# Investigation of Thermal and Sound Insulation Properties of Sapwood and Heartwood of Willow Tree

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The heat and sound insulation properties of the heartwood and sapwood of willow (*Salix alba* L.) were investigated. Based on the experimental results, it was determined that the density value of the heartwood of the willow tree was higher than that of sapwood, while the moisture value was lower in the sapwood. The thermal conductivity coefficient was 0.090 W/m.K in sapwood and 0.103 W/m.K in heartwood; thermal transmittance coefficient was 3.954 W/m².K in sapwood and 4.738 W/m².K in heartwood. The sound absorption coefficient was highest in sapwood at 1000 Hz frequency level with 0.37, while the highest in heartwood was 0.50 at 800 Hz frequency level. These results would be useful in willow wood structural applications.

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## INTRODUCTION

With industrialization and urbanization increasing in parallel with the world population, there has been a rapid change in consumption habits. As a result of this change, there has been a problem of rapid and unconscious consumption of forest products. In order to avoid this problem and to meet the need for forest products effectively, the cultivation of fast-growing tree species is recognized as an effective method (Khalil *et al.* 2012). Willow is cultivated for timber production in France, China, Italy, Eastern Europe, India, and the United States (Leclercq 1997). There are 24 species of willow trees in Turkey, ranging in height from the 2 m Elburz willow (*Salix elbrusensis* Boiss.) to the 30 m white willow (*Salix alba* L.) (Avcı 2012). The willow tree, which is also a medicinal plant, has been the subject of many studies in the food, cosmetics, and pharmaceutical industries (Chavan *et al.* 2018).

In terms of mechanical properties, willow tree is a medium hard wood with low compressive and low flexural strength. Willow specimens also have moderate shear, splitting, and tensile strengths. The dynamic bending strength in the radial direction of heartwood appears to be weaker than that of sapwood. However, heartwood and sapwood have similar values in terms of other properties (Leclercq 1997). Willow wood can be preferred over poplar wood in sports equipment, hand tools, and carving works due to its fine texture structure, physical characteristics (lightness) and mechanical properties (Sacré 1974a,b). Various studies have been carried out to improve the thermal and sound insulation performance values of wood and wood based composite materials (Kaya and İmirzi 2023).

The timber of the willow tree is used in the production of sports equipment, toys, handicrafts, and woodworking applications, as well as in carving and turning, garden furniture, box and crate production, match production, plywood or particle board manufacturing, paper pulp production, and musical instrument making due to its lightness, flexibility, and ease of processing. However, willow wood is not widely used in structural applications that require high durability or hardness (Tunçtaner 1990; Andleeb *et al*. 2011).

The thermal conductivity coefficient expresses the amount of energy passing through the unit thickness of a material under a certain temperature difference (Örs and Keskin 2008). The thermal conductivity value of the wood material varies according to the type of wood, fiber directions in the same wood (Demir 2014), density, moisture content, temperature, and the amount of extractive substances (Özdemir *et al.* 2013). As the density, temperature, and humidity of the wood material increases, the thermal conduction coefficient also increases (Yu *et al.* 2011). It is also stated that the glue used for bonding wood and wood-based composite materials and impregnants applied for protection purposes are also effective in terms of thermal conductivity in such materials (Kol *et al.* 2008, 2010).

Another feature sought in thermal insulation materials is the thermal transmittance coefficient (U) in 1 °C temperature difference between two parallel surfaces of structural materials. This quantity is the amount of heat passing in unit time and unit area. Its unit is $W/m^2.K$ (Ceylan 2021). The thermal transmittance coefficient varies depending on the material density and thickness (Öcal 2016; Şahin 2019).

The sound absorption coefficient of a material can be a determining factor in wooden building systems. It is the ratio of the sound energy absorbed by a material surface to the sound energy incident on that material surface, denoted by "α" (Alpha). The value of alpha varies between 0 and 1 (Çalışkan 2004). The sound absorption coefficient in wood material increases due to factors such as internal voids in the material, surface roughness, and temperature. Further, the sound absorption coefficient generally increases with decreasing density (Berkel 1970; Örs and Keskin 2008; Altunok and Ayan 2012; Bertolini *et al.* 2019)

The goal of this study was to improve the thermal and sound insulation values of industrial lumbers produced from willow wood due to the low density of willow wood. In this context, the thermal conductivity, thermal conductivity coefficient and sound absorption coefficients of the heartwood and sapwood parts of the willow tree were determined.

