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Bazı Tahta Malzemelerin Sertlik Değerlerinin Bilgisayar Destekli Vurma Testi ile Tahmini

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ÖZ

Tarihi binalarda, tarihi eserlerde, inşaatlarda, ev mobilyalarında, çocuklara yönelik oyun parkları ve bahçeleri gibi daha birçok alanda kullanılan çam, kavak ve MDF laminant gibi belirli ahşap malzemelerin mikrosertlik değerlerinin tahribatsız bir yöntemle kısa sürede belirlenmesi, bu malzemelerin kalite kontrolleri ve dayanıklılıklarının belirlenmesi için önemlidir. Bu tür ahşap malzemelerin sertlikleri genellikle tahribatlı geleneksel yöntemler ile gerçekleştirilmektedir. Bu nedenle bu araştırma çam, kavak ve MDF laminant gibi bazı ahşap malzemelerin mikrosertlik (HCATT) değerlerinin ilk kez tahribatsız olarak Bilgisayar Destekli Vurma Testi (BDVT) sistemi ile belirlenmesi ve bu HCATT değerleri ile bu malzemelerin literatürden alınan Brinell sertlik (HB) değerleri arasındaki ilişkinin belirlenmesi amacıyla gerçekleştirilmiştir. Araştırmada kullanılan tahta malzemelerin HCATT değerleri, BDVT cihazının (BDVTC) vurucu ucu ile tahta malzemelerin yüzeyleri arasında geçen temas süresinden yararlanılarak belirlendi. Bu araştırmada kullanılan her bir tahta malzeme için iki farklı sertlik ölçüm yöntemi ile belirlenen sertlik değerleri arasındaki ampirik eşitlikler ve bu ampirik eşitliklerin c sabiti değerleri belirlenmiştir. Araştırmadan elde edilen sonuçlara göre en kısa temas süresi ortalaması 362 µs ile MDF Laminant malzemede, en uzun temas süresi ise 653 µs ile kavak malzemede tespit edilmiştir. BDVT sistemi ile elde edilen temas süreleri kullanılarak belirlenen HCATT değerlerine göre en düşük sertlik değeri 0.34 MNm^{-1} ile kavak malzemede elde edilirken en yüksek HCATT değeri ise 1.10 MNm^{-1} ile MDF Laminant malzemede elde edilmiştir. Diğer yandan bu araştırmada kullanılan malzemelerin HB ile HCATT değerleri arasında görülen yüksek düzeydeki ilişki, bu tür malzemelerin mikrosertlik değerlerinin tespit edilmesinde malzemeye zarar vermeyen BDVT sisteminin tahribatlı yöntemlerin yerine kullanılabileceğini göstermiştir. BDVT, günümüzde yaygın bir şekilde malzemelerin mikrosertlik ölçümü için kullanılan tahribatlı testlere kıyasla hem daha hızlı hem de daha ekonomik olduğundan BDVT'nin ilgili literatüre önemli bir katkı sağlaması beklenmektedir.

Prediction of Hardness Values of Some Wooden Materials Using Computer-Aided Tap Testing

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ABSTRACT

Rapid and non-destructive determination of microhardness values for specific wood materials such as pine, poplar, and MDF laminate, which are widely used in various fields including historic buildings, artifacts, construction, home furniture, children's playgrounds, and gardens, is crucial for assessing their quality and durability. The hardness of such wood materials is typically assessed using destructive traditional methods. Therefore, this research was conducted to determine the microhardness (HCATT) values of certain wood materials such as pine, poplar, and MDF laminate for the first time non-destructively using the Computer Aided Tap Tester (CATT) system and establishing the relationship between these HCATT values and the Brinell hardness (HB) values obtained from the literature for these materials. The HCATT values of the wood materials used in the study were determined by using the contact time between the tip of the CATT device (CATT) and the surfaces of the wood materials. Empirical equations for each wood material used in this research, representing the relationship between hardness values determined using two different hardness measurement methods, were established, including the constants (c-values). According to the results obtained from the research, the shortest contact time, with an average of 362 µs, was observed in the MDF laminate material, whereas the longest contact time, with 653 µs, was observed in the poplar material. Based on the HCATT values determined using the CATT system, the lowest hardness value was 0.34 MNm^{-1} in the poplar material, and the highest HCATT value was 1.10 MNm^{-1} in the MDF laminate material. On the other hand, the high level of correlation observed between the HB and HCATT values of the materials used in this research indicates that the non-destructive CATT system can be used instead of destructive methods for determining the microhardness values of such materials, without causing any harm to the material. CATT is expected to make a significant contribution to the relevant literature because it is both faster and more cost-effective compared to the destructive tests commonly used for microhardness measurement in materials today.

