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Evaluating the strength properties of standing trees through fractometry

Abdullah BERAM

Department of Industrial Design, Faculty of Architecture and Design, Pamukkale University, 20160, Denizli, Türkiye.

Corresponding author: abdullahberam@pau.edu.tr

Abstract

In recent years, significant advancements in non-destructive testing (NDT) methodologies have emerged, with applications spanning various domains, including structural wood quality assessment and planted tree characteristic evaluation. Within the context of planted trees, a range of non-destructive and semi-destructive techniques have been developed to assess the extent of degradation in tree trunks. In this study, various mechanical characteristics of brutian pine (*Pinus brutia* Ten.) trees near the Ertokuş Madrasah in the Atabey district of the province of Isparta are examined. Beside their historical significance, these trees are notable for the potential risk they present in terms of leaning towards the madrasah facade and the risk of falling over. To achieve the goals of research, the resistance characteristics of incremental cores were systematically determined by using a thermal imaging camera in conjunction with a portable, non-destructive testing device called a Fractometer. Totally 15 incremental auger specimens were obtained by extracting three increment core samples, each with a thickness of 5 mm, from the trunks of five distinct trees, all at a consistent height of 1.3 meters above ground level. Bending and compressive strength measurements were recorded at intervals of 6 mm from the core to the outermost layer. Furthermore, the moisture content of the incremental cores was assessed using thermal imaging technology. Following an analysis of the collected data, it was concluded that the mechanical properties of the investigated brutian pine trees within an acceptable range.

Keywords: Non-destructive testing, fractometer, thermal camera, standing trees.

Introduction

Wood has served as a cost-effective and renewable construction material for centuries (Fang et al. 2017; Aydemir et al. 2011; Kaya et al. 2021). In contemporary applications, wood continues to play a vital role in roofing, interior doors, exterior cladding, furniture, flooring, veneer production, barrel crafting, and various other sectors (Jones et al. 2019; Kilicarslan et al. 2020). A comprehensive assessment of wood properties is of paramount importance to determine the optimal utilization of this versatile material. Additionally, the identification of wood defects, including features such as knots, decay, insect infestations, splits, and checks, holds significant relevance, as these imperfections can substantially influence its overall performance. Early detection of these flaws, preferably before the final processing stages, can result in significant cost efficiencies within the manufacturing process (Bravery et al. 1987; Akbulut et al. 2008; Kilicarslan and Turker, 2021).

Wooden structures are vulnerable to degradation over time due to prolonged exposure to loading conditions and fluctuations in environmental factors, such as temperature and humidity. These deteriorations can compromise the structural integrity of wood-based materials, giving rise to safety concerns that necessitate their early identification. Consequently, there is a growing demand for non-destructive methodologies aimed at assessing the integrity of wood and wood-based materials. These methodologies find applications both during the manufacturing phase and throughout the service life of wood products to enhance their overall quality (Riggio et al. 2014; Tannert et al. 2014; Yu et al. 2020).

The strength of wood is significantly compromised by decay, making it a critical consideration in tree risk assessment. The primary objective of such assessments is to detect instances of decay within a tree and subsequently determine the extent and severity of this deterioration. A range of tools and instruments are available for accurately mapping out the degree of decay, with micro-drills and tomography being noteworthy examples. In cases where the extent of decay is either exceptionally high or exceptionally low, this information typically offers clear guidance for recommending appropriate courses of action (Allison et al., 2008; Ganesan and Hamid, 2010). However, there are scenarios in which uncertainty arises regarding whether the weakening caused by decay surpasses an acceptable threshold. In such instances, assessing the quality of the remaining wood becomes a valuable additional criterion to inform decision-making.

Non-destructive testing, as defined by Ross et al. (1998) and Liana et al. (2020), is the process of evaluating material properties without causing disruption to its integrity at its point of use. Non-destructive testing (NDT) is instrumental in gathering information about the physical and mechanical properties of a material, detecting defects without rendering it unusable, and assessing the suitability of a component without causing harm (Ross and Pelerin, 1991-1994; Bucur, 2003). Over time, the interiors of standing trees can decay due to various factors, resulting in imperceptible gaps within the tree's structure. As a consequence of external influences, these trees can suddenly fail or topple. Therefore, it becomes crucial to ascertain the reduction in resistance values of standing trees, which are invaluable natural resources, without causing harm to them, with the aim of their preservation. Various techniques are available to identify material defects within standing trees without causing damage.

