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Compressive strength of beech and birch at different moisture contents and temperatures

Hajir Al-musawi[1,*], Christian Huber[1], Maximilian Grabner[1], Bernhard Ungerer[1], Thomas Krenke[2], Philipp Matz[3], Alfred Teischinger[1], and Ulrich Müller[1]

[1] Department of Material Science and Process Engineering, Institute of Wood Technology and Renewable Materials, University of Natural Resources and Life Sciences, Konrad Lorenz-Strasse 24, 3430 Tulln an der Donau, Vienna, Austria
[2] Innovation Centre W.E.I.Z., W.E.I.Z. Forschungs & Entwicklungs gGmbH, Franz-Pichler-Strasse 30, 8160 Weiz, Austria
[3] Virtual Vehicle Research GmbH (ViF), Inffeldgasse 21/A, 8010 Graz, Austria

ABSTRACT

Owing to increased environmental demands to replace petroleum-derived materials with more environmentally friendly materials, research has been directed towards the potential of using wood in the automotive industry. This study extensively investigates the compressive strength (f_c) of two hardwood species (beech and birch) with different anatomical directions, at various moisture and temperature levels, in an attempt to understand the wood's behaviour during the forming process. The experimental tests were performed at 20, 100 and 140 °C on specimens with five moisture levels, ranging from completely dry to wet conditions. Overall, irrespective of the investigated direction, the measured compressive strength exhibited a clear exponential trend with increasing moisture content over the whole temperature range. This was capitalised on to present a simple predictive equation to roughly estimate the f_c of beech and birch in different moisture and temperature conditions by relating to their dry f_c at a reference temperature of 20 °C. The proposed approach was compared with other procedures and trends reported in the literature for the effect of moisture and temperature on the f_c of wood. Furthermore, the reduction factors for the effect of temperature on the f_c of softwoods, as set out in Eurocode 5 (EN 1995-1-2), were discussed in comparison with the present study findings. It was shown that, although the Eurocode approach is conservative, it may still be applicable for estimating the f_c of hardwood species.

Introduction

Reducing the greenhouse gas emissions of the mobility sector, which is the second largest emitter in the European Union [1], is an essential step towards achieving the climate targets of Paris 2050. This can be done by using more renewable resources in different applications and by a drastic reduction in energy consumption, e.g. by reducing the deadweight of vehicles [2]. Wood and wood-based hybrid materials are among the most promising approaches to achieve the required reductions in the weight of vehicles, and they have therefore, received increasing attention to be used in the automotive industry [3–16]. As demonstrated, 15–20% of the dead weight can be saved by using wood-based material, with comparable performance to conventional metal components [17].

In fact, using wood in vehicles and mechanical engineering is not a new concept. For instance, birch was extensively utilised as a lightweight construction material in historic aircraft. The legendary "Spruce Goose" (Hughes H-4 Hercules) was composed out of laminated birch plies [18], and the British de Havilland Mosquito has birch in the outer layers, with an inner balsa core [19], as diffusive hardwood species are deemed suitable for the production of rotatory cut veneers [20]. For those historical structures, the manufacturing was mainly based on the hands-on experiences of well-trained personnel, who carried out much of the work in a handcraft-like production process that resulted in high production costs. These high costs, combined with 3D-forming limitations of wooden components, compared to simple sheet metal forming, eventually led to a complete substitution of wood-based components in these industries. Likewise, in the field of rail and road vehicles, wooden components were also completely replaced by plastics and metals. Therefore, automated process control and, hence, industrialised production and the development of new approaches in the moulding and shaping of wood-based materials can be considered key parameters in improving the cost efficiency and for the reintroduction of such materials in the field of vehicle engineering.

Wood can be formed to only a limited extent in a cold and dry state. Higher plastic compressive deformation can be achieved by increasing the temperature and/or moisture content of the wood or by a chemical pre-treatment (e.g. ammonia [21]). In tension, however, whether longitudinal or transverse to the grain, structural destruction would still occur, even at very low strains, except in the case of compressing the wood in the axial direction before forming it, as in the "Patentbiegeholz" process [22]. Therefore, in bending formation, as in the well-known Thonet method [23], the convex side of the steamed wood is prevented from stretching beyond breaking limits by using a steel element, while allowing compression on the concave side of the workpiece. Similarly, in veneer formation, a reinforcement of the tensile zone can prevent tensile failure and force the material to undergo ductile compression deformation [24]. In the new moulding processes of wood-metal or wood-fibre composites, the deformation should also be primarily ductile compression. Therefore, fundamental understanding of the deforming behaviour of different wood species and modelling and predicting the deforming process are needed. Yet, the accuracy of FE simulations depends heavily on using accurate material parameters.

While different parameters can affect the compressive behaviour of wood during the forming process, the moisture content of the material and the forming temperature are crucial aspects. In this regard, Wilson [25] evaluated the influence of moisture content on the mechanical properties of many different wood species and suggested that the logarithm of mechanical properties of wood is linearly related to their moisture content. Regarding the compressive strength (f_c) in particular, it can be inferred from various investigations on different wood species [26–31] that the relationship between f_c and moisture content is exponential at the reference testing temperature (20 °C). Kollmann [32] studied the f_c parallel to the grain of oven-dry beech for temperatures between − 190 and + 160 °C. He concluded that the f_c of beech decreased in a linear manner with temperature. One of the best-known studies regarding the effect of moisture content and temperature on wood is that of Sulzberger [33] who investigated the effect of temperature in the range of − 20 to + 60 °C on the f_c of eight wood species with different moisture contents. According to the findings, the linearity of f_c with temperature was also confirmed for wood species with different moisture contents. Gerhards [34] presented an overview on the influence of moisture content and temperature on the mechanical properties of wood, including the compressive strength. He pointed out that the most of mechanical properties of wood appeared to increase as the moisture content decreased below fibre saturation point

(FSP) and as the temperature of testing decreased. The effect of temperature was even more pronounced at higher moisture content levels. While it was common in the literature to relate the mechanical properties linearly to temperature, he noticed that some trends might deviate from this linearity, thereby highlighting the need to perform more studies with different combinations of moisture content and temperature.

Nonetheless, studies on the effect of a combination of high moisture contents and temperatures on the f_c of wood, simulating the conditions of forming processes, have been scarce in the literature, and the available data are limited to temperatures of approximately 70 °C [33, 35, 36], which is more relevant to wood dying conditions. Although the Eurocode 5 (EN 1995-1-2) [37] has presented some reduction factors for the effect of temperature, in the range of 20–300 °C, on the f_c of softwoods, they may not be applicable to hardwood species, especially at high moisture levels.

