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Bamboo Particles-Polyvinyl Chloride Composites: Analysis of Particles Size Distribution and Composites Performance

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Abstract

Analysis of particles size distribution of Malaysian bamboo species (*Bambusa vulgaris* and *Schizostachyum brachycladum*) for polyvinyl chloride (PVC) composites production was conducted using dynamic image analysis (DIA). A wide distribution of bamboo particles length was recorded, varying from almost 0 to 1500-µm for both species. Inadequate amount of actual particles length distribution from each sieve size (75-µm and 1-mm) was also recorded. DIA observed an increase of aspect ratio from small to large particles, and fine particles were recorded to be slightly elongated than the large ones. However, the effects of bamboo particles size on the finished PVC composites performance were uncertain, considerable of numerous other factors that influence the performance. Only impact and water uptake properties of composites have been obviously affected by different particles size. Greater modulus value is observed in composites with high particles loading, though low impact strength and water resistance were recorded. The incorporation of high concentration of selected processing lubricants in the composites formulation helped to improve the impact and water resistance of the composites. Malaysian bamboo particles-PVC composites performance between different species was equivalent, demonstrated that both species displayed identical behaviour for composites production.

Keywords: bamboo, particles size distribution, polymer composites

1. Introduction

Bamboo is a plant for multi uses, not only for traditional, but also for industrial applications. It is a member of subfamily *Bambusoideae* of family *Graminae* (grasses) (Tewari, 1993). Its maturation period is very short, about 3 to 5 years (Wahab, Samsi, Ariffin, & Mustafa, 1997). Bamboo is a renewable resource due to its fast growing and wide availability especially in South East Asia, and it is also relatively cheaper than other wood resources (Gupta & Kumar, 2008). Bamboo is globally classified into 70 genera with over 1500 species (Tewari, 1993). In South East Asia countries such as Malaysia, Wong (1995) documented bamboo into 59 species, where 25 species are introduced or only known in cultivation and 34 are indigenous and found wild. Its wide availability and good properties encouraged some wood-based industries to exploit bamboo for commercial markets: e.g. production of duroplastic composite boards, furniture, papers and textiles made out of bamboo (Gupta & Kumar, 2008). The commercialization of bamboo-based products in Asia has tremendously increased the harvesting, manufacturing and marketing activities of bamboo (Hua & Kobayashi, 2004), therefore, make it possible to utilize its particles for wood polymer composite (WPC) production. Carus and Eder (2014) predicted that the production and use of WPC in the construction and extrusion sectors in Europe will be increased from 190000 t in 2012 to 400000 t in 2020. Therefore, it appears to be an opportunity in exploiting bamboo materials for WPC industry.

For this reason, introducing bamboo particles as a potential filler in WPC manufacturing will be also depending upon its particles behaviour. In principle, particles is commonly used as an extender/filler to reduce the polymer use, but sometimes it can also be used to modify the composite properties; e.g. increase strength and stiffness, scuff resistance, reduce tackiness, enhance electrical properties, and reduce material cost (Lutz & Dunkelberger, 1992). In general, bamboo particles are classified as irregularly shaped particles which make the strength of the resultant composite will decrease with higher filler loading due to the inability of the filler to support stresses transferred from the polymer matrix (Kassim, 1999). In this context, bamboo particles filled-thermoplastic composite properties varied significantly with particles loading. Some correlations of the properties of this composite with filler loading have been previously reported. According to Kassim (1999), the increased of filler loading from 10 to 50%, tensile modulus and flexural modulus were observed to increase by about 95.6% and 22.9% respectively, whereas tensile strength and flexural strength were decreased by 33.8 and 47.6% respectively. Based on a study by Ke and Jyh (2010), the highest bending strength was found in the bamboo particles-high density polyethylene (PE) composites with 20% or 30% bamboo particles with the maximum values of 23.7 MPa. As the flexural modulus of neat polypropylene (PP) was 1008 MPa, the PP composites mixed with 10%, 30%, and 50% bamboo fibre increased by 87.8%, 215.3%, and 383.2% respectively due to the stiffness increases of the composites (Lee, Chun, Doh, Kang, Lee, & Paik, 2009). According to Samal, Mohanty, and Nayak (2009), tensile modulus of PP-bamboo/glass fibre hybrid composites increased steadily with the increase of filler content from 10% – 40%. The increase was attributed to the increased wt% of the fibre loading within the matrix, leading to an efficient stress transfer from matrix to fiber (Samal et al., 2009). In term of impact strength, neat PP showed the values of 2.62 kg cm/cm^2, though the addition of 10% – 50% bamboo fibre to the net PP, the values was ranged from 2.94 – 3.13 kg cm/cm^2 (Lee et al., 2009). However, Ke and Jyh (2010) reported that bamboo particles-high density PE composites with 30% to 60% bamboo particles showed slight decreases in bending strength, and a drastic decrease when it was more than 60%. According to Bouza, Lasagabaster, Abad, and Barral (2008), this was attributed by the aggregation of woody materials in the composition. Ge, Li, and Meng (2004) reported the reduction in strength behaviours was resulted from decreasing interfacial adhesion and homogeneity with increasing particles contents due to the presence of lignin and OH group in cellulose that influenced the agglomeration. With an increase of filler loading from 10% to 50%, the water absorption of composites increased by 750%, accountable to the increase in the filler surface area which was naturally hygroscopic (Kassim, 1999).

Apart from percentage of particles content in polymer composite, it is also understood that the effect of particles size on the properties of this type of composites was great (Kassim, 1999). Atuanya, Government, Okoye, and Onukwuli (2014) also confirmed the small effects of particles size on the strength performance of date palm wood-recycled low density PE composites. A reduction of the bamboo particles size used by Kassim (1999) from 0.25 to 0.12-mm showed that most of the properties such as modulus of elasticity increased by 17.8%, bending strength by 13.8%, tensile strength by 9.74%, and water absorption by 10.4%. The increases could be due to the small particles covered a larger surface area within composites than the same weight of large particles (Kassim, 1999). However, Atuanya et al. (2014) reported only a small increase of tensile strength when the date palm wood particles size was increased. Using date palm wood particles at 30% loading rate, the ultimate tensile strength of composites with 150-μm particles size was 9.48 MPa, 212-μm was 9.51 MPa, and 250-μm was 9.56 MPa. In a different occasion, particles size also influenced the mixing performance of thermoplastic composite (Atuanya et al., 2014). Dispersion uniformity in the matrix becomes poorer when using high aspect ratio particles (Bledzki and Gassan, cited in Kim, Shim, Kim, Lee, Min, Jang, Abas, and Kim, 2015). Satov (2008) added that the fine particles will cause higher melt viscosities which generally influence the processing performance. In a different report by Stark and Gardner (2008), increasing the wood particles size increased the equilibrium moisture content of the composites. Nevertheless, it was specified that the materials with larger aspect ratio are the best candidate for composite's reinforcement (Gardner, Han, & Wang, 2015). In accordance to Stark and Rowlands (2003), it was confirmed that increase in mechanical properties was found to correspond with increase in aspect ratio of particles. Filler with higher aspect ratio has improved the stiffness and stress transfer of composites (Kim et al., 2015). Although the aspect ratio of wood-based particles is only about 1 – 5, the properties of composite made out of these particles are sufficient for many uses (Clemons, 2008). However, the effect of particles size on the properties of WPC is not sufficiently clear due to many factors such as thermoplastic type, wood content, particles geometry, coupling agent type, processing methods, and any other technical considerations.

