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ORIGINAL ARTICLE

Effect of moisture on the edgewise flexural properties of acetylated and unmodified birch plywood: a comparison of strength, stiffness and brittleness properties

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Abstract

Birch plywood has superior mechanical properties compared with that made from most softwoods. However, durability-related issues still limit the application of birch plywood in outdoor structures. A means to enhance its durability is to acetylate birch veneers before processing them into plywood. An earlier study showed that such acetylated birch plywood has equivalent mechanical properties to unmodified ones. However, there is a need to better understand the moisture effect on the mechanical properties of unmodified and acetylated birch plywood for a better design of structural birch plywood elements. Moreover, due to the pronounced in-plane anisotropy of plywood, extra concern should be given to the weakest load angle due to the weakest chain theory. In this study, acetylated and unmodified birch plywood specimens were conditioned in climate chambers under three different environments with a temperature of 20 °C and increasing relative humidity (RH) from 35 to 65% to 95%. Thereafter, their in-plane edgewise flexural properties with load-to-face grain angles of 0, 45, and 90 degrees were tested. The influence of both RH and measured moisture contents on bending strength and stiffness are then presented. Prediction formulas of mechanical properties with moisture contents are derived by performing linear regressions among test results. Variations of brittleness factors and brittleness indexes under various RH conditions and load-face grain angles were also studied.

1 Introduction

The pursuit of sustainable societal development motivates to increase the proportion of bio-based building materials in construction sectors. Timber, together with wood-based products such as engineered wood products (EWPs), has gained increasing popularity during the last several decades due to its renewability and relatively low carbon footprint and emissions. EWPs, as value-added wood products that are made by bonding lumber, veneers, strands, or fibers together, can usually generate dimensionally stable products with high and comparably consistent mechanical performance, which is suitable for large-scale timber structures, and positive prospects for the future of the EWPs can be justified (Manninen et al. 2014).

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Birch (*Betula pendula*) is a short-lived pioneer wood species widespread in the Northern Hemisphere. Birch timber is suitable for construction purposes concerning its strength and stiffness. However, the features that have limited its structural use have been its tendency to distort and crack during drying, and its poor decay resistance (Luostarinen and Verkasalo 2000). Manufacturing birch into plywood solves the above-mentioned distortion and cracking issue; many researchers reported that plywood made from birch has satisfactory mechanical performance, making it ideal for structural usage (Cakiroglu et al. 2019). Several previous studies have addressed birch plywood's structural usage and angle-dependent mechanical properties (Crocetti et al. 2021; Furuheim et al. 2021; Wang et al. 2021, 2022a; Kromoser et al. 2021).

Nevertheless, the poor intrinsic durability of birch still needs to be enhanced when used for structural applications in most outdoor environments. As a well-studied and commercialized way of wood modification, the acetylation process can transform low-durable wood species into wood products with considerably increased durability and form stability (Gardner et al. 2003; Rowell and Dickerson 2014;

Mantanis 2017). Acetylation involves the reaction of wood with acetic anhydride, resulting in the esterification of the accessible hydroxyl groups in the cell wall, forming the by-product acetic acid. This chemical modification method mainly results in a reduced hygroscopicity of the wood substance, i.e., blocking of its hydroxyl accessible for water sorption (Rowell et al. 2009; Rowell and Dickerson 2014). Specifically for acetylated wood, the reduced EMC is attributed to the presence of covalently bonded acetyl groups in the nanopores in the cell-wall matrix, which is consequently not available for sorbed water molecules (Papadopoulos and Hill 2003; Popescu et al. 2014; Cermák et al. 2022). Besides, it is recommended in the literature to acetylate each birch veneer constituting the entire plywood board before processing veneers into plywood (Damay et al. 2015; Slabohm et al. 2022a, b). It is worth addressing the distinction between the impregnation and acetylation of veneers, i.e., for impregnated veneers, the bonding to plywood and curing of the impregnated veneer are combined in one process step (Bliem et al. 2020; Slabohm et al. 2022a). Besides, after acetylation process, the influence of cracks may become apparent on the mechanical properties of veneers. The produced product by gluing acetylated birch veneers together, so-called acetylated birch plywood, has been proven to possess equivalent mechanical properties compared with unmodified ones (Wang et al. 2022b).

Despite the abovementioned benefits, the dimensional instability and susceptibility to fungal decay of wood are strongly influenced by the absorption and desorption of water from and to the surroundings. Water absorption generally results in a decrease in strength and leads to dimensional changes until the wood reaches the fibre saturation point (FSP) (Cermák et al. 2022). Therefore, the knowledge of the moisture influence on the mechanical properties of unmodified and acetylated birch plywood needs to be enhanced for a better design of structural birch plywood elements. In addition, due to the pronounced in-plane anisotropy of plywood, extra concern should be given to the weakest load angle due to the weakest chain theory. These observations have importance for structural design since design codes often assess material parameters based on ambient humidity (Forsman et al. 2021).

Despite the beneficial aspects of acetylation on timber, the literature also reported that acetylation causes an increased brittleness in certain wood species. Reiterer and Sinn (2002) investigated the fracture properties of unmodified and modified (acetylation and heat treatments under various conditions) spruce wood using the wedge-splitting test. They found that the acetylation process leads to a reduction in mechanical properties of only 20%, whereas heat treatments reduce the properties to a much greater extent, approximately 50% to 80%. Forsman et al. (2020) performed a study on the fracture characteristics of unmodified and acetylated modified Scots pine. Their findings demonstrated a significant decrease (between 36 and 50%) in the fracture energy for the acetylated specimens, compared to the unmodified specimens. No significant effect of the acetylation process on the modulus of elasticity, nor on the tensile strength could be concluded. Their study indicates that the acetylation process results in an increased brittleness for Scots pine.

The most common indexes adopted to quantify the brittleness of treated wood in the literature are based on fracture mechanics, e.g., critical stress intensity factors, fracture energy, etc. However, Matsumoto and Nairn (2009) addressed that measuring fracture toughness on wood-based composites can be difficult because wood composites frequently develop fiber-bridging zones at the crack tip. Due to the occurrence of fiber-bridging effects, neither traditional fracture mechanics methods (e.g., ASTM399), nor visual identifications of the crack tip and measure of crack lengths are possible (ASTM-399, 1997). Besides, when fiber-bridging effects are significant, the measured fracture toughness increases as the crack propagates. They concluded that the fracture characterization of wood-based composite materials requires continuous monitoring of toughness as a function of crack growth via albeit non-standard fracture tests. Consequently, these fracture tests are usually effort consuming and require corresponding hardware and measurements with high precision.

Therefore, a relatively effort-saving and robust index is needed to analyze the brittleness of untreated and treated wood. Preferably, it can be derived from the data of static strength tests. Phuong et al. (2007) heat-treated *Styrax tonkinensis* wood under different environments and later conducted static bending tests on all specimens. They calculated the ratio (%) of the work absorbed in the elastic region to the total work absorbed to maximum load, used this ratio as an index to evaluate the brittleness of heat-treated wood, and found that the brittleness increased significantly after heat treatment. Under the most severe heat treatment conditions, brittleness could be increased by as much as four times the original.