Therefore, this study aims to provide extensive information on the effect of moisture and temperature on the f_c of two hardwood species: beech (*Fagus sylvatica*) and birch (*Betula pendula*), with different anatomical directions. Since testing thin veneers in compression is not possible owing to bending issues, solid wood was used instead. The experimental tests were performed at temperatures up to 140 °C on samples with different moisture levels, ranging from zero moisture content to totally wet conditions. Based on the results, regression curves were established, and general recommendations regarding estimating the f_c of beech and birch are discussed. The accuracy of the exponential function to represent the relationship of f_c with moisture content at high temperature levels is assessed and evaluated. Furthermore, the impact of temperature on the f_c of beech and birch in comparison with Eurocode 5 (EN 1995-1-2) recommendations is demonstrated and discussed. This study is expected to facilitate simulating forming processes of beech and birch, thus promoting more environmentally friendly solutions for the mobility sector.

Materials and methods

Air-dried European beech wood (*Fagus sylvatica*) and birch (*Betula pendula* Roth.) that almost fulfil clear wood standards were used in the experiments. Cubic specimens with an edge length of 20 mm were produced from the wooden boards and stored in an environmental chamber (20 ± 2 °C and a relative humidity of 65 ± 5%) according to ISO 554 [38] for six months before moisture and temperature conditioning.

The experiments investigated three temperature levels, 20, 100 and 140 °C, and different nominal moisture contents (MCs; oven dry to zero MC, 10 ± 2%, 13 ± 2%, 22 ± 2% and water saturated to above FSP) for beech and birch oriented in longitudinal, radial and tangential directions (except for 13 ± 2% and 22 ± 2%, which were not investigated for tangential samples). To obtain moisture-free samples, the wooden specimens were further climatised at 45 ± 5% relative humidity before drying in an oven at 103 °C until they reached a constant weight. The beech and birch specimens with 13 and 22% targeted MC were conditioned in containers with different saturated sodium chloride (NaCl) solutions [39], and their weight was regularly checked until equilibrium MC was reached. The above FSP conditions were achieved by water soaking. For wet samples, the longitudinal compressive behaviour was also examined at 60 °C.

Prior to testing, the samples were conditioned according to their individual temperature level (except testing sets of 20 °C) in a laboratory oven for 7–15 min. The time of preheating was determined from preliminary studies performed on equivalent samples to the testing series. The specimens were wrapped in aluminium foil to slow down water evaporation during thermal climatisation. Additionally, for specimens with a targeted moisture content of 13 and 22%, the top and bottom surfaces of the longitudinal samples were coated with Loctite 431 (Cyanoacrylate superglue, 1K universal), while all surfaces of the other samples were coated with silicone (OBI High Temperature Silicone Red, 310 ml) to further slowdown water evaporation during preheating.

After preheating, beech and birch specimens with different orientations were tested in compression using a universal testing machine (Zwick/Roell Z100, Ulm, Germany) equipped with a thermal chamber (Fig. 1). The force was recorded by the machine load cell with a capacity of 100 kN. The samples were loaded until reaching a displacement of 5 mm with a rate of loading of 10 mm/min. Five to ten replicates were used for each configuration. For the longitudinal compressive strength calculations, the maximum force was used to calculate strength when the specimens showed a softening strain; whereas, the maximum force within the first 1% strain was considered for
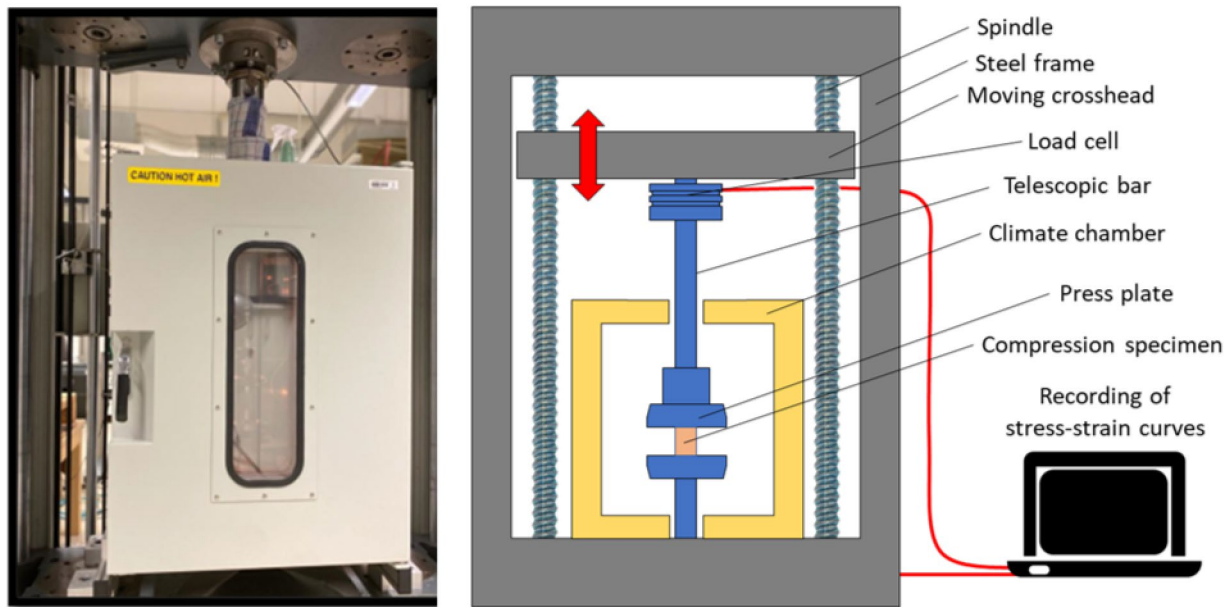
Figure 1 Thermal chamber attached to Zwick testing machine, allowing mechanical tests between -80 and $+300$ °C.

specimens showing a strain-hardening behaviour. In radial and tangential directions, the force corresponding to 1% permanent deformation was adopted for the determination of compressive strength [40].

The samples were weighed before and after preheating and after testing. This mass was considered for dry density calculations of dry samples, while, for the other samples, the dry density was obtained after drying the samples in the oven (according to ISO 13061-2 standard [41]). For this purpose, an analytical balance (± 0.001 g accuracy) and digital callipers (to measure the specimen dimensions with an accuracy of ± 0.02 mm) were used. The average dry density for beech and birch ranged from 0.594 to 0.757 and from 0.561 to 0.645 kg/m^3, respectively. The MC was calculated before and after preheating, as well as after testing, according to ISO 13061-1 standard [42]. The calculations presented in the following sections are based on an average MC for before and after testing.

Results

The compressive strength of beech and birch at different moisture contents and temperatures in longitudinal, radial, and tangential directions is listed in Table 1 and shown in Fig. 2, with the respective standard deviation. The wet samples remained well above FSP values after preheating and testing and

are referred to as > FSP in Table 1. Likewise, the dry samples had zero MC before preheating and after the testing; hence, the samples were weighed after the testing, and only a change in the third digit of the recorded weight (in grams) was noticed. Meanwhile, other samples continued to lose moisture during the preheating process and during testing. It should be noted that the MCs presented in Fig. 2 are based on the average MC for before and after testing. Regression curves for the effect of moisture content on the f_c of beech and birch at each tested temperature level are also presented in this figure.