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INTRODUCTION

The resistance levels of materials to external environmental conditions and external impacts can be determined by their mechanical properties, such as volume modulus, shear modulus, Poisson's ratio, Young's modulus, and hardness value. Hardness is one of the most important indicators of material strength [1, 2]. Hardness, being a relative concept, is defined as the resistance of a material to friction, cutting, drilling, scratching, or plastic deformation[3, 4]. While hardness was measured in some periods by the friction of various materials with each other, nowadays it is measured based on the force applied to the material surface under certain conditions, the resulting indentation depth, or the rebound heights of loads dropped onto the material surface. In hardness tests, the resistance of a material to an indenter or cutting tool inserted into its surface is measured. Indenters can be in the form of a ball, pyramid, or cone, usually made of materials with much higher hardness than the test material, such as hardened steel, sintered tungsten carbide, or diamond. In most standard tests, the load is applied by gradually pressing the indenter perpendicular to the material surface[4]. The hardness of the materials is determined based on either the indentation surface area resulting from the applied load or the indentation depth of the indenter. Therefore, hardness is generally calculated as the ratio of the permanent indentation surface area to the applied load on the material [5].

Various scales and calculation methods, such as Brinell, Shore D, Vickers, and Rockwell, have been developed to determine the hardness of materials. However, despite the advancements in technology in the 21st century, material hardness is still mainly determined using destructive testing methods. Destructive testing methods damage to the tested materials, rendering them unusable for further testing. Furthermore, these tests require expensive equipment, the expertise of qualified personnel, and extensive evaluation, making them economically impractical. Therefore, non-destructive testing methods, such as ultrasonic testing (UT), have been developed and employed to determine the hardness values of different materials [6-8]. Although UT provides accurate and reliable hardness measurements, it requires the calculation of longitudinal and transverse ultrasonic wave velocities and density values in the materials, which takes some time. Therefore, it is essential to develop hardness measurement methods that are both quicker and more economical. In addition, the hardness values of materials are closely related to their other properties [9-11]. Consequently, using hardness values determined by a rapid and economical method, one can approximately predict the mechanical parameters of materials, such as impact resistance, tensile strength, and Young's modulus, through empirical equations. For example, the Young's modulus (E) of polymers can be directly determined using the relationship established between microhardness and E [12]. Similarly, a relationship has been defined between tensile strength and Vickers hardness (HV) for many copper alloys[13].

Recent studies have shown that the contact time obtained from the impact test can be explained using the mass-spring system model, and the local hardness of a material can be determined during the impact process modeled by the connected mass-spring system using the contact time between the striking tip and the material surface[14]. Due to technological advancements, the time between the striking tip and the material surface can now be measured with high precision in impact tests. Recently developed computer-aided impact test systems have become widely used, especially in the aerospace industry. In this study, the "Computer Aided Tap Tester (CATT)," developed by ASI, Inc. (USA), was used to determine the hardness values of some wood materials.

The CATT system was originally developed for the quality control of honeycomb sandwich structures used in aerospace, rockets, and spacecraft, as well as for the quality control of ships, boats, and vessels in the maritime industry [14]. The CATT system uses an accelerometer with a known mass as the striking tip. The electronic circuit of the CATT system can measure the contact time (τ) between the accelerometer and the material surface with high precision. Hsu, Barnard, Peters, and Dayal [14] conducted hardness measurements with both CATT and mechanical tests on various materials with different compositions in the same areas to investigate whether the local hardness value obtained from the impact test represents the actual hardness of the examined material. Because of these measurements, they found that the hardness values determined by the impact test on the examined material surface and those determined by static load tests were highly consistent. However, the CATT system is currently only used for the quality control of honeycomb sandwich structures in the aerospace industry to detect damage in these materials. Therefore, in this study, the CATT system was used for the first time to determine the hardness values (HCATT) of some wood materials such as pine, poplar, and medium-density fiberboard (MDF) laminate.

