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Experimental Study on Mechanical Characterization of Spruce Wood

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ABSTRACT

This paper presents a comprehensive characterization of the properties of spruce wood (Picea abies), establishing a foundation for a subsequent investigation into the fire resistance of wooden and hybrid wood-aluminum columns. The effects of density and moisture content on mechanical performance was assessed through compression, tensile, and bending tests conducted on specimens under controlled moisture conditions (oven-dried, air-dried, and moisture-conditioned). The results reveal a strong inverse relationship between moisture content and mechanical strength. However, increased moisture content enhances deformation capacity and energy absorption under compressive loading. These findings highlight the critical importance of moisture control in structural design and provide valuable insights for the application of spruce wood in environments subject to variable humidity. The outcome of this research work establishes the essential groundwork for modeling the fire performance of composite aluminum-wood columns.

1. INTRODUCTION

Spruce wood (Picea abies) is one of the most widely used softwood in the global timber industry, valued for its straight grain, workability, and favorable strength-to-weight ratio [1]. In agreement with Kollmann et al. [2], the physical and mechanical properties of spruce wood account for its widespread use across a broad range of applications. Owing to its relatively high mechanical performance combined with a comparatively low density, spruce wood is particularly well suited for lightweight structural construction. These desirable properties stem from the wood's microstructure, which is primarily composed of cellulose, hemicellulose, and lignin [2, 3]. In particular, cellulose molecules form long, slender crystalline chains (4–5 µm in length) which contribute significantly to the material's high strength and low density [4]. Owing to these properties, spruce wood is extensively used in structural applications ranging from traditional sawn timber to glued-laminated timber (glulam) and cross-laminated timber (CLT). The increasing use of such materials requires an accurate understanding of their mechanical properties. In this context, Brandner et al. [5] provided a comprehensive state-of-the-art review of CLT, addressing its production, material properties, structural design, and connections. The mechanical behaviour of spruce wood, as with all wood, is inherently orthotropic and strongly governed by two fundamental physical properties: density and moisture content.

The relationship between wood density and mechanical properties is one of the most robust and well-quantified in materials science. Numerous studies have demonstrated that density, which reflects cell wall thickness and the amount of solid wood substance per unit volume, exhibits a strong positive correlation with strength and stiffness. Simic et al. [6] reported statistically significant effects of different planting densities on both timber density and modulus of elasticity. Jaakkola et al. [7] showed that growth rate affects the density of Norway spruce, with slower growth leading to higher density. For Norway spruce, air-dry density typically ranges between 350 and 470 kg/m³, although substantial variations arise from genetics and silvicultural conditions. These variations translate directly into mechanical performance. For instance, the correlation between density and compressive strength in spruce is exceptionally strong, with reported coefficients (R^2) often exceeding 0.7-0.8. Rais et al. [8] demonstrated that high plant densities result in improved mechanical quality of sawn timber. Commercial grading machines extensively use this relationship, employing X-ray or microwave scanning to non-destructively estimate density and thereby predict mechanical performance. Brougui et al. [9] evaluated the mechanical properties of timber structures, through non-destructive testing (NDT) methods, particularly ultrasonic waves. Eder et al. [10] and Huang et al. [11] determined cell wall structure and wood properties.

Similarly, the detrimental effect of moisture content (MC) on the mechanical properties of wood is a fundamental principle of wood mechanics. Indeed, Ike et al. [12] conducted an experimental investigation on the influence of moisture content on the structural behavior of Norway spruce glued-laminated (glulam) timber. Samples were conditioned to six moisture content levels ranging from 5% to 30%. The results demonstrated that increasing moisture content led to a significant reduction in strength in all evaluated mechanical properties. As moisture content increased from dry conditions to the fibre saturation point (approximately 30%), compressive and tensile strengths decreased by more than 50% and 30%, respectively, in both grain directions. Similarly, flexural and shear strengths were reduced by up to 31%, while flexural stiffness exhibited a more pronounced decline of approximately 58%. As a hygroscopic material, wood absorbs water into its cell walls, weakening the hydrogen bonding within the cellulose microfibrils and the lignin-hemicellulose matrix. It is well-established that for most mechanical properties, both strength and stiffness decrease approximately linearly with increasing moisture content (MC) from oven-dry to the fibre saturation point (FSP) [13, 14]. Fajdiga et al. [15] focused exclusively on the three-point bending behavior of clear Norway spruce specimens in order to develop numerical models based on the finite element method.

While the individual effects of density and moisture are well documented [16, 17], their combined and interacting effects on the full range of mechanical properties (compression, tension, and bending) for Norway spruce under rigorously controlled conditioning states are less comprehensively documented within a single study. Existing data are often dispersed across decades of literature, derived from different species or obtained under varying testing conditions. Furthermore, advanced numerical modelling, particularly for simulating complex multi-physical phenomena such as the fire performance of wood-metal composite structures requires a complete and self-consistent dataset obtained from the same sample batch under defined conditions. Therefore, the primary objective of this study is not merely to reaffirm known relationships, but to generate a rigorous, empirical dataset that quantifies the mechanical properties of Norway spruce across its natural density range and under three precisely controlled moisture states: oven-dried (0% MC), air-dried (~12% MC), and fully moisture-conditioned (>FSP). This work addresses two key and novel objectives:

(1) To systematically isolate and analyze the interactive effects of density and moisture content on the orthotropic mechanical properties of spruce, leading to predictive relationships that can be directly applied in material selection and structural design.

(2) To establish a robust experimental benchmark that underpins the development and validation of advanced thermo-mechanical models within ongoing research on the fire performance of wood-aluminum hybrid structures.

By achieving these objectives, the present study delivers critical, high-quality data for engineers and designers aiming to optimize the structural use of spruce in demanding applications, while supporting the advancement of next-generation numerical simulation tools for performance-based timber design.