Based on these results, a MC of zero was chosen as the reference condition, from which the relative changes in compressive strengths were calculated. It is worth mentioning that the end point of the curves at reference temperature (20 °C) was set at FSP (30% moisture content), as no strength reduction is expected higher than this moisture level [28] while, for curves at higher temperatures, the end point was established following the observation of Stamm [43], who reported that the FSP of wood would be expected to decrease linearly with temperature at the rate of approximately 0.1% point for each 1 °C increase in temperature above 25 °C.

As illustrated in Fig. 2, the f_c of both species decreased as the moisture and/or temperature increased, and beech specimens exhibited higher f_c

Table 1 Mean compressive strength (f_c) values (MPa) of beech and birch at different moisture contents (MCs%) tested at 20, 60, 100 and 140 °C

Orientation	°C	Beech			Birch		
		f_c	MC_{bp}[a]	MC_{avg}[b]	f_c	*MC_{bp}	**MC_{avg}
Longitudinal	20	116.92	0.00	0.00	99.15	0.00	0.00
		83.51	8.14	8.14	67.75	9.6	9.6
		63.85	11.43	11.43	52.25	12.28	12.28
		34.71	24.27	24.27	27.70	29.04	29.04
		27.02	>FSP	>FSP	19.79	>FSP	>FSP
	60	16.77	>FSP	>FSP	12.79	>FSP	>FSP
	100	82.14	0.00	0.00	77.49	0.00	0.00
		67.47	8.06	2.92	42.87	9.70	7.97
		29.28	12.75	11.17	24.94	12.48	10.56
		15.07	21.30	18.15	15.02	21.18	16.89
		13.01	>FSP	>FSP	9.03	>FSP	>FSP
	140	72.95	0.00	0.00	67.01	0.00	0.00
		65.22	8.26	1.44	49.26	9.64	3.94
		30.09	11.87	6.89	22.23	12.42	7.05
		17.18	20.26	11.40	15.18	20.54	11.27
		9.38	>FSP	>FSP	7.83	>FSP	>FSP
Radial	20	23.23	0.00	0.00	18.93	0.00	0.00
		18.54	8.27	8.27	13.22	9.69	9.69
		14.42	11.32	11.32	8.63	12.28	12.28
		7.28	25.47	25.47	4.14	28.98	28.98
		6.23	>FSP	>FSP	3.85	>FSP	>FSP
	100	14.87	0.00	0.00	15.21	0.00	0.00
		11.46	8.71	5.49	9.15	9.56	7.70
		5.95	12.87	12.03	3.36	14.69	13.36
		2.27	21.43	18.38	1.63	22.40	18.39
		2.52	>FSP	>FSP	1.31	>FSP	>FSP
	140	13.16	0.00	0.00	12.65	0.00	0.00
		11.78	9.44	1.83	10.68	9.59	3.84
		6.65	12.11	6.91	3.98	12.78	6.84
		4.30	20.52	9.46	2.26	21.45	10.29
		1.87	>FSP	>FSP	1.15	>FSP	>FSP
Tangential	20	13.63	0.00	0.00	11.51	0.00	0.00
		10.75	8.29	8.29	8.08	9.6	9.6
		3.60	>FSP	>FSP	2.59	>FSP	>FSP
	100	11.35	0.00	0.00	9.51	0.00	0.00
		8.45	7.65	4.49	5.24	9.71	7.83
		1.46	>FSP	>FSP	1.26	>FSP	>FSP
	140	9.49	0.00	0.00	7.91	0.00	0.00
		9.19	9.22	2.36	6.09	4.55	3.78
		1.25	>FSP	>FSP	1.06	>FSP	>FSP

[a]Moisture content before preheating (index bp)

[b]Mean moisture content (index avg) for after preheating (before test) and after testing

values than birch specimens throughout the moisture and temperature range. Interestingly, the qualitative trend of the strength-moisture relation was almost the same for both wood species (exponential trend). This exponential relationship between the f_c and MC was observed for all directions over the
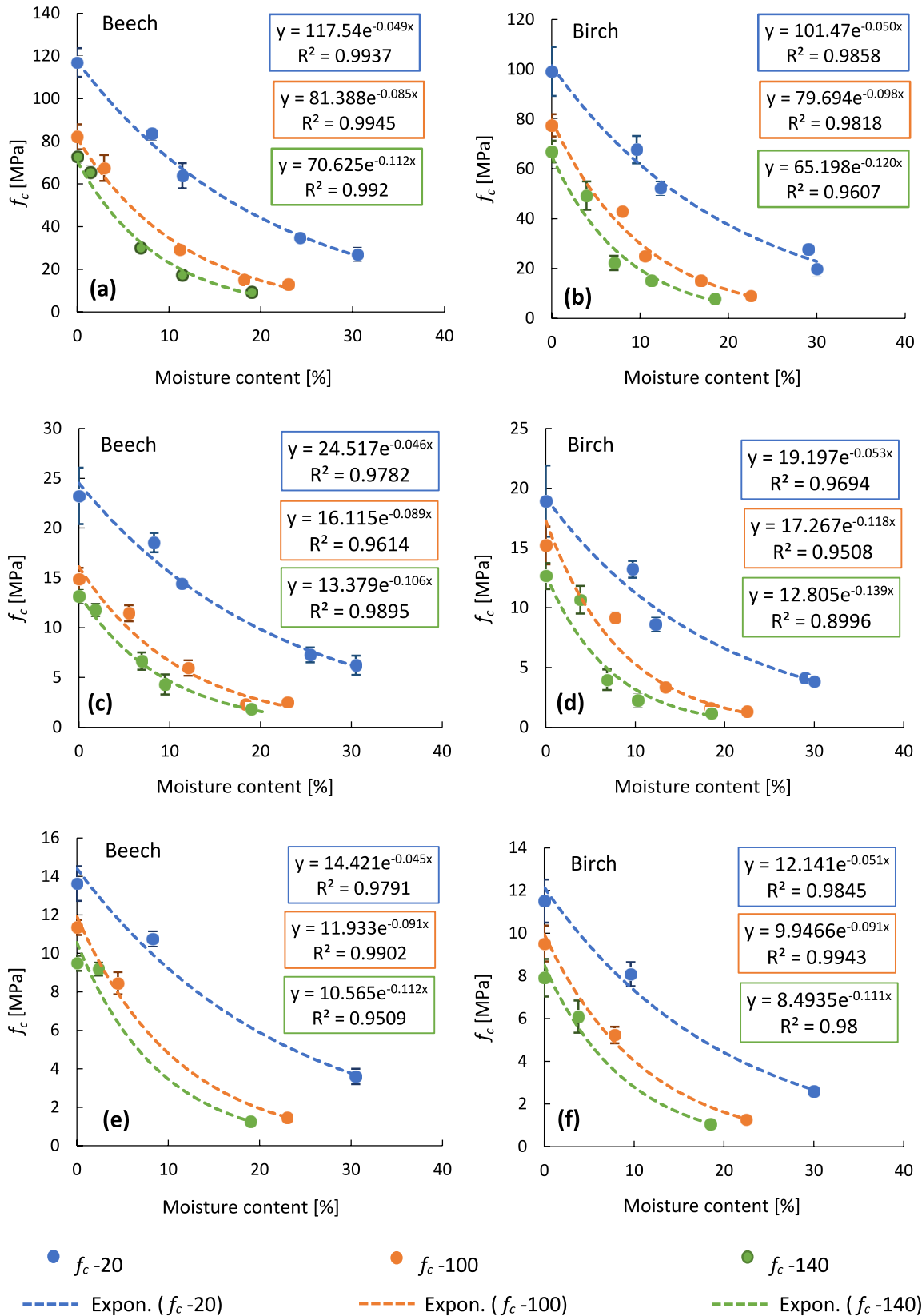
Figure 2 Compressive strength (f_c) of beech and birch with moisture content at different temperatures (20, 100 and 140 °C) in: **a**, **b** longitudinal; **c**, **d** radial and **e**, **f** tangential directions.

