Use of a Pin-penetration Wood Density Meter to Determine the Density of 25 Indonesian Species

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The pin-penetration device is a minimally destructive instrument that is widely used to estimate the physical properties of wood, *e.g.*, density, with advantages such as reduced testing times, low costs, and fewer defects induced in the wood being tested. In this study, such a device was used on 25 Indonesian hardwood species with a strength class (SC) distribution from SC II to IV (according to the Indonesian classification of wood SCs). Tests were conducted on three different orthogonal planes, *i.e.*, cross-sectional, radial, and tangential planes. The wood density ranged from 0.28 to 0.88 g/cm^3, and the specific gravity was 0.25 to 0.76. The cross-sectional plane penetration depth of the wood was significantly greater than that of either the radial or tangential plane, whereas the pin penetration values of the radial and tangential planes were not significantly different. A prediction model for predicting the density and specific gravity of wood via pin penetration showed a significant regression. Thus, the use of a pin-penetration device was found to be suitable for estimating wood density and specific gravity in a range of SCs of tropical wood species regardless of species.

Keywords: Pin penetration; Strength class; Wood density; Specific gravity; Cross section; Pilodyn wood density meter

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INTRODUCTION

The properties of wood can be determined *via* different approaches, which include destructive, nondestructive, and minimally destructive. The latter two categories are procedures that determine the properties of the wood without causing major damage to the material. The probing method is a nondestructive approach that is used to estimate wood density (González *et al.* 2015; Ross 2015; Llana *et al*. 2018a; Schimleck *et al*. 2019; Martínez *et al*. 2020), which is an important characteristic for determining the quality of wood and especially for defining wood strength. According to Carballo *et al*. (2009), the most frequent probing method used to estimate wood density is needle penetration resistance, which is commonly performed with a Pilodyn instrument (Proceq, Schwerzenbach, Switzerland); indeed, this has become a common probing technique in several countries (Schimleck *et al*. 2019; Llana *et al*. 2020). The Pilodyn has been at the forefront of needle penetration resistance since the 1970s; although it was first designed to evaluate the properties of standing trees and electric poles, it was later evolved for applications related to structural evaluation of wood components (Görlacher 1987).

Using the pin penetration device on standing trees can approximate the density of a prominent tree for species selection related to tree breeding activities (Ishiguri *et al*. 2008;

Fukatsu *et al.* 2011; Mäkipää and Linkosalo 2011; Ishiguri *et al*. 2012; Couto *et al*. 2013; Hidayati *et al*. 2013; Neves *et al.* 2013; Chen *et al*. 2015; Anna *et al.* 2018). The device is known for verifying the density of sawn timber and structural wood in relation to both sorting and evaluation of wood quality, *i.e*., determining deterioration (González *et al*. 2015; Fauziyyah *et al.* 2019; Rohanová; 2020). The pin penetration instrument employs a fixed diameter steel pin (normally 2.5 mm), which is driven into the material via a spring calibrated to a constant dynamic force of 6 J. As the penetration depth varies up to 40 mm, the material density can be determined from a regression function related to penetration depth.

Factors that influence the depth of pin penetration are moisture content, proportion of early wood to late wood, and the presence of degraded wood (Llana *et al*. 2018b; Görlacher 1987; Kasal 2003; Drdácký *et al.* 2007; Fauziyyah *et al.* 2019). Total pin penetration depth also depends on surface hardness and wood density. Variability in the correlation between the penetration depth and the wood density is ascertained on the basis of wood species as well as the total number of measurements with a negative value; this variation typically has correlation coefficients ranging from 0.40 to 0.92 (Görlacher 1987; Hansen 2000; Teder *et al*. 2011; Gonzalez *et al.* 2015; Gao *et al*. 2017; Llana *et al*. 2018a; Rohanová 2020). Greater penetration depth indicates lower wood density. Information for approximating wood density is crucial in the process of structural wood sorting as well as *in situ* assessment of wooden structural elements. Ponneth *et al*. (2014) reported that the pin penetration technique is well correlated with static bending modulus of elasticity (MOE) and modulus of rupture (MOR).