2. MATERIALS AND METHODS

2.1 Physical properties

This study was conducted using wood samples of Picea abies (spruce) (Figure 1) from a large conifer (approximately 40 m in eight and 60 years in age) native to North Africa, harvested in the Tebessa region of Algeria. The log was sawn into boards and the freshly cut boards were subsequently machined into 9 specimens with dimensions of 20 × 20 × 30 mm^3 (radial × tangential × longitudinal directions). All specimens were extracted from the same trunk of adult wood. The density of each specimen was determined by dividing its mass by its volume. Moisture content (MC) was measured using the oven-drying method in accordance with relevant standards [18-21]. To ensure consistency across tests, specimens of identical dimensions were used throughout the experimental program. Each sample was first weighed to record its initial (wet) mass and then dried in an oven at 108°C for 24 hours to remove all free and bound water. The selected drying temperature ensured complete moisture removal prior to subsequent testing.

The three air-dried samples were tested in their as-received condition, without any additional treatment to alter their moisture content. For the moisture-conditioned specimens, they were fully submerged in water for 48 hours, and their weights were recorded before and after soaking to evaluate water absorption. This classification allowed for a systematic comparison of the effects of different moisture levels on the density and mechanical behavior of spruce wood.

Figure 1. Illustration of spruce (*Picea abies*) wood

Standardized testing procedures were employed to conduct a series of experimental investigations, providing reliable data on the physical and mechanical performance of spruce wood under controlled conditions. Compression tests parallel to the grain and bending tests were carried out to clarify the relationships between density, moisture content, and mechanical behavior.

2.2 Mechanical properties

Compression, bending, and tensile tests were conducted to evaluate the mechanical properties of the spruce wood specimens. Compression tests were conducted using an LR50K Plus universal testing machine at a controlled displacement rate of 5 mm/min. A total of nine standardized samples (20 × 20 × 30 mm^3), oriented parallel to the grain, were tested under controlled environmental conditions of 20°C and 65% relative humidity. The bending tests were carried out using a three-point loading setup on the same testing machine. Nine specimens with a cross-sectional area of 20 × 20 mm^2 and a loading span of 300 mm were tested, with the load applied at a constant rate until failure. Tensile tests were performed on a Zwick universal testing machine using three specimens. Each specimen was mounted in a strictly vertical alignment to ensure uniform load application and was gripped over a length of 90–95 mm, in accordance with NF B51-017. Tensile loading was applied progressively at a constant displacement rate until fracture, as specified by NF B51-017.

The experimental set up for all mechanical properties testing is shown in Figure 2.

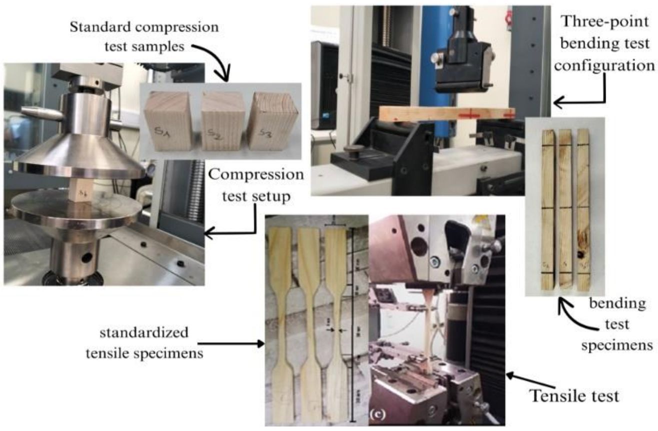

Figure 2. Experimental setup for mechanical testing characterization: (a) Compression, (b) Bending, (c) Tensile

3. RESULTS AND DISCUSSION

3.1 Physical properties

Spruce wood exhibits a moderate density with relatively limited variation among the tested specimens. The average density of 507.25 kg/m³ falls within the typical range reported for spruce [3, 5, 6] which is widely recognized as a lightweight softwood material. According to Huber et al. [22], Norway spruce and other conifers generally display lower variability in density and mechanical properties than deciduous woods, while achieving a more favorable balance between density and bending strength. The results in Table 1 show that the moisture content of the specimens was relatively low averaging around 15.35%, which is consistent with values expected for air-dried wood conditioned under ambient environments [23]. Wood with a moisture content below 20% is considered suitable for structural and construction applications [6, 24], as it minimizes the risks of shrinkage, warping, and decay. Variations in density observed within the same wood type can be attributed to natural growth and material imperfections, such as knots, and moisture condition. As expected, oven-dried specimens displayed the lowest densities due to moisture removal, whereas moisture-conditioned specimens showed increased density due to water absorption.

Table 1. Density and moisture content of used wood

	Number of Samples	Average Density (kg/m^3)	Moisture Content (%)
Oven-dried	3	491.71	13.60
Air-dried	3	507.25	15.35
Moisture conditioned	3	659.44	33.64
StDev	/	92.68	11.10

The data reveal a clear positive correlation between moisture content and density, with increasing moisture content leading to higher wood density, consistent with findings reported in the literature [25]. Although relatively high standard deviations were observed (approximately 92.7 for density and 11.1 for moisture content as shown in Table 1), these values primarily reflect natural variability among individual specimens rather than experimental uncertainty. Even for specimens extracted from the same trunk, substantial differences can arise due to variations in annual ring width, the proportion of earlywood to latewood, and radial position relative to the pith. Local anatomical features including grain deviation and small knots, further contribute to variability in both density and moisture, as reported by previous studies [26, 27]. For moisture-conditioned specimens, this variability is further amplified by non-uniform water penetration and differential swelling of cell walls above the fiber saturation point.