## EXPERIMENTAL

### Material and Methods

In this study, sapwood and heartwood of willow (*Salix alba* L.) were used. The willow wood used in the study was obtained from Viranşehir village of Karlıova district of Bingöl province, Republic of Turkey. Timber selection was made by taking into consideration criteria such as that the fiber directions, free of knots, and it is not destroyed by insects and fungi. Using TS ISO 13061-2 standard, the density and moisture values of the heartwood and sapwood were determined at 20 °C temperature and 65% relative humidity conditions as given in Table 1.

**Table 1.** Density and Moisture Values of the Heartwood and Sapwood of Willow

| Number | Material Name | Density (g/cm³) | Std. Dev. | Moisture content (%) | Std. Dev.: |
|---|---|---|---|---|---|
| 1 | Sapwood | 0.42 | 0.011 | 13.5 | 5.4 |
| 2 | Heartwood | 0.47 | 0.020 | 11.3 | 4.38 |

Std. Dev.: Standard deviation

*Thermal conductivity coefficient and thermal transmittance coefficient*

Determinations of thermal conductivity and thermal transmittance coefficients were made following the TS EN 12667 (2003) standard. Since no single test sample with dimensions of 300 mm × 300 mm; 320 mm × 320 mm was available, panels were prepared from 21 mm × 80 mm × 320 mm heartwood and sapwood wood solid pieces by joining them using PVA (Polyvinyl Acetate: The solid matter content is 54%, the pH value is 5 to 6, and the density is 1.05 g/cm³) glue. The excess of the prepared panels was cut and brought to 300 mm × 300 mm dimensions. The specimens were conditioned under 20 ℃ temperature and 65% relative humidity conditions in an air conditioning cabinet until they reached constant weight. Thermal conductivity and thermal transmittance coefficients were determined in the (Linseis HFM 300 and in the testing laboratory of Gazi University Faculty of Technology) Department of Woodworking Industrial Engineering, Gazi University.

*Determination of sound absorption coefficients*

Determinations of sound absorption coefficients of sapwood and heartwood of willow were performed based on the ASTM E 1050 - 08 standard. The impedance tube (BSWA TECH SW422) method was used. According to this standard, the sound absorption coefficients of the test specimens prepared with a diameter of 100 mm in the frequency bands from 100 Hz to 1250 Hz were determined. The test specimens and impedance tube that were used to determine the sound absorption coefficient are shown in Fig. 1.

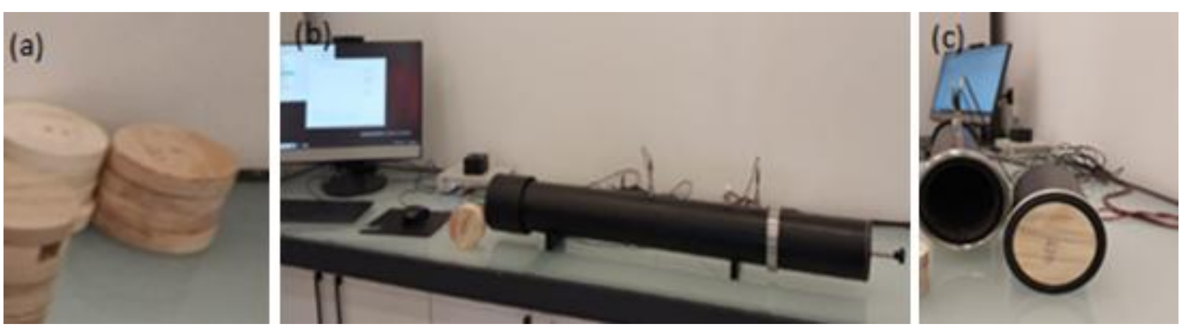


**Fig. 1.** a) Test specimens, b) impedance tube, c) impedance tube with specimen attached

## Data Analysis

SPSS 26 and MSTAT-C programs were used to analyze the data obtained from experimental methods. Using these programs, one way (ANOVA) and multiple comparisons were performed based on 95% confidence index.