Although many hardness measurement methods are used in hardness measurements of materials, the most used methods for wood-type materials are the Janka and Brinell methods [15, 16]. In the research conducted by Schwab [17], different hardness methods were compared for 16 wood species, and it was determined that the Brinell hardness test gave the most reliable results for wood materials. Therefore, the relationship between Brinell hardness values and HCATT values of the materials used in this research was examined.

However, the Brinell hardness test and all others are still destructive testing methods. Thus, these destructive hardness measurement methods are both damaging to the tested materials and economically inefficient. Therefore, this research was conducted to develop a novel, non-destructive, fast, and cost-effective testing method that can be used to measure the microhardness values of various kinds of woods such as pine, poplar, and MDF laminate. In pursuit of this goal, in this study, the microhardness values of various kinds of woods such as pine, poplar, and MDF laminate were determined using a computer-aided tap tester (CATT) system. The microhardness values (HCATT) of these wood materials were compared with the Brinell hardness (HB) values obtained from the literature, and the coefficients of the empirical equations (c-values) established between HCATT and HB.

MATERIALS AND METHODS

Equipment and Materials Used in the Study

In this research, pine (15cmx15cmx2.3cm), poplar (15cmx15cmx2.4cm), and MDF laminate (15 cm x 15 cm x 2.4 cm) wooden materials were procured from the carpentry industry in Konya (Figure 1). A Computer-Aided Tap Tester (CATTV5_3-ASI, USA) was employed for the impact tests and contact time measurements of the wooden materials (Figure 2).

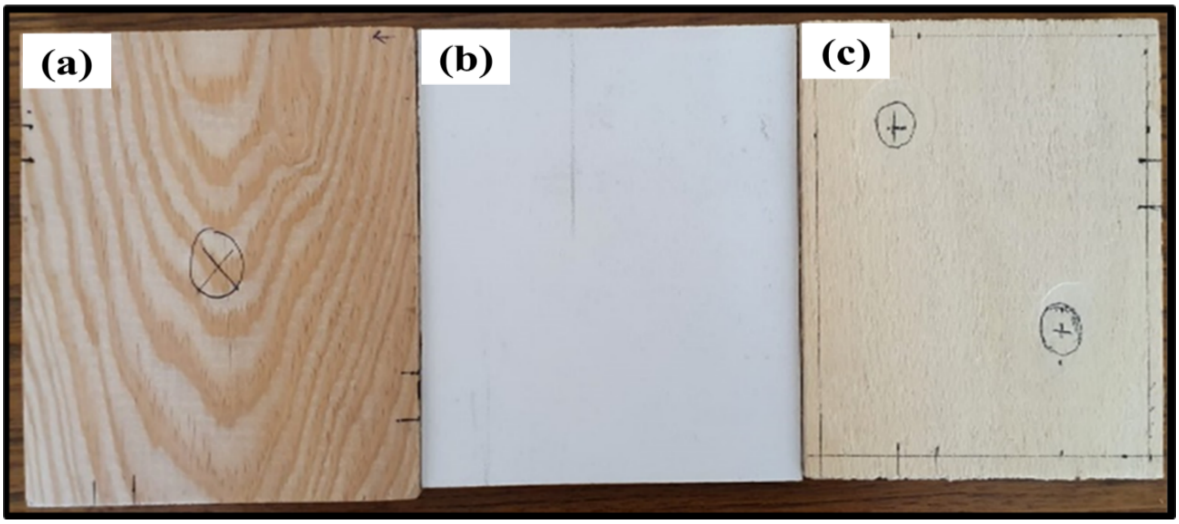

Figure 1. *Images of the wooden materials used in this research: (a) pine, (b) MDF laminate, and (c) poplar*

Computer Aided Tap Tester (CATT) for Microhardness Measurement

Previous studies have shown that the output signal obtained using an accelerometer during the impact process on material corresponds to half of the period of a sinusoidal signal. In the tap test, both the amplitude and width of the obtained signal can be used. The signal width, which represents the contact time, is independent of the applied force in the tap test, whereas the amplitude is force dependent. This is because, in simple harmonic