3.2 Mechanical properties

3.2.1 Compression test (parallel to grain)

Compression tests conducted on spruce wood specimens (S1-S9) under three different conditioning states (Figure 3), oven dried (S1-S3), air-dried (S4-S6) and moisture-conditioned (S7-S9), revealed distinct mechanical behaviors influenced by moisture content and inherent material variability. As shown in Figure 3(a), the oven-dried specimens (S1-S3) exhibited predominantly brittle fracture, characterized by limited deformation, as evidenced by sharp fractures or sudden buckling, attributed to increased stiffness at low moisture content. In contrast, air-dried specimens (S5-S6) displayed moderate deformation prior to failure, reflecting a balance between strength and flexibility. The moisture-conditioned specimens (S7-S9) showed pronounced fiber crushing and buckling, indicative of reduced strength and increased plasticity associated with higher moisture levels. The corresponding tress-strain curves reveal an initial non-linear response for all specimens, likely arising from the viscoelastic behavior of wood and progressive cell-wall buckling. Following the peak stress, a short plateau region was observed, resembling a ductile-like phase, before a gradual reduction in stress. This failure pattern indicates that spruce wood fails in a non-fragile manner, typical of softwoods under axial compression [27].

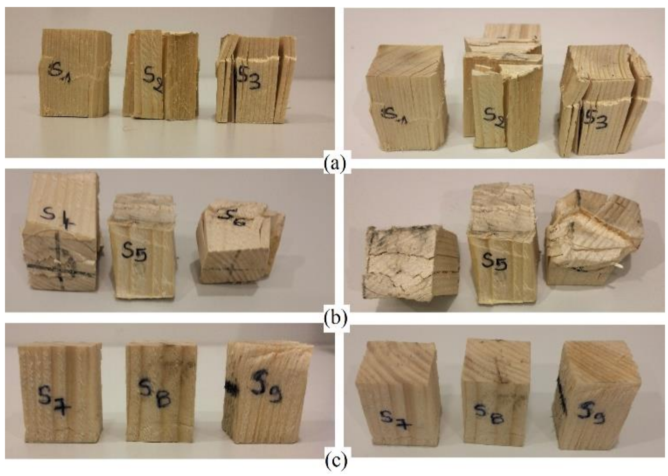

Figure 3. Spruce wood samples after compression testing parallel to the grain, (a) Oven-dried, (b) Air-dried, and (c) Moisture-conditioned

Failure of the specimens generally occurred through a combination of buckling and shear fracture along the grain, with minimal fiber tearing. Among the oven-dried specimens, S2 which contained a small knot, failed at a lower stress than

S1 and S3, highlighting the weakening effect of defects. Overall, the oven-dried specimens exhibited the highest peak stresses, as the absence of moisture increased stiffness and load-bearing capacity. Their stress-strain curves displayed a steep linear elastic region (Figure 4) followed by abrupt post-peak stress softening, which is characteristic of dry wood where microfibril collapse occurs suddenly with limited plastic deformation, in agreement with Báder et al. [24].

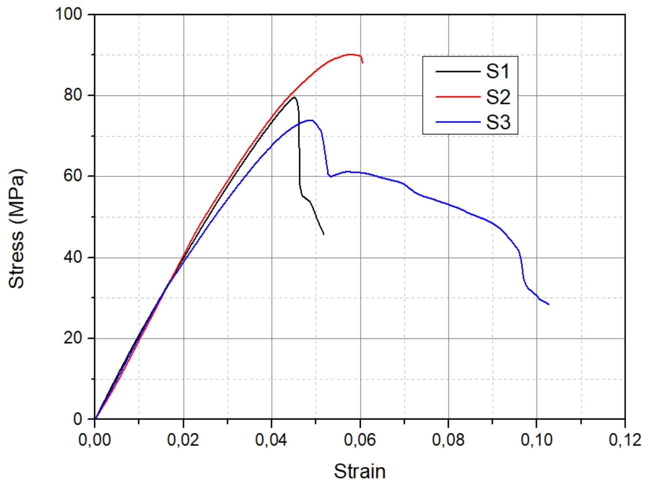

Figure 4. Stress-strain curves of oven-dried spruce wood samples subjected to compression parallel to the grain

For the air-dried specimens, peak stresses were approximately 10-15% lower than those of the oven-dried specimens due to moisture-induced plasticization of the cell wall constituents. A longer post-yield plateau was observed (Figure 5), indicating progressive cell-wall collapse rather than sudden failure and reflecting the enhanced energy-absorbing capacity of air-dried wood. Failure was governed by a combination of shear and crushing, with visible fiber buckling but no explosive splitting (Figure 3(b)). Specimen S5, which exhibited straight grain, sustained higher strains prior to failure than specimen S4, which showed slight grain deviation, emphasizing the influence of grain orientation on deformability.

Moisture conditioned specimens exhibited the lowest strength and stiffness among all groups, with peak stresses reduced by approximately 25–30% relative to oven-dried samples. The elastic region of the stress-strain response was notably shorter, with early microfibril yielding leading to a more gradual curve. The post-peak plateau was the most pronounced of all conditioning states, indicating high deformability. These specimens showed clear barreling deformation (lateral expansion) and fiber kinking (Figure 3c). Across all conditioning states, variations in density, moisture content and natural imperfections (knots, grain deviations) contributed to the observed dispersion of stress and strain responses, consistent with observations reported in the literature.

As shown in Figure 6, the moisture-conditioned specimens exhibited a predominantly ductile mode of failure, characterized by crushed and deformed surfaces with poorly defined cracking. This reflects the increased deformability and energy absorption capacity of spruce wood under compressive loading. Overall, increasing water content shifts fracture behavior from brittle to ductile, reducing crack severity and favoring material yielding over fracturing.

