Penetration Depth Evaluation Approach for Termite-infested *Shorea* spp. Lumber

Shofi Fauziyyah, Lina Karlinasari, and Dodi Nandika *

The pattern of termite infestation was investigated in structural lumber, light Red Meranti (*Shorea* spp.), using a minimally destructive technique. The relationship between the visual inspection and the pin penetration approach in predicting the basic properties of wood was determined, and a pin penetration distribution value was mapped into a contour map based on the Kriging interpolation technique. Small wood block samples were exposed to reared subterranean termites *Coptotermes curvignathus* Holmgren (Isoptera: Rhinotermitidae). The characteristics of termite infestation and the changes in the physical-mechanical properties were investigated. The residual surface area of the samples was evaluated using Pilodyn®. The characteristics of the termite galleries found on small wood block samples were as follows: 1) the termite galleries varied in length, or 2) the galleries consisted of long flat tunnels in a longitudinal direction, clean, not decayed, and contained no soil residue. The weight loss percentage from this study exhibited a similar trend with the pin penetration depth, which was directly proportional to the exposure period. The pin penetration result from Pilodyn® generated distribution map that was represented the conditions and basic mechanical properties of the samples. Pilodyn® can be used a complement for visual inspection in in-situ assessment.

Keywords: Coptotermes curvignathus; Meranti lumber; Nondestructive; Pin penetration; Termite gallery

Contact information: Department of Forest Products, Faculty of Forestry, IPB University, Fakultas Kehutanan Kampus IPB Dramaga, Bogor 16680 Indonesia;
** Corresponding author: nandikadodi@gmail.com*

INTRODUCTION

The high frequency of termite attacks on buildings in Indonesia is estimated to cause economic losses around Rp 8.68 trillion (605 million USD). The main species of termites found in these attacks are *Coptotermes* sp., *Macrotermes* sp., *Nasutitermes* sp., *Odontotermes* sp., and *Schedorhinotermes* sp. (Kuswanto *et al*. 2015; Nandika *et al*. 2015). Kuswanto *et al*. (2015) also reported that 70% of wooden building infestation is caused by *Coptotermes* sp. The intensity of subterranean termite attacks from the *Coptotermes curvignathus* species in Indonesia is tremendous. This termite species is capable of building secondary nests in high-rise buildings (Nandika and Tambunan 1990) and can forage up to the 33rd level of a high-rise building. Termite control services demand elasticity in Indonesia. The demand in Daerah Khusus Ibukota (DKI) Jakarta is especially elastic and affected by the termite control service price and building permits. Customers that utilize this service mainly come from middle to upper income communities; this service has not reached low income communities yet (Rahman 2019). However, the pattern of subterranean termite infestation in structural lumber has hardly been studied. Lee and Wood (1971) stated that the gallery system of subterranean termite infested wood was still little to be known. In contrast, there have been many studies conducted regarding the pattern of dry wood termites in lumber (Himmi *et al*. 2014, 2016a,b).

Meranti wood or *Shorea* spp. is the largest genus of the Dipterocarpaceae family and has a vast variation of species in Indonesia. *Shorea* and other Dipterocarpaceae wood types are economically important species due to their domination in international timber trade, especially in Southeast Asia (Purwaningsih and Kintamani 2018). According to current reports of the Indonesian Central Bureau of Statistics (BPS-Statistics Indonesia 2015), in 2015, 43.87 million m^3 of logs were produced, and approximately 4.43 million m^3 of this was Meranti lumber. Thus, besides emerging into an economically important species, this species also became the second largest quantity of logs extracted in Indonesia. Structural lumber quality assessment as well as evaluation might be performed using various methods such as the nondestructive testing method (NDT). By definition, NDT is a method of identifying the physical and mechanical properties of the material without causing significant damage or changing the final utilization purposes of the material (Ross and Pellerin 1994). Nondestructive testing methods, such as mechanical testing, can be performed to determine the quality and properties of wood (test of drill resistance, hardness, and intrusion behavior) (Niemz and Mannes 2012). One of the nondestructive methods that has been evaluated is the use of Pilodyn®, which has commonly been used on standing trees. Pilodyn® is a portable field instrument that can be used to predict the mechanical properties of wood. Pilodyn® works by measuring the depth of needle penetration. The readable value will indicate the density of the tested wood (Bucur 2003).

