Influence of surface roughness of ten tropical woods species on their surface free energy, varnishes wettability and bonding quality

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Abstract

Purpose – The surface characteristics of wood such as surface roughness, surface free energy (SFE) and wettability are important properties influencing further manufacturing processes such as gluing and coating. The purpose of this study is to determine the influence of surface roughness of ten tropical woods on their SFE, wettability and bonding quality for water-based acrylic and solvent-based alkyd varnishes.

Design/methodology/approach – The woods tested in this study were fast-growing teak, afrika, sungkai, mindi, merbau, durian, lamtoro, pulai, acacia and kempas. Wood surfaces were prepared in unsanded and sanded using an abrasive paper of 120 grits. SFE values were calculated based on the Rabel method. Wettability values were measured based on the contact angle between varnish liquids and wood surfaces using the sessile drop method, and the S/G model was used to evaluate the wettability of the varnishes on the woods surface. The bonding quality of the varnishes was measured using a cross-cut test based on the ASTM 3359-02 standard.

Findings – The results show that unsanded kempas wood had the roughest surface with a Ra value of 16.24 μm, whereas sanded lamtoro wood has the smoothest surface with a Ra value of 6.86 μm. The unsanded afrika wood had the highest SFE value of 53.61 mJ/m^2, whereas sanded fast-growing teak had the lowest SFE value of 36.17 mJ/m^2. Sanded merbau woods had the lowest K value of 0.022 for the water-based acrylic varnish, whereas unsanded afrika wood had the highest K value of 9.253 for the alkyd varnish. Afrika wood with the highest K values (highest wettability) for both acrylic and alkyd varnishes produced the highest bonding quality (grade 4-5). Compared to the water-based acrylic varnish, the solvent-based alkyd varnish was more wettable and generated better bonding quality.

Research limitations/implications – Improving the quality of fast-growing wood from plantation by painting could be considered to increase their use for higher value wood products.

Practical implications – Compared to water-based acrylic varnish, solvent-based alkyd varnish was more wettable and generated better bonding quality.

Originality/value – The originality of this research is to evaluate the values of surface free energy. SFE could be used to quantitatively determined the wettability of paints liquid in the surface of wood

Keywords Surface roughness, Wettability, Acrylic and alkyd varnish, Bonding quality, Surface free energy, Tropical wood species

Paper type Research paper

1. Introduction

Demand for wood as a raw material in the level of log production continues to sustainably increase, especially in the production of all categories of processed timber such as sawnwood, plywood and laminated veneer lumber, chipwood, veneer and wood pulp. In many other ways, the use of wood as raw material still cannot be replaced because it is relatively cheap, strong, environmentally friendly and has an attractive appearance with the characteristic that could not be identified in other materials.

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Ten tropical wood species (fast-growing teak, afrika, sungkai, mindi, merbau, durian, lamtoro, pulai, acacia and kempas) could be extensively used for multiple purposes. These woods might be suitable for construction, furniture, paper, packing materials and panel wood. Merbau and kempas are high-density wood species with high strength (class I-II) (Martawijya *et al.*, 2005). Durian, sungkai, acacia, afrika, mindi and fast growing teak are medium density wood species with good strength (class II-III) (Martawijya *et al.*, 2005). Pulai and lamtoro are low-density wood species with low strength (class IV-V) (Martawijya *et al.*, 2005). Some wood species can be easily machined (Darmawan *et al.*, 2006; Darmawan *et al.*, 2015). There is abundant information about the physical or mechanical properties of these ten tropical woods; however, the information about the surface properties of these woods is still limited and has not investigated yet. The surface properties of wood are one of the most important properties influencing further manufacturing process such as finishing or their adhesive strength characteristics. To complete the information for better utilization of woods, the surface properties of ten woods species need to be studied.

The application of coating such as varnish on wood surfaces is commonly performed. The coating protects wood surface and gives a desired appearance. The coating aims to provide better aesthetic value to wood and serves to cover up some of the weaknesses of wood in terms of both colour and texture. The coating protects wood from external conditions such as weather, temperature, air, sunlight or wood-damaging organisms (Crump, 1993).

According to Moita and Moreira (2003), the increase in surface roughness leads to a decrease in contact angle. Wood with a high surface roughness value has a low contact angle value because the varnish liquid spreads and seeps more quickly into the wood. One of the criteria that can be used to analyze the wetting behaviour of wood is the measurement of its contact angle. Contact angle values larger than 90° indicate a poor wetting characteristics of the varnish liquid, in which it will be difficult for the varnish liquid to wet a surface (Yuan and Lee, 2013).

