



**KARADENİZ TECHNICAL UNIVERSITY**  
**THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES**

**FOREST INDUSTRY ENGINEERING**

**EFFECT OF EPOXIDIZED SOYBEAN OIL AND SYNTHETIC RESINS IMPREGNATION  
AND DENSIFICATION ON POPLAR AND ALDER WOOD PROPERTIES**

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**Trabzon 2024**

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**Ph.D THESIS**

**Anteneh Gezahegn KEBEDE**

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Anteneh Gezahegn KEBEDE

Trabzon 2024

## **DECLARATION**

I hereby declare that I have completed this study titled "Effect of epoxidized soybean oil and synthetic resins impregnation and densification on poplar and Alder wood properties" from beginning to end under the supervision of my advisor, Prof. Dr. Ali TEMİZ, for my Doctoral Thesis. I confirm that I collected the data/samples myself, conducted the experiments/analyses in relevant laboratories, accurately presented the information obtained from other sources in the text and references, adhered to scientific research and ethical standards throughout the study process, and I accept all legal consequences in case of any deviation from this 31/05/2024.

Anteneh Gezahegn KEBEDE

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## ABSTRACT

Ph.D. Thesis

### EFFECT OF EPOXIDIZED SOYBEAN OIL AND SYNTHETIC RESINS IMPREGNATION AND DENSIFICATION ON POPLAR AND ALDER WOOD PROPERTIES

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Low-density Alder (*Alnus glutinosa subsp. Barbata*) and Poplar (*Populus tremula*) wood were impregnated with epoxidized soybean oil (ESO) and synthetic resins (Epoxy, Melamine Formaldehyde, Vinyl Ester, and Blend of ESO and Epoxy (70:30)) and subsequently densified (25% and 40%). The retention level used was in the range of 100–150 kg/m<sup>3</sup>. The set recovery, water absorption, water repellent efficiency, anti-swelling efficiency, mechanical properties (impact bending test, compression strength, MOR and MOE, and Shore D-hardness), and thermal resistance of impregnated and densified wood were evaluated. For epoxy impregnation, the densified set recovery was 1.02% and 3.89% for 25% and 40% densification, respectively, in the case of poplar wood, while for alder wood, these values were 4.88% and 5.88%, respectively. Melamine formaldehyde impregnated and densified wood demonstrated the second highest effectiveness in reducing the set recovery, with values ranging from 9% to 12%. The set recovery of wood impregnated with ESO alone exhibited poor performance, ranging from 39% to 62%. However, through the combination of ESO and Epoxy, the set recovery significantly decreased to a range of 11% to 28%. All treatment approaches employed yielded enhancements in dimensional stability and mechanical properties. Mechanical properties of densified samples increased with compression ratios, except in the case of melamine formaldehyde impregnated and densified poplar wood.

**Key Words:** Alder, Densification, Epoxidized soybean oil, Poplar, Physical, and Mechanical Properties, Set recovery and Synthetic resin

## ÖZET

Doktora Tezi

### EPOKSİTLENMİŞ SOYA YAĞI VE SENTETİK REÇİNELERİN YOĞUNLAŞTIRILMIŞ KAVAK VE KIZILAĞAÇ ODUN ÖZELLİKLERİ ÜZERİNE ETKİSİ

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Düşük yoğunluklu Kızılağaç (*Alnus glutinosa subsp. Barbata*) ve Kavak (*Populus tremula*) odunları Epoksitlenmiş soya yağı (ESO) ve sentetik reçineler (Epoksi, Melamin formaldehit, Vinil ester) ile Epoksitlendirilmiş soya yağı ve Epoksi Karışımı (70:30) ile emprenye sonrası yoğunlaştırılma işlemine tabi tutulmuşlardır (%25 ve %40). 100-150 kg/m<sup>3</sup> aralığında hedeflenen gerçekleştirilmiştir. Emprenye edilen ve yoğunlaştırma işlemine tabi tutulan örneklerde geri esneme (Set recovery), su alma, su itici etkinlik, boyutsal kararlılık, mekanik özellikler (darbe testi, basınç direnci, eğilme ve eğilmede elastikiyet modülü ve Shore D-sertliği) ve termal test değerlendirilmiştir. Epoksi reçineleri ile emprenye edilen kavak odununda %25 ve %40 yoğunlaştırma işlemi için, geri esneme oranları %1,02 ve %3,89 olarak bulunmuştur. Kızılağaç odununda %25 ve %40 sıkıştırma için bu değerler sırasıyla %4,88 ve %5,88 olarak tespit edilmiştir. Melamin Formaldehit emdirilmiş ve yoğunlaştırılmış odun, geri esnemeyi azaltmada %9 ile %12 arasında değişen değerlerle en yüksek ikinci etkinliği göstermiştir. Yalnızca ESO ile emprenye edilmiş örneklerin geri esneme oranı, %39 ila %62 arasında değişen oranlarda düşük performans sergilemiştir. Ancak, ESO ve Epoksi kombinasyonu sayesinde geri esneme önemli ölçüde iyileştirilmiştir (%11 ile %28 oranında). Uygulanan tüm emprenye maddelerinde, boyutsal kararlılık ve mekanik özelliklerde iyileşmeler bulunmuştur. Yoğunlaştırılmış örneklerin mekanik özellikleri sıkıştırma derecesi arttıkça artış tespit edilmiştir.

**Anahtar Kelimeler:** Yoğunlaştırma, Kızılağaç, Kavak, Fiziksel ve Mekanik Özellikler, Epoksitlendirilmiş Soya yağı, Sentetik Reçine

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## 1. BACKGROUND

Wood modification, a process to enhance wood properties and extend its applications, has been practiced for decades. Its contemporary applications aim to improve wood quality across various fields (Hill, 2006; Rowell, 2006). The action of a chemical, biological, or physical agent on the material results in a desirable property enhancement during the service life of modified wood, which is considered a wood modification. It can be classified as active or passive modification (Hill, 2006). The modified wood itself is non-toxic in service, and no hazardous substances should be released at the end of its life following disposal or recycling of the modified wood. Impregnation modification is a passive means of wood modification. Different vegetable oils used for wood treatment show a minor to moderate improvement in water absorption, an increase in resistance to rot and termites, and dimensional stability (Temiz et al., 2008:2013). The tensile strength of wood plastic composites with polyvinyl chloride resin matrix was reduced by adding various amounts of epoxidized soybean oil. However, when the amount of epoxidized soybean oil increased, the rates of thickness swelling and water absorption reduced (Xu et al., 2021). Therefore, the epoxidized soybean oil used in this study was considered based on previous studies where it was used in wood treatment and found to enhance dimensional stability and reduce water absorption. Moreover, the environmentally friendly nature of ESO, its higher availability, and its less costly nature were other qualities of ESO considered.

Wood materials can also be modified through densification, a process involving the heating and compression of wood. This technique has been recognized for decades to alter wood shape and enhance mechanical and physical characteristics (Navi and Heger, 2004). The reduction in cell cavity and a corresponding improvement in load-bearing cell wall densification boost the strength features of wood (Ülker et al., 2012). By minimizing the porosity in wood, the right moisture, temperature, and press pressure allow for an improvement in wood density (Ülker et al., 2012; Laine et al., 2016; Song et al., 2018). Hardness, strength, and abrasion resistance are impacted by improvements in wood density (Rademacher et al., 2017).

It presents an opportunity to increase the use, value, and applications of fast-growing, less significant and low-density wood species (Sandberg et al., 2013; Rademacher et al., 2017). The application of densified wood spans across various fields, showcasing its versatility and potential for diverse uses. It has been utilized in sustainable engineering, where cellulosic blocks were densified to create compact materials with entangled fibers, demonstrating excellent tensile properties suitable for sustainable engineering applications (Frey et al., 2018), construction applications (Navi & Heger, 2004), highly compact laminated structures that can block oxygen infiltration, enabling the development of fire-retardant wood structural materials (Gan et al., 2019), the potential applications of densified wood extend to non-structural uses, such as tabletops, solid wood flooring, and furniture, owing to its excellent performance in surface hardness and dimensional stability when treated with superheated steam (Xiang et al., 2021). Moreover, it has shown promise in the field of medicine, with the material demonstrating a high potential for use as bone implants due to the significant increase in modulus of rupture and modulus of elasticity (Andze et al., 2022).

It has been explored for its potential in flooring applications, with densification being utilized to modify low-density woods to achieve the required hardness for flooring applications (Cruz et al., 2018; Moya & Navarro-Mora, 2021). Additionally, an innovative densification process has been shown to positively affect the mechanical and physical properties of wood veneers, making them suitable for flooring materials (Cencin et al., 2021). Studies on tropical hardwood floors have emphasized the importance of wood density in determining the quality of the flooring material, indicating that densified wood with increased density can offer high-quality flooring options (Costa et al., 2021). Through densification, the density of poplar and alder from 0.3g/cm<sup>3</sup> and 0.5g/cm<sup>3</sup> to become more dense. The lowest density threshold to use for flooring and furniture use can be changed dramatically to more than 0.7g/cm<sup>3</sup>, thus densification can potentially widen the use and applications of solid wood.

Wood densification can be categorized as bulk and surface densification (Rademacher et al., 2017; Laine et al., 2016). Though wood densification in combination with heat treatment or alone improved the density and other physical and mechanical properties, set recovery is the main challenge. To overcome set recovery, different treatments were applied, i.e., pre-steaming (Inoue et al., 2007; 2008), steaming in a densified state (Inoue, 1992), water repellent treatments such as vegetable oils, styrene, and paraffin (Pelit and Emiroglu, 2020; Guo et al., 2019), phenol-

formaldehyde impregnations (Laskowaska et al., 2020), and thermal treatment after densifications (Pelit et al., 2015; 2017). However, chemicals used either before or after densification did not remove the set recovery fully yet. Resin impregnation considerably affects wood properties while improving strength and reducing recovery. Heat treatment at high temperatures for an extended period of time is economically expensive. Set recovery mainly happens immediately after relieving the stress and being exposed to high humidity and moisture. Reducing or complete removal of set recovery by employing water-resistant resins, mainly ESO and other thermoset resins, was considered a prime target that initiated us to conduct this study.

In this study, less dense wood materials, poplar and alder, with densities of  $0.3 \text{ g/cm}^3$  and  $0.5 \text{ g/cm}^3$  respectively, were impregnated with epoxidized soybean oil and thermoset resins such as vinyl ester, melamine formaldehyde, epoxy resin, and a blend of ESO and epoxy, and then cured. The impregnated and cured alder and poplar wood were densified by 25% and 40% from an initial thickness of 20mm in the radial direction. The densified wood impregnated with epoxidized soybean oil and non-biobased resins such as epoxy, vinyl ester resin, and melamine formaldehyde and the blend of epoxidized soybean oil (30:70) were determined and compared with untreated densified wood properties.

### 1.1. Statement of the Problems

Densification of wood is a well-known technique that enhances its density and mechanical properties, making it an excellent material for structural composites. The densification process plays a crucial role in expanding the applications of wood by transforming low-density species into high-density materials suitable for structural purposes (Li et al., 2016; Li et al., 2020; Schwarzkopf, 2020; Koskela et al., 2023). The density of wood is a crucial factor influencing its strength, durability, and suitability for various uses (Hofgaard, 1993; Costa et al., 2021; Sousa et al., 2021). For flooring applications, wood with a higher density is preferred due to its increased durability, wear resistance, and ability to withstand heavy foot traffic (Hofgaard, 1993; Costa et al., 2021; Sousa et al., 2021). Additionally, the strength of wood, including parameters like compression strength, tensile strength, and hardness, is crucial for flooring and structural purposes (Samuelson et al., 2017). Furniture manufacturing also requires wood with adequate density and strength for longevity and stability (Müller et al., 2005; Abdou & Budaiwi, 2005). Moreover, the thermal conductivity of building insulation materials is influenced by wood density (Müller et al., 2005; Abdou & Budaiwi, 2005). Therefore, to improve the density and mechanical properties of poplar and alder, low-density wood materials and widen their use in applications, densification of wood is found to be essential.

Despite the superior mechanical properties exhibited by densified wood, several challenges remain. One significant challenge is the set recovery of densified wood, where the wood tends to return to its original shape after compression, affecting its mechanical strength (Sandberg et al., 2017). Various methods have been explored to address this issue, such as chemical pretreatment, mechanical fixation, impregnation with synthetic resins, heat treatment, and delignification followed by densification (Pelit et al., 2016; Song et al., 2018). Studies have shown that a combination of chemical pretreatment and mechanical compression reduces the set recovery in densified wood (Li et al., 2016; Lykidis et al., 2020; Shi et al., 2020). Superheated steam treatment has been found to significantly decrease set recovery in densified wood (Xiang et al., 2021). High-pressure treatment offers advantages by enabling uniform densification from all sides, resulting in reduced set recovery (Yu et al., 2020). Additionally, the application of

hydrophobic coatings has proven effective in reducing set recovery under different humidity conditions (Yu et al., 2020). However, complete elimination of set recovery has not yet been achieved using existing techniques and treatments. The dimensional stability of compressed wood, particularly in outdoor applications, remains a hurdle limiting its industrial use. Furthermore, developing a cost-effective, environmentally friendly, and scalable production process without compromising performance is a fundamental concern in wood densification.

To reduce set recovery, water absorption and improve dimensional stability, density, thermal resistance, and mechanical properties of low-density wood species such as poplar and alder were found to be important. In addition to overcoming the challenges associated with densified wood and expanding its industrial applications. Researchers have made progress in reducing set recovery through various techniques and treatments. However, complete elimination of set recovery and ensuring dimensional stability in outdoor applications remain challenges. To address these challenges, impregnation with epoxidized soybean oil and other synthetic resins followed by densification considered to be essential. Moreover, developing a cost-effective and environmentally friendly treatment is an issue in the contemporary world. Exploring impregnation with epoxidized soybean oil and other synthetic resins, followed by densification, offers promising avenues for further investigation.

## **1.2. Objectives**

The general objective of this study was to investigate the impact of impregnation using epoxidized soybean oil (ESO) and thermoset resins, followed by densification at 25% and 40% levels, on set recovery, the dimensional stability, density, mechanical properties, and thermal resistance properties of Poplar and Alder wood species as compared to untreated but densified wood.

The specific objectives of this study were:

- Investigate the density of impregnated and densified poplar and alder wood.
- Determine the set recovery of impregnated and densified poplar and alder wood.
- Examine the water repellence and dimensional stability of impregnated and densified properties of alder and poplar wood.

- Determine the mechanical properties of impregnated and densified poplar and alder wood.
- Investigate the thermal resistance properties of impregnated densified poplar and alder wood.

### **1.3. Research Questions**

- ✓ How does the impregnation using epoxidized soybean oil (ESO) and thermoset resins and densification affect the density of poplar and alder wood?
- ✓ What is the set recovery of poplar and alder wood after undergoing impregnation and densification using epoxidized soybean oil (ESO) and thermoset resins at 25% and 40% levels?
- ✓ How does the impregnation and densification process using epoxidized soybean oil (ESO) and thermoset resins at 25% and 40% levels affect the water repellence and dimensional stability of poplar and alder wood?
- ✓ What are the mechanical properties (such as strength, impact, hardness, and elasticity) of poplar and alder wood after undergoing impregnation and densification using epoxidized soybean oil (ESO) and thermoset resins at 25% and 40% levels?
- ✓ How does the impregnation and densification process using epoxidized soybean oil (ESO) and thermoset resins at 25% and 40% levels affect the thermal resistance properties (such as thermal conductivity and heat resistance) of poplar and alder wood?

### **1.4. Hypotheses**

Objective 1: Investigate the density of impregnated and densified poplar and alder wood compared to untreated densified wood.

- Null Hypothesis (H0): There is no statistically significant difference in density between impregnated and densified and untreated densified poplar and alder wood ( $p\text{-value} \geq 0.05$ ).
- Alternative Hypothesis (HA): There is a statistically significant difference in density between impregnated and densified and untreated densified poplar and alder wood ( $p\text{-value} < 0.05$ ).

Objective 2: Determine the set recovery of impregnated and densified poplar and alder wood compared to untreated densified wood.

- Null Hypothesis (H0): There is no statistically significant difference in set recovery between impregnated and densified and untreated densified poplar and alder wood ( $p\text{-value} \geq 0.05$ ).
- Alternative Hypothesis (HA): There is a statistically significant difference in set recovery between impregnated and densified and untreated densified poplar and alder wood ( $p\text{-value} < 0.05$ ).

Objective 3: Examine the water repellence and dimensional stability of impregnated and densified poplar and alder wood compared to untreated densified wood.

- Null Hypothesis (H0): There is no statistically significant difference in water repellence and dimensional stability between impregnated and densified and untreated densified poplar and alder wood ( $p\text{-value} \geq 0.05$ ).
- Alternative Hypothesis (HA): There is a statistically significant difference in water repellence and dimensional stability between impregnated and densified and untreated densified poplar and alder wood ( $p\text{-value} < 0.05$ ).

Objective 4: Determine the mechanical properties of impregnated and densified poplar and alder wood compared to untreated densified wood.

- Null Hypothesis (H0): There is no statistically significant difference in mechanical properties (such as strength, impact, hardness, and elasticity) between impregnated and densified and untreated densified poplar and alder wood ( $p\text{-value} \geq 0.05$ ).

- Alternative Hypothesis (HA): There is a statistically significant difference in mechanical properties (such as strength, impact, hardness, and elasticity) between impregnated and densified and untreated densified poplar and alder wood ( $p\text{-value} < 0.05$ ).

Objective 5: Investigate the thermal resistance properties of impregnated and densified poplar and alder wood compared to untreated densified wood.

- Null Hypothesis (H0): There is no statistically significant difference in thermal resistance properties between impregnated and densified and untreated densified poplar and alder wood ( $p\text{-value} \geq 0.05$ ).
- Alternative Hypothesis (HA): There is a statistically significant difference in thermal resistance properties between impregnated and densified and untreated densified poplar and alder wood ( $p\text{-value} < 0.05$ ).

### **1.5. Significance of the study**

Wood is a renewable material with inherent dimensional instability, hygroscopicity, and vulnerability to degradation. By modifying wood through densification and impregnation with epoxidized soybean oil and synthetic resins, this study is intended to enhance its dimensional stability, mechanical strength, and heat resistance properties. The significance lies in the potential to improve the performance of wood as a structural material, enabling it to compete with non-renewable materials and expand its applications in areas such as flooring, cladding, and furniture. Overcoming set recovery challenges, densification of wood has shown promise in improving its density and mechanical properties. However, one persistent challenge is the set recovery or spring back of the densified wood when exposed to moisture after being relieved from the press. This study aimed to address this issue by investigating the effects of different treatments, including water-repellent impregnation, steaming, compression, and heat treatments. Epoxidized soybean oil and thermosetting resins such as melamine formaldehyde, epoxy, vinyl ester, and a blend of ESO and epoxy impregnation and subsequent compression by 25% and 40% of alder and poplar wood from an initial thickness of 20mm have highly improved density and associated mechanical properties as compared to controlled samples. The findings

will contribute to reducing or overcoming the set recovery problem, thereby advancing the field of wood modification. Broadening the use of low-density wood species Poplar and alder are low-density wood species commonly used in various applications. By examining the effects of wood modification techniques on these specific wood species, the study seeks to broaden their use in flooring, cladding, and furniture purposes. This expansion of their potential applications can lead to economic benefits for the wood industry as well as sustainable practices by utilizing renewable resources effectively. By improving its properties through modification methods, the study contributes to promoting the use of sustainable materials in construction and design. The findings of this research will provide valuable insights for researchers, manufacturers, and practitioners involved in the wood industry, supporting the development of innovative and eco-friendly solutions.

## **1.6. Literature Review**

The literature review is divided into two sections. The first section covers the theoretical background related to wood treatment, impregnation, modification, and densification, as well as their impact on various wood properties. The second section focuses on the conceptual framework and defines the terminologies used in the research.

### **1.6.1. Wood Modification**

Wood is naturally endowed with excellent and poor properties. Some of the inherent properties of wood limit its use as an exterior and modern structural material (Navi and Hager, 2004; Hill, 2006). The natural property varied between species (hardwood and softwood), trees, and parts of a tree (sapwood and heart wood). The basis of wood property is its chemical constituents. Altering the constituents and improving the desired qualities of wood are the targets of wood modifications. Wood modification is expressed as the procedure of applying a chemical, biological, or physical agent to an intended asset. The modified wood should be an environmentally friendly product during and after its service life (Hill, 2006).

Wood modification is broadly grouped into active and passive methods. Passive modification techniques are not targeted at altering the chemistry of wood but rather filling the cavities and surface layer coating to improve durability and reduce water absorption, and the reverse is true for active wood modifications (Hill, 2006). Based on the complexity of the process and properties of modified wood, commercialized modification methods are chemical, thermal, and impregnation techniques (Hill, 2011). Some of the commercially produced thermally modified woods are: thermowood, Plato wood, retification, and oil heat treatment (Rapp, 2001; Hill, 2006); chemically modified wood products such as acetylated wood and furfurylated wood; oil heat-treated wood, or Ecotan (Hill, 2006). Commercialization of wood modification is a recent phenomenon compared to research in the field. Thermal wood modification at the laboratory scale began in the 20th century, with further development in thermal and chemical modification methods carried out before 1940 (Hill, 2011).

### **1.6.2. Thermal Modifications**

Thermally modified wood is known for producing wood with enhanced dimensional stability and resistance to deterioration (Hill, 2006). Thermal wood modification was investigated for the first time by using high heat in saturated conditions, carried out by Thiemann in 1915 and followed by Stam and Hensen in 1916. The treatment temperatures used were 150 and 205 °C, respectively (Hill, 2006). The initial wood properties examined through the thermal treatment process include dimensional stability, durability, and mechanical properties (Esteves and Pereira, 2009). It is the most widely commercialised wood modification method: Lignostone and Lignifol in Germany; Staypak and Staybwood in the USA; Thermowood in Finland; Plato in Holland; Perdure and Retification in France; Le Bois Perdure in Canada; and thermal modifications using oils; Menz Holz in Germany (Hill, 2006). Each process varied in media of treatment (oil, vacuum, water, or inert), treatment duration, atmosphere, temperature, species, size, and catalyst used (Hill, 2006; Hill et al., 2021).

Thermal modification carried out in most commercial and laboratory settings uses temperatures in the range of 180–260 °C. Besides, lower temperatures (140 °C) have no significant effect on wood property, whereas higher temperatures (>300 °C) have a paramount

degrading impact. Thus, the impact of thermal wood treatments on wood property encompasses both positive and negative sides (Hill, 2006). The positive impact includes dimensional stability enhancement, reduction in hygroscopicity, and improvement of resistance to microbiological degradations, whereas reduction in strength properties such as toughness, rupture and abrasion resistance, and formation of splits and cracks are the drawbacks (Hill, 2006). High-temperature treatment of wood causes changes in the chemical constituents of wood through the decomposition of hemicellulose and lignin and the crystallisation of cellulose (Kocaefe et al., 2008). Darkening of colour, mass and volume reduction, change in polymeric constituents, reduction in strength properties except modulus of elasticity, improvement in dimensional stability, decreased anti-swelling efficiency, hygroscopicity, and decay resistance (Hill, 2006; Kocaefe et al., 2008).

The influence of thermal treatment on the chemical constituents of wood is different. Hemicellulose is the most and primarily affected wood polysaccharide; on the other side, cellulose is more resistant, and cellulose crystallinity increased at the expense of amorphous cellulose (Frey and Pereira, 2009). Yildiz et al. (2006) investigated the impact of heat treatment on the compression strength and chemical characteristics of spruce wood. 2, 6, and 10 hours at temperatures of 130, 150, 180, and 200 °C were used. The results demonstrate that the thermal influence of wood causes compression strength to decrease as temperature and exposure time rise.

### **1.6.3. Chemical Modifications**

Wood modifications using chemicals are expressed as a reaction between the wood hydroxyl group and the chemical reagent; thus, a covalent bond is created. Historically, chemical wood modification research was carried out in the early 1930s (Rowell, 1986). Since the middle of the last century, chemical modification has gotten attention (Gerardin, 2016). Like thermal treatment, chemical wood modifications improve dimensional stability, durability, strength, hardness, and hygroscopicity (Rowell, 2005). The wood hydroxyl group is a binding agent that determines natural and modified wood properties due to its affinity for water and reaction site-intentioned reagents (Gerardin, 2016).

Acetylation, furfurylations, and DMDHEU are only a few of the chemical wood alterations processes that exist (Mantanis, 2017). Chemicals used for wood modifications are anhydrides, i.e., acetic, butyric, phthalic, Succinic, Maleic, propionic, and butyric anhydrides, acid chlorides, ketones, carboxylic acids, different types of isocyanates, formaldehyde, acetaldehyde, difunctional aldehydes, chloral phthaldehyde acid dimethyl sulphate, alkyl chlorides,  $\beta$ -propiolactone, acrylonitrile, epoxides, i.e., ethylene, propylene, and butylene oxide, and difunctional epoxides (Rowell, 1983; Hill, 2006).

According to Cetin et al. (2011), acetylation of Scots pine using acetic anhydride and vinyl acetate in the presence of a catalyst increased weight percentage gain. The acetylation of wood, which results from the reaction of acetic anhydride with the substrate, is a widely studied chemical modification (Hills, 2006). The primary downsides of acetylation include acetic acid byproducts, which result in corrosion, an uncomfortable odour, and perhaps reduced wood strength (Hills, 2006; Mai and Miltz et al., 2023). The acetylation process enhances dimensional stability and decay resistance in solid wood, veneers, and composite materials (Rowell, 2004; Rowell and Dickerson, 2014).

The in-situ polymerization of furfuryl alcohol (FA) with ammonium dihydrogen phosphate (ADP) in poplar wood was the main topic of Kong et al.'s (2018) study. The hydrophobic FA resin/ADP network within the wood scaffold was created by the researchers by impregnating the FA precursor solutions into the wood matrix and polymerizing them upon heating. The hydrophobic FA resin was incorporated into the wood, which minimized water absorption and significantly improved dimensional stability.

Altgen et al. (2020) examined how impregnation modification using melamine significantly reduced moisture-related problems and improved dimensional stability. The study emphasized the importance of inserting the resin into the cell wall microstructure rather than just filling the cell lumen to achieve improved dimensional stability. Evans et al. (2015) treated wood with dimethylol dihydroxyethyleneurea (DMDHEU). They found that DMDHEU was able to dimensionally stabilize wood and provide some protection against weathering effects.

The impact of phenol formaldehyde (PF) resin impregnation on the mechanical characteristics and dimensional stability of *Pinus massoniana* wood was examined by (Wang et al., 2019). They discovered that PF resin not only filled the cell lumens but also entered the cell walls and interacted with the polymers within, improving the mechanical and dimensional

stability. In addition to these studies, other researchers have also investigated the effects of thermosetting resins on wood dimensional stability. Kocaefe et al. (2015) studied the dimensional stabilisation of southern yellow pine using MF and melamine-ammeline-formaldehyde (MAF) resins. Bao et al. (2016) discussed the effect of PF resin treatment on the hygroscopicity and surface characteristics of hybrid poplar. Wang et al. (2019) evaluated the effects of PF resin modification on the quasi-static and dynamic mechanics of wood cell walls using nano-indentation. Finally, Wang et al. (2021) investigated the in-situ cross-linking of waterborne epoxy resin inside wood for enhancing its dimensional stability, thermal stability, and decay resistance.

#### **1.6.4. Impregnation Modifications**

Impregnation modification is a process by which a wood material is either partially or fully filled with chemical substances. Thus, the wood cell wall was kept fully or halfway in a swollen state (Hill, 2006). Widely used impregnants are resins such as melamine, urea, phenol formaldehyde (Deka, 2000; Gabrielli and Kamke, 2010; Kocaefe et al., 2015), nano-aluminium (Taghiyari et al., 2017), plant oils such as linseed oil (Pelit and Emiroglu, 2019), modified plant oils such as Epoxidized linseed oil (Jebrane et al., 2015; Temiz et al., 2010; 2013), and epoxidized soybean oil (Demirel et al., 2018; Lebow, 2018), water glass, melamine, silicone, and tall oil (Lahtela and Kärki, 2014), and unsaturated polyester wax, which targets reducing water absorption (Kocafe et al., 2015).

Impregnation modification involves the use of various chemicals to enhance the properties of wood. Melamine formaldehyde is one of the most widely used resins for the impregnation of wood materials. It is used to improve the dimensional stability, moisture resistance of wood, and optimal improvement in hardness and other mechanical properties (Lou et al., 2017). In addition, alkali lignin has also been used for impregnation modification of wood. It is a renewable and toxicity-free industrial lignin that can be combined with heat treatment to enhance the water resistance and dimensional stability of wood (Zhou et al., 2018). Furthermore, other chemicals, such as ferric salt precursors, have been used in impregnation modification to introduce magnetic properties to wood. In situ synthesis of  $\text{Fe}_3\text{O}_4$  in wood through co-precipitation chemical interactions has been achieved using a vacuum impregnation followed

by a pressure impregnation method (Lou et al., 2017). Phase change materials are substances that can absorb and release thermal energy during phase transitions, such as solid-liquid or liquid-gas transitions. Impregnating wood with microencapsulated PCM can enhance its thermal mass and improve its thermal performance. This is particularly useful in applications such as engineered wood flooring, where the wood can act as a thermal energy storage medium (Mathis et al., 2018). Nanoparticles, such as silica nanoparticles, can be impregnated into the wood structure to enhance its mechanical properties. The nanoparticles can fill the voids and reinforce the wood structure, resulting in improved performance, dimensional stability, and moisture resistance in the wood. Polymers are impregnated into the wood structure to enhance its mechanical properties, such as tensile strength and impact resistance. The impregnation of polymers can also improve their durability and resistance to decay and insect attack (Mathis et al., 2018).

This method allows for the transport of an adequate amount of ferric salt precursor into the wood, resulting in the production of magnetic wood with excellent electromagnetic wave-absorbing properties (Lou et al., 2017). The impregnation of wood can improve its mechanical properties, such as bending strength and hardness (Song et al., 2021). In a study on impregnated wood after high-temperature conditions, it was found that the bending strength of the impregnated wood was slightly improved while the elastic modulus remained unaffected (Przystupa et al., 2020). The impregnation of wood with  $\text{SiO}_2$  nanoparticles was found to decrease the flammability of timber (Przystupa et al., 2020). Hydrothermal modification can improve the dimensional stability of wood by altering its chemical composition (Ali et al., 2021).

The impact of nano-clay and nano-sized particles of zinc oxide (ZnO), titanium oxide ( $\text{TiO}_2$ ), aluminium oxide ( $\text{Al}_2\text{O}_3$ ), and magnesium oxide (MgO) impregnation on the Scots pine sapwood on its physical, decay resistance, and thermal properties was studied. The effect of 10% PMMA on dimensional stability was positive, while nanoparticle impregnation slightly affected the water absorption properties; moreover, nanoparticles protect against decay by less than 5% weight loss (Holy et al., 2022).

The impregnation process can increase the resistance of wood to termite attack (Sumardi et al., 2020). In a study on *Falcataria* wood, impregnation with phenol formaldehyde resin successfully increased its dimensional stability and mechanical properties (Sumardi et al.,

2020). The impregnation of wood with SiO<sub>2</sub> particles resulted in an increase in the modulus of strength and impact resistance of the wood (Lemaire-Paul & Foruzanmehr, 2023).

The impregnant size should be small enough for easy permeability, and the wood material must be in a swollen state to facilitate the impregnation process and effective preservation (Hill, 2006). The methods used for wood impregnation involve either monomer impregnation followed by polymerization or the diffusion of a soluble material into the cell wall (Hill, 2006).

### **1.7. Wood Densification**

Wood densification is a process of improving the density of wood through compression (Kollmann et al., 1975; Navi and Heger, 2004; Shi et al., 2020). It improves density by reducing the presence of pores in the wood, which in turn affects hardness, strength, and abrasion resistance, making wood more suitable for structural purposes (Rademacher et al., 2017). Densification has the potential to expand the use of fast-growing, low-density wood species (Sandberg et al., 2013; Rademacher et al., 2017).

The compression direction of wood depends on the inherent properties of the wood. Radial compression is preferable for softwoods, while tangential compression is better for hardwoods (Kollmann et al., 1975; Bloomberg et al., 2005). Different densification methods, such as thermo-mechanical, thermo-hydro-mechanical, and viscoelastic-thermal compression, have been studied to improve the mechanical properties of wood (Albert & Liew, 2022). Chemical modifications, delignification, and the use of innovative coatings have also been explored to enhance the properties of densified wood (Cencin et al., 2021; Julian et al., 2022; Gan et al., 2020).

Densified wood exhibits improved mechanical properties compared to non-densified wood, including increased hardness and Young's modulus (Pelit et al., 2015). High-pressure densification, hydrophobic coating, ammonia treatment, and additional densification have been shown to improve dimensional stability and mechanical properties (Yu et al., 2020; Fang et al., 2019). Transverse compression increases wood density and impacts mechanical and physical properties positively (Hamid et al., 2016). Thermo-hygro-mechanically (THM) densified wood exhibits higher strength properties and improved surface hardness (Skyba et al., 2008). Overall,

wood densification methods have the potential to enhance the mechanical properties, dimensional stability, and fire resistance of wood materials, leading to a wide range of applications.

Table 1. Wood, direction of compression, densifications treatment used and properties examined

| Species used                                                                                                       | Compression Directions          | Comp. Degree      | Properties examined                                           | Densification Types used                                 | Authors                      |
|--------------------------------------------------------------------------------------------------------------------|---------------------------------|-------------------|---------------------------------------------------------------|----------------------------------------------------------|------------------------------|
| <i>Populus deltoides</i> and <i>trichocarpa</i>                                                                    | -                               | -                 | Dimensional stability and strength                            | VTC                                                      | Gabrielli, and Kamke (2010). |
| <i>Populus tomentosa</i>                                                                                           | Radial                          | 50,60 and 70      | Set recovery, Physical& mechanical                            | Thermo hydro mechanical                                  | Bao et al. (2017:2018)       |
| <i>Birch (Betula verrucosa Ehrh)</i>                                                                               | -                               | 6.7, 7.4 and 10.5 | Shear strength, WA and Thickness swelling                     | Short term thermo mechanical                             | Bekta et al (2018)           |
| Sugar maple                                                                                                        | Radial                          | -                 | Hardness, strength, stiffness & Set recovery                  | Thermo-hygro-mechanical                                  | Fu et al., (2017)            |
| Scots pine, Norway spruce silver birch, black alder and etc                                                        | Tangential, Radial Longitudinal |                   | Density, hardness and strength                                | Semi-isostatistical densifications                       | Bloomberg et al., (2005)     |
| Trembling aspen                                                                                                    | -                               | -                 | Density, Hardness, strength and stiffness                     | Thermo-Hygro-mechanical and Oil heat treatment           | Bustos et al.,(2012)         |
| <i>Populus (tremuloides)</i> and <i>hybrid poplar clone</i>                                                        | -                               | 50%               | Set recovery, Brinell hardness , Tensile and bending strength | Densified using heat, steam, and pressure                | Fang et al (2010)            |
| <i>Uludağ fir (Abies Bornmulleriana Mattf.)</i> , <i>Linden (Tiliagrandifolia Ehrh.)</i> , and <i>Black poplar</i> | Radial                          | 20 and 40 %       | WA and Set recovery                                           | Thermo-mechanical densifications and heat post treatment | Pelit et al.,(2018)          |

Table 1. Continued

|                                                     |                       |               |                                                                                                        |                                                          |                          |
|-----------------------------------------------------|-----------------------|---------------|--------------------------------------------------------------------------------------------------------|----------------------------------------------------------|--------------------------|
| <i>Fagus sylvatica</i> and <i>Populus tremula</i>   | Radial                | 10 and 20%    | Impact bending strength and Brinell Hardness                                                           | Mechanical compression                                   | Gaff et al., (2016)      |
| <i>Scots pine</i> and <i>Eastern beech</i>          | Radial                | 20 and 40%    | Hardness and density                                                                                   | Thermomechanical and heat treatment                      | Pelit et al.,(2015)      |
| <i>Fagus sylvatica</i>                              | -                     | -             | Bending strength                                                                                       | Densifications and cyclic loading                        | Gaff and Gasparik (2015) |
| <i>Chinese fir</i>                                  | Radial                |               | Dimensional, MOE and MOR.                                                                              | High pressure                                            | Li et al, 2016           |
| Uludağ fir, Linden Black poplar                     | Radial                | 25& 50 %      | Spring-back (SB), compression ratio recovery (CRR), thickness swelling (TS), and water absorption (WA) | Thermomechanical Densifications and heat post treatment  | Budakçı et al., (2016)   |
| <i>Eucalyptus grandis</i> and <i>pinus elliotti</i> | Radial                | 33%           | Physical and Mechanical                                                                                | Thermo-mechanical densifications                         | Pertuzzatti et al (2018) |
| <i>Pinus radiata</i>                                | Radial                | 50%           | Density, Hardness, MOE & MOR,                                                                          | Thermo-hygromechanical                                   | Cruz et al.,( 2019)      |
| Eech,Oak and pine wood                              | Radial                | 30, 2 and 23% | Density profile and hardness                                                                           | thermo-mechanical treatment                              | Laskowaska (2020)        |
| <i>Beech wood (Fagus sylvatica L.)</i>              | Radial and tangential | 50%           | Plasticization                                                                                         | Densification via microwave softening                    | Dömény et al.,(2017)     |
| <i>Scots pine</i>                                   | Radial                | 40, 50 & 60%  | Hardness and set recovery                                                                              | <i>Mechanical compression followed by heat treatment</i> | Laine et al., (2016).    |
| <i>Populus nigra</i>                                | Radial                | 33%           | Physical and Mechanical Properties                                                                     | <i>Thermal densifications</i>                            | Taghiyari et al., (2016) |

### 1.7.1. Wood Densification Technologies

Wood densification results depend on the ability to adequately control densification parameters, i.e., moisture, medium, time, temperature, and humidity, which can be controlled accurately throughout the treatment, whether it is a closed or open system (Sandberg et al., 2013). Thermo-hydro wood treatment is targeted at improving wood property, dryness, and

plasticity and is meant to avoid internal stress. Thermo-hydro-mechanical processes are, alternatively, intended for shaping, molding, welding, and improving wood quality (Sandberg et al., 2013). Thus, densified wood can be used for flooring (Laine et al., 2016).

Vibro-thermo-mechanical compression of wood is a process that integrates various treatments to enhance the mechanical properties of wood. This method combines vibration, heat, and mechanical compression to achieve the desired outcomes. The thermo-vibro-mechanical densification process has been demonstrated to increase bending strength and modulus of elasticity values by up to 50%, while compression strength can reach 67% higher than untreated wood (Budakçı et al., 2022).

Cyclic thermomechanical densification impacts on Iroko, Tauri, and oak wood were examined. Treatment temperatures used were 100 and 150 °C. The study revealed that the MOR of the Iroko wood, densified at 100 °C or 150 °C, after the second thermo-mechanical modification cycle was twice as high as before the modification, about 56%, in the MOE of oak wood densified at 150 °C (Laskowska, 2020).

Scots pine wood is impregnated with epoxidized soybean and linseed oil combined with boric acid with the aim of enhancing hydrophobic properties. The lowest water absorption values were obtained from wood treated with epoxidized oils. The highest ASE result (70%) was observed on samples treated with epoxidized soybean oil at low retention (108 kg/m<sup>3</sup>). It was also determined that most of the latewood tracheids were filled with oils when compared to the early wood tracheids (Demirel et al., 2020).

According to Li et al. (2021), the novel three-step treatment involving delignification, hydrophobization, and fast hot-pressing applied to basswood was detailed in the study by Li et al. (2021). This research highlighted the significance of delignified wood in various applications beyond traditional wood utilization, emphasising its potential in lightweight yet strong structural materials, energy storage and conversion, environmental remediation, flexible electronics, and bioengineering. Boric phenol formaldehyde resin (BPF) was used to impregnate Chinese fir and, subsequently, densified at different degrees (0, 10, 20, 30, and 40%) to amend the mechanical and combustion properties. The bending and compressive strengths of treated wood showed improvement as the compression degree increased. The ignition time was found to be longer for wood samples treated at a higher degree than untreated and densified wood at a lower degree. Additionally, untreated specimens quickly release more heat overall and at a faster pace than

treated wood does when it is impregnated and densified (Yue et al., 2020). Wood plastic composites of ESBO of different amounts (0, 5, 15, 25, 35 phr), polyvinyl chloride, and wood flour thermal and mechanical properties were evaluated. Thus, water absorption, thickness swelling, and elongation at the break increase as the ESBO amount increases, but the tensile strength, flexural modules, and strength decline. Besides, the thermal stability and melting property increase for 5–15 phr of ESBO addition (Xu et al., 2021).

