The physicomechanical and thermal properties of Algerian Aleppo pine (Pinus halepensis) wood as a component of sandwich panels

Nadia Lakreb (1), Umut Sen (2), Boudjema Bezazzi (3), Helena Pereira (2)

Aleppo pine (Pinus halepensis Mill.) is the main forest species of Algeria occupying more than 35% of the total forest area of the country. However, the physicomechanical and thermal characteristics of Algerian P. halepensis wood are not well-known. This research investigates the physical (moisture, density, swelling, and shrinkage), mechanical (bending strength and modulus of elasticity), and thermal (mass loss under combustion and pyrolysis as well as thermal conductivity) properties of P. halepensis wood from the Darguina (Bejaia) forest in Algeria. The results showed that Algerian P. halepensis wood with a mean density of 540 kg m$^{-3}$ has good dimensional stability in swelling and shrinkage, with 116.43 MPa bending strength and a modulus of elasticity of 17,520 MPa. The wood shows a good thermal resistance under low-temperature range and has a thermal conductivity of 0.21 W m$^{-1}$ K$^{-1}$. The overall results indicate that Algerian P. halepensis wood may be commercially exploited for construction and insulation applications, namely in the production of sandwich composites.

Keywords: Density, Bending Strength, Thermal Conductivity, Shrinkage, Swelling

Introduction

Wood is a natural cellular material characterized by heterogeneous structural features, porosity and high hygroscopicity. The mechanical behavior of wood depends on its specific anatomical structure, density and moisture content as well as on tree-related variables such as age and growth characteristics (Tsoumis 1991, Ross 2010). The properties of wood are species specific and a careful characterization is therefore necessary prior to application of wood.

The Aleppo pine (Pinus halepensis Mill.) belongs to the Pineaceae family and is a species that quickly colonizes abandoned lands (Fekih et al. 2014, Mouri et al. 2016). It is a pyrophyte species naturally distributed throughout the Mediterranean basin, including North Africa, Spain, France, and Italy (Liphschitz & Biger 2001). More than 2.5 million hectares of P. halepensis are located in semi-arid and arid regions (Maestre & Cortina 2004), at low altitudes and along the coast (Mitsopoulos & Dimitrakopoulos 2007). P. halepensis is considered as the most important and dominant forest tree species in Algeria, covering an estimated area of 1,158,533 ha (Benouadah et al. 2019) growing in all bioclimatic zones, with a predominance in the semi-arid zone, from East to West, and from sea level to the major mountain ranges (Ricard & Oliva 1995). Its detailed distribution in Algeria is as follows: in the Eastern region: in the forests of the Têbessa and Aures mountains; in the Central region: in the forests of Ouarsenis; in the Western region: in the wooded mountains of Saida, Mascara, Sidi Bel Abbès; and the Atlas Sahara: in the forests of the Ouled Nail mountains, near Djelfa and Djebel Amour, near Aflou (Nahal 1962).

The easy adaptation of P. halepensis to various eco-climatic conditions and poor soils makes the species a desired tree for reforestation programs in Mediterranean countries (Elaiel et al. 2017, Liphschitz & Biger 2001, Montero et al. 2001, Sghaier & Ammari 2012). Silvicultural treatments of the species have been investigated in different countries (Montero et al. 2001) for forest management. The chemical properties of P. halepensis wood showed that it is a rich source of resin acids and cyclic polyols (Benouadah et al. 2019). Its physicomchanical properties are similar to those of maritime pine wood (Pinus pinaster - Thibaut et al. 1992). Therefore, a replacement of maritime pinewood with P. halepensis wood may be considered for the production of construction timber, plywood, and particle board, particularly for North African countries.

In recent years, P. halepensis wood has been studied as face (skin) layers for the production of cork sandwich composites because it is a renewable and widely available material in Algeria (Lakreb et al. 2015a, 2015b, Llimam et al. 2016). The sandwich composites or sandwich panels are interesting materials for construction because they have high strength-to-weight ratio, high flexural stiffness, and low weight (Gibson & Ashby 1999); therefore, they find a variety of applications in construction. The material properties of sandwich panels including dimensional stability, thermal conductivity, and mechanical strength depend on the properties of face and core layers (Gibson & Ashby 1999). The current research on the wood characteristics of P.
P. halepensis wood is still scarce namely regarding the wood physicomechanical and thermal characteristics of the species in Algeria. The aim of this study is to fill this gap and for the first time determine the physical and mechanical as well as the thermal properties of Algerian P. halepensis wood to lay the groundwork for development of future applications and further research, particularly on cork-based sandwich composites.