Wettability refers to how easily and efficiently a liquid spread over a solid surface (Baldan, 2012). The wettability can be characterized by certain parameters such as contact angles, surface free energy (SFE) and adherence (Wålinder, 2002). The amount of SFE and surface tension affect the value of wood wettability (Yuningsih *et al.*, 2019). Both wettability and SFE are important parameters to support information on interactions between wood surface and liquids (such as water, adhesives and wood finishes) (Qin *et al.*, 2014; Wålinder and Gardner, 2002; Gindl *et al.*, 2004; Rathke and Sinn, 2013). Wettability should be one of important indicator for evaluating the bonding between coatings and wood surface. Higher wettability provides better bonding quality of varnish (Darmawan *et al.*, 2018). Wettability can be determined by measuring the contact angle between liquid and surface. Many factors such as surface tension phenomena, viscosity of liquids, wood aging, drying processing and defects influence penetration (Qin *et al.*, 2014). The purpose of this study is to investigate and to evaluate surface characteristics in term of surface roughness and SFE for ten tropical woods species, as well as their wettability and bonding quality for water-based acrylic and solvent-based alkyd varnishes.

2. Experimental

2.1 Sample preparation

Wood samples were prepared from ten species of fast-growing teak (*Tectona grandis*), afrika (*Maesopsis eminii)*, sungkai (*Peronema canescens*), mindi (*Melia azedarach*), merbau (*Intsia bijuga*), durian (*Durio zibethinus*), lamtoro (*Leucaena leucocephala*), pulai (*Alstonia scholaris*), acacia (*Acacia mangium*) and kempas (*Koompassia malaccens*). Lumbers of the woods were surfaced in a planer. The planed lumbers were cut to produce samples for roughness measurement and wettability test. Wood specimens in dimension of 20 cm x 12 cm x 2 cm (longitudinal x tangential x radial) were prepared by cutting the lumbers. The wood specimens were placed in an air-conditioned room at 23 ± 2°C and relative humidity of 80% ± 5% for two weeks before the roughness and wettability test. The room was lighted and kept clean to retain the surface of wood samples in the same condition. The varnishes used for the wettability test were water-based acrylic and solvent-based alkyd. A mixture of alkyd varnish (90 %) and oil thinner (10 %) was prepared and uniformly stirred. Moreover, another mixture of acrylic varnish (90 %) and water (10 %) was prepared. The viscosity of the alkyd and acrylic mixtures measured by viscometer was in the average of 0.2 and 1.5, respectively.

2.2 Surface roughness test

A set of test specimen was kept unsanded as the control. The other specimen was sanded 50 times parallel to the length with abrasive papers of P120. The measurement of surface roughness of unsanded and sanded wood specimens was perpendicularly performed to the fibre direction at five different positions on tangential surface of each sample using Mitutoyo type SJ-210 tester. The roughness on the tangential surface was measured for decorative purposes. Compared to radial lumber, the tangential lumber provided better decorative appearance, particularly for furniture products coated with clear coats. The roughness measurement according to ISO 4287:1997 (International Standard, 1997) was performed with a diamond tip radius of 5 μm, tracing length of 6 mm, cut off of 0.8 mm and speed of 0.5 mm/s. The value evaluated was the arithmetical mean roughness (Ra).

2.3 Contact angle measurement

The dynamic contact angles of selected standard liquids (water, methanol, toluene and glycerin) for measuring SFE and those of acrylic varnish for measuring wettability were performed with a video measuring system using a high-resolution CCD camera. During measurement, wood specimen was placed on the top of a table in front of the CCD video camera. To obtain the same droplets, the drop of selected standard liquids and acrylic varnish with volume of 20 μl were dropped by a syringe using a screw method. The drop shapes on the wood surface were captured by the CCD camera and saved for 180 s. To obtain the contact angle, five droplets per sample were captured for each standard liquid and acrylic varnish. Each of the captured video images was then cut to an individual image at an interval of 10 *s* for a total duration of 180 s. Image-J 1.46 with drop-snakes plugin analysis was used to measure the contact angle (θ) of the individual image of the drop. The contact angles of each droplet on the surface of wood specimen were measured on both the left side and the right side of the droplet, and then the values were averaged. To obtain a curve of contact angle versus wetting time, a total of nineteen data points were then taken for each recorded drop. The contact angle tests were then conducted at a room temperature of 23 ± 2°C and relative humidity of 80% ± 5 %.