The thermo-hydro-mechanical (THM) method involves exposing solid wood to the effects of temperature, moisture, and mechanical action. The THM technique is one of the methods used to make wood-based panels and a productive strategy to enhance the inherent qualities and create stable materials (Bao, 2017). Poplar wood was surface impregnated with a reactive waterborne acrylic resin, followed by unilateral surface densification and equilibration. The modulus of rupture (MOR) and modulus of elasticity (MOE) of the only surface-densified (OSD) wood increased by 28.2% and 37.6%, respectively, compared with the un-densified control. Samples with low WPG had comparable MOR and MOE to the OSD wood (Wu et al., 2017).

### **1.8. Theoretical Framework**

High-pressure treatment of Chinese fir at different pressure levels (50, 100, 150, and 200 MPa) for five minutes and subsequently densified uniformly. Thus, density, hardness in radial and tangential directions, MOR, and MOE increased, but dimensional stability varied depending on the relative humidity. As the relative humidity increases, the equilibrium moisture content increases. The radial, tangential, and volumetric dimensions of densified wood were unchanged at 33, 55, and 67% relative humidity, and huge swelling occurred at 86 and 93% relative humidity (Li et al., 2016b).

Pelit et al. (2016) investigated the effect of densification and post-thermal treatment of poplar and Uludağ fir wood against spring back, compression ratio recovery, and thickness swelling at two different levels of compression: compression temperature and thermal treatment temperature. In the study, 25 and 50%, 185 and 212 °C, and 100 and 140 °C compression degrees, compression temperatures, and heat treatment temperatures were used. The result showed that the lowest spring back was observed both in poplar and Uludağ fir at lower

temperatures of thermal treatment and compression degrees, but at the highest temperature of compression. Compression ratio recovery is highest in untreated wood, followed by wood densified at 185 °C. In addition, compression recovery declines as the thermal treatment temperature and compression degree increase.

The recovery set of densified wood is a critical factor in determining the dimensional stability and mechanical properties of the material. Set recovery refers to the ability of densified wood to return to its original dimensions after compression. High-set recovery can compromise the mechanical strength of the wood, making it less stable and more prone to deformation when exposed to moisture or changes in environmental conditions (Wang et al., 2021). Therefore, achieving low set recovery is essential for ensuring the long-term performance and durability of densified wood products. Spring back, also known as the spring back effect, is closely related to set recovery. It refers to the tendency of densified wood to return to its original shape or dimensions after being deformed or compressed (Wang et al., 2021). Spring back is important because it influences the overall stability and usability of densified wood products. Minimizing spring back is essential for maintaining the desired shape and structural integrity of the material, especially in applications where dimensional accuracy is critical. There is a distinction between a back and recovery set in densified wood. Spring back specifically refers to the elastic recovery of the material after deformation, while recovery set is a broader term that encompasses both elastic and plastic recovery processes (Scharf et al., 2023). Elastic recovery, or spring back, occurs immediately after the load is removed, while plastic recovery, or set recovery, involves a more gradual return to the original dimensions over time (Xiang et al., 2021).

Calculating the recovery set of densified wood involves measuring the extent to which the material returns to its original dimensions after compression. This can be done by subjecting the densified wood samples to cycles of wet-drying and measuring the dimensional changes after each cycle (Borges et al., 2022). The percentage of set recovery can be calculated by comparing the dimensions of the densified wood before and after the wet-drying cycles, providing valuable insights into the material's stability and performance over time.

The effects of densification, drying, and thermal treatments at 180–220 °C and durations of 2–5 h on wood chemical composition showed that heat treatments at higher temperatures and durations adversely affect the holocellulose content; however, the lignin contents oppositely increased. As a result, treated wood was shown to have lower hydrophobicity than untreated

wood (Li et al., 2016a). Balancing the alterations in holocellulose and lignin content to achieve the desired mechanical strength, durability, and hydrophobicity is essential for the effective utilization of treated wood in different applications. Moreover, treated wood is more dimensionally stable and durable than untreated wood.

Gabrielli et al. (2010), hybrid poplar wood impregnated with phenol formaldehyde and densified using viscoelastic thermal compression (VTC). Two different molecular weights (780 and 172 with 39 and 59% solid content, respectively) and three different concentrations of PF (5, 10, and 20) were applied. Higher-molecular-weight PF resins tend to have higher solid contents. This relationship is due to the fact that higher-molecular-weight resins contain more polymer chains per unit volume, leading to a higher concentration of solid components in the resin solution. As a result, resins with higher molecular weights often exhibit higher viscosities and solid contents, which can impact their impregnation and densification capabilities (Pizzi et al., 2020). Thus, the dimensional stability, anti-swelling efficiency, weight percentage gain, and Young's modulus, or MOE, increased as the concentration and molecular weight of PF increased. Moreover, thickness swelling declines as the concentration and molecular weight of PF increase.

The physical and mechanical properties of spruce wood treated with water, nano-silver, and subsequently densified were compared with those of dried, untreated densified wood and control specimens. Thus, spring back declined both in silver and water-treated wood; however, the best spring back (0.04%) after five cycles of soaking and drying was observed in nano-silver-treated densified wood at 150 °C for 4 h. Concerning the bending strength, untreated dry wood had the highest result, followed by silver-impregnated densified wood. Surface cracks are the main reasons for the decline in the hardness of water-treated wood. Furthermore, MOR and compression temperature showed an inverse relationship. The rigidity of wood increases as the temperature of treatment increases, which is associated with the degradation of hemicellulose at 175 °C. The impact resistance of silver-treated wood is highest at 4 hours of press time (Rassam et al., 2012).

Lykidis et al. (2020) demonstrated that poplar wood impregnated with melamine formaldehyde and subsequently thermo-hydro-mechanically densified at 150°C showed an improvement in overall density as the compression ratio increased. However, there is a declining trend in weight percentage gain with an increase in compression ratio, which is associated with

the leaching out of the resin during densification. Schwarzkopf (2020) densified three different wood species: poplar, spruce, and beech, after phenol-formaldehyde impregnation into wood. The density improvement following densification of poplar, spruce, and beech wood with compression ratios of 2.34, 1.92, and 1.34 resulted in a density change from 0.31 to 0.66 g/cm<sup>3</sup>, 0.42 to 0.71 g/cm<sup>3</sup>, and 0.72 to 1.18 g/cm<sup>3</sup>, respectively. The MOE and MOR of poplar, spruce, and beech wood are 22 and 265 GPa, 24 and 267 GPa, and 18 and 249 GPa, with control sample values of 7.2 and 63 GPa, 9.7 and 63 GPa, and 14.3 and 110 GPa, respectively. His recovery set result shows that spruce (36-38%), poplar (5-19.3%), and beech (1.9–4%) wood have shown decreasing degrees of set recovery, which is related to densification ratio, except in beech wood.

Abies wood densified after being chemically pre-treated using a NaOH/Na<sub>2</sub>SO<sub>3</sub> solution showed an improvement in density of up to 169%, and MOR and MOE also improved significantly. Moreover, sufficiently removing polymers resulted in an increment in the mean compression ratio of 80% in the radial direction (Shi et al., 2020). According to Song et al. (2018), densification of Basswood oak (poplar western red cedar (*Thuja plicata*) and eastern white pine (*Pinus strobus*) in a solution of sodium hydroxide (>97%, Sigma-Aldrich) and sodium sulfite (>98%, Sigma-Aldrich) and deionized (DI) water in two steps resulted in a high-performance structural material of about tenfold increase in strength, toughness, and ballistic resistance as well as greater dimensional stability.

Thermo-mechanical densification of Uludağ fir, Linden, and black poplar woods resulted in improved density, dimensional stability, and mechanical properties, i.e., MOE, MOR, and compression strength parallel to the grain (Pelit et al., 2018). Densification of veneer wood under the effects of heat, steam, and pressure increases density, which in turn affects modules of elasticity, modules of ruptures, and the Brinell hardness of wood materials (Laine et al., 2015; Fang et al., 2012; Kouba and Blanchet, 2008). Moreover, densification of wood materials reduces saturated moisture content and equilibrium moisture content (Kouba and Blanchet, 2008).

One of the drawbacks of wood densification is the inability to completely remove set recovery or memory (Laine et al., 2016; Song et al., 2018; Pelit et al., 2018). However, set recovery of densified Scots pine at 200 °C at compression ratios of 40 and 60% and thermal modification for 6 h following densification almost removed set recovery by 99% (Laine et al., 2016).

According to Fang et al. (2012), aspen and hybrid poplar veneer wood specimens were densified via steam, pressure, and heat. Following densification, oven dry density, Brunel hardness, modules of elasticity, tensile strength, and bending strength increased. In addition, the hygroscopicity of wood declined, i.e., the higher the temperature used for densification, the lower the hygroscopicity, and the mechanical property decreased slightly with increasing temperature. Recovery of veneers decreased at 180 °C, and no recovery was observed at 200 °C.

In comparison to non-densified veneers, aspen wood veneer treated with combined densification and oil heat treatment exhibited two to three times better hardness. A rise in tensile, bending, and dimensional stability was also observed. However, heating oil reduced its mechanical qualities. The tensile modulus of elasticity is not significantly affected by the heat treatment and densification of oil, but the bending modulus is enhanced. As a result, densification and oil heat treatments together improve the mechanical and physical characteristics of veneer wood (Fang et al., 2012).

Oil heat treatment of two wood species of poplar and Robinia wood using linseed, rapeseed, and sunflower in Hungary showed improved anti-shrinkage efficiency, dimensional stability, and compression strength, whereas mechanical properties declined (Bak and Nemeth, 2012). A study conducted by Bao et al. (2017) found that the thermomechanical densification of poplar wood containing high moisture content at 160 °C and different pressures and durations increased the mechanical properties (MOR and MOE) with an increase in the compression ratio.

The impact of steam and heat on the mechanical characteristics and dimensional stability of sugar maple wood that had been thermo-hygromechanically densified was examined (Fu et al., 2017). The densification of the wood involved four temperature stages, for example, 180, 190, 200, and 210°C with and without steam. Steam has been discovered to have a greater effect than heat. Compared to wood that was densified without steam, wood specimens that were densified with steam had enhanced hardness, bending strength, bending stiffness, compression set, and density. Likewise, the recovery of wood was lowered by high temperatures and steam densification.

Densifications of Aspen veneers and follow-up treatment with canola oil and successive nano-indentation techniques performed in early wood cells showed improved longitudinal

modulus of elasticity with or without oil heat treatment. Generally, the combined effect of THM and oil treatment improved the dimensional stability and mechanical properties of veneer wood (Bustos et al., 2012).

Vapour pre-treatment and densification of poplar (*Populus nigra*) wood improved the physical and mechanical properties, but the effect varies depending on the duration of vapour treatment, such that 4 h pre-treatment improved the properties while 6 h pre-treatment affected the contribution densification, but still better than controlled specimens. In other words, impregnation with nano-aluminum improved both the physical and mechanical properties; however, it is not feasible economically. 10-12% spring backs are still the main challenge in outdoor use where prolonged exposure to moisture or humidity is the condition (Taghiyari et al., 2017).

A study conducted to improve hardness and set recovery via surface densification of acetylated radiate pine wood showed improved set recovery and hardness, though compression was limited to 1mm of the outer layer (Laine et al., 2016). The set-recovery of rough or planed surfaces did not show a significant difference between acetylated and un-acetylated wood. This outcome was anticipated since surface roughness is not expected to have a notable impact on the generation or release of internal stresses. Following the second cycle, the set recovery slightly increased to 75% for the un-acetylated samples and 23.9% for the acetylated samples. This increase is likely due to the further release of internal stresses that occurred during compression. However, it is worth noting that the acetylated samples exhibited a higher increase in set recovery after the second cycle (up to 46% higher compared to the first cycle) compared to the un-acetylated samples (only a 3% increase compared to the first cycle).

Heat treatment temperature is found to influence the immediate spring back, set recovery, Brinell hardness, density profile, and mechanical properties of surface-densified wood. Spruce wood treated at 230 °C showed the highest immediate spring back and decreased with decreasing temperature. Bending strength and hardness increased after densification. Set recovery is found to be higher for untreated densified wood, and increasing thermal treatment decreases the MOE and MOR of surface densified wood. The density of surface-densified wood is higher in an untreated specimen than in a treated one (Kariz et al., 2017). This indicates that higher treatment temperatures result in less permanent deformation and better shape retention in the wood. The heat treatment temperature influences the immediate spring back, set

recovery, hardness, density profile, and mechanical properties of surface-densified wood. Higher treatment temperatures result in a higher immediate spring back but a lower set recovery. The densification process improves bending strength and hardness, but increasing thermal treatment decreases MOE and MOR. It also affects the density profile, with untreated wood exhibiting a higher density than treated wood.

The effect of densification on physical and mechanical properties is clear regardless of the type of densification: surface or bulk. However, the recovery of densified wood depends on the pre-treatment of the wood or the post-densification treatment of the wood. According to Steves et al. (2017), heat treatment after densification is more effective than heat treatment before densification. The hot press and thermal treatment of the oil palm trunk were examined by (wang and Hiziroglu (2015) against some properties of the physical and mechanical properties at 140, 180, and 220 °C and 2 MPa for 8 minutes. The oven dry density, hardness, MOR, and MOE increased with press. Hardness values decrease with temperature; densified samples had higher thickness swelling than untreated samples; thickness swelling was found to be higher after 48 hours of soaking in water; MOR values showed maximum at 140 °C and declined onwards; whereas MOE showed the highest at 220 °C and was followed by 140 °C. Generally, densification improves the density and surface quality of wood samples.

Table 2. Wood densification methods, country and press conditions used.

| Name                     | year | Country     | MC % | Pressure | Temp    | Explanations                            |
|--------------------------|------|-------------|------|----------|---------|-----------------------------------------|
| Lignostone               | 1940 | Netherlands | 10   |          |         | Biaxial compression of heated wood      |
| Staypack                 | 1948 | USA         | 6-12 | 12.8     | 160-180 | Compression of thin veneers, then glued |
| Compreg                  | 1951 | USA         | 8    | 8.5      | 140-150 | Compression of veneers                  |
| Impreg                   | 1943 | USA         |      |          |         | As Compreg but without compression      |
| Lignofol                 | 1940 | Germany     | 3-8  | 34       |         | As Compreg                              |
| Kunstharzschichtholz     | 1940 | Germany     | 12   | 60       |         | As Compreg but with synthetic resin     |
| Australian improved wood | 1942 | Australia   |      |          | High    | As Compreg but with synthetic resin     |

## **1.9. Conceptual Framework and Definition of Terms**

### **1.9.1. Impregnation and Densification**

Impregnation with hardening agents or resins can enhance the hardness of wood (Candelier, 2015; Laine et al., 2012) and influence its impact strength by modifying its fracture behavior and energy absorption capacity (Wang et al., 2020). Densification can increase the density and structural integrity, leading to improved impact strength (Candelier, 2015). It improves the dimensional stability of wood by reducing its hygroscopicity and susceptibility to moisture-related changes. Impregnation with hydrophobic agents can decrease water uptake and improve dimensional stability (Esteves & Pereira, 2009).

Densification can reduce the cell wall voids, limiting the swelling and shrinking of wood (Li et al., 2019). It can compress the wood structure, resulting in increased density (Laine et al., 2012). Impregnation and densification can influence the compression strength of wood by modifying its cellular structure and load-bearing capacity. Impregnation with reinforcing agents can enhance the compression strength (Huang et al., 2013). Densification can increase the density and structural integrity of wood, resulting in improved compression strength (Kutnar et al., 2010). Impregnation and densification processes can affect the stiffness of wood by altering its microstructure and load-bearing capacity. Impregnation with rigid polymers or cross-linking agents can increase the stiffness (Gindl et al., 2004) and Densification can induce compression stresses, resulting in increased stiffness (Sandberg et al., 2013).

Conceptual framework of the relationship between impregnation and densification on set recovery, physical and mechanical properties. The study examined effect of independent variables (impregnation/ treatments used and degree of compression) on dependent variables such density, recovery set, dimensional stability, strength, stiffness, other mechanical properties and thermal resistance properties.

### **1.9.2. Set Recovery**

Set recovery in wood refers to the phenomenon where compressed wood regains some of its original shape after the compressive force is removed. It can be influenced by impregnation

and densification processes, which alter the material's elastic and viscoelastic behavior. Impregnation can introduce cross-linking agents or polymers that enhance the recovery properties of wood (Smith et al., 2016). Densification can lead to changes in the cell wall structure and hysteresis effects, affecting the recovery set (Kutnar et al., 2015). Park et al. (2022) demonstrated that impregnation with epoxy can modify the properties of wood, potentially enhancing its elasticity. Furthermore, Neyses et al. (2017) offered insights into techniques to reduce the set-recovery of densified wood cells, which can affect the recovery set of wood.

Several methods have been proposed to address set recovery and enhance the dimensional stability of wood. Heat treatment is a common approach used to improve the dimensional stability of wood by modifying its physical properties (Korkut et al., 2008). Additionally, surface densification and impregnation with substances like phenol resin have been suggested to reduce set recovery in densified wood (Schwarzkopf, 2020; Laine et al., 2016). Chemical treatments, such as furfurylation and impregnation with furfuryl alcohol, have also been shown to enhance the dimensional stability of wood products (Kocaefe & Kocaefe, 2015; Pfriem et al., 2011). Furthermore, studies have investigated the effects of heat treatment, acetylation, and impregnation with substances like sodium silicate on reducing set recovery and increasing the hardness of wood (Sargent, 2019; Neyses et al., 2017). Additionally, the infusion of wood with specific compounds such as suberin monomers or *Tectona grandis* extractives, has been found to improve the dimensional stability of wood (Zhang & Ma, 2021; Li et al., 2017).

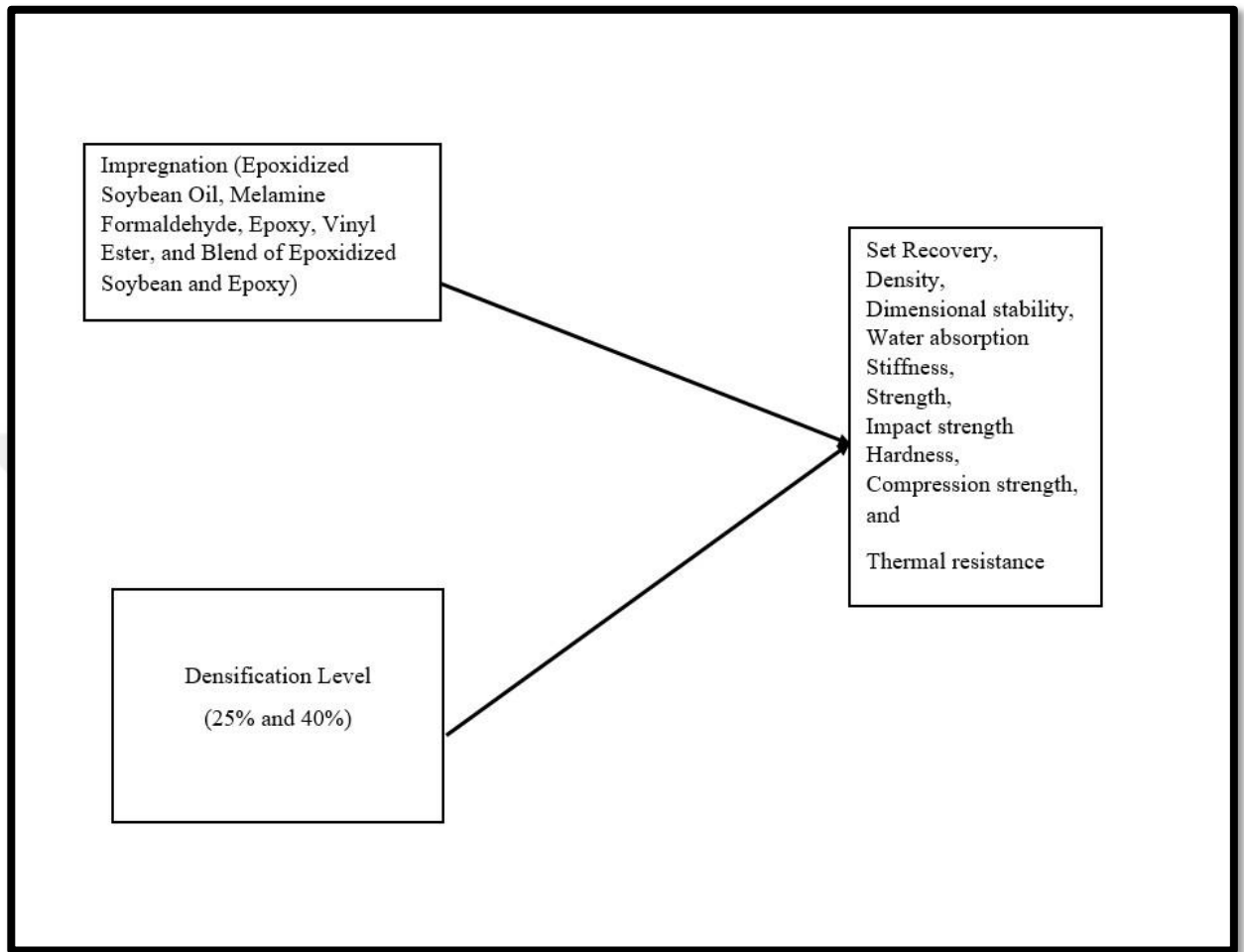


Figure 1. The conceptual framework of the study (independent and dependent variables).

### 1.9.3. Dimensional stability

The dimensional stability of wood is a key consideration in various applications, as it determines the material's ability to maintain its shape and size under changing environmental conditions. The dimensional stability of densified wood is a crucial parameter that can be significantly improved through various treatments and modifications. Studies by Čermák et al. (2015) and Cao et al. (2011) have investigated the effects of thermal modification and steam-heat treatment on the dimensional stability of wood, highlighting improvements in water absorption and swelling coefficients.

Swelling coefficients in wood are crucial indicators of dimensional stability. These coefficients represent the extent to which wood expands when exposed to moisture. Research has shown that various treatments and factors can influence these coefficients. For instance, studies have demonstrated that treatments like zinc chloride–silicone oil treatment can lead to a decrease in the tangential, radial, and volumetric swelling coefficients of wood (He et al., 2019). Additionally, ultrasound pretreatment has been observed to impact the volumetric swelling coefficient of wood (Shu et al., 2016). The analysis of dimensional changes due to chemical treatments has also been linked to changes in swelling coefficients (Ohmae et al., 2002).

Moreover, the presence of compression wood in spruce has been associated with variability in swelling coefficients, with transverse swelling coefficients decreasing proportionally to the increasing percentage of compression wood (Gryc et al., 2007). Anisotropy in swelling has been highlighted, with transverse swelling being significantly greater than longitudinal swelling, indicating that the swelling of wood is influenced by cell wall material at a microscopic level (Zhang et al., 2021). Furthermore, the anti-swelling efficiency of wood treatments has been calculated based on the comparison of swelling coefficients of treated and untreated wood (Medina-Gonzalez et al., 2012). The swelling coefficients of wood are affected by various treatments, wood types, and structural characteristics. Understanding and manipulating these coefficients are essential for enhancing the dimensional stability of wood in different applications.

The anti-swelling efficiency (ASE) has been used as a metric to evaluate the dimensional stability of treated wood, as demonstrated in studies by Yang & Jin (2021) and (Sejati et al., 2016). The dimensional stability of densified wood is influenced by various factors, including the treatment method, temperature, and chemical modifications. Research by Wang et al. (2021) and He et al. (2019) has shown that treatments like delignification and surface impregnation can enhance dimensional stability by reducing water absorption and improving water repellency. Additionally, densification processes like Thermo-Hygro-Mechanical (THM) treatments have been found to improve dimensional stability by reducing set recovery and enhancing mechanical properties (Bao et al., 2017; Fu et al., 2017).

Wood impregnated and densified with thermoset resin treatments exhibit enhanced properties. Research by Sandberg et al. (2017) highlights the positive outcomes of impregnating wood with melamine-formaldehyde (MF) resins, emphasizing the improvements in dimensional

stability and resistance to brown-rot fungi. Similarly, studies by Schwarzkopf (2020) and Shi et al. (2020) demonstrate that resin impregnation, especially with phenol resin, combined with thermal mechanical treatments, leads to densified wood with enhanced mechanical properties and reduced set-recovery.

Moreover, the densification process involving impregnation with thermoset resins followed by pressing and curing at high temperatures, as discussed by (Kocaefe & Kocaefe, 2015), contributes to the dimensional stabilization of wood. This process, known as viscoelastic thermal compression (VTC), has been shown to improve the properties of impregnated wood. Additionally, the work of Lahtela & Kärki (2014) suggests that moderate heat treatment can further enhance the properties of impregnated wood. Furthermore, studies by Pelit & Yalçın (2017) indicate that post-treatments involving steam, heat, and resin impregnation can reduce set-recovery and improve the resistance of densified wood to decay fungi. The research by Wang et al. (2021) also demonstrates that in-situ cross-linking of epoxy resin within wood enhances its dimensional stability, thermal stability, and decay resistance.

#### **1.9.4. Density**

The relationship between wood density and densification processes is crucial for understanding how the mechanical and physical properties of wood can be enhanced. Several studies support this relationship: Frey et al. (2018) emphasized that densification is a prominent process to achieve higher homogeneity in wood, with density being a key factor influencing mechanical properties. Shi et al. (2020) highlighted that wood densification can improve the strength of low-density wood species, thereby expanding the applications of wood products. Wang et al. (2021) reported that densification processes can lead to an increase in wood density, which can positively impact its mechanical properties. Hartono (2023) demonstrated that densification time significantly affects the density of wood, with densified wood showing increased density values compared to control wood. Mania et al. (2022) observed a significant increase in the compressive strength of densified wood, indicating a correlation between densification and density. Schwarzkopf (2020) focused on densified wood impregnated with phenol resin, which resulted in reduced set-recovery and improvements in density. Yalçın &

Esen (2022) highlighted that the densification process can convert low-density wood into high-value products by increasing wood density. Yu et al. (2020) found that densification can increase the mechanical strength of wood by increasing its density.

#### **1.9.5. Mechanical Properties**

Impregnation treatments, with thermosetting resins, can significantly influence the mechanical properties and dimensional stability of wood (Lee et al., 2008; Klüppel, 2017). Incorporation of thermosetting resins into the cell wall can alter the wood's properties, making it more brittle and affecting its modulus of elasticity (Klüppel, 2017). The compatibility of thermosetting resins with wood fibers in composite materials can impact the overall performance of wood-plastic composites (Lee et al., 2008).

Densification processes can lead to increased wood density, affecting its mechanical properties and dimensional stability (Kajaks & Kolbins, 2014; Sandberg et al., 2013). Densification combined with impregnation treatments can enhance impact strength and heat resistance of wood composites (Lima et al., 2022). Thermo-mechanical densification can modify wood to produce a denser and more resistant material, impacting its susceptibility to environmental factors (Lima et al., 2022). The interplay between impregnations with thermosetting resins and alterations in wood density through densification processes can result in improved mechanical properties, dimensional stability, and resistance to environmental factors. Impregnation treatments can enhance the density and dimensional stability of wood, while densification processes can further increase density and improve mechanical properties. The combined effects of impregnations with thermosetting resins and densifications play a crucial role in enhancing the overall performance of wood materials.

Impregnation treatments, such as with acrylate or oil, have been shown to influence the mechanical behavior and dimensional stability of wood (Lafond et al., 2017; Vasiliauskiene et al., 2023). Impregnation with melamine or epoxy nanocomposites can enhance density and dimensional stability, affecting the impact strength and stiffness of the material (Ilyin et al., 2017). Additionally, impregnation with shear-thickening fluids can improve impact resistance and water absorption properties (Koubaa et al., 2011; Ribeiro et al., 2022).

### **1.9.6. Impact Test and Charp's Principle**

The Charpy impact test assesses the material's ability to withstand sudden loading or force, providing insights into its toughness and durability. This test involves striking a notched wooden specimen with a pendulum hammer and measuring the energy absorbed by the specimen upon fracture. The energy absorbed during the impact test indicates the material's resistance to fracture and its ability to absorb impact energy without breaking. Studies like those by Fortin-Smith et al. (2018) have utilized Charpy impact testing to characterize the failure energy and strain-to-failure of wood species like northern white ash and sugar maple. The Charpy impact test is crucial in evaluating the impact resistance of wood, especially in applications where the material is subjected to sudden loading or impact forces, such as in structural components or sports equipment like baseball bats.

The impact test of wood based on the Charpy principle is a valuable method for assessing the material's toughness and ability to withstand impact forces, providing essential information for various engineering and structural applications.

### **1.9.7. Stiffness and Strength**

Stiffness, represented by the modulus of elasticity, is a measure of a material's resistance to deformation when subjected to an applied load. It indicates how much a material will deform under stress and is a crucial parameter in determining the material's ability to maintain its shape and support loads without permanent deformation. On the other hand, strength, as measured by the modulus of rupture, refers to the maximum stress a material can withstand before breaking. It signifies the material's ability to resist external forces and is essential in assessing its structural integrity and load-bearing capacity.

The key difference between stiffness (modulus of elasticity) and strength (modulus of rupture) lies in their respective roles in material behavior. Stiffness, quantified by the modulus of elasticity, primarily reflects a material's rigidity and ability to return to its original shape after deformation, providing insights into its flexibility and resilience under load. In contrast,

strength, as indicated by the modulus of rupture, focuses on the material's ultimate capacity to withstand stress before failure, highlighting its durability and load-carrying capability.

Stiffness (modulus of elasticity) and strength (modulus of rupture) are fundamental mechanical properties that play distinct roles in characterizing a material's behavior under load. While stiffness reflects a material's resistance to deformation, strength indicates its ability to withstand stress before failure, both crucial aspects in assessing the performance and structural integrity of materials.

#### **1.9.8. Compression Strength Parallel to Grain**

Wood impregnation is a process where various substances, such as resins, chemicals, or polymers, are introduced into the wood to enhance its properties. One of the critical measurements associated with wood impregnation is the compression strength parallel to the grain. This measurement assesses the ability of wood to withstand forces applied parallel to the direction of its grain fibers.

The compression strength parallel to the grain is a crucial parameter in determining the load-bearing capacity and structural integrity of wood products. Studies, by (Boonstra et al., 2007; Mankowski & Laskowska, 2021; Ruthes et al., 2023), have investigated the compression strength parallel to the grain of various wood species and the factors influencing this property. Understanding this measurement is essential for designing and constructing wood-based structures that require high strength and stability.

Measuring the compression strength parallel to the grain is essential for assessing the load-bearing capacity and structural performance of wood materials. This parameter plays a critical role in the design and construction of wood-based products, ensuring that they meet the necessary strength requirements for their intended applications. Studies like those by Boonstra et al. (2007) and Zhong et al. (2016) have investigated the effects of thermal modification and temperature exposure on the compression strength parallel to the grain of various wood species, highlighting the importance of this mechanical property in assessing wood performance under different conditions. The compression strength parallel to the grain is a critical parameter in evaluating the mechanical behavior and structural suitability of wood in various applications.

The compression strength parallel to the grain of wood is a key mechanical property that influences the load-bearing capacity and structural performance of wood components. Its measurement and understanding are essential in ensuring the safety, durability, and reliability of wood structures and products



## 2. MATERIALS AND METHODS

### 2.1. Wood

Poplar (*Populus tremula*) and alder (*Alnus glutinosa subsp. Barbata*) wood were used in this study. Both hardwood and low-density wood materials were obtained from local markets: Kepenekler Kollektif Stir, a wholesaler of wood materials; Orthisar; Trabzon; Turkiye.

#### 2.1.1. Poplar wood (*Populus tremula*) (L)

*Populus tremula* is commonly called Eurasian aspen (Caudullo and Rigo, 2016); European aspen or common aspen (Mackes and Lynch, 2001). It is a broad-leafed, medium-sized, reaching a height of 30m and up to 1m in diameter, fast-growing tree species native to cooler temperate and boreal regions of Europe and Asia. Next to Scots pine, it is the second most extensively cultivated species. It can tolerate a wide range of habitats. It is mainly used for veneer, pulp, and paper production. It possesses a low density and is poor in strength for use as structural materials (Mackes and Lynch, 2001; Caudullo and Rigo, 2016).

According to Öner and Aslan (2002), the air-dry and oven-dry densities of poplar wood are 0.42 g/cm<sup>3</sup> and 0.38 g/cm<sup>3</sup>, respectively. The total shrinkage and swelling percentages are 12.045% and 13.37%, respectively. Poor durability, strength, and stiffness are unfavorable properties for furniture and flooring uses (Abraham and Nemeth, 2012). Therefore, modifying and enhancing the natural properties of poplar wood is very vital.

The species belongs to the genus *Populus* in the family of *Salicaceae*. It is a deciduous tree growing up to 15–20 m tall. The species is dioecious. The mean dried weight is 450 kg/m<sup>3</sup>. Specific gravity (basic, 12% MC): 0.35, based on botanical standards of oven dry weight and green volume, and 0.45, wood workers specific gravity. Janka Hardness: 1.650 N, Modulus of Rupture: 62.0 MPa, Elastic Modulus: 9.75 GPa, Crushing Strength: 35.0 MPa, and Shrinkage: Radial: 4.8%, Tangential: 8.3%, Volumetric: 13.2%, T/R Ratio: 1.7, Straight grain with a uniform medium texture, diffuse-porous, solitary, and radial multiples, medium pores in no

particular arrangement, moderately numerous to many, light brown heart wood, and pale yellow to white sapwood; Marginal parenchyma with close-spaced, narrow rays that are considered weak and vulnerable to insect assault no odour, simple to work with both hand and machine equipment, and frequently used for veneer, plywood, boxes, and crates, among other utility uses.

It is a poor-strength material and is not preferred in large constructions, but is freely used for pallets, boxes, and fences and for producing chopsticks, lolly sticks, and wooden cutlery. To some extent, in the pulp and paper industry. The tracheid wood is porous, and no transition from early wood (EW) to latewood (LW) can be distinguished. Vessels and rays, which are small and can only be seen under a light microscope, constitute approximately 30% and 10% of the total wood volume, respectively (Bjurhager, 2007).

### 2.1.2. Alder Wood (*Alnus glutinosa* subsp. *Barbata*)

The birch family (*Betulaceae*), which includes *Alnus glutinosa*, is indigenous to Eurasia and northern Africa. Members of the *Alnus* genus are often referred to as alders; *A. glutinosa* is known as black alder. The *Alnus* genus was discovered by Carl Linnaeus in 1753. It has a 50-foot maximum height. It is frequently grown as an ornament, to enhance soil, and to control erosion. Normal growth ranges from 0 to 1300 meters above sea level. According to Shaw et al. (2014), *A. glutinosa*, a sizable deciduous tree that can reach heights of 20 to 30 m, favors moderate to cold climates and dry to moist soils.

Alder species have diverse uses in silviculture and the wood sector. It is used for coppicing, hedging, carving, and making wooden shoes. The wood has been called Scottish mahogany; it is resistant to rotting. The aesthetic and mechanical characteristics of alder wood make it suitable for many different uses, including charcoal, fibre for paper, though it has the problem of a red coloration, and fibre and particle boarding, but it is not suitable for use where strength is required (Claessens et al., 2010). This plant may become weedy or invasive in some regions or habitats and may displace desirable vegetation if not properly managed (Shaw et al., 2014).

*Alnus* species are represented in Turkey by two species from the *Alnus* subgenus, *Alnus glutinosa* L. and *Alnus orientalis*. These species are made up of six taxa, two of which are endemic. Because of its faster growth rate than the other six *Alnus* taxa, *A. glutinosa* subsp. *barbata* is the most economically valuable of the naturally distributed black alder taxa in Turkey. According to 2019 data, Turkey has 210, 223.1 hectares of *Alnus* spp. forest lands, of which 173, 628.9 ha are productive and 36, 594.2 ha are unproductive. Despite the fact that this taxon has a small share of its forest in Turkey, its fast growth and excellent biological regeneration capabilities make it important, particularly for the region (General Directorate of Forestry, 2020).

Both Poplar (*Populus tremula*) and Alder (*Alnus glutinosa*) wood used in this study are hardwood and low-density wood materials. The wood sample used was free from resin, knots,

and cracks. Air-dried wood, after 2-3 months of storage at 25 °C and 60% relative humidity, is oven-dried and impregnated with different treatments.

## **2.2. Chemicals**

Five different groups of treatments were compared with untreated densified wood. The groups examined in this study were: untreated densified wood, epoxidized soybean oil, and a blend of epoxidized soybean oil and epoxy (70:30). This ratio was determined based on a preliminary study (90:10, 80:20, and 70:30). Based on their impact on set recovery, 70:30 was selected. Melamine formaldehyde, vinyl ester resin, and epoxy were other groups considered in this study. The overall treatment process, including impregnation duration, pressure or vacuum used, and its curing process, as presented in Table 3.

### **2.2.1. Epoxidized soybean oil (ESO)**

Epoxidized soybean oil was bought from CHS Endüstriyel Ürünler San. Tic. A.Ş., Istanbul, Türkiye. Epoxidized soybean oil that was kept in room temperature increased in viscosity; therefore, heat was applied at 70 °C for 1 hour to lower the viscosity of Epoxidized soybean oil (Demirel et al., 2018). Once the epoxidized soybean oil heated for 1 hour to impregnate the wood sample, the rusting process, which included pre-pressure, pressure, and vacuum, was applied depending on the size of the sample with the aim of reducing the retention of oil. Following impregnation of epoxidized soybean oil, the weight of the wood sample was measured, and the retention level was determined. FTIR analyses were carried out to examine the epoxidation of epoxidized soybean oil. The epoxidized soybean oil was polymerized in a vacuum desiccator, where acetic acid was kept underneath a layer that separates ESO-impregnated wood. The epoxidized soybean cures at 70 °C for 14 days and is subsequently densified.

Table 3. Impregnation duration, pressure and vacuum applied in each test groups for poplar and alder

| <i>Treatment</i>     | <b>Dimensions</b> | <b>Pressure and Duration</b> | <b>Vacuum and Duration</b> |
|----------------------|-------------------|------------------------------|----------------------------|
| <b>ESO</b>           | Mechanical test   | 3.5 bar for 20 minutes       | 0.5 bar for 5 minutes      |
|                      | Physical test     | 2 bar for 10 minutes         | 0.5 bar for 5 minutes      |
|                      | Recovery test     | 2 bar for 5 minutes          | 0.5 bar for 5 minutes      |
| <b>Melamine</b>      | Mechanical test   | -----                        | 0.5 bar for 30 minutes     |
|                      | Physical test     | -----                        | 0.5 bar for 20 minutes     |
|                      | Recovery test     | -----                        | 0.5 bar for 15 minutes     |
| <b>Vinyl ester</b>   | Mechanical        | 3.5 bar for 20 minutes       | 0.5 bar for five minutes   |
|                      | Physical          | 2 bar for 10 minutes         | 0.5 bar for 5 minutes      |
|                      | Recovery          | 2 bar for 5 minutes          | 0.5 bar for 5 minutes      |
| <b>Epoxy</b>         | Mechanical test   | 4 bar for 10 minutes         | 0.5 bar for five minutes   |
|                      | Physical test     | 3 bar for 5 minutes          | 0.5 bar for 5 minutes      |
|                      | Recovery test     | 2 bar for 5 minutes          | 0.5 bar for 5 minutes      |
| <b>ESO and Epoxy</b> | Mechanical test   | 3.5 bar for 20 minutes       | 0.5 bar for five minutes   |
|                      | Physical Test     | 2 bar for 10 minutes         | 0.5 bar for 5 minutes      |
|                      | Recovery Test     | 2 bar for 5 minutes          | 0.5bar for 5 minutes       |

### 2.2.2. Melamine Formaldehyde

Melamine formaldehyde powder (37%) and hydrochloric acid were supplied from Gentas, Kimya, Istanbul and used to prepare melamine formaldehyde resin. Melamine-formaldehyde resin is an amine resin formed as a result of the polycondensation of melamine and formaldehyde.

The chemical formulas of melamine and formaldehyde are  $C_4H_8N_6$  and  $CH_2O$ , respectively. The resin is prepared by heating melamine powder of 5% concentration and 2.25% formaldehyde in water at 70 °C. Furthermore, 2.5 ml of HCL acid per 100 ml was added to the solution. The pH was then adjusted to 2, and the mixture was completed. The mixing process takes 12 hours. After the mixing process, it is ready for use when the blue colour appears. Melamine powder dissolves in water at 70 °C. The prepared mixture was impregnated via vacuum impregnation at the proposed retention level.

