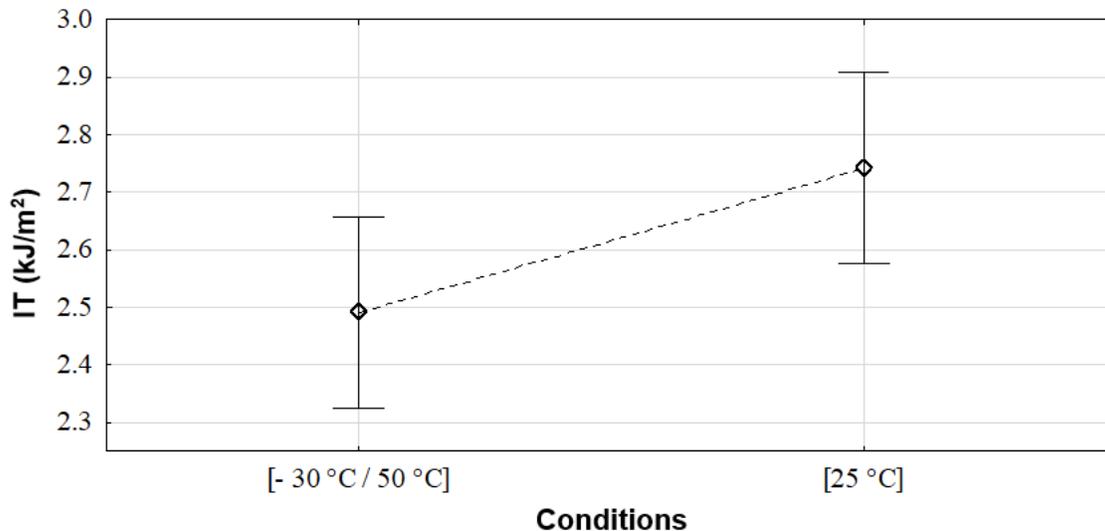
Fig. 12. Graph of 95% confidence interval of the measured impact strength of oak

These findings suggest that the cured epoxy matrix retained its ability to absorb and dissipate dynamic mechanical energy, even under hygrothermal stress. This is consistent with previous studies showing that the impact toughness of epoxy systems is generally less sensitive to environmental degradation than tensile or shear strength, particularly over shorter exposure durations (Pang *et al.* 2018; Guo *et al.* 2020). The highly crosslinked structure of the cured resin appears to maintain its structural integrity and energy-dissipating capacity unless significantly plasticized or embrittled—conditions not reached within the environmental parameters of this study.

The Charpy-type impact test specifically targets localized fracture behavior near the epoxy core of the composite. The consistent performance across climatic treatments implies that neither the bulk resin nor the epoxy–wood interface experienced sufficient degradation to impair crack resistance under impact loading. This contrasts with the tensile strength results, where extreme humidity and heat significantly compromised meranti joint performance. Nonetheless, qualitative observations during post-test inspections revealed more frequent cohesive failure within the meranti joints compared to oak. Although not statistically significant, this pattern mirrors the results of the tensile strength test and may be attributed to species-specific anatomical features. Meranti's higher porosity, variable vessel distribution, and potentially greater extractive content could contribute to less uniform bonding and reduced resistance to crack propagation at the microstructural level (Pizzi and Mittal 2011).

These outcomes support broader conclusions in the literature that epoxy–wood composites are more vulnerable to degradation under sustained mechanical loading (*e.g.*, tensile or shear) than under dynamic, short-term stresses (Cerbu and Cosereanu 2016; Musthaq *et al.* 2023). From a practical standpoint, this suggests that while environmental exposure may undermine long-term load-bearing capacity, the immediate impact resistance of epoxy–wood joints may remain largely unaffected by typical climatic fluctuations.