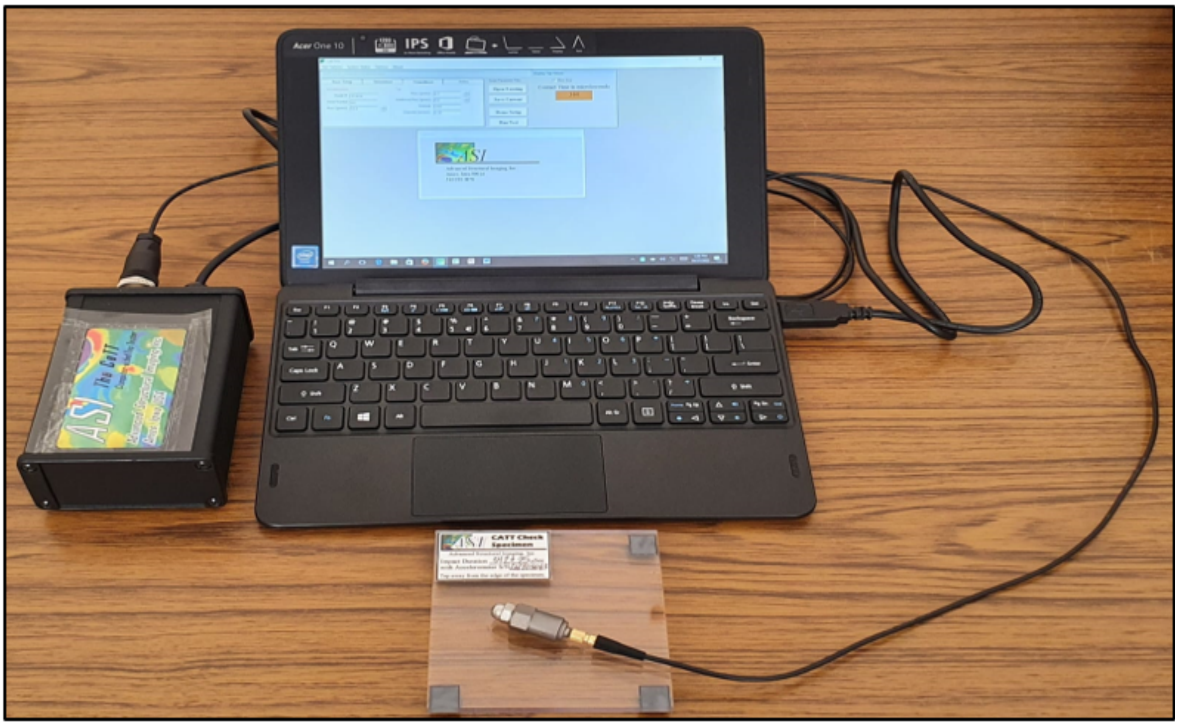

Figure 2. *The computer-aided tap tester system used in this research*

motion, the vibration period is independent of the amplitude of the motion. This finding has been a fundamental factor enabling the tap test to eliminate the human factor and become a test and damage imaging method applicable to materials. Therefore, in the tap test, the mass of the striking tip (m_T) and the contact time (τ) between the striking tip and the material surface are two fundamental variables for calculating the local hardness values (k) on a material surface. Thus, assuming that half of the period of a simple harmonic motion of a mass-spring system corresponds to the contact time (τ) between the striking tip and the material surface during the tapping process, the relationship between the mass of the striking tip (m_T [kg]), the contact time obtained during the tapping process (τ [μs]), and the material hardness (HCATT or k) are given in Equation (1) [14].

$$\boldsymbol{HCATT\ (Nm^{-1}) = \left(\frac{\pi}{\tau}\right)^2 m_T} \qquad \textbf{(1)}$$

In this study, the hardness value (HCATT) of each material was determined at different points on the surface of each wooden material by conducting a tap test using the CATT shown in Figure 2. After repeating the tap test ten times at each point, the average contact times (τ_{avg}) between the striking tip and the material surface and the mass of the striking element (accelerometer + striking head) (m_T) were calculated and used in Equation (1) to determine the hardness value (HCATT). HCATT measurements for wooden materials were performed with a relative error of 10.06%. The Brinell hardness (HB) values shown in Table 2 were obtained from previous studies in the literature without conducting any Brinell tests on the materials.