Despite the favourable features of bamboo particles for WPC products, the application of this type of particles was mostly limited to PP and PE oriented products as stated in the literature. Only few works have been done on polyvinyl chloride (PVC)-based composites. Kim, Peck, Hwang, Hong, Hong, Huh, and Lee (2008) and Wang, Sheng, Chen, Mao, and Qian (2010) focused on the surface modification of China bamboo particles for PVC composites using chemical treatments. Another study by Sheng, Qian, and Wang (2014) concerned the influence of potassium permanganate pre-treatment of China bamboo particles on the properties of PVC composites. Consequently, the use of PVC in thermoplastic composites production should be further increased due to its excellent chemical resilience, long term stability, good weatherability, and strength (Kim and Pal, 2010).

In this study, Malaysian bamboo particles were utilized as filler in PVC composites production, with the specific objectives were to analyse the particles size distribution, and to determine the effect of particles size, particles loading, and processing lubricants concentration level on the basic performance of PVC composites. This study is essential in order to increase the utilization of bamboo particles in PVC/WPC industry and to increase the understanding of its fundamental performance.

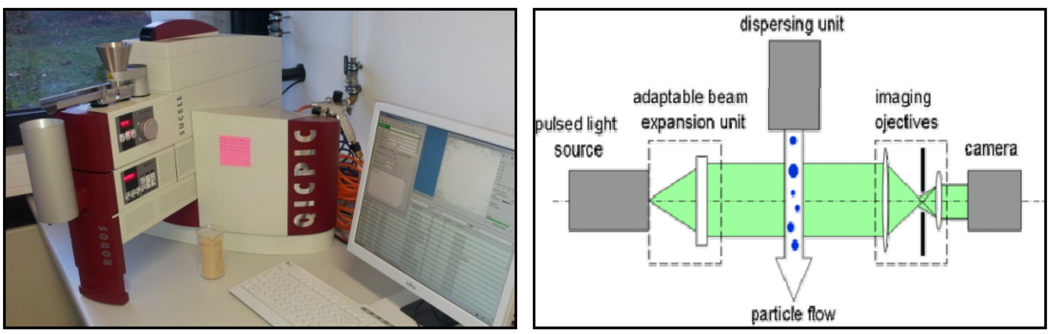
2. Experimental

2.1 Materials

Two Malaysian bamboo species, *Bambusa vulgaris* and *Schizostachyum brachycladum* were selected in this study. The matured bamboos were harvested from a natural bamboo stand in Raub, Malaysia. The bamboo culms were chipped into smaller pieces, at about 10 to 30-mm in length and 1 to 3-mm in thickness, before being air-dried for several weeks. The dried chips were milled using a hammer mill to produce two groups of small particles using two sieve sizes: 75-µm and 1-mm. These particles groups were selected in order to differentiate the effect of a very small and a very large particles size on the overall composite's performance. For composites production, PVC (Solvin, France) was used as a main matrix with other specific additives for PVC extrusion. The PVC's K-value was 63, powder size range was 100 to 150-µm, while T_g was ± 80ºC. The additives used were stabilizer Mark CZ2000 (Chemtura, Philadelphia, USA), processing aid Paraloid K120 (Dow Chemical Co., Michigan, USA), internal lubricant Loxiol G60 (Emery Oleochemicals, Cincinnati, USA), external lubricant Loxiol G21 (Emery Oleochemicals, Cincinnati, USA), external lubricant Ligalub GT (Peter Greven Fettchemie GmbH, Bad Münstereifel, Germany), and external lubricant Licocene PE4201 (Clariant, Muttenz, Switzerland).

2.2 Analysis of Particles Size Distribution

In order to obtain the information on bamboo particles size distribution, the analysis of particles shape and geometry was carried out using the dynamic image analysis (DIA) optical system with QICPIC (Sympatec) sensor machine (Figure 1). A small amount of dried particles from two different sieve size groups (75-µm and 1-mm) were collected and air-conditioned at 22°C and 65% humidity for one week. The range of measurement area in this system was between 5 to 5120-µm (M6). The dispersion of the particles through the scanning optic was performed by a dry dispersion unit in DIA system with 1 bar air pressure. The particles were separated from each other by the transportation of air pressure from this dispersion unit. Typically, more than 1 million particles are needed for each measurement to reach the maximum error value below 1 % (International Organization for Standardization ISO/DIS 14488, 2007). The particles were oriented randomly and captured with the highest possible contrast in order to detect the precise images. The bamboo particles geometry was analysed based on their size (length) distribution and shape (aspect ratio and elongation). The evaluation was also conducted with x_{10}, x_{50} and x_{90} values of statistical interval (means of the x_y value is that y percent of the particles are smaller (shorter) than x) (Grüneberg, 2010). Some specific terms were used in the software analysis, such as length of fibre (LEFI) and diameter of fibre (DIFI). According to DIA system, LEFI is defined as the length of the shortest path between the two most distant end points of the fibres/particles, while DIFI as the projection area of the fibre/particle divided by the length of all fibres/particles sections.



(a) (b)

Figure 1. DIA system: (a) a combination of dynamic image analysis sensor QICPIC, powerful dispersers (dry disperser RODOS/L) and dry feeder, with image analysis software, (b) schematic diagram of optical set-up in combination with dispersion unit for image analysis process (Sympatec)

2.3 Composites Production

The production process of bamboo particles-PVC composites was separated into the following steps. The particles from both size groups and both species were dried in a drying oven at 103°C for several days to reduce the moisture contents to 2% – 3%, before being blended together with PVC and other additives in powder form. The compositions of PVC, additives and bamboo particles in parts per hundred (pph) for dry blend process are shown in Table 1. The content and function of additives such as Mark CZ2000, Paraloid K120, Loxiol G60, Loxiol G21, Ligalub GT and Licocene PE4201 are also listed in the table. Two different blending compositions (based on different processing lubricants concentration levels) were used: 1.2 and 3.6 pph for Loxiol G60 (dicarboxylic acid ester/internal lubricant), and, 0.15 and 0.45 pph for Licocene PE4201 (polyethylene wax/external lubricant). Composition 1 (C_1) indicated the ingredients with low concentration of these lubricants, while composition 2 (C_2) indicated high concentration. The different compositions of lubricants were considered in order to determine the influence of the usage of these lubricants on the overall composites' performance. In point of fact, an independent study on fusion behaviour of bamboo particles-PVC dry blend was conducted, which reported the compounding torque and temperature of dry blending process with different concentration of additives. Excellent mixing stability (low compounding torque and homogeneous temperature) was observed when the concentrations of Loxiol G60 and Licocene PE4201 were increased three times, reason of an increased lubricants concentration.