Table 4. Initial and target Sample size for physical, biological and mechanical tests in radial compression

| No       | Properties                 | Initial Thickness (mm)         | Densified Thickness (mm) |     | Replications |
|----------|----------------------------|--------------------------------|--------------------------|-----|--------------|
| <b>1</b> | Physical                   | Longitudinal*Tangential*Radial | 25%                      | 40% |              |
|          | Water Absorption           | 50*25*20                       | 15                       | 12  | 10           |
|          | Anti-swelling Efficiency   | 50*25*20                       | 15                       | 12  | 10           |
|          | Water repellent Efficiency | 50*25*20                       | 15                       | 12  | 10           |
|          | Density                    | 50*25*20                       | 15                       | 12  | 10           |
|          | Set recovery               | 20*20*20                       | 15                       | 12  | 10           |
| <b>2</b> | Mechanical                 | 300*20*20                      |                          |     |              |
|          | Modulus of Elasticity      | 300*20*20                      | 15                       | 12  | 15           |
|          | Modulus of Rupture         | 300*20*20                      | 15                       | 12  | 15           |
|          | Compression strength       | 30*20*20                       | 15                       | 12  | 15           |
|          | Impact Bending             | 100*10*10                      | 10                       | 10  | 10           |
|          | Hardness                   | 300*20*20                      | 15                       | 12  | 15           |
| <b>3</b> | Thermal Test (TGA)         | Wood powder 3-5gram            |                          |     |              |

### **2.2.3. Vinyl ester resin**

Vinyl ester resin was the other thermoset resin used for the impregnation of both alder and poplar wood. The vinyl ester resin used in this study was Derakane Momentum 470–300, bought from Kompozit Akademi, Istanbul, Turkiye. On a volumetric basis, it is mixed with an initiator, methyl-ethyl-ketone peroxide (P-MEK), and a catalyst 0.6% cobalt naphthenate (NafCO) in the range of 1.0–2.0%. It is a vinyl ester resin with bisphenol-A-based epoxy content. It has medium reactivity and low viscosity (170-250 cps). Vinyl ester resin, in addition to resin, contains cobalt hexa-octanate (an initiator) and methyl ethyl ketone peroxide (a catalyst). The prepared mixture was thoroughly mixed and impregnated using pressure and vacuum. The impregnated wood sample was cured at  $103\pm 2^{\circ}\text{C}$  for 24 hours.

### **2.2.4. Epoxy Resin**

Epoxy resin was bought from Tenomarine, Istanbul, Turkiye. It contains resin and hardener. The epoxy resin used was Teknomarin era-4000, which is colorless. The resin was prepared according to the guidelines of the manufacturer. Thus, epoxy resin was mixed with a hardener of 2:1 in weight; however, the immediate curing of epoxy was the main challenge to keep for hours before densifying impregnated materials. Therefore, epoxy-impregnated wood cures immediately.

In this study, vinyl ester and epoxy were prepared according to instructions from the product manufacturer. Vinyl ester resin, in addition to resin, contains cobalt hexa-octanate (an initiator) and methyl ethyl ketone peroxide (a catalyst). The prepared mixture was thoroughly mixed and impregnated using pressure and vacuum. Impregnated wood sample cured at  $103\pm 2^{\circ}\text{C}$  for 24hrs. Whereas epoxy resin was mixed with a hardener of 2:1; however, the immediate curing of epoxy was the main challenge to keep for hours before densification of impregnated materials. Therefore, epoxy-impregnated wood cures immediately.

### 2.2.5. Blend of ESO and Epoxy

This resin was prepared by mixing epoxidized soybean oil bought from CHS Endüstriyel Ürünler San. Tic. A.Ş. and Teknomarin Era-4000 epoxy bought from Teknomarin epoxy, Istanbul, Türkiye. Before mixing the two epoxies, initially, epoxidized soybean oil was heated at 70 °C for about 1 hour (to reduce the viscosity), while epoxy resin was prepared by mixing the resin with hardener on a volumetric or weight basis. Once both epoxies were prepared, the next step was mixing 70% of epoxidized soybean oil and 30% of epoxy resin. The mixed resin was stirred thoroughly. The blend of ESO and epoxy prepared in this manner was impregnated into the wood sample via vacuum and pressure application.

### 2.3. Impregnation Methods and Retention

The pre-impregnation, impregnation and post impregnation process of the treatment groups used were illustrate in Table 5.

Table 5. Pre-impregnation, impregnation process and curing temperature and duration used

| Treatment              | Pre-impregnation |          | Impregnation process                                                                   | Post impregnation or Curing process                                      |
|------------------------|------------------|----------|----------------------------------------------------------------------------------------|--------------------------------------------------------------------------|
|                        | Temp (°C)        | Duration |                                                                                        |                                                                          |
| ESO                    | 80               | 1h       | Heated oil impregnated using Rueping process by applying pressure, hot bath and vacuum | 70 °C for 14 days using vacuum dessicator in the presence of acetic Acid |
| Melamine Formaldehyde  | 70               | 2 h      | The solution at room temperature impregnated using vacuum                              | 70°C for 2 h                                                             |
| Vinyl ester            | -                | -        | Resin impregnated using Pressure and vacuum                                            | 103°C for 24 h                                                           |
| Epoxy                  | -                | -        | Resin impregnated using Pressure and vacuum                                            | 70°C for 30'                                                             |
| Blend of ESO and Epoxy | 80               | 1h       | The blend impregnated using Pressure and vacuum                                        | 70°C for 24 h                                                            |

The retention level of impregnant calculated according to formula in Equation 1. The oil retention level was within the range of 100-150 kg/m<sup>3</sup> used with aim of reducing oil absorptions, lowering cost and weight of wood sample.

$$\text{Retention (kg/m}^3\text{)} = ((G \times C) / V) \times 10 \quad (1)$$

$$G = G2 - G1$$

- G: The amount of impregnated material absorbed (gr)
- G1: Weight of the sample before impregnation (gr)
- G2: Weight of the sample after impregnation (gr)
- C: Solution concentration (%) and V: Sample volume (cm<sup>3</sup>)

### 2.3.1. Impregnation and Densification Process

During preliminary work to identify the direction of compression, alder and poplar wood densified both in the radial and tangential directions. The radial direction shows better compression without deformation than the tangential direction. To obtain the intended retention (100–150 kg/m<sup>3</sup>), both pressure and non-pressure methods were applied. The dipping method, in which wood samples were immersed in heating oil and only vacuum applied, vacuum pressure, and the empty-cell process were employed to impregnate the wood. Even though getting the intended retention possible with vacuum impregnation and heating in vegetable oil, depth of penetration was limited, thus the empty cell process for epoxidized soybean oil and vacuum-pressure impregnation employed for vinyl ester resin, epoxy, and a blend of epoxidized soybean oil and epoxy.

The impregnated wood with different impregnants was cured and, subsequently, densified to 40 and 25% compression degrees. Following densification, the densified sample was oven-dried. The oven-dried wood sample was kept in the conditioning room ahead of testing at 65±3% relative humidity and 20±2°C to make the wood weight stable following Turkish standards of moisture measurement (TS 2470, 1976) and the physical and mechanical properties measured according to TS 2471, 1976. Finally, the conditioned wood sample is tested according to the properties of the wood. The initial dimensions of the wood sample prepared were grouped into three categories according to the properties of the wood examined. Physical properties: density, retention, densification ratio, water absorption, anti-swelling efficiency, and water repellent efficiency. Compression strength parallel to the grain and set recovery. Mechanical

test (MOE and MOR, Hardness and Impact Strength) with the dimensions of  $20 \times 25 \times 50 \text{ mm}^3$ ,  $20 \times 20 \times 30 \text{ mm}^3$ , and  $20 \times 20 \times 300 \text{ mm}^3$  respectively.

Untreated densified wood was densified at  $160^\circ\text{C}$  without pre- and post-curing temperatures, but to find the oven-dry density of the densified sample, it was oven-dried at  $103^\circ\text{C}$  for 24 hours. For melamine-impregnated wood, a similar procedure was followed with untreated wood, except at room temperature and  $70^\circ\text{C}$  before compression. Epoxidized soybean oil impregnated wood in two different proportions, 100% and 70%, with the remaining 30% acetic acid, which was mixed using a hot plate mechanical stirrer for about 1 hour and cured at  $70^\circ\text{C}$  for two weeks using acetic acid in a vacuum desiccator. The densification temperatures applied were 160 and  $120^\circ\text{C}$ .

Vinyl ester resin impregnated via vacuum, curing, and compression temperature were different. Firstly, curing at room temperature and densification at  $160^\circ\text{C}$  are not effective in reducing set recovery and water absorption. Secondly, vacuum-pressure impregnated vinyl ester resin was cured for less than 30 minutes at  $70^\circ\text{C}$  and densified at the same temperature, and the post-densification curing temperature caused the resin to spring back. Finally, impregnated wood was cured at  $103^\circ\text{C}$  for less than 30 minutes, densified at  $120^\circ\text{C}$ , and post-densification cured at  $120^\circ\text{C}$  for 30 minutes. Curing at  $70^\circ\text{C}$  for less than 30 minutes and subsequent compression at the same temperature are less effective in reducing spring back.

A blend of ESO and epoxy with a proportion of 70:30 was applied. At this stage, epoxy, which is composed of a 2:1 resin and hardener, was mixed with ESO and heated at  $70^\circ\text{C}$ . Only epoxy was applied via pressure and vacuum. To overcome the immediate curing of epoxy, high-pressure vacuum-pressure impregnations were applied.

Thermo-mechanical densification processes used include steaming using an autoclave at  $140^\circ\text{C}$  for 30 minutes, mechanical compression using a hot process at  $160^\circ\text{C}$ , and 10, 20, and  $30 \pm 3$  bar using three successive stages of compression duration of 180, 180, and 800 seconds, respectively. Before densifications, air-dried samples were oven-dried and impregnated with treatments.

### 2.3.2. Densification Process

The cured wood sample was densified in two successive steps: steamed at 140 °C using water vapor for 30 minutes with the purpose of softening and densified to 25 and 40% of its initial thickness. After treatment, the densified wood's physical, mechanical, and thermal properties were evaluated. The compression temperature was selected based on Bao et al (2017) study on poplar wood. The properties of wood are not drastically changed at 140 °C and above, the wood easily densifies to 75%. Therefore, getting a high degree of compression after impregnation is almost impossible, except for less viscosity and lower concentrations of resins, i.e., melamine. In this study, a compression temperature of 160 °C was applied to get better compression without causing degradation of wood polymers.

Table 6. Types of treatments, durations, pressure and curing process applied.

| Treatments                   | Vacuum (bar) | Pressure (bar) | Curing temp (°C) | Compression temp (°C) |
|------------------------------|--------------|----------------|------------------|-----------------------|
| Untreated Densified          | -            | -              | -                | 160                   |
| Epoxidized soybean oil (ESO) | 0.7 bar      | 2.5bar         | 70               | 160                   |
| Blend of ESO and Epoxy resin | 0.7 bar      | 2.5 bar        | 70               | 160                   |
| Melamine Formaldehyde        | 0.7 bar      | 1bar           | 103              | 160                   |
| Vinyl Ester Resin            | 0.7 bar      | 2.5 bar        | 70               | 160                   |
| Epoxy Resin                  | 0.7 bar      | 2.5 bar        | 50               | 160                   |

Untreated and non-densified wood followed a similar procedure, whereas ESO and a blend of ESO and epoxy resin (70:30), melamine formaldehyde, and vinyl ester resin followed a similar procedure. The treated sample was kept in room temperature for a few days, depending on the treatment type, with the purpose of drying the specimens and oven-drying them to polymerize the wood. Impregnated and oven-dried wood was steamed at 140 °C for 30 minutes for small samples and 1 hour for large samples. After steaming, the prepared sample was densified using a hot press of a hydraulic machine at 160 °C and 30±3 bar pressure, which involves three steps of pressure applications: 10, 20, and 30 bar for the durations of 180, 180, and 300 seconds, respectively.

## 2.4. Determining Wood Properties

### 2.4.1. Physical properties

In this study, we assessed various physical properties of wood, including, density (both oven-dry and densified), water absorption, and dimensional stability (water repellent efficiency, anti-swelling efficiency, and Set recovery). Density measurements were conducted in accordance with Turkish standards specified in TS 2472 (1976), while water absorption characteristics were evaluated following the guidelines outlined by the American Wood Preservation Agency (AWPA) E4.

#### Compression Ratio

The compression ratio calculated by using the formula in equation 2.

$$CR = \frac{T_i - T_c}{T_i} * 100 \quad (2)$$

(Tu et al 2014; Wang et al., 2014; Pelit et al., 2018)

Where  $T_o$  is the initial thickness and  $T_c$  is the wood's thickness following compression. The specimens were densified in a 1x1 m<sup>2</sup> hot press for 20 minutes to achieve densification. The densification ratio, which is determined using the thickness after compression  $T_d$  in accordance with Equation 2 shows the actual degree of densification attained.

#### Water Absorptions

The water absorption test for all treatments determined by weighing densified oven dried and weighing wood sample after each water soaking durations for two weeks. The measurements were carried out after 1, 2, 4, 6, 24, 48, 72, 96, 144, 192, 240, 288, and 336 hr.

$$WA (\%) = \frac{W_2 - W_1}{W_1} * 100 \quad (3)$$

Where,  $W_1$  is the weight for each treatment groups ahead of water immersion and  $W_2$  is the weight after each durations of water soaking (Temiz et al., 2013).

### Water Repellent efficiency (WRE)

Water repellent efficiency determined according to the formula indicated in equation 4

$$WRE = \frac{(W_w - W_t)}{W_w} * 100\% \quad (4)$$

Where,  $W_c$  and  $W_t$  is the percentage of water uptake by the control (untreated) specimens and the treated specimens, respectively. Treated specimens in this study implies; Epoxidized soybean oil, Melamine Formaldehyde, Vinyl ester, Epoxy and Blend of ESO and Epoxy impregnated and densified wood. According to equation (4), the specimen weight after soaking and the compacted oven-dry weight specimens were used to calculate both uptake percentages.

An improvement in the decrease of the water/moisture uptake by the oil heat treatment is indicated by a positive, high value of WRE, which signifies that the treated wood absorbs less water/moisture than the untreated wood (Dubey, 2010; Hill, 2006).

$$W_c = \frac{(W_2 - W_1)}{w_1} * 100\% \quad (5)$$

$$W_t = \frac{(W_2 - W_1)}{w_1} * 100\% \quad (6)$$

Where,  $W_1$  is oven dry weight of the specimens before test (g) and  $W_2$  is the weight of the specimens after testing for a specific period (g).

### Swelling coefficient and Anti-swelling Efficiency

One features of dimensional stability indicators of wood is anti-swelling efficiency. It is determined according to Eq. 7 (Gabriel and Kamke, 2008; Schwarzkopf, 2020)

$$ASE = \frac{(S_c - S_t)}{S_c} * 1 \quad (7)$$

In which,  $S_c$  and  $S_t$ , is the volumetric swelling of untreated and treated specimens, respectively. They were determined by the following equation;

$$S_c \text{ or } S_t = \frac{(V_2 - V_1)}{V_2} * 10 \quad (8)$$

Where,  $V_1$  and  $V_2$  is the oven-dry volume of the specimens before and after the test ( $\text{cm}^3$ ). The positive high value of ASE implies that the treatment used reduced the volumetric swelling significantly (Rowell, 2004; Hill, 2006; Dubey, 2010).

#### Density

For the air-dry density, the wood samples were stored in a conditioning chamber at a room temperature of  $20 \pm 2^\circ\text{C}$  and a relative humidity of  $65 \pm 3\%$  until their weight stabilized. Subsequently, the dimensions and weight of the wood samples were determined following the procedure outlined by Pelit et al. (2018). Using an analytical balance with a sensitivity of 0.01 g, the mass ( $M$ ) of each sample was measured. The oven-dry density was determined by measuring the thickness and mass of the wood samples after they had been dried in an oven at  $103 \pm 2^\circ\text{C}$  until constant weight. The oven-dry and air-dry density values were calculated in accordance with Turkish standard 2472 (1976) as follows:

$$\delta = m/v \text{ (g/cm}^3\text{)} \quad (9)$$

#### Set recovery

There are varied ways of evaluating set recovery of densified wood, but fundamentally categorized into water soaking and relative humidity method (Laine et al., 2013). In this study, densified wood set recovery examined through water soaking test. Initially, air dried wood sample dimension measured and subsequently oven dried. Following compression of impregnated wood, oven dried for 24 h kept in room condition overnight and immersed in water for about 24 h and then, oven dried at  $103 \pm 2^\circ\text{C}$ . The sample thickness or dimension recorded after compression, after the densified sample oven dried, after the oven dried sample water immersed for 24 h and finally, the water-soaked sample oven dried. The sample thickness and weight measured before and after treatment (Laine et al., 2016; Fua et al., 2017; Schwarzkopf, 2020).

$$\text{Set recovery} = \frac{(T_r - T_d)}{T_i - T_d} \% \quad (10)$$

Where,  $T_i$  is the original thickness before densification,  $T_r$  is the thickness after soaking and oven drying, and  $T_d$  is the actual thickness after densification.

#### 2.4.2. Mechanical Properties

Evaluation of the mechanical characteristics of impregnated densified wood, including its hardness, impact strength, and compression strength perpendicular to the grain, was another objective of this work. Following densification of wood, the effects of ESO and other treatments on mechanical properties were evaluated.

**Hardness:** The hardness of wood can be determined using different methods, such as the Shore D and Brinell hardness tests. The Shore D hardness test measures the resistance of a material to indentation using a durometer, while the Brinell hardness test measures the resistance of a material to indentation using a hardened steel ball (Sydor et al., 2020). The Brinell hardness test has been widely used for determining the hardness of wood flooring materials. It has been found to provide reliable results compared to other hardness methods (Sydor et al., 2020). In this study, hardness of wood measured using Shore-D hardness and converted into Brinell using a formula developed based on hardness table (Leonghut, 2021; Engineers edge, 2022; Upmold, 2022).

**Strength and stiffness:** Strength and stiffness in bending are generally expressed as modulus of rupture (MOR) and modulus of elasticity (MOE), respectively. The measurement follows three point bending and applied following International organization for standardization (ISO). According to ISO 3349 and ISO 3333:1975, the sample size used to determine modulus of strength and Modulus of elasticity is 20×20×300 mm.

$$\text{MOR} = \frac{3P_{\text{max}} * L}{2bd^2} \quad (11)$$

$$\text{MOE} = \frac{\Delta P * L^3}{4\Delta * b * d^3} \quad (12)$$

Where,  $b$  is the width of test specimen,  $h$  is depth of test specimen (mm),  $L$  is supporting span (mm),  $P_{max}$  is the maximum load when the beam is broken (N),  $P$  is the load in N within the proportional deflection (N) and  $\Delta$  is the deflection at mid-length below the proportion deflection limit (mm).

Compression strength parallel to the grain (CS)

$$CS = \frac{3P_{max}}{bd} \quad (13)$$

Where,  $P_{max}$  is the maximum load applied to the samples (N),  $b$  is the width of the samples (mm),  $d$  is the thickness of the samples (mm).

Impact bending strength: In this study, based on the availability of testing machine, the impact bending strength were determined following charpy's principle. The IBS was calculated in accordance with ISO 3348 (1975), and Equation (14),

$$A = \frac{Q}{bh} \quad (14)$$

Where,  $A_w$  is the IBS of wood ( $J/cm^2$ ),  $Q$  is the work needed for breaking the sample (J),  $b$  is the width of the sample (cm), and  $h$  is the height (thickness) of the sample (cm). The IBS values of unmodified wood were converted to the moisture content of 12% in accordance with ISO 3348 (1975), and

$$A_{12} = A_w[1 + \alpha(w - 12)] \quad (15)$$

Where  $A_w$  is the IBS of wood at certain moisture content during testing ( $J/cm^2$ ),  $A_{12}$  is the IBS of wood at the moisture content 12% ( $J/cm^2$ ),  $w$  is the moisture content of sample during testing (%), and  $\alpha$  is the moisture correction coefficient, which was taken to be equal to 0.02% for all wood species. Impact test determines the amount of energy absorbed by a material during fracture. This absorbed energy is a measure of a given material's toughness. The principle works by failing a hammer from along circular trajectory from one point to another (Gašparík et al., 2016).

**Analytical Tests:** The thermal resistance of untreated and impregnated and densified wood examined without considering the compression ratio using thermogravimetric analysis and the heat resistance property evaluated. Thermal resistance of untreated and treated Alder and Poplar wood were examined at temperature range of 30°C to 800°C, 10°C/min heating rate and 200 ml/min Nitrogen input using HITACHI STA 7000 device. To determine the performance of Impregnated and densified wood against heat, the initial and residual weight were calculated and the percentage weight loss of for each group were formaldehyde, Vinyl ester resin , epoxy and Blend of epoxy and ESO impregnated densified wood were considered for thermal analysis regardless of compression ratio. The thermal analysis were carried out in the range of lowest initial temperature of 25°C-34°C and maximum temperature of 795 °C. The residual weight or weight loss of Poplar and Alder wood after exposed to maximum temperature of 795°C under all treatment conditions. The effect of each treatment groups on heat resistance, determined by calculating the difference weight between initial and residual weight.

## 2.5. Statistical Analysis

Using SPSS version 26's one-way ANOVA and 95% confidence interval, the mechanical, physical, and thermal resistance attributes of treated and untreated densified wood evaluated and compared. Moreover, Duncan test is used to compare treatment groups.

Table 7. Summary of test methods, standards, size and replication to be used

| Property   | Test                                                                                                      | Standards Followed                | Initial dimension         | Replication |
|------------|-----------------------------------------------------------------------------------------------------------|-----------------------------------|---------------------------|-------------|
| Physical   | Water absorption, Water repellent Efficiency , Swelling Coefficient, anti-swelling Efficiency and Density | AWPA E4                           | 20×25×50 mm <sup>3</sup>  | 10          |
| Mechanical | Compression strength and Set recovery                                                                     | TS 2471 and 2472                  | 20x20x30 mm <sup>3</sup>  | 10          |
|            | Modulus of Rupture                                                                                        | TS 2478                           | 20×20×300 mm <sup>3</sup> | 15          |
|            | Modulus of Elasticity                                                                                     | TS 2478                           | 20×20×300 mm <sup>3</sup> | 15          |
|            | Compression strength parallel to the grain                                                                | TS-2595                           | 20×20×30 mm <sup>3</sup>  | 15          |
|            | Impact Bending strength                                                                                   | ISO 13061-10.                     | 10x10x100mm <sup>3</sup>  | 10          |
|            | Hardness test                                                                                             | Shore D Hardness                  | 20x20x300mm <sup>3</sup>  | 15          |
| Analytical | Determination of thermal resistance                                                                       | Thermo-gravimetric analysis (TGA) |                           | 3-5gm       |

### **3. RESULTS AND DISCUSSION**

#### **3.1. Retention of Impregnants**

The retention of chemicals or impregnant used in this study was determined and presented in Table 8. Overall, the mean retention used was between 100 and 150 kg/m<sup>3</sup>. The retention level used for each treatment group and wood type was evaluated due to the variability of wood dimensions used for different wood properties, such as mechanical (MOE, MOR, and hardness) and physical (density, water absorption, water repellent efficiency, swelling coefficient, and anti-swelling efficiency).

The lowest mean retention level recorded in epoxy-impregnated poplar wood was between 117 and 126 kg/m<sup>3</sup>, with the highest retention levels being 150 (ESO) Kg/m<sup>3</sup> and 149 (vinyl ester) Kg/m<sup>3</sup>. Whereas, in alder wood, the highest retention obtained was 150 kg/m<sup>3</sup> with ESO impregnation, 117 kg/m<sup>3</sup>, and 128 kg/m<sup>3</sup> with epoxy impregnation.

Table 8. The average retention level (Kg/m<sup>3</sup>) for both poplar and alder wood

| Treatment Groups | Properties           | Dimension                                           | Poplar (Kg/m <sup>3</sup> ) |             | Alder (Kg/m <sup>3</sup> ) |            |
|------------------|----------------------|-----------------------------------------------------|-----------------------------|-------------|----------------------------|------------|
|                  |                      | (Radial*Tangential*Longitudinal)<br>mm <sup>3</sup> |                             |             |                            |            |
|                  |                      |                                                     | CR:25%                      | CR:40%      | CR:25%                     | CR:40%     |
| ESO              | Mechanical           | 20*20*300                                           | 129 (9.5)                   | 136 (11.00) | 137(7.34)                  | 137(7)     |
|                  | Physical             | 20*25*50                                            | 130 (9.66)                  | 138 (11.79) | 150(16.95)                 | 140(11.70) |
|                  | Set recovery         | 20*20*20                                            | 150 (9.6)                   | 140 (11.65) | 130(14.76)                 | 138(3.90)  |
|                  | Compression Strength | 20*20*30                                            | 130 (14.8)                  | 138 (3.90)  | 150(9.66)                  | 140(11.79) |
| Melamine         | Mechanical           | 20*20*300                                           | 148 (6.5)                   | 142 (11.00) | 142(14.9)                  | 144(7.97)  |
|                  | Physical             | 20*25*50                                            | 141(5.92)                   | 136(10.39)  | 129(5.13)                  | 141(10.38) |
|                  | Set recovery         | 20*20*20                                            | 129(14.13)                  | 141(14)     | 141(9.23)                  | 132(8.82)  |
|                  | Compression Strength | 20*20*30                                            | 141(9.23)                   | 136(8.82)   | 129(14.14)                 | 141(14)    |
| Vinyl ester      | Mechanical           | 20*20*300                                           | 144(7.15)                   | 145(7.08)   | 141(12.25)                 | 141(9.27)  |
|                  | Physical             | 20*25*50                                            | 145(14.58)                  | 141(13.62)  | 146(10.62)                 | 149(21.29) |
|                  | Set recovery         | 20*20*20                                            | 147(9.66)                   | 149(16.74)  | 136(14.06)                 | 136(7.48)  |
|                  | Compression Strength | 20*20*30                                            | 145(14.06)                  | 141(7.48)   | 148(9.66)                  | 149(16.74) |
| Epoxy            | Mechanical           | 20*20*300                                           | 130(10.96)                  | 126(9.11)   | 132(7.24)                  | 130(11.36) |
|                  | Physical             | 20*25*50                                            | 132(10.80)                  | 136(11.53)  | 117(10.79)                 | 128(11.53) |
|                  | Set recovery         | 20*20*20                                            | 117(11.46)                  | 128(16.74)  | 145(10.53)                 | 136(13.27) |
|                  | compression Strength | 20*20*30                                            | 132(10.58)                  | 136(13.27)  | 117(11.46)                 | 128(5.65)  |
| ESO and Epoxy    | Mechanical           | 20*20*300                                           | 127(10.66)                  | 136(16.25)  | 135(19.72)                 | 137(10.52) |
|                  | Physical             | 20*25*50                                            | 134(9.15)                   | 140(3.13)   | 145(8.49)                  | 133(11.89) |
|                  | Set recovery         | 20*20*20                                            | 145(9.66)                   | 133(19.63)  | 141(19.63)                 | 139(9.90)  |
|                  | Compression Strength | 20*20*30                                            | 134(9.36)                   | 140(9.90)   | 145(9.66)                  | 133(19.6)  |

The values in bracket are standard deviation

### 3.2. Compression Ratio

The compression ratios of untreated and treated samples were measured after curing. The initial sample thickness for all samples was 20 mm, except for impact testing, where a thickness of 10 mm was used. These initial thicknesses were densified by 25% and 40%. For the 25% densified sample, the compression ratios ranged from 24.15% to 26.15% and for 40% densified sample, the compression ratio ranges from 38.22% to 42.58%.

Table 9. The actual compression ratio of both wood types

| 25% Densified          | Physical |       | Mechanical |       | Set recovery |       | Compression strength |       |
|------------------------|----------|-------|------------|-------|--------------|-------|----------------------|-------|
|                        | Poplar   | Alder | Poplar     | Alder | Poplar       | Alder | poplar               | Alder |
| Untreated Densified    | 25.82    | 25.84 | 25.59      | 25.81 | 25.47        | 25.47 | 25.59                | 25.47 |
| ESO                    | 26.15    | 24.15 | 25.92      | 24.12 | 25.11        | 25.11 | 25.69                | 25.11 |
| Melamine FD            | 26.09    | 25.26 | 25.86      | 25.23 | 25.13        | 25.13 | 24.72                | 25.13 |
| Epoxy                  | 25.99    | 25.23 | 25.76      | 25.2  | 24.78        | 24.6  | 24.83                | 24.6  |
| Vinyl ester            | 26.06    | 24.18 | 25.83      | 24.15 | 25.46        | 25.98 | 25.29                | 25.98 |
| Blend of ESO and Epoxy | 25.16    | 25.60 | 24.93      | 25.57 | 25.35        | 25.68 | 25.03                | 25.68 |
| 40% densified          | Physical |       | Mechanical |       | Set recovery |       | Compression strength |       |
|                        | Poplar   | Alder | Poplar     | Alder | Poplar       | Alder | Poplar               | Alder |
| Untreated Densified    | 40.36    | 39.91 | 40.74      | 39.83 | 40.31        | 40.31 | 41.067               | 39.83 |
| ESO                    | 41.99    | 41.54 | 39.55      | 38.6  | 41.94        | 41.94 | 39.058               | 38.46 |
| Melamine FD            | 42.42    | 42.18 | 40.20      | 39.38 | 42.37        | 42.58 | 41.376               | 42.33 |
| Epoxy                  | 38.76    | 39.5  | 39.42      | 38.57 | 38.71        | 39.30 | 38.610               | 39.46 |
| Vinyl ester            | 38.63    | 39.1  | 40.65      | 39.92 | 38.58        | 38.90 | 39.030               | 39.01 |
| Blend of ESO and Epoxy | 38.13    | 38.9  | 38.73      | 38.99 | 38.08        | 38.65 | 39.560               | 38.43 |

### 3.3. Physical Tests

#### 3.3.1. Density

Oven dry and densified densities of poplar and alder wood were given in Table 10 and Figure 7. The percentage change in density of impregnated densified and untreated densified wood in Table 10 shows that in poplar wood, vinyl ester brought the highest change, followed by epoxy, melamine formaldehyde, a blend of ESO and epoxy, ESO, and untreated densified wood in their descending order after 40% compression. The highest and lowest change were 132.26% and 87.88%, respectively. In the case of alder wood, vinyl ester resin, epoxy, a blend of epoxy and ESO, melamine formaldehyde, and untreated densified wood, the enhancement of density is shown in decreasing order. The highest change was 102%, while the lowest change

was 63.27% in untreated dense wood. The result supports the claim that impregnation and densification significantly improved the density of both poplar and poplar wood. Therefore, we can accept alternate hypotheses that impregnated and densified wood show a significant density difference over untreated densified wood.

Table 10. Oven dry and densified density of poplar and alder wood

| <b>Poplar Wood</b>             | Oven dry<br>(g/cm <sup>3</sup> ) | CR25%<br>(g/cm <sup>3</sup> ) | %Change      | CR40%<br>(g/cm <sup>3</sup> ) | %Change       |
|--------------------------------|----------------------------------|-------------------------------|--------------|-------------------------------|---------------|
| Untreated Densified            | 0.33                             | 0.42                          | 27.27        | 0.62                          | 87.88         |
| Melamine Formaldehyde Treated  | 0.31                             | 0.51                          | 64.52        | 0.66                          | 112.90        |
| Epoxidized Soybean Oil Treated | 0.32                             | 0.62                          | 93.75        | 0.67                          | 109.38        |
| Blend of ESO and Epoxy (70:30) | 0.32                             | 0.49                          | 53.13        | 0.67                          | 109.38        |
| Epoxy Treated                  | 0.32                             | 0.60                          | 87.50        | 0.69                          | 115.63        |
| Vinyl ester Resin Treated      | 0.31                             | 0.56                          | 80.65        | 0.72                          | 132.26        |
| <i>Average</i>                 | <i>0.32</i>                      | <i>0.53</i>                   | <i>65.80</i> | <i>0.67</i>                   | <i>108.81</i> |
| <b>Alder Wood</b>              |                                  |                               |              |                               |               |
| Untreated Densified            | 0.49                             | 0.64                          | 30.61        | 0.80                          | 63.27         |
| Melamine Formaldehyde Treated  | 0.49                             | 0.69                          | 40.82        | 0.82                          | 67.35         |
| Blend of ESO and Epoxy (70:30) | 0.49                             | 0.75                          | 53.06        | 0.86                          | 75.51         |
| Epoxidized Soybean Oil Treated | 0.49                             | 0.81                          | 65.31        | 0.86                          | 75.51         |
| Epoxy Treated                  | 0.52                             | 0.77                          | 48.08        | 0.93                          | 78.85         |
| Vinyl ester Resin Treated      | 0.50                             | 0.83                          | 66.00        | 1.01                          | 102.00        |
| <i>Average</i>                 | <i>0.50</i>                      | <i>0.75</i>                   | <i>50.67</i> | <i>0.88</i>                   | <i>77.18</i>  |

The degree of density improvement following 25 and 40% compression differs according to the treatment types used. The percentage of density increment for poplar wood after 25 and 40% compression is higher than that for alder wood, which is related to the lower initial oven-dry density of poplar (0.3 g/cm<sup>3</sup>) and the higher alder wood density (0.5 g/cm<sup>3</sup>), which is consistent with studies by Gasparik et al. (2016) and Pelit et al. (2015). With or without treatment, density improves as the compression ratio rises (Bao et al., 2017; Pelit et al., 2018; Fang et al., 2019). Density is even doubled by thermo-hydromechanical compression (Li et al., 2022).

According to another study by Rassam et al. (2011), impregnated densified wood had a higher density than undensified wood. Vinyl ester, epoxy, and ESO-treated and compressed

wood showed the highest density improvement for poplar wood (121.9, 113.8, and 110.9%), respectively. Alternatively, the effect of untreated wood, melamine formaldehyde, and a blend of ESO and epoxy on density was less (102, 95.65, and 88.74%) in their decreasing order. In the case of alder wood, vinyl ester resin, a blend of epoxy and ESO, melamine formaldehyde, ESO, epoxy, and untreated densified wood showed a declining trend of density improvement, which depends on the extent of retention of impregnates after compression. Based on this study, density improvement depends on the interrelated characteristics of the treatment applied: curing degree, retention level, and weight percentage gain following compression. The resin that was fully cured before compression was wood that had been treated with vinyl ester and epoxy. Therefore, density increased due to the weight percentage gain. In other words, for the for the ESO impregnated sample, curing took two weeks, and yet all the impregnated oil was either not fully cured before compression or melted while compressed. Therefore, the retained uncured oil leaked during compression, resulting in a decrease in density improvement. Melamine formaldehyde impregnated and densified wood has a minimal has a minimal impact on wood density due to the fact that 90% of the wood was water and only 10% was solid melamine; thus, its effect on density was low.

A study conducted by Deka et al. (2002) revealed that wood treated with thermosetting resins like melamine and urea formaldehyde improved density and mechanical properties with a 30% weight percentage gain. When a molecular substance is impregnated into the wood structure, the density and hardness of the wood increase (Dirna et al., 2020). The pore-filling ratio (PFR), which quantifies the percentage of luminal porosity filled, can be used to determine the impregnation of wood (Wu et al., 2017). Lumen impregnation works on the voids in the wood rather than the solid bulk, in contrast to conventional wood modification techniques (Wu et al., 2017). The density of wood can also be influenced by factors such as wood species, heating medium, temperature, and duration during hydrothermal modification (Ali et al., 2021). Hydrothermal modification is another method that can affect wood density. During hydrothermal modification, mass loss occurs, which can impact wood density (Ali et al., 2021). Impregnation can also enhance the mechanical properties by compacting its density to a higher level without damaging the cellular structures (Sumardi et al., 2020).

The blend of epoxy and ESO effect on wood density is affected by low retention of epoxy and fully uncured ESO, which leaks during compression at 160 °C (Cruz et al., 2018) for 20

minutes, especially ESO, and finally, the impact of untreated densified wood on density was very low as compared to impregnated wood. In the process of densification, the wood cell structure is compressed in a hot press to create a material with a higher density (Cruz et al., 2018). When the cell lumens are filled with a liquid substance such as polymers, melted natural resins, sulphur, or melted metal, the impregnation technique is frequently utilised in conjunction with densification (Wu et al., 2017). Wood's strength qualities can be improved by densifying and impregnating the material to make it denser (Cruz et al., 2018).

Increasing densification temperature improved the density and mechanical properties of Scots pine due to a decrease in the rate of cavities and an increase in load-bearing cell wall elements per unit volume. However, it was also observed that increasing the densification temperature led to a decrease in strength properties, possibly due to increasing chemical degradation at higher temperatures (Ülker et al., 2012).

A study discovered that the conductivity of impregnated wood samples loaded with copper salt was higher than that of non-impregnated wood samples, suggesting that penetration could raise the density of the wood (Baraski et al., 2021). Impregnation and densification can increase wood density by reducing cavities and increasing load-bearing cell wall elements. The densification temperature and impregnation process can both affect wood density, with higher temperatures potentially leading to increased density but decreased strength properties. Impregnation with substances like copper salt can also contribute to increased wood density.

### **3.3.2. Set Recovery**

Set recovery of impregnated and densified alder and poplar wood were shown in Figure 2. Epoxy impregnated densified wood shown the lowest set recovery both in Alder and Poplar. Epoxy impregnated 25% and 40% densified set recovery was 1.02% and 3.89%, 4.88% and 5.88% for Poplar and Alder wood, respectively. Whereas, in melamine impregnated densified wood 9.63%, 9.41% and 11.14% and 11.47% was the set recovery of Poplar and Alder wood after 40 and 25% densified, respectively. While untreated densified wood shown the highest set recovery followed by Vinyl ester resin treated wood. Epoxy treated wood is the most effective followed by melamine formaldehyde, blend of ESO and Epoxy, ESO treated and densified wood according to their decreasing efficiency of set recovery. The lower densification ratio (25%),

the lower the set recovery except in the case of melamine formaldehyde impregnated and densified poplar wood, where 40% densified wood has shown lower set recovery (lower) than 25% densified wood. The study shows that statistically significant difference between treatments groups observed in Table 11 ( $F_{11, 108}=267.94$ , at  $p < 0.05$ ) and ( $F_{11, 108} = 97.11$  at  $p < 0.05$ ) for both Poplar and Alder wood, respectively. Therefore, we can reject the null hypotheses and accept alternate hypotheses which implies that impregnation and densification significantly hampers set recovery of wood compared to untreated densified wood.

The result of post hoc test using Duncan show that poplar wood treated with epoxy (25%) and epoxy (40%), epoxy (40%) and melamine (40%), melamine (25% and 40%), Blend of ESO and Epoxy (25 and 40%), Untreated Densified (25%), Vinyl ester (25%) and ESO (40%), and Vinyl ester (40%) and Untreated (40%), statistically there is no significant difference between them regarding set recovery, which means each groups found to be homogenous as indicated in Table 12.

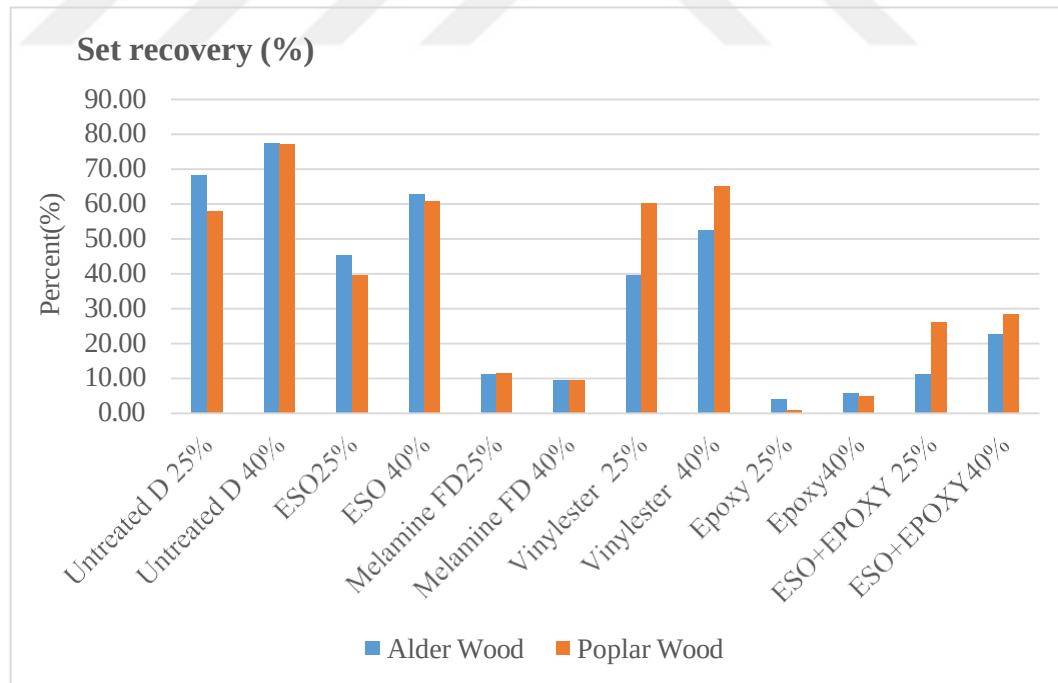


Figure 2. The Average set recovery of impregnated densified and Untreated Densified poplar and Alder wood.