## RESULTS AND DISCUSSION

### Thermal Conductivity Coefficients of Wood Parts

Statistical data on the thermal conductivity coefficients were determined for the heartwood and sapwood of the willow wood according to TS EN 12667. Results are given in Table 2.

**Table 2.** Statistical Data on the Thermal Conductivity Coefficients (W/m.K) of Heartwood and Sapwood of Willow

| Wood Part | N | $X_{min}$ | $X_{max}$ | $X_{mean}$ (HG) | Std. Dev. |
|---|---|---|---|---|---|
| Sapwood | 3 | 0.0890 | 0.0903 | 0.090 (A) | 0.0032 |
| Heartwood | 3 | 0.0998 | 0.1062 | 0.103 (B) | 0.0007 |

LSD: 0.0047 W/m.K; HG: Homogeneity groups.

The analysis of variance for the heartwood and sapwood of willow is given in Table 2. It is shown that there were significant differences between the average thermal conductivity coefficients ($\lambda$). One way analysis of variance was conducted to determine whether these differences were statistically significant. The results of the analysis of variance are given in Table 3.

**Table 3.** One-Way Analysis of Variance on Thermal Conductivity Coefficients (λ) of Heartwood and Sapwood Parts

| Source | Sum of Squares | DF | Mean Square | F Value | Sig. (p<0.05) | Partial Eta Squared |
|---|---|---|---|---|---|---|
| Wood Part | 0.0003 | 1 | 0.0003 | 50.266 | 0.002 | 0.926 |
| Error | 2.133E-5 | 4 | 5.332E-6 | | | |
| Corrected Total | 0.056 | 6 | | | | |
| Total | 0.0003 | 5 | | | | |

According to Table 3, the effects of heartwood and sapwood parts on the thermal conductivity coefficient of willow wood were found to be statistically significant ($p < 0.05$). The effect was found to be at a high level with 92.6%. The Duncan test was performed to determine the differences between the groups of wood parts whose effects were significant, and the results are given in Table 2.

According to Table 2, the thermal conductivity coefficients of sapwood and heartwood of willow were found to be statistically significantly different from each other. It was observed in this study that the thermal conductivity coefficient of heartwood was higher than that of sapwood.

The thermal conductivity coefficient of wood material has been found to vary according to density, fiber angle, extractive content, and structural defects (Raggland *et al.* 1991; Yapıcı *et al.* 2011; Jankowska and Kozakıewıcz 2014). Thermal conductivity coefficient in wood material is an important parameter for heat transfer rate. Heat transfer rate is especially important to consider when determining timber drying models or industrial gluing applications (Gu and Sharp 2005; Zhang *et al.* 2010). These authors have determined that the thermal conductivity coefficients of poplar, cedar, eastern beech, and Swedish pine as 0.133, 0.146, 0.184, and 0.182 W/m.K, respectively (Örs and Senel 1999; Yapıcı *et al.* 2011). Therefore, it can be said that the thermal conductivity coefficients obtained from the sapwood and heartwood parts of the willow in this study are lower than the values in the literature, so it can be said that willow wood is suitable for thermal insulation applications.

## Thermal Transmittance Coefficient of Wood Parts

Statistical data on the thermal transmittance coefficients determined for the heartwood and sapwood parts of the willow wood based on TS EN 12667 (2003) are given in Table 4.

**Table 4.** Statistical Data on Thermal Transmittance Coefficients (W/m².K) of Sapwood and Heartwood Parts

| Wood Part | N | $X_{min}$ | $X_{max}$ | $X_{mean}$ (HG) | Std. Dev. |
|---|---|---|---|---|---|
| Sapwood | 3 | 3.69 | 4.22 | 3.95 (B) | 0.34 |
| Heartwood | 3 | 3.44 | 5.08 | 4.74 (A) | 0.26 |

LSD: 0.0047 W/m².K; HG: Homogeneity groups

When the statistical data of the heartwood and sapwood parts are examined; it is seen that there were significant differences between the average thermal transmittance coefficients (U). One-way analysis of variance was performed to determine whether these differences were statistically significant. The results of the analysis of variance are given in Table 5.