The bamboo particles, PVC, and additives were mixed together to dry blend powder in a hot-cool mixer (Reimelt Henschel, FM L 30 KM 85) until the blending temperature of 120°C (for hot section) and 40°C (for cool section) were reached. Bamboo particles were mixed at different percentage ratio: 25% and 50% w/w. These ratios were considered due to the intention in determining the influence of a very low and a very high content of bamboo particles on the composites performance. In this study, the maximum percentage of bamboo particles was 50%, attributable to high viscosity of the PVC (Müller, 2012) and numerous additives used in the blending process (Jiang and Kamdem, cited in Müller, 2012).

All dry-blend powders were compounded by counter-rotating screw extrusion (Leistritz MICRO 27 40D) to produce granules. The average compounding temperature in the extruder zone was 180°C with a screw rotation of 90 rpm. The granules were finally consolidated into compression molded boards using a temperated hydraulic press. The temperature, pressure and duration of hot press was 190°C, 60 bar and 5 minutes, respectively. Pure PVC (without bamboo particles) using C_1 were also processed under the same conditions for comparison purposes.

Table 1. Compositions of PVC, additives, and bamboo particles for dry-blend process

Raw materials	Contents	Functions	Parts per hundred (pph)	
			C_1	C_2
PVC (K value = 63)		Matrix	100	100
Mark CZ2000	Calcium/zinc	Stabilizer	2.5	2.5
Paraloid K120	Acrylic acid	Processing aid	1.0	1.0
Loxiol G60	Dicarboxylic acid ester	Internal lubricant	1.2	3.6
Loxiol G21	Fatty acid	External lubricant	0.2	0.2
Ligalub GT	Glycerol ester	External lubricant	1.2	1.2
Licocene PE4201	Polyethylene wax	External lubricant	0.15	0.45
Bamboo particles		Filler	106.25	108.95

Note: C_1 = composition 1, C_2 = composition 2

2.4 Performance Test of Composites

Performance of all composites were measured in a 3-point static bending, tensile, impact and water resistance tests. Samples for all tests were cut and conditioned at 22°C and 65% relative humidity for about one week prior to testing. Bending and tensile tests were conducted using a universal testing machine model Zwick/Roell (Z010 Allround Line) equipped with Test Expert II software, fitted with 10 kN load cell according to *Deutsches Institut für Normung* DIN EN ISO 178 (2003) and *Deutsches Institut für Normung* DIN EN ISO 527-1 (1993), respectively. The dimension of bending samples was 80 x 10 x 4 mm (length × width × thickness, respectively). The load was applied at a speed of 1 mm/min until failure occurred. Thickness and width of tensile samples at necked-down section was 4 and 10 mm respectively, while samples' length was 190 mm. The samples were held in small grips while testing, at a crosshead speed of 1 mm/min until fracture. The consequent bending modulus, bending strength, tensile modulus and tensile strength were determined in these tests. Samples with the dimension similar to bending were also prepared for impact and water uptake tests. Impact test was conducted according to *Deutsches Institut für Normung* DIN EN ISO 179 – 1 (2006) in an un-notched state. The test was performed in a Charpy impact machine with 1 Joule (J) hammer and 60 mm support span. Samples for water resistance test were oven-dried at 103˚C to remove moisture prior to the immersion in distilled water at room temperature, according to International Organization for Standardization ISO 62 (2008). The samples were periodically taken out of water in between 1600 hours. The sample's surfaces were wiped before the measurement and weighed for water uptake determination using Equation 1:

$$\text{Weight changes} = (W_{submersed} - W_1/W_1) \times 100\ (\%) \quad \text{... Equation 1}$$

where:

W_1 is weight of dried sample (g), and

$W_{submersed}$ is change in weight (g).

3. Results and Discussion

3.1 Particles Size Distribution

Figure 2 shows the cumulative distribution of particles length from different sieve size (75-µm and 1-mm). Table 2 presents the particles length at x_{10}, x_{50} and x_{90} of statistical interval, while Table 3 displays the cumulative distribution and aspect ratio of particles. The elongation of particles is depicted in Figure 3.

A total number of 9.3 to 24.8 million particles were measured and analysed by DIA for each sieve size group (Table 2). Based on Figure 2, a wide distribution of particles length was recorded, varying from almost 0 to 1500-µm. As an example, analysis of 75-µm size group showed that 95% of *B. vulgaris* and 96% of *S. brachycladum* particles length were less than 250-µm, whereas for 1 mm, 80% and 70% of the respective *B. vulgaris* and *S. brachycladum* particles length were less than 250-µm (Figure 2). This implied that a wide range of particles size was recorded for each particles size group, suggested the insufficient amount of actual particles length distribution for each sieve size.

According to Table 2, the evaluation on x_{10}, x_{50} and x_{90} of statistical intervals confirmed the variation of particles length. X_{10} showed that both sieve size groups had a similar amount of fine particles (between 12.9 to 16.0-µm), whereas x_{50} recorded a wider distribution of particles (between 57.9 to 100.6-µm). Meanwhile, x_{90} showed the highest variation of particles length between different sieve size groups for both species, which ranged from 178.9 to 722.2-µm.

Based on Table 3, both bamboo species showed an increment of aspect ratio from small to large particles for both sieve size groups. A higher aspect ratio was recorded from the longest particles. For all groups, only 5.9% to 7.5% of particles had an aspect ratio of less than 1.7. About 99% of particles from *B. vulgaris*/75-µm group had an aspect ratio of less than 4.2. According to Gardner et al. (2015), the large-sized particles with high aspect ratio provided better mechanical properties than the small-sized particles. Transfer efficiency of load from matrix to wood fiber could be possibly increased with increasing fiber length/diameter ratio (Migneault, Koubaa, Erchiqui, Chaala, Englund, Krause, & Wolcott, 2008). Based on the small increase of aspect ratio in this study, reinforcement and properties of bamboo particles-PVC composite are possibly improved, although the reinforcing potential for this type of composite seems to be quite limited.

