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Influence of Pressing Speed and Adhesive Content on the Physical and Mechanical Performance of Pine-Oak Based MDF Panels

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Research Article

Abstract − This study investigates the effects of pressing speed and adhesive content on the physical and mechanical properties of medium-density fiberboard (MDF) panels produced from pine-oak fiber mixtures. Panels were manufactured under industrial conditions using the available production settings, including pressing speeds of 400 and 420 mm/s and adhesive content levels of 10.7% and 11.2%. The evaluated properties included density, modulus of rupture (MOR), modulus of elasticity (MOE), internal bond strength (IB), surface soundness, screw withdrawal resistance, thickness swelling (TS), and water absorption (WA). The results showed that density varied significantly among the groups ($p<0.05$), with lower values obtained at lower pressing speed. Internal bond strength was significantly higher at the lower pressing speed, whereas screw withdrawal resistance was significantly higher at the higher pressing speed. In contrast, MOR, surface soundness, thickness swelling, and water absorption were not significantly affected by the investigated production conditions ($p>0.05$), while MOE showed a limited but statistically significant variation ($p<0.05$). Although density differed among the groups, the results indicate that panel performance cannot be explained by density alone, and that pressing conditions play a dominant role in determining mechanical behaviour. In conclusion, under the investigated conditions, pressing speed had a more pronounced influence on the balance between core integrity and screw holding performance in MDF panels than variations in adhesive content. However, no consistent improvement associated with the higher adhesive content was observed under the available production conditions.

Keywords – *Adhesive content, internal bond strength, medium-density fibreboard, pressing speed, screw withdrawal*

Çam-Meşe Esaslı MDF Levhaların Fiziksel ve Mekanik Performansı Üzerinde Pres Hızı ve Tutkal Oranının Etkisi

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Araştırma Makalesi

Öz − Bu çalışmada, çam-meşe lif karışımından endüstriyel koşullarda üretilen orta yoğunluklu lif levhaların (MDF) fiziksel ve mekanik özellikleri üzerine farklı pres hızı ve tutkal oranı koşullarının etkileri incelenmiştir. Levhalar, üretim sürecinde mevcut olan koşullar kapsamında 400 ve 420 mm/s pres hızları ile %10,7 ve %11,2 tutkal oranları kullanılarak üretilmiştir. Çalışmada yoğunluk, eğilme direnci (MOR), elastikiyet modülü (MOE), iç yapışma direnci (IB), yüzey sağlamlığı, vida tutma direnci, kalınlığına şişme (TS) ve su alma (WA) özellikleri değerlendirilmiştir. Elde edilen sonuçlar, yoğunluk değerlerinin gruplar arasında istatistiksel olarak anlamlı farklılık gösterdiğini ($p<0,05$) ve düşük pres hızında daha düşük yoğunluk değerleri elde edildiğini ortaya koymuştur. İç yapışma direnci düşük pres hızında anlamlı düzeyde daha yüksek bulunurken, vida tutma direncinin yüksek pres hızında anlamlı düzeyde daha yüksek olduğu belirlenmiştir. Buna karşılık MOR, yüzey sağlamlığı, kalınlığına şişme ve su alma değerleri incelenen üretim koşullarından istatistiksel olarak anlamlı düzeyde etkilenmezken ($p>0,05$), MOE değerlerinde sınırlı ancak istatistiksel olarak anlamlı bir farklılık belirlenmiştir ($p<0,05$). Yoğunluk değerleri gruplar arasında farklılık göstermesine rağmen, levha performansının yalnızca yoğunlukla açıklanamayacağı ve pres koşullarının mekanik davranış üzerinde belirleyici bir rol oynadığı anlaşılmaktadır. Sonuç olarak, incelenen koşullar altında pres hızının MDF levhalarda çekirdek bütünlüğü ile vida tutma performansı arasındaki denge üzerinde tutkal oranındaki değişimlerden daha belirgin bir etkiye sahip olduğu belirlenmiştir. Buna karşılık, mevcut üretim koşulları kapsamında daha yüksek tutkal oranına bağlı tutarlı bir performans iyileşmesi gözlenmemiştir.

