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Investigation of Linearity between Mechanical Properties of Wood Using Graphical Method

(Analisis Hubungan Linear Beberapa Sifat Mekanik Kayu Menggunakan Kaedah Grafik)

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ABSTRACT

Some basic requirements are set for small clear specimen data to incorporate Malaysian timbers into equivalent European timber strength classes. In general, the correlation between structural and small clear specimen test results must be established for every timber group regardless of origin. This paper introduces a sort-plot technique for analysing the correlation of some mechanical properties of timber in selecting appropriate parametric model. Bending test was conducted on mixed species hardwoods for the determination of strength and stiffness values of both structural and small size specimens. The results showed that the sort-plot diagrams demonstrate an obvious linearity pattern between timber properties despite having poor regression values. The technique verified that properties of timber in structural and small size specimens correlated linearly.

Keywords: Coefficient of determination; relationship; strength test

ABSTRAK

Beberapa syarat asas ditentukan ke atas data daripada spesimen bersaiz kecil untuk tujuan pengelasan kayu kayan Malaysia di dalam kumpulan kekuatan kayu Eropah. Secara umum, perhubungan antara hasil ujian spesimen bersaiz struktur dan kecil perlu ditentukan untuk setiap kumpulan kayu tanpa mengira negara sumber. Kertas ini memperkenalkan kaedah atur-plot untuk menganalisis perhubungan beberapa sifat mekanikal kayu dalam menentukan model parametrik yang bersesuaian. Ujian lenturan telah dijalankan ke atas beberapa spesies kayu keras untuk menentukan nilai kekuatan dan elastik spesimen kayu bersaiz struktur dan kecil. Keputusan ujian secara gambarajah atur-plot menunjukkan corak linear yang jelas antara sifat kayu walaupun mempunyai nilai regresi yang lemah. Kaedah tersebut mengesahkan bahawa sifat spesimen kayu bersaiz struktur dan kecil berkait secara linear.

Kata kunci: Hubungkait; pekali penentuan; ujian kekuatan

INTRODUCTION

The concept of correlation between variables is essential to many areas of science and their applications. More specifically, correlation analysis helps to understand how a typical value of dependent variable changes when other variable is varied. In wood science, researchers investigate the interaction between heats applied with the removal of moisture content in wood-based materials (Saiful Bahari et al. 2012). Timber engineers are concern on the limit of elasticity which material remains its' force-deformation linearity (Zaidon et al. 2001). In other words, study on correlation of material properties provides many practical solutions in the world of quantitative research and science. However, in the case where no theoretical model exists, the first thing any scientist wants to worry about is the pattern of the correlation.

Regression analysis is the most applied statistical tool for the investigation of relationship between variables. However, when there are many observations or many variables involved, graphical procedures become tedious (Watson 1964). Furthermore, data distribution for regression analyses were usually showed uneven and scattered plots. Because of the unevenness, mistake occurs when a non-linear correlation is treated as linear and vice versa. These can most likely lead to illusions or false relationships. Thus any mathematical formula developed will be incorrect, especially those values extrapolated beyond the sample's data. Several methods of modern regression analysis were introduced to characterise the function of variables, which are ideal for modeling complex processes. However the disadvantage of most analyses is that they require fairly large, densely sampled data sets in order to produce good models (Cleveland & Devlin 1988).

In order to place sawn timber for structural applications in European market, regardless of origin, requires testing based on EN 408 which specifies laboratory method for the determination of some physical and mechanical properties of timber in structural size (Mansfield-Williams 2010; Ravenshorst & van de Kuilen 2010). Unfortunately, up till now, mechanical properties of Malaysian timbers were derived from standard mechanical tests of small clear specimens. The procedure was similar to BS 373:1957 for 2 inches specimen and ASTM D143-52 (Engku Abdul Rahman

1971; Lee et al. 1993). According to the European regulation, all sawn woods, including tropical, have to be tested based on structural size specimens for the determination of the strength class which will permits the European Conformity (CE) marking. Generally, the objective can be accomplished by manipulating the existing small clear data through correlation factors (Lanvin et al. 2009).