In structural assessments, penetration depth is typically measured in the outer part of the wood (Llana *et al.* 2018a). For *in situ* structures, the end side of the longitudinal direction or cross section, as well as the face side of the radial and tangential directions, is available for testing. In the studies of Bobadilla *et al.* (2007), Gonzalez *et al.* (2015), and Martínez *et al.* (2020) no significant differences were found between radial and tangential measurements of dry wood. It would also be interesting to determine the differences between the side directions and cross sections in the longitudinal direction. As pin-penetrating depth values differ significantly with species density, it would also be useful to produce a model that could predict variation in wood density and represent many species in several strength classes (SCs).

Indonesia has thousands of tropical wood species, which are primarily dominated by hardwood species with heterogeneous wood structures rather than homogeneous softwood species (Ogata *et al*. 2008). One of the primary challenges when using wood for structural purposes is the lack of information on wood species and quality obtained from *in situ* assessments. Consequently, being able to obtain additional information on wood density could improve the wood grading process (based on SC) and the evaluation of wood strength, which refers to the density and/or specific gravity of the regardless of wood species. In the present study, the aim was to provide density estimations through the model development for 25 Indonesian tropical timber species having a wide range of SCs using pin penetration measurements.

EXPERIMENTAL

Materials

The testing materials were in the form of sawn wood, which was obtained from an Indonesian commercial market through nondestructive means. The samples consisted of 25 different wood species from various wood SCs (as shown in Table 1).

Table 1. List of the 25 Wood Species Used in this Study

Wood number	Common name	Botanical name	Family	Strength class	Origin
1	Mayang	*Melanochyla* spp.	Anacardiaceae	IV	West Sumatera
2	Afrika	*Maesopsis eminii* Engl.	Rhamnaceae	IV	Kalimantan
3	Sengon	*Falcataria moluccana* (Miq.) Barneby dan J.W. Grimes	Leguminosae	IV	West Java
4	Jabon	*Neolamarckia cadamba* (Roxb.) Bosser	Rubiaceae	IV	West Java
5	Bayur	*Pterospermum celebicum* Miq.	Malvaceae	III	West Sumatera
6	Medang	*Neolitsea latifolia* (Blume) S. Moore	Lauraceae	III	West Sumatera
7	Surian	*Toona sinensis* (Juss.) M. Roem	Meliaceae	III	West Sumatera
8	Sungkai putih	*Peronema canescens* Jack	Lamiaceae	III	West Sumatera
9	Sungkai kuning	*Peronema canescens* Jack	Lamiaceae	III	West Sumatera
10	Mahoni	*Swietenia mahagoni* (L.) Jacq.	Meliaceae	III	West Sumatera
11	Nyatoh	*Palaquium obtusifolium* Burck.	Sapotaceae	III	West Sumatera
12	Meranti merah	*Shorea leprosula* Miq.	Dipterocarpaceae	III	Kalimantan
13	Duren	*Durio zibethinus* Moon	Bombacaceae	III	Kalimantan
14	Mersawa	*Anisoptera laevis* Ridl.	Dipterocarpaceae	III	Kalimantan
15	Mangium	*Acacia mangium* var. holosericea (A.Cunn. ex G.Don) C.T. White	Fabaceae	III	West Java
16	Borneo	*Dryobalanops* spp.	Dipterocarpaceae	II	West Sumatera
17	Meranti batu/Katu ko	*Parashorea lucida* (Miq.) Kurz.	Dipterocarpaceae	II	Kalimantan
18	Damar laut	*Parashorea stellata* Kurz.	Dipterocarpaceae	II	Kalimantan

Wood number	Common name	Botanical name	Family	Strength class	Origin
19	Keruing	*Dipterocarpus* spp.	Dipterocarpaceae	II	Kalimantan
20	Tembalun	*Coelostegia griffithii* Benth. & Hook.f.	Bombacaceae	II	Kalimantan
21	Kamper banjar	*Dryobalanops* spp.	Lauraceae	II	Kalimantan
22	Kamper singkil	*Dryobalanops* spp.	Lauraceae	II	Kalimantan
23	Kempas	*Koompassia malaccensis* Maingay	Leguminosae	II	Kalimantan
24	Kulim	*Scorodocarpus borneensis* (Baill.) Becc.	Olacaceae	II	Kalimantan
25	Jati	*Tectona grandis* L.F.	Lamiaceae	II	West Java

These wood species were sourced as follows: 9 from West Sumatera, 4 from Bogor (West Java), and 12 from Kalimantan. Local or common names for the species were obtained from the seller, whereas their botanical names were determined with reference to macroscopic analysis results and the Indonesian Wood Atlas (Martawijaya *et al.* 2005). The SC classification was based on specific gravity as stipulated by Oey (1990).