Anahtar Kelimeler – *Tutkal oranı, İç yapışma direnci, orta yoğunluklu lif levha, pres hızı, vida tutma direnci*

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1. Introduction

Medium-density fiberboard (MDF) is one of the most widely used wood-based panel products in furniture and interior applications due to its homogeneous structure, smooth surface quality, and excellent machinability (Bolton & Humphrey, 1988; Gul et al., 2023). In industrial practice, MDF is predominantly manufactured via the dry process using continuous pressing technology, where panel performance is governed not only by raw material characteristics and adhesive content but also by complex thermo-mechanical processes occurring during hot pressing. These include heat and mass transfer, vapor movement, resin curing, and the viscoelastic compression behavior of the fiber mat (Gul et al., 2017; Shalbafan & Thoemen, 2022).

One of the most critical structural features controlling MDF performance is the vertical density profile, which describes the density variation across panel thickness. Typically, MDF panels exhibit denser surface layers and a lower-density core, and this profile strongly influences bending properties (MOR and MOE), internal bond strength (IB), screw withdrawal resistance, and dimensional stability (Gupta et al., 2007; Minhas et al., 2021). While surface densification is closely associated with improved bending performance, core density plays a dominant role in determining internal bonding quality (Wang et al., 2004).

The development of this density profile is primarily controlled by pressing conditions, particularly the pressing speed and press-closing dynamics. Previous studies have shown that faster press closure or higher pressurizing rates tend to increase surface densification while potentially limiting heat transfer to the core, which may result in reduced internal bond strength. Conversely, slower pressing conditions allow more uniform heat distribution and improved core curing, thereby enhancing internal bonding (Gul et al., 2017; Shalbafan & Thoemen, 2022). These findings suggest that pressing parameters introduce a trade-off between surface-dominated and core-dominated properties, ultimately affecting the overall performance balance of MDF panels.

In addition to pressing conditions, adhesive content is another key parameter influencing MDF properties. Urea–formaldehyde (UF) resins remain the most widely used adhesives in MDF production due to their low cost and high reactivity (Savov et al., 2025). Increasing adhesive content generally improves bonding quality and mechanical properties while reducing thickness swelling and water absorption. However, this relationship is not always linear and may depend on panel density, fiber characteristics, and processing conditions (Sarı et al., 2013; Shalbafan & Thoemen, 2022; Engehausen et al., 2025).

Despite the substantial body of literature on MDF production parameters, most studies have been conducted under laboratory-scale conditions or using wide parameter ranges that may not accurately reflect industrial optimization scenarios. In particular, the combined effects of pressing speed and adhesive content under industrial continuous press conditions and within narrow, practical resin ranges remain insufficiently explored, especially for mixed wood species systems such as pine-oak fiber combinations.

In this context, the present study aims to evaluate the influence of different industrial pressing speed and adhesive content conditions on the physical and mechanical properties of MDF panels produced from pine–oak fiber mixtures under industrial conditions. The investigated properties include density, modulus of rupture (MOR), modulus of elasticity (MOE), internal bond strength (IB), surface soundness, screw withdrawal resistance, thickness swelling (TS), and water absorption (WA).

The findings of this study are expected to provide insights into how pressing conditions influence panel densification behavior and the balance between surface and core performance, thereby contributing to the optimization of MDF manufacturing processes.

2. Materials and Methods

Medium density fiberboard (MDF) panels were produced using a mixture of 80% pine (*Pinus* spp.) and 20% oak (*Quercus* spp.) fibers. The fibers were supplied from an industrial MDF production line operated by Kastamonu Entegre Wood Industry and Trade Inc., Adana, Türkiye. A urea-formaldehyde (UF) resin with a solid content of 62% was used as the adhesive. The panels were manufactured with a nominal thickness of 18 mm and a target density of approximately 710 kg/m³.

2.1. Experimental Design and Manufacturing Process

The study was conducted to investigate the effects of pressing speed and adhesive content on the physical and mechanical properties of MDF panels. Pressing speeds were set at 400 and 420 mm/s, while adhesive content levels were 10.7% and 11.2%. The experimental design and panel groups are presented in Table 1. These adhesive levels corresponded to different amounts of resin solids incorporated into the panel structure. The panels were produced under industrial conditions using combinations of these parameters.