Material and methods

Materials

The P. halepensis wood samples were obtained from the region of Darguina (Bejaia, Algeria) by felling two 70-year-old trees with straight stems having an acceptable sanitary state and over 40 cm diameter at 1.50 m above the ground. The Darguina region has an annual temperature of 16.2 °C, an annual precipitation of 771 mm, and a climate type of “Csa” according to Köppen. The region has an annual temperature of 16.2 °C, an annual temperature of 16.2 °C, and over 40 cm diameter at 1.50 m above the ground. The Darguina region has an annual precipitation of 771 mm, and a climate type of “Csa” according to Köppen. The region has an annual temperature of 16.2 °C, and over 40 cm diameter at 1.50 m above the ground. The Darguina region has an annual temperature of 16.2 °C, and over 40 cm diameter at 1.50 m above the ground.

Physical characterization

Moisture mapping

The water content of the wood was determined as the proportion of free and bound water relative to the dry weight of sample by the standard BS1-004 (1985). A 20 mm wide wood stem cross-section was cut from the P. halepensis logs and immediately cut into 45 small prisms of 20 × 20 × 40 mm, covering the whole cross-section and numbered according to the location of each sample in the disk. Each prism was weighed using a balance with ±1 mg accuracy (moist-weight), dried in a stove at 103 °C to obtain approximately 12% moisture content in wood samples before the physicomechanical and thermal tests.

Fig. 1 - Preparation of specimens for physical and mechanical characterization (directions: R, radial; T, tangential; and L, longitudinal).

Determination of swelling

For the determination of density, a total of 20 solid wood specimens were produced with radial × tangential × longitudinal dimensions of approximately 20 × 20 × 300 mm for mechanical tests. The physical and mechanical properties, namely density, moisture content, dynamic elastic modulus, as well as thermal degradation and thermal conductivity were determined according to the respective standards, as explained in the following sections. The wood samples were conditioned under 65% relative humidity and 20 °C temperature to obtain approximately 12% moisture content in wood samples before the physicomechanical and thermal tests.

Mechanical characterization

Bending strength and modulus of elasticity

The 3-point bending test (BS1-009 1985) was carried out using a Zwick universal machine provided with a force sensor using a 10 kN load at a speed of 2 mm min⁻¹. A total of 20 samples with 20 × 20 × 300 mm dimensions were used in the bending test. The machine was computer controlled and the software testXpert® v. 1.20 (ZwickRoell, Genoa, Italy) was used for data acquisition. For the determination of bending strength (modulus of rupture, MOR), the following equation was used based on DIN-52186 standard (DIN-52186 1978, Siegel et al. 2020 – eqn. 1):

\[ \sigma = \frac{3F}{2bh^3} \]  

where \( b \) is width, \( h \) is thickness, \( l \) is the distance between the centers of the supports, and \( F \) is the maximum force applied. The bending modulus of elasticity is the ratio of stress to corresponding strain within the elastic region and was calculated based on EN-310 (1993) standard using the following formula (eqn. 2):

\[ \text{MOE} = \frac{l^3}{4bh^3} \frac{\Delta F}{\Delta l} \]

In this equation the elastic range was calculated between 10% and 40% of the maxi-
um force. $\Delta F$ shows the variation in the force (N) and $\Delta \sigma$ shows the variation in the deflection (mm – Siegel et al. 2020).

**Thermal properties**

**Low-temperature thermal degradation**

The thermal behavior of the *P. halepensis* wood was analyzed with particle (approximately 5 mm) and powder (<250 µm) wood samples at temperatures between 25 and 250 °C using a thermogravimetric analyzer. A four step heating program was used under air and Ar gon gas flow conditions: heating from 25 to 100 °C at a heating rate of 10 °C min$^{-1}$, an isothermal step at 100 °C for 30 min, heating from 100 to 250 °C at a heating rate of 10 °C min$^{-1}$, and finally an isothermal step at 250 °C for 5h. Air or Argon gas flow rates were set to 60 ml min$^{-1}$.