**Table 5.** One-Way Analysis of Variance for Thermal Transmittance Coefficients (U) of Sapwood and Heartwood Parts

| Source | Sum of Squares | DF | Mean Square | F Value | Sig. Factor (P < 0.05) | Partial Eta Squared |
|---|---|---|---|---|---|---|
| Wood Part | 0.922 | 1 | 0.922 | 9.898 | 0.035 | 0.712 |
| Error | 0.373 | 4 | 0.093 | | | |
| Corrected Total | 114.621 | 6 | | | | |
| Total | 1.295 | 5 | | | | |

Table 5 reveals that the effects of heartwood and sapwood parts on the thermal transmittance coefficients of willow wood were statistically significant (p<0.05). The effect of the wood part on the coefficient was found to be at a high level with 71.2%. According to the analysis of variance table, Duncan test was performed to determine the differences between the groups of wood parts whose effects were significant, and the results are given in Table 4.

According to Table 4, the thermal transmittance coefficients of the heartwood and sapwood parts of the willow wood were found to be significantly different from each other. In this study, the thermal transmittance coefficient of heartwood was higher than that of sapwood. At the same time, it can be said that the difference in the thermal transmittance coefficients between sapwood and heartwood was due to the density values of willow wood as given in Table 1.

Thermal transmittance coefficient (U) is the resistance of structural materials to heat transfer. A low coefficient of thermal conductivity means that the thermal insulation performance of the material is superior.

There have been few studies on the thermal transmittance coefficient of wood material in the literature. The thermal transmittance coefficients of sandwich panels with thicknesses of 8.9 mm and 12.4 mm were determined as 13 and 9.7 W/m².K, respectively (Kawasaki and Kawai 2006). In another study, the thermal transmittance coefficients of

Scots pine, oak, and chestnut woods were determined to be 5.593, 6.719, and 6.946 W/m².K, respectively (Saçli *et al.* 2021).

The thermal transmittance coefficients obtained in this study were found to be lower than the thermal conductivity coefficients obtained in similar studies in the literature. Thus, it can be said that the thermal insulation values of both the heartwood and sapwood of the willow wood were superior compared to those in the literature.

## Sound Absorption Coefficients of Heartwood and Sapwood

The statistical data related to the sound absorption coefficients of the heartwood and sapwood of willow are given in Table 6.

**Table 6.** Statistical Data on Sound Absorption Coefficients of Sapwood and Heartwood Parts of Willow

| Wood Part | N | Frekans (Hz) | $X_{min}$ | $X_{max}$ | $X_{mean}$ (HG) | Std. Dev. |
|---|---|---|---|---|---|---|
| Sapwood | 3 | 125 | 0.05 | 0.07 | 0.06 ( F ) | 0.010 |
| | 3 | 250 | 0.08 | 0.08 | 0.08 (EF) | 0.000 |
| | 3 | 500 | 0.13 | 0.14 | 0.13 (DE) | 0.015 |
| | 3 | 800 | 0.27 | 0.3 | 0.29 ( C ) | 0.015 |
| | 3 | 1000 | 0.33 | 0.41 | 0.37 ( B ) | 0.040 |
| | 3 | 1250 | 0.22 | 0.31 | 0.27 ( C ) | 0.045 |
| Heartwood | 3 | 125 | 0.05 | 0.05 | 0.05 ( F ) | 0.000 |
| | 3 | 250 | 0.07 | 0.09 | 0.07 (FF) | 0.010 |
| | 3 | 500 | 0.12 | 0.15 | 0.12 (DE) | 0.030 |
| | 3 | 800 | 0.54 | 0.45 | 0.50 ( A ) | 0.045 |
| | 3 | 1000 | 0.33 | 0.45 | 0.39 ( B ) | 0.060 |
| | 3 | 1250 | 0.10 | 0.18 | 0.14 ( D ) | 0.040 |

LSD: 0.05; HG: Homogeneity group

According to Table 6, it can be seen that the sound absorption coefficients of the sapwood and heartwood parts were different from each other based on the wood part and frequency level. Multiple variance analysis was performed to determine whether this difference was significant or not. The results of multiple analysis of variance are given in Table 7.