Groundwork testing was conducted on some selected commercial species of Malaysian timbers to witness a potential correlation between structural size and small clear specimens' properties. The objective was to develop quantitative models on the assumptions about how test results of structural size and small clear specimens correlate.

A study on bending test of six *Dryobalanops* species of Sarawak's timbers showed that modulus of rupture (MOR) of small clear and structural size specimens were correlated linearly with $r^2 = 0.56$ in green condition and slightly lower at $r^2 = 0.55$ in air-dried condition. The MOR relationships between small clear and structural size specimens of green and air-dried were $y[structural] = 0.66x + 49.2$ and $y[structural] = 0.60x + 78.7$, respectively (Alik & Badorul Hisham 2006). In a different study, regression plots between bending strength and global modulus of elasticity were investigated for both full size and small non-clear specimens of cumaru (*dypterix odarata*). The results showed that for both sizes good correlations of MOR versus global MOE were present. The ratio between the slope of the two regression lines was 0.0061/0.0092 = 0.6, considered as the size effect between small and full size specimens (Ravenshorst & van de Kuilen 2010).

The method presented in this article demonstrates a graphical tool that can give insight into the behaviour of material properties and help us choose the appropriate parametric model. A technique based on sorting and plotting data points is discussed to establish the regression pattern using mechanical tests results of timber.

Materials and Methods

Seventy five planks of mixed hardwood species were cut into structural and small clear specimens each. Mixed hardwoods of density ranging from 570 to 1100 kg/m³ were processed into two nominal sizes, 50 × 50 × 762 mm (2 × 2 × 30 inches) and 50 × 100 × 1930 mm (2 × 4 × 76 inches). The modulus of rupture (MOR) of small clear timber specimen in three-point bending test was calculated based on the following equation:

$$MOR_{SC} = \frac{3PL}{2bd^2},$$

where P = applied load (N), L = span (mm), b = width (mm) of the specimen and d = depth (mm) of the specimen.

Modulus of elasticity (MOE) of small clear timber specimen in three-point bending was calculated using the following equation:

$$MOE_{SC} = \frac{1}{4} \times \frac{P'L^3}{\Delta' bd^3},$$

where P = applied load at the limit of proportionality (N), L = span (mm), Δ' = deflection at the limit of proportionality (mm), b = width (mm) of the specimen and d = depth (mm) of the specimen.

The local modulus of elasticity of structural size specimen in four-point bending test was calculated from the following equation:

$$MOE_{f,local} = \frac{a l_1^2 \Delta F}{161 \, \Delta w},$$

where a = distance (mm) between a loading point and the nearest support, l_1 = gauge length (mm), I = second moment of area (mm⁴), ΔF = increment of load (N) and Δw = increment of deformation (mm) corresponding to ΔF. The deflection for local MOE was measured on one side of the specimen. Simultaneously, deflection for global MOE was measured at centre-bottom within the two supports. The global modulus of elasticity in four-point bending test was calculated from the following equation:

$$MOE_{f,global} = \frac{l^3 \Delta F}{bh^3 \, \Delta w}\left[\left(\frac{3a}{4l}\right) - \left(\frac{a}{l}\right)^3\right],$$

where a = distance (mm) between a loading point and the nearest support, l = bending span (mm), b = width (mm) of the specimen, h = depth (mm) of the specimen, ΔF = increment of load (N) and Δw = increment of deformation corresponding to ΔF (mm).

Modulus of rupture in four-point bending test was determined by loading the specimens to failure through similar testing arrangement. The modulus of rupture (MOR) in four-point bending was calculated from the following equation:

$$MOR_f = \frac{F_{max} a}{2W},$$

where F_{max} = maximum load (N), a = distance (mm) between an inner load point and the nearest support and W = section modulus (mm³).

A small portion was cut from every specimen for the determination of wood density. The density of specimen at test was calculated from the following equation:

$$\rho_{test} = \frac{m}{V},$$

where ρ_{test} = density (kg/m³) at test, m = mass (kg) at test and V = volume (mm³) at test.