Several studies have been shown to utilize Pilodyn® in predicting the density of softwood lumbers (Llana *et al.* 2018), nondestructive assessment of historic timber truss (Branco *et al.* 2017), evaluation of wood poles, and until the most common utilization of Pilodyn® are for standing tree grading (Morrell *et al*. 1994). However, scientific studies regarding the utilization of Pilodyn® in termite-infested structural lumber have not been reported. Hence, the evaluation of termite infestation on structural lumber will be challenging. For the industry and expert it is paramount to know the pattern of subterranean termite infestation as a baseline information to achive sustainable pest management and its effective assessment This study aims to depict the activities of subterranean termites in their infestation pattern and to determine the reliability of the visual inspection method along with the minimally destructive testing method of pin penetration in explaining basic physical-mechanical properties, such as weight loss, density, and specific gravity, of *Shorea* spp. infested lumber. Based on the results of pin penetration from minimally destructive testing method, a density contour will be generated.

EXPERIMENTAL

Materials

Samples preparation

The samples used in the study were untreated light Red Meranti (*Shorea* spp.) lumber, which was acquired from a commercial sawmill (Inti Buana CV) venture in Bogor, West Java, Indonesia. The full-scale structural lumber specimen had dimensions of 6 cm (R) × 12 cm (T) × 300 cm (L) (Fig. 1) with an initial moisture content of 54.6% and was divided into smaller units as shown in Fig. 1.

In total, 80 small clear wood block samples were obtained from the lumber with the dimensions of 5 cm (R) × 5 cm (T) × 4 cm (L) cm. The small wood block samples were air-dried until reaching the moisture content of 8% to 10%.

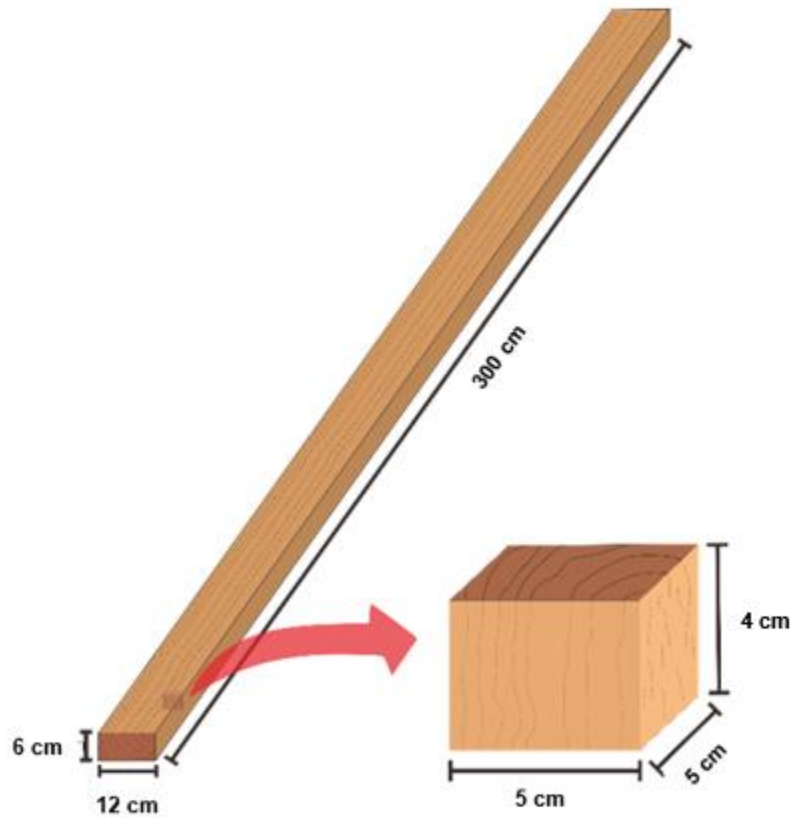
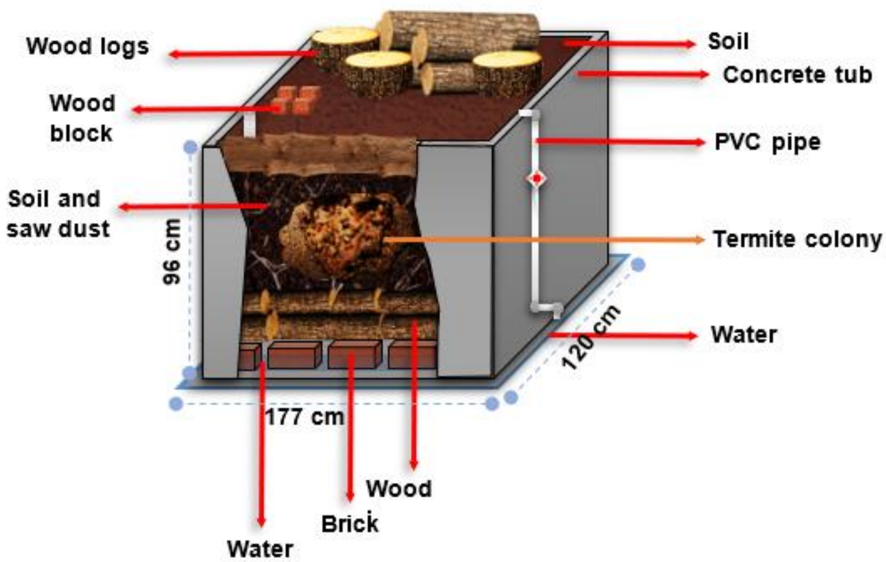


