POTENTIAL OF FINES AS REINFORCING FIBRES IN ALKALINE PEROXIDE PULP OF OIL PALM EMPTY FRUIT BUNCH

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Pulp from the alkaline peroxide mechanical pulping (APMP) of oil palm empty fruit bunch, EFB, was fractionated with varying mesh-size screens to examine the effects imposed by size-specific fines on the produced pulp network. Occurring mainly as a result of refining, fines elements with dimensions almost resembling EFB fibres were the long tube-like tapered vessels from the arrays of adjoined cell walls detached along the perforation lines. These fibrillated vessel elements constituting the P250/R300 fines fraction improved pulp network strength by gluing onto multiple fibres. More profound strength enhancement was promoted by the segments of the fibrillated vessel elements constituted in the P300/R400 fines fraction. With reduced dimensions, these elements enhanced pulp network strength by filling the micro-voids in the pulp network. By eliminating gaps that would otherwise interrupt inter-fiber bonding, 12% P300/R400 fines fraction enhanced the EFB APMP pulp network tensile strength by 100%.

Keywords: APMP; EFB; Fines; Filler; Reinforcing; Vessel elements; Fibrillar

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INTRODUCTION

Global resources consumption for 2010 reveals a persistent dependency on wood as a natural resource for pulping and papermaking, and this intensifies concerns over world carbon emission from deforestation. To gradually reduce the 70%-to-30% portion of wood-to-nonwood fibre supply, pulp and paper consumption patterns need to be revisited (Madakadze *et al*. 2010). Adaptation of existing technology and innovation of technology for pulping and processing of non-woody materials, which can be extra demanding in comparison to wood pulping (Rousu and Niniimaki 2005), also needs extensive research and proper documentation. Renewed interest in non-wood utilization research activities need proper monitoring and redirecting to ensure adherence to sustainability strategies such as cradle-to-cradle and cradle-to-gate product life cycle, as well as zero-waste systems. These efforts point to waste minimisation and benign carbon accounting results.

Asia is an influential source of non-wood pulp from annual fiber crops, agricultural residue (or agro-waste), and non-plant fibrous mass such as algae, rags, and animal waste. In the course of palm oil milling in Malaysia, for instance, 19.3 million tonnes of EFB is generated each year as the palms are pruned for oil extraction (Hoggard 2011). Traditionally, the EFB are left to rot in the environment or burnt in open air, which creates tremendous environmental concern. While open burning pumps in carbon dioxide into the atmosphere (an excess of which can lead to global warming), leaving the residual fruit bunch to rot in the environment attracts pests, besides being a source of foul odour. Utilisation of the industrial-cum-agricultural residue, therefore, offers productive management of the waste from the country's major cash crop. From a pulp productivity perspective, per hectare palm oil plantation could generate EFB pulp at least double the per annum pulp harvested from the local rainforest. This corresponds to savings of an equivalent of over 88 million trees, on the assumption that all EFB could be converted to pulp (Hoggard 2011).

To date, research on utilization of EFB continues to grow. EFB can be minimally processed to suit application as pollutant sorbents (Ahmad *et al*. 2010, 2011a,b). It is also a type of biomass currently researched for the practical possibility of biofuel production, despite the often-said snags. Beyond research, today a small amount of EFB is used as medium-density fibreboard, mats, mattresses, cushions, and for light furniture. It is also compressed as briquettes and incinerated for electricity generation (Hoggard 2011). Similarly, destruction of EFB lignocellulose matrix allows production of melt siliceous glaze by high temperature incineration of the biomass. This has enticed creative application such as glazing of ceramics and pottery (Ghazali *et al*. 2009), for interior decoration application. In a contrasting application, as EFB has a predominance of cellulose, has lower lignin in comparison to most local wood, and has unique fibre characteristics, the residue has greater viability as raw material for pulping and conversion to paper-based products (Ghazali *et al*. 2006; Zainon 2011; Anon 2011) as compared to bioenergy (Anon. 2011) and glazing applications.

Pulp extraction from EFB was therefore attempted by applying an environmentally benign (Ghazali *et al*. 2009) process concept of the alkaline peroxide mechanical pulping, APMP. Being sulfur- and chlorine-free, the technique incorporates pulping and bleaching in a single process, thus eliminating the need for a separate bleach plant and the ensuing operation and maintenance costs. Apart from the acclaimed (Xu, 1999, 1999a; 2000b; Bukhart *et al*. 2001; Xu 2001a, 2001b, 2001c) simplicity, various possible adjustments can be made to the refining parameters, alkaline peroxide level, stages, and temperature of the alkaline peroxide to suit the choice of biomass and the resultant pulp quality. The process flexibility and high adaptability to a wide spectrum of biomass was first demonstrated by Cort and Bohn (1991) based on the success of APMP^{TM} of wood species such as aspen. Subsequent works reported successful application of the system to birch, maple, and poplar (Blodgett *et al*. 1997; Francis *et al*. 2001). Through certain upgrading measures, Xu and co-workers reported success of adapting a modified APMP system (Xu 1999) to kenaf, straw, baggase, and jute (Xu, 2001a,b,c), as well as to selected tropical hardwood such as acacia mangium (Xu, 2000b).