Results and Discussion

In general, the results indicated that modulus or rupture of structural size specimen was lower compared to small clear. Three-point bending method of small clear specimen eliminates most of the influence of injurious defects, knots and cross grain and does not bring horizontal shear effect, as does structural size specimen method. Thus, bending strength values obtained from small clear specimens gave considerably higher results than structural size specimens (Newlin 1930).

The linear equation showed that modulus of rupture between structural and small clear specimens correlated through $y[small\ clear] = 0.51x + 27.3$. Indeed this is only true for prediction and estimation due to the non-homogeneity and anisotropic features of wood, where in reality it is often inaccurate. Nevertheless, the results showed that the differences were uneven and did not compare well to fit a straight relationship (Figure 1). The two measurements were linearly correlated with coefficient of determination $r^2 = 0.40$. Thus, by relying on regression value alone, the linearity of the relationship becomes uncertain.

A regression analysis by Alik and Badorul Hisham (2006) on bending strength of *Dryobalanops* species showed that structural and small clear specimens were linearly correlated with $r^2 = 0.56$ and $r^2 = 0.55$ in green and air-dried conditions, respectively. The reason for the slightly better relationship was probably due to the lesser density range of 630-820 kg/m^3. In general, their results agreed that modulus of rupture of small size specimens are higher than structural size planks with linear relationship of $y[structural] = 0.66x + 49.2$. Even so, based on poor r^2 values obtained from both past and present regression analyses, the linearity of the correlation is still doubtful.

To build the degree of confidence in the linearity of two variables, a graphical technique named 'sort-plot' is demonstrated (Figure 2). The graphical analysis was conducted using Microsoft Excel. One parameter, in this case the structural MOR values, is sorted to an ascending plot. Whilst a trend line is established for the other parameter which is the small clear MOR. Even though the round markers (small clear MOR) are scattered, virtually the dashed-straight line can be observed parallel to the triangle data points (structural MOR). The dashed line is a simple, real-time trend line built with a few clicks using Microsoft Excel. The trend line showed that the difference of the two variables was neither increasing nor decreasing, thus the relationship was more possible to be linear rather than exponential or logarithm. Despite having poor regression value, $r^2 = 0.40$, a linear correlation between structural and small clear specimens for MOR is clearly observed in this diagram.

Based on the abysmal correlation value, it can be understood that strength ratio of structural and small clear specimens was greatly influenced by the quality of the timber. The result of defects, such as knots and cross grain, on strength had been fairly well established and recognized in the basic timber testing rules. Fully as important as the actual presence of the defects are their size, quantity and location in the test piece. Obviously, defects will have their greatest effect when at points of maximum stress (Desch & Dinwoodie 1996; Madsen 1992). Alik and Badorul Hisham (2006) also concluded in their study that the presence of defects in structural size specimens could be the major factor affecting the correlation. It was suggested by Mansfield-Williams (2010) that the planks should be graded before the test to develop a functional correlation. The test results of the rejects should not be included in the calculation of characteristic values, but they should demonstrate that the grading rules successfully excluded the weak material.

Nevertheless, even when every precaution has been taken to avoid all factors known to influence the strength of timber, it will still be found that one piece of timber is