2.4 Determination of equilibrium contact angle and constant contact angle change rate

To determine the equilibrium contact angle (θe) value, a segmented regression model was used. It is assumed that developing contact angle during wetting process can be described by two functions in a curve (Figure 1). The first function is a steep slope (quadratic) of the curve over the first second beginning of spreading and penetration, whereas the second function is a constant slope (plateau) for the later part of the curve (constant contact angle). The fitted regression model for the functions takes the form of a quadratic model with a plateau. The transition point between the two functions (t_e) was directly obtained using nonlinear least-squares procedures (PROC NLIN) in SAS STAT (SAS Institute, 2004).

The contact angle change rate depends on the contact angle at a particular time. In this work, the contact angle change rate (K-value) on the S/G model (Shi and Gardner, 2001) was used to quantitatively evaluate the wettability. The equation of S/G model can be expressed as follows:

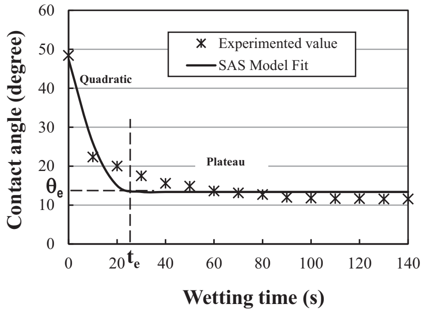
$$\theta = \frac{\theta \mathrm{i}.\theta \mathrm{e}}{\theta \mathrm{i} + (\theta \mathrm{e} - \theta \mathrm{i})\exp\left[K\left(\frac{\theta \mathrm{e}}{\theta \mathrm{e} - \theta \mathrm{i}}\right)t\right]} \tag{1}$$

where θ is the contact angle at a certain time, θi is the initial contact angle, θe is equilibrium contact angle, K is the constant contact angle change rate and t is wetting time. A non-linear regression model was then used to calculate the K value using the defined function to fit the S/G equation using XLSTAT Addinsoft (2007).

2.5 Determination of surface free energy components

Many methods have been used to calculate the SFE of wood. The two-liquid method is modified to be a multi-liquid method to determine the SFE value, and its components are proposed by Rabel (1971) using a regression line as in Equation (2):

Figure 1 Determination of equilibrium contact angle (θe) from a plot of the contact angle as a function of time using a segmented regression model



$$(1 + \cos\theta \mathrm{e})\frac{\gamma_l}{\left(\gamma_l^d\right)^{1/2}} = \left(\gamma_s^d\right)^{1/2} + \left(\gamma_s^p\right)^{1/2}\left(\frac{\gamma_l^p}{\gamma_l^d}\right)^{1/2} \tag{2}$$

where θe is equilibrium contact angle, y_l is the value of total surface tension, γ_l^d is dispersive surface tension, γ_s^d is dispersive component of SFE, γ_s^p is polar component of SFE and γ_l^p is polar surface tension. For determining wood SFE (γs), the size of the equilibrium contact angle (θe) of the standard liquid droplets (with known γl) on the surface of the woods samples is used. In a linear regression line (Y= A + BX), as $\mathrm{Y} = (1 + \cos\theta \mathrm{e})\frac{\gamma_l}{\left(\gamma_l^d\right)^{1/2}}$, X= $\left(\frac{\gamma_l^p}{\gamma_l^d}\right)^{1/2}$, the slope (B) will be $\left(\gamma_s^p\right)^{1/2}$ and the intercept (A) will be $\left(\gamma_s^d\right)^{1/2}$. The values of X and Y in this study were calculated by the four standard liquids, as shown in Table 1. Furthermore, the Y value was calculated by measuring the contact angles of the standard liquids in Table 1 on each surface of woods specimens. The value of SFE should be $\mathrm{A}^2 + \mathrm{B}^2 = (\left(\gamma_s^d\right)^{1/2})^2 + (\left(\gamma_s^p\right)^{1/2})^2$.

2.6 Coating application and bonding test

The unsanded and sanded wood samples were coated by the abovementioned varnish types for bonding quality evaluation. Two coats were then applied on the wood surfaces to achieve a total application of 150 g/m^2 wet film and a dry film thickness of 60 ± 5 μm. Based on the surface area of the samples, the required weight of each coat to achieve these spread rates was calculated. The varnishes were then applied by brush on the front face and the back of the samples. A drying time of 24 h was allowed before the second coat was applied. When the second coat had dried, the coated samples were conditioned for 1 week in a clean room at a temperature of approximately 25°C and a relative humidity of 75%.