The wood samples were obtained by cutting the sawn timber into boards with dimensions of 120 × 60 × 400 mm (width × thickness × length), with three replicates used for each species; thus, 75 wood samples were obtained in total. The samples were conditioned under standard conditions to achieve air-dry moisture content.

Experimental Procedures

Pin penetration

Pin penetration was performed with a Pilodyn wood density device to assess wood samples; this process was executed by firing the Pilodyn needle into a wood sample. Penetration testing was performed for three cross-sectional planes (cross-sectional, tangential, and radial; Fig. 1), each of which was conducted at four different points before an average value of these measurements was calculated.

Fig. 1. Pin penetration measurement. Pin penetration points were situated at three different orthogonal planes (Cs= cross-sectional; R= radial; T= tangential)

Measuring the physical properties of wood

Density, specific gravity, and moisture content were measured according to ASTM D4442-92 (2003) and ASTM D2395 (2017). The physical properties of samples were evaluated on a wooden cube with dimensions of 2 × 2 × 2 cm (width × thickness × length). The samples were weighed to obtain the initial mass (m_M), and the dimensional measurements were taken to obtain the sample volume at moisture content (V_M). The samples were then dried in an oven at 103 ± 2 °C for 24 h. Subsequently, they were placed in a desiccator for approximately 15 min until the sample reached a constant oven-dry mass (m_0). The moisture content (M) was calculated according to Eq. 1:

$$M = \frac{m_M - m_0}{m_0} \times 100, \qquad (1)$$

where m_M is the initial mass (g) and m_0 is the oven-dry mass (g). The density (ρ_M) at moisture content (M) was calculated according to Eq. 2:

$$\rho_M = \frac{m_M}{V_M}, \qquad (2)$$

where V_M is the sample volume at moisture content M (cm^3). The specific gravity (S_M) was calculated according to Eq. 3:

$$S_M = \frac{K m_0}{V_M}, \qquad (3)$$

where K is a constant with a value of 1.000 cm^3/g.

Statistical analysis

Statistical analysis was performed to determine the influence of a section of wood on the depth of pin penetration as well as the wood density, specific gravity, and moisture content. In addition, a linear regression model was generated to predict wood properties based on penetration depth.

RESULTS AND DISCUSSION

Distribution of the Physical Characteristics of the Tested Wood Species

Of the 25 Indonesian hardwood species, sengon wood (*Falcataria moluccana*) had the lowest average density (0.28 g/cm^3), with a specific gravity of 0.25 and an average penetration depth of 2.49 mm, whereas kulim wood (*Scorodocarpus borneensis*) had the highest density (0.88 g/cm^3), with a specific gravity of 0.76 and an average penetration depth of 0.99 mm.

Further clarification of the physical properties and pin resistance of the tested wood species are presented in Table 2. The wood samples with higher densities and specific gravities typically had lower pin penetration depths: the higher the density, the lower the penetration depth.

Table 2. Average Pin Penetration Depth and Wood Properties of the 25 Tested Wood Species

Wood species no.	ρ* (g/cm^3)	SG*	MC* (%)	Pin penetration* (mm)	Strength class
1	0.43	0.37	15.05	2.16	IV
2	0.42	0.37	11.50	1.34	IV
3	0.28	0.25	15.20	2.49	IV
4	0.32	0.29	15.20	1.98	IV
5	0.50	0.43	16.27	1.49	III
6	0.56	0.49	15.99	1.38	III
7	0.62	0.53	16.06	1.40	III
8	0.61	0.53	13.15	1.23	III
9	0.65	0.57	13.09	1.31	III
10	0.62	0.53	15.25	1.27	III
11	0.66	0.57	16.42	1.29	III
12	0.61	0.54	14.21	1.74	III
13	0.48	0.43	12.29	1.42	III
14	0.47	0.42	13.06	2.13	III
15	0.58	0.51	14.56	1.58	III
16	0.77	0.65	17.88	1.25	II
17	0.77	0.65	17.47	1.25	II
18	0.78	0.68	14.06	1.26	II
19	0.79	0.69	15.62	1.33	II
20	0.82	0.72	13.81	1.19	II
21	0.85	0.75	12.40	1.49	II
22	0.87	0.76	15.19	1.15	II
23	0.87	0.75	14.77	1.03	II
24	0.88	0.76	16.34	0.99	II
25	0.71	0.63	14.30	1.32	II

Note: *The value is an average; ρ= density; SG= specific gravity; M= moisture content.