Based on the elongation analysis depicted in Figure 3, particles from 75-µm size group for both species were a little more elongated than 1-mm. However, its effect on the actual composite properties was not definitely ascertainable, as the amount of actual particles length in each sieve size group was inadequate. Many other factors influencing the composite properties (e.g. processing conditions and other raw material attributes such as particles loading and processing lubricants concentration) have to be considered. This phenomenon is explained through composite's performance results in the following discussion.

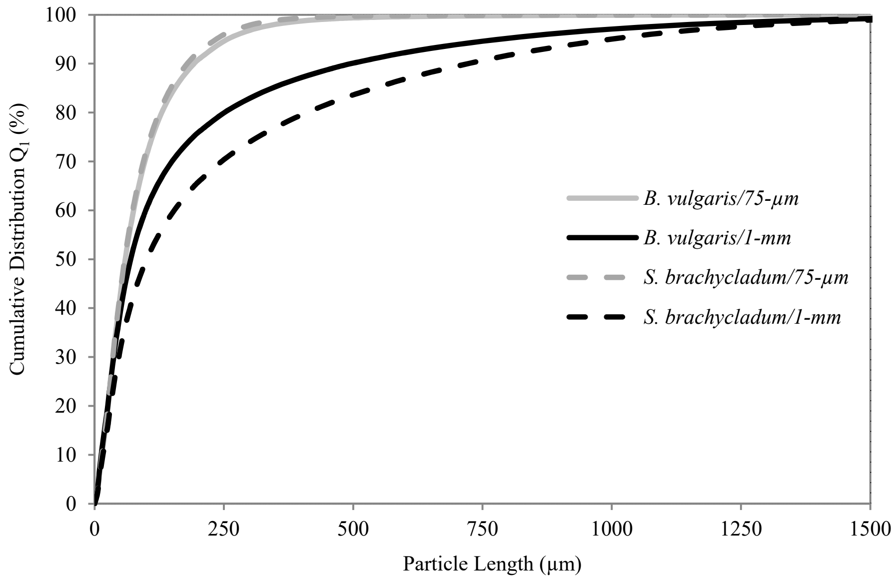


Figure 2. Particle length cumulative distribution of Malaysian bamboo species from different sieve size (75-µm and 1-mm) measured from DIA optical system

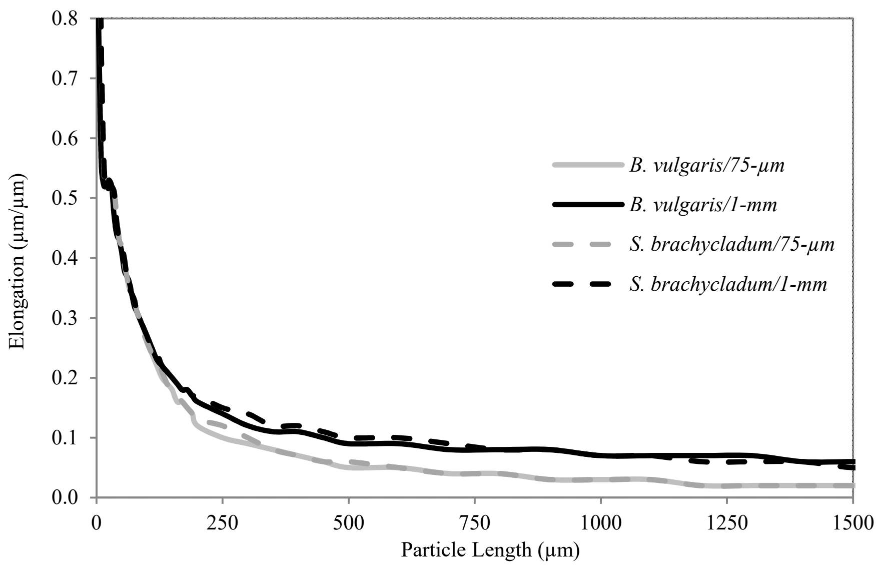


Figure 3. Particle elongation of Malaysian bamboo species from different sieve size (75-µm and 1-mm) measured from DIA optical system

Table 2. Evaluation on particle length of Malaysian bamboo species from different sieve size at x_{10}-, x_{50}- and x_{90}-value of statistical intervals

Species	Sieve size	No. of analysed particles (Million)	x_{10}-value (µm)	x_{50}-value (µm)	x_{90}-value (µm)
Bv	75-µm	24.1	14.1	59.2	192.5
	1-mm	13.3	12.9	69.8	495.8
Sb	75-µm	24.8	14.2	57.9	178.9
	1-mm	9.3	16.0	100.6	722.2

Note: Bv = *B. vulgaris*, Sb = *S. brachycladum*

Table 3. Cumulative distribution and aspect ratio of Malaysian bamboo particles

Species	Sieve size	Length (µm)	Cumulative distribution (%)	Aspect ratio
Bv	75-µm	10	6. 7	1.7
		100	71.1	2.1
		500	99.4	4.2
	1-mm	10	7.5	1.7
		100	60.3	2.1
		500	90.1	4.0
Sb	75-µm	10	6.6	1.7
		100	72.2	2.1
		500	99.7	3.3
	1-mm	10	5.9	1.7
		100	49.9	2.2
		500	83.6	3.4

Note: Bv = *B. Vulgaris*, Sb = *S. brachycladum*

3.2 Composites Performance

3.2.1 Bending and Tensile Properties

Based on the observation, *B. vulgaris* and *S. brachycladum* were comparable in term of composites performance; established an understanding that both species behaved identically. Shown in Figures 4 and 5 are the bending properties of the composites with different particles size, particles loading, and processing lubricants concentration for *B. vulgaris* and *S. brachycladum*, respectively, whereas the tensile properties are shown in Figures 6 and 7 for the respective bamboo species. Impact property of the composites for both species is depicted in Figure 8. Water uptake property of the composites is displayed in Figures 9 and 10 for *B. vulgaris* and *S. brachycladum*, respectively.

According to Figures 4 (a) and 5 (a), Malaysian bamboo particles size had a very small effect on bending modulus properties of PVC composites, in which, a slight increase of bending modulus was recorded for composites with 1-mm particles size in comparison to 75-µm. The improvement of bending modulus of composites with large particles can be related to the increased aspect ratio of the longest particles as listed in Table 3 that influenced the better bending modulus. Particles or fibres with a higher aspect ratio may improve the stress transfer between matrix and particles/fibres and finally tend to strengthen the bending modulus properties of the composites (Gozdecki, Zajchowski, Kociszewski, Wilczyñski, & Mirowski, 2011). However, this trend is observed only for composites from C_1 formulation. Based on Figure 6 (a), in contrast, the *B. vulgaris* particles-PVC composites from C_1 showed slightly lower tensile modulus value when using 1-mm particles size. On the other hand, it was observed that the influence of particles size on bending modulus and tensile modulus of composites from C_2 formulation was uncertain (Figure 4 (a), 5 (a), 6 (a), and 7 (a)). In this condition, the variation of bending modulus and tensile modulus of composites from C_2 formulation does not depend on the different of particles sizes.

