



Analysis of shape changes during different stages of air drying at the hornbeam (*Carpinus Betulus* L.)

Hugo M. Uličný,
Peter Vilkovský, *ORCID: 0000-0002-2832-4619*
Ivan Klement, *ORCID: 0000-0003-3349-0125*

Faculty of Wood Sciences and Technology, Technical University in Zvolen, 960 01 Zvolen, Slovakia

*Corresponding author: xvilkovsky@tuzvo.sk

Abstract

This study focuses on the analysis of shape changes at the hornbeam timber (*Carpinus betulus* L.) during different phases of air drying. The main objective was to identify and quantify warp bow, warp crook, warp cup, and warp twist at various drying stages. The research was conducted on hornbeam timber samples that were subjected to air drying. Measurements were carried out at regular intervals throughout the drying process, with the influence of moisture on the development of different types of warp being observed. The results showed that warps increased exponentially at the beginning of air drying, with twist-warp being most pronounced in radial-type timber. Significant changes were observed when the relative humidity of the air was reduced from 80.2% to 40.3%, and the temperature was lowered from 11.1°C to 3.3°C. The greatest shape change increase was recorded in November. The warp of some samples was found to have increased up to 25 mm. The observed variability in warp was closely linked to the original position of the samples within the log and the spiral grain structure. This study provides essential insights for optimizing the drying process of hornbeam timber to minimize shape changes.

Keywords: hornbeam, warps, air drying, timber, twist

Introduction

European Hornbeam (*Carpinus betulus* L.) is a medium-sized deciduous tree species typically reaching heights of 20-25 m. The average wood density of European Hornbeam is approximately 790 kg/m³, though its utilization in the wood industry is limited by significant shape instability, which negatively affects its application e.g. in wood constructions. Furthermore, due to its limited durability, hornbeam wood is not suitable for exterior applications (Sikkema, Caudullo & Rigo 2016; Fodor, Lankveld, Németh & 2017). According

to recent data from the Green Report 2023 (Zelena sprava 2023), the proportion of European Hornbeam in Slovak forests has been steadily increasing and currently represents 6.0% of the total tree species composition. This trend indicates its gradual expansion in Central European forest ecosystems. The challenges associated with air drying are generally related to uncontrolled timber drying processes (Bergman 2021). During air drying, moisture reduction in wood leads to warps (Vilkovský, Uličný, Klement, & Vilkovská, 2024). These changes are asymmetric and result in various types of warps. According to Ormarsson, Dahlblom, & Petersson (2000) and Northway (2002), these deformations are influenced by annual ring orientation, moisture content, and drying methods. When moisture content falls below the fiber saturation point (FSP), significant shrinkage occurs, increasing susceptibility to warps. (Dinwoodie 2000; Siau 1984). The drying rate plays a crucial role in the development of drying stresses. If the outer layers of timber experience rapid moisture evaporation, surface checking may occur while the inner layers retain higher moisture content (Kollmann & Côté, 1968; Stamm 1964). This phenomenon creates internal stresses that can lead to warps and timber degradation (Harris 1989). Drying behavior varies significantly among wood species. European Hornbeam is classified as a high-density hardwood, making its drying process more challenging compared to softwoods (Welling et al. 2018; Panshin & de Zeeuw 1980). Dense hardwoods exhibit lower permeability, resulting in higher drying stresses (Espinoza & Bond 2016; Tsoumis 1991). This often leads to increased susceptibility to Warp Twist, particularly in quarter-sawn timber (Kollmann 1951). Drying methods significantly influence the final dimensional stability of timber. Air drying occurs at lower temperatures over extended periods, reducing cracking risk but potentially causing non-uniform warps due to differential exposure to weather conditions (Simpson 1991; Rietz 1999). The development of warps in air dried timber is also affected by the original position of timber in the log (Ormarsson et al. 1999; Ormarsson et al. 2000; Ormarsson & Johansson 2006).

Aim and scope of work

The main aim and scope of work was to analyze and quantify shape changes in European hornbeam (*Carpinus betulus* L.) timber during different stages of air drying. First, the individual types of warps occurring during air drying, namely: Warp Bow, Warp Crook, Warp Cup, and Warp Twist, were identified and evaluated. Second, the development of these warps was monitored in relation to changes in wood moisture content at different stages of the air drying process. Next, the air drying behavior of timber with spiral grain was compared with that of timber with no spiral grain. Furthermore, the influence of air drying climatic conditions, particularly temperature and relative humidity, on the intensity and character of warps was evaluated.