The Fractometer II, a portable wood testing device (developed by Instrumenta Mechanik Labor (IML), Karlsruhe, Germany), serves as the central tool in this study. This device is specifically engineered to measure the elasticity and fracture strength of wood (Bethge et al., 1996; Malanowski et al., 2019). Furthermore, the Fractometer II, in addition to assessing fracture angles and radial bending strength, possesses the capability to determine longitudinal compression strength in wood samples, as highlighted by Mattheck et al. (1997) and Tang et al. (2016). Longitudinal compression strength indicates the wood trunk's resistance to failure under axial stress. The fracture angle offers insights into whether the wood sample experiences a brittle or non-brittle fracture, while radial bending strength indicates the wood's ability to withstand failure under perpendicular stress. It is essential to acknowledge a limitation associated with the use of the Fractometer II, namely that it requires prior knowledge of the expected breaking strengths for sound wood, as discussed by Lonsdale (1999), Živanović et al. (2019), and Li et al. (2022).

There are many studies that determine the mechanical properties of wood by Fractometer II device in the literature. Şimşek (2017) received increment core from brutian pine tree and determined the compressive strength values in the Fractometer device. Genesan and Hamid (2010) determined some mechanical properties of 25 different wood species by the Faktometre II device. They stated that the fractometer device can be used in determination of the mechanical properties of the standing tree. Chiu et al. (2006) and Lin et al. (2007) received increment core of Taiwania (*Taiwania cryptomerioids*) tree and the mechanical properties of the juvenile wood-mature wood parts were examined by the fractometer. Matsumoto et al. (2008) had 5 mm increment cores of 2 Japanese wood (sugi, *Cryptomeria japonica* and akamatsu, *Pinus densiflora*) and evaluated compressive strength values of the cores. As a result of these studies, it was concluded that the mechanical properties can be determined with the Fractometer device while the tree is standing. In addition to these studies, there are many studies to determine the mechanical properties of the standing tree with the Fractometer device (Bethge et al. 1996; Wang et al. 2008; Matsumoto et al. 2010; Tang et al. 2016; Živanović et al. 2019). Thermography method is also used for the determination of rotten and cavities in the interior of planted trees (Catena et al. 1990; Catena, 1991, 1992; Catena and Catena 2000, 2008; Catena 2002, 2003; Dragavtsev and Nartov, 2015; Zevgolis et al. 2022).

This study was conducted on brutian pines located in front of the Ertokuş Madrasa in the Atabey district of Isparta. These historical trees exhibit a slight slope towards roof of the madrasah, raising concerns about potential risks, including the possibility of them falling over. These concerns were reported by madrasah officials and the general public, prompting the need for this study. In the context of this study, the mechanical properties of brutian pines were examined using a semi-destructive testing device known as the Fractometer. Additionally, the moisture level in the cores of these trees was evaluated using a thermal camera.

2. Material and Methods

2.1. Study area and sampling

In this study, the mechanical properties of pine trees near the Ertokuş madrasah in Isparta-Atabey district were investigated by non-destructive testing method. The image of the pine trees in front of the Ertokus madrasah is given in Figure 2.1A, B. In order to determine their mechanical properties, 3 increment core of 5 mm thickness were taken from 5 different trees at a height of 1.3 m from the ground. The image of receiving the increment core is given in Figure 2.1C.