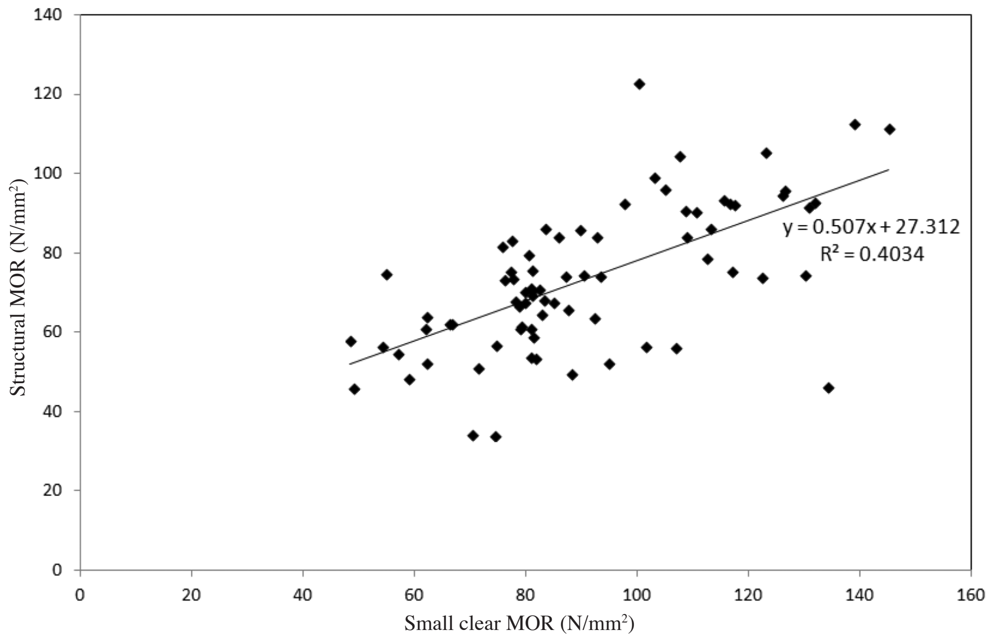

FIGURE 1. Regression analysis of MOR between structural size and small clear specimens

inexplicably 10 to 15% stronger than another (Thomas 1931). That's explain the scattered data points in Figure 2. Until today, the main scientific conclusion for the variation is due to the genetic variability of timber as a natural material (Desch & Dinwoodie 1996).

The local MOE values were generally higher than the global MOE. Figure 3 shows that they were correlated to $r^2 = 0.84$. Good correlation justified the consistency and reliability of the two measurements. The present result is similar to the previous study, which showed that local MOE was greater than the global (Bostrom 1999). Consistent result was also obtained by Aicher et al. (2002). Via the sort-plot technique demonstrated in Figure 4, a smoother data distribution is observed. The parallel pattern between the two variables is visible even without the dashed-trend line.

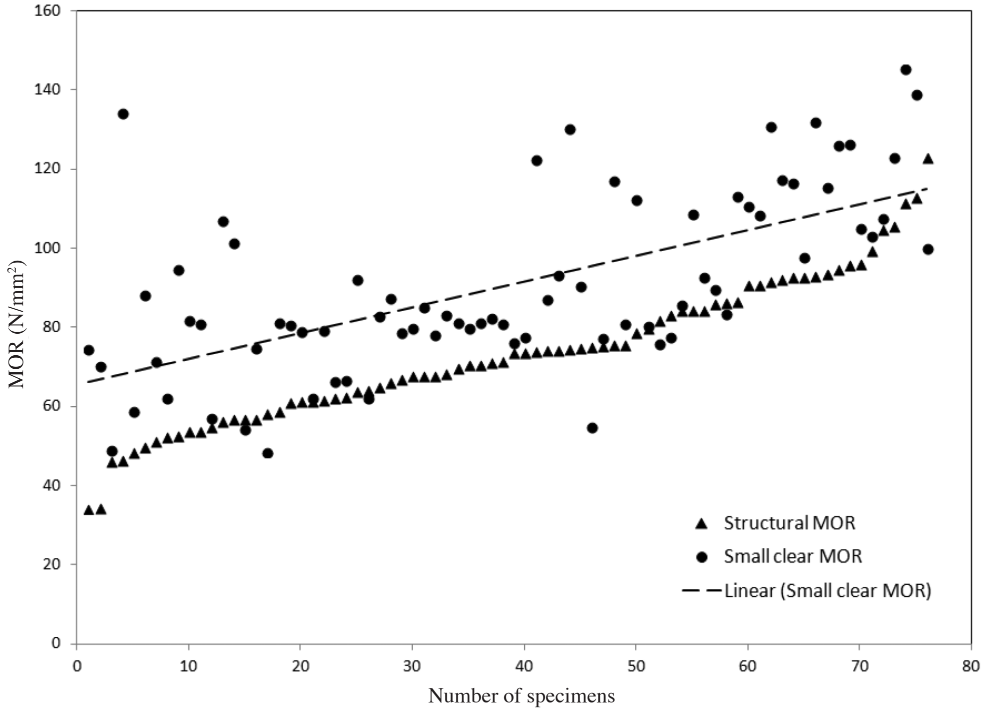

FIGURE 2. Sort-plot method of MOR between structural size and small clear specimens