Table 1. Experimental design and panel groups
Tablo 1. Deneysel tasarım ve panel grupları

Sample code	Pressing speed (mm/s)	Adhesive content (%)
400-H*	400	11.2
420-L	420	10.7
420-H	420	11.2

* H and L represent high (11.2%) and low (10.7%) adhesive contents, respectively

It should be noted that the present study was conducted using MDF panels produced under industrial manufacturing conditions. Consequently, the experimental groups were limited to the production conditions available during the manufacturing campaign, and the combination of 400 mm/s pressing speed and 10.7% adhesive content was not available for evaluation. Therefore, the study was intended to compare the performance of the available industrial production conditions rather than to establish a complete 2 × 2 factorial design. As a result, the interaction effects between pressing speed and adhesive content could not be formally evaluated, and the findings should be interpreted within the scope of the investigated production conditions.

Logs were debarked and chipped using a disc chipper, and the chips were screened to remove fines and oversized particles. The selected chips were subjected to thermo-mechanical pulping at approximately 170°C and 8 bar pressure for 5 minutes. Following defibration, paraffin was applied to the fibers to improve water resistance. The fibers were then blended with urea-formaldehyde (UF) resin and hardener chemicals in a blow-line system and dried to the determined moisture content.

After drying, the fibers were pneumatically conveyed and formed into a uniform mat using an air-forming system. The fiber mat was subsequently hot-pressed at approximately 230°C and 3 N/mm² pressure. During pressing, the predefined pressing speeds and adhesive contents were applied according to the experimental design. After pressing, the panels were trimmed, conditioned under controlled environmental conditions, and prepared for further processing and testing.

2.2. Sample Preparation, Testing Methods and Statistical Analysis

Test specimens were prepared from the produced panels in accordance with the relevant standards. The physical and mechanical properties of the MDF panels were determined according to the standards presented in Table 2.

Table 2. Standards used for determining the physical and mechanical properties of MDF panels
Tablo 2. MDF levhaların fiziksel ve mekanik özelliklerinin belirlenmesinde kullanılan standartlar

Measured Property	Testing Standard
Density	TS EN 323
Modulus of rupture (MOR) and modulus of elasticity (MOE)	TS EN 310
Internal bond strength (IB)	TS EN 319
Surface soundness	TS EN 311
Screw withdrawal resistance (edge)	TS EN 320
Thickness swelling (TS) and water absorption (WA)	TS EN 317

Test specimens with dimensions of 410 × 50 × 18 mm were prepared for the determination of modulus of rupture (MOR) and modulus of elasticity (MOE), whereas specimens measuring 75 × 75 × 18 mm were used for screw withdrawal resistance. Specimens with dimensions of 50 × 50 × 18 mm were prepared for internal bond strength, surface soundness, thickness swelling, and water absorption tests. For each experimental condition, eight specimens were tested for modulus of rupture (MOR) and modulus of elasticity (MOE), while 12 specimens were used for the determination of internal bond strength (IB), surface soundness, screw withdrawal resistance, thickness swelling (TS), and water absorption (WA). The obtained data were statistically analyzed using IBM SPSS Statistics. Analysis of variance (ANOVA) was performed, followed by Duncan's multiple range test to compare group means at a significance level of $p < 0.05$.

3. Results and Discussion

The mechanical properties of the MDF panels, together with their density values, are presented in Table 3 and discussed considering the influence of processing conditions on panel structure and performance.

Table 3. Mechanical properties and density of MDF panels under different pressing speeds and adhesive contents

Tablo 3. Farklı pres hızları ve tutkal oranları altında üretilen MDF levhaların mekanik özellikleri ve yoğunluk değerleri

Processing conditions	Density (kg/m^3)	IB (MPa)	Screw Withdrawal (N)	MOR (MPa)	MOE (MPa)	Surface Soundness (MPa)
400–11.2	707±6^a	0.673±0.04^a	934±105^a	36.25±1.07^a	3689±157^a	1.76±0.16^a
420–10.7	719±9^b	0.617±0.03^b	1012±60^b	36.50±2.20^a	3479±143^b	1.78±0.16^a
420–11.2	717±9^b	0.610±0.05^b	999±32^b	36.28±1.63^a	3622±249^{ab}	1.87±0.13^a

Values are mean ± standard deviation. Different letters within the same column indicate significant differences at $p < 0.05$ according to Duncan's multiple range test.