The following results present an assessment of the joint quality, with an emphasis on detecting defects in the adhesive or cohesive properties of the joint.
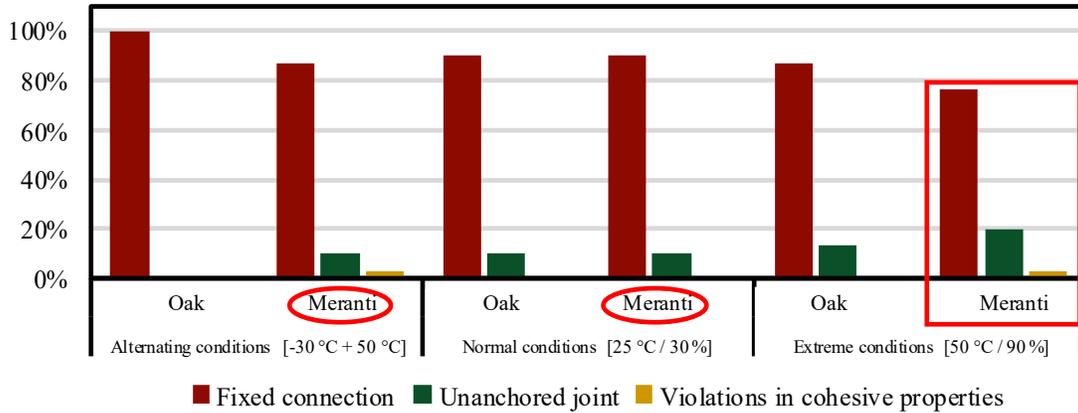
Fig. 13. Comparison of joint quality between wood species in the tensile strength test

Meranti joints   Oak joints

Fig. 14. Representative distribution of joint failures

Figure 13 shows that a higher number of defective joints were found in meranti wood, especially in specimens exposed to extreme conditions. No deterioration in the cohesive properties of the cured epoxy resin was observed in oak specimens (Fig. 14).
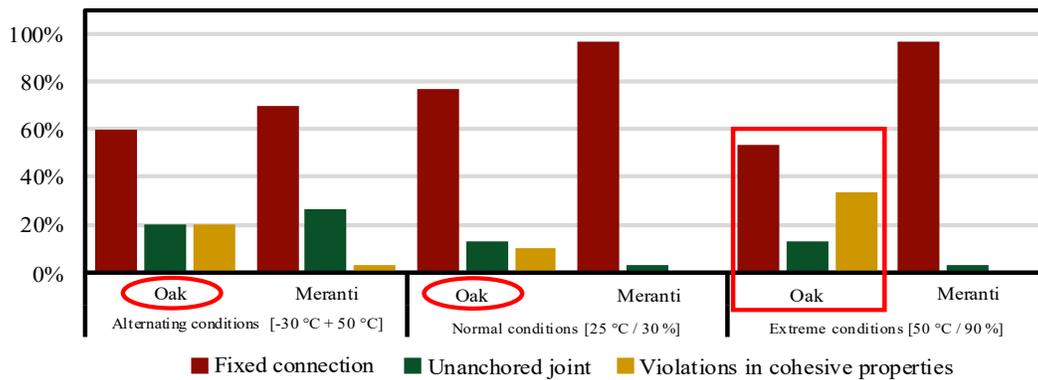

Fig. 15. Comparison of joint quality between wood species in the impact strength test