RESULTS

In this section of the study, the contact times obtained from the tap test conducted with CATT for each material are presented in Table 1. In addition, the hardness values obtained using CATT and the Brinell (HB) values obtained from the literature are provided in Table 2. These results were analyzed, interpreted, and occasionally compared with literature findings.

Contact times obtained from the Tap Test of Wooden Materials

The contact times obtained from the tap tests repeated ten times on the upper surfaces of some wooden materials at different points are presented in Table 1.

Table 1. *Data on contact times were obtained from computer-aided tap tests for some wooden materials.*

MATERIALS	*Contact times (τ[s])*										*$\bar{\tau}$(μs)*	*St.Dev.*
Poplar	718	700	729	686	663	650	603	528	630	621	653	58
Pine	429	391	401	394	437	422	409	398	396	400	408	15
MDF Laminate	365	372	345	375	352	360	367	355	357	369	362	09

In the computer-aided tap tests, average contact times of 362 μs for MDF laminate, 408 μs for pine wood, and 653 μs for poplar wood were obtained between the striking tip and the surfaces of the wooden materials (Table 1).

Hardness Values Obtained from Tap Tests on Wooden Materials

In this section of the study, the Brinell hardness values (HB) obtained from the literature and the hardness values (HCATT) obtained from the computer-aided tap tester (CATT) for the wooden materials used in this research were analyzed. Table 2 presents the HB hardness values obtained from the literature and the HCATT hardness values determined using the CATT system for some wooden materials (poplar, pine, and MDF laminate). The constant value (c) of the empirical equation that enables a simple conversion of the calculated HCATT hardness values to HB values for these wooden materials is also provided in Table 2. A graphical representation of the hardness values from the two different methods is shown in Figure 3, and the regression equation and coefficient depicting the relationship between these two hardness values are presented in Figure 4.

Table 2. *Brinell hardness values (HB) and hardness values (HCATT) were measured with a computer-aided tap tester for some wooden materials and the conversion coefficient values between these values.*

MATERIALS	*HB (MPa)*	*HCATT (MN.m^{-1})*	*c (m^{-1})*
Poplar	16.71 [18]	0.34	49
Pine	01.60 [19]	0.87	2
MDF Laminate	33.47 [20]	1.10	30

The data in Table 2 and Figure 3 show that for some wooden materials used in this research, the Brinell hardness values obtained from the literature range from 1.60 MPa to 33.47 MPa [18, 20, 21], whereas the hardness values obtained with the CATT system range from *30.34 MNm^{-1}* to *1.10 MNm^{-1}*. In the research conducted by Zanuttini, et al. [22], it was determined that the Brinell hardness value of various poplar ply woods varied between 8.3 N.mm^{-2} and 10.8 N.mm^{-2}. In another study conducted by Sydor, Pinkowski, and Jasińska [23], two different hardness values were revealed for pine using the Brinell method: HB_d, which represents plastic deformation, and HB_H, which represents both elastic and plastic deformation. Sydor, Pinkowski, and Jasińska [23] obtained the HB_d and HB_H values of pine as 1.81 N.mm^{-2} and 1.43 N.mm^{-2}, respectively.

According to the data in Table 2, the constant values (c) of the empirical equation that enables a simple conversion of HCATT values to HB values are as follows:

For poplar sample: c = 49 m^{-1}

For pine sample: c = 2 m^{-1}

For MDF laminate sample: c = 30 m^{-1}

According to the data in Figure 4, there is a second-degree polynomial relationship between the Brinell hardness values (HB) obtained from the literature for the wooden materials used in the research and the HCATT hardness values calculated from the contact times obtained with the CATT system. The coefficient of determination (R^2) for this relationship is also 1.00, indicating a perfect fit. When the literature is reviewed, it is observed that empirical equations based on hardness measurements have been developed to predict the flow resistance [24], tensile strength [25], and density [26] of various materials. However, in all these studies, the