Furthermore, the incorporation of Malaysian bamboo particles has greatly improved the bending modulus and tensile modulus of PVC composites. According to Figures 4 (a), 5 (a), 6 (a), and 7 (a), composites with 50% bamboo particles loading had bending modulus of up to 34% higher and tensile modulus of up to 32% higher compared to composites with 25% bamboo particles loading. In relation to the pure PVC composites in Table 4, it was recorded that the bending modulus and tensile modulus of Malaysian bamboo particles-PVC composites were up to 81% higher and 59% higher for the respective bending modulus and tensile modulus as compared to pure PVC composites. The high bending modulus and tensile modulus of Malaysian bamboo particles-PVC composites in this study were influenced by the high ratio of particles that increased the stiffness of the composites. Based on the records, *S. brachycladum* particles-PVC composites with 1-mm particles size/50% particles loading/C_1 showed the highest bending modulus (5203 N/mm^2), meanwhile *B. vulgaris* particles-PVC composites with 75-µm particles size/50% particles loading/C_2 showed the highest tensile modulus (5380 N/mm^2) among others.

However, based on Table 4, Figures 4 (b), 5 (b), 6 (b), and 7 (b), the bending strength and tensile strength of composites with presence of bamboo particles and high particles loading were generally lower. The high ratio of bamboo particles in the composites did not help in supporting maximum bending rupture and maximum tensile rupture. Kassim, Rahman, and Ramlan (2007) in their study reported that reduced modulus of rupture of natural particles-filled thermoplastic composites was a consequence of decreased deformability of rigid interphase between particles and matrix. It is previously reported that micro voids were typically formed in thermoplastic composites based on natural filler, due to interfacial failure between natural fillers and matrix, which finally influenced the low tensile strength in general (Chen, Mao, Xue, Deng, & Lin, 2013). According to the current study, the maximum value of bending strength was recorded by *B. vulgaris* particles-PVC composites with 1-mm particles size/25% particles loading/C_1 (60 N/mm^2), whereas, *S. brachycladum* particles-PVC composites with 75-µm particles size/25% particles loading/C_1 showed the highest tensile strength value (31 N/mm^2).

Based on Figures 4 and 5, there were no significant effects of processing lubricants concentration level on bending and tensile properties of composites in this study. In this case, modifying the processing lubricants concentration has no impact on the bending and tensile properties of the Malaysian bamboo particles-PVC composites.

Overall results showed that the bending and tensile properties of Malaysian bamboo particles-PVC composites were superior when compared to the other study on bamboo-based thermoplastic composites. Chen, Guo, and Mi (1998) reported the values of tensile strength of bamboo fibre-PP composites (at 20% – 60% bamboo loading) were less than 20 MPa, tensile modulus values were less than 4000 MPa, whereas Mohanty and Nayak (2010) revealed the value of bending modulus and bending strength of untreated bamboo-high density PE composites (at 40% bamboo loading) were 2987.70 MPa and 25.35 MPa, respectively.

Table 4. Properties of pure PVC (without bamboo particles) composites using C_1

Properties	Mean values
Bending modulus (N/mm^2)	2866 (44.2)
Bending strength (N/mm^2)	73 (2.7)
Tensile modulus (N/mm^2)	3295 (546.1)
Tensile strength (N/mm^2)	52 (7.5)
Impact (kJ/m^2)	23 (0.9)