**Table 7.** Multiple Analysis of Variance for Sound Absorption Coefficients of Heartwood and Sapwood Parts of Willow

| Source | Sum of Squares | DF | Mean Square | F Value | Sig. Factor ($P < 0.05$) | Partial Eta Squared |
|---|---|---|---|---|---|---|
| Wood Part (A) | 0.002 | 1 | 0.002 | 1.812 | 0.191 | 0.070 |
| Frequency (B) | 0.662 | 5 | 0.132 | 127.706 | 0.000 | 0.964 |
| AXB | 0.089 | 5 | 0.018 | 17.210 | 0.000 | 0.782 |
| Error | 0.025 | 24 | 0.001 | | | |
| Corrected Total | 2.299 | 36 | | | | |
| Total | 0.777 | 35 | | | | |

According to the results of multiple analysis of variance, it was determined that the effect of wood part on the sound absorption coefficient of willow wood was not significant ($p>0.05$). However, the singular effect of the frequency level and the effect of the interaction of the wood part and the frequency level were found to be significant ($p<0.05$). When the impact levels were analyzed, it was observed that the impact of the frequency level was at a high level (96.4%). The Duncan test was performed to determine the differences between the groups of factors with significant effects. The data obtained for homogeneity groups depending on the frequency level are given in Table 8.

**Table 8.** Homogeneity Groups for Sound Absorption Coefficients According to Frequency Levels

| Frequency (Hz) | $\bar{X}$ (α) | HG |
|---|---|---|
| 125 | 0.06 | D |
| 250 | 0.08 | D |
| 500 | 0.12 | C |
| 800 | 0.39 | A |
| 1000 | 0.38 | A |
| 1250 | 0.20 | B |

LSD: 0.04; HG: Homogeneity groups.

Table 8 reveals that the sound absorption coefficients of the wood parts in willow wood according to the frequency levels were significantly different in general, but there was no statistically significant difference between the sound absorption coefficients at the 800 and 1000 Hz levels. However, it was found that the sound absorption coefficients at frequencies of 800 and 1000 Hz were higher than the other frequencies.

The sound absorption coefficient expresses the ability of a material or a surface to absorb sound. If a certain percentage (55%) of the available sound energy is absorbed at certain frequencies, the sound absorption coefficient at that frequency is expressed as 0.55 In general, porous materials have lower sound absorption coefficients at low frequencies (Hz<350) and higher at high frequencies (Özel 2017). In parallel with this, sound absorption occurs in the same direction in density and thickness factors (Vidinlimen 2010).

The results of the Duncan's test for the binary interaction of wood part and frequency level, which had a significant effect on the sound absorption coefficient in this study, are given in Table 6.

According to Table 6, the sound absorption coefficient between sapwood and heartwood was found to be different only at frequencies between 800 and 1250 Hz. At other frequency levels, there was no statistical difference for both wood parts. When the sound absorption coefficient values of the binary interaction of wood part and frequency level were analyzed the sound absorption coefficient of heartwood was higher than sapwood. This may be due to the fact that the heartwood has a higher density and lower moisture content than sapwood. In addition, the fact that the contents of extractive substances (tannins, some carbohydrates, polysaccharides) in the heartwood are more than that in the sapwood and that this could increase the sound absorption coefficient as these substances tends to increase density. Sound absorption coefficients increase as the density of sound absorbing materials increases, especially at values above 250 Hz frequency level. This is because sound energy is converted into more heat energy as it travels between the fibers (Samsudin *et al*. 2016).

## CONCLUSIONS

In this study, the thermal conductivity coefficient (W/m.K), thermal transmittance coefficient (W/m².K), and sound absorption coefficients (α) of the heartwood, and sapwood parts of willow wood were investigated. Accordingly;

1. When examining the thermal conductivity coefficients of the sapwood, and heartwood parts of willow wood, it was found that the value for the sapwood was lower.
2. The thermal transmittance coefficients of the heartwood, and sapwood parts of willow wood, like the thermal conductivity coefficients, were observed to be lower in the sapwood section.
3. It was found that there was no significant difference between the sound absorption coefficients of the heartwood and sapwood parts of willow wood. However, a significant difference was observed, depending on the frequency level. Accordingly, the highest sound absorption level in the sapwood occurred at a frequency of 1000 Hz, while the highest sound absorption coefficient in the heartwood was observed at a frequency of 800 Hz.
4. Based on the data obtained from the conducted study, it can be suggested that willow wood, which has a high growth potential, could have more applications in furniture manufacturing, decoration, and wooden structural applications due to its excellent thermal and acoustic insulation properties

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