Chen et al. (2020) performed flexural tests on bamboo and proposed a similar index based on the elastic bending stress-strain curves, to which they referred to as the ductility factor (DF). Flexural ductility was evaluated by the ductility factor (DF), which measures the capacity of a material to withstand plastic deformation before it breaks. A similar concern was addressed in several design standards for timber structures (American Society for Testing and Materials 2017). The reciprocal of the proposed ductility factor is converted into so-called brittleness factors in this study, and both the brittleness indexes (BI) and brittleness factors (BF) were adopted to analyze the influence of moisture on the ductility of unmodified and acetylated specimens. The details are illustrated later in the materials and methods section.

This study aims to investigate the effect of moisture on the mechanical properties of unmodified and acetylated birch plywood specimens. Specifically, specimens with three different grain orientations were cut from acetylated and unmodified plywood boards. They were first conditioned under three relative humidity (RH) levels (from 35% to 65% to 95%) and then tested under three-point bending. The strength and stiffness values were evaluated and correlated with corresponding RH and moisture contents. Due to the in-plane anisotropy of birch plywood, an extra concern was also given to the weakest load angle. The mechanical properties reduction under different service classes was derived and compared with the recommended values in Eurocode 5 (European Committee for Standardization (CEN) 2004b). Moreover, the brittleness indexes (BI) and brittleness factors (BF) proposed by other researchers were both adopted in this study to give a brittleness comparison on different groups of specimens.

2 Materials and methods

2.1 Unmodified and acetylated birch plywood

The manufacturing process of acetylated birch plywood involves several steps. Firstly, the birch lumber was rotary cut into veneers with a thickness of around 1.5 mm. Then the birch veneers were acetylated by Accsys Technologies (Arnhem, The Netherlands). According to their industrial methods optimized for treating solid lumber, the veneers were acetylated to a sufficiently high acetyl content of around 20-22%. High-performance liquid chromatography (HPLC) was applied to measure the acetyl content. Please refer to Beckers et al. (2003) for more details on determining the acetyl content. The process consists of a vacuum-pressure impregnation of liquid acetic anhydride, followed by heating (gas) and the removal of the acetylated veneers with the by-product acetic acid. The treatment temperature is around 130-150°C, and the treatment time varies from 16 to 24 hours per wood dimension (Forsman et al. 2021; Yin et al. 2021). After the treatment, the acetylated birch veneers were sent back to the plywood manufacturer Koskisen Oy (Järvelä, Finland). Finally, by hot-pressing (130 °C and the applied pressure of around 18 bars (1.8 MPa)) and gluing 21 veneers orthogonally with phenol formaldehyde resorcinol (PRF) adhesive, 400 mm-by-400 mm acetylated plywood panels with a total thickness of around 31.5 mm were produced. The PRF adhesive is of the type Aerodux 185/HRP 155 from the manufacturer Dynea (Lillestrøm, Norway). Figure 1 presents the schematic illustration of the manufacturing process. Additional manufacturing details and schematic illustrations can be found in the literature (Wang et al. 2022b).

The unmodified birch plywood investigated in this study is a commercial plywood product provided by Koskisen Oy (Järvelä, Finland). It has a nominal thickness of 30 mm with in total 21 veneers. The inner 19 veneers have the identical thickness $t_1 = 1.5\ mm$, while the face veneers are slightly thinner ($t_2 = \frac{1}{2} \cdot t_1$) since the surfaces of the plywood were sanded during the panel production process. A phenol–formaldehyde (PF) resin was used as the adhesive in the plywood processing. See Fig. 2a for the veneer layup of acetylated and untreated birch plywood specimens.

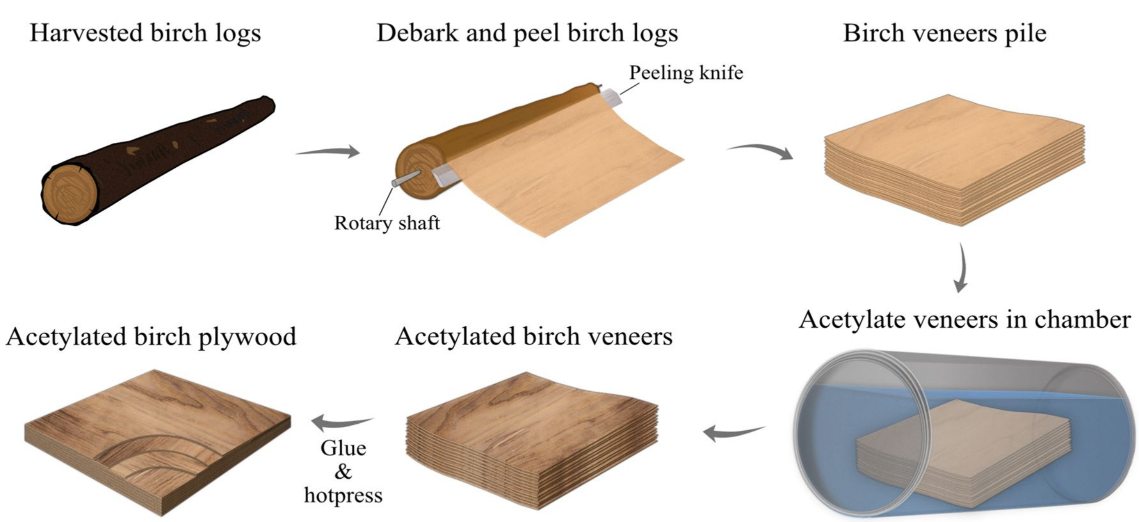

Fig. 1 Manufacture process of acetylated birch plywood (ABP) boards. The figure is reused from the author's previously published work (Wang et al. 2022b)

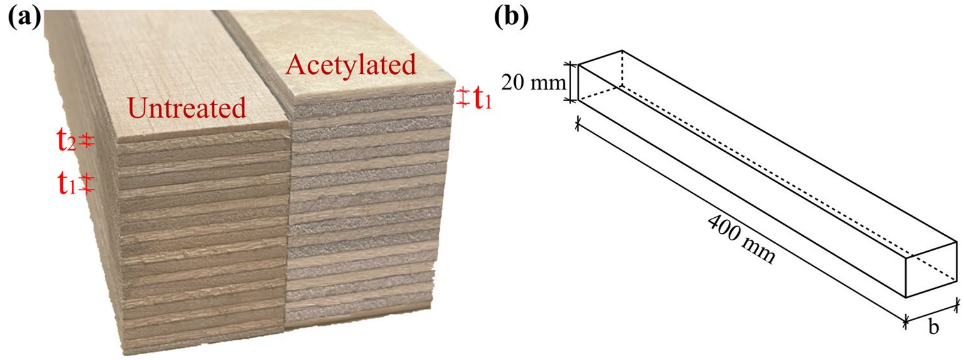

Fig. 2 **a** Veneer layup of untreated and acetylated birch plywood specimens, **b** dimensions of a test specimen

Hereinafter, plywood made of acetylated birch veneers is referred to as acetylated birch plywood, abbreviated as ABP, and the unmodified birch plywood is abbreviated as UBP. It is worth mentioning that due to the difference between ABP and UBP in terms of adhesive types, board thickness, veneer set-up, etc., the experimental result may not serve as evidence to directly evaluate the effect of acetylation. Instead, this study compares the global mechanical behavior between commercial birch plywood and pilot acetylated plywood. Therefore, the relevant values, such as strength, stiffness, and brittleness factors measured in this paper, are based on the context that considers both the unmodified and acetylated birch plywood specimens as a whole.