Materials and Methods

Both sampling for the research was mining in the Žiar nad Hronom district, within the cadastral area of the village of Hronská Dúbrava, at an altitude of 457 m a.s.l. The study was conducted on two logs, one with spiral grain and one with no spiral grain. Finding a hornbeam tree with spiral grain and with no spiral grain at this site was difficult due to its low occurrence in the local stand. The two logs, therefore, differed only in internal wood structure (presence or absence of spiral grain), not in site conditions. The ages of the logs ranged from approximately 52 to 60 years. In the mentioned locality, deciduous tree species are predominant, specifically European beech (*Fagus sylvatica* L.) and Hornbeam (*Carpinus betulus* L.). The dimensional characteristics of the logs are detailed in (Table 1.) and in the (Fig. 1) are samples before mining.

Table 1. Dimensional characteristics of selected logs

	Log with no spiral grain	Log in with the spiral grain
Small end diameter	0.380 m	0.350 m
Center diameter	0.410 m	0.370 m
Large end diameter	0.490 m	0.430 m
Log length	2.965 m	3.040 m
Deviation per 1 m of length before air drying \bar{x}	0°	5.8°
Deviation per 1 m of length after air drying \bar{x}	3°	10.6°
Sample density ρ_0	1158.14 kg/m ³	1151.56 kg/m ³



Fig 1. Selected samples in the forest a) with no spiral grain, b) with spiral grain

The log was processed using a live sawing pattern (Fig. 2), which is the most commonly employed method for hardwoods. Sawing was carried out on a Mebor 1200 horizontal band saw. Unedged boards were produced and later edged into samples with the following dimensions: thickness $t = 0.025$ m, width $w = 0.095$ m, and length $l = 2$ m. The 2 m length was selected in accordance with the standard STN EN 1309-3 (49 1013). Finally, the research specimens were prepared from the sawn timber.

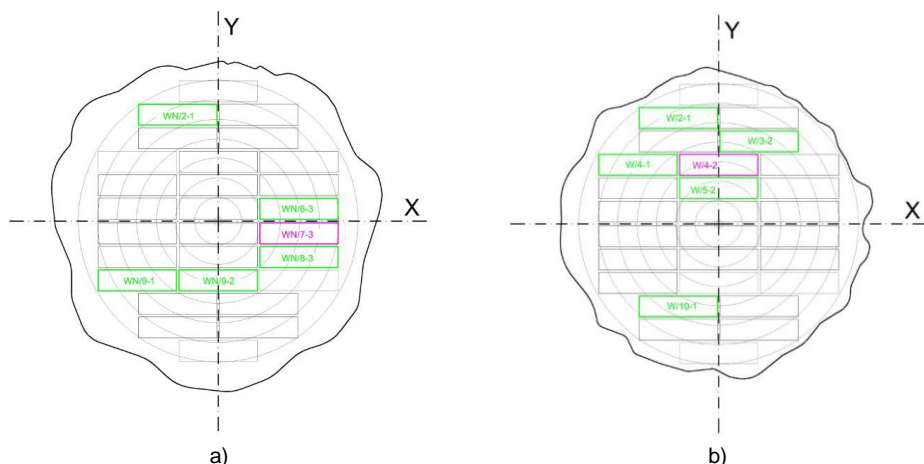


Fig. 2. Position the samples in the log with a) with no spiral grain and b) with spiral grain

Measurement of warps

The measurements were carried out one per week, every Wednesday, throughout the three month research period, using a digital caliper. The measurements were measured on 10 samples (boards; five with spiral grain, five with no spiral grain), taken from the top layer of the air drying cages. All measurements were performed on a flat reference surface of a new panel saw located in the Technical University in Zvolen.

Air drying conditions

The samples were stored in cages during air drying, which took place from November 10, 2022, to February 14, 2023. The drying conditions (temperature in °C and relative humidity in %) were recorded hourly using a Data Logger Device Comet S3631.

From the remaining ten pieces of timber, one piece was selected, and drying samples were sawn from it to monitor and calculate moisture content during the process. To prevent rapid moisture loss, the fronts of the moisture samples (both with and without spiral grain) were coated with a silicone layer (Fig. 3). The samples were weighed weekly at a temperature of $103 \pm 2^\circ$.