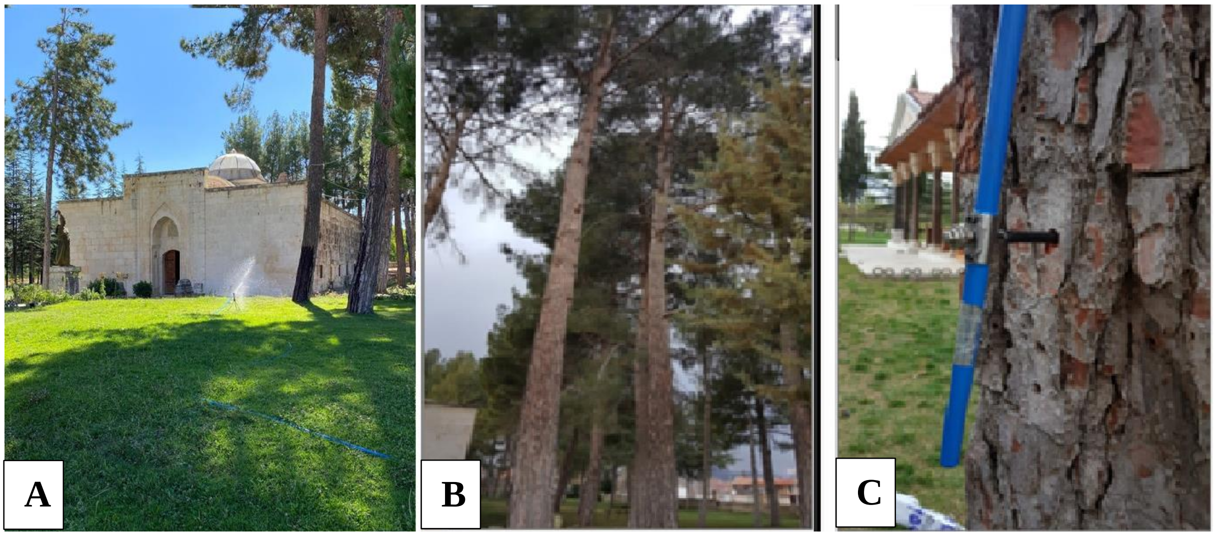

Figure 2.1. A and B: image of pine trees near the Ertokuş madrasah, C: image of receiving the increment core

After the increment core were removed, they were placed in plastic tubes and stored in a cooler bag. Later, increment cores was brought to Isparta University of Applied Sciences Faculty of Forestry to conduct experiments.

2.2. Determination of strength properties

Images of the increment cores were taken with a FLIR INFRACAM thermal camera (Figure 2.2). The characteristics of the thermal camera used in the measurements are given in Table 2.1.

Figure 2.2. Thermal camera used in the study

Table 2.1. Characteristics of the thermal camera used in the study

Operating temperature	−15°C +50°C
Storage temperature	−40°C +70°C
Battery type	Fast charging Li-ion battery
Lifetime	5 hour
Weight	0.34 kg
Dimension	223 mm x 79 mm x 83 mm
Measuring range	-20°C to +250°C

Thermal camera software and image analysis technique were used to evaluate the obtained images. Environmental temperature and relative humidity values were noted after the increment core were taken. These values were used during the measurements in the thermal camera software program. Surface temperature measurement images in the thermal camera software program are given in Figure 2.3.

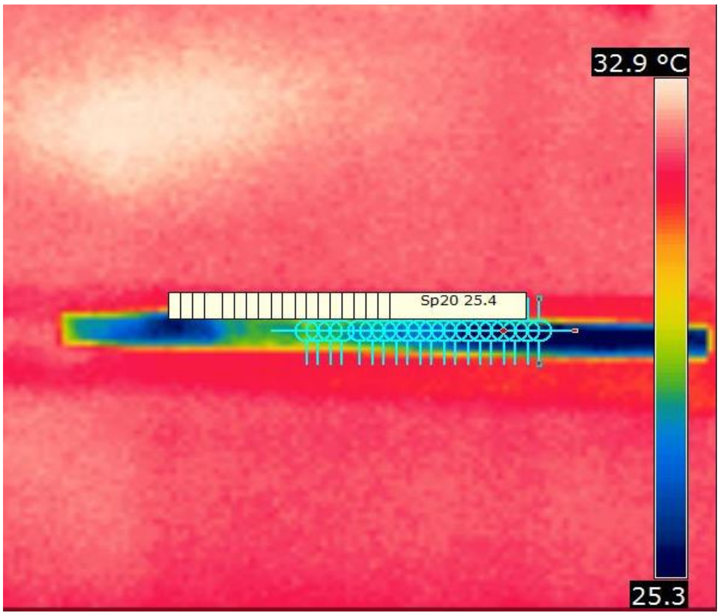

Figure 2.3. Surface temperature measurement image

The 5 mm increment core were first placed in the air conditioning cabin (20 C0, 65% relative humidity) and brought to 12% equilibrium humidity. In order to verify the temperature and relative humidity values displayed on the air conditioning cabin screen, the humidity and temperature meter device was placed in the air conditioning cabin and measurements were made. The codes and properties of the increment core are given in Table 2.2.

Table 2.2. Tested increment core codes

Tree Number	**Sample number**	**Code**
1	1	1-a
1	2	1-b
1	3	1-c
2	1	2-a
2	2	2-b
2	3	2-c
3	1	3-a
3	2	3-b
3	3	3-c
4	1	4-a
4	2	4-b
4	3	4-c
5	1	5-a
5	2	5-b
5	3	5-c

The mechanical properties of the residuals were determined by the Fractometer device given in Figure 2.4. Measurements are made every 6 mm from the pith to the bark (Figure 2.5).