To evaluate the resistance of the coating films to separation from wood surfaces, a cross-cut tape test method was applied (ASTM, 1997). A cross-cut pattern was made through the film using a sharp cutter head. Pressure-sensitive tape was then applied over the cut. The tape was smoothed into place using a pencil eraser over the incision area, and then the tape was removed by pulling it off rapidly back over itself close to an angle of 180°. Bonding quality was then assessed on a 0 to 5 scale; note that scale 5 is 0 % area removed, whereas scale 0 is greater than 65% area removed. The five cross-cut patterns per sample were

Table 1 The value of total surface tension, polar component of surface tension and dispersive component of surface tension for standard liquids (mJ/m^2)

Liquids	γl^p	γl^d	γl
Water	21.8	51.0	72.8
Methanol (50%)	12.9	22.7	35.6
Toluene	2.3	26.1	28.4
Glycerin	30.0	34.0	64.0

Notes: γl^p, polar component of surface tension; γl^d, dispersive component of surface tension; γl; the value of total surface tension developed for each varnish coating; two samples were used and ten measurements of cross-cut were obtained. The scales of the adhesion were then averaged.

3. Results and discussion

3.1 Surface roughness

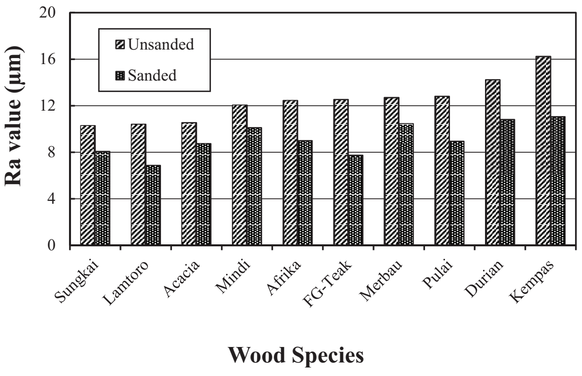
In terms of surface quality, surface roughness is an important property, particularly in finishing treatments (Buyuksari *et al.*, 2011). The result in Figure 2 shows that sanding with 120 grit paper contributed to a decrease in surface roughness values (Ra) for all wood species. The result indicates that kempas had the roughest surface for both sanded and unsanded with a Ra value of 11.06 and 16.24 μm, respectively. Lamtoro had the smoothest surface after sanding with a Ra value of 6.86 μm. Note that the surface roughness of wood can be affected by certain factors such as annual ring variation, density, cell structure, latewood/earlywood ratio and type of machining (Amorim *et al.*, 2013; Kilic *et al.*, 2005).

A higher surface roughness produces a higher surface hydrophilicity that tends to produce better wetting with a lower contact angle (Piao *et al.*, 2010). The void size in the wood may influence surface roughness. Wood with a larger lumen and diameters would usually result in open grain after machining, which leads to higher surface roughness (Syahirah *et al.*, 2019). In this work, surface roughness of the woods tested should be important for determining its SFE and wettability for both water-based acrylic and oil-based alkyd varnish.

3.2 Surface free energy

To calculate the SFE of the tested woods, the equilibrium contact angle (θe) as measured. The equilibrium contact angles were then calculated using a segmented regression model; the results are shown in Table 2. Unsanded frika wood had the lowest θe of 20.6° and 25.2° for water-based acrylic and solvent-based alkyd varnishes, whereas sanded lamtoro wood had the lowest θe value of 6.1° and 6.8° for water-based acrylic and solvent based alkyd varnishes, respectively. Otherwise, unsanded and sanded merbau woods were the highest in θe value of 39.8° and 41.8°, respectively for water-based acrylic varnish, and 14.2° and 15.9°, respectively, for solvent based alkyd varnish. The values of these θe demonstrated a correlation with a surface roughness of the woods, in which a rougher wood surface tended to produce a lower θe value.