Fig. 3. Drying sample with silicone layer

Moisture gradient

The drying of samples to determine both the moisture gradient and the initial moisture content of the timber before drying was carried out in a Memmert UFE 500 drying chamber. The heating temperature of the samples was set to $103\pm 2^{\circ}\text{C}$.

The first set of samples, which were immediately taken from the processed logs (Fig. 4.), was dried until a constant weight was achieved. The weight of the samples was measured gravimetrically three times a day at four-hour intervals (8:00, 12:00, and 16:00). The moisture gradient and moisture content samples were taken from a distance of 500 mm from the end of the timber.

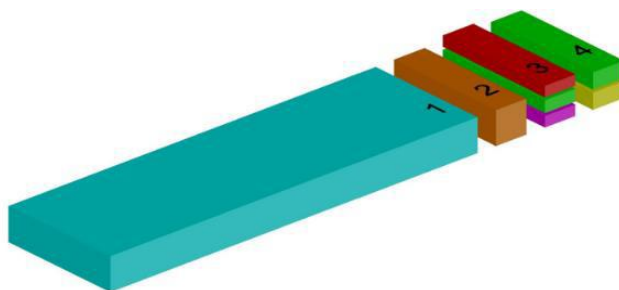


Fig. 4. 3D model, how were the samples for drying selected for research from the timber. 1. drying sample, 2. moisture sample, 3. moisture gradient, 4. covering

Air drying cages

After processing the cuts, the sawn timber was transferred to the drying cages (Fig. 5), where two drying cages were prepared - one for timber with spiral grain and another for timber with no spiral grain. The cages were placed on four concrete pedestals on an asphalt base. The boards were stacked in three layers, with five samples per layer, arranged in the following sequence: tangential - radial - tangential - radial - tangential.



Figure 5. Two drying cages (green with no spiral grain), (blue with spiral grain)

Statistical analyses

The data obtained from measurements were subjected to statistical processing to evaluate the impact of spiral grain factors on warps. Linear regression analysis ($N = 10$) was employed to analyze the simultaneous influence of temperature and relative humidity on the development, specifically - Warp Bow. The statistical significance of the model was assessed using the F-test, while the contribution of individual independent variables was determined through p-values at a significance level of $\alpha = 0.05$.

Furthermore, linear regression was used to quantify the mathematical relationship between temperature and the value of warp. The strength of these relationships was expressed by the correlation coefficient (R) and the coefficient of determination (R^2).

Results and Discussion

From the data of the Comet S3631 Data Logger Device (Fig. 6), it was observed that the ambient temperature fluctuated within a range of -14.3°C to 9.2°C , indicating a wide temperature range and the associated shape changes in the dried samples. The relative humidity was recorded between 23.1% and 93.1%, with higher values occurring during the night, which is consistent with the typical daily cycle of moisture.

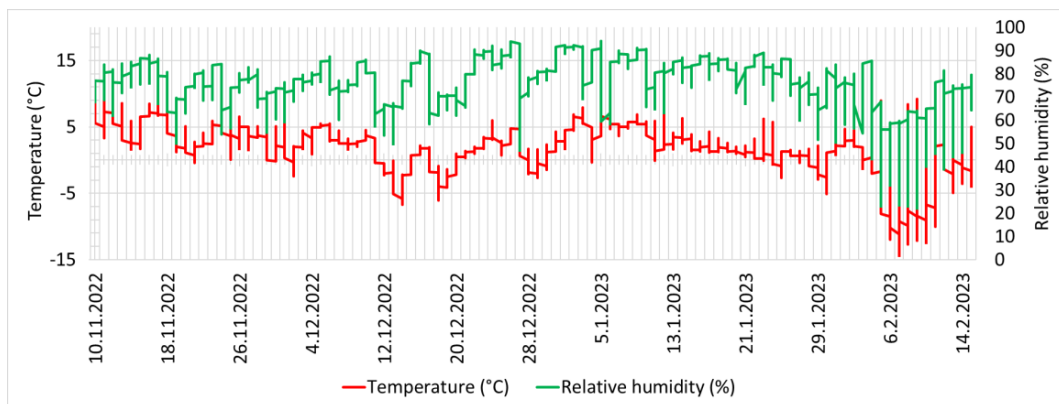


Fig. 6. Air-drying conditions were monitored over the three-month research period

Moisture gradient

High initial moisture levels ranging from 64.07% to 66.30% were observed in the W-series samples, which were significantly reduced to 19.49-27.43% after air-drying, demonstrating a substantial moisture reduction of approximately 40-45 percentage points. The most effective drying was achieved by sample W/10-1, where residual moisture was lowered to only 19.49%.