On the basis of the density and specific gravity distribution, the 25 tested wood species were grouped from SC II to IV. The Indonesian SC, determined according to the specific gravity of wood at an air-dried moisture content (Oey 1990). SC I–IV are woods with specific gravities of >0.9, 0.6 to 0.9, 0.4 to 0.6, and <0.3, respectively.

Figure 2 shows the variation in density, specific gravity, and moisture content of the wood samples. Although the range of specific gravities in SC III was relatively narrow (*i.e.*, 0.4 to 0.6), the data distribution of the tested wood parameters was diverse. However, the distribution of moisture content data was wider in the SC IV group. This is presumably due to the ability of low-density wood to absorb water more rapidly because of a larger cavity in the lumen.

Previously, Llana *et al*. (2018b) reported the influence of moisture content on penetration depth in some softwood pine species. The pin penetration depth was sensitive to MC changes below fiber saturation point (FSP) and depended on species.

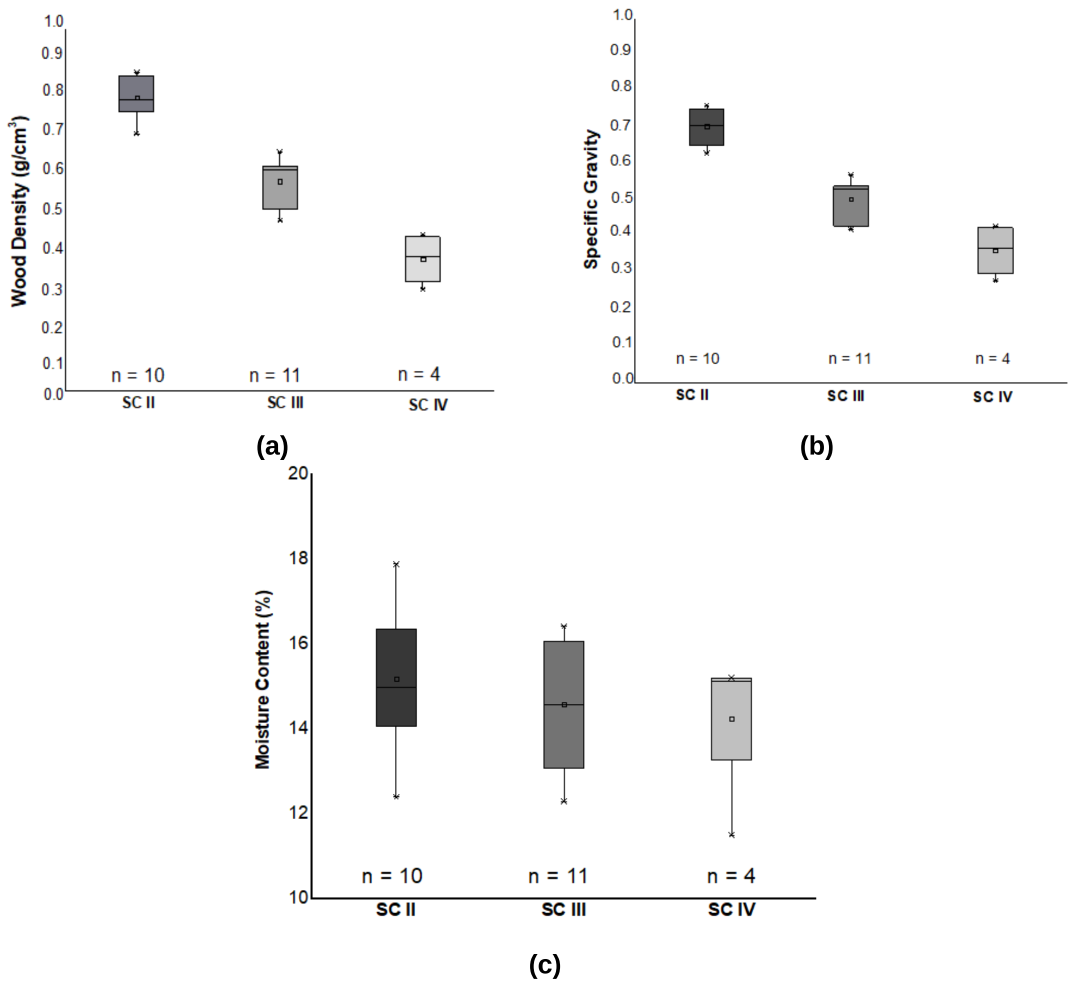


Fig. 2. Distribution of the physical properties of tested wood based on (a) density, (b) specific gravity, and (c) moisture content