Fig. 1. Illustration of small wood block samples cut from *Shorea* spp**.** lumber

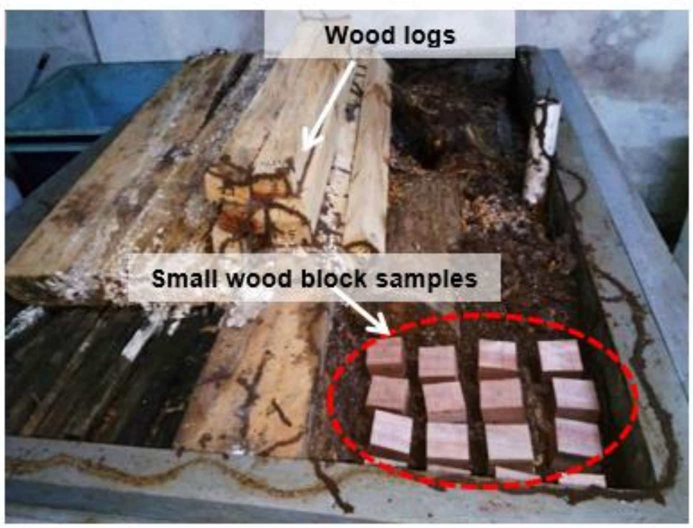
Exposure test

A total of 64 small wood block samples, taken from 80 small wood block samples, were placed inside a termite rearing unit with a reared subterranean termite from the species of *Coptotermes curvignathus* Holmgren. This was done inside the rearing unit in the Termite Laboratory, Faculty of Forestry, Bogor Agricultural University (Fig. 2) (Bogor, Indonesia). The termite colony were reared in the culture tub inside the laboratory (Fig. 2 a). The *C. curvignathus* termite colony was obtained from Yanlappa Experimental Forest, Bogor, Indonesia and has been successfully bred since 2012. The abundance and sustenance of the termite were maintained by routine feeding and culture tub ecosystem maintenance on a daily basis. Based on the research conducted by Arinana *et al.* (2016) and Philippines *et al.* (2008), the temperature inside the culture room or rearing stations fluctuated following the surrounding temperature, and ranged between 29.4 °C to 33.8 °C. This temperature range was 1.3 °C warmer than the temperature outside the culture room.

The small wood block samples were placed in each culture tub (Termite Rearing Unit of Department of Forest Products, IPB University, Bogor, Indonesia) and were arranged at random orientations without considering the tangential sections or radial sections. The culture tub, as illustrated in Fig. 2, had dimensions of 177 cm × 120 cm × 96 cm (length, width, and height), and was made from concrete with a small canal of water surrounding the tub to keep termites inside the designated area. The structure of each tub from top to bottom consisted of pine boards, sawdust, a mixture of soil and sawdust, tree trunk, and brick. Every month, air-dried pine boards (IPB University, Bogor, Indonesia) were fed to each culture tub to ensure the termites' survival.



(a)



(b)

Fig. 2. Culture tub (a) and top view of culture tub and small wood block samples placement (b)

Visual evaluation of exposed small wood block samples

An evaluation was conducted after the small wood block samples were exposed to termite infestation for 3, 6, and 9 weeks. The samples were scraped clean and oven-dried. Afterwards, the infested sample surface was scanned using a CanonScan 4400F scanner (Canon Inc., Beijing, China). The characteristics of the termite gallery and tunnels, such as the length and diameter of excavation tunnel, were quantitatively measured using ImageJ 1.46r software (Wayne Rasband, Maryland, USA) and qualitatively through observing and evaluating the characteristics, conditions, or traits of the infestation. The severity of the infested small wood block samples was measured visually in accordance with the ASTM D3345 (2017) standard, as presented in Table 1.