Note: Standard deviations in parentheses

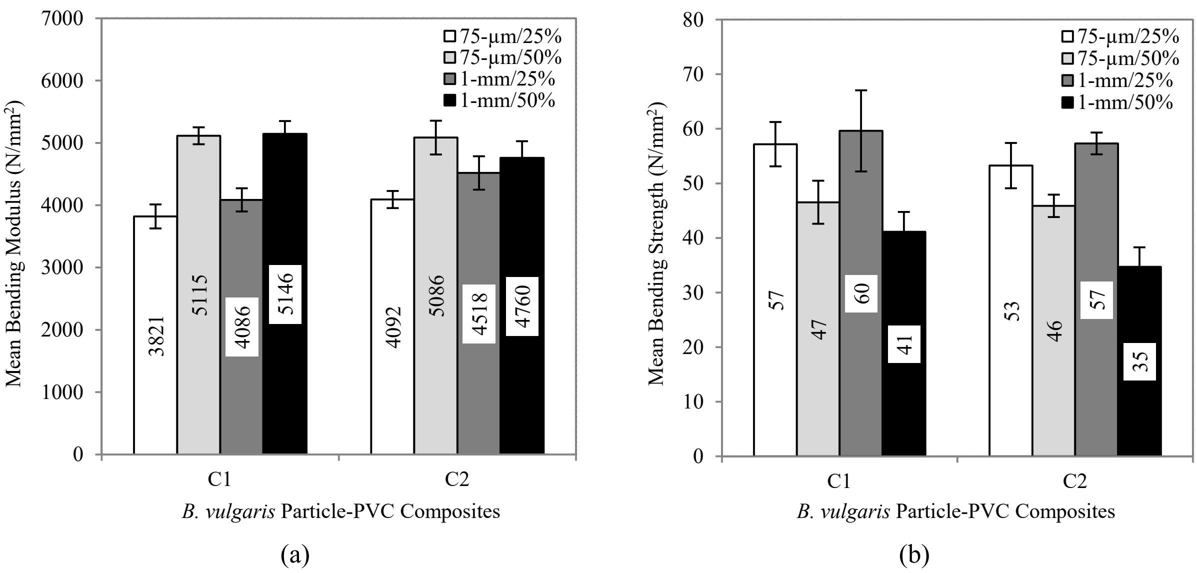
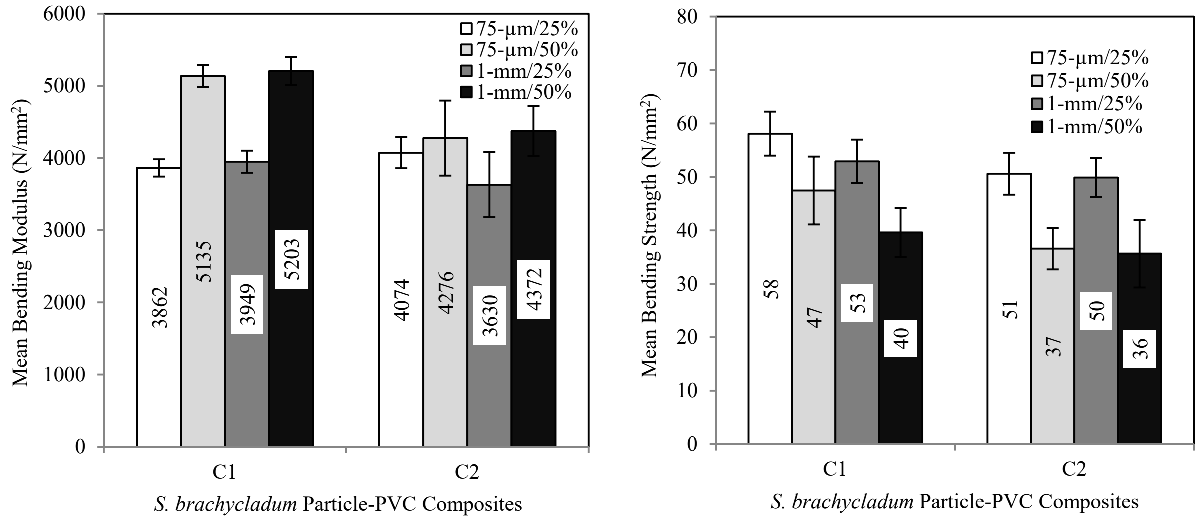
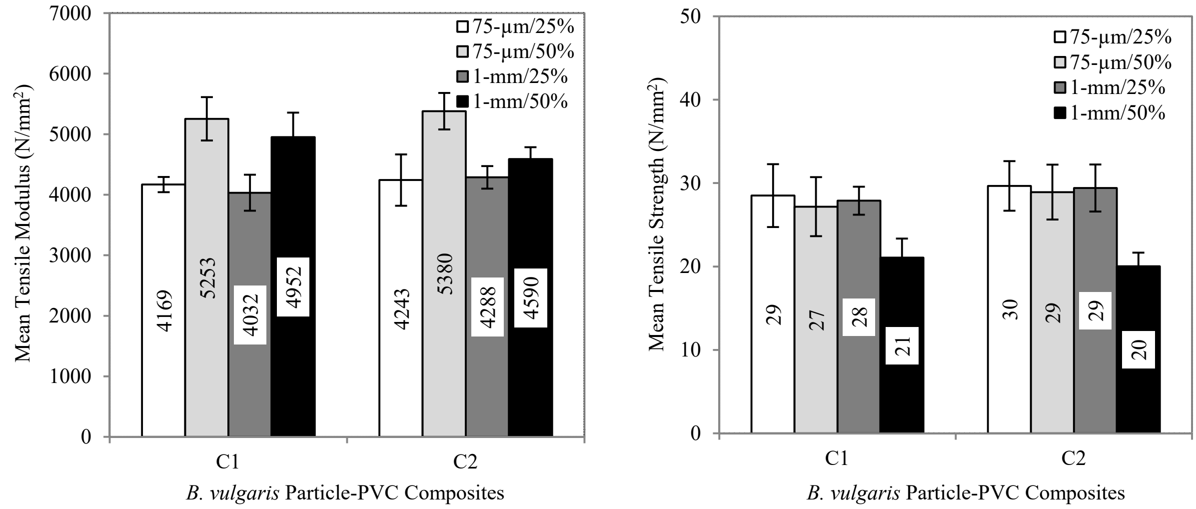


Figure 4. Bending property of *B. vulgaris* particles-PVC composites with different particles sieve size, particles mixing ratio and processing lubricants content level; (a) mean bending modulus, (b) mean bending strength



(a) (b)

Figure 5. Bending property of *S. brachycladum* particles-PVC composites with different particles sieve size, particles mixing ratio, and processing lubricants content level; (a) mean bending modulus, (b) mean bending strength



(a) (b)

Figure 6. Tensile property of *B. vulgaris* particles-PVC composites with different particles sieve size, particles mixing ratio, and processing lubricants content level; (a) mean tensile modulus, (b) mean tensile strength

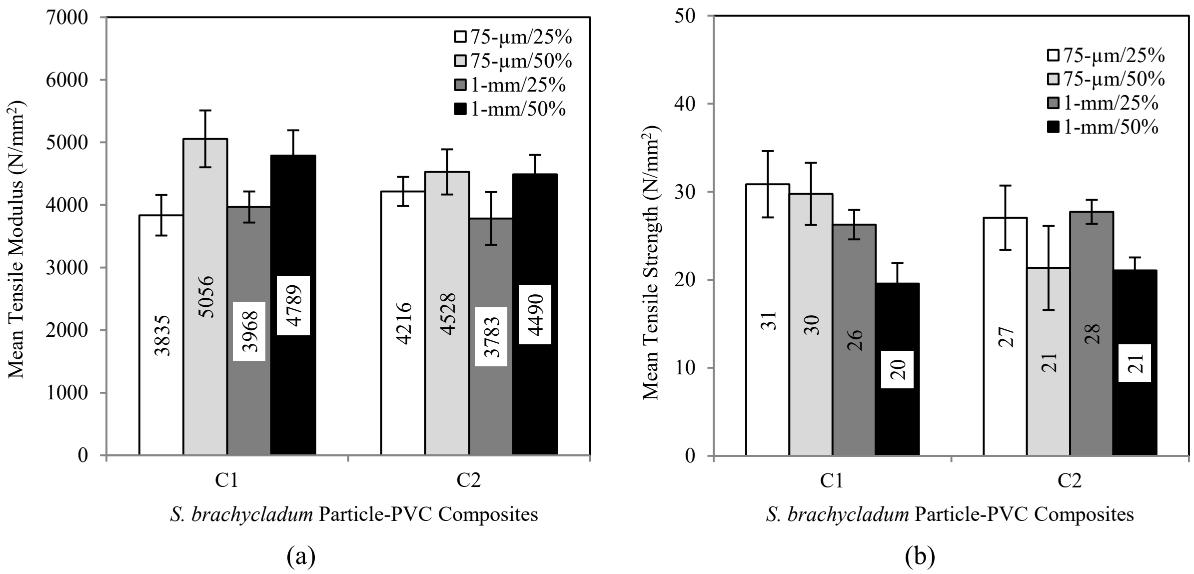


Figure 7. Tensile property of *S. brachycladum* particles-PVC composites with different particles sieve size, particles mixing ratio, and processing lubricants content level; (a) mean tensile modulus, (b) mean tensile strength