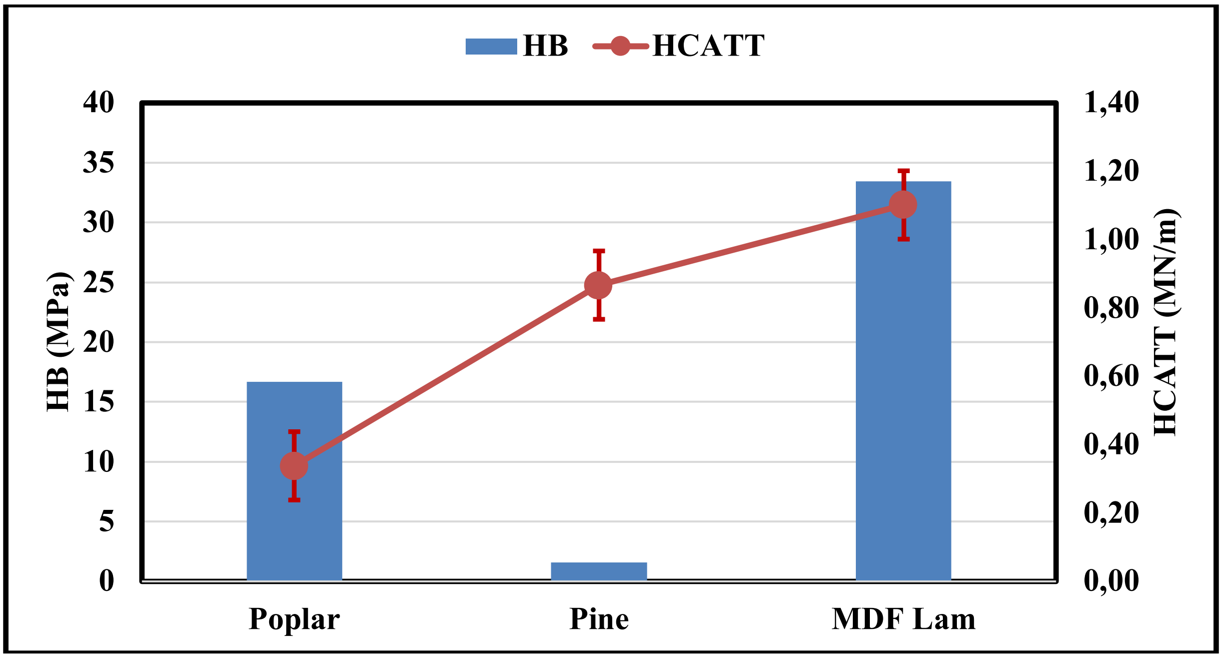

Figure 3. *Brinell hardness values (HB) and computer-aided tap test hardness values (HCATT) for some wooden materials.*