Table 1. Rating System for Laboratory Evaluation of Wood and Other Cellulosic Materials for Resistance to Termite According to ASTM D3345 (2017)

Score	Description
10	Sound, surface nibble permitted (uninfested)
9	Lightly attacked
7	Moderately attacked, penetration
4	Heavy
0	Failure

Physical properties measurement

Meanwhile, another 16 small wood block samples that were unexposed to the termite colony were used as a benchmark for evaluating the physical properties of wood, including the density, specific gravity, and initial pin penetration depth. This observation unit also acted as a control group for the exposed treatment. After visual evaluation was completed, the changes in density, specific gravity, and weight loss of 64 exposed small wood block samples were noted. The weight loss (*WL*; gram) of the small wood block samples was measured from the initial oven-dried weight (W_0; gram) and the oven-dried weight after each exposure time (W_1; gram), and was calculated using the following Eq. 1:

$$WL\ (\%) = [W_0 - W_1] / W_0 \times 100 \quad (1)$$

Pin penetration measurement

The intact ground surface of each small wood block sample as well as the unexposed samples acted as control treatment was divided into 16 grids for the pin penetration point as shown in Fig. 3.

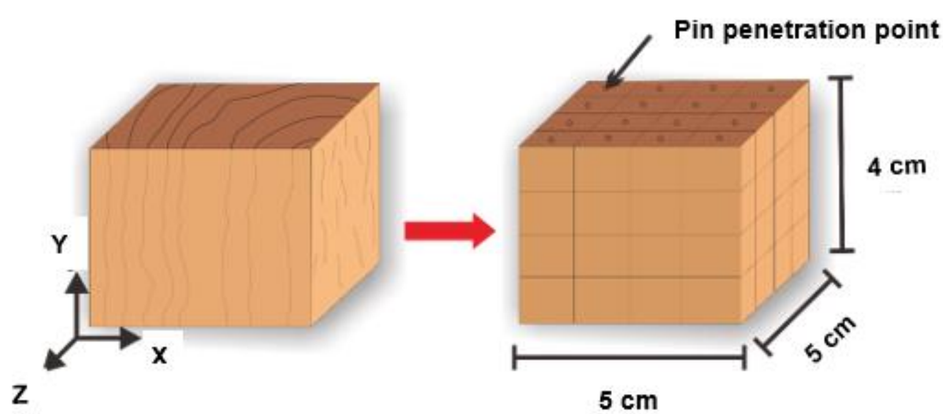


Fig. 3. Small wood block sample preparation for pin penetration test

The samples were subjected to pin penetration tests using the PILODYN® 6J-Forest tester (Proceq, Schwerzenbach, Switzerland) with a pin diameter of 2.5 mm and a measurement range of 0 nm to 40 nm. A custom holder was made from *Tectona grandis* wood, a high-density wood species, to keep the samples in place when they received impact from the testing force (Fig. 4). The pin penetration testing entailed driving a pin into the wood at a constant energy and then measuring its penetration depth. Here, measurements were taken along the bottom surface or the ground intact surface of each of the small wood block samples. The pin penetration results of the unexposed small wood block sample were used as the benchmark for the pin penetration value in sound condition.

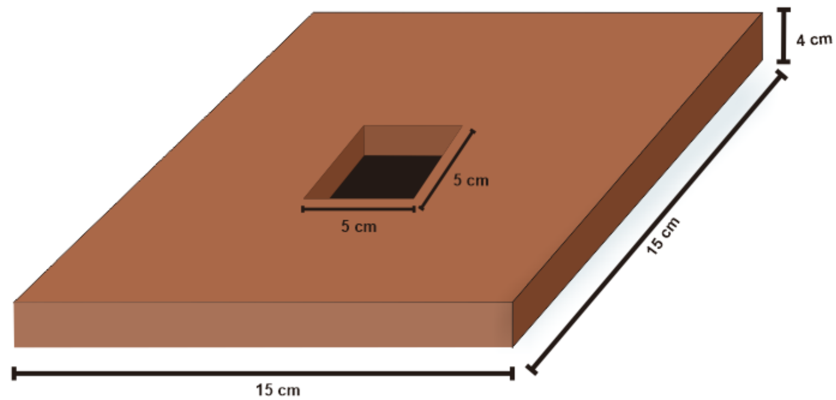


Fig. 4. Custom holder for small wood block sample testing

Pin penetration distribution

The distribution of the pin penetration depth of the exposed and unexposed small wood block samples were plotted using Surfer® 15.3.307 (Golden Software, Golden, CO, USA) (64-bit). There were 16 testing points on each sample (Fig. 5), and the indentation of the pin on the surface of the small wood block samples was interpolated to create a pin penetration contour map.