In the WN-series samples, lower initial moisture content (51.74-55.61%) was recorded, and levels of 20.79-23.49% were reached after drying, showing a slightly less pronounced but still considerable reduction of 30-33 percentage points. More consistent post-drying results were displayed by the WN-series, with all samples being clustered within a narrower 2.7% range compared to the 7.9% range of the W-series, suggesting potentially more uniform material properties or drying behavior in these samples.

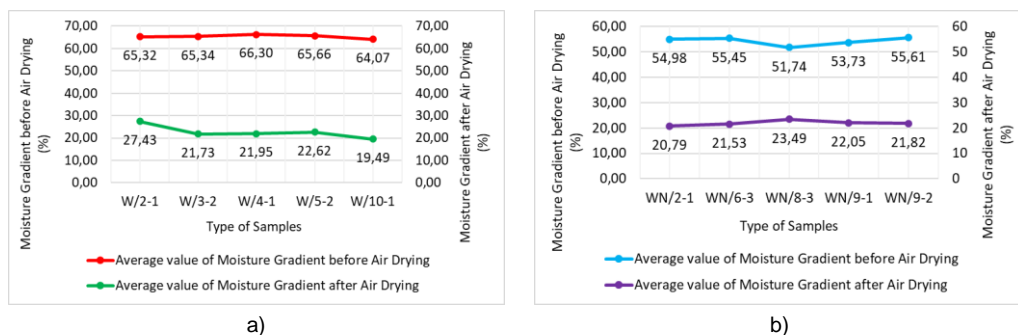


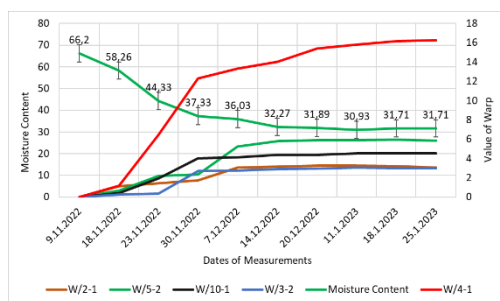
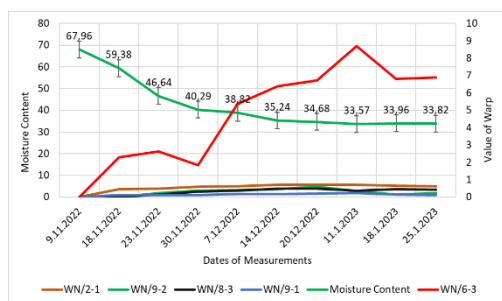
Fig. 7. a) Moisture of samples at the samples with spiral grain b) Moisture of samples at the samples with no spiral grain (W - mean, sample with spiral grain, 2 - mean second row and 1 mean first sample from the row. The same applies to the second sample, but WN means samples with no spiral grain)

Shape changes during different stages of air drying

(Comment - WN: log with no spiral grain; W log with spiral grain; First number is the rank in y-axis; Second number is the rank in x-axis. Example: WN/2-1 - log with no spiral grain / second rank in the y-axis and first rank in the x-axis).

Warp Bow

The initial moisture content is observed to decrease sharply from 67,96 % to 33,82% in the samples with no spiral grain (Fig. 8a), indicating the early stages of drying, where uneven stress or warping is suggested by dimensional measurements. In the (Fig. 8b), a more gradual decline in moisture from 66,2% to 31,71 % is recorded, and the sample labels (e.g., “W/3-2”) imply that shape changes have been stabilized but not fully eliminated. The deformation of bow warps during drying is highlighted in both images, with rapid warping risks identified in the early phase and equilibrium-focused adjustments noted later. Controlled air drying is emphasized as necessary to minimize defects.