The unmodified test specimens were cut from six 1500 mm-by-3000 mm UBP panels, and the acetylated specimens were cut from ten 400 mm-by-400 mm ABP panels. All specimens were stochastically numbered to eliminate the biases from the batch differences. Each beam test specimen had the dimensions 400 mm × 20 mm × t (plywood thickness). In one aspect, the specimen dimension is pragmatically designed according to the available panel sizes; in another, it also took the slenderness ratio of beam specimens adopted in the literature as a reference, which will be explained in Sect. 2.2.

2.2 Experimental setups

In this study, both ABP and UBP specimens were conditioned in climate rooms under three different moisture environments (Env1: 20°C 35% RH; Env2: 20°C 65% RH; Env3: 20°C 95% RH). Specimens with load-to-face grain angles of 0, 45, and 90 degrees were selected for mechanical testing. Each test series consists of around 10 replicates. The density of birch plywood pieces was calculated by dividing each part's weight by its respective nominal volume. The moisture content was determined on tested specimens using the oven-dry method, as described in EN 322 (European Committee for Standardization (CEN) 1993).

After the conditioning, specimens were tested following the three-point bending test scheme. The testing standard EN 13879 (2004) describes the edgewise bending testing method for wood-based panels. It also suggested that the test of small-size specimens should be in accordance with EN 310, where the 3-point bending test is elaborated (EN 310, 1993). The small size specimen is defined with a length of 550 mm and a depth of 25 mm, which is similar to the size of the tested specimens in this study.

Bier (1984) and Wang et al. (2022b) performed edgewise bending tests on plywood made of different species in 3-point bending with a span-to-height ratio of 14 and 16, respectively. For flatwise bending of plywood, a much higher span-to-height ratio is suggested according to the standards, i.e., EN 789 (2004a), AS/NZS 2269 (2012), and ASTM D3043 (2017). In this paper, the span-to-height ratio was 16 and kept constant to study the influence of studied variables, i.e., moisture content and face grain angles. Therefore, in the adopted edgewise bending test, the beam depth (height) d and beam span L were determined to be 20 mm and 320 mm, respectively. The beam width b was designed to equal the panel thickness, which was 30 mm for UBP specimens and 31.5 mm for ABP specimens, as shown in Fig. 2b.

In this study, all the experiments were performed on the MTS810 universal test machine (MTS Systems Corporation, United States), and the experimental data was logged using the onboard test software in the system. The loading head motion was constant at around 5 mm/min throughout the tests to limit the test duration to 10 minutes. The load signal was recorded by the load cell (10 kN-capacity). For determining the modulus of elasticity, the placing of external displacement measuring devices is essential since the displacement recorded from the testing machine also incorporates the test apparatus compliance and the loading head indentation. The displacement at mid-span was measured by two linear variable differential transformers (LVDTs) attached on both sides of the specimens. See Figure 3 for the test setup and illustrations on the load-face grain direction.

The ultimate moment capacity is defined as the bending moment at mid-span corresponding to the maximum load (see Equation 1), and the edgewise bending strength of each test specimen is calculated according to Equation 2.

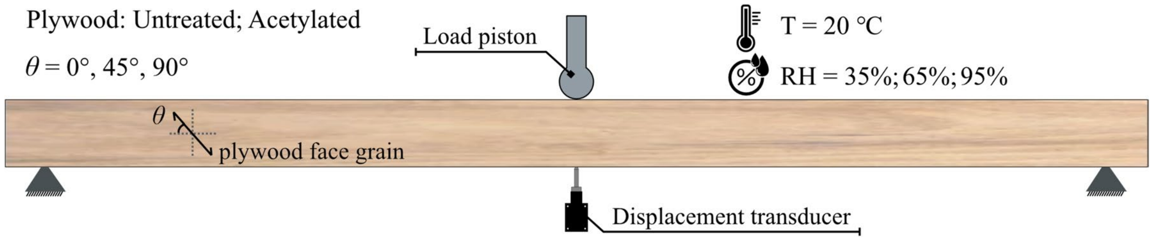

Fig. 3 Illustration of the in-plane three-point bending test scheme with placing of measuring devices

$$M_{u,exp} = \frac{F_{max} \cdot L}{4} \tag{1}$$

$$f_b = \frac{M_u}{W} = \frac{6 \cdot M_{u,exp}}{b \cdot d^2} \tag{2}$$

where $M_{u,exp}$ is the experimental ultimate moment capacity; F_{max} is the maximum force during the loading; L is the span of the tested specimen; b and d are respectively the width and depth of the beam cross-section.

Thereafter, the bending modulus of the beam can be determined based on the mid-span deflection under the three-point bending test regime. The shear deformation was subtracted from the measured deflection, according to the Timoshenko beam theory.

$$MOE_m = \frac{\Delta F \cdot L^3}{48 \cdot I \cdot \Delta u_m} = \frac{\Delta F \cdot L^3}{4 \cdot b \cdot d^3 \cdot (\Delta u_{LVDT} - \Delta u_s)} \tag{3}$$

$$\Delta u_s = \frac{\Delta F \cdot L}{4 \cdot k \cdot G \cdot A} \tag{4}$$

where ΔF and Δu_m are respectively the force and bending deflection interval either measured or calculated between 10 and 40% of the specimens' load capacity; I is the cross-section's second moment of inertia; b and d are respectively the beam width and depth; Δu_{LVDT} is the interval of LVDT readings; Δu_s is the shear deformation interval calculated from the force interval; k is the shear correction coefficient. In this study, k is assumed to be 5/6, which is a common value for beams with rectangular cross-sections when the beam's height-to-width ratio is around or over 1 (Gruttmann and Wagner 2001). G and A are respectively the panel shear modulus and the cross-sectional area of the specimen.

2.3 Definitions on brittleness indexes (BI) and factors (BF)

As mentioned earlier, the brittleness indexes (BI) proposed by Phuong et al. (2007) were derived based on the test results of static bending tests. In this study, following their method, the test curves were plotted using the load data collected by the load cell and the mid-span beam deflection collected by the LVDTs. The slope of the linear portion on the curve was then calculated as the slope measured between the displacement and piston load points that correspond to the interval of 10% and 40% of the maximum test load. By drawing a straight line from the coordinate origin with the calculated slope, the point where the vertical distance measured from the straight line to the test curve exceeds 1% of the maximum load, was defined as the proportion limit point, as shown in Fig. 4.