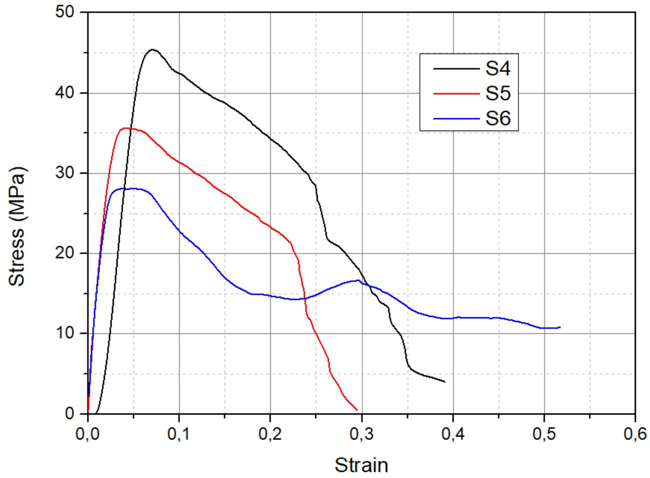

Figure 5. Stress-strain curves of air-dried spruce wood samples subjected to compression parallel to the grain

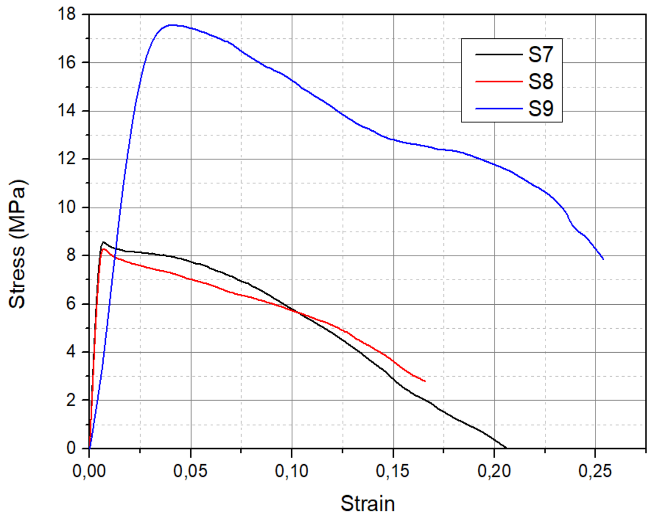

Figure 6. Stress–strain curves of moisture-conditioned spruce wood samples subjected to compression parallel to the grain

Table 2. Mechanical properties of spruce wood specimens subjected to compression testing

Sample Name	Young's Modulus (MPa)	Average (MPa)	Stiffness ($N.m^2$)	Average (MPa)
S1	2183.6	2126.6	29115.0	28347.33
S2	2119.8		28265.0	
S3	2074.6		27662.0	
S4	1243.9	1778.9	16586.0	23718.66
S5	1902.5		25366.0	
S6	2190.3		29204.0	
S7	2189.7	1655.04	29196.0	22067.33
S8	2024.9		26999.0	
S9	750.51		10007.0	

Compression test results for spruce wood specimens (S1-S9), shown in Table 2, under three conditioning states reveal clear moisture-dependent trends. Oven-dried specimens exhibited the highest mechanical performance, characterized by consistent Young's Modulus and Stiffness, indicating superior strength and reliability for structural applications. Air-dried specimens showed intermediate performance but with greater variability, suggesting less predictable behavior under compressive loading. In contrast, moisture-conditioned specimens displayed the lowest strength and stiffness with particularly poor results for specimen S9, underscoring the detrimental effect of elevated moisture content on load-bearing capacity. These observations highlight the strong relationship between moisture content and mechanical properties. As reported in the study [26], the stiffness modulus of spruce wood is affected by the structure of the annual rings, while the study [27] showed that crystallinity increases from fourth to the tenth ring measured from the pith and remains approximately constant beyond this region.

3.2.2 Profilometry and optical microscopy of samples after compression tests

Profilometry images of the spruce wood specimens (S1-S9) obtained after compression testing reveal distinct surface morphologies and fracture features that vary with the conditioning state.

The profilometry images presented in Figure 7 illustrate the surface behavior of oven-dried spruce wood specimens subjected to compression testing. The upper row of 3D surface maps reveals the surface topography and highlights dominant deformation features. The left image shows relatively smooth areas with minor surface markings, indicating either elastic or early plastic deformation. In contrast, the central and right images display distinct longitudinal cracking and raised fiber structures, suggesting the onset of tensile splitting and fiber pull-out along the grain direction, a typical failure mechanism in wood subjected to axial compressive loading.

The lower row, consisting of high-resolution optical images, provides a closer look at the microstructural changes. The left image clearly shows a deep, sharp crack, characteristic of brittle failure and localized shear or tensile stress. The central and right images further confirm the presence of cracks oriented parallel to the grain, indicating longitudinal splitting. This crack pattern reflects the anisotropic nature of spruce wood, which possesses high strength along the grain but reduced resistance to stresses acting in transverse directions [28]. The raised, torn fibers suggest micro-fiber pull-out and local crushing around the cracked zones. Overall, the observed surface features are consistent with the brittle behavior of oven-dried spruce wood, where low moisture content reduces ductility and promotes crack propagation along the grain.