**Thermal conductivity**

The thermal conductivity of the materials used was measured using a thermal conductivity analyzer (TC-Meter). In the measurement, through a combination of a heating element and a temperature sensor, the temperature increase in the wood sample was measured during a pre-defined heating power and heating period in a transient state. The sensor wire is placed between the two test samples of the same material. This probe is disposed in a kapton membrane connected in series with a voltmeter and a current generator that measures, through the Joule’s law, the heat emitted at the surface of the test material.

The thermal conductivity analyses were performed on *P. halepensis* wood veneer samples in the longest and smallest directions by triplicate measurements. The test samples (15 x 15 x 2 cm) have been obtained from veneers of 1.5 x 0.5 m$^2$ dimensions and a thickness of 1.5 mm. The ISO 8894-1 (2010) standard was followed in the measurement of thermal conductivity.

**Results and discussion**

**Moisture mapping and density**

The average moisture was 96% in the green wood, in agreement with the generally found moisture content in recently felled trees (Tsoumis 1991). The moisture mapping shows that the water content distribution was not homogeneous along the cross-section while being more variable in the sapwood and more uniform in the heartwood (Fig. 2). Moisture content increases gradually from the center of the log to the outside in accordance with the previous observations in softwoods (Tsoumis 1991).

The water content was maximal in the area of the sapwood (moisture content between 60% and 160%) while the less moist heartwood contained moisture levels between 30% and 60%. These findings are in accordance with those reported in the literature (moisture contents of 30-40% and 60-100% for heartwood and sapwood, respectively – Daoui et al. 2007).

Tab. 1 summarizes the range, mean and standard deviation of density of Algerian *P. halepensis* wood, as well as the values from a comparative study with *P. halepensis* wood from different Mediterranean countries. The mean density of Algerian *P. halepensis* wood was 540 kg m$^{-3}$ which is within the range reported. For instance, Nahal (1962) reported a density (without specifying the moisture content) between 532 and 866 kg m$^{-3}$, while Erten & Sözen (1996) found an air-dry density of Turkish *P. halepensis* wood between 540 and 614 kg m$^{-3}$. Similarly, Langbour et al. (2008) reported the density of French *P. halepensis* wood between 530 and 580 kg m$^{-3}$. Another similar density value (580 kg m$^{-3}$) was reported by Limam et al. (2016). These values suggest that the reported density values may vary as high as 60% for *P. halepensis* wood. This variation occurs possibly due to the differences in measuring density (oven-dry basis or air-dry basis) and differences in moisture content and chemical composition between the tested *P. halepensis* woods (Tsoumis 1991).

**Swelling properties**

The variation in wood dimensions (in longitudinal, radial, and tangential directions) and wood mass during water immersion of the *P. halepensis* wood is shown in Fig. 3. The mass increase due to water absorption was significant in the first 24 h, then decreased sharply and attained a rather stable condition after 5 days. The wood dimensional variation along time shows that most of the swelling occurred in the first two days of immersion. Also, a clear anisotropy in swelling was observed with a very small swelling in the longitudinal direction (0.3% after 11 days of immersion) and the highest value for the tangential direction (5.0% and 1.6% for the tangential and radial swelling respectively). The volumetric swelling was 6.9% (Tab. 2).

The results indicate that the swelling of Algerian *P. halepensis* wood is smaller than that of Turkish *P. halepensis* wood (2.2-9.4% and 5.0-5.7% for tangential and radial

![Fig. 2 - Mapping of moisture on a cross-section of *P. halepensis* wood. Moisture content increases from black-grey to green colours corresponding to drier and moist regions, respectively. Adapted from Lakreb (2015).](image)

![Fig. 3 - Mass and dimensional changes in the three main directions: longitudinal (L), radial (R), and transverse (T) of *P. halepensis* wood along time during water immersion.](image)

