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Bending Performance of *Populus Deltoides* Wood: Influence of Ammonia, Sodium Hydroxide, Temperature and Additives

Svojstva savijanja drva *Populus deltoides*: utjecaj amonijaka, natrijeva hidroksida, temperature i aditiva

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ABSTRACT • Wood bending has a wide range of possible uses, such as in making bent furniture, musical instruments, and sporting goods. The study is centred on using a full factorial design of experiments to understand the main and interaction effects of factors like ammonia (20 % and 25 %), NaOH (2.5 % and 0 %), temperature (90 °C and room temperature), and additives (10 % polyethylene glycol (PEG) and 10 % fabric conditioner (FC) on the bending properties of *Populus deltoides* wood specimens of size 20.3 cm × 1 cm × 1 cm. Two levels of each factor were used to find the response to wood bending properties. Deflection to the load ratio (D/L) was evaluated for the treated specimens using a universal testing machine. The ease of bending, bending defects, and spring-back properties of bent wood were also evaluated. Results indicate that NaOH and temperature have significant influences on the D/L ratio and ease of bending. The bending defect was influenced not only by factors like use of NaOH and temperature but also by the interaction effect between ammonia-NaOH and NaOH-temperature. Although the effect of ammonia on wood bending was significant, no difference was found between the two ammonia concentrations (20 % and 25 %) on the bending properties of the wood. Factors such as FC and PEG did not exhibit any significant influences on wood bending properties. These findings suggest that focusing on factors like NaOH, temperature, and ammonia would be more effective in achieving the desired wood bending outcomes.

KEYWORDS: *Populus deltoides*; wood bending; NaOH; temperature; ammonia

SAŽETAK • Savijanje drva čest je postupak u proizvodnji namještaja, primjerice u izradi savijenog namještaja, glazbenih instrumenata i sportske opreme. Istraživanje je usmjereno na primjenu potpunog faktorskog dizajna eksperimenata kako bi se razumjeli glavni i interakcijski utjecaji čimbenika poput amonijaka (20 i 25 %), NaOH (2,5 i 0 %), temperature (90 °C i sobne temperature) te aditiva (10 % polietilen glikola – PEG i 10 % omekšivača za tkanine – FC) na svojstva savijanja uzoraka drva *Populus deltoides* dimenzija 20,3 cm × 1 cm × 1 cm. Za pronalaženje odgovora o utjecaju navedenih čimbenika na svojstva savijanja drva odabrane su dvije razine svakoga

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od njih. Omjer progiba i opterećenja (D/L) za tretirane uzorke procijenjen je uz pomoć univerzalnog uređaja za ispitivanje. Također su procijenjene lakoća savijanja, greške savijanja i elastični povrat savijenog drva. Rezultati pokazuju da NaOH i temperatura znatno utječu na omjer D/L i lakoću savijanja. Na greške savijanja utjecali su upotreba NaOH i temperatura, ali i interakcija između amonijaka i NaOH te između NaOH i temperature. Iako je utjecaj amonijaka na savijanje drva bio znatan, nije utvrđeno da je na svojstva savijanja utjecala razlika između dviju koncentracija amonijaka (20 i 25 %). Čimbenici poput FC-a i PEG-a nisu pokazali bitan utjecaj na svojstva savijanja drva. Navedeni rezultati upućuju na to da bi za postizanje željenih rezultata savijanja drva bilo učinkovitije fokusiranje na čimbenike poput NaOH, temperature i amonijaka.

KLJUČNE RIJEČI: *Populus deltoides*; savijanje drva; NaOH; temperatura; amonijak

1 INTRODUCTION

1. UVOD

Wood is a versatile and sustainable natural resource that has been used for various applications for thousands of years. Wood stiffness is a desirable property for engineering applications. However, stiffness prevents the bending of wood for various applications like furniture, arches, etc. The potential applications of wood bending are vast and include the manufacturing of curved furniture, architectural features, musical instruments, and sports equipment. The use of wood plasticization can allow for creation of unique and intricate designs that would be difficult or impossible to achieve using traditional woodworking techniques. Additionally, the use of wood as a renewable and sustainable material can contribute to the development of environmentally friendly products.

The degree of plasticity in wood is primarily influenced by the softening of the middle lamella, which contains lignin as its primary component. Lignin plays a crucial role in determining the plastic properties of wood, although it is not the sole factor. The glass transition temperature (T_g) of lignin in its dry state is approximately 205 °C, but various studies have reported different glass transition temperature for lignin that is dependent on various temperature conditions, e.g., 60 °C (Kelley *et al.*, 1987), 50 to 100 °C (Furuta *et al.*, 1997) and 170 °C (Ibach, 2010). Increased moisture content or using a plasticizer can lower the T_g for all wood components (Ibach, 2010), lignin exhibiting a T_g of about 100 °C, when wood is saturated with water. Additionally, the T_g of cellulose, hemicellulose and lignin in wet conditions can range from 222 to 250 °C, 54 to 142 °C, and 77 to 128 °C, respectively (Goring, 1963).