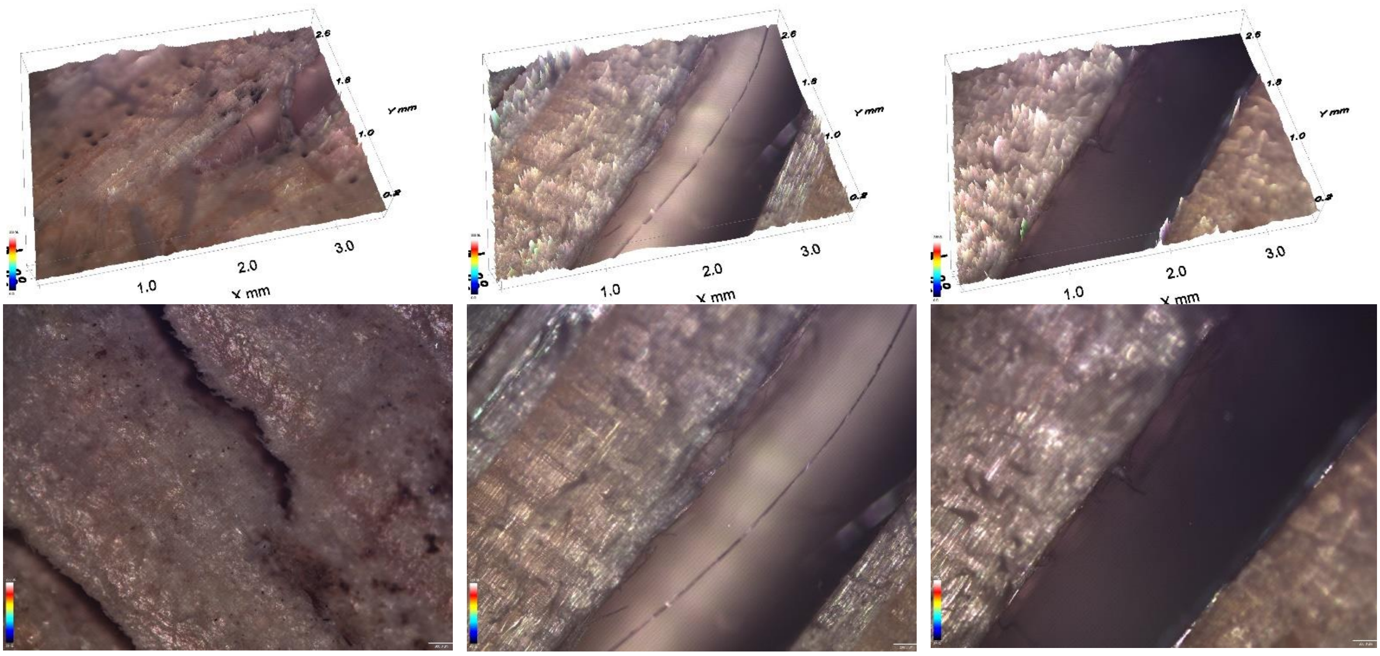

Figure 7. 3D profilometry (top) and optical microscopy (bottom) images of oven-dried spruce wood samples (S1–S3) after compression tests parallel to the grain highlighting cracks and surface imperfections

The profilometry images of air-dried specimens (Figure 8) confirm the presence of a large, open cavity with delaminated internal surfaces, indicating tearing and separation between fiber layers. such features are commonly observed when the internal cohesion of the wood matrix is compromised under compressive loading. The second image reveals a pronounced longitudinal crack with rough edges, characteristic of brittle fracture initiated along weak zones within the grain structure. The third image shows more subtle surface damage with partially separated fibers and micro-cracking, indicating areas that may have experienced progressive failure under compressive stress.

Overall, the air-dried spruce specimens exhibited a mixed mode failure behavior under compression, dominated by longitudinal splitting, fiber separation, and delamination. Compared with the oven-dried samples, the air-dried wood retained slightly more ductility, allowing some localized deformation before final failure. Nevertheless, the prevailing failure mechanism still reflects the inherently brittle compressive response of spruce wood, particularly along the grain direction.

Consistent with the findings of Kollmann et al. [2], the mechanical properties of wood are strongly affected by its growth ring structure, the presence of defects such as knots and spiral grain, and moisture content. The profilometry and optical microscopy images of moisture-conditioned spruce wood specimens (Figure 9) reveal surface features indicative of a more ductile failure behavior under compressive loading. The 3D surface profiles (top row) exhibit less aggressive surface cracking compared to oven and air-dried samples.

Observed cracks are narrower, smoother, and more continuous, suggesting that plastic deformation and energy dissipation through fiber buckling and internal shear rather than abrupt fiber rupture. The fiber structure appears more compliant, exhibiting localized compression and surface folding rather than widespread delamination or tearing. These characteristics are typical of wood at elevated moisture contents, where water absorbed within the cell walls acts as a plasticizer, softening the lignin and hemicellulose matrix and thereby reducing the material's brittleness. Although an increased lignin content may contribute to compressive strength, its effect appears to be minimal.

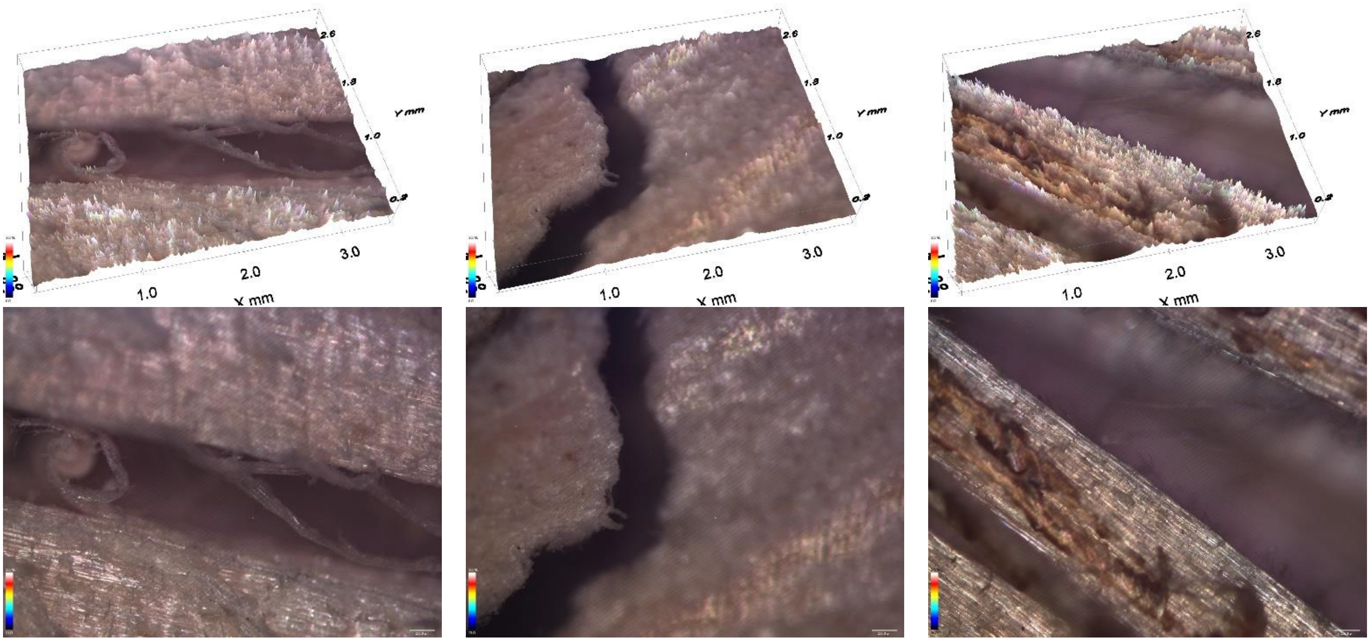

Figure 8. 3D profilometry (top) and optical microscopy (bottom) images of air-dried spruce wood samples (S4–S6) after compression tests emphasize cracks and deformation features