After determining the proportional limit point, the BI was calculated by using the ratio (%) of the work absorbed in the elastic region to the total work absorbed to the maximum load, as shown in Equation 5:

$$\text{BI} = \frac{\text{Area1}}{\text{Area1} + \text{Area2}} \tag{5}$$

It is assumed that for ideally brittle material, the specimen failed without any presence of Area 2, which gives a BI of one, and for an ideally ductile material, the energy absorbed within the elastic range of the curve (Area 1) is negligible compared to the energy absorbed in the plastic

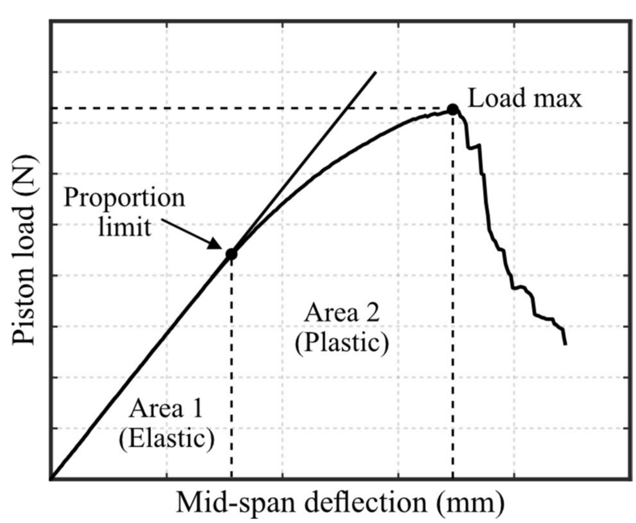

Fig. 4 Definition of brittleness index (BI) based on the load–deflection curves in bending tests

stage (Area 2), which gives a BI of zero. Therefore, the BI is on the scale of zero to one, and the material with a higher BI is considered more brittle.

As aforementioned in the introduction section, flexural ductility can also be evaluated considering the ductility factor (DF), which corresponds to the capacity of a material to withstand plastic deformation before it breaks. A similar concern was addressed in several design standards for timber structures (American Society for Testing and Materials 2017). The adopted ductility factors (DF) of test specimens, in both the literature and standard, were calculated as the ratio of the elastic strain at specimen failure, to the elastic strain at the proportional limit, as illustrated in Figure 5.

The proportional limit point was determined in the same way as mentioned above in the calculation for brittleness indexes. After determining the proportional limit point, the ductility factor can be calculated as shown in Equation 6 and 7:

$$\varepsilon = \frac{6 \cdot d \cdot u_m}{L^2} \tag{6}$$

$$\text{Ductility factor} = \frac{\varepsilon_f}{\varepsilon_y} \tag{7}$$

where u_m is the mid-span deflection due to bending; d and L are respectively the beam depth and span; Δu_s is the shear deformation interval derived from the force interval; the yield strain ε_y is defined as the maximum bending strain corresponding to the proportional limit; the failure strain ε_f is specified as the bending strain at specimen failure, which is the strain corresponding to 0.8 times the bending stress after reaching the peak load (Swiss Society of Engineers and Architects 2003; CEN European Committee for Standardization 2005).

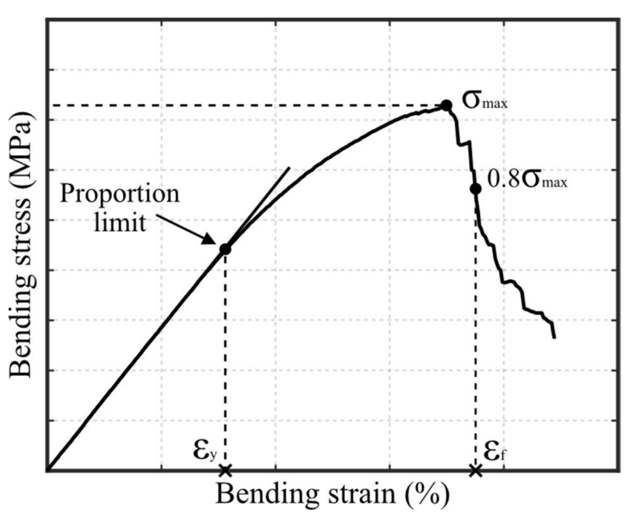

Fig. 5 Definition of the ductility factor based on the stress–strain curves in bending tests

The magnitude of this ductility factor is greater than one. The higher the ductility factor is, the more ductile the test material is considered to be. In this study, for a comparison with the energy-based brittleness index (BI), the ductility factor was converted into its reciprocal, which is hereafter referred to as the so-called brittleness factor (BF):

$$\text{BF} = \frac{1}{\text{Ductility factor}} = \frac{\varepsilon_y}{\varepsilon_f} \tag{8}$$

It is worth mentioning that both the energy-derived BI and the strain-derived BF are the measurements of the specimens' brittleness. That is to say, the higher the index/factor is, the material depicts more brittleness, thus, less ductility.

A comparison of the moisture effect on the bending strength, bending stiffness, BI, and BF, at different load-to-face grain angles was conducted later in the results and discussion section.

3 Results and discussion

3.1 Failure modes and load–deflection curves

All specimens were conditioned in climate rooms with the target RH levels for four weeks before the test. The typical failure modes of specimens at different load-face grain angles are presented in Figure 6c. The propagated crack paths are marked with red-colored solid lines.

After being conditioned under the atmosphere of 20°C and 95% RH for four weeks, mold started to grow at the end grain surface of unmodified specimens, as a result of visual inspection. No significant mold growth was observed for acetylated specimens.

The average density, moisture content, and the number of test replicates for ABP and UBP specimens conditioned under the three RH environments are summarized in Table 1. For each test series, 10 ABP and 12 UBP specimens were prepared. In total, 198 specimens were tested in this study.

As shown in Table 1, due to the acetylation process and the addition of non-polar acetyl groups onto the wood substance, the density of the ABP was 35-40 kg/m^3 higher than for the UBP. The increase in density can be more intuitively reflected in terms of the oven-dry density. Rowell and Banks (1987) reported that at a weight gain of approximately 20%, dry wood volume increased by about 10%. This ended up with an oven-dry density increase of around 10%. Dreher (1964) and Larsson and Tillmann (1989) also found values from 7 to 10% increase of oven-dried density.

Furthermore, since the acetylation process replaced some of the hydrophilic hydroxyl groups on the cell wall

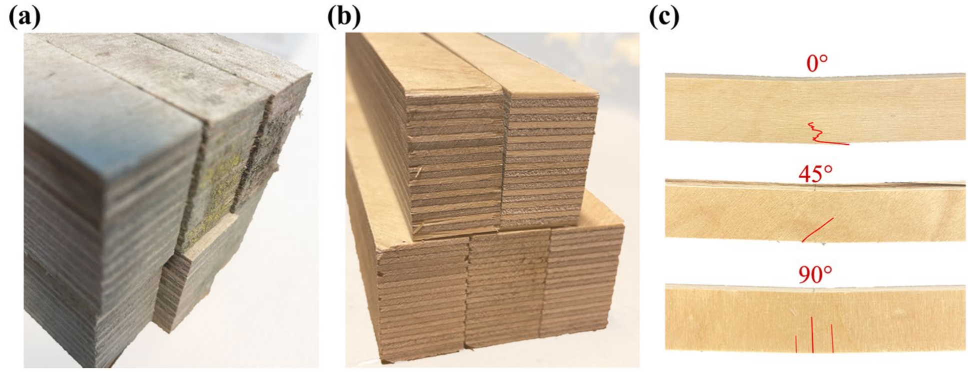

Fig. 6 **a** UBP and **b** ABP specimens conditioned under Env3 (T = 20 °C, RH = 95%) after four weeks; **c** typical failure modes for specimens at all three load-face grain angles (color figure online)