Figure 2.4. The image of the Fractometer device

Figure 2.5. Schematic image of measurement plan on increment core

To determine the resistance properties of wood, samples are generally prepared by cutting trees and resistance values are determined on the prepared samples in universal testing machines. In addition to the classical method, there is a device called "Fractometer", developed in cooperation with Instrumenta Mechanic Labor GmbH and Forschhungszentrum Karlsruhe, to determine some resistance properties without cutting down trees (Mattheck et al. 1995; Götz et al. 2002; Lin et al. 2007). In this study, in determining the increment items and resistance values, Chih-Ming et al. (2006) and Wang et al. (2008)

a parallel method to the method applied by was applied. In order to determine the compression strength and flexural strength properties of the Fractometer (Type II; IML, Germany) device, the experiments were carried out by placing the increment core in the chambers given in Figure 2.6. First of all, the bending strengths of the increment core from pith to bark were determined. Compressive strength tests were carried out by placing the increment core, whose bending properties were determined, into the compression strength determination chamber.

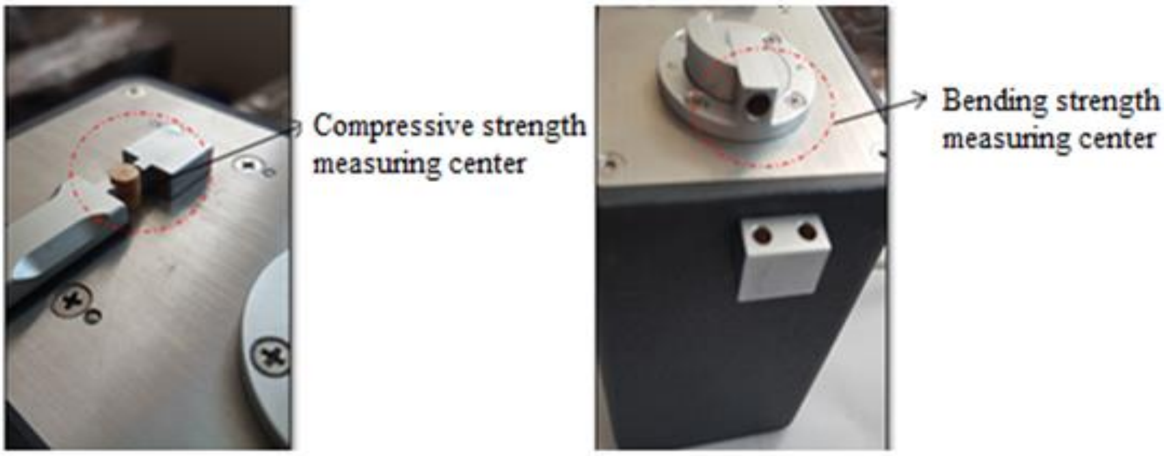

Figure 2.6. Bending and compressive strength measuring device

In addition to the fracture angle and radial bending strength, the Fractometer II measures longitudinal compression strength for a wood sample (Mattheck et al. 1995). The longitudinal compression strength is the resistance that the trunk opposes to a failure by applying axial stress. The fracture angle indicates whether the wood sample undergoes a brittle or non-brittle fracture while the radial bending strength is the resistance which the tree opposes to a failure by perpendicular stress (Lonsdale 1999).

2.3. Statistical Analysis

In the statistical analysis process, firstly, averages and standard deviations were determined for both compressive and bending strengths. Pearson correlation analysis was then applied to determine whether there was a significant relationship between compressive and bending strengths. All statistical analyses were performed in Rstudio software (Rstudio Team, 2020).

3. Results and Discussion

In this study, 3 increment core were taken from 5 different brutian pine trees in front of the madrasah. In order to determine the mechanical properties of the increment core, flexural and compressive strength values, thermal camera images were measured. Thermal camera images of the increment core are given in Figure 3.1, and surface temperature graphs are given in Figure 3.2. Thermal camera images of the increment core are given. It has been determined that the moisture content of wood material affects thermal camera images. Thermal image taken from the increment core in this study is similar to the data of the previous studies (Leuzinger et al. 2010; Simsek Turker, 2017; Beyaz and Ozkaya, 2021; Jiang et al. 2022). Therefore, the moisture content of the trees in front of the madrasah was determined to be equivalent to a brutian pine.