There are three major theories of wood bending: Lubricity theory suggests that polymer deformation arises from intermolecular friction; Gel theory proposes that the rigidity of a polymer stems from its internal three-dimensional structure formed through loose attachment along polymer chain; and Free Volume Theory indicates that increased polymer mobility is facilitated by the expansion of the free volume induced by plasticizer (Sunny, 2021).

Steaming of wood allows for bending by softening its fibers through heat and moisture. However,

pressurized steam is not effective as it can lead to compression, wrinkling and increased resistance to curvature (Kollmann and Cote, 1968). Spring-back commonly occurs in steam bending (Kang, 2010). Wood impregnated with anhydrous, liquid ammonia or aqueous solution of ammonia allows it to be bent and retain the desired shape after the ammonia evaporates. NH_3 penetrates the amorphous region of cell walls, cellulose crystal structure, and phenolic lignin bonds, disrupting H-bonds responsible for wood rigidity (Huttunen, 1975). Softening the cellular structure enables fibers to slide past each other under external forces and upon ammonia evaporation, H-bond reforms, restoring the original rigidity of wood (Hon and Shiraishi, 2000). Apart from NH_3 , NaOH can also be utilized for wood bending. NaOH treatment has significant effects on wood such as delignification, swelling, and surface modification and it also has the potential for damage of the wood structure when used excessively or for prolonged periods (Nakano and Nakano, 1995).

Temperature and moisture content have a significant effect on the physical and mechanical properties of wood; with a decrease in strength, the plastic deformability increases (Miksik *et al.*, 2023). Higher temperatures facilitate better solution penetration into the wood fibers, resulting in improved flexibility and pliability for bending purposes (Gaff *et al.*, 2017). Fabric conditioner (FC), which is a mixture of quaternary ammonium compounds and fatty acids, can also penetrate the cell walls of wood and soften cellulose. Polyethylene Glycol (PEG), on the other hand, is a water-soluble polymer that can penetrate the cell walls of wood and fill the pores, resulting in increased dimensional stability and water resistance.

The present study employs a design of experiment approach to investigate the influence of NaOH, NH_3 , temperature, and additives (PEG and FC) on wood bending properties. This research aims to uncover sustainable and efficient methods for enhancing wood bending and its interaction. By utilizing a factorial design experiment, it was aimed to identify the most effective parameters and their impact on wood bending, with implications for the construction and furniture industries. This systematic approach ensures a reliable and practical exploration of wood bending solution.

2 MATERIALS AND METHODS

2. MATERIJALI I METODE

2.1 Preparation of wooden specimens

2.1. Priprema uzoraka drva

Poplar logs (*Populus deltoides*), from tree aged 5-6 years, were flat sawn into wood specimens of dimensions of 20.3 cm × 1 cm × 1 cm. Mean density of the wood was 0.45 g/cm³. The specimens with any type of defects, fungal infection, knots, etc. were discarded in the beginning. The specimens were air dried to moisture content range of 15-18 %.

2.2 Preparation of treatment solution: preliminary experimentation

2.2. Priprema otopine za tretiranje uzoraka drva: preliminarno istraživanje

To determine an acceptable ammonia concentration that balances effectiveness with tolerable pungency, a brief sensory survey was conducted using aqueous ammonia solutions of 20 %, 25 %, 30 %, and 35 %. The survey indicated that concentrations below 30 % (i.e., 25 % and 20 %) were within a bearable range for working conditions. Therefore, these two concentrations (20 % and 25 %) were selected for subsequent experiments.

The treatment solutions were formulated to promote wood plasticization primarily through physicochemical interactions rather than through chemical reactions among the components. Aqueous ammonia penetrates the amorphous regions of the cell wall, disrupts hydrogen bonding in lignin and hemicelluloses, and induces reversible swelling, whereas sodium hydroxide contributes to partial delignification, particularly in the middle lamella, leading to loosening of the cell wall structure. At the concentrations and treatment durations used, no significant chemical reaction between ammonia and NaOH was expected; instead, their effects are considered additive or synergistic, with ammonia enhancing matrix accessibility and facilitating NaOH penetration. The additives (PEG and fabric conditioner) are not expected to react chemically with the alkali treatments and likely act as secondary softening agents by reducing intermolecular friction within the cell wall, thereby enhancing temporary plasticization and bendability. In the initial phase, ten test specimens were immersed in each of five treatment solutions: (i) 20 % aqueous ammonia, (ii) 25 % aqueous

ammonia, (iii) 20 % aqueous ammonia containing 10 % FC, (iv) 20 % aqueous ammonia containing 10 % PEG (PEG-1000), and (v) water (control). The specimens were submerged for four hours, after which their deflection-to-load (D/L) ratio till breaking point was measured using a universal testing machine.