Figure 2 The values of surface roughness for the ten tropical wood species



Note: FG-Teak = Fast growing teak

Table 2 The value of equilibrium contact angle for 10 tropical wood species

Wood	Water-based acrylic paint		Oil-based alkyd paint	
	θe (Unsanded)	θe (Sanded)	θe (Unsanded)	θe (Sanded)
Afrika	20.6	25.2	6.1	7.1
Acacia	29.0	29.2	8.9	9.8
Kempas	26.9	28.2	9.7	12.7
Lamtoro	29.4	29.7	6.3	6.8
Durian	28.3	30.0	7.3	7.5
Sungkai	29.6	31.7	11.3	12.1
Pulai	31.7	31.8	8.2	10.1
Mindi	30.1	34.3	8.9	10.3
FG-Teak	33.7	37.9	10.8	11.4
Merbau	39.8	41.8	14.2	15.9

Note: FG-Teak = Fast growing teak

The results in Table 2 show that θe values of acrylic and alkyd varnishes for all wood surfaces were prominently different. The water-based acrylic varnish generated higher values of θe. Its higher viscosity (1.5 poise) compared to solvent-based alkyd varnish (0.3 poise) could be the reason. The lower θe of solvent-based alkyd varnish indicated the ease in spreading the varnish liquid and lead to beneficial substrate wetting and penetration in wood. The lower θe of solvent-based alkyd indicates that it should create more intimate contact on wood surface than water-based acrylic.

Table 3 shows the SFE values of woods; the SFE decreased as the roughness of the woods decreased. It was reported by Gindl *et al.* (2001) that sanded surfaces of woods show lesser total SFEs. Unsanded and sanded fast-growing teak had the lowest SFE values of 38.60 and 36.17 mJ/m^2, respectively, whereas unsanded afrika and sanded kempas woods were the highest in SFE values of 53.61 and 45.46 mJ/m^2, respectively. The higher SFE value of the wood imposed the higher energy on the surfaces of the wood that can be used for breakdown the liquid to spread and penetrate on their surfaces. A rougher

Table 3 The value of total SFE and components for ten wood species (in mJ/m^2)

Wood	Unsanded			Sanded		
	$\gamma_s{}^d$	$\gamma_s{}^p$	$>\gamma_s$	$>\gamma_s{}^d$	$\gamma_s{}^p$	γ_s
FG-Teak	23.60	15.00	38.60	26.55	9.62	36.17
Merbau	40.29	6.96	47.26	43.35	3.57	46.92
Acacia	41.69	7.31	49.00	36.60	7.16	43.76
Sungkai	42.16	7.64	49.80	35.52	7.85	43.37
Pulai	40.78	9.65	50.43	30.61	12.12	42.72
Durian	35.63	14.91	50.54	32.03	14.12	46.15
Mindi	35.53	15.52	51.05	27.91	17.69	45.60
Lamtoro	34.25	16.87	51.12	22.24	19.11	41.35
Kempas	46.49	6.85	53.34	41.46	7.10	48.55
Afrika	44.48	9.13	53.61	36.02	9.44	45.46

Notes: $\gamma_s{}^p$, polar component of SFE; $\gamma_s{}^d$, dispersive component of SFE; γ_s, the value of total SFE wood surface tended to produce a higher SFE. This could attributed to the contact area on the rougher surfaces, which was higher than that on smoother surfaces.

3.3 Wettability

For quantifying the wettability of varnish liquid on the surface of wood, K value is important. K-value of 0 indicates very poor wettability. The K values of woods tested in this work are shown in Table 4. Both unsanded and sanded merbau woods demonstrated the lowest K values of 0.027 and 0.022, respectively, for water-based acrylic varnish. The unsanded pulai and sanded sungkai showed the lowest K value of 3.627 and 3.485, respectively, for the solvent-based alkyd varnish. Otherwise, unsanded and sanded afrika woods generated the highest K values of 0.055 and 0.051, respectively, for the acrylic varnish, and of 9.253 and 8.202, respectively, for the alkyd varnish.

Table 4 shows that the solvent-based alkyd showed larger K values compared to water-based acrylic because solvent-based alkyd was lower in viscosity (0.3 poise) compared to water-based acrylic varnish (1.5 poise). According to Gavrilovic-Grmusa *et al.* (2012), wettability value decreased with increase in the viscosity of an adhesive. A decrease in surface tension within the liquid could result in greater wettability. The solvent-based alkyd varnish had a lower surface tension of 66.32 mJ/m^2 compared to water-based acrylic varnish of (80.52 mJ/m^2. Moreover, it appears from the results in Table 4 that the unsanded wood samples had a larger K value than sanded woods for both acrylic and alkyd varnish. As noted in Darmawan *et al.* (2018), rougher surface of woods generated lower contact angle and ensures better wettability. Shi and Gardner (2001) reported that with greater K-values, the time required for the liquid to spread and penetrate on the wood surfaces is faster. By considering the fact that both acrylic and alkyd varnishes in this study were prepared and applied based on the manufacturer's instructions, it can be concluded that alkyd varnish produced better wettability compared to acrylic varnish for all ten wood surfaces.