3.1. Density

As presented in Table 3, density values of the MDF panels varied significantly among the processing conditions ($p < 0.05$). The density ranged from 694 to 746 kg/m³, with mean values of 707, 719, and 717 kg/m³ for the 400–11.2, 420–10.7, and 420–11.2 conditions, respectively.

Although the panels were produced with a target density of 710 kg/m³, slight variations were observed among the groups. Such variations are typical for industrial MDF production and are generally attributed to process-related fluctuations during mat formation and pressing (Park et al., 2024).

The results suggest that differences in the available production conditions were associated with variations in panel densification. Higher density values obtained at increased pressing speed can be associated with enhanced mat compaction and reduced springback during the pressing process, as reported in previous studies (Wong et al., 1998; Wang et al., 2004; Çamlıbel & Aydın, 2021).

Since density is a key factor influencing the mechanical and physical properties of MDF panels, the observed differences, particularly in internal bond strength and screw withdrawal resistance, may be partially attributed to variations in panel density (Park et al., 2024). However, the trends observed across different properties suggest that density alone cannot fully explain the performance differences, and that processing conditions also played a significant role.

3.2. Internal Bond Strength (IB)

As presented in Table 3, the internal bond (IB) strength of the MDF panels was significantly affected by the processing conditions ($p < 0.05$). Mean IB values were 0.673 ± 0.040, 0.617 ± 0.030, and 0.610 ± 0.050 MPa for the 400–11.2, 420–10.7, and 420–11.2 conditions, respectively (n = 12 per condition). According to

Duncan's multiple range test, the 400–11.2 condition showed significantly higher IB values than the other conditions, while no statistically significant difference was observed between the 420–10.7 and 420–11.2 conditions.

The most informative comparison is between the 400–11.2 and 420–11.2 conditions, where the adhesive content was kept constant. Increasing the pressing speed from 400 to 420 mm/s resulted in an approximately 9.4% reduction in IB, indicating that lower pressing speed favored core bonding performance. Notably, higher IB values were obtained in the 400–11.2 condition despite its lower density, suggesting that pressing conditions had a dominant influence on internal bonding performance.

This behavior can be attributed to improved heat transfer and more effective resin curing in the core layer at lower pressing speeds, which enhance fiber–fiber bonding (Ramos et al., 2020; Shalbafan & Thoemen, 2022; Gul et al., 2023). At higher pressing speeds, reduced effective pressing time and limited heat penetration into the core may lead to insufficient curing, thereby weakening internal bonding.

Although density is generally expected to positively influence internal bond strength by increasing fiber contact, bond quality in wood-based composites is also governed by porosity, moisture content, curing history, and vertical density profile. Therefore, density alone does not fully determine IB performance (Korai, 2021; Moreno-Anguiano et al., 2022).

Similar trends have been reported in previous studies, where increasing press speed resulted in a reduction in internal bond strength due to insufficient core consolidation and curing (Çamlıbel & Aydın, 2021; Gul et al., 2023). The findings clearly demonstrate that pressing speed had a more pronounced influence on internal bond strength than adhesive content within the tested range.

The contrasting responses of internal bond strength and screw withdrawal resistance to processing conditions are illustrated in Figure 1.