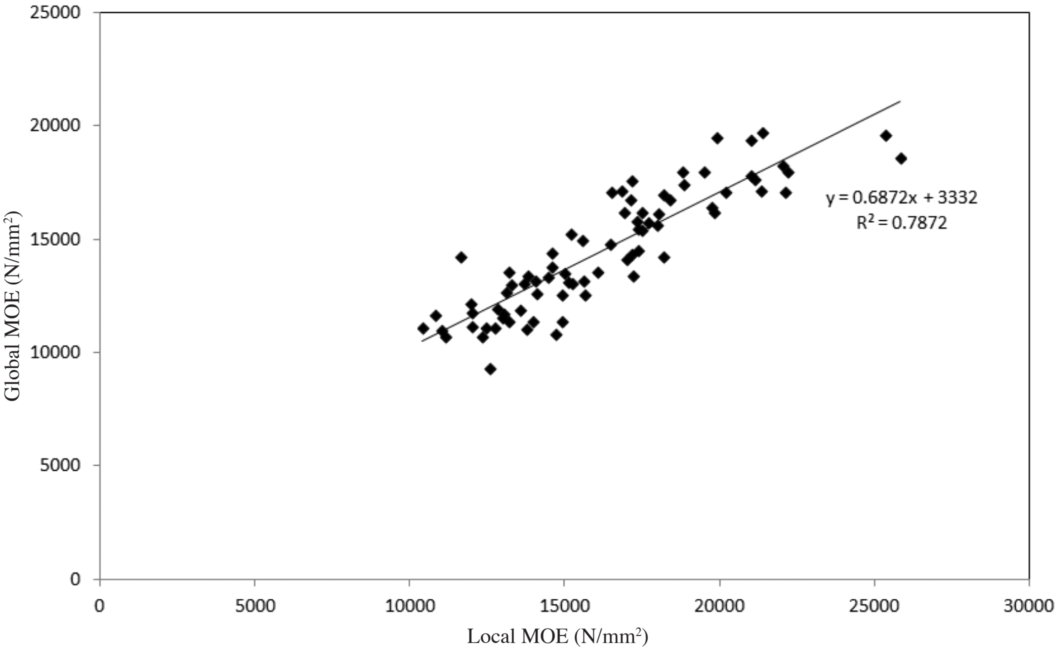

FIGURE 3. Regression analysis between local and global MOE

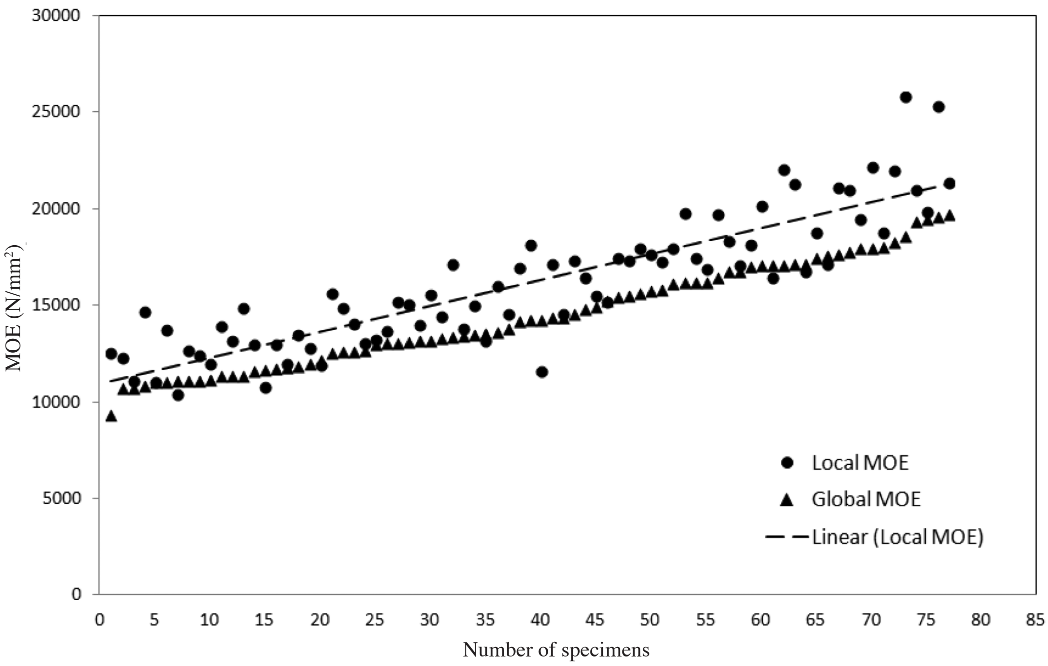

FIGURE 4. Sort-plot method between local and global MOE

However, the results showed a few specimens with great deviation of local MOE values especially at the higher points. The fact was that the deflection measurements for local MOE values were extremely small, often less than 1 mm. Therefore the method is very sensitive to measurement error. The accuracy requirement of deflection measurement for local MOE is somewhat difficult to achieve (Mansfield-Williams 2010). It was reported by Solli (1996) that the risk of inaccurate deflection measurement was much higher for local MOE compared to global MOE. This was caused by the ratio of the local and global deflections since the global deflection was normally about ten times the local.

The major source of error in edgewise bending will be linked to the initial twist of the timber piece. The effects of twisting will depend on how the deflection is measured, for examples from one or two side at the neutral axis, on the tension or the compression edge. Since the local deflection is just a tenth of the global, any effect from initial twist will be more vital. This circumstance was agreed by Bostrom (1999) as some extreme values were obtained from the local MOE measurements.

This inaccuracy was probably contributed by the single measurement from one side of the plank, thus twisting of the specimen during test led to erroneous deformation values. Even if the test pieces were preloaded with some stresses, the influence of initial twist did not disappear (Kallsner & Ormarsson 1999). With the consideration of some inaccurate local MOE measurement, the relationship between local and global MOE is shown to be linear.