Table 1 Measured density, moisture content, and the replicates of specimens under various humidity environments

Relative humidity (T = 20 °C)	Specimen types	Density (kg/m^3)	Moisture content (%)	Number of replicates
35%	ABP	728.2	4.2	10 × 3
	UBP	691.8	8.4	12 × 3
65%	ABP	731.5	5.9	10 × 3
	UBP	696.5	10.8	12 × 3
95%	ABP	767.3	10.8	10 × 3
	UBP	733.0	21.6	12 × 3
				Total = 198

polymers with bonded hydrophobic acetyl groups, thereby reducing the hygroscopicity of the wood substance (Rowell and Dickerson 2014), the equilibrium moisture contents of the ABP were around half that of the UBP for all RH levels. Similar results have been reported in the literature, i.e., that the equilibrium moisture content of *Pinus sylvestris*, *Pinus elliotti* and *Populus tremula* was found to be reduced by around 50% due to the acetylation process (Hillis 1984; Minato et al. 2003; Hill et al. 2005; Rowell et al. 2009). The mechanism behind the reduced wood-moisture interaction is that the acetylation process replaces some hydroxyl groups on the cell wall polymers with bonded acetyl groups (Papadopoulos and Hill 2003; Hill 2007; Popescu et al. 2014). The presence of covalently bonded acetyl groups in the nanopores in the cell-wall matrix is consequently not available for sorbed water molecules. As a result, the hygroscopicity of wood is reduced (Rowell and Dickerson 2014).

The piston load-mid-span deflection curves of all six groups of tests series under all three condition environments are presented in Figure 7. Red and blue colored lines respectively represent acetylated and unmodified birch plywood specimens. The solid, dashed, and dotted line respectively presents the test results obtained under 35%, 65%, and 95% RH environments. For better visibility, only the typical curves (the ones with the least deviation from the mean curves) are presented.

As can be observed in Figure 7, at all three load-face grain angles, the acetylated specimens usually give stronger and stiffer responses than the unmodified specimens, except for 45° specimens under 35% and 65% RH, the strength of some acetylated specimens are slightly lower than that of unmodified specimens. With the increase of RH in the atmosphere from 35% to 65% to 95%, namely, with the line type transited from solid to dash to dotted lines in Fig. 7, the UBP specimens (blue lines) encounter a much more significant strength reduction than the ABP specimens. A similar but much less significant reduction was observed in stiffness.

3.2 Bending strength, stiffness, brittleness terms and correlation with moisture parameters

Adopting the terms definition given in Equations 2 and 3, the average bending strength and stiffness were calculated and are summarized in Table 2. The numbers within the parentheses indicate the standard deviations.

Besides, to derive an effort-saving and robust index to quantify and compare the brittleness of untreated and acetylated wood and their variation with moisture. The energy-derived BI and elastic strain-derived BF were calculated based on the test curves and summarized in Table 3.

Summarizing the test data in Table 2 and Table 3, the variation of the edgewise bending strength, stiffness, and brittleness index of both UBP and ABP specimens under

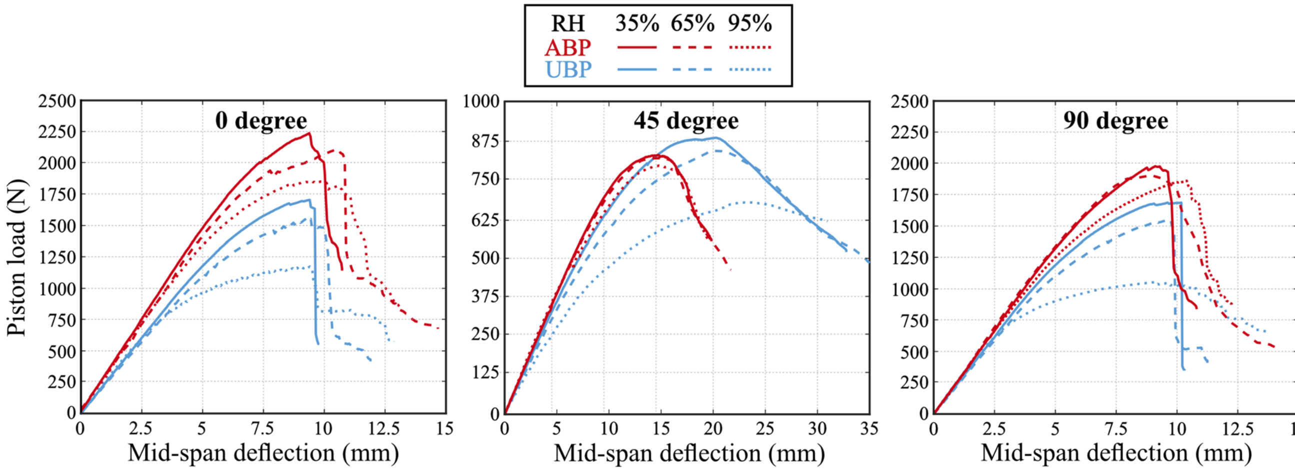

Fig. 7 Load–deflection curves of acetylated and unmodified birch plywood specimens conditioned under three humidity environments at different load-to-face grain angles (color figure online)

Table 2 Bending strength and modulus of elasticity of acetylated and unmodified specimens at three load-face grain angles, under three condition atmospheres. The numbers within the parentheses indicate the standard deviations

Specimens	RH %	Bending strength (MPa)			MOE_m (GPa)		
		0°	45°	90°	0°	45°	90°
ABP	35	93.3 (4.0)	34.9 (1.9)	86.3 (4.0)	11.9 (0.6)	2.7 (0.1)	10.5 (0.5)
	65	86.5 (2.7)	34.4 (1.7)	80.1 (2.0)	10.9 (0.7)	2.6 (0.1)	9.7 (0.3)
	95	77.1 (4.7)	32.8 (1.4)	72.2 (3.3)	10.4 (0.9)	2.4 (0.1)	9.0 (0.4)
UBP	35	74.5 (2.0)	35.4 (1.1)	73.3 (1.5)	9.8 (0.4)	2.2 (0.1)	9.4 (0.2)
	65	69.9 (2.0)	33.3 (1.5)	66.4 (2.6)	9.3 (0.4)	2.0 (0.1)	8.4 (0.2)
	95	42.9 (2.8)	24.8 (1.8)	40.3 (2.5)	8.4 (0.9)	1.5 (0.2)	7.7 (0.5)

Table 3 Brittleness index (BI) and brittleness factor (BF) of ABP and UBP specimens at three different load-face grain angles and RH levels