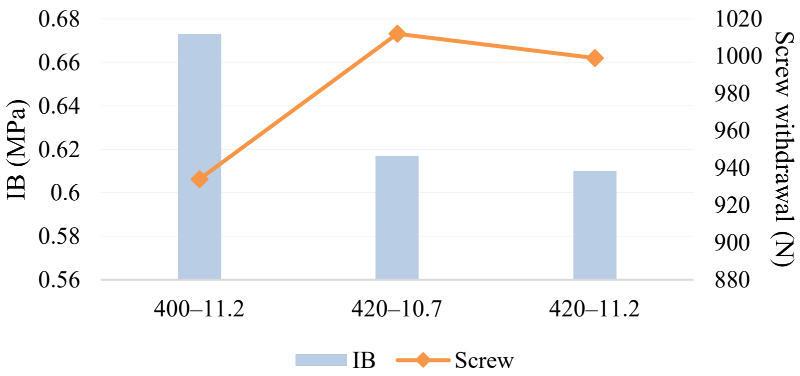

Figure 1. Opposing trends of internal bond strength and screw withdrawal resistance under different processing conditions. Internal bond strength (IB) is shown as columns (left axis), while screw withdrawal resistance is presented as a line (right axis).
Şekil 1. Farklı üretim koşullarında iç yapışma direnci (IB) ile vida tutma direncinde gözlenen zıt eğilimler. İç yapışma direnci sütunlarla (sol eksen), vida tutma direnci ise çizgi ile (sağ eksen) gösterilmiştir.

These results demonstrate that pressing conditions have contrasting effects on internal bond strength and screw withdrawal resistance of MDF panels.

3.3. Screw Withdrawal Resistance

As presented in Table 3, screw withdrawal resistance was significantly affected by the processing conditions ($p < 0.05$). The values ranged from 934 to 1012 N, with the lowest value obtained in the 400–11.2 condition and higher values observed in the 420–10.7 and 420–11.2 conditions. According to Duncan's multiple range test, the 400–11.2 condition differed significantly from the other conditions, whereas no significant difference was found between the 420–10.7 and 420–11.2 conditions.

A clearer trend emerges when comparing the 400–11.2 and 420–11.2 conditions, where the adhesive content was kept constant. Under these conditions, increasing the pressing speed from 400 to 420 mm/s led to an approximately 6.9% increase in screw withdrawal resistance. This increase is likely associated with enhanced local densification in the screw-engaged region at higher pressing speed. As screw withdrawal resistance is primarily governed by the density and integrity of the region engaged by the fastener threads, higher local densification results in improved holding performance (Yorur et al., 2020; Tasdemir et al., 2023).

In the present study, the higher pressing speed conditions were also associated with higher overall density, suggesting that screw withdrawal resistance reflects a combined effect of processing conditions and panel density. However, this effect is likely mediated by localized densification in the screw-engaged region rather than improvements in core bonding. In contrast to internal bond strength, which was enhanced at lower pressing speeds, screw withdrawal resistance increased at higher pressing speeds.

3.4. Bending Properties (MOR and MOE)

As presented in Table 3, the bending properties of the MDF panels were only slightly affected by the investigated processing conditions. MOR values varied within a narrow range between 36.25 and 36.50 MPa, while MOE values ranged from 3479 to 3689 MPa. Although MOR values did not differ significantly among the groups, MOE exhibited limited but statistically significant variation according to Duncan’s multiple range test.

Notably, the condition with the highest density (420–10.7) exhibited the lowest MOE value, suggesting that factors other than average panel density may contribute to bending performance. This observation suggests that bending performance may be influenced by the vertical density profile and surface layer characteristics rather than average panel density alone (Rodríguez et al., 2024).

The relatively stable bending performance suggests that the variations in pressing speed and adhesive content applied in this study were insufficient to substantially alter the surface layer characteristics responsible for bending resistance. Since bending stresses are mainly concentrated in the outer layers of MDF panels, significant modifications in surface densification or vertical density profile are generally required to produce measurable changes in MOR and MOE (Wong et al., 1998; Shalbafan & Thoemen, 2022).

These findings indicate that bending properties were less sensitive to the investigated process parameters than internal bond strength and screw withdrawal resistance. Therefore, within the tested industrial production range, pressing speed primarily influenced internal bond strength and screw withdrawal resistance rather than overall bending behavior.

3.5. Surface Soundness (SS)

Surface soundness (SS) of the MDF panels showed no significant variation among the processing conditions ($p > 0.05$). The values ranged from 1.76 to 1.87 MPa, as summarized in Table 3. According to Duncan’s multiple range test, all conditions were classified within the same statistical subset.