Table 11. One-Way ANOVA Results of Set Recovery of Both Alder and Poplar wood

| ANOVA  |                |                |     |             |         |       |
|--------|----------------|----------------|-----|-------------|---------|-------|
|        |                | Sum of Squares | df  | Mean Square | F       | Sig.  |
| Poplar | Between Groups | 78943.41       | 11  | 7176.674    | 267.977 | 0.000 |
|        | Within Groups  | 2892.33        | 108 | 26.781      |         |       |
|        | Total          | 81835.75       | 119 |             |         |       |
| Alder  | Between Groups | 78412.79       | 11  | 7128.436    | 97.021  | 0.000 |
|        | Within Groups  | 7935.05        | 108 | 73.473      |         |       |
|        | Total          | 86347.85       | 119 |             |         |       |

Table 12. The mean set recovery and homogenous grouping using Duncan

| Set Recovery (%) |                   | N  | Mean                | Std. Deviation |
|------------------|-------------------|----|---------------------|----------------|
| Wood types       | Groups            |    |                     |                |
| Poplar           | Untreated 25%     | 10 | 58.08 <sup>f*</sup> | 6.49           |
|                  | Untreated 40%     | 10 | 77.28 <sup>g</sup>  | 5.73           |
|                  | ESO 25%           | 10 | 39.55 <sup>e</sup>  | 3.79           |
|                  | ESO 40%           | 10 | 60.77 <sup>f</sup>  | 1.80           |
|                  | Melamine 25%      | 10 | 11.47 <sup>c</sup>  | 5.51           |
|                  | Melamine 40%      | 10 | 9.41b <sup>c</sup>  | 2.32           |
|                  | Vinyl ester 25%   | 10 | 60.16 <sup>f</sup>  | 6.48           |
|                  | Vinyl ester 40%   | 10 | 65.10 <sup>g</sup>  | 4.16           |
|                  | Epoxy 25%         | 10 | 1.02 <sup>a</sup>   | 0.06           |
|                  | Epoxy 40%         | 10 | 4.89 <sup>abf</sup> | 3.29           |
|                  | ESO and Epoxy 25% | 10 | 26.15 <sup>d</sup>  | 9.55           |
|                  | ESO and Epoxy 40% | 10 | 28.42 <sup>d</sup>  | 5.66           |
| Alder            | Untreated 25%     | 10 | 68.25 <sup>e</sup>  | 6.41           |
|                  | Untreated 40%     | 10 | 77.31 <sup>g</sup>  | 4.82           |
|                  | ESO 25%           | 10 | 45.36 <sup>cd</sup> | 1.64           |
|                  | ESO 40%           | 10 | 62.90 <sup>e</sup>  | 1.82           |
|                  | Melamine 25%      | 10 | 9.63 <sup>a</sup>   | 2.86           |
|                  | Melamine 40%      | 10 | 11.14 <sup>a</sup>  | 4.48           |
|                  | Vinyl ester 25%   | 10 | 39.51 <sup>c</sup>  | 22.38          |
|                  | Vinyl ester 40%   | 10 | 52.62 <sup>d</sup>  | 11.98          |
|                  | Epoxy 25%         | 10 | 3.89 <sup>a</sup>   | 0.23           |
|                  | Epoxy 40%         | 10 | 5.76 <sup>a</sup>   | 0.34           |
|                  | ESO and Epoxy 25% | 10 | 11.36 <sup>a</sup>  | 3.99           |
|                  | ESO and Epoxy 40% | 10 | 22.80 <sup>b</sup>  | 11.08          |

According to Dostarian et al. (2020), the effect of ESO on the set recovery of poplar wood. The study showed that 30% compressed and ESO-impregnated wood showed a reduced set recovery than raw soybean oil-treated wood, and further improvement of about 43% was obtained by heat treatment, which is almost similar to this finding without heat treatment.

Melamine formaldehyde is the second most effective treatment group in reducing the recovery of compressed wood. Where 40% and 25% compressed poplar and alder wood set recovery is 9.63% and 9.41% and 11.14% and 11.47%, respectively, which supports the study by Lykidis et al. (2020; Schwarzkopf, 2020; Kocaefe et al., 2015) in which melamine impregnated densified wood reduced set recovery in poplar wood. However, unlike other treatment groups, as the compression ratio increases, set recovery decreases, particularly for poplar wood. The lower the densification ratio (25%), the lower the set recovery, except in the case of melamine formaldehyde impregnated and compressed poplar wood, where 40% compressed wood has shown better set recovery (lower) than 25% compressed wood, which is associated with the plasticizing effect of melamine formaldehyde (Han et al., 2022). It is possible to reduce the set recovery by increasing the concentration of melamine formaldehyde (Schwarzkopf, 2020; Lykidis et al., 2020). According to Altgen et al. (2020), impregnating wood with melamine formaldehyde resin can counteract the resin's tendency to absorb moisture, which can have an impact on the set recovery of densified wood. The dimensional stability of the wood may benefit from resin depositions within the cell lumens (Altgen et al., 2020).

Although epoxy resin has been found to be the most effective in reducing set recovery, there is no research that supports the use of epoxy resin, a typical thermosetting compound for wood impregnation and densification, or where set recovery is examined. The use of epoxy resin to improve dimensional stability and thermal stability was highlighted by Wang et al. (2021). The epoxy resin's drying inside the wood can create network structures that enhance the material's mechanical characteristics and shield it from decay fungus. Like epoxy resin, vinyl ester, blend of ESO, and epoxy for impregnation and densification, their impact on set recovery was not found, but various studies show that epoxy (Deka et al., 2000; Wang et al., 2021; Guo et al., 2022), vinyl ester (Islam et al., 2011; Razavi et al., 2015), and blend of epoxidized vegetable oil and epoxy (Alsagayar et al., 2015; Kumar et al., 2017) have been used in wood

and wood composites treatment and found to enhance the dimensional stability of treated materials.

### 3.3.3. Water Absorption

The water absorption of both treated and untreated wood samples was monitored over a two-week period, totaling 336 h. The average water absorption rate after 336 h indicates that untreated densified wood was found to be the highest water absorber among other materials. The lowest water absorption rate was observed in epoxy-treated wood. Based on their performance, epoxy-treated densified wood exhibited the highest effectiveness in reducing water absorption rates, followed by epoxidized soybean oil, vinyl ester resin, and melamine formaldehyde in descending order.

The average water absorption rate of 25% and 40% densified poplar is presented in Figures 3 and 4. The average water absorption rate of alder wood densified at 25% and 40% is presented in Figures 4 and 5. The one-way ANOVA result showed that there is a significant difference between treatment groups over the course of the water treatment duration for both alder and poplar wood ( $\alpha < 0.05$ ) (Table 15 and 16). The findings show that the null hypotheses were rejected because there is a statistically significant difference between the treatment and control groups.

In the study, the water absorption rates of untreated densified and impregnated densified poplar wood after two weeks (336 h) of water soaking revealed that untreated densified at 40% and untreated densified at 25% exhibited the highest water absorption, while epoxy (25%) and vinyl ester (25%) demonstrated the lowest water absorption, indicating their superior effectiveness in reducing water uptake.

The water absorption rate of untreated densified and impregnated densified poplar wood after two weeks (336 h) of water soaking showed that the average water absorption in the first 6 h of water soaking was untreated densified 40%, untreated densified 25%, melamine formaldehyde 25%, blend of epoxy and ESO 40%, and melamine formaldehyde 40% were the highest water absorbers in their decreasing order, whereas ESO 40%, ESO 25%, vinyl ester 40%, ESO and epoxy and ESO 40%, and melamine formaldehyde 40% were the highest water

absorbers in their decreasing order, whereas ESO 40%, ESO 25%, vinyl ester 40%, ESO and Epoxy 25%, Epoxy 40, vinyl ester 25%, and Epoxy 25% were the lowest water absorbers in their decreasing order or increasing efficiency in decreasing water absorption. The maximum mean water absorption rate of untreated 25% densified poplar wood was 32.5% after 1 hour and 60% after 3 h of water soaking, which is followed by melamine formaldehyde (13.73% and 54.6%), a blend of ESO and epoxy (10.88% and 52.7%), vinyl ester resin (8.78% and 45.7%), epoxidized soybean oil (7.99% and 39.73%), and epoxy (7.7% and 38%). Whereas, for 40% densified poplar wood, following untreated densified wood, a blend of ESO and epoxy, and melamine formaldehyde impregnated densified wood takes the lowest level in prohibiting water, as shown in figure 3.

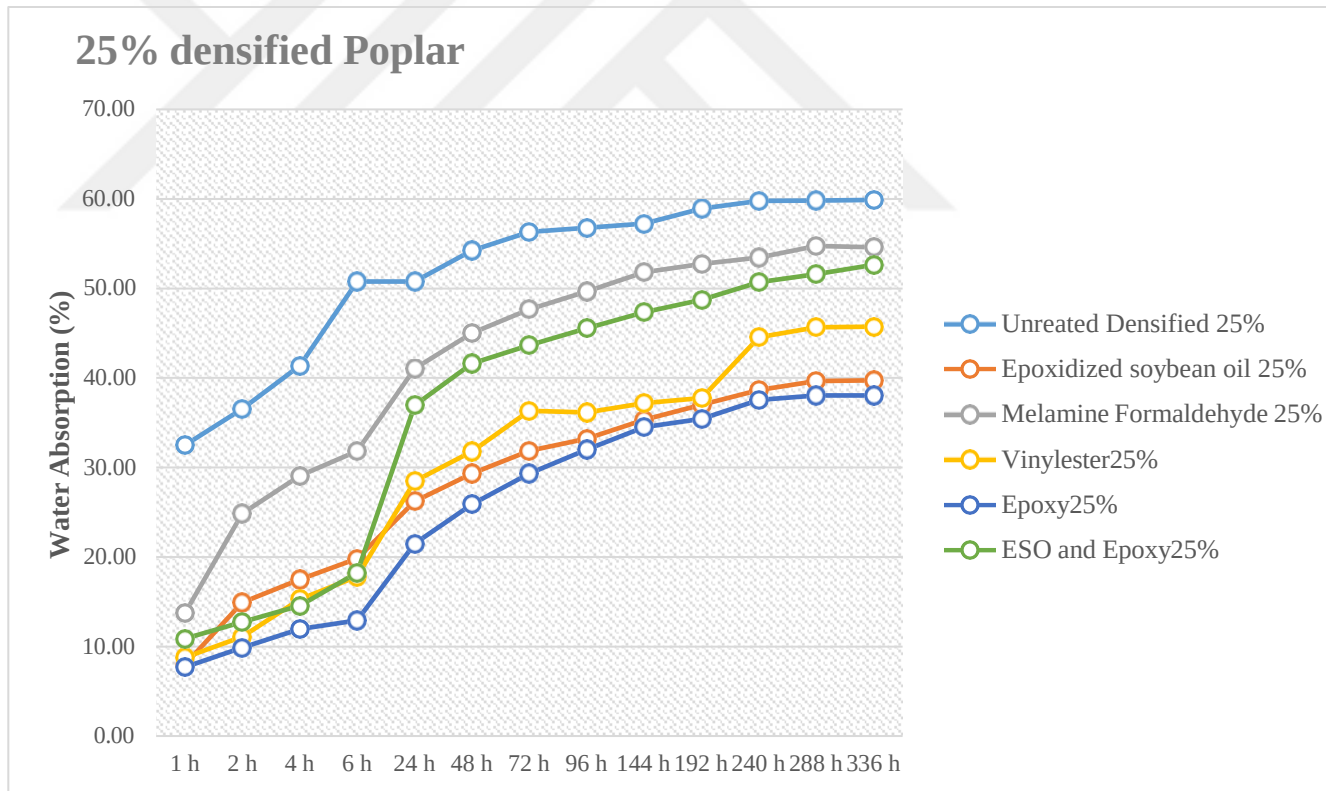


Figure 3. The average water absorption rate of untreated and impregnated densified (25%) poplar wood

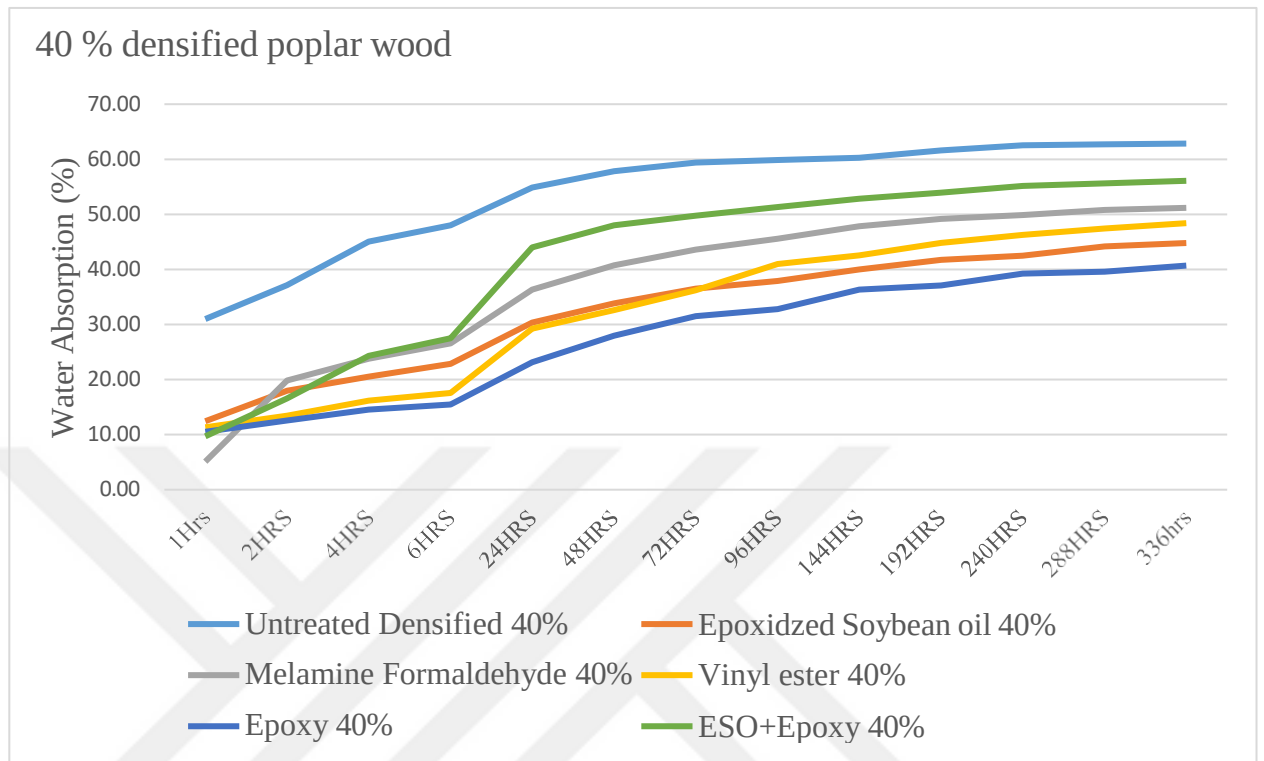


Figure 4. The Average Water Absorption Rate of untreated and Impregnated 40% densified Poplar wood

Over the course of water testing duration, water absorption rate of both 25% and 40% densified poplar wood shown that untreated and densified wood shown the highest rate of water absorption followed by blend of ESO and Epoxy. Whereas, Epoxy resin, ESO and Vinyl ester resin impregnated densified wood shown the lowest water absorption in their descending order of efficiency.

Post hoc test using Duncan show that impregnated and densified poplar wood after 336h of water testing in Table 14, Epoxy (a), Vinyl ester and Melamine Fd 40% (b), Blend of ESO and Epoxy 40% and ESO 25% (c), ESO 25% and 40% and Blend of ESO and Epoxy 25%(d), Melamine Fd 25% (e) and UD (f) in their descending order of efficiency. Likewise, In Alder wood, Epoxy (a), Vinyl ester and Melamine Fd (b), Blend of ESO and Epoxy 40% and ESO 25% (c), blend of ESO and Epoxy 25%, ESO 25% and 40%, Melamine Fd 25% (e) and UD (f) were homogenous group.

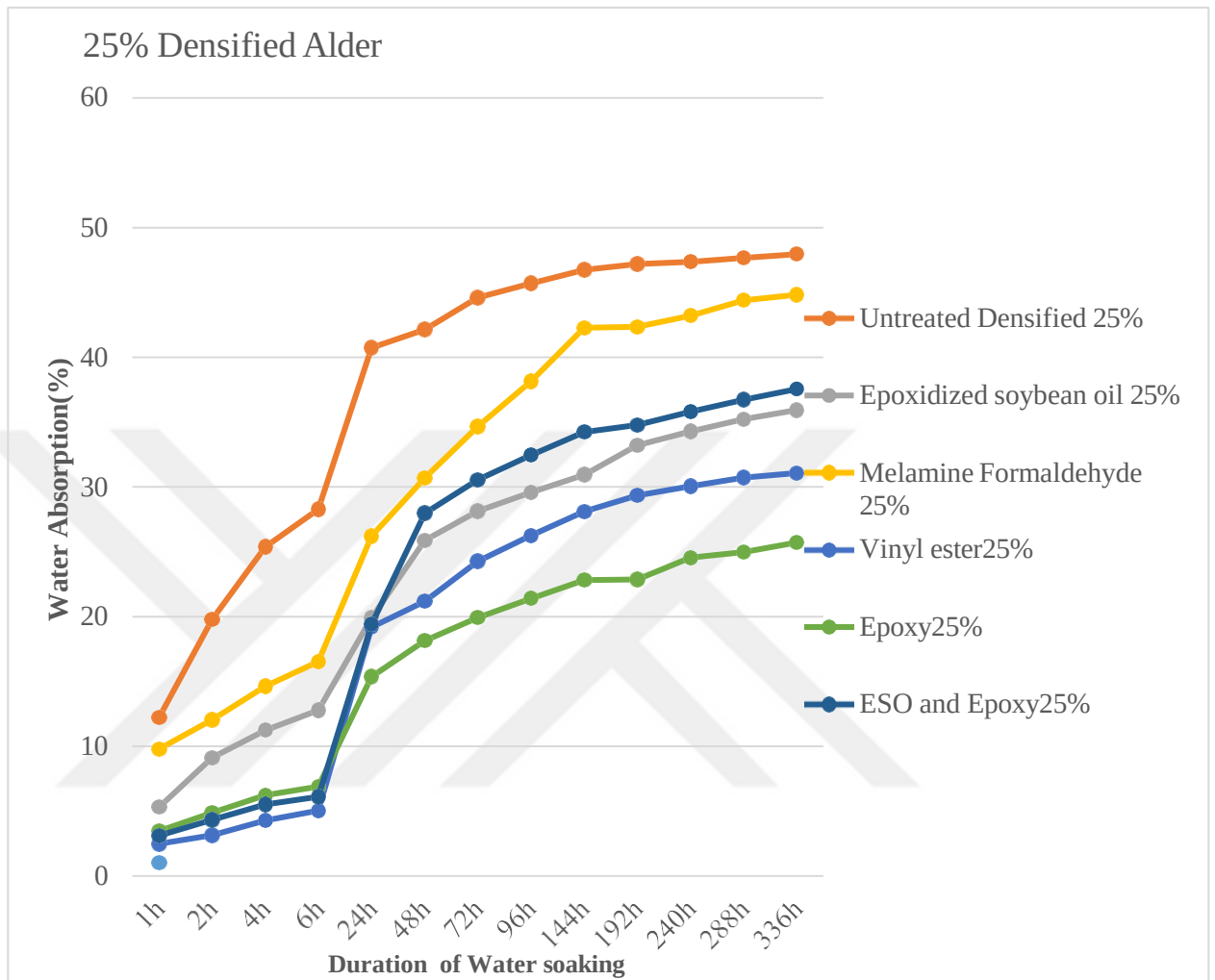


Figure 5. The Average Water Absorption Rate of 25% densified Untreated and Impregnated Alder wood

The result of this study also shows that after 336h of water soaking in 25% impregnated and densified Alder with melamine formaldehyde shown the highest water absorption rate next to untreated wood (48%) with (44.82%), which is followed by blend of ESO and Epoxy (37.5%), ESO (35.93%), Vinyl ester (31%) and Epoxy (25.7%), in their increasing Efficiency against water absorption. At the same time, in 40% treated and densified Alder, there was no disparity between treatment groups with 25% densified sample in terms of their ranking, particularly between 48-336 h of water soaking as indicated in figure 5 above.

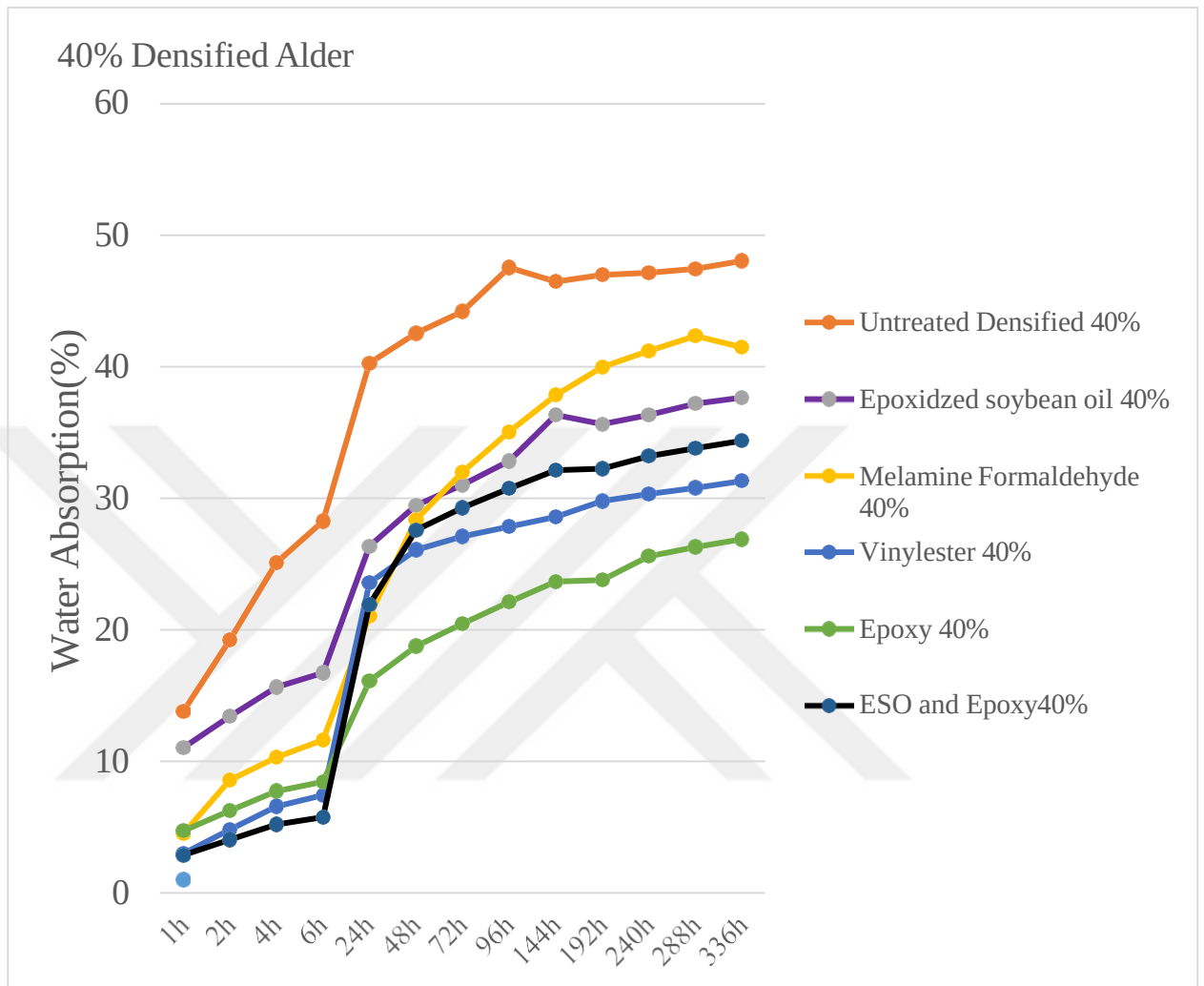


Figure 6. The average water absorption rate of impregnated and 40% densified alder wood

Table 13. The Mean water absorption of densified poplar and alder wood (1-72h) and their homogenous groups

| Wood   | Treatment Groups  | 1h                   | Std.<br>Dev. | 2h                    | Std.<br>Dev. | 4h                  | Std.<br>Dev. | 6h                   | Std.<br>Dev. | 24h                  | Std.<br>Dev. | 48h                  | Std.<br>Dev. | 72h                 | Std.<br>Dev. |
|--------|-------------------|----------------------|--------------|-----------------------|--------------|---------------------|--------------|----------------------|--------------|----------------------|--------------|----------------------|--------------|---------------------|--------------|
| Poplar | UD 25             | 32.49 <sup>e</sup>   | 9.76         | 36.56 <sup>h</sup>    | 12.73        | 41.36 <sup>f</sup>  | 11.55        | 50.75 <sup>g</sup>   | 6.71         | 50.75 <sup>f</sup>   | 6.71         | 54.22 <sup>e</sup>   | 6.06         | 56.32 <sup>f</sup>  | 5.75         |
|        | UD 40%            | 30.99 <sup>e</sup>   | 9.70         | 37.17 <sup>h</sup>    | 8.12         | 45.06 <sup>f</sup>  | 6.25         | 48.04 <sup>g</sup>   | 5.27         | 54.88 <sup>f</sup>   | 2.76         | 57.85 <sup>e</sup>   | 2.68         | 59.42 <sup>f</sup>  | 2.47         |
|        | ESO 25%           | 7.99 <sup>abc</sup>  | 2.81         | 14.9 <sup>cdef</sup>  | 3.94         | 17.50 <sup>bc</sup> | 4.24         | 19.80 <sup>cd</sup>  | 4.18         | 26.21 <sup>bcd</sup> | 4.82         | 29.32 <sup>b</sup>   | 4.87         | 31.86 <sup>c</sup>  | 5.06         |
|        | ESO 40%           | 12.44 <sup>cd</sup>  | 8.81         | 17.98 <sup>ef</sup>   | 8.82         | 20.54 <sup>cd</sup> | 8.83         | 22.86 <sup>de</sup>  | 8.43         | 30.37 <sup>e</sup>   | 6.35         | 33.80 <sup>cd</sup>  | 5.74         | 36.53 <sup>d</sup>  | 5.14         |
|        | Melamine Fd 25%   | 13.73 <sup>d</sup>   | 8.91         | 24.37 <sup>g</sup>    | 6.12         | 29.06 <sup>d</sup>  | 6.04         | 31.81 <sup>f</sup>   | 5.57         | 41.06 <sup>e</sup>   | 3.04         | 45.00 <sup>d</sup>   | 2.29         | 47.64 <sup>c</sup>  | 2.08         |
|        | Melamine Fd 40%   | 5.09 <sup>ab</sup>   | 4.69         | 19.83 <sup>g</sup>    | 4.17         | 23.79 <sup>de</sup> | 4.30         | 26.56 <sup>ef</sup>  | 4.00         | 36.33 <sup>d</sup>   | 3.42         | 40.74 <sup>b</sup>   | 3.10         | 43.59 <sup>c</sup>  | 2.69         |
|        | VE 25%            | 8.78 <sup>abcd</sup> | 2.98         | 11.08 <sup>abcd</sup> | 3.51         | 15.29 <sup>bc</sup> | 4.93         | 17.81 <sup>bcd</sup> | 5.17         | 28.47 <sup>abc</sup> | 3.64         | 31.79 <sup>a</sup>   | 3.56         | 36.35 <sup>b</sup>  | 4.38         |
|        | VE 40%            | 3.69 <sup>a</sup>    | 1.90         | 5.91 <sup>a</sup>     | 3.54         | 8.29 <sup>a</sup>   | 4.41         | 10.24 <sup>a</sup>   | 5.01         | 27.90 <sup>d</sup>   | 9.17         | 32.62 <sup>d</sup>   | 7.17         | 36.22 <sup>c</sup>  | 5.60         |
|        | Epoxy 25%         | 7.70 <sup>abc</sup>  | 1.64         | 9.87 <sup>abc</sup>   | 1.80         | 11.93 <sup>ab</sup> | 1.97         | 12.93 <sup>ab</sup>  | 2.05         | 21.48 <sup>a</sup>   | 2.47         | 25.89 <sup>b</sup>   | 2.66         | 29.32 <sup>ab</sup> | 2.88         |
|        | Epoxy 40%         | 10.52 <sup>bcd</sup> | 2.30         | 12.57 <sup>bcd</sup>  | 2.00         | 14.53 <sup>bc</sup> | 1.74         | 15.48 <sup>abc</sup> | 1.63         | 23.17 <sup>ab</sup>  | 2.09         | 27.97 <sup>a</sup>   | 2.54         | 31.48 <sup>a</sup>  | 2.82         |
|        | ESO and Epoxy25%  | 4.83 <sup>ab</sup>   | 0.85         | 8.74 <sup>ab</sup>    | 1.85         | 12.32 <sup>a</sup>  | 2.87         | 14.00 <sup>ab</sup>  | 3.33         | 36.93 <sup>bcd</sup> | 4.95         | 41.62 <sup>d</sup>   | 3.93         | 43.67 <sup>d</sup>  | 3.63         |
|        | ESO and Epoxy 40% | 6.53 <sup>ab</sup>   | 2.37         | 16.59 <sup>def</sup>  | 7.31         | 24.28 <sup>de</sup> | 10.85        | 27.50 <sup>aef</sup> | 12.22        | 44.02 <sup>cd</sup>  | 7.45         | 47.99 <sup>bcd</sup> | 5.46         | 49.78 <sup>cd</sup> | 4.37         |
| Alder  | UD 25%            | 12.21 <sup>cd</sup>  | 6.38         | 19.79 <sup>e</sup>    | 3.67         | 25.38 <sup>e</sup>  | 5.72         | 28.28 <sup>d</sup>   | 6.19         | 40.74 <sup>e</sup>   | 4.67         | 42.15 <sup>f</sup>   | 4.91         | 44.60 <sup>f</sup>  | 1.84         |
|        | UD 40%            | 13.80 <sup>d</sup>   | 2.03         | 19.23 <sup>e</sup>    | 3.12         | 25.12 <sup>e</sup>  | 5.59         | 28.26 <sup>d</sup>   | 6.18         | 40.29 <sup>e</sup>   | 4.58         | 42.55 <sup>f</sup>   | 4.51         | 44.21 <sup>f</sup>  | 2.06         |
|        | ESO 25%           | 5.30 <sup>b</sup>    | 1.60         | 9.12 <sup>c</sup>     | 1.57         | 11.24 <sup>c</sup>  | 2.28         | 12.79 <sup>b</sup>   | 2.18         | 19.91 <sup>bcd</sup> | 2.96         | 25.89 <sup>b</sup>   | 3.96         | 28.15 <sup>c</sup>  | 3.34         |
|        | ESO 40%           | 11.04 <sup>c</sup>   | 3.29         | 13.41 <sup>d</sup>    | 3.08         | 15.65 <sup>d</sup>  | 2.98         | 16.73 <sup>c</sup>   | 2.96         | 26.36 <sup>e</sup>   | 3.08         | 29.47 <sup>d</sup>   | 2.65         | 31.03 <sup>e</sup>  | 2.33         |
|        | Melamine Fd 25%   | 9.79 <sup>c</sup>    | 1.08         | 12.04 <sup>d</sup>    | 1.41         | 14.62 <sup>d</sup>  | 1.63         | 16.54 <sup>c</sup>   | 1.86         | 26.21 <sup>e</sup>   | 1.89         | 30.70 <sup>d</sup>   | 1.43         | 34.67 <sup>e</sup>  | 1.19         |
|        | Melamine Fd 40%   | 2.98 <sup>ab</sup>   | 0.93         | 4.82 <sup>ab</sup>    | 1.45         | 6.59 <sup>ab</sup>  | 1.95         | 7.44 <sup>a</sup>    | 2.19         | 23.58 <sup>a</sup>   | 3.10         | 26.08 <sup>bc</sup>  | 2.57         | 27.10 <sup>c</sup>  | 2.63         |
|        | Vinyl ester 25%   | 3.47 <sup>a</sup>    | 3.40         | 4.87 <sup>ab</sup>    | 3.72         | 6.23 <sup>a</sup>   | 4.08         | 5.04 <sup>a</sup>    | 2.69         | 19.19 <sup>abc</sup> | 7.69         | 21.17 <sup>c</sup>   | 3.39         | 24.27 <sup>b</sup>  | 2.49         |
|        | Vinyl ester 40%   | 5.32 <sup>b</sup>    | 2.65         | 6.25 <sup>b</sup>     | 3.30         | 7.73 <sup>a</sup>   | 3.61         | 8.45 <sup>a</sup>    | 3.77         | 23.58 <sup>de</sup>  | 3.10         | 26.08 <sup>bc</sup>  | 2.57         | 27.10 <sup>c</sup>  | 2.63         |
|        | Epoxy 25%         | 2.48 <sup>ab</sup>   | 2.03         | 3.15 <sup>a</sup>     | 2.15         | 4.29 <sup>a</sup>   | 2.51         | 6.89 <sup>a</sup>    | 4.28         | 15.37 <sup>a</sup>   | 5.26         | 18.14 <sup>a</sup>   | 4.56         | 19.92 <sup>a</sup>  | 4.29         |
|        | Epoxy 40%         | 2.98 <sup>ab</sup>   | 0.93         | 4.82 <sup>ab</sup>    | 1.45         | 6.59 <sup>ab</sup>  | 1.95         | 7.44 <sup>a</sup>    | 2.19         | 16.11 <sup>ab</sup>  | 4.57         | 18.75 <sup>a</sup>   | 3.82         | 20.47 <sup>a</sup>  | 3.53         |
|        | ESO and Epoxy 25% | 3.09 <sup>ab</sup>   | 0.61         | 4.33 <sup>ab</sup>    | 0.76         | 5.52 <sup>ab</sup>  | 0.93         | 6.11 <sup>a</sup>    | 1.01         | 19.61 <sup>cd</sup>  | 4.19         | 28.14 <sup>bcd</sup> | 3.28         | 30.67 <sup>d</sup>  | 2.18         |
|        | ESO and Epoxy 40% | 2.85 <sup>ab</sup>   | 0.26         | 4.02 <sup>ab</sup>    | 0.52         | 5.15 <sup>ab</sup>  | 0.78         | 5.71 <sup>a</sup>    | 0.90         | 21.91 <sup>cd</sup>  | 4.09         | 27.62 <sup>bcd</sup> | 2.81         | 29.30 <sup>cd</sup> | 2.49         |

Table 14. The Mean Water Absorption of densified Poplar and Alder wood (96-336h) and their homogenous groups (Duncan)

| Wood   | Treatment Groups         | 96H                 | St.dev | 144H               | St.dev | 192H                | St.dev | 240H                | St.dev | 288H                | St.dev            | 336H                | St.dev |
|--------|--------------------------|---------------------|--------|--------------------|--------|---------------------|--------|---------------------|--------|---------------------|-------------------|---------------------|--------|
| Poplar | UD 25                    | 56.79 <sup>f</sup>  | 5.61   | 57.25 <sup>f</sup> | 5.48   | 58.94 <sup>g</sup>  | 5.18   | 59.78 <sup>g</sup>  | 5.17   | 59.83 <sup>f</sup>  | 5.18              | 59.89 <sup>f</sup>  | 5.18   |
|        | UD 40%                   | 59.86 <sup>f</sup>  | 2.39   | 60.30 <sup>f</sup> | 2.31   | 61.62 <sup>g</sup>  | 2.02   | 62.54 <sup>g</sup>  | 2.07   | 62.70 <sup>f</sup>  | 2.08              | 62.85 <sup>f</sup>  | 2.09   |
|        | ESO 25%                  | 33.21 <sup>cd</sup> | 5.18   | 35.33 <sup>c</sup> | 5.36   | 37.01 <sup>cd</sup> | 5.68   | 38.65 <sup>cd</sup> | 6.14   | 35.77 <sup>c</sup>  | 11.97             | 36.73 <sup>cd</sup> | 11.39  |
|        | ESO 40%                  | 37.92 <sup>e</sup>  | 5.00   | 40.02 <sup>c</sup> | 4.89   | 41.71 <sup>e</sup>  | 4.90   | 42.52 <sup>e</sup>  | 4.84   | 44.15 <sup>d</sup>  | 4.84              | 44.79 <sup>d</sup>  | 4.76   |
|        | Melamine Fd 25%          | 49.66 <sup>f</sup>  | 1.97   | 51.81 <sup>e</sup> | 1.76   | 52.75 <sup>f</sup>  | 2.17   | 53.47 <sup>f</sup>  | 1.70   | 54.75 <sup>e</sup>  | 1.97              | 54.59 <sup>e</sup>  | 1.78   |
|        | Melamine Fd 40%          | 45.57 <sup>bc</sup> | 2.56   | 47.84 <sup>b</sup> | 2.53   | 49.20 <sup>b</sup>  | 1.99   | 49.87 <sup>b</sup>  | 1.89   | 50.80 <sup>b</sup>  | 1.91              | 51.18 <sup>b</sup>  | 1.66   |
|        | VE 25%                   | 36.14 <sup>b</sup>  | 11.70  | 37.20 <sup>b</sup> | 4.62   | 37.77 <sup>b</sup>  | 4.73   | 44.55 <sup>b</sup>  | 4.28   | 45.65 <sup>b</sup>  | 4.25              | 45.73 <sup>b</sup>  | 4.31   |
|        | VE 40%                   | 41.01 <sup>b</sup>  | 4.74   | 42.52 <sup>b</sup> | 3.42   | 44.81 <sup>b</sup>  | 2.81   | 46.25 <sup>b</sup>  | 2.46   | 47.43 <sup>b</sup>  | 2.33              | 48.40 <sup>b</sup>  | 2.21   |
|        | Epoxy 25%                | 32.01 <sup>ab</sup> | 2.91   | 34.49 <sup>a</sup> | 2.97   | 35.45 <sup>a</sup>  | 2.98   | 37.56 <sup>a</sup>  | 2.94   | 38.04 <sup>a</sup>  | 2.93              | 39.02 <sup>a</sup>  | 2.79   |
|        | Epoxy 40%                | 32.81 <sup>a</sup>  | 6.72   | 36.31 <sup>a</sup> | 2.91   | 37.06 <sup>a</sup>  | 2.89   | 39.23 <sup>a</sup>  | 3.08   | 39.59 <sup>a</sup>  | 3.18              | 40.69 <sup>a</sup>  | 3.30   |
|        | ESO an Epoxy25%          | 45.56 <sup>e</sup>  | 3.43   | 47.33 <sup>d</sup> | 3.32   | 48.73 <sup>d</sup>  | 3.52   | 50.70 <sup>de</sup> | 3.36   | 51.58 <sup>d</sup>  | 3.44              | 52.65 <sup>d</sup>  | 3.57   |
|        | ESO and Epoxy 40%        | 51.35 <sup>de</sup> | 3.71   | 52.81 <sup>c</sup> | 3.20   | 53.91 <sup>c</sup>  | 2.78   | 55.17 <sup>c</sup>  | 2.59   | 55.63 <sup>c</sup>  | 2.38              | 56.09 <sup>c</sup>  | 2.12   |
| Alder  | UD 25%                   | 45.70 <sup>f</sup>  | 1.52   | 46.75 <sup>f</sup> | 1.35   | 47.20 <sup>f</sup>  | 1.34   | 47.37 <sup>g</sup>  | 1.28   | 47.66 <sup>f</sup>  | 1.40              | 47.95 <sup>f</sup>  | 1.52   |
|        | UD 40%                   | 47.54 <sup>f</sup>  | 1.58   | 46.48 <sup>f</sup> | 1.63   | 46.99 <sup>f</sup>  | 1.54   | 47.15 <sup>g</sup>  | 1.52   | 47.45 <sup>f</sup>  | 1.62              | 48.05 <sup>f</sup>  | 1.82   |
|        | ESO 25%                  | 29.59 <sup>cd</sup> | 3.04   | 30.94 <sup>c</sup> | 3.32   | 33.20 <sup>cd</sup> | 2.33   | 34.27 <sup>c</sup>  | 2.07   | 35.24 <sup>cd</sup> | 1.92              | 35.93 <sup>cd</sup> | 1.81   |
|        | ESO 40%                  | 32.85 <sup>e</sup>  | 2.30   | 36.34 <sup>e</sup> | 1.68   | 35.65 <sup>e</sup>  | 1.83   | 36.34 <sup>e</sup>  | 1.68   | 37.21 <sup>c</sup>  | 1.73              | 37.60 <sup>d</sup>  | 1.62   |
|        | Melamine Fd 25%          | 38.16 <sup>e</sup>  | 1.12   | 42.27 <sup>d</sup> | 1.88   | 42.35 <sup>f</sup>  | 1.23   | 43.21 <sup>f</sup>  | 1.18   | 44.40 <sup>e</sup>  | 1.37              | 44.82 <sup>e</sup>  | 1.37   |
|        | Melamine Fd 40%          | 27.85 <sup>bc</sup> | 2.60   | 28.58 <sup>b</sup> | 2.58   | 29.80 <sup>b</sup>  | 2.50   | 30.32 <sup>b</sup>  | 2.49   | 30.80 <sup>b</sup>  | 2.53              | 31.32 <sup>b</sup>  | 2.54   |
|        | Vinyl ester 25%          | 26.25 <sup>b</sup>  | 2.05   | 28.11 <sup>b</sup> | 2.04   | 29.35 <sup>b</sup>  | 2.26   | 30.06 <sup>b</sup>  | 2.32   | 30.73 <sup>b</sup>  | 2.35              | 31.08 <sup>b</sup>  | 2.42   |
|        | Vinyl ester 40%          | 27.85 <sup>bc</sup> | 2.60   | 28.58 <sup>b</sup> | 2.58   | 29.80 <sup>b</sup>  | 2.50   | 30.32 <sup>b</sup>  | 2.49   | 30.80 <sup>b</sup>  | 2.53              | 31.32 <sup>b</sup>  | 2.54   |
|        | Epoxy 25%                | 21.40 <sup>a</sup>  | 4.03   | 22.82 <sup>a</sup> | 3.81   | 22.86 <sup>a</sup>  | 3.62   | 24.54 <sup>a</sup>  | 3.75   | 24.98 <sup>a</sup>  | 3.94 <sup>a</sup> | 25.72 <sup>a</sup>  | 3.76   |
|        | Epoxy 40%                | 22.11 <sup>a</sup>  | 2.98   | 23.68 <sup>a</sup> | 2.52   | 23.80 <sup>a</sup>  | 2.28   | 25.60 <sup>a</sup>  | 2.25   | 26.29 <sup>a</sup>  | 2.43              | 26.90 <sup>a</sup>  | 2.28   |
|        | Blend of ESO & Epoxy 25% | 32.54 <sup>de</sup> | 1.78   | 34.31 <sup>d</sup> | 1.45   | 34.79 <sup>de</sup> | 1.46   | 35.81 <sup>c</sup>  | 1.41   | 36.73 <sup>d</sup>  | 1.35              | 37.56 <sup>d</sup>  | 1.29   |
|        | Blend of ESO & Epoxy 40% | 30.73 <sup>de</sup> | 2.42   | 32.10 <sup>c</sup> | 2.38   | 32.20 <sup>c</sup>  | 2.21   | 33.16 <sup>c</sup>  | 2.32   | 33.78 <sup>c</sup>  | 2.25              | 34.33 <sup>c</sup>  | 2.27   |