Meranti joints   Oak joints

Fig. 16. Representative distribution of the joint failures in impact test

As illustrated in Fig. 16, meranti joints demonstrated a higher incidence of both adhesive and cohesive failures, particularly under extreme environmental exposure (50 °C and 90% relative humidity). In contrast, oak specimens generally maintained cohesive integrity, indicating a more robust interaction between the epoxy matrix and the wood substrate. This variation in failure behavior can be attributed to fundamental anatomical and chemical differences between the two wood species. Meranti, as a tropical hardwood, features larger and more heterogeneous vessel structures and a higher extractive content, both of which have been shown to hinder adhesive penetration and curing uniformity (Pizzi and Mittal 2011; Rindler *et al.* 2019). These characteristics increase the likelihood of non-uniform bond lines, voids, and weak interfacial zones, which are prone to early failure under tensile stress (Fig. 16). Furthermore, meranti's susceptibility to moisture-induced dimensional instability may lead to micro-cracking or delamination at the wood–resin interface, particularly under hygrothermal cycling. Such behavior aligns with previous reports that moisture-driven wood movement can generate internal stresses in adhesive joints, accelerating bond degradation (Lettieri and Frigione 2012; Máchová *et al.* 2019).

In the case of impact strength testing (Fig. 15), failure patterns were observed across both species, although specimens conditioned under normal climatic conditions displayed fewer cohesion-related defects. This supports earlier research indicating that moisture uptake can plasticize the epoxy matrix, reducing its resistance to crack initiation and propagation under high-rate loading (Cerbu and Cosereanu 2015). Interestingly, a greater proportion of cohesive failures was recorded in impact tests compared to tensile tests. This is likely due to the localized and abrupt nature of Charpy-type impact loading, which concentrates stress within the resin-rich zone of the joint. The observed transition in dominant failure mode—from adhesive in tensile tests to cohesive in impact tests—corresponds with findings by Islam *et al.* (2022), who highlighted the influence of environmental conditioning and loading type on the failure mechanism of bonded wood joints. High humidity, in particular, can induce internal weakening of the epoxy resin, making it more prone to cohesive failure even when global strength measurements appear unaffected.

Overall, these findings underscore the critical role of substrate selection and environmental conditions in determining the performance and durability of epoxy–wood composite joints. Oak's superior behavior under both tensile and impact loading can be attributed to its denser structure, lower porosity, and greater compatibility with epoxy adhesives (Frihart 2003; Pizzi and Mittal 2017). These attributes make oak a more reliable material choice for adhesive applications subjected to variable or extreme environmental conditions. The results shown in Fig. 16 suggest that test specimens exposed to normal climatic conditions are less prone to defects. In comparison with the tensile strength test, a higher percentage of defects was observed in the cohesive properties of the cured epoxy resin.

The chemical resistance of the epoxy casting resin was further evaluated through a conversion quality test to assess the influence of oak wood dust as a bio-based additive.
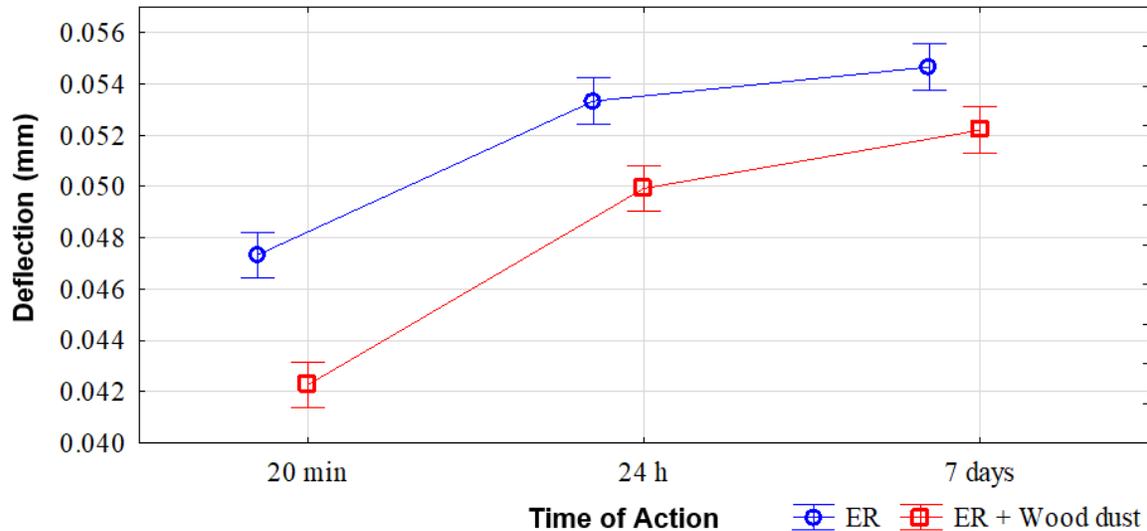
Fig. 17. Graph of 95% confidence interval of effect of chemicals (toluene, naphtha and ethanol) and exposure time on cure quality