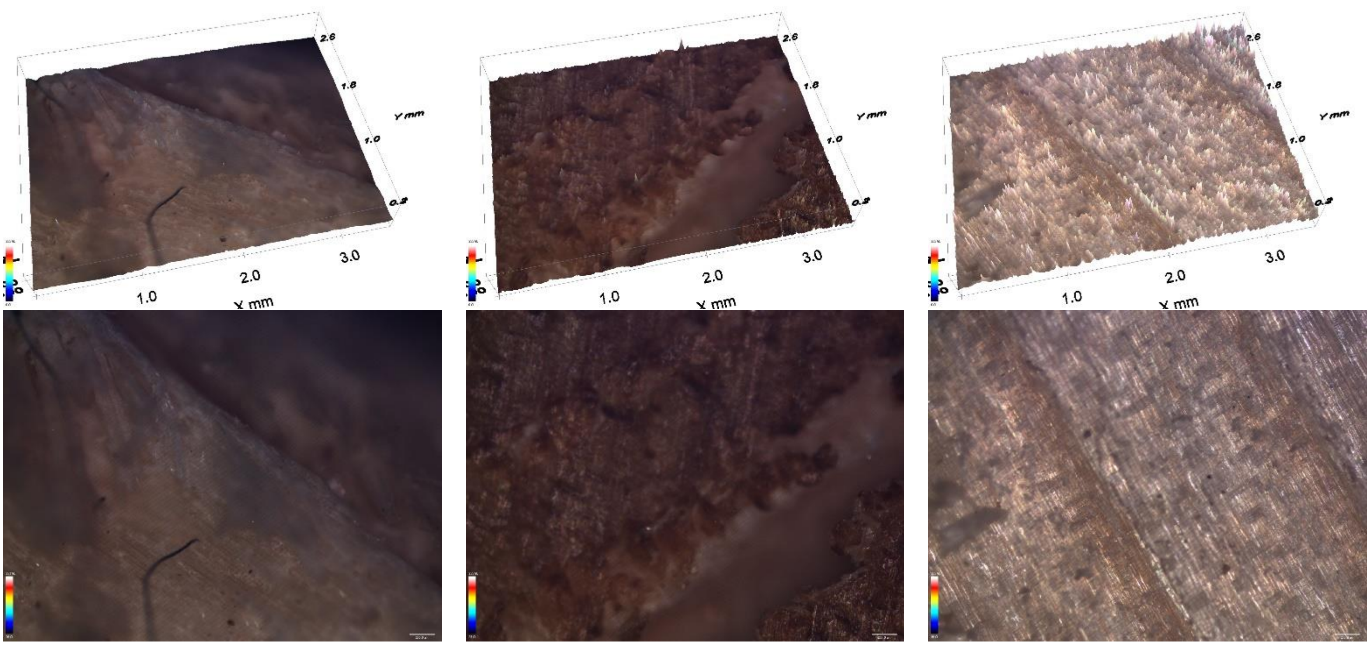

Figure 9. 3D profilometry (top) and optical microscopy (bottom) images of moisture-conditioned spruce wood samples (S7–S9) after compression tests highlighting deformation patterns and surface imperfections

3.2.3 Bending tests

Three-point bending tests performed on spruce wood samples (S1-S9) under three conditioning states, oven-dried (S1-S3), air-dried (S4-S6) and moisture-conditioned (S7-S9), revealed distinct bending behaviors as function of moisture content. The results of these tests are illustrated in Table 3. The oven-dried specimens exhibited the highest stiffness and strength but the lowest ductility, resulting in sudden failure and brittle failure under increasing load (Figure 10(a). The air-dried samples displayed intermediate behavior, achieving a balance between strength and flexibility, with moderate moisture content permitting limited plastic deformation prior to failure (Figure 10(b)). In contrast, the moisture-conditioned samples showed the lowest stiffness and strength but the greatest ductility, as increased moisture content softens the wood and promotes increased deformation and energy absorption before failure (Figure 10(c)). These results underscore the critical role of moisture content in the mechanical performance of spruce wood, with drier samples being stronger but more brittle, and wetter samples being softer but weaker, which is essential for structural applications under variable environmental conditions as reported in previous research [29, 30]. In their research, Hidayat et al. [29] suggested an inverse relationship between temperature and key mechanical properties of wood, particularly compressive strength and hardness. This effect was attributed to thermal degradation of hemicellulose, leading to increased wood crystallinity. Budiyantoro and Yudhanto [30] observed that Sengon sawdust is the optimal reinforcement filler among Teak, Pine, and Sengon, owing to its superior crystallinity (52.8%) and aspect ratio (5.8), both of which are critical parameters for enhancing the performance of bio-composite materials.