Specimens	RH %	Brittleness index (BI)			Brittleness factor (BF)		
		0°	45°	90°	0°	45°	90°
ABP	35	0.53 (0.07)	0.49 (0.06)	0.44 (0.05)	0.63 (0.03)	0.52 (0.03)	0.60 (0.03)
	65	0.42 (0.04)	0.45 (0.06)	0.41 (0.05)	0.55 (0.04)	0.51 (0.03)	0.57 (0.03)
	95	0.41 (0.02)	0.39 (0.05)	0.39 (0.04)	0.55 (0.05)	0.46 (0.03)	0.54 (0.02)
UBP	35	0.45 (0.06)	0.31 (0.04)	0.39 (0.03)	0.62 (0.04)	0.38 (0.03)	0.58 (0.03)
	65	0.39 (0.04)	0.30 (0.01)	0.36 (0.03)	0.56 (0.04)	0.36 (0.02)	0.54 (0.03)
	95	0.15 (0.04)	0.20 (0.03)	0.17 (0.04)	0.26 (0.06)	0.32 (0.02)	0.27 (0.04)

three RH environments and moisture contents, are presented in Figure 8. The solid, dashed, and dotted line types respectively stand for specimens with the load-to-face grain angle at 0, 45, and 90 degrees.

One observation in Figure 8a–d is that for a certain line type, the red curves are usually above the blue ones. This indicates that in all condition atmospheres with three RH levels, the acetylated specimens usually possess higher bending strength and stiffness. When increasing the RH from 65% to 95%, the strength of acetylated specimens encounters a reduction of around 10%, while the unmodified specimens are weakened by nearly 40% from 69.9 MPa to 42.9 MPa. No significant difference was observed in terms of bending stiffness reduction. On the other hand, the higher BI and BF indicate that the ABP specimens are usually more brittle under the same RH level. With the increase of RH, both BI and BF of UBP and ABP specimens decrease, which reflects a decreased brittleness, therefore, an increased ductility. This observation is more significant in unmodified specimens.

Besides, the variation of mechanical properties can also be plotted versus the measured moisture contents, as shown in Figure 8e–h. With the increase in moisture content, a linear trend in the reduction of bending strength and stiffness values was depicted for both acetylated and untreated

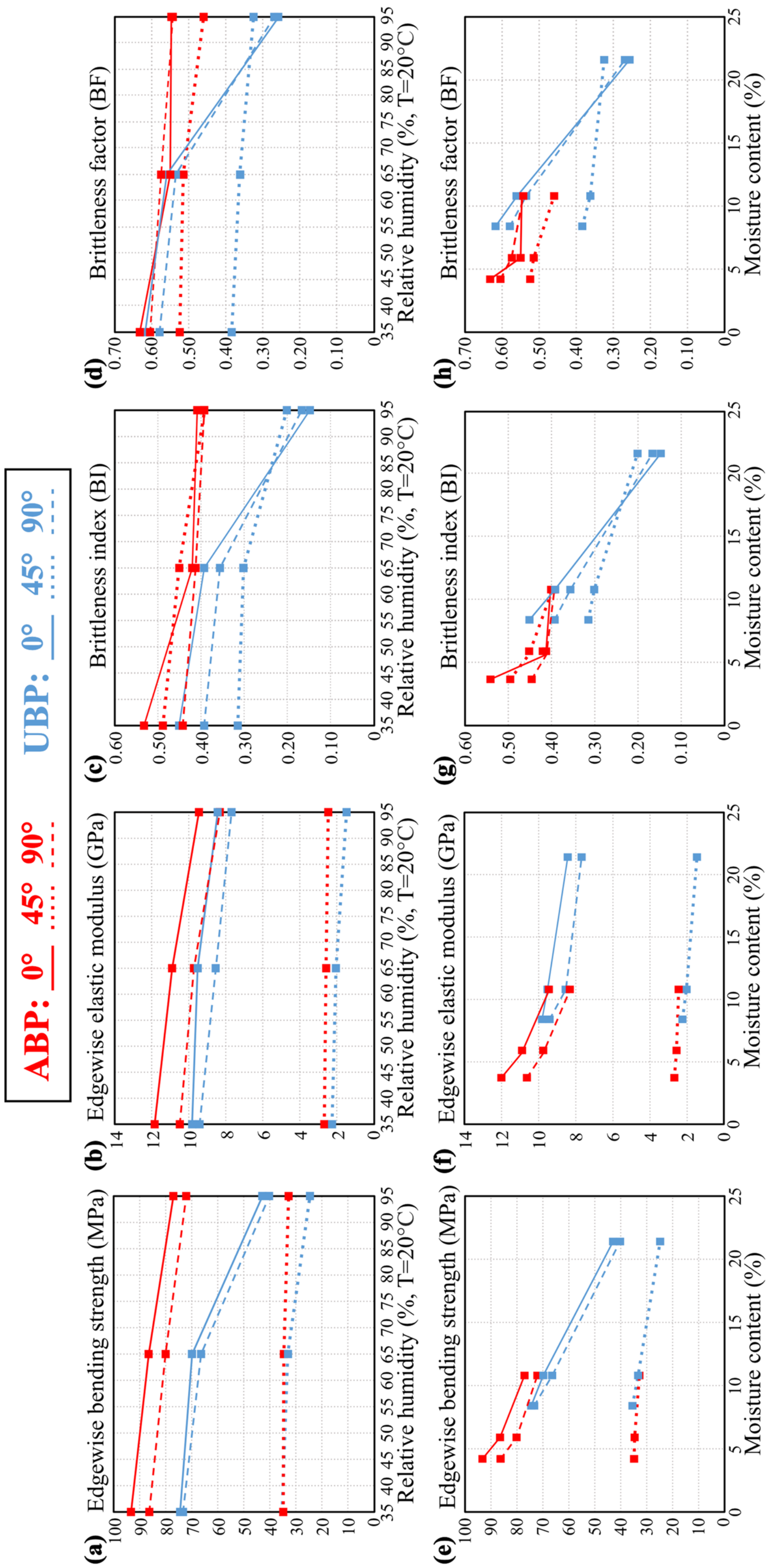

Fig. 8 Variation of edgewise bending strength, bending stiffness, BI, and BF of acetylated and unmodified birch plywood specimens conditioned under three humidity environments and moisture contents (color figure online)

specimens. It is also noticeable that the better moisture resistance of acetylated specimens is usually discussed in the context of under the same environment, namely, in the same atmosphere where the temperature and RH is the same. However, this disparity is less significant if one evaluates the properties of ABP and UBP specimens under the same moisture content. This phenomenon reflects the working principle of the acetylation process.

Compared to unmodified specimens, most of the mechanical properties enhancement for acetylated specimens is due to reduced moisture content levels when being conditioned in the same atmosphere. This is in line with the phenomena reported by Bongers et al. (2014), Kollmann and Cote Jr (1968), and Bongers and Beckers (2003). The slightly higher bending strength for ABP specimens under the same moisture content in some cases is explained by the increased density due to the acetylation process, and the positive correlation between specimen strength and density (Tsoumis 1991; Dinwoodie 2000; Bongers and Beckers 2003; Lechner et al. 2013).