2.3 Testing specimen deflection to load ratio (D/L ratio)

2.3. Ispitivanje omjera progiba i opterećenja uzoraka (omjer D/L)

Using a universal testing machine, a three-point static bending test (as shown in Figure 1) was carried out, and the load (kg) and deformation (mm) of each specimen was recorded to calculate D/L ratio. The applied load was recorded in kilogram-force (kgf) as displayed by the universal testing machine; for reference, 1 kgf (kg) corresponds to 9.81 N. The D/L ratio data was used for ANOVA and post-hoc analyses (Tukey's HSD test) using SPSS statistical software package. Based on the results, further experimentation was carried out using full factorial design of experiment technique.

All test specimens were prepared from flat-sawn boards with a consistent annual ring orientation, and the ring position was kept uniform across all treatments to minimize its influence on bending results.

2.4 Full factorial experimental design

2.4. Potpuni faktorski dizajn eksperimenata

For the full factorial experimental design, four factors, each with two levels, were taken for the study: aqueous ammonia solution, NaOH, temperature and additives (FC and PEG). Table 1 presents the factors and their levels.

Ten wood specimens for each treatment combination were submerged in the respective solution for four hours. After treatment, the specimens were remo-

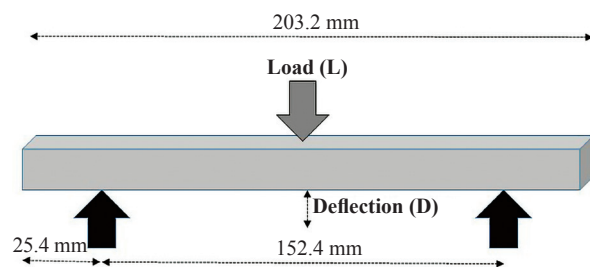


Figure 1 Scheme of static bending tests

Slika 1. Shema statičkih ispitivanja savijanja

Table 1 Treatment combinations

Tablica 1. Kombinacije tretmana

Sl. No. Red. br.	Factors / Čimbenici	Level 1 Razina 1.	Level 2 Razina 2.
1.	Aqueous ammonia solution / vodena otopina amonijaka	20 %	25 %
2.	NaOH solution / otopina NaOH	2.5 %	0 %
3.	Solution temperature / temperatura otopine	90 °C	Room temperature
4.	Additives (10 %) / aditivi (10 %)	Fabric softener	PEG

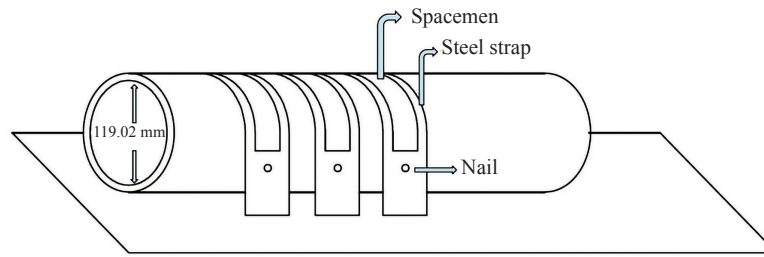


Figure 2 Diagram of curved frame setup

Slika 2. Dijagram postavljanja zakrivljenog okvira

ved, the excess solution was wiped off, and they were subjected to bending tests.

Unscrambler 10.2 software (CAMO Software AS, Oslo, Norway) was used for the full factorial experimental design. A factorial design (2^4) was created with 2 replications of each experiment. Thus, 16 experiments were replicated 2 times to make a total of 32 experiments with the measurement of 4 response variables. The power of experiment was 0.9 after the randomization. The software generated randomized order of the experiments was used to carry out the experiments. The response variables were analyzed using the Unscrambler software.

A general form of the model (two-way interaction) can be represented as follows:

$$y = \beta_0 + \sum \beta_i x_i + \sum \beta_{ik} x_i x_k + \sum \beta_{ii} x_i^2 \quad (1)$$

Where: y is the dependent variable (response); β_i is the coefficients of factor/variable; β_{ik} is the coefficient of interactions and x_i is factor/variable. This model represents the effects of process variables (Aqueous ammonia solution, NaOH, temperature and additives) and their interactions on the response variables (D/L ratio, ease of bending, spring-back and bending defects). On the basis of the analysis of variance (ANOVA), validity of the models was established.