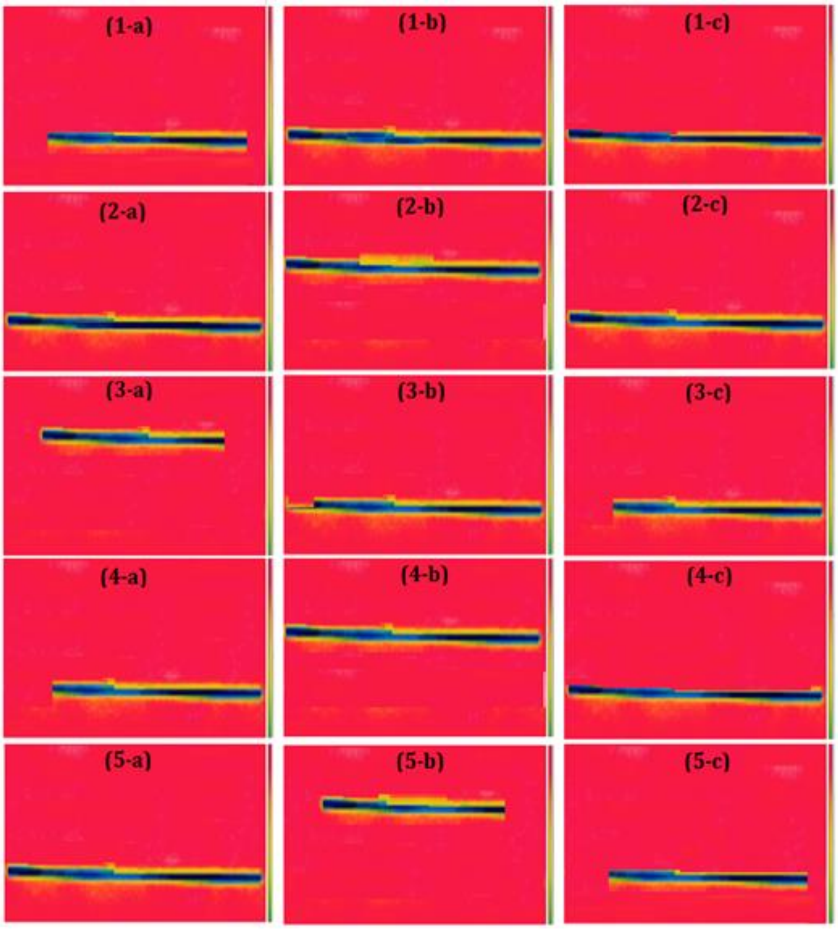

Figure 3.1. Thermal camera image of incremental core

For each sample, the average compressive and bending strength values were determined by calculating the mean of three individual measurements. These average values for compressive and bending strengths are comprehensively presented in Table 3.1. This approach ensures a robust and precise representation of the material's mechanical properties, as outlined in methodology.

Table 3.1. Means and standard deviations for compressive and bending strengths

			Compressive Strength		
Sample	1	2	3	4	5
Mean	36.14	38.79	37.83	36.38	36.48
Std. Dev.	3.67648	3.08735	3.89115	3.8472	4.61827
			Bending Strength		
Sample	1	2	3	4	5
Mean	62.19	63.07	62.90	60.33	58.24
Std. Dev.	6.74532	7.62158	8.20093	9.02229	9.97983

Pearson correlation analysis was applied using Rstudio software to determine whether there was a relationship between compressive and bending strengths.