It is worth mentioning that there are also decreasing factors for the mechanical properties of acetylated plywood. Acetylated wood is permanently swollen. Therefore, the amount of fibers and lignocellulose decreases per volume compared to untreated wood. Besides, the acetylation process includes heat treatment under acetic conditions (respectively caused by acetylation agent and by-product), which causes a certain amount of degradation of various chains of cellulose, hemicellulose, and lignin. This is attributed to a reduction of mechanical properties (Bongers and Beckers 2003).

The literature has reported that acetylated specimens possess better moisture resistance (Rowell et al. 1989; Ahmed et al. 2020). Combing all eight subfigures in Figure 8, this better moisture resistance of acetylated specimens can be interpreted from two perspectives. First, under the same temperature and RH levels, the bending stiffness and strength of acetylated specimens are usually higher in number than the untreated specimens. Second, with the increase of RH in the atmosphere, the decline of mechanical values, especially bending strength, is also less significant in acetylated specimens than in unmodified specimens.

Despite the influence on mechanical properties brought by acetylation on timber, the literature also addressed that acetylation would cause an increased brittleness in certain wood species (Reiterer and Sinn 2002; Forsman et al. 2020, 2021). This concern is illustrated by calculating the energy-derived BI and strain-based BF. As in Figure 8c, d, g, h, both indexes give similar trends on the influence of moisture contents on the brittleness of specimens. When the moisture increases, both the brittleness index and factor decrease, which indicates a reduced brittleness, i.e., an increased ductility. This increased ductility with moisture increase is favorable in terms of structural design, since a more ductile material will increase the structures' static ductility, allow force/stress redistribution, allow energy dissipation, and increase the structural robustness of the building (Blaß and Schädle 2011; Fragiacomo et al. 2011; Jorissen and Fragiacomo 2011). However, this beneficial increase in ductility brought by moisture increases is contradicted by the moisture resistance ability. As a result, the ductility increase is more noticeable for unmodified specimens compared with acetylated ones. It is worth mentioning that this ductility difference may be not only due to the acetylation process but also other disturbance factors, e.g., different adhesives (PF and PRF), veneer set-up, etc.

Moreover, to derive a generalized correlation between mechanical properties and moisture content values at different load-face grain angles, linear regressions were performed in Matlab R2019b (The MathWorks Inc. 2019) by inputting the moisture content as independent variables, and the mean test values of bending strength and stiffness as dependent variables. The corresponding fitted equations and R-square values are presented in Table 4.

The error bars of test values are plotted versus the fitted equations as a comparison in Fig. 9.

As presented in Figure 9, linear regressions give a satisfactory correlation between moisture content variation and mechanical properties within the studied hygroscopic range.

Table 4 The fitted equations of bending strength and stiffness with moisture content values and corresponding R-square values

Specimens	Angle	Bending strength (MPa)		Bending stiffness (GPa)	
		Fitted equation	R^2	Fitted equation	R^2
ABP	0°	− 2.19 × MC + 100.40	0.98	− 0.20 × MC + 12.49	0.79
	45°	− 0.30 × MC + 36.08	0.99	− 0.04 × MC + 2.83	0.98
	90°	− 2.02 × MC + 93.61	0.96	− 0.21 × MC + 11.20	0.92
UBP	0°	− 2.42 × MC + 95.32	0.99	− 0.09 × MC + 10.43	0.96
	45°	− 0.80 × MC + 42.00	0.99	− 0.05 × MC + 2.64	0.99
	90°	− 2.48 × MC + 93.66	0.99	− 0.11 × MC + 9.96	0.81

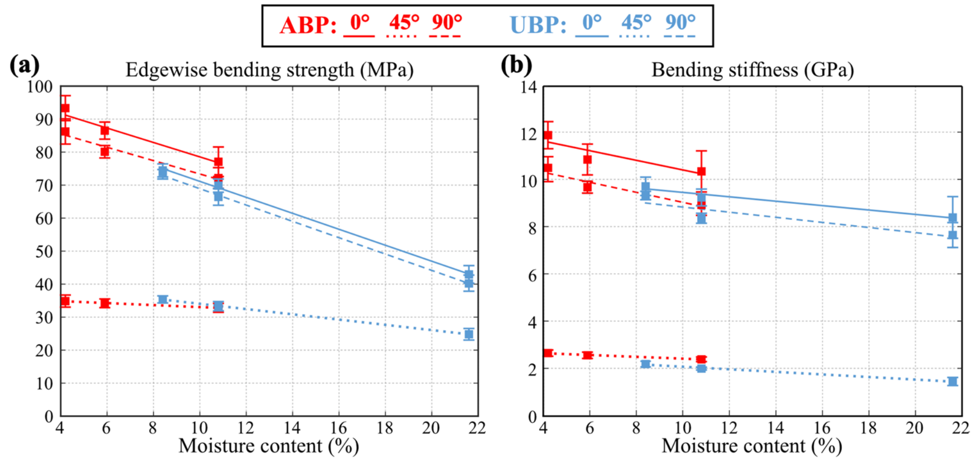

Fig. 9 Comparison between linear-fitted prediction equations and mean values of **a** edgewise bending strength, **b** edgewise elastic modulus, at different moisture contents. The error bars represent the standard deviation

3.3 Nominal comparison under different service classes

Moreover, for a comparison between properties with different magnitudes, the bending stiffness and strength values of acetylated and untreated birch plywood specimens were converted into nominal values. The mechanical properties measured for specimens conditioned under Env2 (20°C 65% RH) were taken as the reference. At a certain load-face grain angle, by dividing the test values at different RH environments by the test values under Env2 (20°C 65% RH), the nominal values are defined as:

$$k_{nominal} = \frac{MOE(f)_{m,\theta,RH}}{MOE(f)_{m,\theta,65\%}} \quad (5)$$

while $\theta = 0°, 45°, 90°$ and $RH = 35\%, 65\%, 95\%$.

The nominal values of bending stiffness and strength of acetylated and unmodified specimens at three different load-face grain angles under different RH levels are presented in Table 5.

An observation drawn from Table 5 is that, with RH increase, the mechanical property reduction was more significant in unmodified than in acetylated specimens, and more severe in strength than in stiffness. Under the same RH increment interval, the reduction was more significant at high RH levels.

Specifically, when increasing the RH from 35% to 65%, the bending strength and stiffness of both the ABP and UBP specimens showed a reduction of up to ca 10%. Increasing the RH further from 65% to 95%, the bending strength and stiffness of the ABP once again encountered a reduction by ca 10%. However, the mechanical weakening for unmodified specimens was much more significant at this RH interval. At both parallel and perpendicular to the face grain directions, the bending strength of UBP was reduced by over 40%. This strength reduction was less severe at 45° but still around 25%. The bending stiffness reduction of UBP specimens was around 10% at parallel and perpendicular to the grain direction and around 25% for the sample with 45° face grain orientation.

A similar observation was found by Rowell et al. (1989), who performed a study on the influence of moisture content increase on the mechanical properties of particleboards manufactured from acetylated wood and found that the reduction was more severe in bending strength than in elastic modulus, valid for both acetylated and control samples, although more pronounced for the latter samples.