2.5 Response variables

2.5. Istraživane varijable

Four response variables viz. D/L ratio, ease of bending, spring-back and bending defects were recorded for each experiment. The process of recording the response variable values is explained in the next section.

2.6 Wood bending and evaluation of ease of bending

2.6. Savijanje drva i procjena lakoće savijanja

For the bending test, a cylinder with a diameter of 119.02 mm was used. The samples were securely held onto the cylinder using steel straps and nails, and the specimens were bent and kept in bend condition for a duration of 24 hours (Figure 2). All bending tests and ease-of-bending assessments were performed by the same trained operator in a randomized sequence, with regular rest intervals and limited session duration to minimize fatigue and maintain consistent physical and

mental conditions. The operator was asked to grade the ease with which bending was done from scale 0 (difficult to bend) to 10 (easy to bend) after bending each specimen.

2.7 D/L ratio

2.7. Omjer D/L

After the treatment, D/L ratio was recorded immediately by adopting the methodology as explained in the previous section.

2.8 Spring-back in bent specimens

2.8. Elastični povrat savijenih uzoraka

After keeping the bent wooden specimens clamped in the curved frame for 24 hours, they were unclamped, and the distance between the two ends of each specimen was measured (D1). The specimens were then fully dried in an electric kiln at 45 °C and 70 % RH till the final moisture content came in the range of 8-12 %, after which the distance between the two ends was measured again (D2). The difference between these two measurements represented the spring-back of the specimen: a negative value indicated shrinkage (inward movement), while a positive value indicated a tendency of the specimen to return toward its original straight form (Figure 3).

2.9 Evaluation of bending defects

2.9. Evaluacija grešaka savijanja

After the samples were fully dried to the final moisture content of 10-12 %, a defect rating scale ranging from 0 (no defects) to 10 (severe defects) was used to assess the quality and presence of any defects in the samples (Table 2). Any major crack and wood failure during bending was given defect score 10, whereas less severe crack was given defect score 9. A seve-

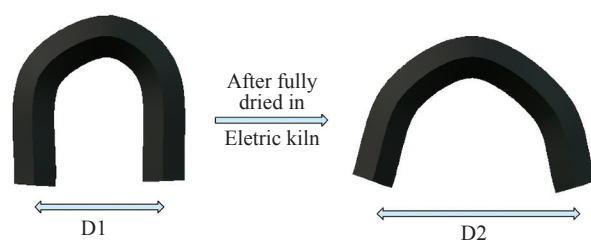








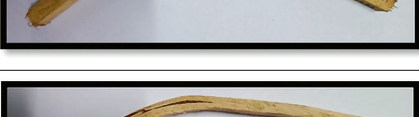
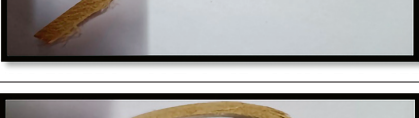
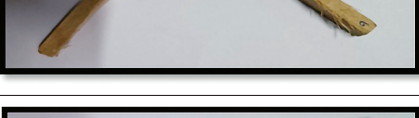


Figure 3 Movement in test specimens

Slika 3. Pomak ispitivanih uzoraka

Table 2 Defect rating scale (0–10) used for visual evaluation of bending defects in wooden specimens, where 0 indicates no defects and 10 indicates complete failure

Tablica 2. Ljestvica ocjenjivanja grešaka (0 – 10) za njihovu vizualnu procjenu pri savijanju uzoraka drva, na kojoj 0 znači da nema grešaka, a 10 označava potpuni lom drva

Bent wooden specimens / Savijeni uzorci drva	Defect value / Ocjena greške
	0
	1
	2
	3
	4
	5
	6
	7
	8
	9
	10

re failure at central line (slip) was given score 8, whereas medium and minor failure were given the defect scores 7 and 6, respectively. Defect scores 5 and below were given to the minor defects based on severity. The wooden specimens with no defects were allotted defect score 0.

3 RESEARCH METHODS

3. METODE ISTRAŽIVANJA

3.1 Effect of ammonia and additives (PEG and FC) on bendability of wood: results of preliminary experiments

3.1. Utjecaj amonijaka i aditiva (PEG i FC) na savitljivost drva: rezultati preliminarnih istraživanja

Table 3 presents test results of D/L ratio at various combinations using 20 % ammonia, PEG and FC. The mean D/L ratio varied considerably among the different treatments. Samples treated with 20 % ammonia alone exhibited the highest mean D/L ratio (0.14 mm/ kg load \pm 0.06), followed by 20 % ammonia combined with 10 % PEG (0.12 mm/ kg load \pm 0.05) and 20 % ammonia with 10 % FC (0.10 mm/ kg load \pm 0.04). In contrast, treatments with 10 % PEG (0.08 mm/ kg load \pm 0.03) or 10 % FC alone (0.07 mm/ kg load \pm 0.03) showed only slight increases over the control (0.07 mm/ kg load \pm 0.01). The 95 % confidence intervals indicated that ammonia-based treatments resulted in higher D/L ratios than the control, whereas the effect of additives alone was marginal. These observations suggest that ammonia is the primary factor responsible for improving the D/L ratio, while the addition of PEG or FC alone has little effect. When combined with ammonia, these additives slightly moderated the effect but did not surpass the impact of ammonia alone.