whole range of testing temperatures (see Fig. 2a–f), with very good correlation coefficients; R^2 ranged from 0.99 to 0.89.

To better understand the materials' behaviour with respect to temperature, the strength values at various temperatures were divided by the f_c at 20 °C ($f_{c\text{-ratio}}$), which was plotted against the testing temperature for different moisture conditions (Fig. 3).

The established regression functions are also presented in Fig. 4.

For both wood species, irrespective of the investigated direction, the $f_{c\text{-ratio}}$ decreased as the temperature increased. This reduction was more prominent when the MC increased, but with a lower rate for wet samples, and followed an exponential trend, while, for dry samples, the $f_{c\text{-ratio}}$ seemed to follow a linear trend with

Figure 3 Relationship of the ratio of f_c at various temperatures to f_c at 20 °C ($f_{c\text{-ratio}}$) with temperature for beech and birch in: **a** longitudinal; **b** radial; **c** tangential directions.
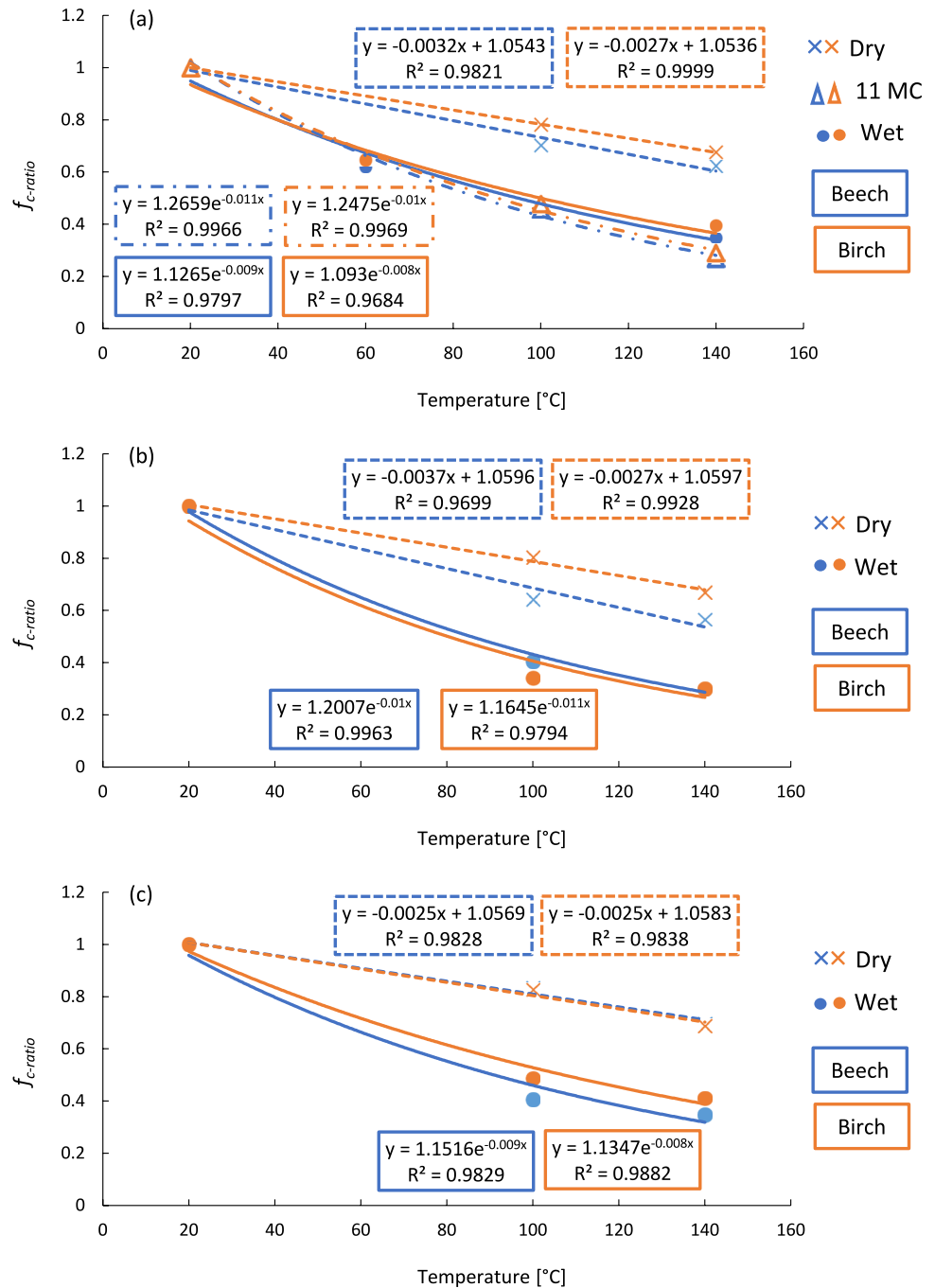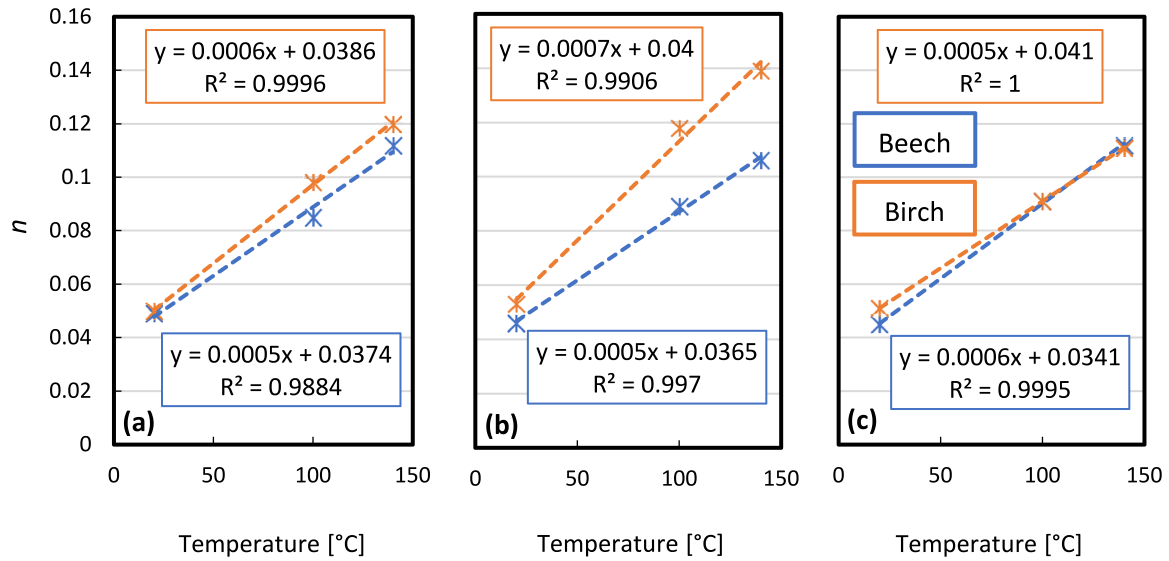
Figure 4 The relationship of *n* with temperature for beech and birch in: **a** longitudinal; **b** radial; and **c** tangential directions.