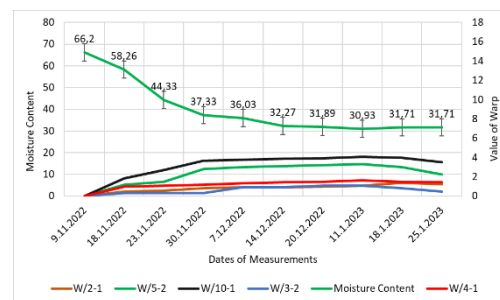
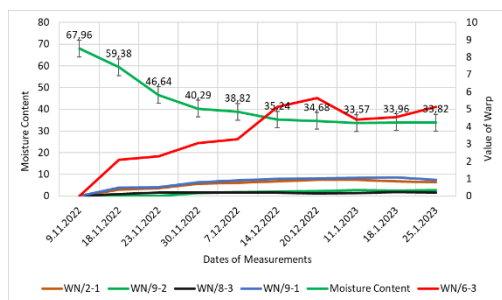


a) b)
Fig. 8 Impact of sample moisture content on the size of warp bow

Warp crook

A sharp reduction in moisture content from 67.96% to 33.82% is observed in the (Fig.9a), with the values being recorded at different stages of drying. The samples, labeled as WN/2-1, WN/9-2, and others, are monitored to track deformation, where uneven drying stresses are indicated by the numerical progression.

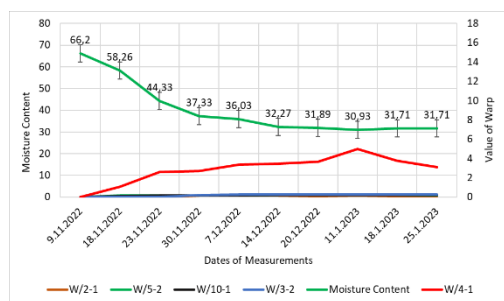
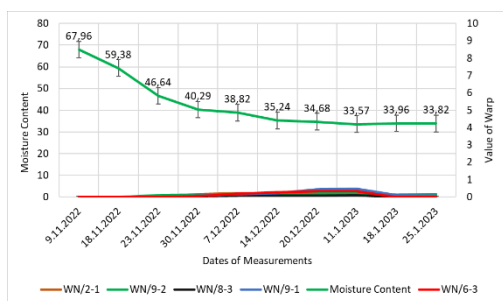
In the (Fig. 9b), a similar trend is displayed, with moisture levels being reduced from 66.2% to 31.71%, followed by an anomalous 18.18% reading that suggests localized drying variations. The samples, designated as W/3-2, W/2-1, and similar, are analysed to assess warp crook development as equilibrium is gradually approached.



a) b)
Fig. 9. Quantifying the impact of moisture content on warp crook in air dried samples

Warp cup

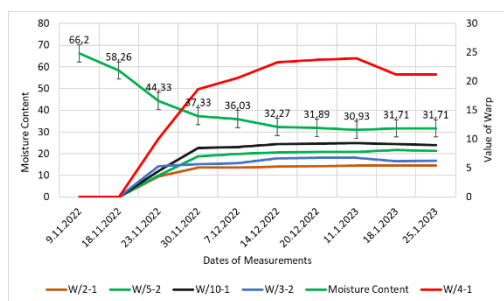
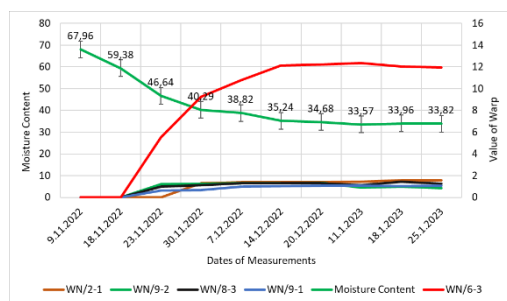
The drying characteristics of the wooden specimen are systematically documented through progressive moisture content measurements (Fig. 10a / Fig. 10b). A consistent reduction from 67.96% to 33.82% is observed, with the most substantial decrease occurring in the initial phase (67.96% to 46.64%). The subsequent gradual decline to approximately 33% indicates the approach toward equilibrium moisture conditions. Minor fluctuations between 34.68% and 33.96% are noted in the final stages, suggesting the presence of residual stresses within the material's cellular structure.



a) b)
Fig. 10. Moisture content of samples at warp cup for air-dried hornbeam

Warp twist

A progressive moisture reduction from 67.96% to 33.82% (Fig. 11a). Fluctuations between 33.57% and 33.96% are noted, indicating residual stresses that may contribute to warp-twist deformation. The secondary data suggests a warp twist development accelerates when moisture falls below 30%. The stabilization phase between 31.89% and 31.71% reveals persistent internal stresses.



a) b)
Fig. 11. Warp twist in air dried hornbeam samples

Influence of temperature on the size of warps

Table 2 presents the results of a linear regression analysis ($N = 10$) examining the influence of temperature and moisture content on the dependent variable, revealing a strong overall correlation ($R = 0.837$) with statistically significant model fit ($F(2,7) = 8.174$, $p < 0.015$). Temperature showed a significant effect $p=0.005$, while relative humidity had a non-significant influence $p = 0.355$.