Although the 420–11.2 condition exhibited the highest numerical value, the overall results indicate that the selected processing conditions did not substantially affect surface integrity. This behavior can be attributed to the relatively stable surface densification achieved under all production conditions, which plays a dominant role in determining surface strength (Gul et al., 2023). In addition, SS values were consistently higher than IB values across all conditions, which is expected since SS failure occurs in the denser surface layers, whereas IB typically reflects the weaker core region. This observation is consistent with previous studies emphasizing the importance of near-surface density in governing surface-related properties (Colosimo et al., 2015; Wronka et al., 2022). Similar to bending properties, surface soundness exhibited limited sensitivity to the applied processing conditions, in contrast to the more pronounced response observed in internal bond strength.

3.6. Thickness Swelling and Water Absorption (TS and WA)

Thickness swelling (TS) and water absorption (WA) values of the MDF panels showed no significant variation among the processing conditions ($p > 0.05$). As presented in Table 4, TS values ranged from 8.04% to 8.66%, while WA values varied between 31.30% and 34.86%. According to Duncan's multiple range test, all conditions were classified within the same statistical subset for both properties.

Table 4. Thickness swelling and water absorption values of MDF panels under different processing conditions
Tablo 4. Farklı üretim koşulları altında üretilen MDF levhaların kalınlığına şişme ve su alma değerleri

Processing conditions	Thickness Swelling (%)	Water Absorption (%)
400–11.2	8.42±1.49[a]	34.86±6.40[a]
420–10.7	8.04±2.77[a]	31.30±7.77[a]
420–11.2	8.66±1.85[a]	34.26±5.47[a]

Values are given as mean ± standard deviation. Different letters within the same column indicate significant differences at $p < 0.05$.

Although minor numerical differences were observed, these variations were not statistically significant, indicating that pressing speed and adhesive content within the tested range did not substantially influence moisture-related properties. This behavior suggests that the overall panel structure and bonding conditions remained sufficiently similar across all production conditions to maintain comparable dimensional stability.

The lack of significant response in TS and WA is consistent with previous findings indicating that moderate changes in resin content or density do not necessarily lead to measurable improvements in moisture resistance unless they significantly alter the internal structure or moisture transport pathways (Akbulut & Ayrilmis, 2019; Böhm et al., 2019).

4. Conclusion

This study investigated the effects of pressing speed and adhesive content on the physical and mechanical properties of MDF panels produced from pine-oak fiber mixtures under industrial conditions. The results indicate that, within the investigated process conditions, pressing speed had a more pronounced influence on panel performance than the variation in adhesive content.

A clear contrast was observed between internal bond strength and screw withdrawal resistance. Lower pressing speed (400 mm/s) resulted in significantly higher internal bond strength, indicating improved bonding within the panel core. In contrast, higher pressing speed (420 mm/s) enhanced screw withdrawal resistance, suggesting increased local densification in the screw-engaged region. These findings demonstrate that pressing conditions have contrasting effects on internal bond strength and screw withdrawal resistance.

Although density differed significantly among the groups, the results suggest that panel performance cannot be explained by density alone. Instead, the distribution of density through the panel thickness and the curing conditions developed during pressing appear to play a more critical role in determining mechanical behavior. Modulus of rupture, surface soundness, thickness swelling, and water absorption were not significantly affected, whereas modulus of elasticity showed a limited but statistically significant variation within the applied production range.

From an industrial perspective, the findings suggest that process optimization should focus on balancing internal bonding and screw holding performance. Lower pressing speeds are preferable when internal cohesion is critical, whereas higher pressing speeds are advantageous for improving screw holding capacity. Within the investigated production conditions, no consistent improvement associated with the higher adhesive content was observed in the evaluated properties.

In conclusion, the findings indicate that, under the investigated conditions, pressing speed has a more pronounced influence on the balance between core integrity and screw holding performance in MDF panels than variations in adhesive content. Future studies should employ a complete factorial experimental design and include vertical density profile analysis to further clarify the independent effects of pressing speed and adhesive content, as well as the mechanisms underlying the observed behavior.

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Author Contributions
AKA: Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing.
BÖ: Investigation, Data curation, Resources, Validation.
İB: Conceptualization, Supervision, Writing – review & editing.

Conflicts of Interest
The authors declare that there is no conflict of interest.

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