Table 15. One –Way ANOVA table for impregnated and densified Poplar wood

|      |                | Sum of Squares | df  | Mean Square | F      | Sig. |
|------|----------------|----------------|-----|-------------|--------|------|
| 1h   | Between Groups | 10291.253      | 11  | 935.56      | 27.83  | .000 |
|      | Within Groups  | 3629.485       | 108 | 33.60       |        |      |
|      | Total          | 13920.738      | 119 |             |        |      |
| 2h   | Between Groups | 11425.116      | 11  | 1038.64     | 26.79  | .000 |
|      | Within Groups  | 4186.402       | 108 | 38.76       |        |      |
|      | Total          | 15611.518      | 119 |             |        |      |
| 4h   | Between Groups | 14710.090      | 11  | 1337.28     | 32.10  | .000 |
|      | Within Groups  | 4499.279       | 108 | 41.66       |        |      |
|      | Total          | 19209.369      | 119 |             |        |      |
| 6h   | Between Groups | 19072.610      | 11  | 1733.87     | 48.67  | .000 |
|      | Within Groups  | 3846.771       | 108 | 35.61       |        |      |
|      | Total          | 22919.380      | 119 |             |        |      |
| 24h  | Between Groups | 12814.934      | 11  | 1164.99     | 43.02  | .000 |
|      | Within Groups  | 2924.615       | 108 | 27.08       |        |      |
|      | Total          | 15739.550      | 119 |             |        |      |
| 48h  | Between Groups | 12208.512      | 11  | 1109.86     | 55.89  | .000 |
|      | Within Groups  | 2144.518       | 108 | 19.85       |        |      |
|      | Total          | 14353.030      | 119 |             |        |      |
| 72h  | Between Groups | 10754.980      | 11  | 977.72      | 58.12  | .000 |
|      | Within Groups  | 1816.542       | 108 | 16.82       |        |      |
|      | Total          | 12571.522      | 119 |             |        |      |
| 96h  | Between Groups | 9961.474       | 11  | 905.58      | 32.14  | .000 |
|      | Within Groups  | 3042.978       | 108 | 28.17       |        |      |
|      | Total          | 13004.452      | 119 |             |        |      |
| 144h | Between Groups | 8756.908       | 11  | 796.083     | 56.47  | .000 |
|      | Within Groups  | 1522.456       | 108 | 14.097      |        |      |
|      | Total          | 10279.364      | 119 |             |        |      |
| 192h | Between Groups | 8925.790       | 11  | 811.43      | 59.59  | .000 |
|      | Within Groups  | 1470.636       | 108 | 13.61       |        |      |
|      | Total          | 10396.426      | 119 |             |        |      |
| 240h | Between Groups | 7589.071       | 11  | 689.91      | 52.07  | .000 |
|      | Within Groups  | 1430.972       | 108 | 13.25       |        |      |
|      | Total          | 9020.042       | 119 |             |        |      |
| 288h | Between Groups | 8123.575       | 11  | 738.50      | 33.42  | .000 |
|      | Within Groups  | 2386.535       | 108 | 22.09       |        |      |
|      | Total          | 10510.110      | 119 |             |        |      |
| 336h | Between Groups | 7557.853       | 11  | 687.07      | 33.117 | .000 |
|      | Within Groups  | 2240.689       | 108 | 20.74       |        |      |
|      | Total          | 9798.541       | 119 |             |        |      |

Table 16. One –Way ANOVA Table for impregnate and densified Alder wood

|      |                | Sum of Squares | df  | Mean Square | F       | Sig. |
|------|----------------|----------------|-----|-------------|---------|------|
| 1h   | Between Groups | 1945.690       | 11  | 176.881     | 25.200  | .000 |
|      | Within Groups  | 758.067        | 108 | 7.019       |         |      |
|      | Total          | 2703.757       | 119 |             |         |      |
| 2h   | Between Groups | 3899.905       | 11  | 354.537     | 59.479  | .000 |
|      | Within Groups  | 643.752        | 108 | 5.961       |         |      |
|      | Total          | 4543.657       | 119 |             |         |      |
| 4h   | Between Groups | 6221.509       | 11  | 565.592     | 53.999  | .000 |
|      | Within Groups  | 1131.201       | 108 | 10.474      |         |      |
|      | Total          | 7352.710       | 119 |             |         |      |
| 6h   | Between Groups | 7731.491       | 11  | 702.863     | 58.308  | .000 |
|      | Within Groups  | 1301.867       | 108 | 12.054      |         |      |
|      | Total          | 9033.358       | 119 |             |         |      |
| 24h  | Between Groups | 7548.764       | 11  | 686.251     | 36.457  | .000 |
|      | Within Groups  | 2032.963       | 108 | 18.824      |         |      |
|      | Total          | 9581.727       | 119 |             |         |      |
| 48h  | Between Groups | 6626.305       | 11  | 602.391     | 48.899  | .000 |
|      | Within Groups  | 1330.459       | 108 | 12.319      |         |      |
|      | Total          | 7956.764       | 119 |             |         |      |
| 72h  | Between Groups | 6844.755       | 11  | 622.250     | 85.322  | .000 |
|      | Within Groups  | 787.640        | 108 | 7.293       |         |      |
|      | Total          | 7632.395       | 119 |             |         |      |
| 96h  | Between Groups | 7529.960       | 11  | 684.542     | 113.330 | .000 |
|      | Within Groups  | 652.350        | 108 | 6.040       |         |      |
|      | Total          | 8182.310       | 119 |             |         |      |
| 144h | Between Groups | 7259.292       | 11  | 659.936     | 116.488 | .000 |
|      | Within Groups  | 611.847        | 108 | 5.665       |         |      |
|      | Total          | 7871.139       | 119 |             |         |      |
| 192h | Between Groups | 7049.414       | 11  | 640.856     | 134.030 | .000 |
|      | Within Groups  | 516.396        | 108 | 4.781       |         |      |
|      | Total          | 7565.810       | 119 |             |         |      |
| 240h | Between Groups | 6399.411       | 11  | 581.765     | 123.196 | .000 |
|      | Within Groups  | 510.006        | 108 | 4.722       |         |      |
|      | Total          | 6909.418       | 119 |             |         |      |
| 288h | Between Groups | 6395.969       | 11  | 581.452     | 116.812 | .000 |
|      | Within Groups  | 537.588        | 108 | 4.978       |         |      |
|      | Total          | 6933.557       | 119 |             |         |      |
| 366h | Between Groups | 6302.247       | 11  | 572.932     | 117.988 | .000 |
|      | Within Groups  | 524.432        | 108 | 4.856       |         |      |
|      | Total          | 6826.680       | 119 |             |         |      |

A study conducted by Hao et al., (2022) on poplar wood impregnated with Ammonium Polyphosphate–Waterborne Epoxy shows that the impregnant used reduced water absorption. According to their performance, epoxy-treated densified wood were the most effective in reducing water absorption followed by Epoxidized soybean oil, Vinyl ester resin and Melamine Formaldehyde in their descending order.

Varied study shows that Epoxidized vegetable oil treated wood shown better performance in reducing water absorption rate by 20% than untreated sample (Hao et al., 2022; Demirel et al., 2018; Temiz et al., 2013; Tomak et al., 2011; Jebrane et al., 2017). The blend of Epoxidized linseed oil with vinyl acetate showed that by increasing the curing time, temperate and 8% weight gain improves dimensional stability and decay resistance, respectively (Shengzhen, 2016).

Oriental beech coated with bio-based epoxide amine nano-coatings shown that improvement in dimensional stability (Yahya et al., 2023). According to Saho et al., (2015), blend of Epoxidized soybean oil with petroleum based epoxy (DGEBA) shown that an improvement in dimensional stability. ESO is known to improve the toughness of epoxy resin, which can indirectly affect water absorption and dimensional stability (Roudsari et al., 2014). Epoxy resin is inherently brittle, and the addition of ESO can enhance its toughness, making it less prone to cracking or delamination when exposed to moisture (Roudsari et al., 2014).

Oriental beech, when coated with bio-based epoxy-amine nano-coatings, demonstrated a significant enhancement in dimensional stability, as reported by Yahya et al. (2023). According to Saho et al., (2015), blend of Epoxidized soybean oil with petroleum based epoxy (DGEBA) shown improvement in Physical properties. The study found that the waterborne epoxy polymerized within the wood and resulted in improved dimensional stability, without compromising the mechanical properties of the wood. In contrast, the use of melamine formaldehyde was found to increase the rate of polymer retention in uncompressed wood and result in increased volumetric swelling, as reported by Deka et al. (2000). However, Lahtela and Kärki (2014) found that melamine-treated Scots pine showed excellent impregnation and improved swelling rates. Study by Altun and Tokdemir et al., (2017) scots pine and poplar wood treated with Urea- melamine formaldehyde improved dimensional stability and reduced water uptake.

### 3.3.4. Water Repellent efficiency

Water repellent efficiency of impregnated and densified poplar wood was compared with untreated, but densified sample. After 336 h of water soaking test, 25% and 40% densified poplar wood, epoxy shown the highest average water repellence efficacy (35.88 and 36.7 %), respectively. The same is true in Alder wood where epoxy impregnated densified wood was the highest water repellent with 47.5 and 44.5 % for 25% and 40 % compressed woods, as illustrated in figure 7 and 8. The lowest water repellent efficiency was obtained in melamine formaldehyde impregnated densified wood in both alder and poplar, except in 40% compressed poplar wood where blend of ESO and epoxy was the lowest.

Based on their performance, Water repellent efficiency of treatment groups from the highest to the lowest in their descending order; Epoxy, ESO, Vinyl ester resin, Blend of ESO and Epoxy and Melamine Formaldehyde. Water repellent efficiency of treatments groups varied before and after 24 h of water soaking. For instance, at the beginning of water soaking duration of 1hrs, 2hrs, 4hrs and 6hrs, water repellence efficacy of blend of Epoxidized soybean oil and Epoxy (70:30) is found to be the highest and followed by epoxy treated and vinyl ester resin treated wood. Whereas, ESO and Melamine Formaldehyde treated compressed shown lowest water repellence efficacy in the beginning of six hours of water soaking. However, after 24 h of water soaking up to 336 h of water soaking, epoxy treated wood found to be the most effective followed by ESO, Vinyl Ester Resin, Blend of ESO and Epoxy. Whereas, melamine formaldehyde was the lowest of all treatment groups. Regarding densification ratio, except for Melamine formaldehyde impregnation wood, 25% compressed wood shown better water repellence efficacy than 40% compressed wood. Statistically significant difference observed between treatment groups reveals that the null hypothesis is rejected. Likewise, the water repellent efficiency values indicated in Table 18 shows all are a positive value which indicates all treatments groups shown better repellence efficiency than untreated densified sample.

Table 17. The average water repellent efficiency of impregnated densified poplar and alder Wood after 1, 2, 4, 6, 24 and 48 h of water soaking.

| Wood Species | Treatment Group            | 1 h           | 2 h           | 4 h           | 6 h           | 24 h          | 48 h          |
|--------------|----------------------------|---------------|---------------|---------------|---------------|---------------|---------------|
| Poplar       | ESO25%                     | 72.49(14.84)b | 56.90(20.2)b  | 56.09(18.04)b | 59.76(13.14)b | 47.05(17.37)  | 44.70(14.86)  |
|              | Melamine FD 25%            | 55.69(29.67)a | 31.28(24.58)a | 28.59(20)a    | 36.57(11.6)a  | 18.58(11.2)a  | 16.04(10.22)a |
|              | Vinylester25%              | 60.86(14.46)a | 55.10(17.98)b | 52.02(15.42)b | 56.81(11.34)b | 43.41(10.66)b | 40.68(9.21)   |
|              | Epoxy25%                   | 74.26(7.79)b  | 72.24(8.3)c   | 70.63(7.64)c  | 74.07(5.38)c  | 57.07(9.57)c  | 51.54(8.52)   |
|              | Blend of ESO and Epoxy     | 83.79(5.79)c  | 75.80(6.34)c  | 70.20(6.96)c  | 72.23(6.07)c  | 27.27(8.94)a  | 22.63(8.33)a  |
|              | ESO40%                     | 55.91(32.37)a | 48.85(27.06)b | 53.05(21.77)b | 51.36(19.69)a | 44.32(12.84)  | 41.31(11.01)b |
|              | Melamine FD 40%            | 84.43(13.09)c | 45.28(12.7)b  | 46.72(9.97)b  | 44.38(8.75)a  | 33.62(7.4)b   | 29.48(5.68)a  |
|              | Vinyl ester 40%            | 86.52(9.20)c  | 83.94(8.99)c  | 81.47(9.77)d  | 78.51(10.59)c | 49.25(16.24)b | 43.63(12.15)b |
|              | Epoxy 40%                  | 63.98(10.56)b | 65.19(7.03)b  | 67.36(4.77)c  | 67.53(4.03)c  | 57.70(4.29)c  | 51.57(4.9)b   |
|              | Blend of ESO and Epoxy 40% | 77.95(9.61)b  | 55.28(19.94)b | 46.79(22.83)b | 43.27(24.5)a  | 19.55(14.26)a | 16.81(10.59)a |
| Alder        | ESO25% Alder               | 39.41(44.1)   | 52.56(11.1)   | 53.37(14.92)  | 52.43(14.2)   | 50.50(9.45)   | 37.50(13.57)  |
|              | Melamine FD Alder25%       | 30.35(22.18)  | 37.41(14.09)  | 38.92(19.02)  | 38.18(18.49)  | 34.49(12.29)  | 26.18(9.89)   |
|              | Vinylester25%              | 75.23(17.70)  | 83.48(12.13)  | 82.17(11.39)  | 81.37(10.64)  | 53.02(17.56)  | 49.45(8.26)   |
|              | Epoxy25%                   | 74.15(22.33)  | 73.95(20.28)  | 74.14(18.00)  | 74.46(16.98)  | 61.72(14.72)  | 56.14(13.70)  |
|              | Blend of ESO and Epoxy 25% | 64.61(22.93)  | 77.40(5.87)   | 77.23(5.91)   | 77.49(5.5)    | 51.56(10.02)  | 32.75(8.48)   |
|              | ESO 40%                    | 19.12(23.5)   | 29.06(17.77)  | 35.03(18.46)  | 38.02(18.25)  | 33.27(14.68)  | 29.92(10.78)  |
|              | Melamine FD 40% Alder      | 66.19(10.31)  | 54.40(22.03)  | 57.23(18.08)  | 57.23(16.18)  | 46.79(13.62)  | 32.52(12.79)  |
|              | Vinyl ester 40% Alder      | 77.62(8.57)   | 74.04(9.64)   | 72.38(10.53)  | 72.45(9.84)   | 40.76(10.11)  | 38.26(7.29)   |
|              | Epoxy 40% Alder            | 65.85(20.87)  | 67.33(16.79)  | 68.79(14.06)  | 69.77(12.69)  | 59.75(11.16)  | 55.32(10.87)  |
|              | ESO and Epoxy 40% Alder    | 78.91(3.68)   | 78.60(4.31)   | 78.50(5.73)   | 78.87(5.6)    | 45.52(8.40)   | 34.77(6.29)   |

The values in the bracket are the standard deviations (St. Dev)

Table 18. The Average Water Repellence Efficacy of Impregnated Densified Poplar and Alder Wood after 72, 96, 144, 192, 240, 288, 336hrs of water soaking

| wood species | Treatment Group            | 72 h         | 96 h         | 144 h        | 192 h        | 240 h        | 288 h        | 336h         |
|--------------|----------------------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|
| Poplar       | ESO25%                     | 42.37(14.20) | 40.48(14.29) | 37.27(14.57) | 36.35(13.94) | 34.51(14.34) | 34.51(14.34) | 32.78(14.99) |
|              | Melamine fd 25%            | 14.58(9.53)  | 11.73(9.77)  | 8.66(10.01)  | 9.93(7.63)   | 9.87(9.17)   | 9.87(9.17)   | 7.81(9.35)   |
|              | Vinylester25%              | 34.913(9.43) | 35.58(22.01) | 34.81(7.22)  | 35.79(6.73)  | 25.14(7.74)  | 25.14(7.74)  | 23.34(7.95)  |
|              | Epoxy25%                   | 47.30(8.54)  | 42.97(8.84)  | 39.1(9.12)   | 39.3(8.46)   | 36.63(8.3)   | 36.63(8.3)   | 35.88(8.32)  |
|              | Blend of ESO and Epoxy25%  | 21.93(7.92)  | 19.20(9.39)  | 16.75(8.73)  | 16.84(8.31)  | 14.7(8.12)   | 14.7(8.12)   | 13.29(8.4)   |
|              | ESO40%                     | 38.31(9.76)  | 36.47(9.39)  | 33.46(9.17)  | 32.18(8.79)  | 31.88(8.64)  | 31.88(8.64)  | 29.46(8.59)  |
|              | Melamine fd 40%            | 26.55(4.84)  | 23.80(4.67)  | 20.56(5.2)   | 20.09(3.88)  | 20.2(3.56)   | 20.2(3.56)   | 18.91(3.67)  |
|              | Vinyl ester 40%            | 39.04(9.18)  | 31.46(7.85)  | 29.4(6.12)   | 27.22(5.03)  | 25.97(4.72)  | 25.97(4.72)  | 24.26(4.66)  |
|              | Epoxy 40%                  | 46.95(5.03)  | 45.17(11.2)  | 39.73(5.18)  | 39.81(4.9)   | 37.22(5.35)  | 37.22(5.35)  | 36.79(5.58)  |
|              | Blend of ESO and Epoxy 40% | 16.03(8.6)   | 14.04(7.62)  | 12.26(6.86)  | 12.39(5.85)  | 11.68(5.6)   | 11.68(5.6)   | 11.16(5.34)  |
| Alder        | ESO25% Alder               | 36.73(.63)   | 35.10(7.83)  | 33.86(6.35)  | 29.51(6.43)  | 27.53(5.89)  | 27.53(5.89)  | 25.94(5.73)  |
|              | Melamine F Alder25%        | 22.10(4.97)  | 16.39(4.20)  | 9.47(5.55)   | 10.2(4.28)   | 8.7(4.10)    | 8.7(4.1)     | 6.73(4.69)   |
|              | Vinylester25% Alder        | 45.62(4.56)  | 42.58(3.66)  | 39.88(3.86)  | 37.84(4.29)  | 36.56(4.45)  | 36.56(4.45)  | 35.53(4.53)  |
|              | Epoxy25%Alder              | 55.23(10.06) | 53.11(9.12)  | 51.15(8.34)  | 51.54(7.93)  | 48.14(8.26)  | 48.14(8.26)  | 47.53(8.65)  |
|              | ESO and Epoxy 25%          | 31.17(5.01)  | 28.73(4.25)  | 26.55(3.67)  | 26.25(3.62)  | 24.36(3.44)  | 24.36(3.44)  | 22.87(3.48)  |
|              | ESO 40% Alder              | 29.70(5.78)  | 30.85(5.19)  | 21.76(4.16)  | 24.07(4.28)  | 22.87(4.04)  | 22.87(4.04)  | 21.51(4.33)  |
|              | Melamine fd 40% Alder      | 27.33(9.80)  | 26.12(7.74)  | 18.43(7.68)  | 14.76(7.39)  | 12.46(7.29)  | 12.46(7.29)  | 10.62(7.15)  |
|              | Vinyl ester 40% Alder      | 38.62(6.27)  | 41.40(5.41)  | 38.48(5.58)  | 36.55(5.29)  | 35.65(5.36)  | 35.65(5.36)  | 35.05(5.38)  |
|              | Epoxy 40% Alder            | 53.63(8.21)  | 53.44(6.54)  | 49.01(5.65)  | 49.34(4.88)  | 45.67(4.86)  | 45.67(4.86)  | 44.55(5.24)  |
|              | ESO and Epoxy 40% Alder    | 33.68(5.71)  | 35.32(5.1)   | 30.93(4.84)  | 31.47(4.22)  | 29.66(4.41)  | 29.66(4.41)  | 28.8(4.22)   |

The values in the bracket are the standard deviations (St. Dev).

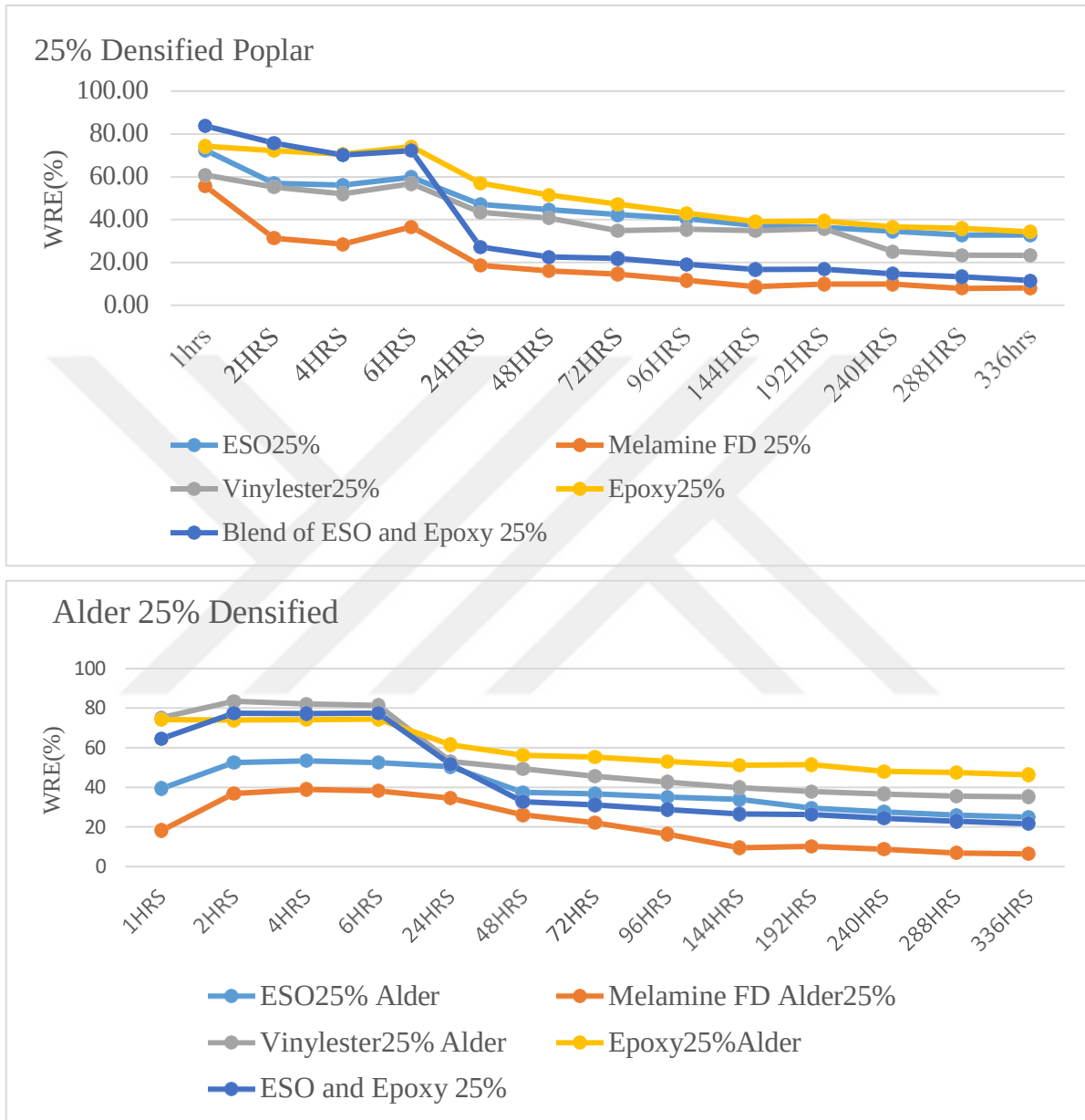


Figure 7. Water Repellent efficiency of 25% compressed Poplar (Upper) and Alder (Lower) wood



Figure 8. Water repellence efficiency of 40% compressed poplar (upper) and Alder wood (lower)

The findings of this study support studies conducted on densified wood and composites using various treatments. According to Wang et al. (2021) and Guo et al. (2022), the application

of epoxy has been found to enhance dimensional stability by 50%. The study found that when waterborne epoxy polymerizes within the wood, it leads to improved stability and thermal resistance without compromising the properties of the wood.

On the other hand, Sun et al. (2021) examined Chinese fir impregnated with a water-borne epoxy hybrid and found improvements in water resistance properties. Oriental beech coated with bio-based epoxide amine nano-coatings has shown an improvement in dimensional stability (Yahya et al., 2023). The same is true where epoxidized vegetable oil-treated wood shows better performance in improving water repellence efficacy (Demirel et al., 2018; Tamia et al., 2013; Tomak et al., 2011; Jebrane et al., 2017). The blend of epoxidized linseed oil with vinyl acetate showed that by increasing the curing time, temperature and 8% weight gain improve dimensional stability and durability (Shengzhen, 2016).

Softwood treated with melamine formaldehyde (MF) shows an improvement of 68% in dimensional stability for 30–35% weight percentage gain (Deka and Saikia, 2000). The study found that using melamine formaldehyde increased the retention rate of polymers in uncompressed wood, resulting in increased volumetric swelling. However, Lahtela and Kärki (2014) found that melamine-treated Scots pine exhibited impregnation capabilities and improved swelling rates.

The improvement of the toughness and mechanical qualities of furfurylated wood by using biosourced epoxidized soybean oil was studied by Liu et al. (2021). According to the study, filling the wood's cell walls and lumens with hydrophobic furfural alcohol (FA) resin and FA-ESO thermosets enhances the wood's structural stability. Similar to tropical hardwood, the FA-ESO-modified wood demonstrates good physical and mechanical qualities (Liu et al., 2020).

The impact of water repellents on the hygroscopicity and dimensional stability of densified Fir and Aspen woods was examined in a study by Pelit and Emiroglu (2020). According to the study, in situ polymerization of vinyl monomers filling up the spaces between wood cells increased the effectiveness of the wood's ability to repel water and increased their structural stability. Qiu et al. (2018) looked at how grafting water-soluble vinyl monomers onto cell walls could increase the performance of wood. According to the study, the water-soluble vinyl monomers successfully entered the wood cell walls and formed covalent connections with the hydroxyl groups of the lignin and polysaccharides. The grafting procedure increased the wood's resistance to water. According to Nadlene et al. (2016), chemical treatment has an impact

on the characteristics of roselle fibre-reinforced vinyl ester composites. According to the study, treated Roselle fibre considerably improved the vinyl ester composites' ability to repel water as compared to untreated fibre. The most efficient chemical treatment for lowering water absorption was determined to be the application of a silane coupling agent. The study provides more proof of the saline treatment's value in enhancing water repellency.

### 3.3.5. Swelling Coefficient

Swelling coefficients of untreated and impregnated densified Poplar wood were presented in Figure 9 and Figure 10. In 25% densified sample, after 336 h of water soaking testing UD (32%), Vinyl ester (30%), ESO (18.5%), Melamine (18.3%), Blend of ESO and epoxy (17.4%), and epoxy (13.7%) were arranged in their increasing order of efficiency against swelling. In 40% densified Poplar, swelling coefficient values in ascending order of effectiveness were UD (60.5), Vinyl ester (59.04%), blend of ESO and Epoxy (42.4%), Melamine fd (29.7%), ESO(24.3%) and Epoxy (22.14%).

The mean swelling coefficients of 25% densified Alder wood in increasing order of efficiency illustrated in figure 11 and 12, UD (38.9%), Blend ESO and epoxy (29.6%), Melamine (28.7%), ESO (27.8%), Vinyl ester (24.5) and epoxy (14.42%). Whereas, in 40% densified Alder, UD (52.5%), Vinyl ester (50.64%), Melamine (47.02%), ESO (30%), Blend of ESO and Epoxy (27.95%) and epoxy 27%). The results of One-way ANOVA indicates that swelling coefficients over the course of water soaking duration 1-336hrs shown that statistically significant difference obtained between treatment groups both for Alder and Poplar Wood( $\alpha < 0.05$ , F table). Thus, our null hypotheses are rejected, because statistically there is significant difference between treatment and control groups.

Post hoc test carried out to identify homogenous groups presented in Table 19 and Table 20. The homogenous groups varied over the course of water soaking test. By considering swelling coefficients after 336 h, epoxy resin and other treatment groups used were reduced swelling coefficient than untreated wood.

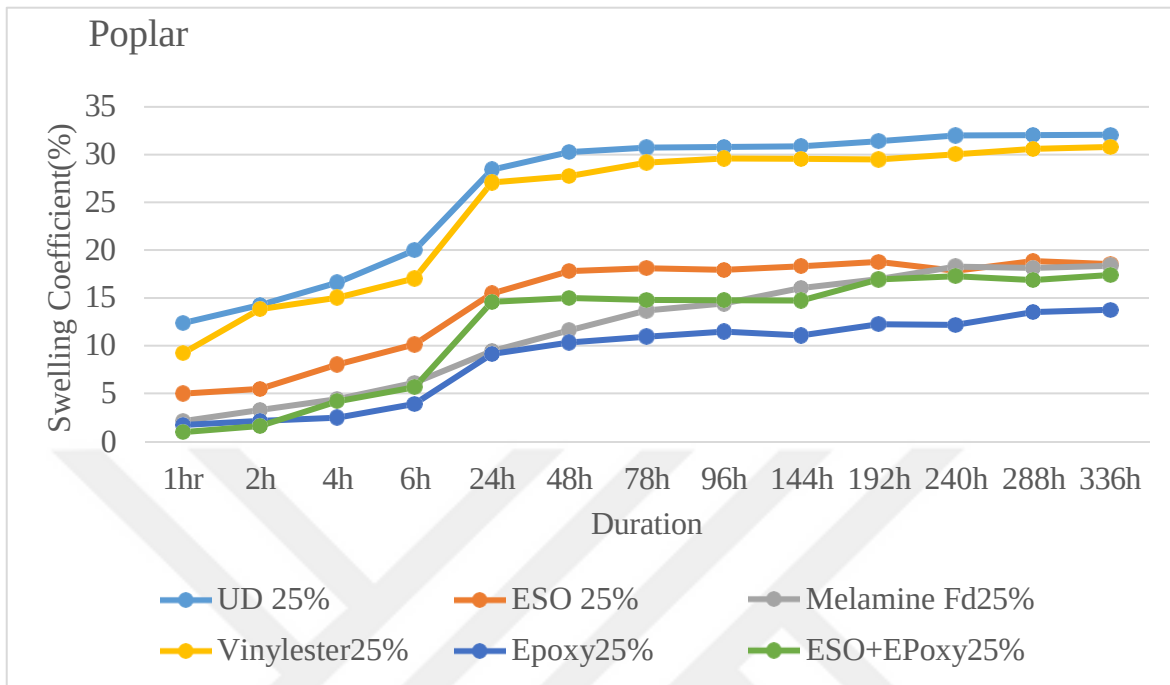


Figure 9. The mean swelling coefficient of untreated and treated 25% densified Poplar

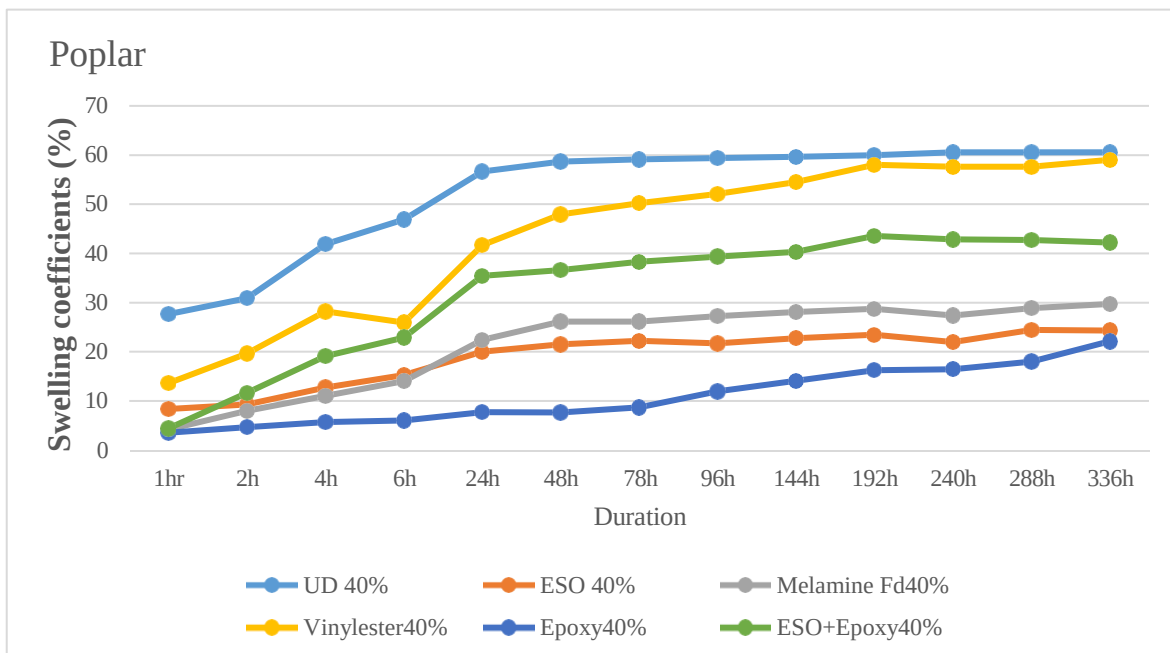


Figure 10. The mean swelling coefficient values of untreated and treated 40% densified poplar

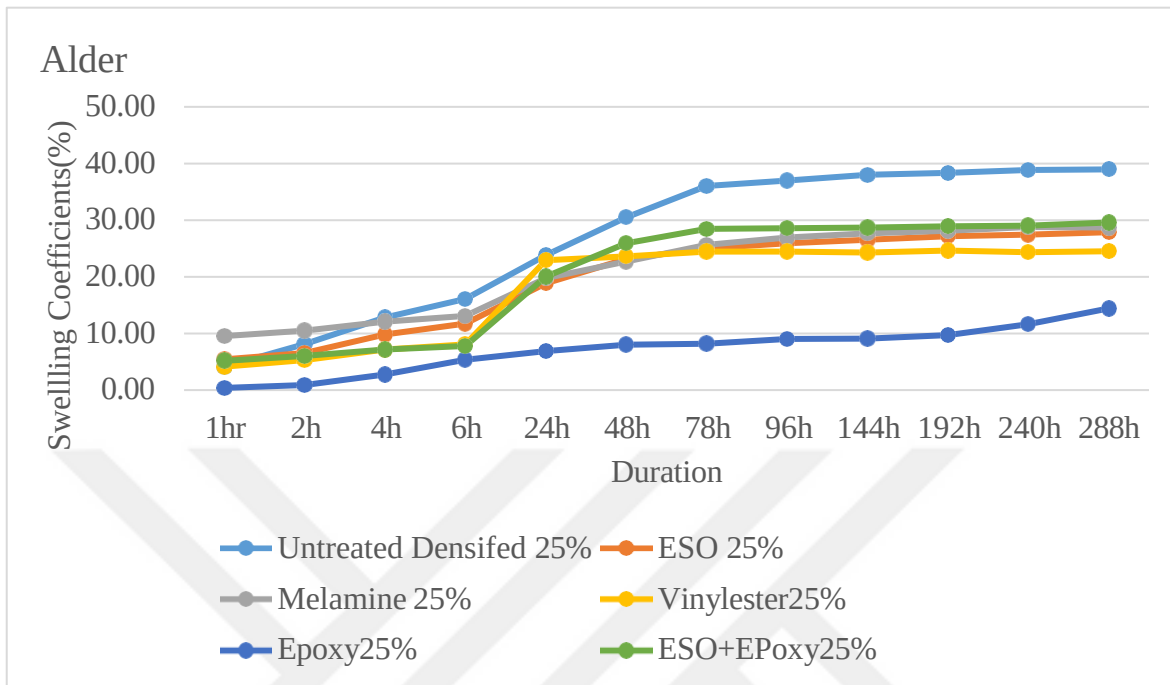


Figure 11. The mean swelling coefficient values of untreated and treated 25% densified Alder

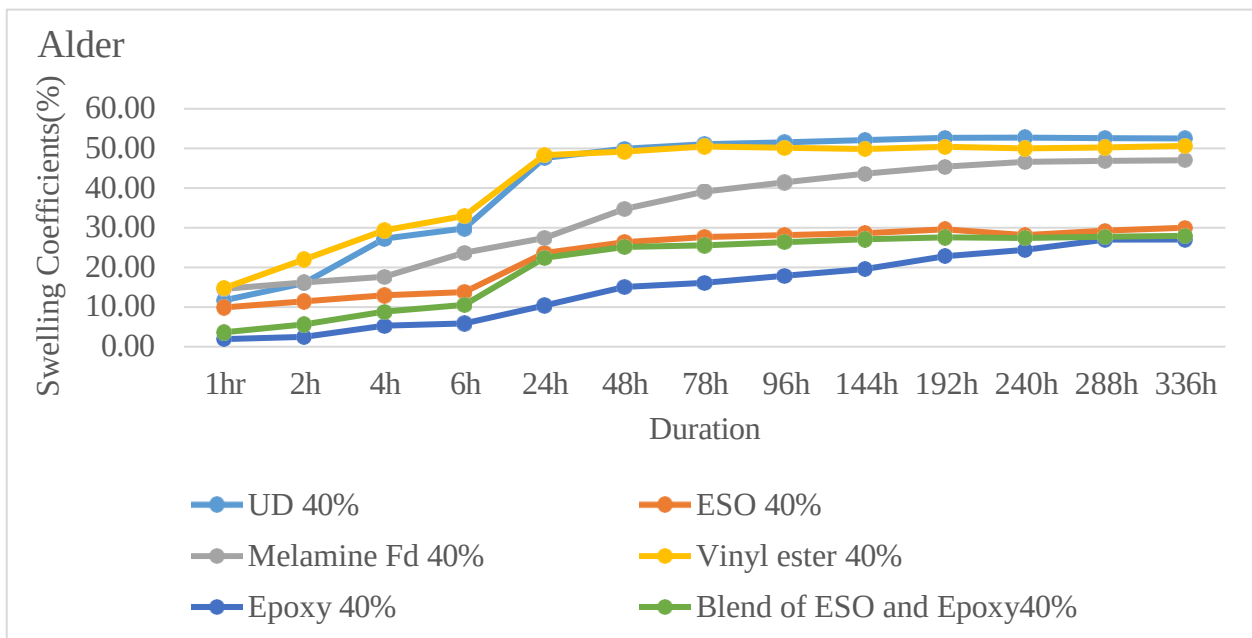


Figure 12. The mean swelling coefficient values of untreated and treated 40 % densified Alder

Table 19. The mean Swelling Coefficients and homogenous groups of poplar and alder (1-72h).