temperature, with a high coefficient of determination ($R^2 = 0.96$–0.99). On average, the $f_{c\text{-ratio}}$, for dry samples, ranged from 0.64 to 0.83 and from 0.57 to 0.7, whereas for wet samples, the $f_{c\text{-ratio}}$ ranged from 0.34 to 0.49 and from 0.3 to 0.41, for the different orientations, at 100 and 140 °C, respectively.

Discussion

Overall, the measured compressive strength demonstrated a clear exponential trend with MC over the whole tested temperature range, however, with different exponential parameters (*n*). These parameters ranged from 0.046 to 0.053 at the reference temperature of 20 °C and from 0.106 to 0.139 at 140 °C for the different anatomical directions. This general behaviour of the influence of the material MC on the f_c of beech and birch is consistent with observations in the literature at the reference temperature [25, 28, 31]. For instance, longitudinal f_c values in relation to the MC of different wood species reported in Kollmann [28] can be well represented in exponential curves, with *n* of 0.048 and 0.049 for beech and birch, respectively. When moisture enters the cell wall, it forms secondary bonds with the polar groups in the polymer molecules. This replacement of hydrogen bonds within the polymer network by bonds between water–hemicelluloses, water–lignin, and water–paracrystalline cellulose increases the

flexibility of the polymers [31], thereby softening the wood cell wall, which reduces the strength of wood as the MC increases.

In order to better demonstrate the influence of the temperatures on *n* parameters, their values, in relation to the testing temperature, for beech and birch are presented in Fig. 4. As shown, *n* increases in an almost linear manner with temperature up to 140 °C, with excellent coefficients of determination, R^2 ranging from 0.99 to 1. This can be utilised to estimate *n* values of other testing temperatures. Notably, *n* values of the longitudinal and tangential directions of beech and birch were almost identical, while in the radial direction, the values of *n* for birch were clearly higher than beech at all testing temperatures. This means that the decline rate of f_c of beech due to moisture with increasing temperature is slower for beech than for birch, a rather unexpected finding, since beech has a higher percentage of wood rays and thus might be expected to feature less thermal resistance along the radial direction compared to birch.

Corresponding to the effect of temperature on the compressive strength of wood, in general, the f_c of beech and birch, irrespective of the orientation, decreased as the temperature increased owing to the known softening effect of temperature on the mechanical properties of wood. Gerhards [34] has shown that moisture has a higher effect on f_c parallel to the grain compared with perpendicular to the

grain, while the latter is more sensitive to temperature changes. The data presented in Fig. 3 show that dry beech specimens and wet birch with radial orientations exhibited more reduction in their strength ratios compared to their longitudinal counterparts at the same temperature level; whereas, the tangential samples did not follow the same trend. Specifically, the dry material along tangential directions demonstrated smaller reduction rates in their $f_{c\text{-ratio}}$s compared to material analysed along the longitudinal direction; whereas, the behaviour of wet samples was comparable along the longitudinal and tangential directions.

Based on the above results and discussions above, the relationship between f_c at any moisture content and temperature range between 0 and 150 °C can be best approximated by an exponential function for all anatomical directions, as given in Eq. (1),

$$f_c(u, T) = f_c(0, T) \cdot e^{-n.u} \tag{1}$$

where, $f_c(u, T)$ is the mean compressive strength at any moisture content (u) and temperature (T) in the temperature range between 0 and 150 °C; $f_c(0, T)$ is the mean compressive strength at zero moisture content at that specified temperature T; n is a material parameter that determines the rate of strength decrease with moisture, which for beech and birch can be taken or approximately calculated from Fig. 4; u is the moisture content of wood in percent, and T is the testing temperature of wood in °C.

It is worth noting that the f_c of dry beech and birch wood at any temperature can be roughly approximated from their f_c at the reference temperature (20 °C) by using the linear expression presented in Eq. (2),

$$f_c(0, T) = f_c(0, 20) \cdot \left[1 - P(T - 20)\right] \tag{2}$$

where $f_c(0, 20)$ is the mean dry compressive strength at temperature of 20 °C; P is a material parameter that determines the rate of strength reduction as the temperature increases. For instance, by using the n values and $f_c(0, 20)$ shown in Figs. 2 and 3 with estimated P values, $f_c(30, 60)$, the wet compressive strength at a temperature of 60 °C of the material, can be roughly estimated as 16.19 and 12.8 MPa, which is in excellent correspondence with their experimental measured values shown in Table 1 (16. 77 and 12.79 MPa). Hence, it is possible approximately to calculate $f_c(u, T)$ of beech and birch when their $f_c(0, 20)$ is known, using the suggested procedure.

As an example, Eq. (2) was applied to data presented by Kollmann [28] for dry beech samples tested in compression at temperatures between zero and 160 °C, results of which are plotted in Fig. 5 against estimated values, using $P = 0.0032$ and $f_c(0, 20) = 96.6$ MPa (interpolated from the data presented in Kollmann). As shown, the linear function (Eq. 2) can represent the measured data with high accuracy.