An ANOVA analysis of D/L ratio showed a significant difference among the treatments ($p = 0.005$). The

post hoc analysis using Duncan's test categorized all variables into four subsets i.e. set 1 (control and FC 10 %), set 2 (PEG 10 % and Ammonia + FC 10 %), set 3 (Ammonia 10 % + PEG 10 %), set 4 (20 % Ammonia). It can be interpreted that ammonia has the highest significance among all six variables.

The post hoc analysis provides valuable insights into the significance of different variables in wood bending. It highlights the strong impact of ammonia and indicates that the presence of other variables in combination with ammonia may alter its effects. Ammonia solution infiltrates plant cell lignin, swelling cellulose and altering its crystal lattice, disrupting hydrogen bonds in wood polysaccharides. Liquid ammonia softens fibers, promoting macromolecule flow, inducing tension or compression in wood (Schuerch *et al.*, 1966). Conversely, FC and PEG do not show a significant influence on wood bending according to this analysis.

3.2 Results of full factorial experiments

3.2. Rezultati potpunih faktorskih eksperimenata

3.2.1 Cube plots

3.2.1. Kockasti dijagrami

The cube plot of factor interactions (Figure 4a) shows the combined influence of ammonia concentration (A), NaOH concentration (B) and temperature (C) on the deflection/load (D/L) ratio. The values at the vertices indicate that the highest D/L ratio (0.5425 mm/ kg) was obtained when all three factors were at their high levels, whereas the lowest values (0.1925 – 0.2205 mm/kg) occurred when all factors were at low levels. Among the three factors, ammonia concentration exerted the strongest positive effect on the D/L ratio, with a marked increase whenever it was at its higher level. NaOH concentration and temperature also contributed positively, but their effects were more evident when combined with high ammonia. The interaction patterns

Table 3 Deflection to load ratio due to effect of ammonia in isolation and in combination

Tablica 3. Omjer progiba i opterećenja zbog utjecaja amonijaka kao jedinog aditiva i u kombinaciji s drugim aditivima

Treatments Tretmani	N	D/ L ratio, mm/kg load Omjer D/L, mm/kg opterećenja	Std. Deviation SD	Std. Error SE	95 % Confidence interval for mean 95 %-tni interval pouzdanosti za srednju vrijednost		Minimum, mm/kg load Minimum, mm/kg opterećenja	Maximum, mm/kg load Maximum, mm/kg opterećenja
					Lower bound Donja granica	Upper bound Gornja granica		
20 % ammonia	10	0.14	0.06	0.02	0.10	0.18	0.08	0.22
20 % ammonia+10 % FC	10	0.10	0.04	0.01	0.07	0.13	0.06	0.18
20 % ammonia+10 % PEG	10	0.12	0.05	0.02	0.08	0.15	0.06	0.22
10 % PEG	10	0.08	0.03	0.01	0.06	0.11	0.06	0.12
10 % FC	10	0.07	0.03	0.01	0.06	0.11	0.05	0.13
Control	10	0.07	0.01	0.00	0.06	0.08	0.05	0.09

highlight that ammonia is the dominant factor influencing the D/L ratio, with synergistic effects arising from its combination with NaOH and elevated temperature.

The cube plot depicting the combined effects of ammonia concentration (A), NaOH concentration (B) and temperature (C) on the ease of bending (Figure 4b) reveals that the ease of bending improved substantially when all three factors were maintained at their high levels, resulting in the highest score (5.4550). Conversely, the lowest values (approximately 2.8330 – 3.0980) were recorded when the factors were at their low levels. Among the three factors, ammonia concentration again showed the most pronounced influence, with a marked increase in bending ease observed at its higher level. The effects of NaOH concentration and elevated

temperature were comparatively smaller when applied individually, but their interaction with high ammonia produced synergistic improvements. These results indicate that chemical softening combined with heat treatment has a cumulative effect on improving the bending performance of wood.