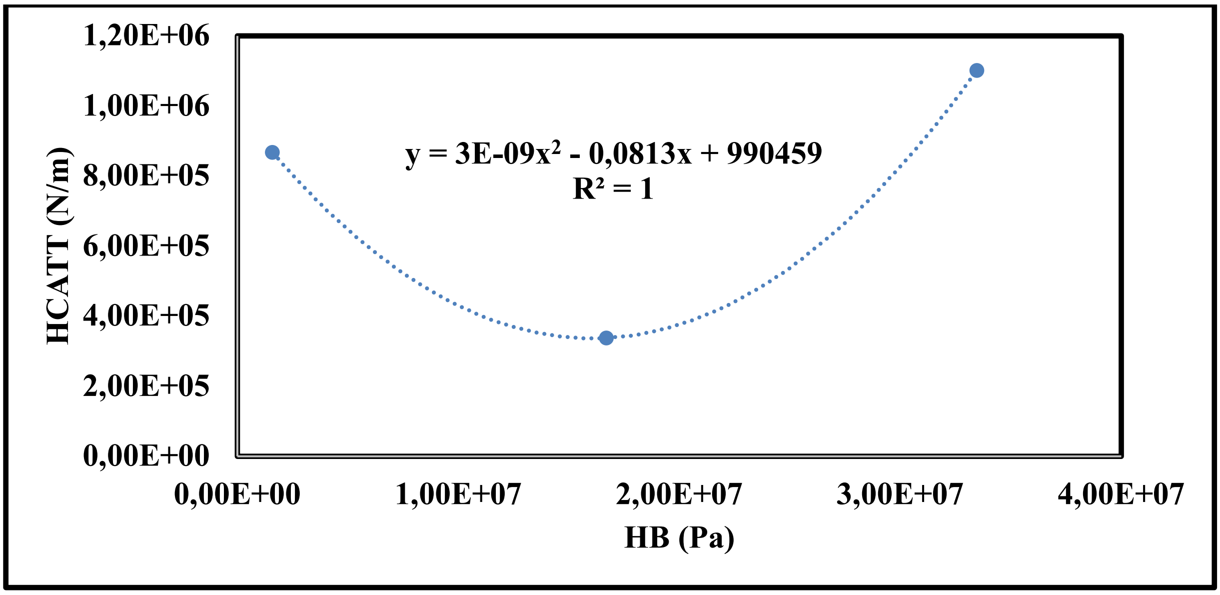

Figure 4. *Relationship between Brinell hardness values (HB) and computer-aided tap test hardness values (HCATT) for some wooden materials.*

hardness values of the materials were determined using destructive methods. Hardness, which is positively and negatively correlated with density and moisture content, is an important physical property of wooden materials [23]. Therefore, the relationship obtained between the Brinell hardness values of the wooden materials used in this research and the HCATT values obtained non-destructively with the CATT method in a short time and economically can be used as an alternative hardness measurement method for such materials. Hence, this finding suggests that the determined HCATT values can be used in these empirical formulas to determine the Brinell hardness values of wooden materials.

DISCUSSION AND CONCLUSIONS

The study results indicate that the microhardness values of the materials are inversely proportional to the contact durations. This implies that a decrease in the contact duration between the accelerometer and the material surface during the impact process signifies a higher hardness value for the investigated material. According to the contact durations for each material group, the shortest contact time was recorded for the MDF laminate, whereas the longest contact time was measured for the poplar board. Consequently, MDF laminate materials exhibit the highest hardness value, whereas poplar materials possess the lowest hardness value.

Numerous researchers have highlighted the significant relationship between hardness/microhardness and other material properties, using them for measurement purposes [3, 10, 24, 27-29]. For instance, Cheng and Cheng [28] established a direct correlation between Young's modulus and tensile mechanical hardness, which are crucial considerations for various mechanical design applications. Briscoe and Sinha [27] demonstrated the association between the microhardness of polymers and various microstructural parameters, making microhardness measurement a viable means to monitor changes in the physical and mechanical properties of polymers. Additionally, Lorenzo, Pereña, and Fatou [29] proposed an exponential relationship between the flexibility modulus and the microhardness of polymers.

The data from Table 2 reveal that the lowest HB value is 1.60 MPa for the pine board sample, whereas the highest HB value is 33.47 MPa for the MDF laminate sample. Within the scope of this study, the lowest HCATT hardness value, obtained through CATT from the material surfaces, is 0.34 MNm^{-1} for poplar, and the highest HCATT value is 1.10 MNm^{-1} for the MDF laminate sample. The conversion equation between HCATT and HB values for some wood materials used in the study yields the smallest constant c as 2 m^{-1} for pine and the largest c value as 49 m^{-1} for poplar. Furthermore, the R^2 value above 0.70 in Figure 4 suggests a strong second-degree polynomial relationship between the HCATT and HB values. This highlights the significance of the non-destructive CATT system as a replacement for destructive hardness measurement methods for the wooden materials used in this study. When reviewing the relevant literature, it is evident that various studies have investigated the relationship between the hardness values of different materials and other material properties, derived empirical formulas, and calculated their constants.

For example, Cahoon, Broughton, and Kutzak [24] developed an empirical equation using simple hardness measurements to predict the yield strength of copper, aluminum, and steel. Similarly, Krishna, Gangwar, Jha, and Pant [13] established a linear relationship between yield strength and Vickers hardness (HV) for copper alloys, with an obtained constant of 2.874. Krishna, Gangwar, Jha, and Pant [13]also identified a linear relationship between yield strength and Vickers hardness (HV) in copper alloys, yielding an R^2 value of 0.916 for this relationship. Kaymakci and Ayrilmis [25] investigated the correlation between Brinell hardness and tensile strength for wood-plastic composites as a function of wood filler content using linear regression and found a strong correlation between Brinell hardness and the tensile strength of wood composites when the filler content ranged from 30% to 40% by weight. They suggested that Brinell hardness could be an effective indicator of the tensile strength of wood-plastic composites. Klisz, Ukalska, Noskowiak, Wojda, Jastrzębowski, Mionskowski, and Szyp-Borowska [26] conducted a study in Western Poland on the relationship between wood density and hardness in flat-sawn black acacia trees, determining hardness values of 0.66 radially and 0.61 tangentially for three different wood zones.