Research regarding the influence of temperature on the axial f_c of beech and birch with high MC is scarce in the literature; hence, the data presented by Sulzberger [33] for the effect of temperature on the axial f_c of two hardwood species (silver quandong and coachwood) were reviewed (see Fig. 6). For this purpose, the f_c of the dry and wet materials at 40 °C was interpolated from the linear graphs shown in the latter
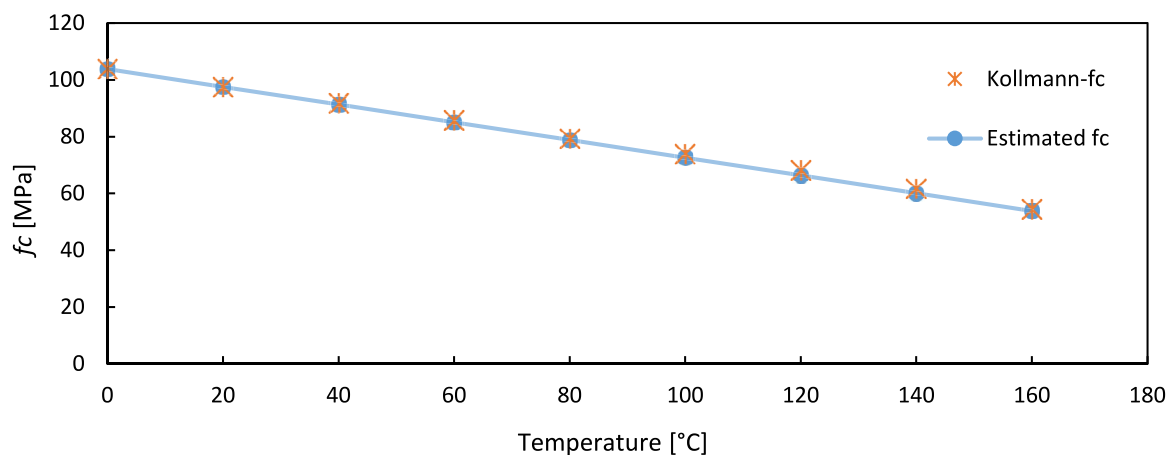
Figure 5 A comparison between measured f_c by Kollmann [28] and predicted f_c, using the proposed approach for dry beech samples.
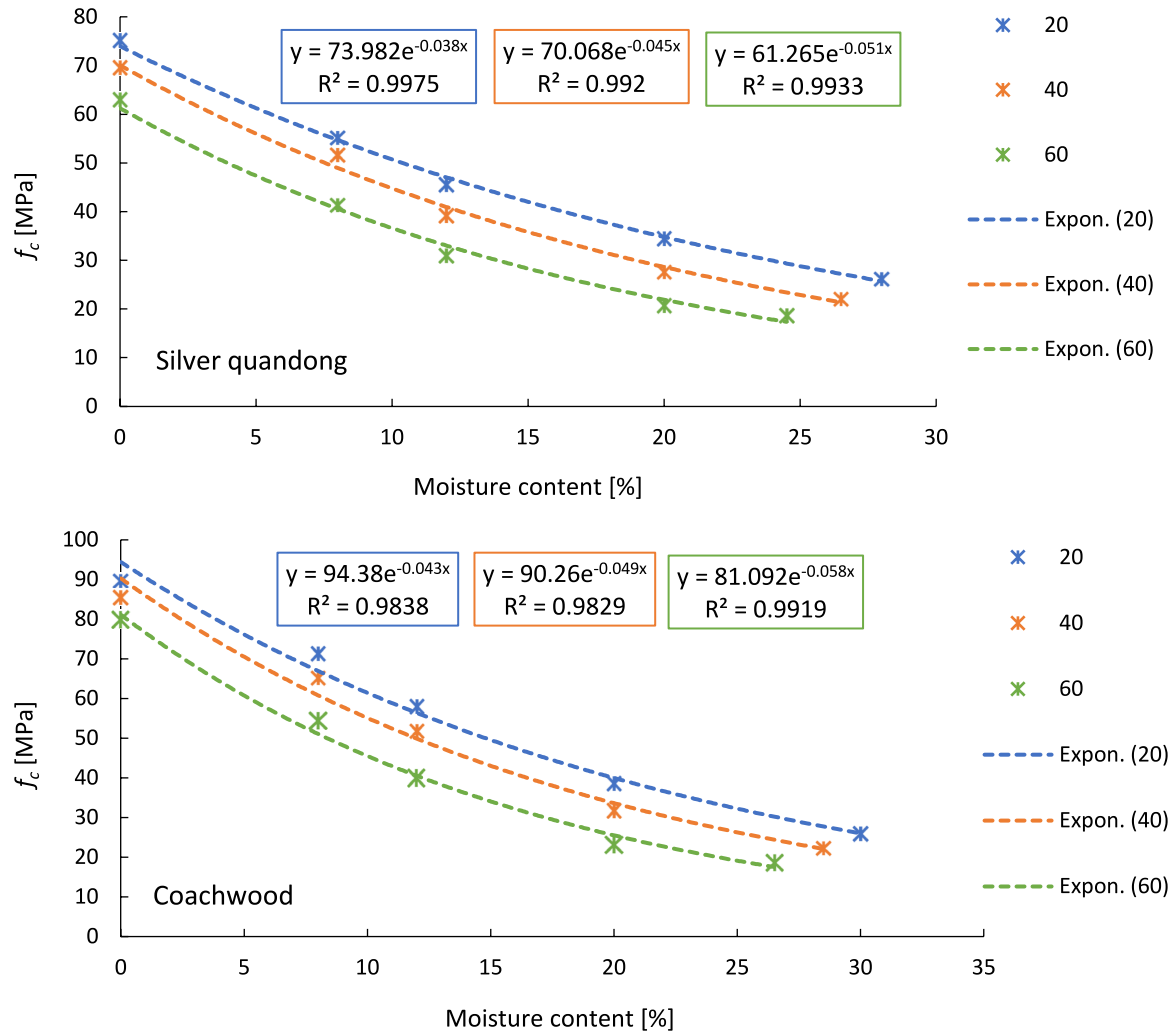
Figure 6 Axial f_c of two hard wood species with moisture content at three temperature levels, 20, 40 and 60 °C, represented by different colours in the diagrams (reported in Sulzberger [33]).

reference. As illustrated, the exponential function can well capture the influence of MC on the f_c of the analysed woods at all investigated temperatures. In this context, it is expected that material parameters, e.g. n, will be different for different wood species. Similar to the n relationship with temperature presented in this study for beech and birch, the n of silver quandong and coachwood appeared to follow a linear relationship with temperature, with excellent coefficient of determination, $R^2 = 0.98–0.99$.