**Tab. 1 - Density of Algerian *P. halepensis* wood and comparison with other *P. halepensis* woods from the Mediterranean area.**

| Provenances   | References       | Density range (kg m$^{-3}$) | Average density (kg m$^{-3}$) |
|---------------|------------------|----------------------------|-------------------------------|
| Algeria       | This work        | 500-580                    | 540                           |
| Algeria, Lebanon, France | Nahal (1962)  | 532-866                    | 724                           |
| Tunisia       | Quiquandon (1966)| -                          | 560                           |
| France, Italy, Spain, Portugal, Tunisia, Morocco, Israel | Thibault et al. (1992) | -                          | 570                           |
| Turkey        | Erten & Sözen (1996) | 540-610                  | 575                           |
| France        | Langbour et al. (2008) | 450-580                  | 515                           |
| Algeria       | Limam et al. (2016) | -                          | 580                           |
| Tunisia, Italy, Spain, Israel | Elaieb et al. (2017) | 520-620                  | 570                           |
swelling values, respectively – Erten & Söz- en 1995). This difference in swelling prop-
eries possibly arises from the differences in
wood density and wood moisture con-
tent (Tsounis 1991).

Drying properties
As in swelling, the moisture loss was sig-
nificant in the first days of drying and re-
duced towards the end of the shrinkage test. The shrinkage of P. halepensis wood was not the same in all three directions with higher dimensional change in the tan-
gential and radial directions than in the lon-
gitudinal direction.

The mean values of the radial, transverse,
and longitudinal shrinkage of P. halepensis wood are summarized in Tab. 2. The radial and tangential shrinkage values of Algerian P. halepensis wood was 3.76% and 4.76%, re-
spectively (Tab. 2). These results are similar but lower than the Tunisian P. halepensis wood values with a radial shrinkage from 4.4% to 6.0% and a tangential shrinkage from 6.9% to 7.5% (Elaiib et al. 2017). The Algerian P. halepensis wood also shrinks less than French and Turkish P. halepensis woods in terms of radial, tangential, and volumetric shrinkage values (4.5%, 7.4%, 11.8% and 4.8%, 7.2%, 12.5%, respectively – Thibaut et al. 1992, Erten & Söz-en 1997). The shrinkage properties of Algerian Aleppo pine were also better than black pine (P. nigra) and Italian stone pine (P. pinea) which had radial, tangential, and volumet-
ric shrinkage values of 5.0%, 7.2%, 12.5% and 3.1%, 5.7%, and 8.8%, respectively (As et al. 2001).

Shrinkage is affected by factors such as
density, moisture content, anatomical structure, mechanical stress and chemical com-
position of wood (Tsounis 1991). When wood dries, the free water is re-
moved first; it moves to the surface of wood and evaporates, usually without
causing detrimental effect to the wood. When cells do not contain free water, the wood reaches the fiber saturation point (FSP) and if the drying process continues beyond this point, wood starts to shrink. Shrinkage shows a similar anisotropy as that of swelling (Thibaut et al. 1992). The anisotropy (A) of the shrinkage indicates the dimensional stability of the wood and is calculated by the ratio between the tan-
gential and radial shrinkage values. The wood anisotropy of P. halepensis shrinkage (1.26) is lower than that of other conifer-
ous species such as Pinus pinea (1.53), Pinus pinaster (2), Pinus sylvestris (1.7) or Pseu-
dotsuga menziesii (1.7 – Elaiib et al. 2015). The low T/R shrinkage ratio indicates that the Algerian P. halepensis wood has a good
dimensional stability.

Mechanical properties
The results of the 3-point bending tests on the P. halepensis wood are shown in Tab. 3. The Young’s modulus (MOE) found
in this study (17241 MPa) is considerably higher than the other reported MOE values (between 8300 and 13500 Mpa, respective-
ly – Langbour et al. 2008). The bending strength (MOR) of the Algerian P. halepen-
sis wood (116 MPa) was also higher than other values reported for the same species (Tab. 3). Different authors found bending strength values between 43 MPa and 138 MPa for P. halepensis wood (Thibaut et al. 1992, As et al. 2001, Langbour et al. 2008, Elaiib et al. 2017). On the other hand, low
MOE values were reported for other pine species such as 82 MPa for Turkish pine (P. brutia) and 100 MPa for Scots pine (As et al. 2001). Only the MOR values of black pine (P. nigra: 96-120 MPa) exceeds the bending strength of Algerian Aleppo pine wood (As et al. 2001).