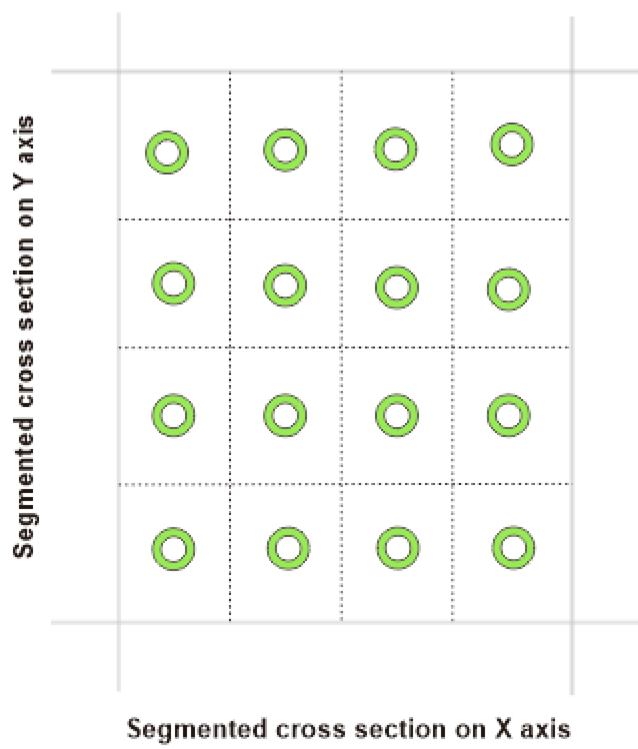


Fig. 5. Testing points distribution

Statistical analysis

Data analysis for the physical properties was conducted to determine the homogeneity of the obtained data. If the data on the physical properties were homogenous, then the data were analyzed by a one-way analysis of variance (ANOVA); if the data was varied, a *post hoc* data analysis would be performed using an analysis of covariance (ANCOVA) to observe the dependency between variables. Multiple comparisons for different exposure periods to pin penetration depth and weight loss were calculated using the Tukey pairwise comparison method using the Minitab 18.1 software (Minitab Ltd., Coventry, United Kingdom). The relationship of the visual inspection method and pin penetration method to the fundamental physical-mechanical properties of the samples was analyzed using simple linear regression. The significance level was set to 0.05.

RESULTS AND DISCUSSION

Visual Evaluation

Termites are cryptobiotic organisms; as such, they were difficult to predict, control, and detect, thus the need for visual observation (Kuswanto *et al*. 2015). The cryptobiotic nature of termites is indicated by its behavioral activity in subterranean nest building, inside trees, and within the walls of buildings (Evans 2002). The results of this study showed that termite attacks came from ground contacted surfaces. However, on some certain small wood block samples the tunnels were interconnected with each other and samples from the above ground surfaces, usually with small pin holes covered by soil. Most of the damage was in the form of tunnels on the ground intact surfaces.

The presence of termite tunnels usually indicated termite infestation (Fig. 6a). The first stage of termite infestation began with the presence of termite tunnels, and in the period of research activity it was found that termite tunnels were molded by hardened soil. According to Oshima (1919), the nest of *Coptotermes* sp. consists of abdominal excretion and a clay or sand mixture that is bonded together with secretion from the termite's salivary gland, which makes the structure rigid and compact. Furthermore, Houseman *et al*. (2001) added that the soil is moist in an active infestation as depicted in Fig. 6a.

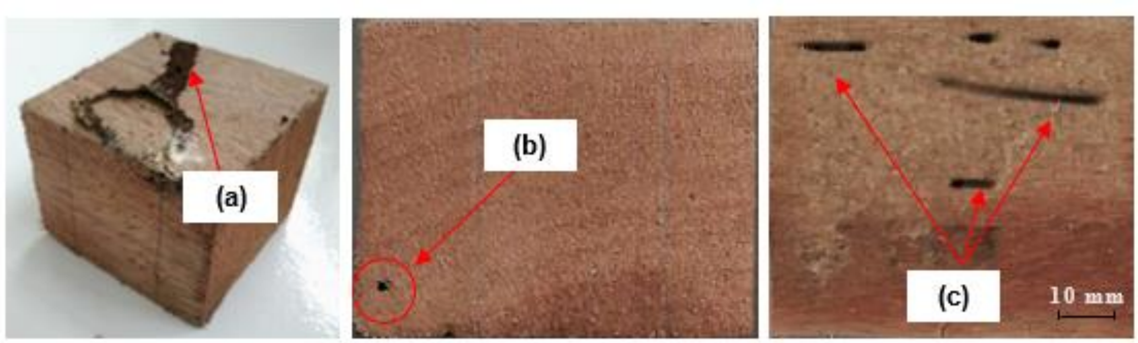


Fig. 6. Termite tunnel (a), entrance hole (b), and gallery pattern (c) on the infested small wood block samples