The combined effects of ammonia concentration (A), NaOH concentration (B) and temperature (C) on spring-back are shown in Figure 4c. Negative values indicate a reduction in spring-back, which is desirable for improved shape stability after bending. The plot reveals that the largest negative value (-22.15) was obtained when all three factors were at their high levels, signifying the greatest reduction in spring-back. Conversely, minimal changes (-0.65 to -1.50) were obser-

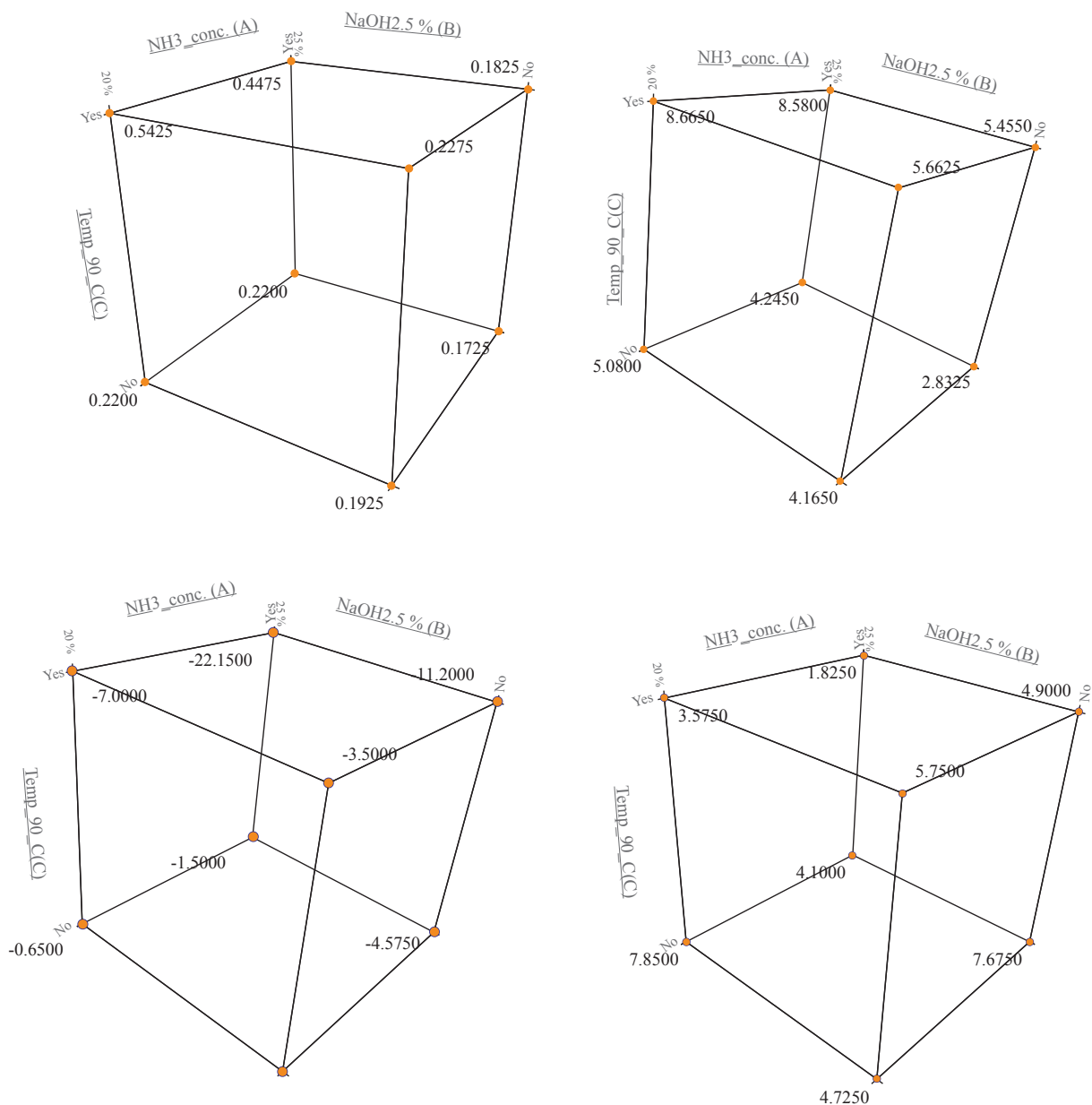


Figure 4 Cube plots influence of Ammonia, NaOH and temperature on deflection/ load ratio (a), ease in bending (b), spring-back (c) and defects due to bending (d)

Slika 4. Kockasti dijagrami utjecaja amonijaka, NaOH i temperature na omjer progib/opterećenje (a), lakoću savijanja (b), elastični povrat (c) i greške savijanja (d)

ved when the factors were at their low levels. Ammonia concentration exerted the strongest influence, and the effect was amplified when combined with higher NaOH concentration and elevated temperature. This interaction suggests that chemical softening, particularly using ammonia, in combination with heat treatment, is effective in reducing spring-back and enhancing the dimensional stability of bent wood.