Figure 5 shows that local MOE values were generally higher compared to the small clear MOE. The relationship was shown to be more consistent compared to MOR in terms of linear regression value. The two measurements were correlated with $r^2 = 0.64$. Sort-plot diagram (Figure 6) demonstrates a linear pattern of the two properties. The MOE data points for structural size and small clear specimens showed the same trend, which means that the local MOE can be predicted out of the small clear MOE. Apart from that, consistent trend between global and dynamic MOE was also observed for tropical hardwoods (Ravenshorst & van de Kuilen 2010). Again, some extreme deviations were observed from local MOE measurements due to inaccurate deflection measurements.

There were very few archives on the comparison between structural and small clear specimens of Malaysian timbers to support the MOE result obtained from this assessment. Ahmad et al. (2010) demonstrated that mean MOE from structural size tensile tests of Kedondong timber is higher than the small clear specimens. Lanvin et al. (2009) however took the mean MOE of the small clear specimen as the value for structural size MOE or in brief, $MOE_{structural} / MOE_{small\ clear} = 1$. Stiffness and density values are less dependent on defects so they were taken from small clear data without modification (Mansfield-Williams 2010). The results obtained from this study showed that density, moisture content and defects had minor effect on the MOE relationship of structural and small clear timber specimens.

The sort-plot technique was also able to demonstrate correlation of more than two variables simultaneously. Through scale adjustments of the values, correlations between wood density, MOR and MOE are shown in Figure 7. Even with mixed-up and scattered data points, the graphical technique clearly showed that modulus of elasticity and modulus of rupture are linearly correlated.