According to these results, it seems that the Algerian P. halepensis has superior me-
chanical properties (bending strength and Young’s module, respectively) to those of other conifers such as maritime pine (P. pinaster: 86, 8800 MPa), Scots pine (P. sylvestris: 90, 11900 MPa), Douglas pine (Pseudotsuga menziesii: 85, 12100 MPa), sil-
ver fir (Abies alba: 68, 12200 MPa) and Nor-
way spruce (Picea abies: 71, 11000 MPa – Benoit 2007). It is important to note that
these results were obtained on wood sam-
plies that did not present defects such as
knots or resins pockets that could decrease the wood mechanical strength (Tsounis 1991). For instance, the presence of knots or resins reduced the modulus of elasticity by 15% and the stress at break in bending by 11% compared to the average values recorded on specimens without defects (Langbour et al. 2008).

The findings of the physical and mechani-
cal properties of P. halepensis wood need to be interpreted with caution because they are limited with a small number of tests, in this study. However, these results provide a basis for the development of fu-
ture applications along with the results of thermal behavior.

Thermal behavior
Low-temperature thermal degradation
The low-temperature thermal degrada-
tion of Algerian P. halepensis wood was in-
vestigated between 120 and 250 ºC. The

| Values | Variable | Parameter | Mean ± STD |
|--------|---------|-----------|------------|
| Experimental values | L (%) | α | 0.29 ± 0.11 |
| | R (%) | | 1.14 ± 0.31 |
| | T (%) | | 3.76 ± 1.04 |
| | V (%) | | 5.00 ± 1.56 |
| | A (%) | | 4.76 ± 1.34 |
| Calculated values | | | |
| | V (%) | α | 6.87 |
| | R | 8.34 |
| | | A (%) | 1.26 |

Tab. 2 – Mean swelling (α), shrinkage (R), volumetric swelling and shrinkage (V), and Anisotropy (A) of P. halepensis wood in the three directions (L, R and T). (STD: standard deviation.)

| Parameters | Units | Values |
|------------|-------|--------|
| Fmax | N | 2070 |
| fmax | mm | 15.2 |
| f1 | mm | 0.55 |
| f2 | mm | 2.04 |
| F1 | N | 207 |
| F2 | N | 828 |
| MOR | MPa | 116.4 ± 8.5 |
| MOE | MPa | 17520 ± 1500 |

Tab. 3 – Test results of 3-point bending of the P. halepensis wood. F is force (N), f is deflection (mm), f1 and f2 are deflec-
tions occurred at 10% (f1) and 40% of maximum force (f2), MOR is modulus of rupture (MPa) and MOE is elasticity modulus (Mpa).

| Parameter | Direction (Units) | Value |
|-----------|------------------|-------|
| Thermal conductivity | α/ (W m⁻¹ K⁻¹) | 0.17 ± 0.10 |
| | λ⊥ (W m⁻¹ K⁻¹) | 0.25 ± 0.11 |
| Thermal resistance | R/ (m² K W⁻¹) | 0.12 ± 0.09 |
| | R∥ (m² K W⁻¹) | 0.07 ± 0.10 |
| Average thermal diffusivity | α (m² s⁻¹) | 0.25 ± 0.06 × 10⁻² |

Tab. 4 – Thermal conductivity and thermal resistance of P. halepensis wood veneer in different directions (α/ is the thermal conductivity in longest direction; α⊥ is the ther-
mal conductivity in smallest direction; R/ is the thermal resistance in longest direc-
tion; R∥ is the thermal resistance in smallest direction. |
The Algerian *P. halepensis* wood veneer has an average thermal conductivity of 0.21 W m⁻¹ K⁻¹. The overall results of the study suggest that Algerian *P. halepensis* wood has a promising potential in the use of face layers in sandwich panel formulations with insulating core layers for the production of structural members and thermal insulation.

**Acknowledgements**

Umют Sen acknowledges support from FCT (Fundação para a Ciência e a Tecnologia, Portugal) through a research contract (DL 57/2016). The Centro de Estudos Florestais is a research unit funded by FCT (UIDB/00239/2020).

**Conflict of Interest**

The authors of the article certify that they have no involvement in any organization or entity with any financial interest.

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