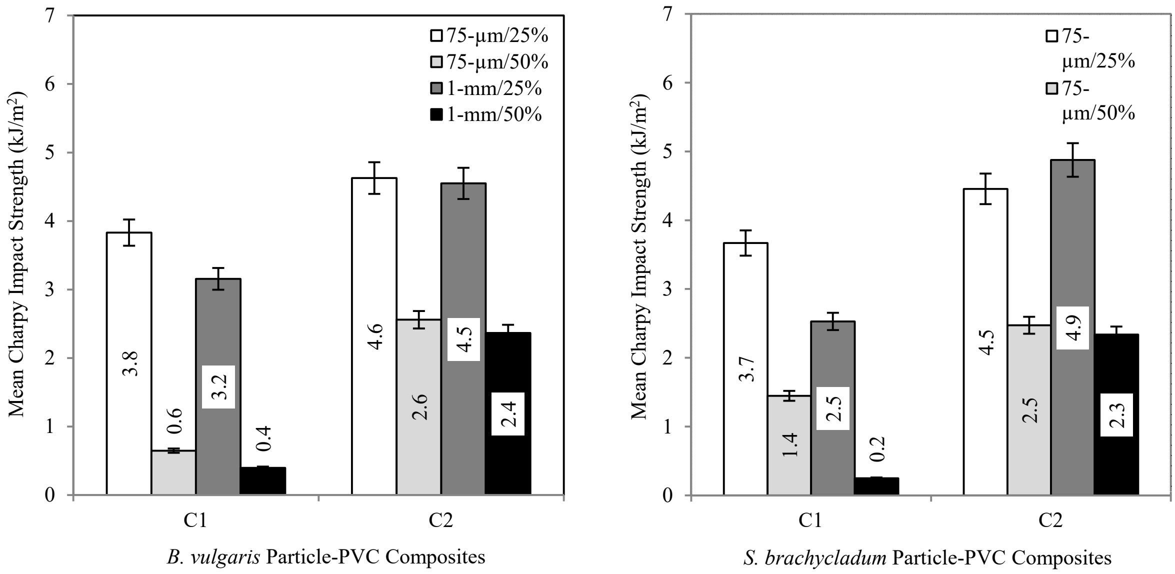
3.2.1 Impact Properties

According to Figure 8, the use of fine bamboo particles (75-µm) in the formulation was capable in influencing the increases of impact strength of the composites. This was probably due to the binding competency of particles with the matrix due to fine size. Fine natural fibres entangle less, have more resistance to breaking, and have a high surface area that make their distribution into the polymer matrix is more homogeneous (Zazyczny & Matuana, 2005), therefore, help to improve the impact resistance of the composites.

For particles loading aspect, the impact strength of composites with 25% bamboo particles was from 77 to 1150% greater than composites with 50% bamboo particles. However, in a general comparison to pure PVC composites in Table 4, the impact strength of bamboo particles-filled PVC composites is diminished by the presence of bamboo. The presence of bamboo particles in the formulation has possibly influenced the defieciency in supporting the sudden impact loads.

Furthermore, composites with high concentration of processing lubricants (C_2) exhibited higher impact strength compared to low concentration (C_1). The incorporation of high amount of these internal and external processing lubricants helped to improve the impact strength of the composites in this study. As the internal lubricant promote the fusion process and reduce the melt viscosity of PVC-filler mixing, the external lubricant tends to migrate to the surface of PVC composites mixture to reduce the friction between PVC melt and processing machine surfaces (Thacker, 2008), thus simultaneously help to improve the resistance toward impact load. According to Figure 8, the maximun mean impact strength value that the composite from C_2 can achieve was 4.9 kJ/m^2 (recorded from *S. brachycladum*/1-mm particles sieve size/25% particles mixing ratio).

While excellent bending modulus and tensile modulus have been recorded, impact result shows that the average impact strength of Malaysian bamboo particles-PVC composites are considered inferior in the context of high-rated sudden load applications. Under the best of circumstances, a balance of stiffness and impact resistance is desired for any kind of composites products to be used in load-bearing application (Robinson, Ferrigno, & Grossman, 2008). Due to the outstanding modulus of the composites regardless of particles size and particles loading, the formulation of 75-µm particles size/25% particles loading/C_2 for *B. vulgaris*, and 1-mm particles size/25% particles loading/C_2 for *S. brachycladum* may be used in order to achieve the optimum impact resistance stipulated in Figure 8.



(a) (b)

Figure 8. Impact of Malaysian bamboo particles-PVC composites with different particles size, particles mixing ratio, and processing lubricants content level: (a) *B. vulgaris*, (b) *S. brachycladum*

3.2.2 Water Resistance

An extensive increase of water uptake at the early stage of 1600 h water soaking was observed for composites from both bamboo species, especially for 50% particles loading (Figures 9 and 10). This was followed by a gradual raise thereafter, until the completion of water absorption measurement. Although increased rapidly, composites with 50% particles loading reached the equilibrium level faster than 25% loading. In relation to this observation, the water absorption of bamboo particles-PVC composites can be typically divided into two diffusion steps: the first one occurred over a rapid diffusion rate, while the second one was at a slower rate close to zero (Petchwattana, Covavisaruch, & Pitidhammabhorn, 2013).

A significant different of composites' water uptake property was recorded between different particles size. Composites with fine bamboo particles (75-µm) have less water uptake percentage compared to composites with large bamboo particles (1-mm). The low water uptake percentage of composites with fine particles was probably due to the compact mixture between fine particles and matrix which influenced the less water absorption. Compared with large filler in composition, the use of fine particles in the composition reduces the voids formation (Yu, Huang, & Yu, 2014). Consequently, fillers with a smaller particles size have a higher adhesion interaction with polymer than those with large size (Zazyczny & Matuana, 2005). This phenomenon reduces the tendency of composites to absorb water.

On the other hand, composites with 25% bamboo particles show less water uptake compared to composites with 50% particles. In a comparison to pure PVC (Figure 9 (a) and 10 (a)), water uptake of bamboo particles-filled PVC composites was extremely higher due to the high water uptake capability of bamboo particles as natural filler. The presence of hydrophilic –OH groups in the fibres/particles has influenced the high moisture uptake capacity of any types of natural filled-polymer composites (Samal et al., 2009).

Composites with high lubricants concentration (C_2) showed lower water uptake percentage compared to low lubricants concentration level (C_1). The presence of internal and external lubricants at high content level has reduced the water uptake ability. It is recorded in Figure 9 (b) and 10 (b) that composite from C_2 group using 75-µm particles sieve size with 25% particles mixing ratio exhibited the lowest water uptake percentage throughout the entire soaking period.

As a comparison, the water uptake property of Malaysian bamboo particles-PVC composites in this study is considered favourable when referring into the other study by Kassim (1999) (increases of 750% water absorption of composites from 10 to 50% bamboo fillers loading) and Kushawa and Kumar (2009) (water uptake values of bamboo fibre-epoxy composites (at 64% bamboo loading) of up to 40%).