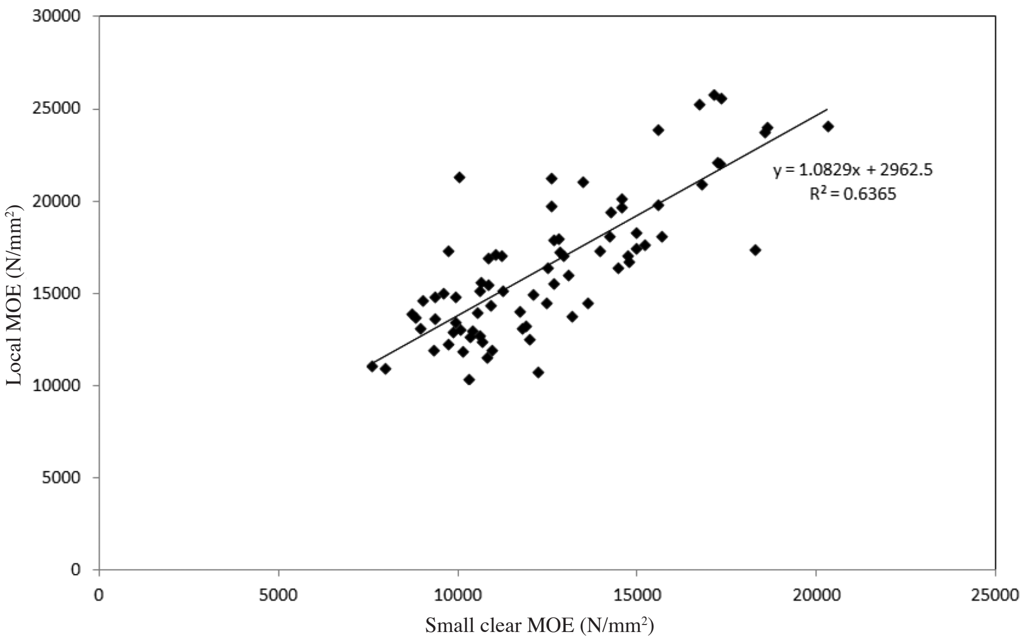

FIGURE 5. Regression analysis of MOE between local and small clear specimens

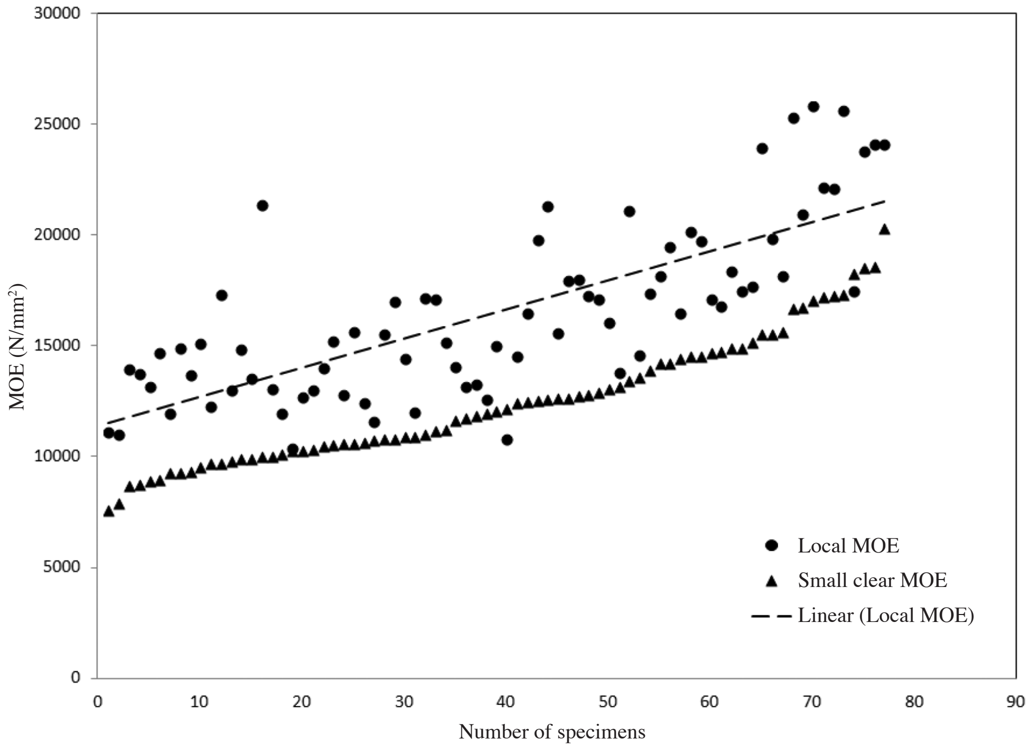

FIGURE 6. Sort-plot method of MOE between local and small clear specimens

Investigators must be cautious on interpreting the results obtained from regression analysis. Although the statistical computations used to produce the association may be correct, understanding about the data hypotheses itself is one important parameter in the study. The circumstance is shown in Figure 7 by the density correlation which shows different pattern compared to the two trend lines.