The influence of ammonia concentration (A), NaOH concentration (B) and temperature (C) on the occurrence of bending defects is illustrated in Figure 4d. Lower values correspond to fewer visible defects. The cube plot shows that the minimum defect score (1.8250) occurred when all three factors were maintained at high levels, whereas the maximum defect scores (7.6750 – 7.8500) were recorded when the factors were at their low levels. Ammonia concentration again appeared to be the most dominant factor, substantially reducing the number of defects when applied at its higher level. The combined use of high NaOH concentration and elevated temperature further minimized the occurrence of defects. These results demonstrate that chemical softening using ammonia, supplemented with NaOH and heat treatment, significantly improves the bending quality by reducing surface and internal defects.

3.2.2 ANOVA table and effect summary

3.2.2. ANOVA tablica i sažetak utjecaja

Table 4 presents ANOVA table and effect summary of the models, ammonia concentration, NaOH, temperature, additives and their combined interaction effects on deflection/ load ratio, ease in bending, spring-back and defects values. The fitted model for D/L was statistically significant ($p = 0.0026$), explaining approximately 67 % of the total variability ($R^2 = 0.6688$). Among the individual factors, NaOH concentration ($F = 16.59$; $p = 0.0006$) and temperature ($F = 13.66$; $p = 0.0013$) had highly significant effects on the response, whereas ammonia concentration (20 % and 25 %) alone was not significant ($p = 0.3315$). A significant interaction was observed between NaOH concentration and temperature ($F = 9.84$; $p = 0.0050$), indicating a synergistic effect when these two factors were combined. Neither the FC nor its interactions contributed significantly to the response ($p > 0.05$). The lack-of-fit test was not significant, confirming that the model adequately described the data. Overall, the results highlight that NaOH concentration and temperature are the dominant factors affecting the response variable D/L ratio, with their combined influence being particularly important.

The results of the analysis of variance (ANOVA) for ease in bending revealed that the fitted model was statistically significant ($p = 0.0031$), explaining

66.18 % of the total variation in the response with an adjusted R^2 of 0.5008. Among the individual factors, NaOH concentration ($p = 0.0027$) and temperature ($p = 0.0001$) exerted a significant influence on the response, whereas NH_3 concentration (20 % and 25 %) ($p = 0.3347$) and the FC ($p = 0.4041$) were not significant. This can be explained by the partial delignification that leads to a partial loosening of the cell wall. None of the two-way interaction terms showed a significant effect ($p > 0.05$), indicating that the factors acted largely independently. The model check confirmed that a linear model adequately described the data ($p = 0.0002$) without a significant contribution from higher-order interactions. Although the model exhibited a reasonable fit, the relatively low predicted R^2 (0.2147) and a coefficient of variation of 31.54 % suggest moderate variability and scope for improving predictive performance in ease of bending.

ANOVA (Table 3) showed that the model for spring-back was significant ($p = 0.0161$) with an R^2 of 0.59, although the adjusted (0.39) and predicted (0.05) R^2 values indicate limited predictive strength. Among the factors, NaOH concentration ($p = 0.0036$) and the soft additive ($p = 0.0133$) had significant effects, as well as the interaction between temperature and the soft additive ($p = 0.0305$). Other main effects and interactions were not significant. The linear model was adequate ($p = 0.0061$), but the high variability (CV = 63.7 %) suggests scope for improvement.

The model for bending defects was significant ($p = 0.0248$) with an R^2 of 0.5661, though the adjusted R^2 was 0.3595 and the predicted R^2 was very low (-0.0075), suggesting weak predictive ability. Among the factors, temperature ($p = 0.0068$) had the strongest effect, followed by the interaction between NH_3 concentration and NaOH ($p = 0.0121$); NaOH concentration was marginally significant ($p = 0.0520$). Other main effects and interactions were not significant. The linear model was adequate ($p = 0.0187$), but the high variability (CV = 38.7 %) indicates scope for model refinement. Temperature increased the solubility of treatment chemicals, enabling more thorough and efficient penetration into the structure of the wood. Better interaction between the treatment compounds and the wood components was made possible by this greater penetration, which may have improved the wood bending capabilities (Suleman, 2015). The effect of temperature on wood bending is two-pronged as many studies demonstrate that the higher temperature reduces the wood strength significantly. Bending strength and modulus of elasticity decrease as temperature is increased (Sonderegger and Niemz, 2006, Zhong *et al.*, 2015).