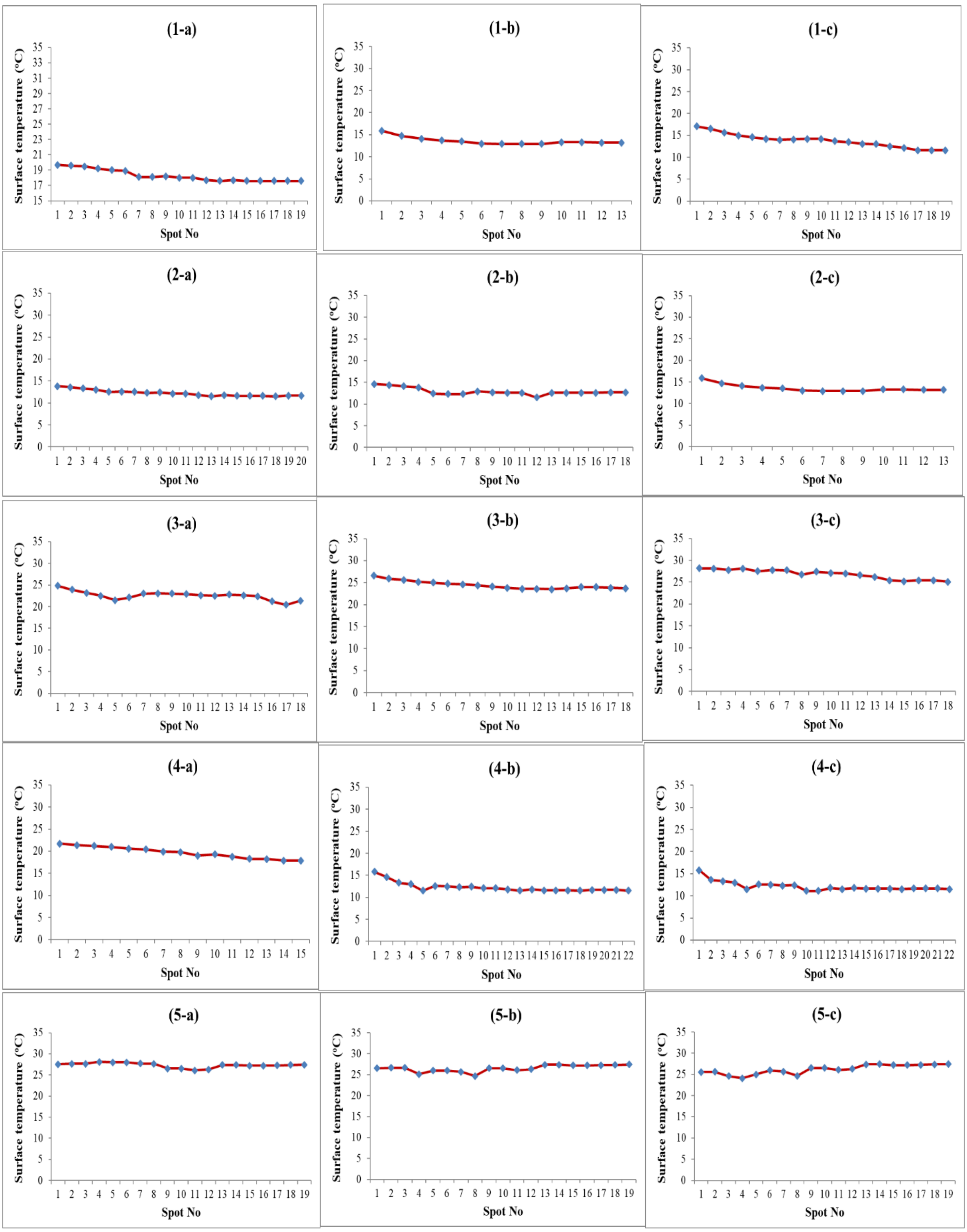

Figure 3.2. Surface temperature graphs of increment core

Upon close examination of Figure 3.3, a highly significant relationship ($p<0.001$) between compressive and bending resistances becomes evident. In essence, this relationship indicates that an increase in compressive strength corresponds to a concurrent increase in bending resistance. These findings underscore the strong correlation between these two parameters, which is a noteworthy observation in the context of study.

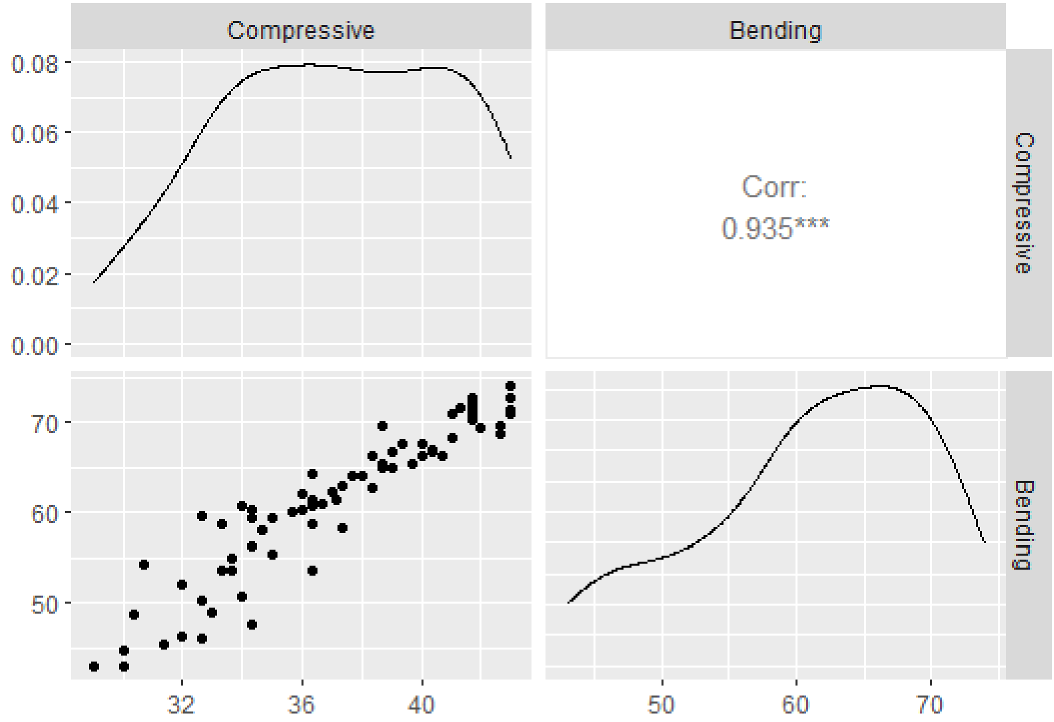

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Figure 3.3. Pearson correlation analysis results between compressive and bending strengths