Careful interpretation has to be exercised in the results involving wood density since the density of a piece of wood is determined not only by the amount of wood substance, but also by the presence of both extractives and moisture (Desch & Dinwoodie 1996). In this study, the density for each specimen was measured during test, which includes specimens with high moisture content. Thus, the higher

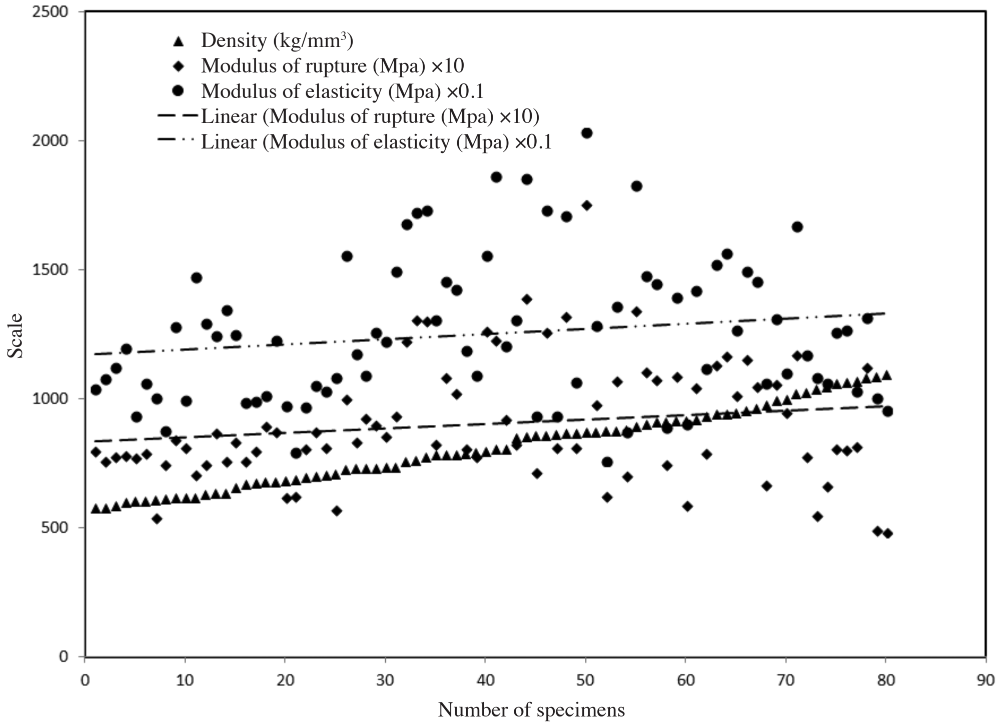

FIGURE 7. Sort-plot method between wood density, MOR and MOE

density values in Figure 7 could be contributed by the high moisture content which lowers the strength and stiffness of timber material (Engku Abdul Rahman 1971; Newlin 1930).

CONCLUSION

In general, the results indicated that the differences between some properties of timber are uneven and do not show a good regression values for linear function. These results are rational since variation in wood is well-established even within one specimen. The sort-plot diagram demonstrated a simple and practical technique to justify the correlation pattern between two or more properties. However, the graphical technique is better to be assisted with explanations concerning strayed data that contribute to the ambiguous pattern. In this study, the results showed that non-homogeneity and anisotropic features of wood materials influence the correlation between small and large size timber specimens results. Using the graphical tool demonstrated in this article called 'sort-plot' technique, the linearity pattern between mechanical properties of timber was clearly observed.

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