| Poplar            | 1h                   | Std. Dev | 2h                   | Std. Dev | 4h                  | Std. Dev | 6h                   | Std. Dev | 24h                 | Std. Dev | 48h                 | Std. Dev | 72h                 | Std. Dev |
|-------------------|----------------------|----------|----------------------|----------|---------------------|----------|----------------------|----------|---------------------|----------|---------------------|----------|---------------------|----------|
| UD 25             | 9.20 <sup>cde</sup>  | 6.21     | 14.76 <sup>ef</sup>  | 1.34     | 16.59 <sup>de</sup> | 7.07     | 19.99 <sup>de</sup>  | 7.80     | 28.44 <sup>f</sup>  | 7.66     | 30.28 <sup>e</sup>  | 7.77     | 30.74 <sup>g</sup>  | 7.98     |
| UD 40%            | 27.663 <sup>ef</sup> | 13.70    | 39.33 <sup>h</sup>   | 7.21     | 41.87 <sup>g</sup>  | 10.25    | 46.89 <sup>g</sup>   | 9.00     | 56.68 <sup>h</sup>  | 4.80     | 58.70 <sup>h</sup>  | 6.46     | 59.11 <sup>j</sup>  | 6.07     |
| ESO 25%           | 4.98 <sup>abc</sup>  | 3.03     | 5.49 <sup>abc</sup>  | 3.74     | 8.03 <sup>abc</sup> | 4.12     | 10.15 <sup>bc</sup>  | 4.41     | 15.46 <sup>bc</sup> | 2.75     | 17.81 <sup>cd</sup> | 2.08     | 18.11 <sup>cd</sup> | 2.36     |
| ESO 40%           | 8.37 <sup>bcd</sup>  | 2.81     | 9.30 <sup>cd</sup>   | 1.72     | 12.72 <sup>cd</sup> | 3.62     | 15.30 <sup>cd</sup>  | 3.68     | 20.01 <sup>cd</sup> | 3.05     | 21.53 <sup>d</sup>  | 3.34     | 22.24 <sup>de</sup> | 3.35     |
| Melamine Fd 25%   | 1.70 <sup>a</sup>    | 1.01     | 2.13 <sup>a</sup>    | 2.17     | 2.47 <sup>a</sup>   | 2.36     | 3.89 <sup>a</sup>    | 2.38     | 9.14 <sup>a</sup>   | 2.45     | 10.33 <sup>ab</sup> | 2.92     | 10.93 <sup>ab</sup> | 2.93     |
| Melamine Fd 40%   | 4.22 <sup>ab</sup>   | 3.08     | 7.98 <sup>bcd</sup>  | 2.78     | 11.04 <sup>bc</sup> | 3.03     | 14.05 <sup>c</sup>   | 3.07     | 22.42 <sup>ef</sup> | 1.68     | 26.15 <sup>e</sup>  | 1.74     | 26.14 <sup>ef</sup> | 1.72     |
| Vinyl ester 25%   | 12.36 <sup>de</sup>  | 2.48     | 14.24 <sup>f</sup>   | 3.09     | 27.4 <sup>bf</sup>  | 4.68     | 23.04 <sup>ef</sup>  | 9.87     | 27.09 <sup>ef</sup> | 3.42     | 17.77 <sup>cd</sup> | 4.67     | 29.16 <sup>fg</sup> | 3.14     |
| Vinyl ester 40%   | 13.62 <sup>e</sup>   | 4.25     | 19.63 <sup>g</sup>   | 3.29     | 28.22 <sup>f</sup>  | 9.39     | 25.95 <sup>f</sup>   | 4.22     | 41.72 <sup>h</sup>  | 9.62     | 47.94 <sup>g</sup>  | 7.20     | 50.24 <sup>i</sup>  | 6.03     |
| Epoxy 25%         | 2.09 <sup>a</sup>    | 0.90     | 3.25 <sup>bc</sup>   | 0.75     | 4.41 <sup>a</sup>   | 0.60     | 6.11 <sup>ab</sup>   | 0.61     | 9.44 <sup>a</sup>   | 1.19     | 11.61 <sup>ab</sup> | 1.39     | 13.67 <sup>bc</sup> | 1.47     |
| Epoxy 40%         | 3.55 <sup>a</sup>    | 1.00     | 4.70 <sup>abc</sup>  | 0.36     | 5.72 <sup>ab</sup>  | 0.19     | 6.07 <sup>ab</sup>   | 0.21     | 7.75 <sup>a</sup>   | 5.91     | 7.65 <sup>a</sup>   | 5.64     | 8.73 <sup>a</sup>   | 6.54     |
| ESO and Epoxy 25% | 0.95 <sup>a</sup>    | 0.85     | 1.60 <sup>a</sup>    | 0.82     | 4.19 <sup>ab</sup>  | 0.91     | 5.65 <sup>ab</sup>   | 0.99     | 14.58 <sup>b</sup>  | 1.12     | 14.99 <sup>bc</sup> | 1.36     | 14.78 <sup>bc</sup> | 1.29     |
| ESO and Epoxy 40% | 4.43 <sup>ab</sup>   | 2.35     | 11.62 <sup>def</sup> | 5.32     | 19.10 <sup>ef</sup> | 9.13     | 22.86 <sup>ef</sup>  | 11.13    | 35.45 <sup>g</sup>  | 9.50     | 36.6 <sup>f</sup>   | 8.50     | 38.32 <sup>h</sup>  | 7.55     |
| Alder             | 1h                   | Std.Dev  | 2h                   | Std. Dev | 4h                  | Std. Dev | 6h                   | Std. Dev | 24h                 | Std. Dev | 48h                 | Std. Dev | 72h                 | Std. Dev |
| UD 25             | 4.11 <sup>cd</sup>   | 1.38     | 8.13 <sup>cd</sup>   | 1.47     | 12.80 <sup>d</sup>  | 1.81     | 16.08 <sup>c</sup>   | 1.80     | 23.81 <sup>cd</sup> | 1.49     | 30.48 <sup>de</sup> | 1.36     | 36.01 <sup>e</sup>  | 1.07     |
| UD 40%            | 11.70 <sup>f</sup>   | 2.91     | 16.07 <sup>f</sup>   | 4.23     | 27.27 <sup>e</sup>  | 11.86    | 29.86 <sup>d</sup>   | 11.87    | 47.62 <sup>e</sup>  | 8.70     | 49.96 <sup>f</sup>  | 5.12     | 51.06 <sup>f</sup>  | 4.27     |
| ESO 25%           | 5.43 <sup>c</sup>    | 4.78     | 6.56 <sup>c</sup>    | 6.10     | 9.83 <sup>bcd</sup> | 9.45     | 11.72 <sup>abc</sup> | 9.61     | 18.85 <sup>c</sup>  | 13.66    | 23.18 <sup>c</sup>  | 13.59    | 25.01 <sup>c</sup>  | 13.19    |
| ESO 40%           | 9.91 <sup>e</sup>    | 3.22     | 11.45 <sup>e</sup>   | 3.04     | 12.99 <sup>d</sup>  | 3.07     | 13.77 <sup>bc</sup>  | 3.17     | 22.43 <sup>cd</sup> | 7.15     | 25.18 <sup>c</sup>  | 7.04     | 25.58 <sup>cd</sup> | 7.48     |
| Melamine Fd 25%   | 9.53 <sup>de</sup>   | 2.67     | 10.48 <sup>de</sup>  | 2.83     | 12.10 <sup>cd</sup> | 2.97     | 6.10 <sup>a</sup>    | 2.26     | 12.69 <sup>b</sup>  | 4.15     | 15.60 <sup>b</sup>  | 3.98     | 18.51 <sup>b</sup>  | 3.86     |
| Melamine Fd 40%   | 5.99 <sup>cd</sup>   | 0.61     | 7.60 <sup>cd</sup>   | 0.80     | 9.04 <sup>bcd</sup> | 0.94     | 15.10 <sup>c</sup>   | 15.09    | 26.05 <sup>d</sup>  | 3.14     | 33.87 <sup>e</sup>  | 3.13     | 30.23 <sup>d</sup>  | 2.64     |
| VE 25%            | 4.1 <sup>bc</sup>    | 3.17     | 5.31 <sup>bc</sup>   | 3.09     | 7.15 <sup>abc</sup> | 3.24     | 8.08 <sup>ab</sup>   | 3.61     | 22.90 <sup>cd</sup> | 2.79     | 23.62 <sup>c</sup>  | 2.83     | 24.47 <sup>c</sup>  | 2.83     |
| VE 40%            | 14.78 <sup>g</sup>   | 11.37    | 22.03 <sup>g</sup>   | 6.44     | 29.33 <sup>e</sup>  | 4.03     | 32.99 <sup>d</sup>   | 5.25     | 48.33 <sup>e</sup>  | 3.11     | 49.19 <sup>f</sup>  | 3.10     | 50.50 <sup>f</sup>  | 3.45     |
| Epoxy 25%         | 0.39 <sup>a</sup>    | 0.01     | 0.89 <sup>a</sup>    | 0.01     | 2.75 <sup>a</sup>   | 0.05     | 5.35 <sup>a</sup>    | 0.09     | 6.88 <sup>a</sup>   | 2.15     | 8.00 <sup>a</sup>   | 1.87     | 8.20 <sup>a</sup>   | 2.16     |
| Epoxy 40%         | 1.91 <sup>ab</sup>   | 0.80     | 2.48 <sup>ab</sup>   | 1.03     | 5.28 <sup>ab</sup>  | 1.41     | 5.83 <sup>a</sup>    | 1.47     | 10.41 <sup>ab</sup> | 2.34     | 15.06 <sup>b</sup>  | 1.35     | 16.15 <sup>b</sup>  | 1.65     |
| ESO and Epoxy 25% | 5.16 <sup>c</sup>    | 3.42     | 6.02 <sup>c</sup>    | 3.86     | 7.18 <sup>ab</sup>  | 4.08     | 7.77 <sup>ab</sup>   | 4.27     | 20.07 <sup>c</sup>  | 3.68     | 25.91 <sup>cd</sup> | 3.79     | 28.45 <sup>cd</sup> | 3.70     |
| ESO and Epoxy 40% | 3.63 <sup>bc</sup>   | 3.23     | 5.59 <sup>bc</sup>   | 2.89     | 8.89 <sup>abc</sup> | 4.43     | 10.53 <sup>abc</sup> | 5.79     | 23.59 <sup>cd</sup> | 4.56     | 26.35 <sup>cd</sup> | 3.51     | 27.65 <sup>cd</sup> | 3.97     |

Table 20. The mean swelling coefficients and homogenous groups of poplar and alder (96-336h).

| Poplar            | 96h                            | Std.Dev | 144h                | Std.Dev | 192h                 | Std.Dev | 240h                | Std.Dev | 288h                | Std.Dev | 336h                | Std.Dev |
|-------------------|--------------------------------|---------|---------------------|---------|----------------------|---------|---------------------|---------|---------------------|---------|---------------------|---------|
| UD 25             | 30.80 <sup>d</sup>             | 7.96    | 30.86 <sup>d</sup>  | 7.95    | 31.42 <sup>d</sup>   | 8.47    | 32.01 <sup>d</sup>  | 8.22    | 32.05 <sup>d</sup>  | 8.43    | 32.0 <sup>d</sup>   | 8.65    |
| UD 40%            | 59.38 <sup>g</sup>             | 5.82    | 59.65 <sup>g</sup>  | 5.63    | 59.97 <sup>f</sup>   | 6.47    | 60.56 <sup>f</sup>  | 6.12    | 60.56 <sup>f</sup>  | 6.38    | 60.57 <sup>f</sup>  | 6.67    |
| ESO 25%           | 17.94 <sup>bc</sup>            | 2.56    | 18.32 <sup>b</sup>  | 2.93    | 18.79 <sup>b</sup>   | 2.37    | 17.83 <sup>bc</sup> | 3.59    | 18.86 <sup>b</sup>  | 3.03    | 18.55 <sup>ab</sup> | 3.64    |
| ESO 40%           | 21.74 <sup>c</sup>             | 4.42    | 22.74 <sup>c</sup>  | 4.02    | 23.48 <sup>c</sup>   | 4.15    | 21.99 <sup>c</sup>  | 5.81    | 24.45 <sup>c</sup>  | 5.02    | 24.33 <sup>c</sup>  | 5.41    |
| Melamine Fd 25%   | 11.49 <sup>a</sup>             | 2.99    | 11.07 <sup>a</sup>  | 3.38    | 12.24 <sup>a</sup>   | 3.24    | 12.18 <sup>a</sup>  | 3.26    | 13.50 <sup>a</sup>  | 3.22    | 13.76 <sup>a</sup>  | 3.23    |
| Melamine Fd 40%   | 27.27 <sup>d</sup>             | 1.24    | 28.07 <sup>d</sup>  | 2.95    | 28.75 <sup>d</sup>   | 1.83    | 27.38 <sup>d</sup>  | 3.55    | 28.88 <sup>d</sup>  | 1.79    | 29.73 <sup>d</sup>  | 1.33    |
| VE 25%            | 29.61 <sup>d</sup>             | 3.30    | 29.56 <sup>d</sup>  | 3.53    | 29.50 <sup>d</sup>   | 3.60    | 30.05 <sup>d</sup>  | 3.10    | 30.61 <sup>d</sup>  | 2.59    | 30.81 <sup>d</sup>  | 2.46    |
| VE 40%            | 52.13 <sup>f</sup>             | 6.09    | 54.53 <sup>f</sup>  | 6.15    | 58.00 <sup>f</sup>   | 6.09    | 57.61 <sup>f</sup>  | 6.11    | 57.66 <sup>f</sup>  | 5.99    | 59.04 <sup>f</sup>  | 6.57    |
| Epoxy 25%         | 14.43 <sup>ab</sup>            | 1.56    | 16.02 <sup>b</sup>  | 1.57    | 16.96 <sup>b</sup>   | 1.39    | 18.26 <sup>bc</sup> | 1.44    | 18.14 <sup>ab</sup> | 1.40    | 18.36 <sup>ab</sup> | 1.08    |
| Epoxy 40%         | 11.96 <sup>a</sup>             | 6.85    | 14.10 <sup>ab</sup> | 7.17    | 16.22 <sup>ab</sup>  | 6.89    | 16.42 <sup>ab</sup> | 6.57    | 17.98 <sup>ab</sup> | 6.63    | 22.14 <sup>c</sup>  | 6.93    |
| ESO and Epoxy25%  | 14.76 <sup>ab</sup>            | 1.34    | 14.74 <sup>ab</sup> | 1.65    | 16.94 <sup>b</sup>   | 1.43    | 17.26 <sup>bc</sup> | 2.05    | 16.87 <sup>ab</sup> | 2.10    | 17.40 <sup>ab</sup> | 2.36    |
| ESO and Epoxy 40% | 39.33 <sup>e</sup>             | 7.21    | 40.35 <sup>e</sup>  | 7.16    | 43.56 <sup>e</sup>   | 4.54    | 42.84 <sup>e</sup>  | 5.68    | 42.77 <sup>e</sup>  | 5.11    | 42.24 <sup>e</sup>  | 5.71    |
| Alder             | 96h                            | Std.Dev | 144h                | Std.Dev | 192h                 | Std.Dev | 240h                | Std.Dev | 288h                | Std.Dev | 336h                | Std.Dev |
| UD 25             | 37.02 <sup>e</sup>             | 1.27    | 38.02 <sup>d</sup>  | 1.50    | 38.34 <sup>c</sup>   | 1.48    | 38.88 <sup>d</sup>  | 1.43    | 38.96 <sup>d</sup>  | 1.61    | 39.13 <sup>d</sup>  | 2.10    |
| UD 40%            | 51.58 <sup>f</sup>             | 4.40    | 52.10 <sup>e</sup>  | 4.95    | 52.69 <sup>f</sup>   | 4.71    | 52.73 <sup>e</sup>  | 4.47    | 52.60 <sup>e</sup>  | 4.88    | 52.53 <sup>e</sup>  | 5.14    |
| ESO               | 25.92 <sup>c</sup>             | 13.32   | 26.54 <sup>c</sup>  | 14.62   | 27.14 <sup>cd</sup>  | 12.96   | 27.42 <sup>c</sup>  | 13.07   | 27.87 <sup>c</sup>  | 13.21   | 27.66 <sup>c</sup>  | 13.21   |
| ESO 40%           | 26.33 <sup>c</sup>             | 7.13    | 27.09 <sup>c</sup>  | 6.81    | 27.58 <sup>cd</sup>  | 7.00    | 27.4 <sup>4c</sup>  | 6.55    | 28.16 <sup>c</sup>  | 6.92    | 27.75 <sup>c</sup>  | 6.84    |
| Melamine Fd 25%   | 26.26 <sup>c</sup>             | 4.56    | 20.56 <sup>b</sup>  | 4.51    | 21.02 <sup>b</sup>   | 4.58    | 21.66 <sup>b</sup>  | 3.91    | 21.59 <sup>b</sup>  | 4.25    | 21.77 <sup>b</sup>  | 4.25    |
| Melamine Fd 40%   | 32.64 <sup>d</sup>             | 2.99    | 34.75 <sup>d</sup>  | 3.82    | 36.56 <sup>e</sup>   | 3.72    | 37.75 <sup>d</sup>  | 3.43    | 38.02 <sup>d</sup>  | 3.33    | 38.12 <sup>d</sup>  | 3.27    |
| VE 25%            | 24.44 <sup>c</sup>             | 2.92    | 24.30 <sup>bc</sup> | 3.33    | 24.63 <sup>bcd</sup> | 2.88    | 24.31 <sup>bc</sup> | 2.85    | 24.53 <sup>bc</sup> | 3.11    | 24.81 <sup>bc</sup> | 3.10    |
| VE 40%            | 50.18 <sup>f</sup>             | 3.25    | 49.86 <sup>e</sup>  | 3.28    | 50.41 <sup>f</sup>   | 3.29    | 50.03 <sup>e</sup>  | 3.24    | 50.29 <sup>e</sup>  | 3.57    | 50.64 <sup>e</sup>  | 3.64    |
| Epoxy25%          | 9.01 <sup>a</sup>              | 1.80    | 9.10 <sup>a</sup>   | 2.17    | 9.72 <sup>a</sup>    | 2.18    | 11.64 <sup>a</sup>  | 2.36    | 14.42 <sup>a</sup>  | 2.41    | 16.14 <sup>a</sup>  | 2.69    |
| Epoxy40%          | 17.90 <sup>b</sup>             | 1.53    | 19.60 <sup>b</sup>  | 1.47    | 22.84 <sup>a</sup>   | 1.69    | 24.46 <sup>bc</sup> | 1.79    | 26.99 <sup>bc</sup> | 1.61    | 29.08 <sup>bc</sup> | 1.84    |
| ESO and Epoxy25%  | 28.57 <sup>c<sup>u</sup></sup> | 3.89    | 28.68 <sup>c</sup>  | 4.12    | 28.92 <sup>d</sup>   | 4.39    | 29.02 <sup>c</sup>  | 4.22    | 29.59 <sup>c</sup>  | 3.83    | 29.24 <sup>c</sup>  | 3.87    |
| ESO and Epoxy40%  | 28.13 <sup>cd</sup>            | 4.42    | 28.62 <sup>c</sup>  | 4.99    | 29.56 <sup>d</sup>   | 5.60    | 28.15 <sup>c</sup>  | 4.81    | 29.29 <sup>cc</sup> | 4.50    | 30.01 <sup>c</sup>  | 4.81    |

Table 21. ANOVA table of the effect of treatment groups on swelling coefficient of poplar wood

| Poplar |                | Sum of Squares | df  | Mean Square | F       | Sig. |
|--------|----------------|----------------|-----|-------------|---------|------|
| 1h     | Between Groups | 6183.168       | 11  | 562.106     | 23.597  | .000 |
|        | Within Groups  | 2572.642       | 108 | 23.821      |         |      |
|        | Total          | 8755.811       | 119 |             |         |      |
| 2h     | Between Groups | 7946.834       | 11  | 722.439     | 27.920  | .000 |
|        | Within Groups  | 2794.527       | 108 | 25.875      |         |      |
|        | Total          | 10741.361      | 119 |             |         |      |
| 4h     | Between Groups | 16132.855      | 11  | 1466.623    | 44.603  | .000 |
|        | Within Groups  | 3551.226       | 108 | 32.882      |         |      |
|        | Total          | 19684.081      | 119 |             |         |      |
| 6h     | Between Groups | 16489.461      | 11  | 1499.042    | 41.768  | .000 |
|        | Within Groups  | 3876.133       | 108 | 35.890      |         |      |
|        | Total          | 20365.593      | 119 |             |         |      |
| 24h    | Between Groups | 24194.683      | 11  | 2199.517    | 77.726  | .000 |
|        | Within Groups  | 3056.212       | 108 | 28.298      |         |      |
|        | Total          | 27250.895      | 119 |             |         |      |
| 48h    | Between Groups | 27387.142      | 11  | 2489.740    | 96.162  | .000 |
|        | Within Groups  | 2796.245       | 108 | 25.891      |         |      |
|        | Total          | 30183.387      | 119 |             |         |      |
| 72h    | Between Groups | 27393.485      | 11  | 2490.317    | 107.208 | .000 |
|        | Within Groups  | 2508.714       | 108 | 23.229      |         |      |
|        | Total          | 29902.199      | 119 |             |         |      |
| 96h    | Between Groups | 27336.578      | 11  | 2485.143    | 104.694 | .000 |
|        | Within Groups  | 2563.612       | 108 | 23.737      |         |      |
|        | Total          | 29900.190      | 119 |             |         |      |
| 144h   | Between Groups | 27879.729      | 11  | 2534.521    | 102.102 | .000 |
|        | Within Groups  | 2680.932       | 108 | 24.823      |         |      |
|        | Total          | 30560.660      | 119 |             |         |      |
| 192h   | Between Groups | 28827.116      | 11  | 2620.647    | 115.390 | .000 |
|        | Within Groups  | 2452.818       | 108 | 22.711      |         |      |
|        | Total          | 31279.933      | 119 |             |         |      |
| 240h   | Between Groups | 28837.504      | 11  | 2621.591    | 103.580 | .000 |
|        | Within Groups  | 2733.467       | 108 | 25.310      |         |      |
|        | Total          | 31570.971      | 119 |             |         |      |
| 288h   | Between Groups | 27522.812      | 11  | 2502.074    | 107.718 | .000 |
|        | Within Groups  | 2508.625       | 108 | 23.228      |         |      |
|        | Total          | 30031.437      | 119 |             |         |      |
| 336h   | Between Groups | 27089.594      | 11  | 2462.690    | 95.161  | .000 |
|        | Within Groups  | 2794.944       | 108 | 25.879      |         |      |
|        | Total          | 29884.539      | 119 |             |         |      |

Table 22. ANOVA table of the effect of treatment groups on swelling coefficient of Alder wood

| Alder |                | Sum of Squares | df  | Mean Square | F      | Sig. |
|-------|----------------|----------------|-----|-------------|--------|------|
| 1h    | Between Groups | 1974.156       | 11  | 179.469     | 10.099 | .000 |
|       | Within Groups  | 1919.343       | 108 | 17.772      |        |      |
|       | Total          | 3893.499       | 119 |             |        |      |
| h     | Between Groups | 3768.483       | 11  | 342.589     | 27.326 | .000 |
|       | Within Groups  | 1354.000       | 108 | 12.537      |        |      |
|       | Total          | 5122.483       | 119 |             |        |      |
| 4h    | Between Groups | 7355.637       | 11  | 668.694     | 25.286 | .000 |
|       | Within Groups  | 2856.057       | 108 | 26.445      |        |      |
|       | Total          | 10211.695      | 119 |             |        |      |
| 6h    | Between Groups | 9110.371       | 11  | 828.216     | 17.319 | .000 |
|       | Within Groups  | 5164.556       | 108 | 47.820      |        |      |
|       | Total          | 14274.927      | 119 |             |        |      |
| 24h   | Between Groups | 18036.753      | 11  | 1639.705    | 48.625 | .000 |
|       | Within Groups  | 3641.918       | 108 | 33.721      |        |      |
|       | Total          | 21678.671      | 119 |             |        |      |
| 48h   | Between Groups | 17430.606      | 11  | 1584.601    | 56.351 | .000 |
|       | Within Groups  | 3036.977       | 108 | 28.120      |        |      |
|       | Total          | 20467.583      | 119 |             |        |      |
| 72h   | Between Groups | 17543.438      | 11  | 1594.858    | 58.391 | .000 |
|       | Within Groups  | 2949.869       | 108 | 27.314      |        |      |
|       | Total          | 20493.307      | 119 |             |        |      |
| 96h   | Between Groups | 15963.882      | 11  | 1451.262    | 51.464 | .000 |
|       | Within Groups  | 3045.577       | 108 | 28.200      |        |      |
|       | Total          | 19009.459      | 119 |             |        |      |
| 144h  | Between Groups | 16602.475      | 11  | 1509.316    | 46.135 | .000 |
|       | Within Groups  | 3533.277       | 108 | 32.716      |        |      |
|       | Total          | 20135.752      | 119 |             |        |      |
| 192h  | Between Groups | 16239.224      | 11  | 1476.293    | 50.112 | .000 |
|       | Within Groups  | 3181.676       | 108 | 29.460      |        |      |
|       | Total          | 19420.900      | 119 |             |        |      |
| 240h  | Between Groups | 15287.511      | 11  | 1389.774    | 50.353 | .000 |
|       | Within Groups  | 2980.870       | 108 | 27.601      |        |      |
|       | Total          | 18268.381      | 119 |             |        |      |
| 288h  | Between Groups | 13867.211      | 11  | 1260.656    | 44.039 | .000 |
|       | Within Groups  | 3091.582       | 108 | 28.626      |        |      |
|       | Total          | 16958.793      | 119 |             |        |      |
| 336h  | Between Groups | 13213.448      | 11  | 1201.223    | 40.881 | .000 |
|       | Within Groups  | 3173.427       | 108 | 29.384      |        |      |
|       | Total          | 16386.875      | 119 |             |        |      |

Densified wood can be released when exposed to humidity and the swelling coefficients increases with compression ratio (Buchelt et al., 2013; Lanie et al., 2016; Sadatnezhad et al., 2017; Wang et al., 2021). Both the reversible and irreversible swellings can occur in densified wood due to moisture adsorption/desorption (Yu et al., 2020). Due to water resistant nature of epoxy resin (Hoa et al., 2021; Sun et al., 2021; Wang et al., 2021; Guo et al., 2022), Vinyl ester (Razavi et al., 2015; Pelit and Emiroglu, 2020;) melamine formaldehyde (Deka and Saikia, 2000) and blend of ESO and Epoxy (Sahoo et al., 2015; Liu et al. (2021)) showed improvement in terms of water resistance as compared to untreated samples.

Various study conducted shows that Epoxidized soybean oil treated wood shows that less swelling coefficient than untreated wood (Temiz et al., 2013; Jebrane et al., 2015; Demiril et al., 2018; Rosu et al., 2021).

### **3.3.5. Anti-swelling efficiency**

Anti-swelling efficacy of treated compressed Poplar and Alder wood were assessed and compared with untreated densified sample in their respective compression degree and presented in

Figure 13. Statistically significant difference revealed between treatment groups during the course of water soaking duration ( $\alpha \leq 0.05$ ) for both Alder and poplar wood. Post hoc test was conducted to identify source of the significance difference based on mean Table 22 and Table 23.

Accordingly, after 336h of water soaking test, both in poplar and Alder wood, treated and densified wood showed lower swelling coefficients than untreated and densified wood samples which had direct effect on anti-swelling efficiency. In poplar wood, after 336h there was significant difference between anti-swelling efficiency of poplar wood treated and densified with vinyl ester 25% (6.72%) and ESO25% (37.32%) and ESO 40%(59.54%), epoxy 25%(38.25%) and epoxy 40% (62.34%) and blend of ESO and epoxy 25% (8.42%) and 40% (4.72%).

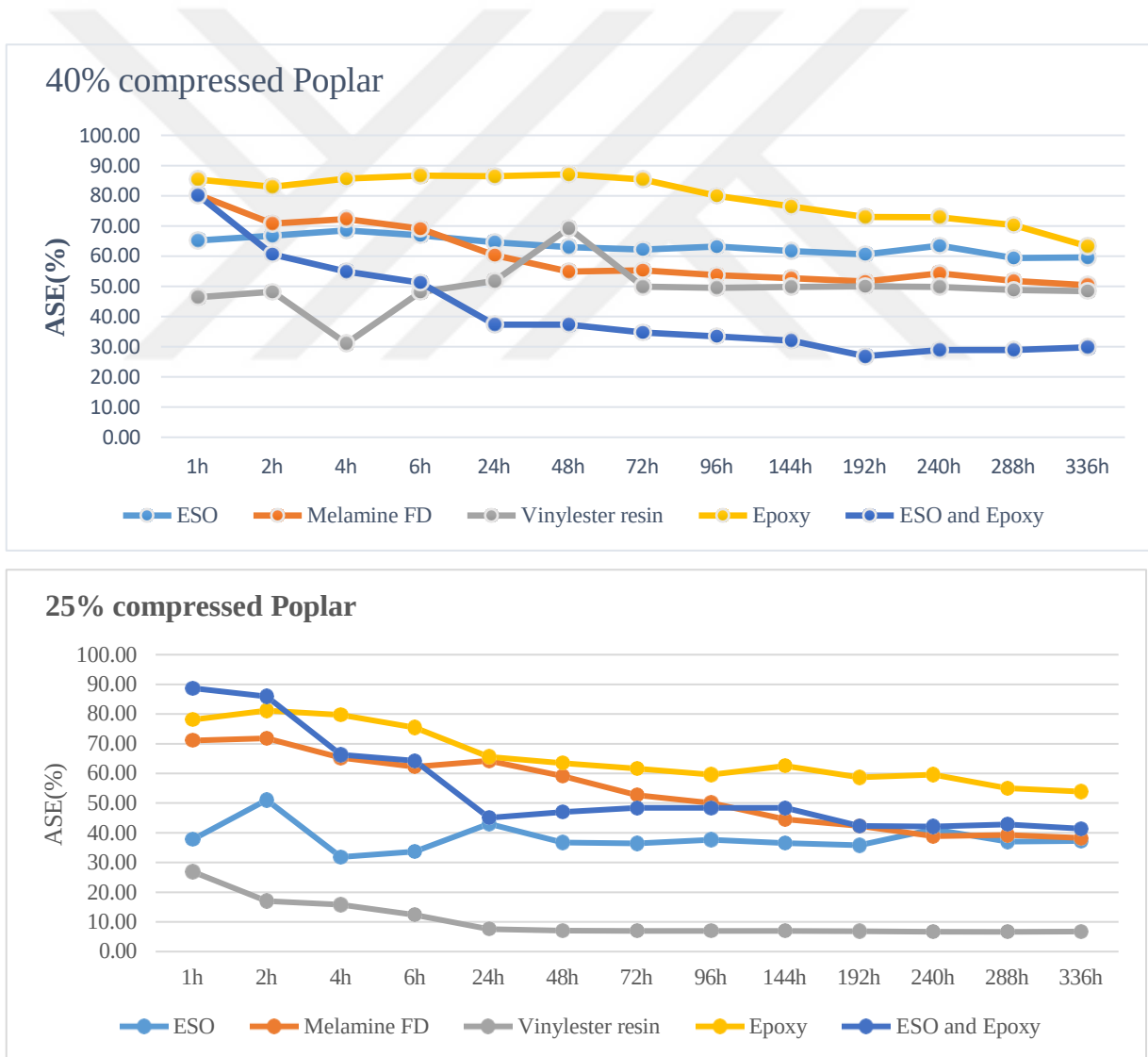
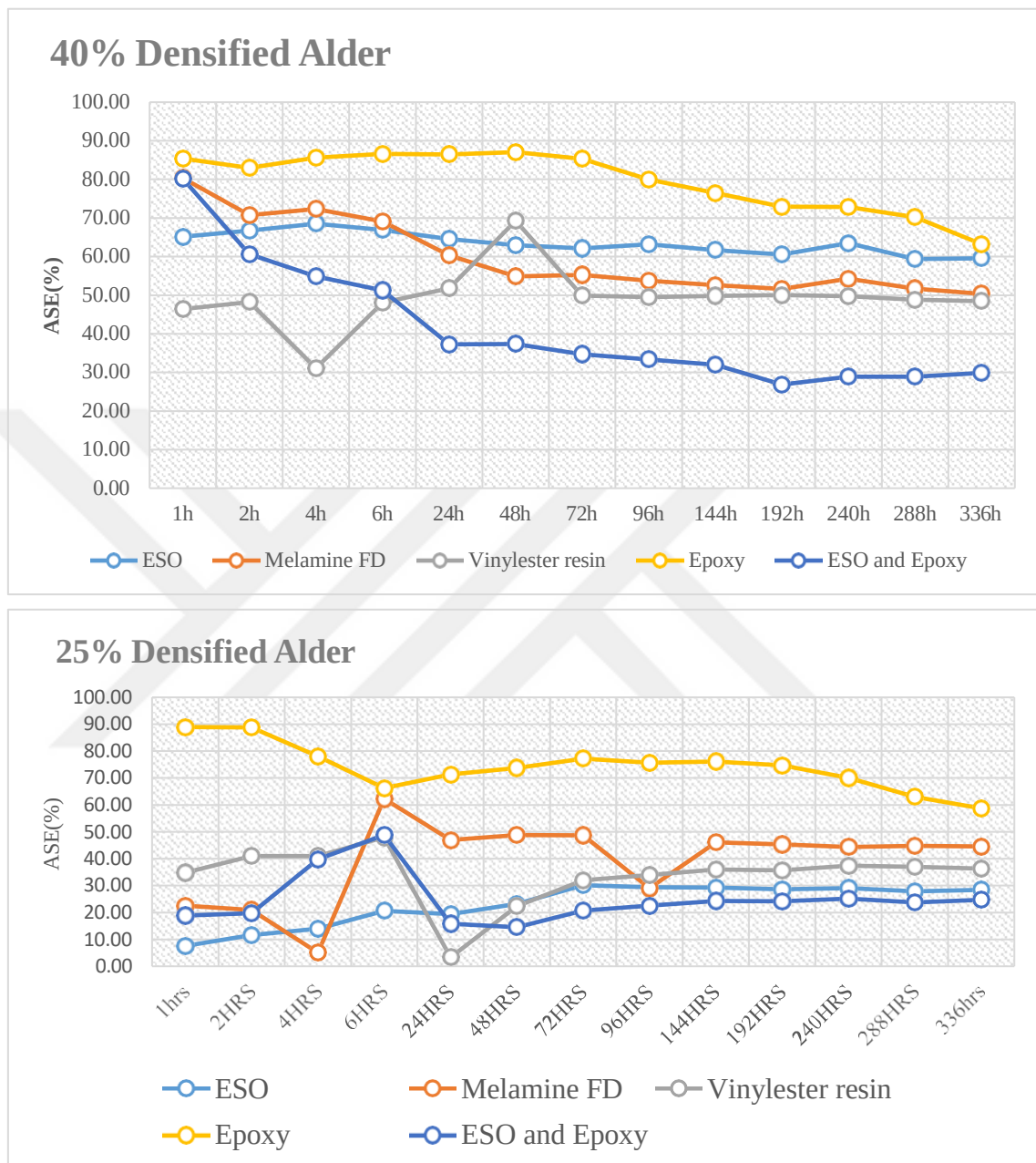


Figure 13. Anti-swelling efficiency of impregnated and densified Poplar wood

Anti-swelling efficacy of 25% compressed Poplar wood in the 1st and 336 h of water testing, Blend of ESO and epoxy shown the highest (89 and 85%) anti-swelling rate. Nevertheless, epoxy impregnated and 25% compressed wood found to be more effective against anti-swelling efficiency than other treatment groups. Whereas, Vinyl ester resin impregnated densified shown the lowest anti-swelling efficacy which about 46% after 1hrs of water testing and 6.7% after 336hrs of water soaking duration as shown in figure 13.

In the case of 40% compressed poplar wood, still epoxy was the most effective throughout the water soaking duration where the highest value of anti-swelling were 87.7 % and the lowest was 58.75 % anti-swelling efficacy over untreated wood after 336hrs of water soaking test. The same is true in the case of alder wood compressed either 25 or 40%.