Relationship between the Pin Penetration Depths at Three Wood Planes and the Physical Properties of Wood

Wood has anisotropic properties, which are modeled in orthotropic materials with three different wood planes, *i.e.*, cross-sectional, radial, and tangential planes. Thus, the properties of wood are influenced by the wood plane sections (Melzerova *et al.* 2016). Figure 3 shows the difference in the penetration depth of the Pilodyn instrument for different wood SCs. The average depth of pin penetration in SC IV wood samples was 26% and 38% greater than the average pin penetration depths in SC III and SC II wood samples, respectively. The pin penetration depth in the cross-sectional plane was approximately 18%

greater than the pin penetration depth in the radial and tangential planes for all SCs. The presence of ray resistance anatomically in the radial and tangential planes is the likely reason for reduced penetration. An analysis of variance (Anova) test showed that the wood section, *i.e.*, the plane, had a significant effect (α = 5%) on penetration pin depth. There was a significant difference between the depth of penetration in the cross-sectional planes and the depth of penetration in the radial and tangential planes; however, there was no significant difference in pin penetration depth between the radial and tangential planes (Fig. 3). These results were in agreement with those of (Bobadilla *et al.* 2007; Gonzalez *et al.* 2015; and Martínez *et al.* 2020), who also reported no significant difference in penetrating depth between the radial and tangential planes.

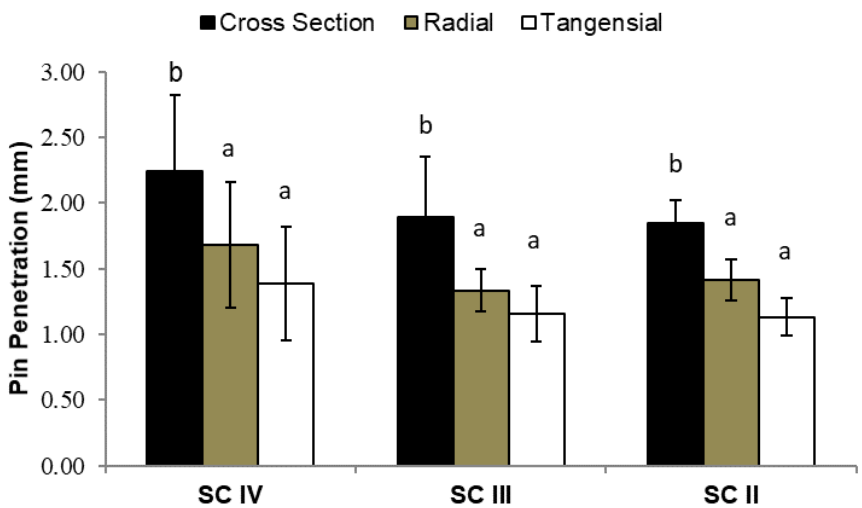


Fig. 3. Pin penetration distribution for the cross-sectional, radial, and tangential planes of the 25 tested Indonesian wood species

In the process of assessing building structures, the radial and tangential sections (or planes) are more commonly and easily tested than the cross sections. However, the end cross section in a longitudinal direction should also be tested if possible. Studies by (Llana *et al*. 2018b; Rohanová 2020; Martínez *et al.* 2020) reported that pin penetration depth is influenced by wood density; moisture content; wood anatomical properties, *e.g.*, variability in growth ring direction; and the tested wood plane, *i.e.*, cross-sectional, radial, and tangential planes.

Linear regression analyses generated from the fit relationships between the pin penetration depth and the density or specific gravity for each plane are shown in Fig. 4. The average values of the coefficient of determination (R^2) for the density and specific gravity of the cross-sectional, radial, and tangential planes were 49%, 58%, and 64%, respectively. In addition, the average correlation coefficients (*r*) for the density and specific gravity of the cross-sectional, radial, and tangential planes were −0.700, −0.762, and −0.802, respectively, with significant model equations obtained. According to the statistical results, the generated model could be used to predict the properties of the tested wood. In general, an assessment using a pin penetration instrument should be conducted in different directions. A study on standing eucalyptus wood by Raymond and MacDonald (1998), as well as tests on jabon wood by Anna *et al.* (2018) using a pin penetration device in four cardinal directions (*i.e.*, north, south, west, and east), showed that the *r* value varied considerably from −0.20 to −0.91. Correlation analysis results from standing trees varied greatly given that the green moisture content conditions during testing could be extremely diverse.