Considering the angle-dependency, for both the UBP and ABP samples, the reduction in bending strength at higher RH levels was more significant for 0° and 90° than for 45°.

Table 5 Nominal values of bending strength and MOE of ABP and UBP specimens at three different load-face grain angles and RH levels

Specimens	RH %	Bending strength (MPa)			MOE_m(GPa)		
		0°	45°	90°	0°	45°	90°
ABP	35	1.08	1.01	1.08	1.09	1.04	1.08
	65	1.00	1.00	1.00	1.00	1.00	1.00
	95	***0.89***	***0.95***	***0.90***	***0.95***	***0.92***	***0.93***
UBP	35	1.07	1.06	1.10	1.05	1.10	1.12
	65	1.00	1.00	1.00	1.00	1.00	1.00
	95	***0.61***	***0.74***	***0.61***	***0.90***	***0.75***	***0.92***

*Bold and italic values are the nominal ratios of mechanical properties conditioned under 95% RH over that under 65% RH, namely, the SC3/SC1 values for bending properties of ABP and UBP specimens

However, the opposite trend was observed in the bending stiffness reduction. Namely, the stiffness reduction at higher RH levels was most pronounced for 45° specimens. Similar phenomena were reported in the literature on hoop pine plywood specimens at various moisture content levels (Sulzberger 1953). However, the proper explanation for this phenomenon is yet to be investigated.

Eurocode 5 considered different service classes for assigning timber strength values in different load situations and relevant environmental conditions (EN 1995-1-1, 2004b). The service class classifications are defined as follows:

- Service class 1 (SC1) is characterized by a moisture content in the materials corresponding to a temperature of 20 °C and the RH of the surrounding air only exceeding 65% for a few weeks per year (average moisture content in most softwoods will not exceed 12%).
- Service class 2 (SC2) is characterized by a moisture content in the materials corresponding to a temperature of 20 °C and the RH of the surrounding air only exceeding 85% for a few weeks per year (average moisture content in most softwoods will not exceed 20%).
- Service class 3 (SC3) is characterized by climatic conditions leading to higher moisture content than in service class 2.

In this study, the measured moisture contents for unmodified specimens under three conditioning environments are 8.4%, 10.8%, and 21.6%, respectively. Accordingly, the first (Env1: 20°C 35% RH) and second humidity environment (Env2: 20°C 65% RH) are classified as service class 1, and the third environment (Env3: 20°C 95% RH) is classified as service class 3. Therefore, the nominal ratio of mechanical properties conditioned under 95% RH over that under 65% RH, is classified as the SC3/SC1 values for the bending properties of ABP and UBP specimens, as indicated by the bold italic values in Table 5.

EN 1995-1-1 (2004b) considers the factor k_{mod} to modify strength values for various load-duration and service classes. For plywood, depending on different load-duration classes, the ratio of service class 3 k_{mod} value to service class 1 k_{mod} value ranges from 0.78 to 0.83. This is simply a consequence of rounding errors, with the intended SC3/SC1 ratio being 0.8, as reported by Bongers et al. (2014).

In Table 5, for acetylated specimens, the SC3/SC1 ratios for both the bending strength and stiffness are over 0.89 at all three angles. This reflects the conservatism of Eurocode 5. For unmodified specimens, on the other hand, the SC3/SC1 ratio for bending strength varied from 0.61 to 0.74, and that for bending stiffness varied from 0.75 to 0.92. This suggests that when accounting for the mechanical properties' reduction of unmodified birch plywood specimens due to moisture, lower SC3/SC1 bending strength factors than the recommended values (0.8) in the Eurocode 5 were observed at all three angles. As for the stiffness reduction of unmodified specimens, the recommended SC3/SC1 factor by Eurocode 5 is conservative on bending stiffness at 0° and 90° but non-conservative at 45°.

As summarized by Bongers et al. (2014), the above-mentioned disparity between the observed and the values recommended by EN 1995-1-1 is because the latter only gives a single set of k_{mod} values for all stress types. This may have been a pragmatic decision by the code writers, putting ease of use over accuracy for this design aspect, since most structural wood-based materials are mainly in function under service class 1 or 2. Such pragmatism might be sensible for solid timber. However, in the case of plywood, as presented in this study, a more accurate conversion from service class 1 values to service class 3 values is suggested for both unmodified and acetylated specimens, preferably also taking angle dependency into account.

4 Conclusion

This study reveals the moisture effect on the angle-dependent flexural properties of acetylated and unmodified birch plywood. Samples with three different load-face grain orientations were manufactured from unmodified and acetylated plywood panels, denoted UBP and ABP, respectively. The samples were conditioned in three different environments at 20 °C with increasing RH levels from 35% to 65% to 95% and subsequently tested under three-point bending. The experimental results were analyzed and discussed regarding bending strength, stiffness, and brittleness.

Under all three RH levels, the moisture content of the acetylated specimens was around half that of unmodified specimens. With increasing RH, the edgewise bending strength and stiffness decreased for both the ABP and the UBP. When conditioned in the same RH, the bending stiffness and strength of the ABP were higher than that of the UBP. In addition, with increasing RH, the decline of the mechanical properties, especially the bending strength, was also less significant for the ABP than for the UBP. This better moisture resistance of the ABP is particularly noticeable at high humidity levels.

Considering the angle-dependency, for both UBP and ABP, the reduction of bending strength with elevating moisture content is more significant at 0° and 90° than at 45°. Quite the opposite trend was observed in the bending stiffness reduction, i.e., the stiffness reduction when increasing the RH levels was most significant at 45°.

In terms of the brittleness-terms BI and BF, it was found that under the same RH level, the ABP was generally more brittle than the UBP, as indicated by the higher BI and BF.

With increasing RH, both BI and BF decreased, demonstrating a more ductile performance with higher RH. This is beneficial in terms of structural design. However, since the mechanical properties of acetylated specimens are less prone to moisture variation, the ductility benefits from moisture increase are less pronounced for ABP specimens.

The limitations of this study should also be mentioned. In this study, both the brittleness index (BI) and brittleness factor (BF) showed similar reduction trends when analyzing mechanical properties under elevating RH levels. Although other researchers have also utilized both factors in evaluating the brittleness of other wood or wood-based materials, both factors only served as ways to quantify the abstract term brittleness. More specialized test series within the context of fracture mechanics should be performed to derive externally valid terms. Quantities such as fracture energy, critical stress intensity factors, critical energy release rate, etc., should be measured to compare with other materials or serve as the input values for more detailed numerical models. In addition, the atmosphere with 95% RH is defined as the most humid environment in this study, which is more appropriately defined as a moist condition. Future test series with water-saturated specimens are also suggested to represent the wet condition.

5 Limitations of this study and further actions

Several limitations of this study need to be addressed. First, the difference in utilized adhesives, board thicknesses, and veneer setups between UBP and ABP boards is non-negligible in this study. The effect of acetylation can be better revealed if a similar test series can be performed on unmodified and acetylated birch veneer/lumber. Besides, systematic durability tests series and rot/fungi resistance tests should be planned in the future to better characterize the durability of both acetylated and unmodified birch plywood.

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Data availability The data used in this study is available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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