As shown in Fig. 17, the addition of 0.05% oak wood dust to the epoxy formulation significantly improved resistance to chemical exposure. Specimens containing the additive exhibited reduced surface indentation after contact with a chemical mixture of toluene, naphtha, and ethanol, particularly after prolonged exposure intervals (24 h and 7 days). This indicates enhanced surface hardness and structural integrity of the cured resin. The improvement can be explained by several likely mechanisms. First, the oak dust particles may function as bio-based micro-fillers, physically occupying voids in the epoxy matrix and reducing polymer free volume. Additionally, the lignocellulosic composition of oak dust may enable secondary hydrogen bonding or physical entanglement with the epoxy network, which contributes to a denser, more chemically resistant structure. Mohan (2013) highlighted that incorporating lignocellulosic additives into epoxy systems can enhance thermal and chemical stability by reducing polymer mobility and promoting secondary interactions such as hydrogen bonding. Similarly, Bartoli *et al.* (2022) demonstrated that biomass-derived carbon fibers significantly improved the mechanical and thermal properties of epoxy composites, suggesting that the presence of micro-structured fillers leads to a denser, more resilient network. In the present study, oak dust served a comparable function by limiting solvent ingress and enhancing the dimensional stability of the resin system.

The observed trend is consistent with prior research on natural and hybrid filler systems in thermosetting resins. Studies by Szewczak and Szeląg (2019) demonstrated that low-percentage additions of biomass-derived fillers can enhance not only mechanical properties but also chemical and thermal resistance (Szewczak and Szelag 2019). Similarly, Hamid *et al.* (2019) reported improved dimensional stability and reduced solvent permeability in epoxy resins modified with organic and nanoclay reinforcements. The use of the Buchholz indentation method in this study provided a sensitive assessment of surface degradation due to chemical exposure. The lower indentation values observed in additive-enhanced samples reflect a higher crosslink density and reduced plasticization over time, which is consistent with established understanding of filler-induced improvements in epoxy network rigidity (Starkova *et al.* 2021).

CONCLUSIONS

1. Exposure to extreme environmental conditions (50 °C and 90% relative humidity) caused a statistically significant reduction in tensile strength, particularly in meranti joints. No significant reduction in tensile strength was observed in joints exposed to alternating temperature cycles (−30 to +50 °C) compared to those kept under normal conditions.

2. Impact strength tests showed no statistically significant influence of climatic conditions on either oak or meranti joints.

3. Meranti joints showed a higher frequency of adhesive and cohesive failures under extreme temperature and humidity, reflecting its anatomical vulnerability to interfacial degradation. Oak joints, while more resilient overall, exhibited more cohesive failures during impact testing under standard conditions.

4. The addition of oak wood dust (0.05 wt%) as a bio-based filler significantly improved the epoxy's chemical resistance. Treated samples showed less surface indentation after solvent exposure, especially at longer intervals.

5. It should be noted that the study's climatic exposure durations, though representative, were limited. Additionally, the focus on only two wood species (oak and meranti) limits generalizability. Future work should include a broader range of temperate and tropical hardwoods.

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Author's Contributions

The authors have accepted responsibility for the entire content of this manuscript and approved its submission. In contrast, the authors assisted in important tasks, such as manuscript preparation, clerical assistance, and technical assistance.

Data Availability

All data generated or analysed during this study are included in this published article.

Conflict of Interest

Authors state no conflict of interest.

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