Figure 3.4 presents a graphical representation of the variations in compressive strength observed within the annual growth rings of the obtained incremental cores. Utilizing the Fractometer II device, compressive strength values of the brutian pine increment cores were assessed, revealing a consistent trend of increasing compressive strength values from the pith (innermost region) towards the bark (outermost region). The compressive strength of the brutian pine wood falls within the range of 27-44 MPa.

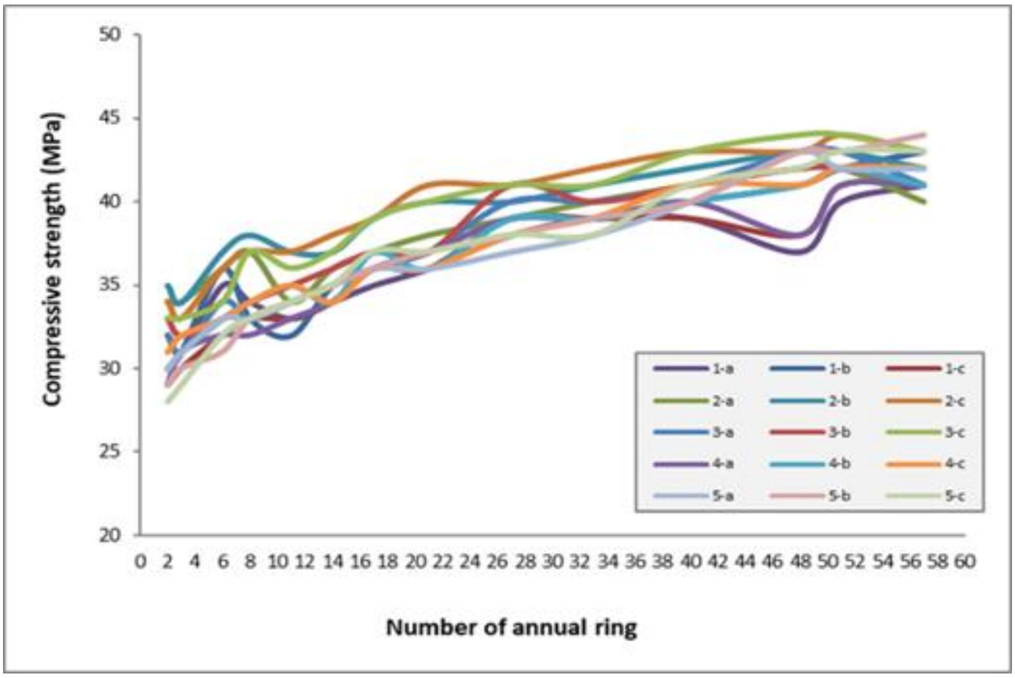

Figure 3.4. Compressive strength values based on annual ring

Notably, upon a comprehensive examination of the compressive strength data, it is evident that there is no discernible degradation in the mechanical properties of the wood. Furthermore, this consistency in results was reaffirmed by the similar compressive strength values obtained from increment cores extracted from five distinct trees. Şimşek (2017) measured the compressive strength of red pine wood increments in order to distinguish between young wood and mature wood. Red pine wood's compressive strength has been found to be between 20 and 50 MPa.

In the study, bending strength values of 6 mm were determined on the increment core. The bending strength values per annual ring are given in Figure 3.5. Upon examination of the bending strength values, a discernible trend emerged, indicating an increment in these values from the pith (innermost region) towards the bark (outermost region).