Table 3. Mechanical properties of spruce wood specimens subjected to bending tests

Sample Name	Young's Modulus (MPa)	Average (MPa)	Flexural Rigidity ($N.m^2$)	Average (MPa)
S1	5543.7	6375.20	75.111	83.876
S2	6245.3		94.887	
S3	7336.6		81.632	
S4	4275.1	5074.83	73.916	85.017
S5	4742.1		83.271	
S6	6206.7		97.821	
S7	7116.5	6390.73	63.228	67.661
S8	5633.3		57.001	
S9	6122.4		82.756	

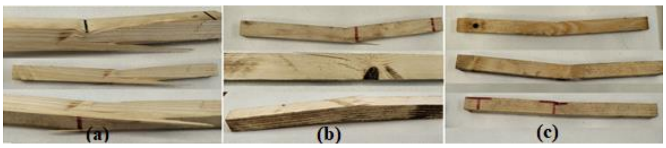

Figure 10. Spruce wood samples after three-point bending tests for (a) Oven-dried, (b) Air-dried, and (c) Moisture-conditioned

The results of the three-point bending tests reveal several key aspects of the mechanical response of spruce wood under different moisture conditions. All samples exhibited an initial linear elastic region, in which stress increased proportionally with deformation (Figures 11-13). During this stage, the cellular structure of wood resists deformation through elastic bending of the cell walls and the alignment of the microfibrils. This elastic stage was followed by distinct non-linear deformation, indicating the start of permanent damage through mechanisms such as the reorientation of microfibrils and the formation of microcracks in the lignin matrix [31]. Post-fracture behavior varied considerably according to the conditioning states. The oven-dried samples (S1-S3) were more resistant to the effects of the drying process and exhibited sudden fracture with minimal plastic deformation, characteristic of brittle fracture in desiccated wood where hydrogen bonds within the cell wall structure break catastrophically. In contrast, the air-dried samples (S4-S6) showed progressive softening, attributed to fiber bridging and interfibrillar shear. Moisture-conditioned samples (S7-S9) displayed the most pronounced non-linearity and energy dissipation, with deformation governed by viscoelastic flow and delamination. Based on the study [32], a lower stiffness modulus was attributed to the trees' characteristics as fast-growing clones, which yielded wood with a large share of juvenile material due to cultivation on fertile ground.

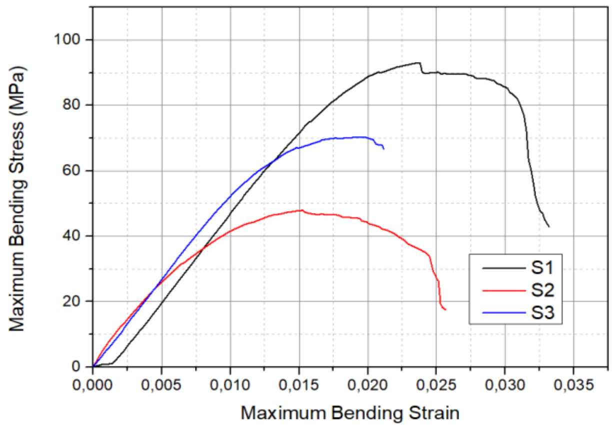

Figure 11. Stress–strain curves of oven-dried spruce wood samples subjected to bending tests

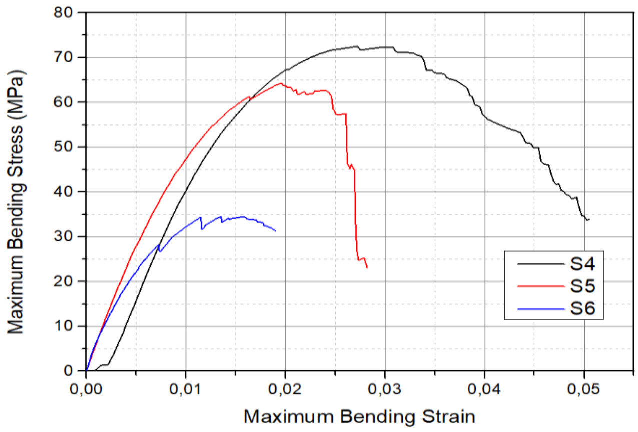

Figure 12. Stress–strain curves of air-dried spruce wood samples subjected to bending tests

The scatter observed in the stress-strain curves can be largely attributed to natural heterogeneities inherent to wood, including density variations (up to 15% within the same board), the presence of knots (which can reduce local strength by 30-50%) and grain orientation (which cause anisotropic response). These effects are particularly evident when comparing samples such as S2 and S3. Consistent with previous studies [33], a reduction in moisture content can enhance the mechanical properties of spruce wood by up to 10% under certain conditions [34].

3.2.4 Profilometry and optical microscopy of samples after bending tests

Based on the initial observations, profilometric analysis provides evidence of the strong impact of moisture content on fracture mechanisms at the microstructural level. In the oven-dried samples (Figure 14), surface topography is highly irregular, characterized by deep grooves and fragmented fiber structures, indicative of brittle fracture resulting from severe moisture loss. These features suggest catastrophic fractures with minimal energy dissipation. In contrast, the air-dried samples (Figure 15) exhibit more uniform and less fragmented surfaces, suggesting more stable crack growth with moderate energy absorption and partial plasticity. The presence of ambient moisture appears to preserve a degree of flexibility in the wood matrix.

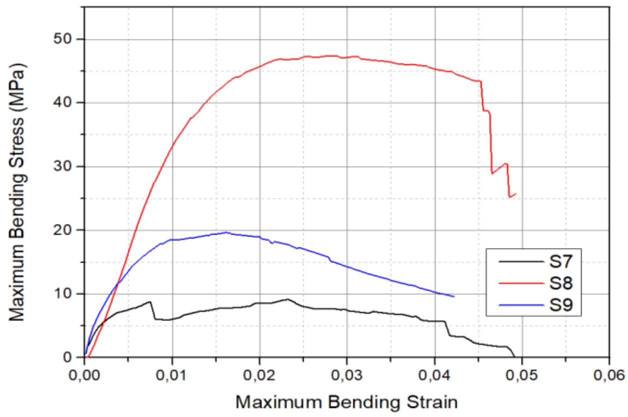

Figure 13. Stress–strain curves of moisture-conditioned spruce wood samples subjected to bending tests

Figure 14. Profilometry images of oven-dried spruce wood samples (S1–S3) subjected to three-point bending tests highlighting cracks and fracture zones

Figure 15. Profilometry images of air-dried spruce wood samples (S4–S6) after three-point bending tests showing crack propagation and surface imperfections

Figure 16. Profilometry images of moisture-conditioned spruce wood samples (S7–S9) after three-point bending tests illustrating microcracks and fiber pull-out

The moisture-conditioned samples (Figure 16) show the smoothest surface contours, with shallower cracks and clear evidence of fiber pull-out and bridging, which are characteristic of ductile failure [35]. The enhanced energy absorption observed in these specimens is attributed to the plasticizing effect of moisture on the lignin and hemicellulose components, resulting in a more gradual and energy-dissipative failure. Overall, the profilometry results clearly demonstrate that increasing water content improves the toughness and ductility of spruce wood subjected to bending stress, shifting the fracture behavior from a brittle to a more ductile mode.