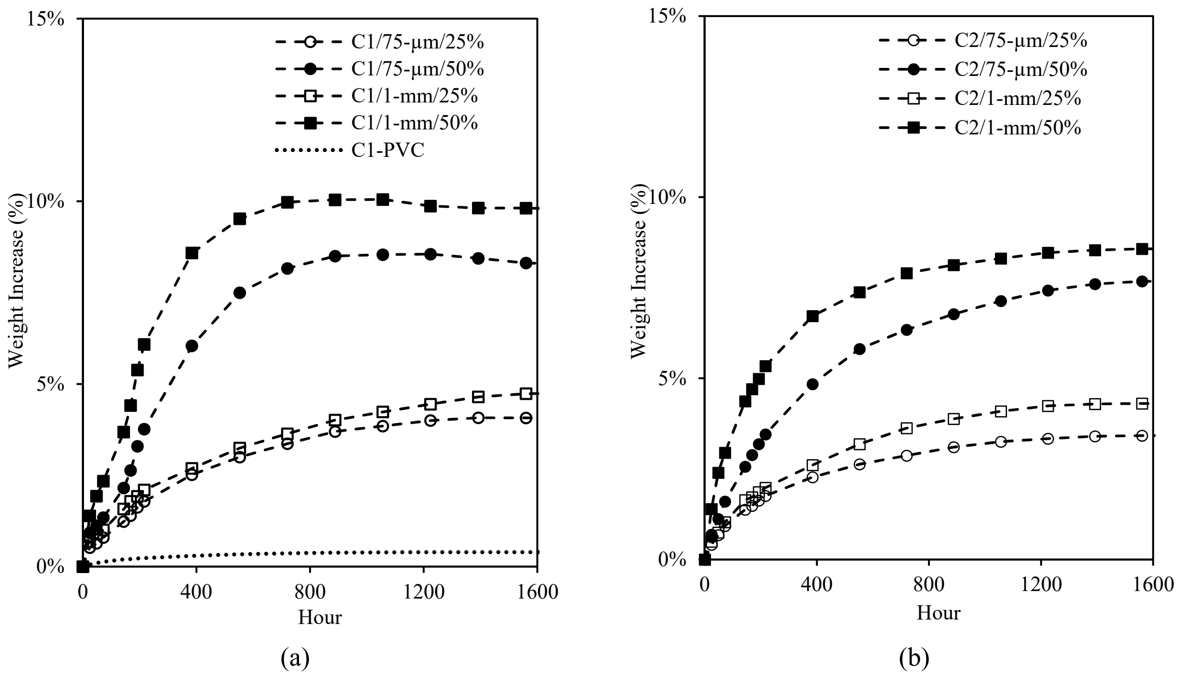


Figure 9. Water uptake of *B. vulgaris* particles-PVC composites for both C_1 and C_2 using different particles size, particles mixing ratio, and processing lubricants content level: (a) C_1, (b) C_2

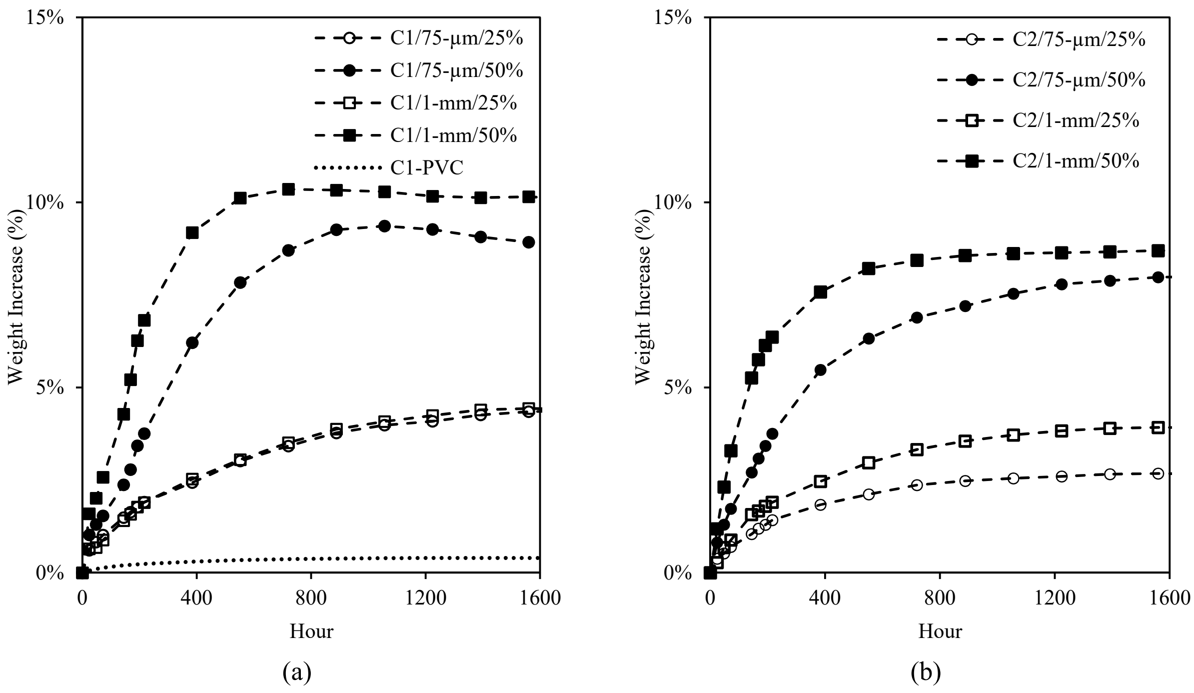


Figure 10.Water uptake of *S. brachycladum* particles-PVC composites for both C_1 and C_2 using different particles size, particles mixing ratio, and processing lubricants content level: (a) C_1, (b) C_2

4. Conclusion

DIA revealed a wide distribution of Malaysian bamboo particles (*B. vulgaris* and *S. brachycladum)* length ranged from 0 to 1500 µm. Insufficient amount of actual particles length distribution from each sieve size (75-µm and 1-mm) has been also recorded. Aspect ratio has been increased with particles length, although particles from small sieve size group exhibited a little more elongation than 1 mm. Due to these features, particles size had only a minor impact on the composites performance. Simultaneously, bamboo particles loading has tremendously increased the bending modulus and tensile modulus of PVC composites, however in contrast, decreased the resistance towards maximum bending load, maximum tensile load, impact and water uptake. The consumption of high processing lubricant content level in composites provided remarkably support with regard to impact load, and promoted better resistance towards water absorption. No significant different of composites performance has been recorded between different bamboo species. It is concluded that Malaysian bamboo particles are possible to be mixed with PVC to produce composites, with particles loading plays the most important role in the composite's properties.

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