After generating foraging tunnels, *C. curvignathus* started to make an entrance on the ground-contacted surfaces of the small wood block samples. According to Nandika and Tambunan (1990), termites swarm by making tunnels to avoid light exposure and sustain the microclimate inside the nest. External factors that influence the development of termites are temperature, light exposure, rainfall, humidity, and wind. The termite gallery began with a small hole that was less than 1 mm in diameter. The shape of the entrance hole tended to be circular, as shown in Fig. 6b. The damage pattern from the infestation was displayed as holes and tunnels on the small wood block samples' surfaces. According to Nandika *et al*. (2015), termite feeding activity is generally characterized by several important things, such as termite food resources, such as cellulose, and there is a relationship between termites and the symbiont organism inside its digestive tract, such as protozoa in lower level termites and bacteria in higher level termites (Termitidae) as well as trophallaxis behavior. In the study of termite attack detection, Nanda *et al*. (2018) states that the acoustic signal between normal wood and termite infested wood is different. Furthermore, termites produce acoustic signals during eating, foraging, and head-banging activities related to the wood (Chapman 1998; Evans *et al*. 2007).

The termite galleries of the infested wood were clean and tended to follow the direction of the wood fiber, as shown in Fig. 6c. The exposed portion of the tunnel galleries was varied. Based on the observation, the longest exposed termite gallery was 19 mm, and the shortest gallery was 5 mm (Fig. 6c). Houseman and Gold (2003) conducted research on the tunneling rate of subterranean termites (*Reticulitermes flavipes*), and the same family as *C. curvignathus* reported tunneling rates that are strongly influenced by the environment such as soil texture, moisture availability, and tactile orienting stimuli. Furthermore, tactile stimuli were used by subterranean termite in terms of the orientation of the tunneling arenas. These tactile stimuli might have influenced the boundaries for tunnels based on natural environmental conditions such as roots, rocks, pipes, cables, and other structures. In addition, Green *et al.* (2005) found that soil moisture positively affects tunneling rates.

Termite gallery systems, as shown in Fig. 6c, mainly consisted of elongated chewed spots. The galleries were primarily constructed along the wood grain direction, presumably because of several factors, such as cell wall thickness, extractive content, and the anatomical structure of the small wood block samples, to aid the termite in the search of food sources. In general, termite galleries have an average diameter of 1 mm, similar to the diameter of the entrance hole. There was no indication that these termite colonies made their nest inside the infested samples. In contrast, Cabrera and Scheffrahn (2001) reported that drywood termite galleries of *Incisitermes minor* are irregular in construction, which is different from the characteristics of the subterranean termite gallery found in this study. Additionally, Himmi *et al*. (2016b) also reported that *I. minor* built its nests inside the infested wood. A previous study conducted by Costa-Leonardo *et al*. (2005) underlined that the trail of pheromones of termite species orients and recruits termites, creating an efficient search system that optimizes the tunnel length and routes to and inside food.

Weight Loss and Pin Penetration Evaluation

Results of this study suggested that the value of weight loss increased along with the exposure period (Fig. 7). Consequently, 9 weeks of exposure had the highest weight loss percentage (1.25%) followed by 6 weeks of weight loss (1.21%), and the least weight loss was associated with the exposure period of 3 weeks (0.91%). Previous studies implied that termites' feeding activity might be influenced by wood type, fungal decay, wood size, *etc.* (Cornelius *et al*. 2004; Evans *et al*. 2005; Osbrink *et al*. 2005). However, the results of further analysis using Tukey pairwise comparisons between the exposure periods and weight loss revealed that the weight loss obtained from each exposure period was relatively indifferent at the 5% significance level. Yii *et al*. (2016) stated that termite feeding preference is significantly affected by the sizes of bait, and that the consumption of rubber wood sawdust is 4 times higher than the block form.

Table 2. Statistical Results Weight Loss, Pin Penetration Depth, Density and Specific Gravity of Samples

Variable	Week	Mean	SE Mean
Weight loss (%)	3	0.91	0.537
	6	1.21	0.599
	9	1.25	0.640
Pin (cm)	3	1.22	0.021
	6	1.26	0.016
	9	1.28	0.015

The value of the pin penetration depth moved upwards along with increases in the exposure period (Table 2). The mean results of pin penetration depth obtained from this study for 3 weeks, 6 weeks, and 9 weeks were 1.22 cm, 1.26 cm, and 1.28 cm, respectively. The pin penetration test was performed to evaluate the severity of termite infestation based on its depth by measuring the residual wood sections, and to obtain the correlation between physical properties from the general test and weight loss. The depth of the pin penetration hinted at the wood's resistance to the penetration of the pin, and a shallower indentation led to higher resistance. Several factors that might influence pin penetration depth are the basic properties of wood, such as wood density, moisture content, and anatomical structures, as well as technical aspects, like striker-to-year-ring orientation (radial, tangential, or intermediate), reaction wood, wood defects, and wood species (Tannert *et al*. 2014).