Table 2. Linear regression analysis of warp bow dependence on temperature and relative humidity

R= .83677633 R2= .70019463 Adjusted R-Squared = .61453596 F(2,7)=8.1742 p<.01475 Standard Error from estimate 6.6612						
N=10	b*	Standard Error from z	b	Standard Error from z	t(7)	p-value
Intersection			-3,612	27,663	-0,131	0,900
Temperature	-0,827	0,208	-2,442	0,613	-3,985	0,005
Relative Humidity	0,205	0,208	0,368	0,371	0,990	0,355

The graph (Fig. 12), displays a linear regression model for Warp Bow ($23.651 - 2.396 \times$ Temperature) showing a significant inverse relationship between temperature and warp bow, where each 1°C increase in temperature reduces warp bow by 2.396 units, with the intercept (23.651 units at 0°C) suggesting baseline deformation under neutral thermal conditions.

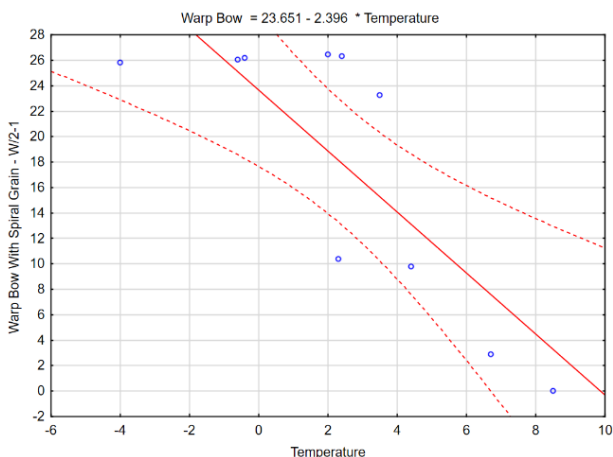


Fig.12. Linear relationship between temperature and warp bow deformation

Temperature dominates for warps deformations. The strong inverse relationship ($p = 0.005$) between temperature and example - Warp Bow (slope = -2.396 units/°C) suggests thermal contraction is the primary driver of Warp Bow. This aligns with prior work on hardwood drying stresses Ormarsson et al. (2000), but the magnitude of temperature sensitivity in hornbeam exceeds reported values for other hardwoods like oak (-1.8°C) (Bergman 2021). While moisture gradients theoretically induce warping SIAU (1984), our regression showed no significant effect of relative humidity ($p = 0.355$). However, the observed 40-45% moisture reduction in early drying stages (Fig. 7) coincided with exponential warp increases, supporting Dinwoodie's (2000) fiber saturation point (FSP) threshold hypothesis. The lack of statistical significance may reflect our study's narrow relative humidity range (23-93%) compared to controlled kiln experiments. Samples with spiral grain exhibited 3.6× higher post-drying deviation (10.6° vs. 3° per meter; Table 1),

validating Kollmann's (1951) model of shear stress accumulation in anisotropic wood structures. Radial-type timber showed pronounced twist (Fig. 11), likely due to differential tangential/radial shrinkage (Espinoza & Bond 2016). Hornbeam was concluded to be particularly sensitive to thermally-induced warping, with spiral grain introducing additional risk, supporting its preferential use in non-structural applications where greater warp tolerance exists.

Conclusions

- Early air-drying stages often cause warps due to uneven moisture loss.
- The effectiveness of air-drying for moisture removal was confirmed by both sample groups, though the absolute reduction magnitude was found to depend on initial moisture levels.
- Greater variability in the W-group (with spiral grain) results was observed, indicating these samples may be more sensitive to drying conditions.
- The data confirms that warp developments are closely tied to moisture gradient-induced stresses during air-drying.
- Slower moisture loss in later stages reduces warp risk, but residual stresses may persist.
- The effect of relative humidity is not statistically significant ($p > 0.05$).
- The effect of temperature is statistically significant ($p < 0.05$).

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