. Figure 14. Anti-swelling efficiency of impregnated and densified Alder wood

**Table 23. The mean Anti-swelling efficiency of poplar and alder wood and homogenous groups 1-72h**

| <b>Poplar</b>     | 1h                  | Std.  | 2h                   | Std.  | 4h                   | Std.d | 6h                   | Std.d | 24h                 | Std.  | 48h                  | Std.  | 72h                | Std.  |
|-------------------|---------------------|-------|----------------------|-------|----------------------|-------|----------------------|-------|---------------------|-------|----------------------|-------|--------------------|-------|
| ESO25%            | 37.7 <sup>a</sup>   | 42.98 | 51.08 <sup>bc</sup>  | 38.47 | 31.85 <sup>ab</sup>  | 65.57 | 33.73 <sup>ab</sup>  | 55.24 | 43.02 <sup>bc</sup> | 13.99 | 36.74 <sup>b</sup>   | 23.46 | 6.43 <sup>b</sup>  | 24.50 |
| Melamine Fd 25%   | 78.13 <sup>cd</sup> | 17.01 | 81.18 <sup>ef</sup>  | 23.07 | 79.77 <sup>de</sup>  | 21.44 | 75.44 <sup>de</sup>  | 20.18 | 65.58 <sup>e</sup>  | 12.53 | 63.45 <sup>de</sup>  | 13.78 | 1.66 <sup>d</sup>  | 15.18 |
| Vinyl ester 25%   | 26.91 <sup>a</sup>  | 18.78 | 17.0 <sup>a</sup>    | 8.14  | 15.75 <sup>a</sup>   | 11.46 | 12.34 <sup>a</sup>   | 7.63  | 7.58 <sup>a</sup>   | 2.35  | 7.07 <sup>a</sup>    | 2.08  | 0.99 <sup>d</sup>  | 2.15  |
| Epoxy 25%         | 71.05 <sup>cd</sup> | 25.30 | 71.8 <sup>bc</sup>   | 16.92 | 65.28 <sup>cde</sup> | 24.91 | 62.26 <sup>cde</sup> | 23.16 | 64.24 <sup>e</sup>  | 12.60 | 59.05 <sup>cde</sup> | 13.68 | 2.65 <sup>a</sup>  | 14.39 |
| ESO and Epoxy 25% | 88.72 <sup>d</sup>  | 8.98  | 85.95 <sup>f</sup>   | 11.09 | 66.32 <sup>cde</sup> | 26.97 | 64.27 <sup>cde</sup> | 24.80 | 45.11 <sup>bc</sup> | 15.98 | 47.01 <sup>b</sup>   | 16.79 | 8.42 <sup>cd</sup> | 16.50 |
| ESO 40%           | 65.13 <sup>cd</sup> | 17.24 | 66.76 <sup>cde</sup> | 10.17 | 68.52 <sup>cd</sup>  | 9.46  | 66.85 <sup>cde</sup> | 7.34  | 64.54 <sup>e</sup>  | 5.64  | 62.96 <sup>de</sup>  | 6.70  | 2.14 <sup>d</sup>  | 6.13  |
| Melamine FD40%    | 80.33 <sup>cd</sup> | 18.35 | 70.78 <sup>def</sup> | 14.34 | 72.30 <sup>cd</sup>  | 9.81  | 69.07 <sup>cde</sup> | 9.23  | 60.28 <sup>de</sup> | 3.48  | 54.90 <sup>c</sup>   | 6.12  | 5.28 <sup>cd</sup> | 5.96  |
| Vinyl ester 40%   | 46.40 <sup>ab</sup> | 24.16 | 48.22 <sup>ab</sup>  | 19.01 | 31.09 <sup>ab</sup>  | 20.33 | 48.09 <sup>bc</sup>  | 28.99 | 51.74 <sup>cd</sup> | 8.37  | 69.28 <sup>e</sup>   | 9.44  | 9.91 <sup>cd</sup> | 9.24  |
| Epoxy 40%         | 85.37 <sup>cd</sup> | 6.12  | 83.00 <sup>d</sup>   | 5.26  | 85.62 <sup>d</sup>   | 3.55  | 86.63 <sup>e</sup>   | 2.59  | 86.45 <sup>f</sup>  | 10.26 | 87.07 <sup>f</sup>   | 9.08  | 5.35 <sup>e</sup>  | 10.83 |
| ESO & Epoxy40%    | 80.16 <sup>cd</sup> | 11.47 | 60.62 <sup>bc</sup>  | 16.54 | 54.87 <sup>bc</sup>  | 20.62 | 51.23 <sup>cde</sup> | 24.28 | 37.25 <sup>b</sup>  | 16.56 | 37.31 <sup>b</sup>   | 13.95 | 4.72 <sup>b</sup>  | 13.68 |
| <b>Alder</b>      |                     |       |                      |       |                      |       |                      |       |                     |       |                      |       |                    |       |
| ESO 25%           | 21.98 <sup>ab</sup> | 29.88 | 50.56 <sup>cd</sup>  | 23.28 | 49.68 <sup>b</sup>   | 26.01 | 47.90 <sup>bc</sup>  | 22.03 | 37.97 <sup>cd</sup> | 31.09 | 37.59 <sup>cd</sup>  | 25.09 | 8.29 <sup>bc</sup> | 25.10 |
| Melamine Fd 25%   | 22.59 <sup>ab</sup> | 12.70 | 20.93 <sup>ab</sup>  | 3.96  | 5.05 <sup>a</sup>    | 23.11 | 62.29 <sup>bc</sup>  | 14.41 | 46.92 <sup>d</sup>  | 16.64 | 48.85 <sup>d</sup>   | 12.90 | 8.66 <sup>c</sup>  | 10.36 |
| Vinyl ester 25%   | 34.78 <sup>ab</sup> | 33.50 | 41.00 <sup>bd</sup>  | 29.04 | 40.93 <sup>b</sup>   | 34.02 | 47.95 <sup>bc</sup>  | 27.09 | 3.32 <sup>a</sup>   | 14.55 | 22.29 <sup>a</sup>   | 10.74 | 1.96 <sup>ab</sup> | 8.39  |
| Epoxy 25%         | 88.95 <sup>d</sup>  | 6.18  | 88.77 <sup>cd</sup>  | 2.08  | 78.10 <sup>c</sup>   | 3.44  | 66.28 <sup>bc</sup>  | 4.17  | 71.33 <sup>c</sup>  | 8.11  | 73.76 <sup>c</sup>   | 5.96  | 7.24 <sup>d</sup>  | 5.95  |
| ESO & Epoxy 25%   | 18.86 <sup>a</sup>  | 41.69 | 19.69 <sup>ab</sup>  | 60.07 | 39.82 <sup>b</sup>   | 39.91 | 48.82 <sup>bc</sup>  | 31.90 | 15.79 <sup>b</sup>  | 14.04 | 14.52 <sup>b</sup>   | 15.24 | 0.74 <sup>a</sup>  | 11.82 |
| ESO 40% Alder     | 13.05 <sup>a</sup>  | 27.62 | 27.03 <sup>bc</sup>  | 16.22 | 47.72 <sup>bc</sup>  | 14.47 | 50.63 <sup>bc</sup>  | 10.79 | 53.02 <sup>d</sup>  | 10.67 | 49.83 <sup>d</sup>   | 11.86 | 0.03 <sup>bc</sup> | 13.20 |
| Melamine Fd 40%   | 46.80 <sup>bc</sup> | 10.28 | 49.82 <sup>cd</sup>  | 13.46 | 60.58 <sup>b</sup>   | 17.43 | 40.72 <sup>b</sup>   | 64.12 | 43.29 <sup>d</sup>  | 14.56 | 31.43 <sup>bc</sup>  | 10.65 | 0.45 <sup>bc</sup> | 6.71  |
| Vinyl ester 40%   | 27.48 <sup>ab</sup> | 23.58 | 0.84 <sup>a</sup>    | 27.00 | 5.93 <sup>a</sup>    | 35.44 | 5.05 <sup>a</sup>    | 42.94 | 26.79 <sup>bc</sup> | 37.34 | 32.85 <sup>d</sup>   | 24.42 | 4.04 <sup>b</sup>  | 23.24 |
| Epoxy 40% Alder   | 82.19 <sup>d</sup>  | 10.38 | 82.96 <sup>bc</sup>  | 9.42  | 76.21 <sup>c</sup>   | 12.36 | 76.47 <sup>c</sup>   | 12.04 | 76.90 <sup>d</sup>  | 8.43  | 69.44 <sup>c</sup>   | 5.02  | 8.05 <sup>d</sup>  | 4.98  |
| ESO & Epoxy 40%   | 65.52 <sup>cd</sup> | 36.92 | 62.45 <sup>de</sup>  | 23.68 | 62.35 <sup>b</sup>   | 22.29 | 61.11 <sup>bc</sup>  | 23.68 | 48.78 <sup>d</sup>  | 13.35 | 46.60 <sup>d</sup>   | 10.30 | 5.43 <sup>bc</sup> | 9.83  |

Table 24. The mean Anti-swelling efficiency of poplar and alder wood and homogenous groups 96-336h

| <b>Poplar</b>     | 96h                  | Std.  | 144h                 | Std.  | 192h                | Std.  | 240h                 | Std.  | 288h                 | Std.  | 336h                 | Std.  |
|-------------------|----------------------|-------|----------------------|-------|---------------------|-------|----------------------|-------|----------------------|-------|----------------------|-------|
| ESO25%            | 37.69 <sup>bc</sup>  | 22.04 | 36.57 <sup>cd</sup>  | 22.65 | 35.81 <sup>bc</sup> | 22.17 | 41.20 <sup>bc</sup>  | 21.07 | 37.00 <sup>bc</sup>  | 22.87 | 37.23 <sup>bc</sup>  | 27.33 |
| Melamine Fd 25%   | 59.60 <sup>de</sup>  | 15.93 | 62.54 <sup>e</sup>   | 13.87 | 58.67 <sup>e</sup>  | 15.06 | 59.59 <sup>ef</sup>  | 14.60 | 55.06 <sup>ef</sup>  | 15.88 | 53.88 <sup>def</sup> | 16.45 |
| Vinyl ester 25%   | 6.97 <sup>a</sup>    | 2.12  | 6.95 <sup>a</sup>    | 2.09  | 6.84 <sup>a</sup>   | 2.03  | 6.69 <sup>a</sup>    | 1.97  | 6.70 <sup>a</sup>    | 2.03  | 6.72 <sup>a</sup>    | 2.09  |
| Epoxy 25%         | 50.00 <sup>cd</sup>  | 15.45 | 44.58 <sup>cd</sup>  | 17.04 | 42.30 <sup>cd</sup> | 17.21 | 38.84 <sup>bc</sup>  | 19.57 | 39.30 <sup>bc</sup>  | 18.45 | 38.26 <sup>cde</sup> | 19.95 |
| ESO and Epoxy 25% | 48.42 <sup>cd</sup>  | 17.44 | 48.42 <sup>cd</sup>  | 18.50 | 42.29 <sup>cd</sup> | 16.92 | 42.14 <sup>cd</sup>  | 18.47 | 42.88 <sup>cd</sup>  | 21.15 | 41.39 <sup>f</sup>   | 19.91 |
| ESO 40%           | 63.15 <sup>e</sup>   | 7.76  | 61.66 <sup>e</sup>   | 7.10  | 60.57 <sup>e</sup>  | 7.21  | 63.50 <sup>fg</sup>  | 9.52  | 59.36 <sup>fg</sup>  | 8.50  | 59.54 <sup>ef</sup>  | 9.18  |
| Melamine Fd 40%   | 53.72 <sup>de</sup>  | 4.41  | 52.63 <sup>de</sup>  | 6.15  | 51.61 <sup>de</sup> | 5.54  | 54.28 <sup>def</sup> | 7.75  | 51.73 <sup>def</sup> | 6.82  | 50.35 <sup>cd</sup>  | 6.10  |
| Vinyl ester 40%   | 49.47 <sup>cd</sup>  | 8.82  | 49.80 <sup>de</sup>  | 9.11  | 50.00 <sup>de</sup> | 9.73  | 49.74 <sup>cde</sup> | 8.44  | 48.81 <sup>cde</sup> | 7.81  | 48.43 <sup>a</sup>   | 8.02  |
| Epoxy40%          | 79.95 <sup>f</sup>   | 11.19 | 76.45 <sup>f</sup>   | 11.56 | 72.93 <sup>f</sup>  | 11.17 | 72.83 <sup>g</sup>   | 10.59 | 70.22 <sup>g</sup>   | 10.62 | 63.24 <sup>bc</sup>  | 11.29 |
| ESO and Epoxy 40% | 33.37 <sup>b</sup>   | 12.62 | 32.01 <sup>b</sup>   | 12.19 | 26.85 <sup>b</sup>  | 8.60  | 28.86 <sup>b</sup>   | 9.67  | 28.90 <sup>b</sup>   | 9.40  | 29.84 <sup>bcd</sup> | 9.49  |
| <b>Alder</b>      |                      |       |                      |       |                     |       |                      |       |                      |       |                      |       |
| ESO 25%           | 37.48 <sup>bcd</sup> | 24.75 | 36.75 <sup>bcd</sup> | 27.75 | 35.92 <sup>bc</sup> | 24.40 | 35.77 <sup>bcd</sup> | 24.51 | 35.20 <sup>bcd</sup> | 24.40 | 35.88 <sup>bc</sup>  | 24.81 |
| Melamine FD 25%   | 29.08 <sup>abc</sup> | 11.86 | 46.05 <sup>d</sup>   | 11.06 | 45.29 <sup>cd</sup> | 11.20 | 44.40 <sup>de</sup>  | 9.23  | 44.75 <sup>de</sup>  | 9.78  | 44.54 <sup>c</sup>   | 9.41  |
| Vinyl ester 25%   | 33.90 <sup>bcd</sup> | 8.18  | 36.02 <sup>bcd</sup> | 8.92  | 35.66 <sup>bc</sup> | 7.98  | 37.37 <sup>cd</sup>  | 7.62  | 36.94 <sup>cde</sup> | 8.34  | 36.35 <sup>bc</sup>  | 9.15  |
| Epoxy 25%         | 75.73 <sup>f</sup>   | 4.52  | 76.09 <sup>f</sup>   | 5.53  | 74.67 <sup>e</sup>  | 5.59  | 70.06 <sup>f</sup>   | 5.97  | 63.00 <sup>f</sup>   | 6.05  | 58.72 <sup>d</sup>   | 6.64  |
| ESO and Epoxy 25% | 22.56 <sup>ac</sup>  | 12.02 | 24.28 <sup>ab</sup>  | 12.33 | 24.21 <sup>ab</sup> | 13.41 | 25.16 <sup>ab</sup>  | 11.82 | 23.74 <sup>ab</sup>  | 11.72 | 24.77 <sup>ab</sup>  | 12.71 |
| ESO 40%           | 48.92 <sup>e</sup>   | 12.79 | 47.76 <sup>d</sup>   | 12.63 | 47.52 <sup>cd</sup> | 12.47 | 47.84 <sup>de</sup>  | 11.67 | 46.31 <sup>de</sup>  | 12.32 | 46.99 <sup>cd</sup>  | 12.38 |
| Melamine FD 40%   | 36.48 <sup>bcd</sup> | 5.85  | 33.11 <sup>bc</sup>  | 6.21  | 30.19 <sup>ab</sup> | 8.53  | 28.06 <sup>abc</sup> | 7.85  | 27.29 <sup>abc</sup> | 7.99  | 26.94 <sup>ab</sup>  | 8.33  |
| Vinyl ester 40%   | 17.46 <sup>a</sup>   | 20.14 | 19.69 <sup>a</sup>   | 18.69 | 19.26 <sup>a</sup>  | 18.99 | 19.54 <sup>a</sup>   | 18.26 | 19.51 <sup>a</sup>   | 18.78 | 18.56 <sup>a</sup>   | 19.44 |
| Epoxy 40%         | 64.95 <sup>f</sup>   | 5.10  | 61.93 <sup>e</sup>   | 5.73  | 56.23 <sup>d</sup>  | 5.93  | 53.18 <sup>e</sup>   | 6.34  | 48.19 <sup>e</sup>   | 6.55  | 44.01 <sup>c</sup>   | 7.83  |
| ESO and Epoxy 40% | 45.09 <sup>de</sup>  | 10.10 | 44.70 <sup>cd</sup>  | 10.87 | 43.64 <sup>cd</sup> | 11.25 | 46.34 <sup>de</sup>  | 10.13 | 43.86 <sup>e</sup>   | 10.45 | 42.43 <sup>c</sup>   | 10.96 |

Rubber wood treated with 30% sucrose and 70% tung oil improved anti-swelling efficiency by 60%; an even better result was obtained when the combined treatment was used than the tung oil-treated sample. High-pressure densification, followed by coating with tung oil and epoxy, improved set recovery and anti-swelling efficiency, where epoxy coating showed a better result than tung oil.

In order to increase dimensional stability, Altgen et al. (2020) and Zheng et al. (2022) investigated impregnation modification utilising thermosetting resins such as melamine formaldehyde (MF). In order to achieve these benefits, the study emphasizes the significance of inserting resin into the cell wall microstructure as opposed to just filling the cell lumen. Methylated melamine-treated wood with a 5% bulking effect increased anti-swelling by 30% (Kiemann et al., 2016). The impregnation of FA resin improved dimensional stability (Zheng et al., 2022; 2023; Han et al., 2022).

Due to the water-resistant nature of epoxy resin (Hoa et al., 2021; Sun et al., 2021; Wang et al., 2021; Guo et al., 2022), vinyl ester (Pelit and Emiroglu, 2020), melamine formaldehyde (Deka and Saikia, 2000; Altgen et al., 2020), and a blend of ESO and epoxy (Sahoo et al., 2015; Liu et al., 2021), the water resistance of treatment groups improved as compared to untreated samples.

### **3.3. Mechanical Properties**

#### **3.3.1. Impact Bending Strength**

Impact strength test of untreated and impregnated densified Poplar and Alder wood are shown in Figure 15 and 16. The Impact test results revealed that alder wood shown more impact resistance than poplar wood. Statistically significant difference revealed between treatment groups in both Alder and polar wood Table 25. Amongst the treatment groups, poplar wood impregnated with Vinyl ester resin shown the highest impact resistance of 5.36 and 3.88 J for 40% and 25 compression ratio, respectively. The lowest Impact resistance was Melamine formaldehyde (2.02 J) impregnated and compressed 40% sample as indicated in figure 15

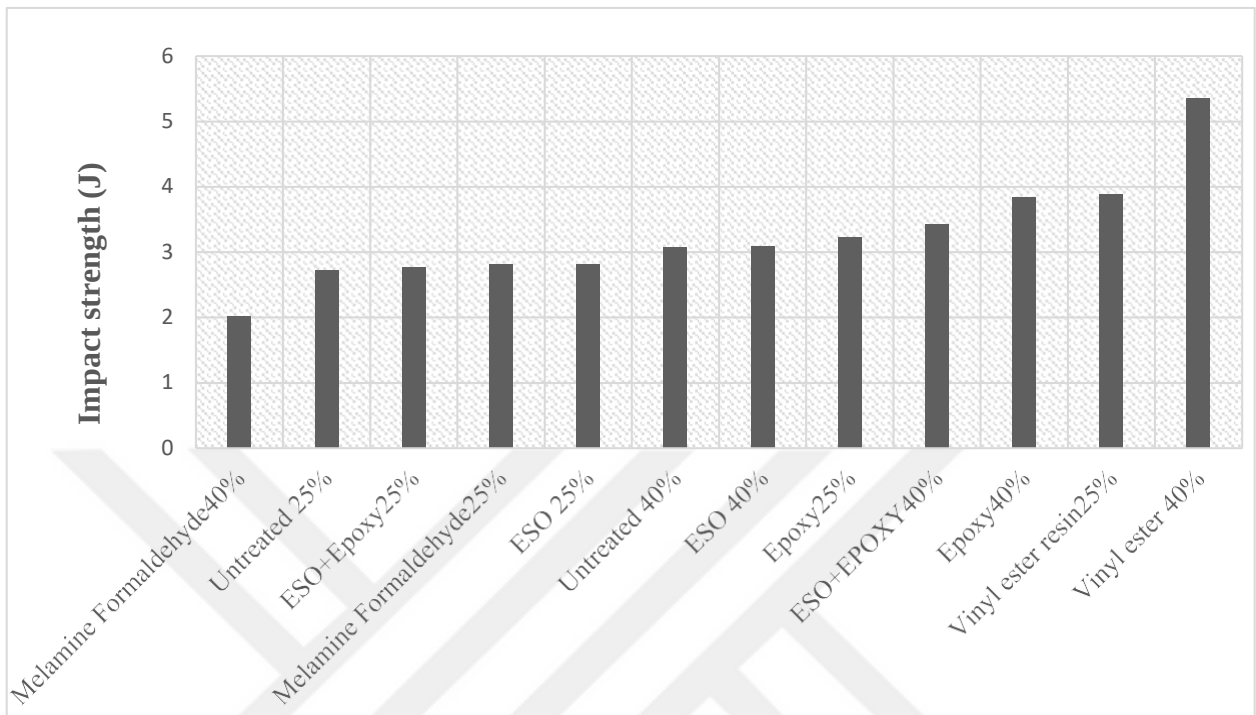


Figure 15. Impact strength test of untreated and Impregnated Densified Poplar wood

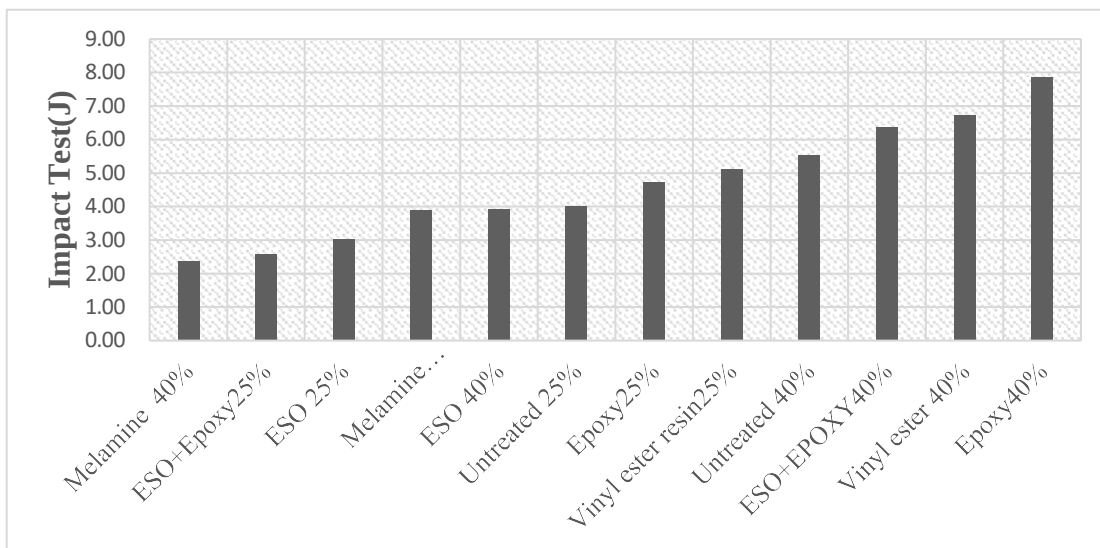


Figure 16. Impact Test of Untreated and Impregnated Densified Alder wood

In Alder wood, Epoxy impregnated and 40% compressed shown the best impact resistance than other treatment groups, which is followed by Vinyl ester impregnated and blend of ESO

and Epoxy. The lowest impact resistance was found in melamine formaldehyde impregnated compressed wood as indicated in figure 15.

Table 25. One-way ANOVA results of impact tests of untreated and impregnated and densified alder and poplar

|        |                | Sum of Squares | df  | Mean Square | F     | Sig. |
|--------|----------------|----------------|-----|-------------|-------|------|
| Alder  | Between Groups | 291.917        | 11  | 26.538      | 2.647 | .005 |
|        | Within Groups  | 1082.803       | 108 | 10.026      |       |      |
|        | Total          | 1374.720       | 119 |             |       |      |
| Poplar | Between Groups | 76.667         | 11  | 6.970       | 7.164 | .000 |
|        | Within Groups  | 105.074        | 108 | .973        |       |      |
|        | Total          | 181.742        | 119 |             |       |      |

Based on the post hoc test results and impact bending strength of poplar wood, there was no significant difference between Melamine Fd 25%, 40%, Vinyl Ester 25%, UD 25%, ESO 25%, and Blend of ESO and Epoxy 25%, but there was a significant difference between Melamine Fd 40%, Vinyl Ester 40%, and Epoxy 40%. In alder wood, there was a significant difference between the blend of Melamine Fd 40%, the blend of ESO and Epoxy (40%), and the blend of Epoxy 40%.

In research studies, bending wood samples under impact has been tested using a variety of techniques. The Sand Collision Test is one technique that was developed in accordance with Standard ASTM D 968-05 (Liu et al., 2014). In this test, a piece of wood is placed at a 45-degree angle to a horizontal surface, and 50 g of commercial sand grains—diameter 100–300  $\mu$ m—are dropped from a height of 30 cm onto the super hydrophobic wood surface. According to Liu et al. (2014), the sand collision test simulates the harm caused by the collision of solid particles falling with gravity.

Charpy Impact testing is another technique that has been used to describe the high strain-rate behavior of wood species like ash and maple (Fortin-Smith et al., 2018). This testing procedure adheres to the guidelines set forth by the Federal Highway Administration (FHWA) for describing southern yellow pine. High-speed testing can better characterize the material behavior of wood during impact by using these testing approaches on different wood species

(Fortin-Smith et al., 2018). The effects of a high-speed collision on wood samples have also been studied using finite element modelling. Finite element models are useful for gaining an understanding of the mechanical behavior of wood under impact, as previous studies have shown. According to Fortin-Smith et al. (2018), these models have been used to examine the effects of high-speed impact on wood baseball bats as well as the connections between bat profile, wood quality, and durability.

Table 26. The mean Impact bending strength (J) and homogenous groups (Duncan) for both Alder and Poplar

| Wood   | Groups of Treatment        | N  | Impact Strength (J) | Std. Deviation |
|--------|----------------------------|----|---------------------|----------------|
| Alder  | UD 25%                     | 10 | 4.02 <sup>bc</sup>  | 2.03           |
|        | UD 40%                     | 10 | 5.54 <sup>bc</sup>  | 2.56           |
|        | ESO 25%                    | 10 | 3.01 <sup>ab</sup>  | 2.97           |
|        | ESO 40%                    | 10 | 3.91 <sup>ab</sup>  | 0.46           |
|        | Melamine Fd 25%            | 10 | 3.90 <sup>ab</sup>  | 0.79           |
|        | Melamine Fd 40%            | 10 | 2.36 <sup>a</sup>   | 2.21           |
|        | Vinyl ester 25%            | 10 | 5.51 <sup>bc</sup>  | 0.56           |
|        | Vinyl ester 40%            | 10 | 6.73 <sup>bc</sup>  | 2.23           |
|        | Epoxy 25%                  | 10 | 4.72 <sup>bc</sup>  | 1.64           |
|        | Epoxy 40%                  | 10 | 7.86 <sup>c</sup>   | 2.68           |
|        | ESO and Epoxy 25%          | 10 | 2.57 <sup>ab</sup>  | 1.89           |
|        | ESO and Epoxy 40%          | 10 | 6.36 <sup>bc</sup>  | 0.80           |
| Poplar | UD 25%                     | 10 | 2.71 <sup>ab</sup>  | 0.35           |
|        | UD 40%                     | 10 | 3.08 <sup>bc</sup>  | 0.99           |
|        | ESO 25%                    | 10 | 2.82 <sup>ab</sup>  | 0.71           |
|        | ESO 40%                    | 10 | 3.08 <sup>bc</sup>  | 0.80           |
|        | Melamine Fd 25%            | 10 | 2.81 <sup>ab</sup>  | 0.46           |
|        | Melamine Fd 40%            | 10 | 2.03 <sup>a</sup>   | 0.99           |
|        | Vinyl ester 25%            | 10 | 3.88 <sup>bc</sup>  | 1.45           |
|        | Vinyl ester 40%            | 10 | 5.35 <sup>c</sup>   | 1.71           |
|        | Epoxy 25%                  | 10 | 3.22                | 0.69           |
|        | Epoxy 40%                  | 10 | 3.84 <sup>c</sup>   | 1.11           |
|        | Blend of ESO and Epoxy 25% | 10 | 2.77 <sup>ab</sup>  | 0.89           |
|        | Blend of ESO and Epoxy 40% | 10 | 3.43 <sup>bc</sup>  | 0.78           |

Impact test results show that alder wood is found to be more impact resistant than poplar wood, which is associated with the inherent density of wood. Less dense wood has shown the highest improvement in mechanical property following mechanical densification compared to

higher-density wood (Perttuzatti et al., 2018). Impact test results of melamine formaldehyde (Pittman et al., 2006; Altun and Tokdemir, 2017) and ESO impregnated densified wood were lower than those of untreated densified wood. This corroborates a study on modified plant oils, in which treated wood mechanical properties were specifically lower than those of thermally treated wood mechanical properties (Hill, 2006; Temiz et al., 2010; 2013; Demirel, 2018). Whereas vinyl ester, epoxy, a blend of ESO and epoxy, and untreated densified poplar wood 40% compressed show 5.36, 3.84, 3.43, and 3.08 J, respectively. The lowest impact tests of alder wood were 2.36 and 3.02 J for melamine formaldehyde and ESO impregnated densified. The highest impact test values of 40% compressed epoxy, untreated densified epoxy, and blends of ESO and epoxy were 7.86, 6.73, and 6.36 J, respectively, in their descending order. In both alder and poplar wood, the lowest impact strengths were 40% compressed Melamine formaldehyde impregnated and 40% densified wood (2.36 J and 2 J, respectively).

Stalin et al. (2021) examined the physical and mechanical properties of Tamarid seed reinforced with vinyl ester resin. Mohit et al. (2021) examined sugar cane vinyl ester nanocomposites, and the results show enhanced physical and mechanical properties.

This study's findings, which indicate that wood impregnated with melamine formaldehyde and compressed to 40% has the lowest impact strength, are in line with those of Pittman et al. (2006) and Altun and Tokdemir (2017), who found that treating wood with melamine actually made it less mechanically strong than untreated wood.

### **3.3.2. Modules of Elasticity and Modulus of Rupture**

MOE and MOR results are shown in Figure 23 and 24. Modulus of elasticity of poplar wood is lower than Alder wood in all treatment conditions figure 15. In both Poplar and Alder wood, ESO treated and 40% compressed wood shown the highest modulus of elasticity followed by Melamine Formaldehyde, vinyl ester resin and epoxy treated wood. The lowest MOE of Alder wood were untreated and Blend of ESO and Epoxy sample. MOE of ESO treated 40% and 25% compressed Alder and poplar wood (72 985 MPa and 66 855 MPa) and 46157.3 (MPa) and 30623.40 (MPa), respectively. Vinyl ester resin treated and 40% and 25% compressed Alder and poplar wood (30071.5 Mpa, 21762.2Mpa) and (29729.11Mpa) and (12682 Mpa), respectively.

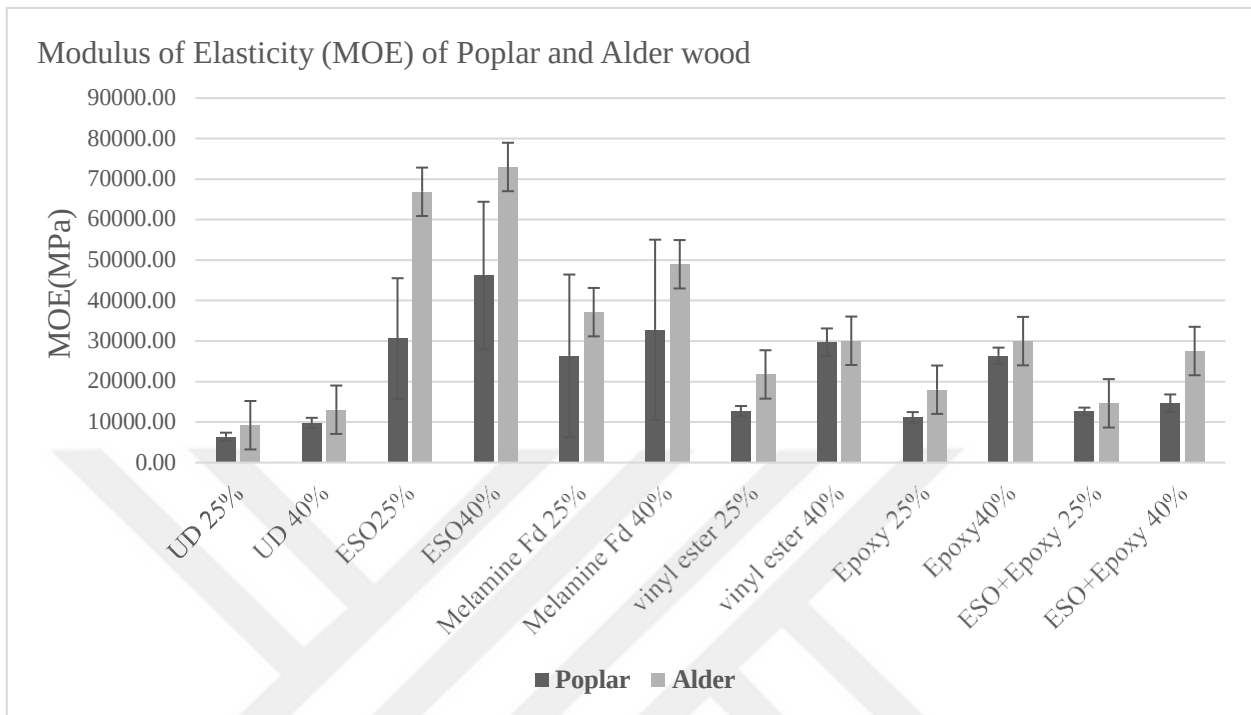


Figure 17. MOE of untreated and Impregnated Compressed Poplar and Alder Wood

Modulus rupture of Alder was found to be higher than Poplar wood figure 16. Among the treatments groups, Epoxy treated wood and 40% compressed wood shown the highest MOR (222.74MPa), followed by Blend of ESO and epoxy (201.86MPa), vinyl ester resin (182.45MPa), Melamine Formaldehyde (177MPa), Untreated densified wood (124 MPa) and ESO treated wood was the lowest MOR of in both wood types. The ANOVA table (Table 29) shows that statistically significant difference observed between treatments ( $\alpha \leq 0.05$ ).

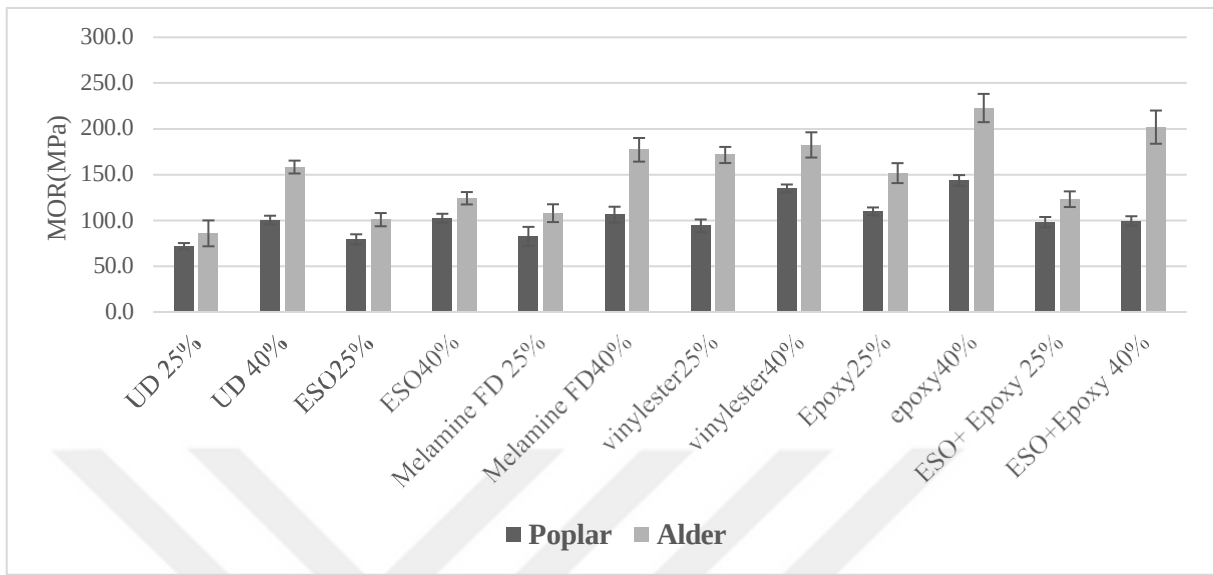


Figure 18. Modulus of Rupture of untreated compressed alder and poplar wood

Table 27. The ANOVA analysis of modulus of rupture and modulus of elasticity of poplar and alder wood

|            |                | Sum of Squares  | df  | Mean Square    | F     | Sig. |
|------------|----------------|-----------------|-----|----------------|-------|------|
| Poplar MOR | Between Groups | 356081.347      | 11  | 32371.03       | 51.56 | .000 |
|            | Within Groups  | 105472.048      | 168 | 627.810        |       |      |
|            | Total          | 461553.39       | 179 |                |       |      |
| Poplar MOE | Between Groups | 46184494931.72  | 11  | 4198590448.338 | 4.905 | .000 |
|            | Within Groups  | 143797610279.46 | 168 | 855938156.42   |       |      |
|            | Total          | 189982105211.18 | 179 |                |       |      |
| Alder MOR  | Between Groups | 290101.91       | 11  | 26372.901      | 10.77 | .000 |
|            | Within Groups  | 411360.13       | 168 | 2448.572       |       |      |
|            | Total          | 701462.04       | 179 |                |       |      |
| Alder MOE  | Between Groups | 81077764160.50  | 11  | 7370705832.774 | 4.033 | .000 |
|            | Within Groups  | 307053462331.34 | 168 | 1827699180.544 |       |      |
|            | Total          | 388131226491.85 | 179 |                |       |      |

Table 28. The mean modulus of rupture of poplar and alder wood and homogenous groups

| Treatment groups      | N  | Poplar             | Std. Deviation | Alder                | St. Deviation |
|-----------------------|----|--------------------|----------------|----------------------|---------------|
| UD 25%                | 15 | 71.8 <sup>a</sup>  | 13.27          | 71.84 <sup>a</sup>   | 54.77         |
| UD 40%                | 15 | 100.4 <sup>c</sup> | 18.44          | 154.65 <sup>cd</sup> | 26.79         |
| ESO25%                | 15 | 79.3 <sup>ab</sup> | 15.13          | 99.56 <sup>ab</sup>  | 25.98         |
| ESO40%                | 15 | 102.4 <sup>c</sup> | 20.89          | 121.31 <sup>bc</sup> | 25.84         |
| Melamine Fd 25%       | 15 | 82.5 <sup>ab</sup> | 10.14          | 93.92 <sup>ab</sup>  | 37.60         |
| Melamine Fd 40%       | 15 | 106.3 <sup>c</sup> | 33.44          | 117.12 <sup>bc</sup> | 49.98         |
| Vinyl ester resin 25% | 15 | 94.1 <sup>b</sup>  | 26.38          | 173.00 <sup>de</sup> | 33.17         |
| Vinyl ester resin 40% | 15 | 134.9 <sup>d</sup> | 50.32          | 184.32 <sup>de</sup> | 82.64         |
| Epoxy 25%             | 15 | 109.8 <sup>c</sup> | 17.03          | 145.63 <sup>cd</sup> | 40.29         |
| Epoxy 40%             | 15 | 143.7 <sup>d</sup> | 26.32          | 184.20 <sup>de</sup> | 68.76         |
| ESO and Epoxy 25%     | 15 | 98.1 <sup>c</sup>  | 22.11          | 99.96 <sup>ab</sup>  | 32.27         |
| ESO and Epoxy 40      | 15 | 99.3 <sup>c</sup>  | 20.77          | 197.61 <sup>e</sup>  | 71.35         |

The post hoc test (Table 28) analysis showed that in poplar wood, there is a difference between untreated densified (25%) and Vinyl ester, blend of ESO and Epoxy and epoxy impregnated and densified poplar wood. Likewise in Alder wood, there is a difference between Untreated densified and ESO (40%), Melamine Fd (40%), vinyl ester, epoxy and Blend of ESO and epoxy (40%). Regarding modulus of elasticity as indicate in table 29 of poplar wood, there is a difference between epoxy impregnated and 40% densified wood with untreated and densified wood and other groups of treatment. While, in Alder wood, there is statistically significant difference between UD25% and Melamine Fd 40%, ESO 25% and Epoxy 40% groups of treatments.

Table 29. The mean modulus of elasticity of Poplar and Alder wood and homogenous groups

| Groups of treatment   | Poplar                | Std. Deviation | Alder                   | Std. Deviation |
|-----------------------|-----------------------|----------------|-------------------------|----------------|
| UD 25%                | 9226.97 <sup>a</sup>  | 3092.93        | 6390.57 <sup>a</sup>    | 3859.91        |
| UD 40%                | 9967.90 <sup>a</sup>  | 4566.97        | 13503.98 <sup>ab</sup>  | 4230.85        |
| ESO25%                | 10513.26 <sup>a</sup> | 1992.28        | 60139.58 <sup>cd</sup>  | 52009.34       |
| ESO40%                | 16644.78 <sup>a</sup> | 4562.71        | 83190.45 <sup>cd</sup>  | 73390.55       |
| Melamine Fd 25%       | 13209.97 <sup>a</sup> | 1294.06        | 37139.68 <sup>abc</sup> | 77806.35       |
| Melamine Fd 40%       | 22805.12 <sup>a</sup> | 4581.64        | 48964.38 <sup>bc</sup>  | 86097.43       |
| Vinyl ester resin 25% | 12252.36 <sup>a</sup> | 4232.60        | 22212.83 <sup>ab</sup>  | 4733.13        |
| Vinyl ester resin 40% | 29648.68 <sup>a</sup> | 11391.60       | 34566.16 <sup>abc</sup> | 11482.43       |
| Epoxy 25%             | 11165.48 <sup>a</sup> | 1426.92        | 17161.56 <sup>ab</sup>  | 4968.42        |
| Epoxy 40%             | 68953.66 <sup>b</sup> | 100005.02      | 25407.50 <sup>abc</sup> | 8659.26        |
| ESO and Epoxy 25%     | 12615.82 <sup>a</sup> | 3346.60        | 14939.34 <sup>ab</sup>  | 3509.62        |
| ESO and Epoxy 40      | 14433.34 <sup>a</sup> | 5608.69        | 26796.16 <sup>abc</sup> | 8695.83        |

Alder wood modulus of elasticity is higher than poplar wood in all conditions, which supports the idea that the higher the density of wood, the higher the modulus of elasticity (Vega et al., 2020). In addition, the higher the compression degree, the higher the MOE obtained, which goes in line with the impact of density on mechanical property (Li et al., 2016; Kim et al., 2020). The highest modulus of elasticity in densified wood impregnated with epoxidized soybean oil is likely due to the thermal effects resulting from the application of heat during curing at 70 °C, steaming at 140 °C, and densification at 160 °C. One of the factors that affects the modulus of elasticity of wood is moisture content (Hering et al., 2011); therefore, ESO impregnated densified wood showed the highest modulus of elasticity as compared to other treatment groups, which likely related to the complete curing of epoxy, vinyl ester, and melamine formaldehyde impregnated wood and the softening role of ESO (Garcia-Campo et al., 2017; Liu et al., 2021).

A study conducted by Hao et al. (2022) on poplar wood impregnated via water-borne epoxy shows that well-impregnated wood material improves mechanical properties as well as thermal resistance. The blend of epoxy, epoxidized linseed oil, and an anhydride showed improvements in elastic modulus and glass temperature (Miyagawa et al., 2004). According to

Guo et al. (2022), the modulus of rupture and elasticity of solid wood impregnated with epoxy monomer improved by 20 and 24%, respectively.

It has been discovered that impregnating solid wood with water-soluble MF resin increases the surface hardness and elastic modulus (Wang et al., 2017; Rahayu et al., 2021). Altun and Tokdemir (2016) also investigated the influence of melamine-formaldehyde impregnation on the transverse compression strength of spruce wood, but it was negatively affected.

The modulus rupture of alder wood was higher than that of poplar wood, which was related to its inherent density and compression ratio (Figure 18). 40% compression degree shows a higher MOR than 25% compressed wood. Among the treatment groups, epoxy-treated wood and 40% compressed wood showed the highest MOR (222.74 MPa), followed by a blend of ESO and epoxy (201.86 MPa), vinyl ester resin (182.45 MPa), melamine formaldehyde (177 MPa), and untreated dense wood (158 MPa). Untreated and ESO-treated wood had the lowest MOR of both wood types. A statistically significant difference was observed between treatment groups ( $\alpha \leq 0.05$ ).

Modulus of rupture of epoxy, blend of ESO and epoxy, vinyl ester, and ESO impregnated densified wood improved by 41, 27, 15, and 10%, respectively. While ESO impregnated densified wood compression degree showed an even lower MOR than untreated and 40% compressed wood. In 25% compressed wood, the lowest MOR found in untreated wood was 71.8 and 85.8 MPa, respectively, for poplar and alder wood. Compared to 25% compressed untreated wood, epoxy, a blend of ESO and epoxy, vinyl ester, melamine formaldehyde, and ESO impregnated densified wood enhanced the MOR by (76.6, 53.2), (43.5, 36.5), (99.7, 30.9), (25.7, 15), and (17.4, 10) percentages for both alder and poplar wood, respectively.

According to Guo et al. (2022), the modulus of rupture and elasticity of solid wood impregnated with epoxy monomer were enhanced by 20 and 24%, respectively. Based on the findings of Guo et al. (2022), the compressive strength of epoxy impregnated wood improved by more than 40%. Cheng et al. (2022) and Yue et al. (2020) support that the effects of resin impregnation and densification greatly amend the fire resistance of fast-growing poplar wood. Ultra-strong wood is prepared by combining compression and subsequent impregnation with epoxy. Thus, the compressive, impact, flexural, and modulus strengths improved by more than 200% (Guo et al., 2022). A study on bamboo delignification, densification, and subsequent

impregnation with epoxy and assisted using microwaves resulted in 80.9% and 42.9% improvement in flexural and compressive strength, respectively (Liu et al., 2022).