3.2.5 Tensile test

To complement the compression and three-point bending tests performed on spruce wood under different moisture conditions, tensile tests were carried out on air-dried samples of the same species. These tests were intended to evaluate axial strength, stiffness and fracture behavior under tension, thereby providing a more comprehensive assessment of the mechanical properties of spruce wood for structural applications. In particular, tensile testing focuses on the elongation resistance and ultimate tensile strength of spruce wood, contributing to more complete understanding of its load-bearing capacity. Figure 17 presents the specimens after tensile testing and shows clean fracture surfaces with minimal fiber pull-out, characteristic of brittle failure. The observed failure mechanisms include fiber rupture as well as failure along the middle lamella, where separation occurs at the interface between adjacent fibers. These mechanisms may occur independently or simultaneously, contributing to the overall brittle behavior.

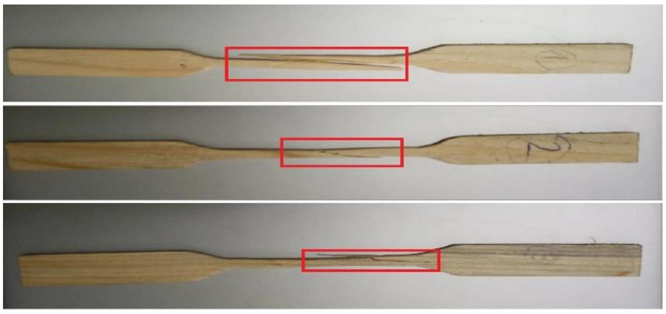

Figure 17. Air-dried spruce wood samples subjected to tensile testing

The variability in failure modes among the specimens can be attributed to inherent heterogeneities in the wood microstructure, such as differences in fiber alignment and the presence of minor defects, as also reported in the literature. Tensile test results for the three air-dried spruce wood specimens loaded parallel to the fiber direction provide important insights into the material's mechanical behavior. As shown in Figure 18, the stress-strain relationship is nearly linear up to the point of failure, indicating predominantly elastic behavior with minimal plastic deformation. This linear response confirms the inherently brittle nature of spruce wood when subjected to tensile loading in the fiber direction. The average tensile strength of the tested specimens was approximately 100 MPa, which is consistent with reported values for spruce wood [35]. However, failure occurred abruptly without significant warning, such as yielding or extensive deformation. Previous studies have shown that various modification techniques, including heat treatment, can be employed to alter and, some cases, enhance the mechanical properties of different wood species [36, 37]. Trismawati et al.

[38] propose: 1) optimizing leaching by combining xylanase with enzymes like cellulase or laccase, and 2) applying these treatments to recycled fibers to improve pulp quality and sustainability.

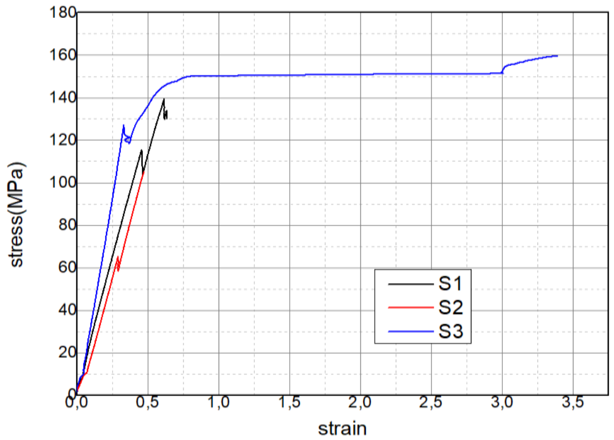

Figure 18. Stress–strain curves of air-dried spruce wood samples subjected to tensile testing

4. CONCLUSIONS

This study examined the mechanical behavior of spruce wood (Picea abies) with emphasis on the effects of moisture content and density under three conditioning states; oven-dried, air-dried, and moisture-conditioned. The results indicate that these two physical parameters dominate the mechanical response of spruce wood under compression, bending, and tensile loading. Oven-dried specimens exhibited the highest mechanical performance but failed in a brittle manner with minimal deformation. Air-dried specimens demonstrated intermediate strength and stiffness with improved ductility and energy absorption, offering a more balanced response for structural applications. Moisture-conditioned specimens exhibited the lowest strength, with reduction of approximately 25-30% compared to oven-dried samples but failed through ductile mechanisms such as fiber buckling and barrel formation due to moisture-induced plasticization.

Higher density generally resulted in improved mechanical performance, likely due to the presence of fewer defects which would have contributed scatter in results. Compression and bending tests revealed a transition from brittle to ductile failure in dry wood to progressively more ductile behavior with increasing moisture content, which was further confirmed by profilometric analysis. Tensile tests on air-dried specimens showed a predominantly elastic response up to abrupt brittle failure at high tensile stresses of approximately 100 MPa, mainly influenced by defects such as microfibril misalignment and knots.

Overall, the present findings highlight the need of controlling moisture content and accounting for density variability when designing with spruce wood, particularly for structural applications, to ensure predictable mechanical performance, long-term durability and safety in wood engineering, particularly in variable environmental conditions.

Future work will extend the present experimental program to thermo-mechanical testing under elevated temperatures under fire exposure, with particular attention to moisture migration, stiffness degradation, and residual load-bearing capacity. The resulting dataset will support the development and validation of advanced numerical models of wood and wood–aluminum hybrid structural elements subjected to fire, thereby contributing to the optimized and safe design of hybrid timber-based systems operating under severe environmental conditions.

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