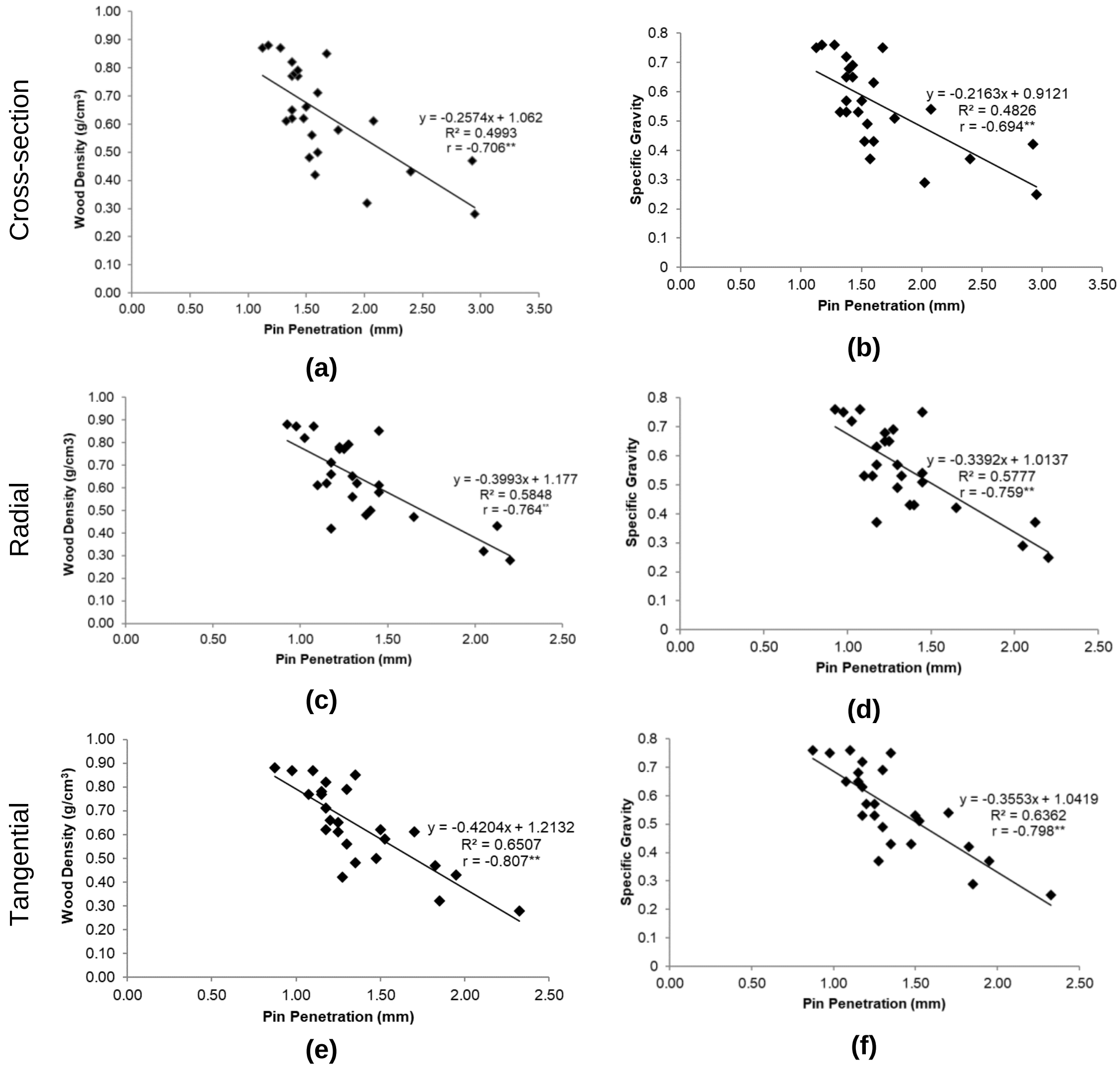
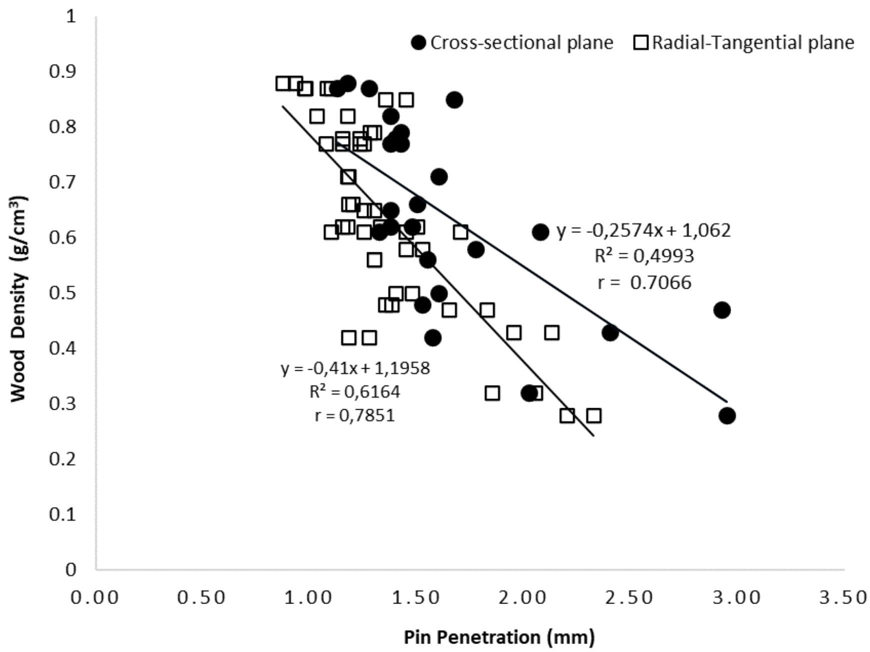