Moreover, the effect of NaOH on wood delignification rate is doubled on a temperature increase of 10 °C (Lusby and Maass, 1937). NaOH causes partial

Table 4 ANOVA table and effect summary
Tablica 4. ANOVA tablica i sažetak utjecaja

Factors and interactions <i>Čimbenici i njihova međusobna djelovanja</i>	D / L		Ease in bending <i>Lakoća savijanja</i>		Spring-back <i>Elastični povrat</i>		Defects <i>Greške</i>	
	p-value	Effect value	p-value	Effect value	p-value	Effect value	p-value	Effect value
Model (p-value) <i>model (p-vrijednosti)</i>	0.0026		0.0031		0.3346		0.0248	
Ammonia conc. (A) <i>koncentracija amonijaka (A)</i>	0.3315	-0.04	0.3347	-0.615	0.1627	-5.6688	0.2328	-0.85
Sodium hydroxide (B) <i>natrijev hidroksid (B)</i>	0.0006	0.1638	0.0027	2.1138	0.6875	-1.6063	0.052	-1.425
Temperature (C) <i>temperatura (C)</i>	0.0013	0.1488	0.0001	3.01	0.0611	-7.8813	0.0068	-2.075
Additives (D) <i>aditivi (D)</i>	1	0	0.4044	-0.53	0.4739	-2.8688	0.6182	-0.35
A × B	0.8539	-0.0075	0.8059	0.155	0.5645	-2.3313	0.0121	-1.9
A × C	0.4642	0.03	0.46	0.4687	0.9211	-5.7563	0.5225	-0.45
B × C	0.005	0.1263	0.1421	0.95	0.3241	-5.6188	0.0975	-1.2
A × D	0.83	-0.0087	0.3674	-0.5738	0.3033	0.7313	0.4564	0.525
B × D	0.8062	-0.01	0.4402	0.49	0.1042	4.1688	0.4999	-0.475
C × D	0.4283	0.0325	0.7558	-0.1963	0.9099	-0.4563	0.5456	-0.425

loosening of the cell wall through partial delignification. Increasing the temperature enhances the solubility of treatment agents, allowing for better penetration into the wood structure and potentially improving bending properties. On the other hand, the main effects of NH₃ concentration and the presence of FC are non-significant, suggesting no significant impact on defects.

An interesting interaction effect trend is observed between NH₃ and NaOH on bending defects. Bending defects reduced significantly when NH₃ was used in presence of NaOH. The ligno-cellulose surface area is increased by the ammonia treatment (Mankar *et al.*, 2021), allowing NaOH to more easily de-lignify the cell wall. Hence, mixing NH₃ and NaOH at greater concentrations lowers bending defects, and applying 2.5 % NaOH at 90 °C further reduces defects, probably as a result of delignification, partial cell-wall loosening, and enhanced plasticization. In comparison to other combinations, the synergistic effect of temperature and NaOH concentration results in better bending performance and bending defects.

Two concentrations of ammonia (20 % and 25 %) have been compared and presented in Table 3. It may be seen that the difference due to concentrations of NH₃ on all the four responses (deflection/ load ratio, ease in bending, spring-back and defects) is non-significant ($p > 0.05$) at alpha 0.05, i.e. the performance of ammonia at 20 % was found to be equal to that of 25 %.

Across all four ANOVA models, the regression analyses confirm that the process is predominantly influenced by temperature and NaOH concentration, while NH₃ concentration and the additives generally have weaker or inconsistent effects. In most models, interaction effects were largely insignificant, with only

a few cases (e.g., temperature × additive and NH₃ × NaOH) showing statistical significance. The models are statistically valid overall ($p < 0.05$), but their predictive capability is limited, as reflected by moderate R² values (0.56–0.66), low adjusted and predicted R², and high coefficients of variation. These results suggest that temperature and alkali concentration are the primary drivers of the response, and future model refinement (e.g., additional factors, non-linear terms) may be needed to improve prediction accuracy.

4 CONCLUSIONS

4. ZAKLJUČAK

The factorial design of the experiment resulted in significant models using the effects of factors like ammonia, NaOH, temperature, and additives on the responses deflection/load (D/L) ratio, ease of bending, and bending defects. However, the model was not significant for spring-back response. The comprehensive analysis of the experimental results highlights the varying effects of different variables on wood bending properties. NaOH and temperature demonstrated significant influences on the D/L ratio and ease of bending. The most important factor in reducing spring-back was temperature. Bending defects are influenced not only by factors like NaOH and temperature but also by the interaction effect between ammonia-NaOH and NaOH-temperature. The effect of ammonia on wood bending was significant, but no difference was found between the effects due to the two ammonia concentrations (20 % and 25 %). Factors such as FC and PEG did not exhibit any significant influences on wood bending properties. These findings imply that the reaction is

primarily driven by temperature and alkali concentration in combination with ammonia, and that more model modification (e.g. additional components, non-linear terms) may be required to increase forecast accuracy.

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