Altindag and Guney [30] aimed to reveal the relationships between brittleness and compressive strength and between tensile strength and Shore hardness of rocks. Similarly, Akbay, Ekincioglu, Altindag and Sengun [3] determined four different brittleness values for carbonate rocks using hardness values measured with a digital Shore hardness device. In the study conducted by Akbay et al. (2021), the relationship between Shore hardness values and four different brittleness values of rocks was examined using simple regression. Because of this, it was revealed that two of the four different brittleness values of the rocks can be safely estimated from the hardness values measured with Shore D (HSD), Vickers (HV), and Rockwell (HR) hardness methods. As can be seen from these studies, destructive methods have consistently been used for hardness measurements of different materials, and despite being in the 21st century, many recent studies still rely on destructive hardness measurement methods [31-37]. These destructive methods are time-consuming, damaging to the material, and require expensive equipment. Therefore, the practical, fast, and economical method of computer-aided tap testing used in this study highlights the importance of this method in determining hardness for the first time.

Thus, similar to the HCATT_HB relationship obtained for some wood materials in this study, HCATT values determined for different materials can be experimentally determined along with the relationships between these HCATT values and other material properties such as Shore D (HSD), Vickers (HV), and Rockwell (HR) hardness values and other physical properties of materials. Even the experimental equations obtained about hardness can be used to obtain information quickly and economically about other material properties by using other empirical equations previously revealed by other researchers for other physical properties of materials. However, since hardness represents resistance to plastic deformation, the relationships with the experimentally determined hardness test are not universal relationships or formulas, but relationships specific to the experiments and the materials tested.

When the relevant literature is examined, the relationships between hardness and yield strength for copper, aluminum, and steel[13, 24], hardness tensile strength of wood-filled plastic composites depending on wood filler [25], hardness wood density in black acacia trees[26], hardness fracture toughness value of carbonate rocks [3], and the static hardness of honeycomb sandwich materials HCATT [14] have been investigated. However, no study has been found in the literature that determines the microhardness value in wooden materials using the CATT system. The absence of such a study in the literature demonstrates the originality of this research. In addition, the use of the CATT method for the first time in this research to determine the local hardness of various wood materials and thus the introduction of a non-destructive new method that can be used for hardness measurement of materials is highly significant. The findings obtained from this research can be summarized as follows:

1) The microhardness (HCATT) values of the materials change inversely with the contact duration. Therefore, it can be stated that long contact durations with the striker tip correspond to low HCATT values, whereas short contact durations correspond to high HCATT values.
2) According to the obtained contact durations for each material group, the shortest contact time (362 µs) was obtained for the MDF laminate, and the longest contact time was measured for the poplar board (653 µs).
3) Based on the obtained HCATT values, the mechanical strengths of the materials used in the research are in the order of poplar board < pine board < MDF laminate.
4) The coefficient value of the empirical equation (c-value), which simply enables the conversion of HCATT values to HB values, was determined as 49 m^{-1}, 2 m^{-1}, and 30 m^{-1} for poplar, pine, and MDF laminate, respectively.

The CATT system provides a practical, fast, and economical method for determining the microhardness values of the materials.

RECOMMENDATIONS

The CATT system used in this research to obtain microhardness values is expected to make a significant contribution to the relevant literature. Especially given the high correlation obtained between HCATT_HB for some wood materials in this study, for the global validity of the hardness measurement system through CATT, similar measurements should be repeated for other wood, metal, and polymer materials outside the scope of this study. Therefore, further research is recommended to measure microhardness in different materials using the CATT system. Similar to this research, many properties of different materials may be predicted from the measured HCATT values. Indeed, relationships between hardness and other physical properties revealed in this way can also be used in a short time and in a more economical way by using other empirical equations previously revealed by other researchers for other physical properties of materials. However, since hardness represents resistance to plastic deformation, the relationships with the experimentally determined hardness test are not universal relationships or formulas, but relationships specific to the experiments and the materials tested.

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