Utilising the compressive strength data of eight hardwood and softwood species, Sulzberger [33] suggested a linear relationship, similar to Eq. (2), to estimate the f_c of wood at any given MC and temperature from the strength at any other temperature and the given moisture. It was stated that the relation

is valid for temperatures − 20 to 60 °C and for MCs up to 20% and up to 90 °C for dry wood. The relationships of the ratio of f_c at various temperatures to f_c at 20 °C ($f_{c\text{-ratio}}$) for the estimated f_c of beech, at various moisture conditions, with temperature are given in Fig. 7. Subsequently, the resulting P values were compared against suggested P values for the average eight wood species tested by Sulzberger, as well as values extrapolated for coachwood (Fig. 8). It can be observed from the figure that the estimated P values for beech agreed well with P values from Sulzberger's study. Notably, this parameter seemed to follow a linear trend with moisture conditions up to 25%. After that, it decreased in a curvilinear fashion as moisture increased to wet conditions. This means that the rate of strength reduction increased
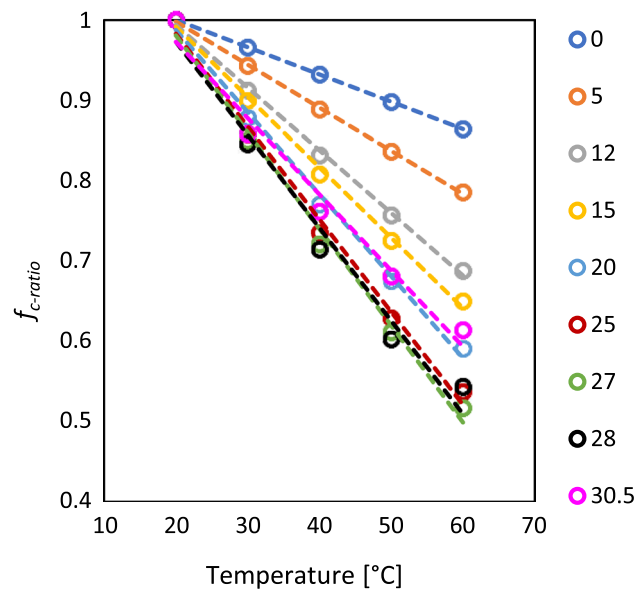
Figure 7 $f_{c\text{-ratio}}$ for estimated axial f_c of beech (different colours represent the various moisture contents in %).
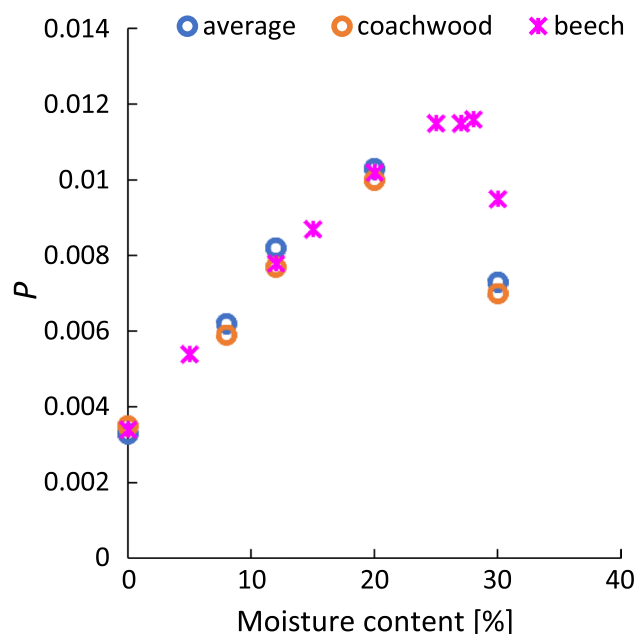
Figure 8 A comparison of P values of beech with P for coachwood and average wood species reported in Sulzberger.

with moisture, but then slowed down after reaching a moisture content of 25%.

To examine this behaviour closely, the experimental and estimated $f_{c\text{-ratio}}$ of beech parallel to the grain was plotted against temperature up to 140 °C (see Fig. 9). Evidently, the $f_{c\text{-ratio}}$ relationship with

temperatures was not linear for temperatures higher than 60 °C when the MC increased and became more curvilinear, and the curves themselves were shifted up as the temperature increased. For instance, the $f_{c\text{-ratio}}$ for wet material had similar values to beech with 10–12% MCs. This may be because FSP decreases when the temperature increases. In this regard, Wilson [25] suggested that heating the wood to temperatures close to 100 °C, as in a steam bending, may release some of the water that was imbibed or bound at lower temperatures, which would be added to the already existing free water within the cavities.

It is worth to mention that Sulzberger used a thermal chamber with air conditioning, in which humidity conditions were better controlled than in the present study. Based on the above discussions and the resemblance in behaviour of the analysed materials in this study with Sulzberger's tested woods, one can assume that there was no substantial moisture gradient within the samples tested in this study. This makes the usage of the average moisture content measured in experiments tenable for calculations and deriving relationships.

In a more recent study [44], the f_c of beech along the radial and tangential directions was measured at 90 and 110 °C. According to the results, the behaviour of beech at the two temperature levels was similar. Therefore, the six stress–strain curves of each direction were averaged and then the compressive strength was calculated and compared with estimated strength at 100 °C of this study. The estimated f_c values were approximately 7.6 and 5.2 MPa in the radial and tangential directions, respectively, which were in good agreement with the calculated f_c values of 8.5 and 5.5 MPa (in the radial and tangential orientations, respectively).

Gerhards [34] presented an overview on the influence of MC and temperature on the mechanical properties of wood, including the compressive strength. In his study, he described average effects and trends resulting from observations of various wood species. Table 2 features a comparison made between relative changes in estimated f_c (u, T) values of beech and birch obtained in this study and average relative changes in f_c pointed out by Gerhards [34] as a middle trend for the effect of moisture and temperature. Although it may not be possible to directly compare percentages for f_c perpendicular to the grain, as the strengths were calculated at different strain levels,
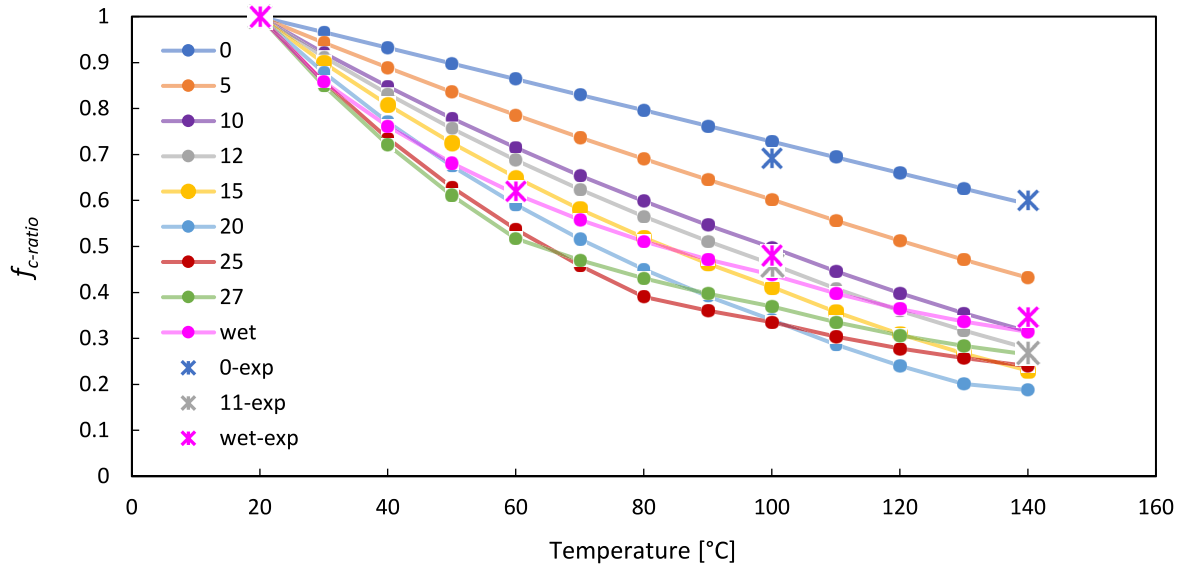
Figure 9 Relationship of experimental and estimated $f_{c\text{-ratio}}$ of beech with temperature in longitudinal direction (different colours represent the specified moisture contents in %).