Most of the studies about vinyl ester resin were carried out on composites (Stalin et al., 2019; 2021; Rajkumar et al., 2019; Mohit et al., 2021; Kumar et al., 2020; Gosh et al., 2011; Palaniyappan et al., 2022; Shahedifar & Rezadoust, 2013; Zhang et al., 2023). Vinyl ester-treated wood composites have shown an improvement in mechanical properties, particularly flexural strength (Shahedifar & Rezadoust, 2013; Razzali et al., 2016; Stalin et al., 2021; Zhang et al., 2023).

The impact of a blend of ESO and epoxy impregnation and densification on mechanical properties studied by various researchers shows an improvement (Das and Karak, 2009; Gogoi et al., 2015; Subbiah et al., 2022). Mashouf-Roudsari et al. (2017) studied the use of epoxidized vegetable oils as toughening agents in epoxy resin. The wood's mechanical attributes, such as its strength and impact resistance, may be improved by the blend's improved toughening capacity. Vegetable oils that have been epoxidized are also less expensive and contain less sodium, which makes them appealing substitutes for improving the performance of epoxy resin. In the contemporary world, ESO is widely used as a plasticizer. In a study by Liu et al. (2021), the addition of 20% ESO to the furfuryl alcohol (FA) solution resulted in improved toughness and mechanical properties of the furfurylated wood. The role of epoxidized soybean oil or other vegetable oil in improving mechanical properties is not remarkable (Temiz et al., 20213; Demirel et al., 2018; Jebrane et al., 2016). Shi et al. (2020) discuss the fabrication of densified wood using a combination of chemical pretreatment, hot-pressing, and post-mechanical fixation. The densified softwood exhibits improved modulus of rupture (MOR) and modulus of elasticity (MOE).

### **3.3.3. Compression Strength**

Compression strengths parallel to the grain of Alder and Poplar wood are presented in Figure 25. Untreated and treated compressed Alder wood shown better compression strength than poplar wood. Statistically significant difference between treatments groups were observed

( $\alpha < 0.05$  and  $F_{11, 119} = 57.35$  and  $F_{11, 119} = 14.479$  for poplar and Alder Wood, respectively. To identify the homogenous group, post hoc test were examined as illustrated in Table 32.

Vinyl ester resin impregnated and compressed Alder wood shown the highest compression strength followed by Epoxy, Blend of ESO and Epoxy, ESO, Untreated densified and Melamine formaldehyde as illustrated in figure 18. In addition, the result revealed that Melamine treated and compressed Poplar wood drastically affected by the process, even lower than untreated densified sample.

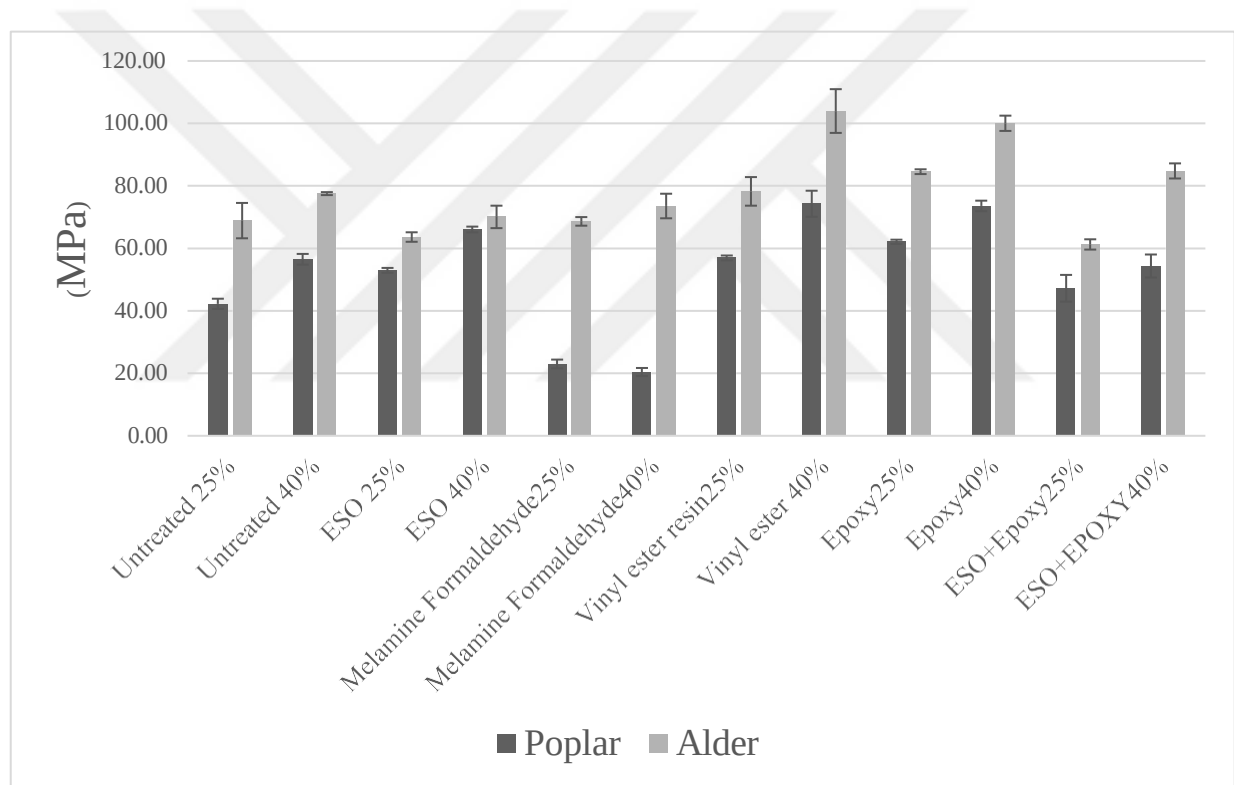


Figure 19. The Mean Compression Strength Value of untreated and Treatment groups of Alder and Poplar wood

Table 30. The mean compression strength and homogenous group

| Wood type | Treatment Group            | N  | Mean (J)              | Std. Deviation |
|-----------|----------------------------|----|-----------------------|----------------|
| Poplar    | UD 25%                     | 10 | 42.25 <sup>b</sup>    | 5.15           |
|           | UD 40%                     | 10 | 56.50 <sup>de</sup>   | 5.44           |
|           | ESO 25%                    | 10 | 52.96 <sup>cd</sup>   | 2.47           |
|           | ESO 40%                    | 10 | 66.058 <sup>f</sup>   | 2.87           |
|           | Melamine Fd 25%            | 10 | 22.99 <sup>a</sup>    | 4.45           |
|           | Melamine Fd 40%            | 10 | 20.42 <sup>a</sup>    | 4.12           |
|           | Vinyl ester 25%            | 10 | 57.98 <sup>d</sup>    | 4.06           |
|           | Vinyl ester 40%            | 10 | 74.27 <sup>f</sup>    | 13.21          |
|           | Epoxy 25%                  | 10 | 62.10 <sup>ef</sup>   | 2.15           |
|           | Epoxy 40%                  | 10 | 74.94 <sup>g</sup>    | 3.47           |
|           | Blend of ESO and Epoxy 25% | 10 | 47.22 <sup>bc</sup>   | 13.54          |
|           | Blend of ESO and Epoxy 40% | 10 | 54.35 <sup>d</sup>    | 11.65          |
| Alder     | UD 25%                     | 10 | 68.89 <sup>abc</sup>  | 17.89          |
|           | UD 40%                     | 10 | 77.53 <sup>cd</sup>   | 1.51           |
|           | ESO 25%                    | 10 | 63.63 <sup>ab</sup>   | 4.81           |
|           | ESO 40%                    | 10 | 70.075 <sup>abc</sup> | 11.36          |
|           | Melamine Fd 25%            | 10 | 68.65 <sup>abc</sup>  | 4.34           |
|           | Melamine Fd 40%            | 10 | 73.56 <sup>bc</sup>   | 12.43          |
|           | Vinyl ester 25%            | 10 | 78.25 <sup>cd</sup>   | 14.46          |
|           | Vinyl ester 40%            | 10 | 103.97 <sup>e</sup>   | 22.13          |
|           | Epoxy 25%                  | 10 | 84.52 <sup>d</sup>    | 2.41           |
|           | Epoxy 40%                  | 10 | 100.04 <sup>e</sup>   | 7.73           |
|           | Blend of ESO and Epoxy 25% | 10 | 61.26 <sup>a</sup>    | 5.19           |
|           | Blend of ESO and Epoxy 40% | 10 | 84.79 <sup>d</sup>    | 7.63           |

Post hoc test using Duncan in Table 32 shows at least there was a mean difference between untreated densified 25% (42.5 MPa) and ESO (25, 96 MPa, 66.05MPa), Vinyl ester(57.8 MPa and 74.2 MPa), epoxy(62 MPa, 74 MPa )and, blend of ESO and epoxy 40% (54.35Mpa) where the lowest compression strength was Melamine Fd (20MPa an 22Mpa). Likewise, Alder wood compression strength was higher than poplar wood. The was a mean difference between untreated densified 25% (68.89 MPa) and Vinyl ester 40% (103.97 MPa), epoxy (84.52 MPa, 100.04 MPa) and blend of ESO and epoxy (84.79 MPa) Vinyl ester resin impregnated and

densified Alder wood shown the highest compression strength followed by Epoxy, Blend of ESO and Epoxy, ESO, Untreated densified, and Melamine formaldehyde wood as illustrated in figure 18. Which confirms study conducted by Liu et al., (2022) shown that Epoxy impregnated densified wood improved compression strength by 42 % as compared to untreated wood. Based on finding of Guo et al., (2022) the compressive strength epoxy impregnated wood improved by more than 40%.

In addition, the study revealed that melamine-treated compressed Poplar wood was drastically affected by the process, thus its compression strength was even lower than that of the untreated wood sample, which supports studies by Pittman et al. (2006) and Altun and Tokdemir (2017). However, a study by Yao et al. (2017) showed that Chinese fir impregnated with modified melamine formaldehyde improved compression strength parallel to the grain by 60–80% by increasing the concentration of melamine by more than 30%. In terms of mechanical property, epoxy resin is higher than vinyl ester, even though the former is more costly. The result of this study shows that vinyl ester impregnated densified wood shows better compression strength than epoxy, which is likely caused by weight percentage gain. Due to the swift curing of epoxy, the impregnation duration was lower than that of vinyl ester resin. Nevertheless, the difference between vinyl ester and epoxy was around 2.5 MPa; thus, this finding is consistent with various studies (Yue et al., 2020; Samin et al., 2021; Gou et al., 2022; Cheng et al., 2022). Based on the findings of Guo et al. (2022), the compressive strength of epoxy impregnated wood improved by more than 40%. The toughness of wood may be improved by impregnating it with a mixture of epoxy and epoxidized soybean oil (Zhao et al., 2018). According to Zhao et al. (2018), the toughening impact of ESO in blends with polylactide (PLA) led to the blends' exceptional toughness. Researchers found that the internal ESO cavitation-induced shear yielding of the PLA matrix could effectively diffuse the fracture energy of the PLA/ESO blends (Zhao et al., 2018).

#### **3.3.4. Hardness of wood**

To evaluate the Shore-D hardness of wood samples, record of indentation were obtained from three points on the sample surface and the average of the replication considered for

evaluation. Accordingly, Poplar wood had lower surface hardness than Alder wood. Statistically, significant difference between treatment groups were observed ( $\alpha < 0.05$ ). The mean hardness values presented in their ascending order in figure 19. Accordingly, the blend of ESO and Epoxy impregnated (40%) and 25% compressed shown the lowest surface hardness whereas, 40% compressed epoxy impregnated sample shown the highest (61). The shore-D hardness of Alder wood illustrated in figure 19 shows that ESO impregnated and 25% compressed sample shown the least resistance to indentation (60.93) and Vinyl ester resin impregnated and 40% compressed sample shown the highest resistance to indentation (73.3). The result show that statistically significant difference between treatment groups observed ( $p < 0.05$ ,  $F_{11, 179} = 21.516$ , and  $F_{11, 179} = 18.516$ ) for Alder and poplar wood, respectively shown in figure 19.

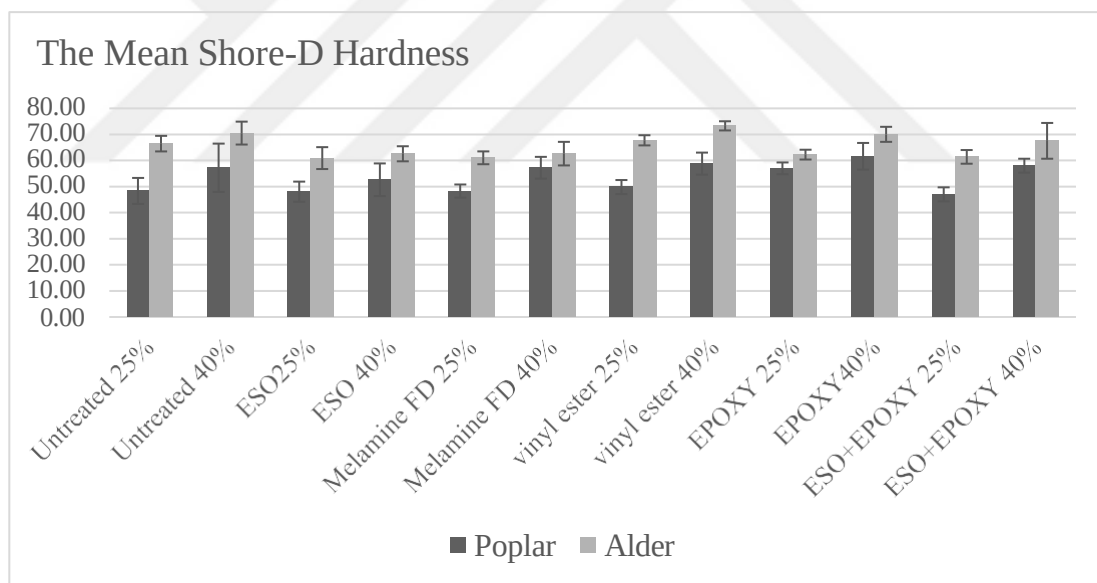


Figure 20. The mean Shore-D Hardness of untreated and treated densified Alder and Poplar wood

The homogeneity carried out show that in poplar wood there was no difference between UD25%, ESO 25%, Melamine Fd 40%, Vinyl ester 25% and blend of ESO and Epoxy, but there was a difference statistically between UD 25%, ESO 40%, Melamine Fd 40%, vinyl ester 40% and 25% an 40% epoxy. In Alder wood, statistically significance difference revealed between

ESO and other treatment groups except in Melamine Fd and 25% densified Epoxy. Where in both Alder and Poplar, Melamine Fd, UD and ESO shown the lowest shore D- hardness.

Shore D hardness value can be converted approximately to Brinell and Rockwell hardness using the formula derived from hardness table (Leonghut, 2021; Engineers edge, 2022; Upmold; 2022). These conversion values does not precisely describe the figure in all cases, because the materials used and the scale is very different.

Rockwell Hardness: There is no direct conversion formula between Shore D and Rockwell hardness. However, a rough estimate can be made by using the following formula:

$$\text{Rockwell hardness} = 100 - (10 \times \text{Shore D hardness}).$$

Brinell hardness: The relationship between Shore D hardness and Brinell hardness depends on the material being tested. However, a rough estimate can be made by using the following formula:  $\text{Brinell hardness} = (10.4 \times \text{Shore D hardness}) + 11$

This study examined the wood hardness test using Shore-D hardness. Various studies conducted by Karamanoglu and Akyildiz (2013), Li et al. (2018), Sahin and Onay (2020), and Esteve et al. (2021) recommend that it is possible to carry out hardness tests for private and small-scale industries using Shore D. The higher the values of the Shore D recording, the higher the hardness of the material. The value closer to 1 was found to be more resistant to indentation than the other. Accordingly, epoxy-treated and 40% densified alder wood showed the highest value, followed by a blend of ESO and epoxy, untreated densified wood, vinyl ester resin, ESO, and melamine formaldehyde samples for alder wood in their descending order. However, melamine-formaldehyde-treated poplar showed the lowest values of all samples examined. Sample values were obtained from three points (two from the edge and one from the middle) of the sample surface, and the average of the replication was considered for evaluation. Accordingly, poplar wood had a lower surface hardness than alder wood. Statistically, a significant difference between treatment groups was observed ( $\alpha \leq 0.05$ ).

A study by Mania et al. (2020) and Juliette et al. (2020) supports that wood hardness following densification depends on innate density and the remaining percentage of chemicals following delignification. Moreover, 40% compressed wood showed better surface hardness than its 25% compressed counterpart, which corroborates the study by Gasparik et al. (2019; Laine et al. (2016) as the densification rate increased, the hardness of the wood increased even

more than double as compared to undensified wood. Mania et al. (2020) examine the hardness of densified wood in relation to its changed chemical composition.

Table 31. The mean Shore-D Hardness of untreated and treated densified Alder and Poplar Wood

| Treatment groups           | Shore-D Hardness |       | Brinell hardness (N/mm <sup>2</sup> ) |        |
|----------------------------|------------------|-------|---------------------------------------|--------|
|                            | Poplar           | Alder | Poplar                                | Alder  |
| UD 25%                     | 48.35            | 66.48 | 513.89                                | 702.37 |
| UD 40%                     | 57.22            | 70.52 | 606.10                                | 744.43 |
| ESO25%                     | 48.05            | 60.93 | 510.67                                | 644.71 |
| ESO 40%                    | 52.62            | 62.59 | 558.27                                | 661.92 |
| Melamine FD 25%            | 48.30            | 61.04 | 513.31                                | 645.86 |
| Melamine FD 40%            | 57.24            | 62.64 | 606.33                                | 662.50 |
| vinyl ester 25%            | 49.82            | 67.76 | 529.16                                | 715.66 |
| vinyl ester 40%            | 58.81            | 73.30 | 622.63                                | 773.32 |
| Epoxy 25%                  | 57.00            | 62.27 | 603.80                                | 658.57 |
| Epoxy 40%                  | 61.62            | 70.04 | 651.87                                | 739.46 |
| Blend ESO and Epoxy 25%    | 47.02            | 61.40 | 500.05                                | 649.56 |
| Blend of ESO and Epoxy 40% | 58.02            | 67.56 | 614.43                                | 713.58 |

The study shows that densified wood has increased hardness due to the reduction in porosity and the support of folded cell walls. The densification of wood after impregnation has a big impact on how hard the wood is. Wood's strength qualities improve as a result of the densification process, which entails making wood denser by reducing cavity volume (Ülker et al., 2012). The hardness of wood tends to rise along with its density. The effect of *Pinus radiata* wood's chemical composition on its physical and mechanical qualities after thermo-hygro-mechanical densification was examined in the study by Cruz et al. (2018). The samples were divided according to how much lignin they contained. The outcomes demonstrated that the process of densification changed the chemical composition and enhanced the material's physical and mechanical qualities, including hardness.

Table 32. The average Shore D hardness and converted Brinell hardness of Poplar and Alder wood

| Shore-D Hardness |                   | N  | Mean                | Std. Deviation |
|------------------|-------------------|----|---------------------|----------------|
| Alder            | UD 25%            | 15 | 66.48 <sup>b</sup>  | 2.99           |
|                  | UD 40%            | 15 | 70.52 <sup>d</sup>  | 4.39           |
|                  | ESO25%            | 15 | 60.93 <sup>a</sup>  | 4.20           |
|                  | ESO40%            | 15 | 62.59 <sup>a</sup>  | 2.88           |
|                  | Melamine Fd 25%   | 15 | 61.05 <sup>a</sup>  | 2.46           |
|                  | Melamine Fd 40%   | 15 | 62.64 <sup>a</sup>  | 4.52           |
|                  | Vinyl ester 25%   | 15 | 67.76 <sup>bc</sup> | 1.95           |
|                  | Vinyl ester 40%   | 15 | 73.30 <sup>e</sup>  | 1.76           |
|                  | Epoxy 25%         | 15 | 62.27 <sup>a</sup>  | 1.88           |
|                  | Epoxy 40%         | 15 | 70.05 <sup>cd</sup> | 2.88           |
|                  | ESO and Epoxy 25% | 15 | 61.40 <sup>a</sup>  | 2.62           |
|                  | ESO and Epoxy 40% | 15 | 67.56 <sup>a</sup>  | 6.86           |
| Poplar           | UD 25%            | 15 | 48.35 <sup>a</sup>  | 4.97           |
|                  | UD 40%            | 15 | 57.22 <sup>c</sup>  | 9.26           |
|                  | ESO25%            | 15 | 48.05 <sup>a</sup>  | 3.87           |
|                  | ESO40%            | 15 | 52.62 <sup>b</sup>  | 6.27           |
|                  | Melamine Fd 25%   | 15 | 48.30 <sup>a</sup>  | 2.52           |
|                  | Melamine Fd 40%   | 15 | 57.24 <sup>c</sup>  | 4.17           |
|                  | vinyl ester 25%   | 15 | 49.82 <sup>ab</sup> | 2.70           |
|                  | vinyl ester 40%   | 15 | 58.81 <sup>cd</sup> | 4.24           |
|                  | Epoxy 25%         | 15 | 57.00 <sup>cd</sup> | 2.27           |
|                  | Epoxy 40%         | 15 | 61.62 <sup>d</sup>  | 5.12           |
|                  | ESO and Epoxy 25% | 15 | 47.02 <sup>a</sup>  | 2.70           |
|                  | ESO and Epoxy 40% | 15 | 58.02 <sup>a</sup>  | 2.67           |

### 3.4. Thermal Test Analysis

Thermogravimetric analysis results of the groups of treatments of both Alder and Poplar wood are presented in shown in Table 33. A study conducted by Deka and Saika (2002) and Pittman et al. (2006) shows that melamine formaldehyde-treated wood exhibited improved thermal resistance within the range of 300–650 °C compared to untreated wood, with the greatest improvement observed in wood treated with a higher concentration of melamine. Additionally, the study found that the thermal stability of MF-treated wood was enhanced by the formation of a char layer on the surface of the wood, which helped to protect the underlying wood from further thermal degradation.

Wang et al. (2017) examine the thermal degradation and fire performance of wood treated with melamine urea formaldehyde (MUF) resin and boron compounds. After melamine, ESO and epoxy show better resistance to heat. A study conducted by Rosu et al. (2018) on wood treated with epoxidized grape seed oil showed improved heat resistance over other synthetic resins applied, i.e., succinic anhydride mixed with glycidyl methacrylate and diglycidyl ether of bisphenol A.

The thermal resistance of untreated and treated Alder and Poplar wood were examined at temperature range of 30°C to 800°C, 10°C/min heating rate and 200 ml/min Nitrogen input using HITACHI STA 7000 device. To determine the performance of Impregnated densified wood against heat, the initial and residual weight were calculated and the percentage weight loss of for each group were formaldehyde, Vinyl ester resin , epoxy and Blend of epoxy and ESO impregnated densified wood were considered for thermal analysis regardless of compression ratio.

The thermal analysis was carried out in the range of lowest initial temperature of 25°C-34°C and maximum temperature of 795 °C. The residual weight or weight loss of Poplar and Alder wood after exposed to maximum temperature of 795°C under all treatment conditions, less weight loss was observed in Alder than Poplar wood.

Regarding treatment groups, difference revealed between Alder and poplar wood. In poplar wood, the highest weight loss was found in untreated densified, Vinyl ester treated, Blend of Epoxy and Epoxidized soybean oil treated densified wood, whereas the lowest weight loss were found in Melamine Formaldehyde, ESO and Epoxy impregnated densified wood in their

descending order. Therefore, Melamine formaldehyde is the highest thermal resistance from their respective groups of treatment, followed by ESO and Epoxy.

In Alder wood, the highest weight loss was found in Vinyl ester resin, Untreated and Blend of Epoxy and ESO impregnated wood in their descending order. The lowest weight loss observed in ESO, Melamine Formaldehyde and Epoxy impregnated and densified wood according to their decreasing order. Based on the result, ESO, Melamine Formaldehyde, and Epoxy are better resistance to heat than the remaining treatment groups.

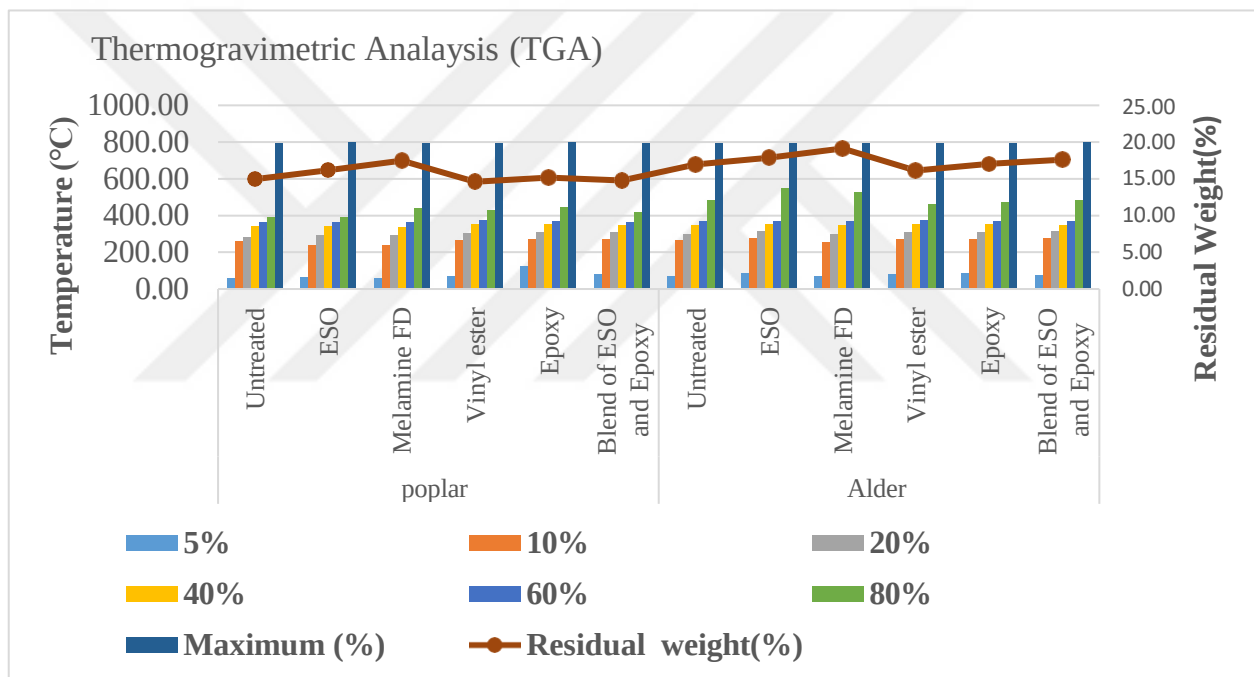


Figure 21. The temperature, weight loss and residual weight of treated and untreated densified poplar and Alder wood based on TGA results

A study conducted by Deka and Saika (2002) and Pittman et al. (2006) shows that melamine formaldehyde-treated wood exhibited improved thermal resistance within the range of 300–650 °C compared to untreated wood, with the greatest improvement observed in wood treated with a higher concentration of melamine. Additionally, the study found that the thermal stability of MF-treated wood was enhanced by the formation of a char layer on the surface of the wood, which helped to protect the underlying wood from further thermal degradation.

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Table 33. The Initial and Maximum Temperature Used and Residual Weight of Densified Alder and Poplar Wood after Thermal Analysis

| Poplar Wood                    | Initial Temp (°C) | Maximum Temp (°C) | Initial Weight (µg) | Residual Weight (µg) | Residual Weight (%) | Ranking |
|--------------------------------|-------------------|-------------------|---------------------|----------------------|---------------------|---------|
| UD                             | 34.01             | 790.68            | 2530.36             | 380.45               | 14.94               | 4       |
| ESO                            | 25.26             | 795.77            | 1747.72             | 284.95               | 16.30               | 2       |
| Melamine Fd                    | 25.41             | 795.13            | 2706.48             | 474.69               | 17.54               | 1       |
| Vinyl ester Resin              | 28.19             | 795.56            | 3553.52             | 520.33               | 14.64               | 6       |
| Epoxy Resin                    | 25.62             | 795.88            | 4930.43             | 748.54               | 15.18               | 3       |
| Blend of Epoxy and ESO (30:70) | 30.62             | 794.82            | 4124.49             | 611.22               | 14.82               | 5       |
| Alder Wood                     | Initial Temp (°C) | Maximum Temp (°C) | Initial Weight (µg) | Residual Weight (µg) | Residual Weight (%) | Ranking |
| Untreated Densified            | 30.53             | 790.89            | 5807.88             | 985.17               | 16.94               | 5       |
| ESO                            | 25.76             | 795.11            | 3267.82             | 626.81               | 17.86               | 2       |
| Melamine fd                    | 24.07             | 793.88            | 5221.03             | 933.75               | 19.13               | 1       |
| Vinyl ester Resin              | 23.70             | 795.23            | 7529.30             | 1214.75              | 16.13               | 6       |
| Epoxy Resin                    | 26.36             | 794.70            | 3489.49             | 595.800              | 17.03               | 4       |
| Blend ESO and epoxy (30:70)    | 29.153            | 795.808           | 4621.810            | 816.650              | 17.62               | 3       |

Wang et al. (2017) and (2018) observed that wood treated with ESO and vinyl ester had improved thermal stability, indicating better resistance to heat. Yu et al. (2020) investigated the effects of epoxy impregnation on the thermal stability and mechanical properties of wood and found that the treated wood had improved thermal stability and mechanical properties, with a higher onset temperature for thermal degradation and better resistance to bending and compression.



#### 4. CONCLUSION

The combined effect of impregnation and densification was examined with the aim of counterbalancing the weaknesses of one over the other. The retention level used was in the range of 100–150 kg/m<sup>3</sup>, and the impregnation process was carried out either by pressure, vacuum, or both. The physical, mechanical, and thermal properties of the impregnated densified wood were assessed, and the results were compared to those of untreated densified wood. The mechanical qualities of untreated densified wood, such as impact bending strength, modulus of elasticity, modulus of rupture, hardness, and compression strength parallel to the grain, were not as strong as those of impregnated densified wood, except in Melamine formaldehyde impregnated densified poplar wood, where impact and compression strength were found to be lower than untreated wood, which might be caused by the thermal effect of Melamine formaldehyde impregnated wood during compression at 160 °C applied for softening for 40–60 minutes and at 160°C for 20 minutes, which hampered the wood's inherent properties. Regarding impregnation treatment on dimensional stability, epoxy impregnated densified wood has shown the highest effectiveness in reducing set recovery.

**Density:** There is a statistically significant difference in density between impregnated and densified poplar and alder wood and untreated densified wood. The density of both alder and poplar wood increased following impregnation and densification. By compression, the original volume of the wood sample shrinks; thus, density increases depending on the degree of compression. Furthermore, impregnation and densification enhanced density more than an untreated densified sample, where wood pores were filled with impregnants to a certain extent. Impregnation densification can further enhance the density of the wood compared to untreated densified samples, as the impregnants fill the wood pores to a certain extent, contributing to the overall increase in density (Yu et al., 2020; Mania et al., 2020; Julian et al., 2022). The impregnation of wood with resins or other substances during the densification process can lead to a more significant increase in density due to the filling of void spaces within the wood structure. This impregnation helps to compact the wood fibres and enhance the overall density of the material, resulting in improved mechanical properties and dimensional stability (Zor &

Can, 2020; Sumardi et al., 2020; Mania et al., 2022). Nevertheless, the extent of density enhancement is affected by the inherent density of wood, the viscosity of the impregnant, the retention level, the weight percentage gain following compression, the curing or polymerization rate of the impregnant, and the degree of compression. Accordingly, vinyl ester, epoxy, a blend of ESO and epoxy, ESO, and melamine formaldehyde are listed in descending order based on their impact on density.

**Set Recovery Analysis:** There is a statistically significant difference in set recovery between impregnated and densified poplar and alder wood and untreated densified wood. Set recovery was 1.02 and 3.89, 4.88 and 5.88%, for Poplar and Alder wood, respectively, for epoxy impregnated and 25 and 40% compressed wood. Whereas, in melamine-impregnated densified wood, 9.63, 9.41, 11.14, and 11.47% were the set recovery of poplar and alder wood after 40 and 25% compression, respectively. The blend of epoxy and ESO was found to be the third effective treatment group in reducing the set recovery of 25 and 40% of poplar and alder wood (1.36, 22.80, and 26.15, 28.42), followed by ESO and vinyl ester resin, respectively. The highest set recovery was observed in untreated densified wood with 68.25, 77.31, and 58.08, 77.28 % for 25 and 40% densified poplar and alder wood, respectively. Epoxidized soybean oil impregnated densified wood is not satisfactory in reducing set recovery; thus, non-renewable resin, in this case, epoxy, is water-proof and commonly used for wood finishing purposes and composites. Based on this result, the blend of ESO and epoxy was included in his study.

**Water Repellence and Dimensional Stability:** There is a statistically significant difference in water repellence and dimensional stability between impregnated and densified poplar and alder wood and untreated densified wood. The water absorption, water repellence, and anti-swelling efficiency results revealed that regardless of compression degree, epoxy, ESO, and melamine formaldehyde were found to be effective in reducing water absorption, increasing water repellence, and increasing the anti-swelling efficacy of both alder and poplar wood in their decreasing order of effectiveness. Blends of ESO and epoxy, vinyl ester, and untreated densified wood took the lowest tiers, and lastly, untreated densified wood. Even though the effects of ESO on Set recovery were insignificant for outdoor use applications, in repelling water, ESO was found to be better than melamine formaldehyde and other treatment groups,

except epoxy impregnated densified wood, which was associated with the change in temperature and medium of testing for Set recovery evaluation.

**Mechanical Properties:** There is a statistically significant difference in mechanical properties (strength, impact, stiffness, Hardness and compression strength) between impregnated and densified poplar and alder wood and untreated densified wood. Improvement in density affected variably the mechanical properties of wood, i.e., MOE, MOR, impact strength, compression strength parallel to the grain, and hardness, except for poplar wood impregnated with melamine formaldehyde, which is lower than untreated densified wood, especially impact resistance and compression strength parallel to the grain.

**Thermal Resistance Properties:** There is a statistically significant difference in thermal resistance properties between impregnated and densified poplar and alder wood and untreated densified wood. The thermal resistance of alder and poplar wood was investigated. Based on the residual weight, regardless of compression degree, ESO, melamine formaldehyde, and epoxy-impregnated densified wood were found to have better heat resistance than other treatment groups. Impregnated densified alder wood has relatively shown the highest residual weight compared to poplar wood. Melamine, ESO, and Epoxy (19.18, 17.88, and 17.67%), while poplar wood residual weight was 16.30, 17.54, and 15.18%, respectively. The variation was found in the same treatment groups, but 25 and 40% compressed wood were probably associated with the extent and depth of retention and also weight percentage gain following compression.

#### 4. RECOMMENDATION

This study used bio-based and non-biobased impregnants to reduce the weakness of densified wood. Accordingly, five different treatment and untreated (control) groups, two densification degrees, and two wood types were included in this study. Based on the findings of this study, the following recommendations were sought:

- To gain the better result required in the contemporary world from densified wood products, clearly evaluate the efficiency of the technique applied, and compare with similar studies, compression machines with a cooling phase and gradual weight lifting following compression could potentially enhance the result gained.
- To reduce the set recovery of impregnated densified wood, epoxy, melamine formaldehyde, and a blend of ESO and epoxy are recommended. Considering the different temperature ranges that are optimum for each treatment used during steaming and compression improves the set recovery. Though cost-wise, epoxy is expensive and challenging due to its quick curing nature once a hardener is added, alternative chemicals that potentially extend the duration of curing are recommended.
- Optimizing the blend of ESO and epoxy and the temperature applied improves the overall properties of wood, particularly its dimensional stability.
- In ESO impregnation and densification, the inability to cure 100% was the challenge, which lowers the weight percentage gain. Therefore, lowering the temperature applied for steaming, compression, and set recovery testing might bring better results. Moreover, increasing the duration of curing ESO in the presence of acetic acid is recommended.
- Epoxy and vinyl ester resins impact on wood dimensional stability in a largely opposite way. Though epoxy is effective, it is expensive and challenging for impregnation and densification treatment. Whereas, vinyl ester resin is non-effective at all.

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## 6. APPENDIX

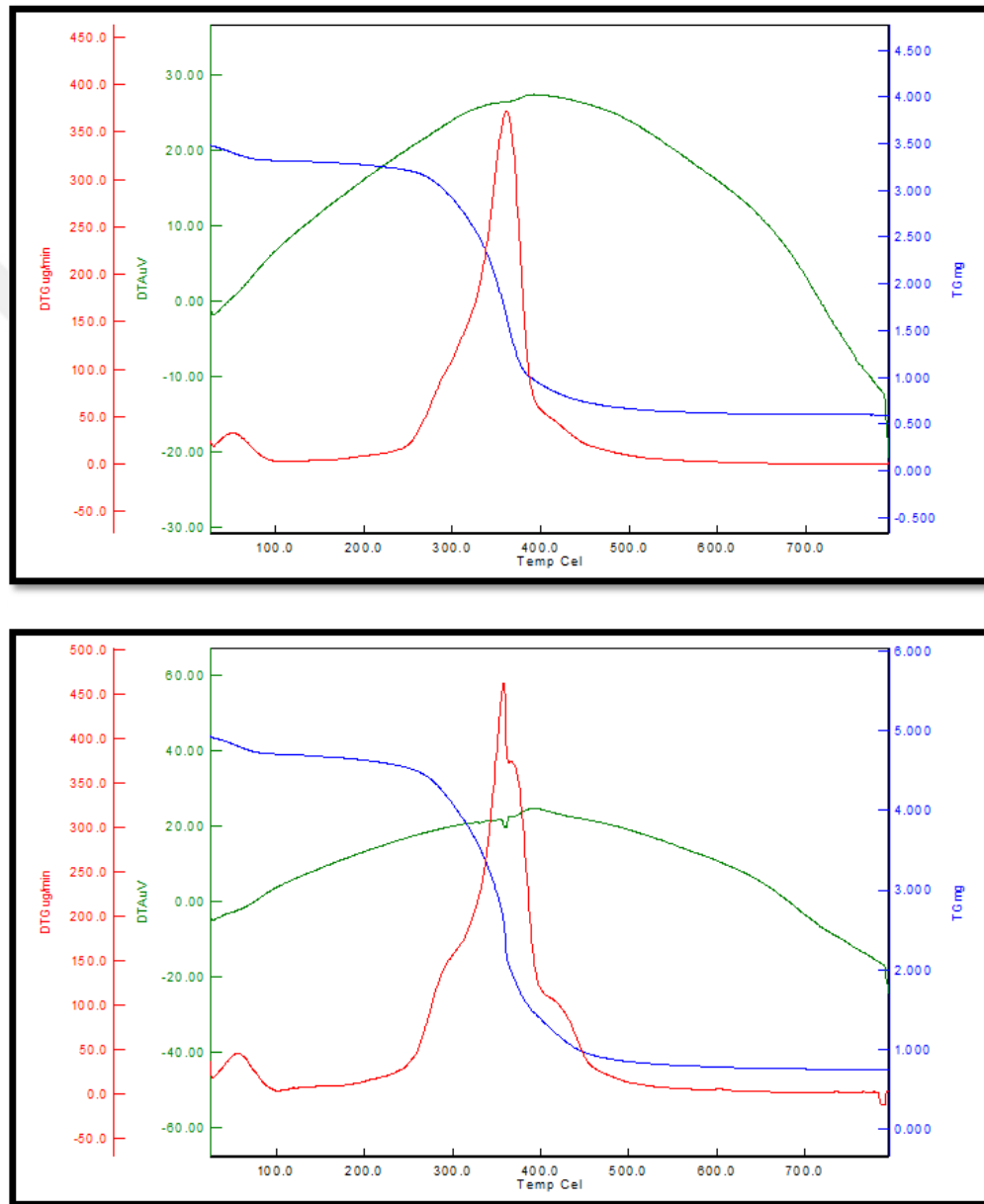


Figure 22. TGA, DTA and DTG of epoxy treated densified Alder (upper) and Poplar wood (lower)

**Curriculum Vitae**

Oromia National Regional state, Ethiopia. He completed his primary and secondary school in Ginchi Primary, Secondary and preparatory school. After he took University entrance exam, he joined Hawassa University, Wondogenet College of Forestry and Natural Resources and graduated B.Sc. in General Forestry with distinction. In September 2010, he employed in Madda Walabu University in the position of Graduate Assistant for about 1 year and started his MSc. Study. In December 2013, he graduated in watershed Management from Wondogenet College of forestry and Natural Resources with very Great distinction. He was working in lecturer Position in Madda Walabu University, Department of Natural Resource Management, till he Joined karadeniz Technical University via Turkish Government scholarship scheme for PhD study.