3.4 Bonding quality

Bonding qualities of ten wood species are presented in Table 5. It is seen from Table 5 that, compared to sanded woods, bonding quality of unsanded woods was slightly better. Both afrika and sungkai provided the highest average of bonding quality compared to others because of their high K values. Pulai and lamtoro provided the lowest average of bonding quality because of their low K values.

Table 5 Bonding quality of water-based acrylic paint and oil-based alkyd paint for ten wood species

Wood	Water-based acrylic Paint Unsanded	Water-based acrylic Paint Sanded	Oil-based alkyd Paint Unsanded	Oil-based alkyd Paint Sanded
Afrika	5B	5B	5B	4B
Lamtoro	4B	3B	3B	3B
Durian	3B	3B	5B	4B
Acacia	4B	3B	4B	3B
Pulai	3B	3B	3B	3B
Mindi	3B	3B	5B	4B
FG-Teak	5B	4B	5B	4B
Sungkai	5B	4B	5B	5B
Kempas	3B	2B	5B	2B
Merbau	5B	3B	3B	3B

Note: FG-Teak = fast growing teak

Anatomical structure would be one of the major factors affecting the interaction between coating and wood material. Afrika wood had a porous structure that would result in better absorption and penetration of coating to its surface, and then cause a higher magnitude of interface that enhanced bonding quality characteristics. The results indicate that sanding decreased the bonding quality value. The increase in surface roughness will tend to increase the bonding quality. It was reported by Darmawan *et al.* (2018) that when the surface was smoother, the coating lacked mechanical interlocking with the substrate, thus weakening the adhesion. A rough surface was proposed to enhance intrinsic adhesion by providing greater interfacial area. The coating liquid flowed and filled the wood pores, holes, crevices and microvoids to achieve a strong bond between the wood surface and coating material.

The results in Table 5 demonstrate that, for most of ten wood species, alkyd varnish produced a higher bonding quality than acrylic varnish. The better wettability of alkyd varnish (higher K values) contributed to better bonding quality.

Table 4 K-values of water-based acrylic paint and oil-based alkyd paint for ten wood species

Wood	Water-based acrylic paint K-value (Unsanded)	Water-based acrylic paint K-value (Sanded)	Oil-based alkyd paint K-value (Unsanded)	Oil-based alkyd paint K-value (Sanded)
Merbau	0.027	0.022	5.600	4.249
Lamtoro	0.032	0.028	7.452	6.898
Pulai	0.033	0.029	4.506	3.627
Kempas	0.036	0.034	5.148	4.619
Mindi	0.037	0.034	7.447	6.310
Acacia	0.038	0.033	7.260	5.389
FG-Teak	0.038	0.032	5.730	5.038
Durian	0.041	0.035	6.637	6.531
Sungkai	0.052	0.038	5.557	3.485
Afrika	0.055	0.051	9.253	8.202

Note: FG-Teak = Fast growing teak

Sonmez *et al.* (2009) noted that solvent-based alkyd varnish completes its polymerization reaction on the wood surfaces, which allows for chemical bonding on wood surfaces. The lower bonding quality of water-based acrylic varnish is considered because the water used as a solvent causes the swelling of wood fibres and decreases penetration near the wood surfaces, which leads to a weakening of the interface of wood and coating material (Meijer *et al.*, 2000).

4. Conclusion

Based on the results in this work, the following general conclusions were drawn. Sanding with 120 grit number decreased the roughness of the wood surfaces. The equilibrium contact angles increased as the roughness of the planed surface of the woods decreased. The SFE values decreased as the equilibrium contact angles of the wood increased. The higher SFE values generated higher K-values. The higher K-value indicated higher wettability and bonding quality of varnishes. Afrika wood had the greatest SFE and K values among other wood species and produced the highest bonding quality. The solvent-based alkyd varnish was more wettable and generated better bonding quality compared to water-based acrylic varnish. In this work, the K-values of all woods tested were >0, which provides an indication that the varnish liquids (acrylic and alkyd) can spread and penetrate the surface of the woods tested. Improving the quality of especially fast-growing wood from plantation by painting could be considered to spread their use for higher value wood products.

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