The pin penetration distribution of small wood block samples displayed different indentations of Pilodyn® testing. The localized testing point obtained from Pilodyn® was able to be simulated into the pin distribution contour. The difference between the penetration depth on each grid of the sample resulted in a different trend of contour. The lighter color area represented a shallow indentation, and the darker color area denoted a deeper pin penetration.

The unexposed small wood block samples shown in Fig. 9a displayed a narrow color range, which indicated an expected similar surface depth. In contrast, the exposed small wood block samples exhibited a wider color range, and the extended exposure period presented a darker area and indicated higher pin indentation (Figs. 9b through 9d). A similar trend for quantitative results of pin penetration can also be found in Table 2. The distribution of pin penetration depicted the conditions and basic mechanical properties of the small wood block samples. Nevertheless, the Pilodyn® device allowed reading with an accuracy of 0.5 mm. Wood, as an anisotropic material, has high heterogeneity factors that contributed to a considerable amount of errors. However, the data might be improved by using a Bayesian updating procedure using at least one additional measurement parameter (Kelly and Smith 2009), such as deflection, modulus of elasticity, and other measurement parameters.

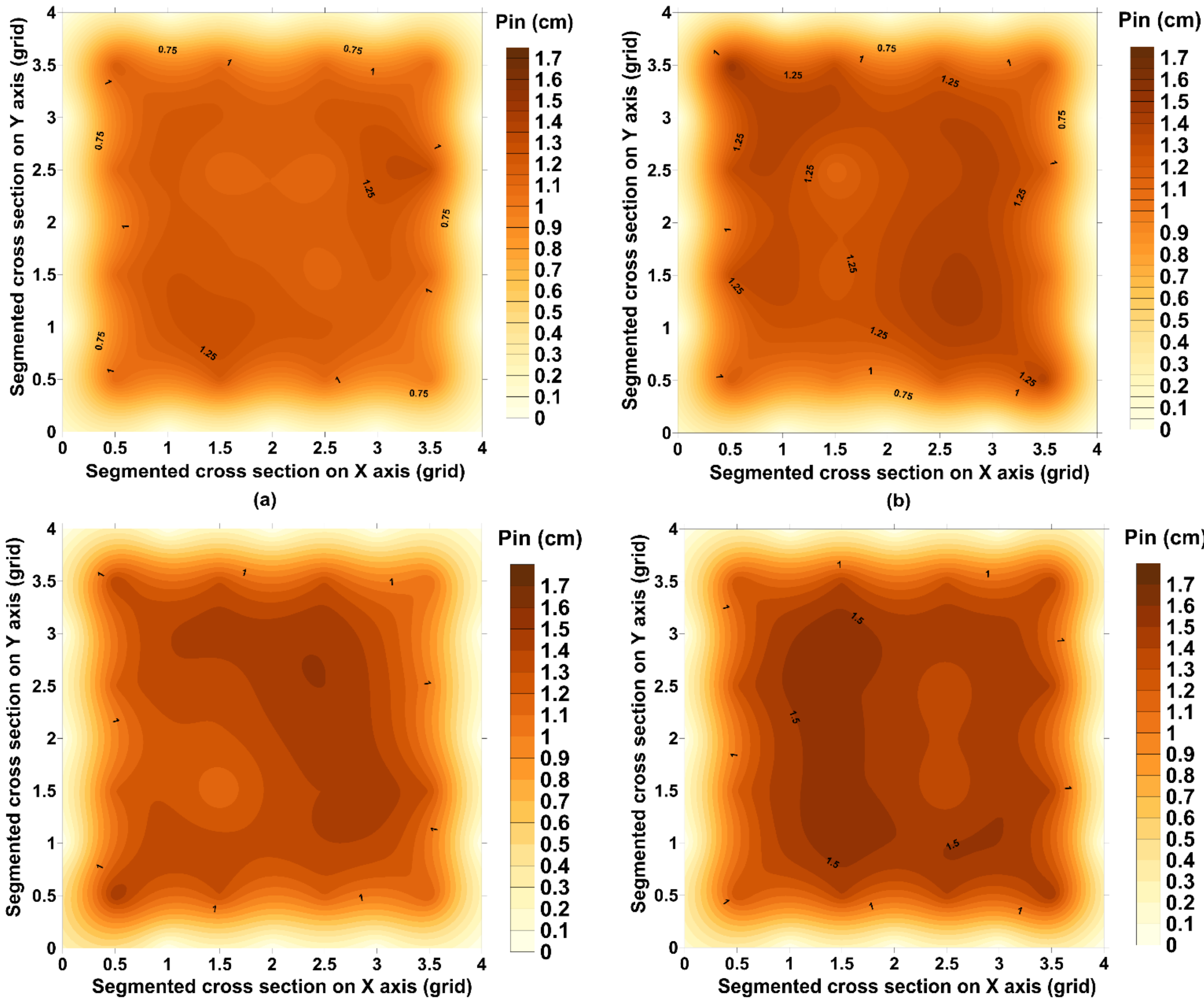


Fig. 9. Distribution of pin penetration depths of samples taken from: unexposed (a), 3 weeks exposed (b), 6 weeks exposed (c), and 9 weeks exposed (d), the small wood block sample group

The results from the pin penetration evaluation were used as an indicator to determine the condition of wood members near the ground intact surface related to the wood density (Melzerová *et al*. 2015). Therefore, evaluation of the condition of the structural wooden building and the appropriate treatment requires reliable knowledge of the physical and mechanical properties of the timber and the remaining bearing capacity of the elements. Meanwhile, the relationship between pin penetration depth and the observed parameters (density, specific gravity, and weight loss) was negative (Table 3). This trend meant that the higher pin penetration value leads to the decrease basic properties of the small wood block sample; however, this result was not significant at the 5% level, and thus general conclusion can't be made. In contrast, the visual inspection approach revealed a positive correlation for the relationship between density and visual inspection, and positive correlation with the specific gravity and the weight loss parameters. Nevertheless, the pin penetration tests managed to closely predict the compressive strength parallel to the grain to the results obtained from destructive tests on chestnut wood (*Castanea sativa* Mill.)

(Sousa *et al*. 2013). This study demonstrated the likelihood of qualitatively predicting weight loss using visual inspection. However, basic properties of wood, such as specific gravity and density, were likely to be assessed using the pin penetration approach; hence, the quantitative result was obtained. The pin penetration test managed to instantly obtain the density and specific gravity values; in contrast, visual observation did not provide such competencies.