Table 2 A comparison between relative changes in estimated f_c (u, T) values of beech and birch obtained in this study and average relative changes in f_c reported in Gerhards [34]

Property	Moisture content u (%)	Gerhards	This study Beech	This study Birch
Relative changes in f_c due to moisture content changes from 12% at reference temperature				
f_c parallel to the grain	6	+35	+34	+35
	20	−35	−32	−33
f_c perpendicular to the grain at the proportional limit	6	+30	+32	+37
			+31*	+36*
	20	−30	−31	−35
			−30*	+34*
Relative changes in f_c due to temperature effect at 50 °C from 20 °C at various moisture contents				
f_c parallel to the grain	0	−10	−10	−9
	12	−25	−24	−26
	>FSP	−25	−32	−36
f_c perpendicular to the grain at the proportional limit	0	−20	−12	−7
			−7*	−8*
	10	−35	−25	−27
			−21*	−20*
	>FSP	−35	−37	−46
			−36*	−30*

*Percentage in tangential direction

the percentages obtained in the present study demonstrated reasonable similarity to those compiled from the literature.

It should be emphasised here that the material parameters (i.e. n and P) suggested in this study represent the average behaviour of beech and birch. To obtain more accurate estimations for wood with different densities, namely for high density wood, more studies should be conducted to examine the effect of density on the material's performance. At any rate, the overall aim of this study was not to establish the fundamental relationships between moisture and temperature and the compressive strength of wood, but rather to offer an easy yet accurate approach to estimate the strength of beech and birch at different conditions of temperature and moisture contents.

Concerning the behaviour of wood at elevated temperatures, Eurocode 5 (EN 1995-1-2) [37] has defined temperature-dependent reduction factors for the compressive strength of softwoods when exposed to high temperatures. Now, if the normalised strength of the investigated materials at 12% moisture content is considered, it is possible to compare the reduction factors suggested by the Eurocode with the factors obtained in this study for beech and birch (see Fig. 10). The continuous lines represent the estimated data within the tested temperatures range in this study, while dashed lines represent data produced by extrapolating n values for
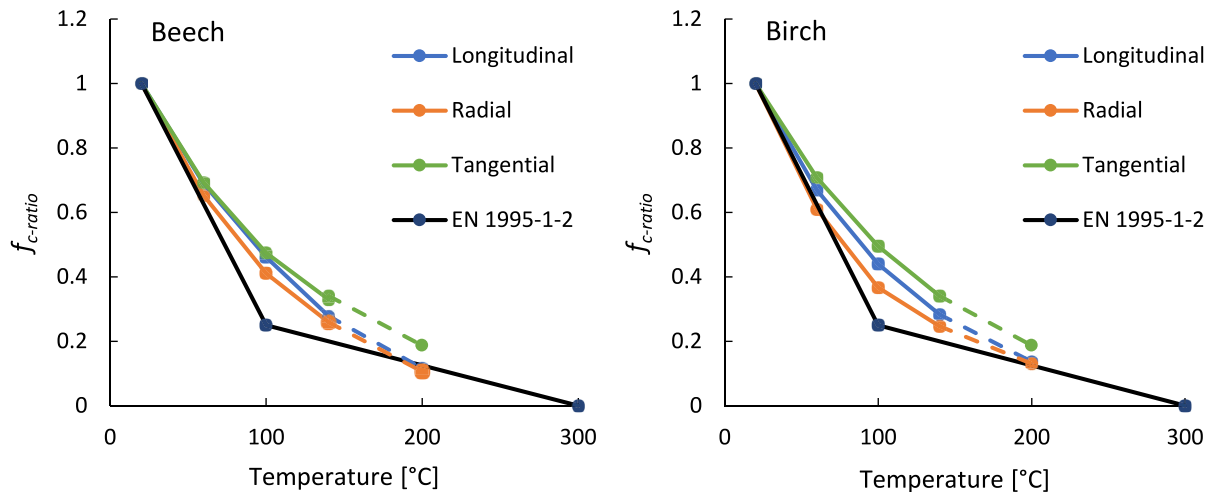
Figure 10 Comparison between $f_{c\text{-ratio}}$ presented in the Eurocode and estimated $f_{c\text{-ratio}}$ of beech and birch with temperature.

temperatures up to 200 °C on the assumption that n values would continue to increase in a linear manner with temperature.

Examination of the different curves in Fig. 10 reveals that, while the Eurocode seems to be conservative, it may still be applicable for hardwood species such as beech and birch. Nevertheless, further investigations are needed to understand how material parameters like n would react at temperatures in the range of 150–300 °C and the strength behaviour in this range before reaching definitive conclusions in this regard.

Conclusions

A combination of experimental and analytical investigations was performed to understand the effect of moisture and temperature on the compressive strength of beech and birch. It was found that, in general, irrespective of the investigated direction, the measured f_c showed a clear exponential trend with moisture content over the whole tested temperature range, but with different exponential parameters. These parameters ranged from 0.046 to 0.053 at a reference temperatures of 20 °C and from 0.106 to 0.139 at 140 °C for the different anatomical directions, which means that the effect of moisture on compressive strength is more prominent at higher temperature levels.

Based on the results, a simple predictive equation was introduced to roughly estimate the f_c of beech and birch at different moisture and temperature conditions by knowing their dry f_c at the reference

temperature of 20 °C. A major advantage of the proposed approach to estimate f_c in this study is its ability to cover wider ranges of MCs and temperatures.

The experimental and estimated f_c values were compared with other data reported in previous studies for the effect of moisture and temperature and shown to have the same order of magnitude to those compiled from the literature. It was also demonstrated that while Eurocode 5 (EN 1995-1-2) seems to be conservative, it may still be applicable for hardwood species such as beech and birch.

By providing extensive experimental data, it is hoped that this study will facilitate simulating the forming processes of beech and birch, thus contributing to the development of more environmentally friendly solutions in the automotive industry.

Acknowledgements

Data availability

The data used to support the findings of this study are not available for legal reasons.

Declarations

Conflict of interest   The authors declare that there are no potential conflicts of interest in this work.

Ethical approval   Not applicable.

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