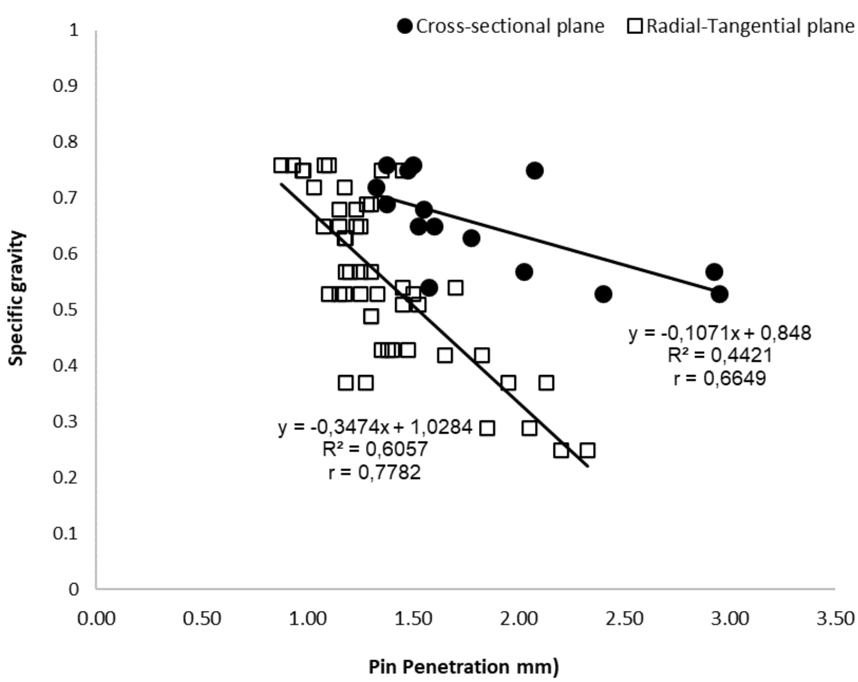