Table 3. Comparison between Pearson's Correlation of Visual Inspection Approach and Pin Penetration Depth Approach in Predicting Basic Physical-mechanical Properties of Small Wood Block Samples

Response (Y)	Evaluation Approach (X)	
	Visual Inspection	Pin Penetration Depth
Density	0.072	-0.012
Specific gravity	-0.003	-0.072
Weight loss	-0.697	-0.181

According to Sousa *et al*. (2014), NDT (ultrasound resistance drilling and pin penetration test) was used as a complement for visual inspection to assess the depth of decay along the length of each element, thus allowing for more accurate definition of the residual cross-section and providing reliable data in assessing the condition of structural lumbers. Based on previous studies, Pilodyn® revealed reliable results on round wood, because the orientation of the measurement was in the radial direction. For structural timber with rectangular cross-sections, the arrangement of Pilodyn® measurements will vary from completely radial to completely tangential and include all intermediate directions. As the direction of the indentation measurement in reference to the growth ring orientation strongly influences the penetration resistance, this also affects the respective results obtained by those tests (Hansen 2000; Tannert *et al*. 2014). However, for standards, the number of samples used in this study was on the limited scale for laboratory study, and the data distribution obtained from this study was laid on a limited range as well. Therefore, to minimize the effect of errors, larger pools of samples are required to obtain common trends across one condition to another.

Albeit with the limited data range, this study demonstrated that the evaluation of termite infestation through visual inspection and the pin penetration approach provides possibility for NDT inspection to take place. The utilization of pin penetration should be further explored to define the precision and, considering the error factors, optimum conditions and adjustment factors for visual to quantitative inspection. Following this study several recommendations were proposed:

1) To reduce bias in the data obtained from pin penetration tests, clear wood segmentations are needed, such as distinct radial, tangential, and longitudinal sections, to eliminate the effects of wood anatomical properties.

2) Optimum mesh or grid concentration required in testing lumber is important to be considered, including sample geometry, to obtain efficient and distributive data and to adjust the specifications of NDT instruments.

3) To improve data distribution to fulfill certain distribution attributes, data updating should be completed using a statistical approach.

CONCLUSIONS

1. Termite infestation was initiated by the presence of foraging tunnels containing an entrance hole on the small wood block samples. The shape of the gallery was a long flat tunnel that tended to follow the wood grain direction; in addition, it had no termite mud. The weight loss percentage and pin penetration depth from this study had a similar tendency to the expanding of the exposure period.
2. The pin indentation results can be used to generate a visual representation in the form of contour maps to predict wood condition after various exposure period. This study showed the capability of the pin penetration approach as a complementary procedure for visual evaluation to show basic characteristics of wood.

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