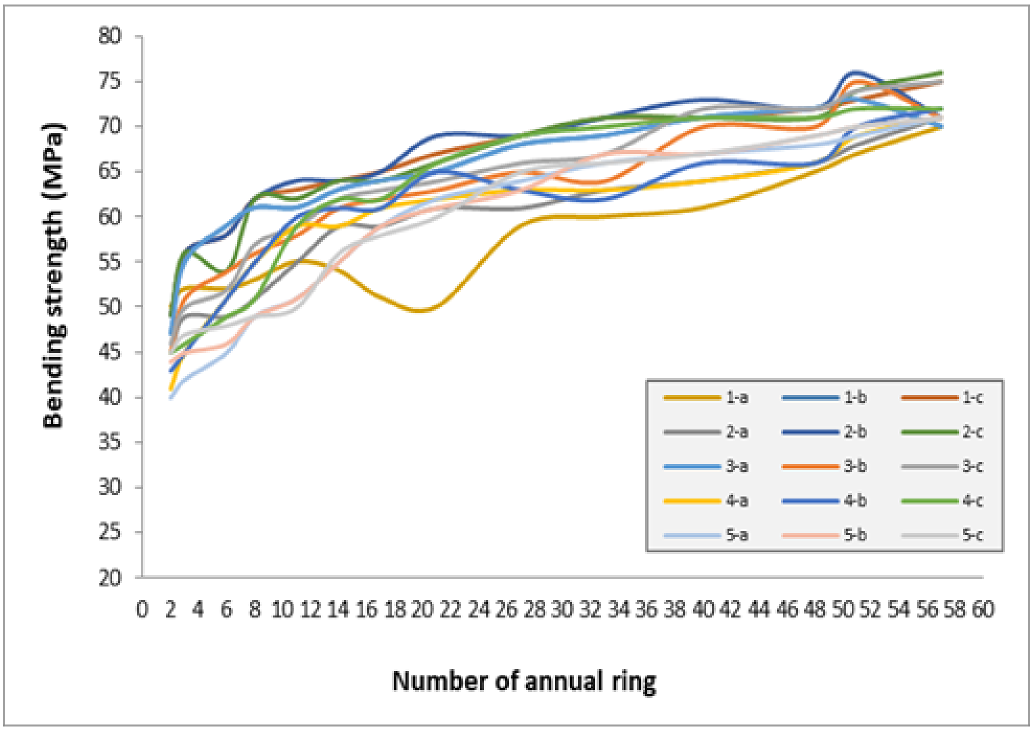

Figure 3.5. Bending strength values based on annual ring

This observed phenomenon aligns with findings articulated by Şimşek Türker (2017) and Clark (2007), who attribute this increase to the transition from the juvenile wood phase to the mature wood phase. Specifically, the bending strength values for brutian pine wood, as ascertained in this study, were found to range between 57 and 80 MPa. Notably, the work of Çetin and Gündüz (2017) provides a reference point, asserting that the resistance of pine trees typically hovers around 80 MPa. In contrast, the findings of the present study indicate a bending strength range of 40-75 MPa for brutian pine wood. Importantly, a meticulous analysis of these bending strength data demonstrates the absence of any significant mechanical property degradation. Furthermore, the consistency of results was reaffirmed through the parallel evaluation of increment cores collected from five distinct trees. A similar issue is revealed by other investigations in the literature. Data indicate compatibility (Lin et al., 2008; Wang et al. 2008; Matsumoto et al. 2010; Jonstone et al. 2010).

4. Conclusion

In this study, the compression and bending properties of standing trees were assessed using the non-destructive increment core method. Upon analyzing the data, it became apparent that the values for compressive and bending strength closely aligned with those of a typical, undried pine tree.

Additionally, upon evaluating the obtained bending and compressive strength values, a discernible pattern emerged, indicating a gradual decrease from the pith towards the bark. This finding sheds light on the structural variations within the tree and its implications for material properties.

Determining and monitoring the decay and cavities in the inner parts of the standing trees at the right time is an important issue in terms of taking the necessary protection measures for these trees. Depending on the species and environmental effects, after a certain age (especially in species whose heartwood is not resistant), fungus etc. With the effect of this effect, decay starts in the inner parts of the trees, and after a while, cavities are formed in these parts. Protection measures are taken when the internal cavities in some trees are visible or can be predicted with the help of some external indicators. However, when the rot and voids inside the trees cannot be detected from the outside, very valuable assets such as monumental trees and stands, which are taken under protection due to some of their qualities, are suddenly broken and overturned. In addition, trees in this situation in urban and roadside afforestation, wind, snow, etc. It can become a situation that threatens the safety of people and all kinds of objects by impacts or suddenly overturning.

As a result, it is of great importance to determine and follow up the rots and cavities in the inner parts of the planted trees, to protect these trees, to prevent material and moral damages, and to prevent situations that may even cost human life when appropriate. Determination and monitoring of mechanical losses in the interior of standing trees, protection of these trees, prevention of material and moral damages, and for preventing the situations that may even cost human life has great importance. So, it is possible to get an idea about them without cutting the trees, selection of sample trees in scientific studies or for the suppliers of wood raw materials.

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