Fig. 4. The relationships between wood density (a, c, and e) or specific gravity (b, d, and f) and the pin penetration depth in three orthogonal planes on tested wood from 25 Indonesian wood species

Pin penetration evaluation with the Pilodyn device involves a pin of a specific size penetrating a tested material via a spring system applied with a constant force; the depth at which the pin penetrates shows the hardness of the material. Figure 5 shows the relationships between pin penetration depth and the density or specific gravity for all 25 Indonesian tested wood species; in both cases, a strong negative correlation was observed.



(a)



(b)

Fig. 5. Correlations between (a) the density and (b) the specific gravity of wood with pin penetration based on cross-sectional and radial–tangential planes

According to the model, the *r* of the tangential or radial plane plane was higher ($r > 0.75$) than the *r* of the cross-sectional ($r = 0.66$ to 0.70). The regression model analysis results were significant; therefore, it was concluded that pin penetration depth can be used to predict the density and specific properties of wood regardless of species in a range of property SCs. Rohanová (2020) studied spruce wood as a structural wood and reported that it had a correlation coefficient of −0.34 between depth of penetration and density of spruce wood. In a study of standing trees, Anna *et al.* (2020) found a weak negative relationship between pin penetration depth and the density ($r = -0.172$) and the specific gravity ($r = -0.282$) in jabon wood. Carrillo *et al.* (2017) also reported negative relationships between pin penetration values and basic wood density in *Eucalyptus globulus* ($r = -0.53$) and *Eucalyptus nitens* ($r = -0.68$). Stronger negative correlations between pin penetration depth and density and specific gravity were reported by Couto *et al.* (2013) for *Eucalyptus grandis* and *Eucalyptus urophylla* and Carrillo *et al.* (2017) for *E. globulus* and *E. nitens*. Stronger and weaker correlations between pin penetration depth and wood density or specific properties were presumably related to the number of tested samples and the uniformity of the sample conditions, especially in relation to moisture content. In the present study, no correlation was found between pin penetration and moisture content at 10% to 20% (Fig. 6). Llana *et al*. (2018b) explained that a 0.73% increment in pin penetration occurred with every 1% increase in moisture content detected in the 12 to 21% moisture content range.

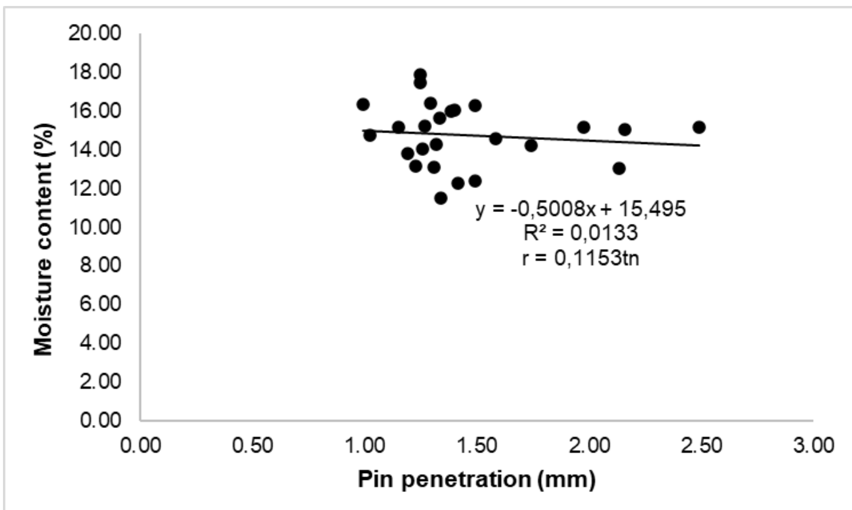


Fig. 6. Correlation between moisture content and pin penetration in the 25 tested wood species

In practical terms, the assessment and evaluation of materials using a pin penetration instrument is a suitable technique, especially when testing without complete information on the wood species. However, it should be noted that during the pin penetration evaluation, the sample conditions of uniformity, sample size, and testing points must be distinguished. Görlacher (1987) stated that the R^2 value can increase from 40% to 85% if the number of shooting points is increased to sixteen times.

CONCLUSIONS

1. Testing to determine approximate density and specific gravity values was conducted on tropical hardwoods with strength classes (SCs) ranging from II to IV, *i.e.*, equivalent to a distribution of specific gravity of 0.25 to 0.76 in samples with an air-dried moisture content of 12% to 17%.

2. Results of the pin penetration test results on cross-sectional planes were greater than and significantly different from the equivalent results of radial and tangential plane tests; however, the pin penetration depths of the radial and tangential planes were not significantly different.
3. Stronger correlations were found between pin penetration and wood density or specific gravity in the radial or tangential plane than were found in the cross-sectional planes.
4. Regardless of wood species, pin penetration depth can be used to predict wood density and specific gravity in a wide range of SCs, which could be useful for predicting these properties in the market.

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