Early attempts of adapting APMP to EFB (Ghazali *et al.* 2006, 2009; Muhd Yusof *et al.* 2010) observed the wide possibility of pulp quality by adjustments of experimental parameter and machinery. The usefulness of fines co-generated by the mimicked APMP system (hereby denoted APP for alkaline peroxide pulping) was also observed (Ghazali *et al.* 2011), in contrast to the undesirable effects of wood fines and short fiber (Colley 1973) reported previously. Usefulness of wood and non-wood market pulp fines is in wider literature coverage (Gorres *et al*. 1996; Sundberg *et al.* 2003; Rousu and Niinimaki 2005; Chevalier-Billiosta *et al.* 2007; Subramanian *et al.* 2008; Dooley and Weinberg

2009; Asikainen *et al.* 2011). Lukko and Paulapuro (1999) found that desirable fines were generated with intensified refining. While flakes were found to be of less value (Luukko and Paulapuro 1999; Subramanian *et al.* 2008), fibrillar structures were found to render paper density, less of solid-air extension and therefore improved optical qualities. Early attempts of APP of EFB not only showed encouraging effects of fines on paper strength (Ghazali *et al*. 2011) but also 70% improvement in refining discharge clarity, which is important in reduction of total suspended solids (TSS) in used process water. At the present level of knowledge, TSS reduction is achieved by backwash filtration technology, adopted in the whitewater closed-loop systems where reuse of water in the water-intensive industry is made more efficient (Shukla *et al*. 2012). This paper presents the types of fines elements in EFB APP pulp and identifies the strength-reinforcing potential of the pulping by-products. As EFB pulp is gaining worldwide acceptance as blended pulp in many industrial paper and packaging products, knowledge of the characteristics and potential uses of the waste material is especially important in maximization of process yield and minimization of waste.

EXPERIMENTAL

Materials

The fibrous strands of EFB were obtained from Sabutek (Malaysia) Sdn Bhd in bales of dried long fibrous strands. These consisted of vascular bundles that were washed and air-dried upon receipt and the strands were then cut into 2±0.5 cm segments at Universiti Sains Malaysia (USM) laboratory.

Methods

Pulp preparation

APMP of EFB was carried out by simplification of the previously adopted method (Ghazali 2006). On a partially extractive-free EFB segments that were obtained by soaking the biomass in distilled water at 70°C for 30 minutes in water bath, 15 psi or 103 kPa pressure was applied on the decanted EFB using an impregnation device. Upon release of pressure, the alkaline peroxide chemicals were allowed to impregnate into the biomass at a consistency of 10-to-1 liquor to EFB ratio. The alkaline peroxide containing 2% sodium hydroxide (NaOH) and 2.5% hydrogen peroxide (H_2O_2) was reacted with EFB, and this cooking process was allowed for 30 minutes to soften and brighten the biomass. This was again pressed at 15 or 103 kPa until reaching a dewatering rate of three drops per minute. The EFB was next refined using Sprout-Bauer 12” single disc refiner with resultant specific refining energy of 54.95 kWh/t for 4% pulp consistency and refining temperature of 33.5^{o}C

Fines Collection

Fines generated at the discharge of pulp from the refiner were collected by sequentially placing the fabricated sieves of 250-, 300-, and 400- mesh screens at the discharge of the 200-mesh sieve (76 μm x 76 μm). These were stainless steel square opening mesh sieves with 63 μm x 63 μm, 53 μm x 53 μm, and 37 μm x 37 μm square apertures corresponding to 250, 300, and 400-mesh, respectively. The collected fines, therefore, are associated with pulp mass separated by their width and length, based on the Sherwood Fiber Quality Analysis principle – see Table 2. These were retained on specific mesh sieves due to their inability to escape the 76 μm aperture of the 200-mesh screens trapping the accepts. The fines collected on the respective sieves are therefore denoted P200/R250, P250/R300, and P300/R400 with P denoting 'pass' and R denoting 'retain'. Both the accepts and collected fines constitute 95% yield of the attempted APMP of EFB with loss having association with 1.5% extractives from dewaxing stage, about 1% minerals and 2.5% fines and other organics escaping 400-mesh sieve. Based on the 12-20% range of fines by the 3 mesh fractions, the R200-to-fines fines proportion is approximately 60:40.

Making of Handsheet

Handsheets were prepared in accordance to the TAPPI procedure (TAPPI 1997). Where fines were incorporated, the P200/R250, P250/R300, and P300/R400 fines fractions were added before mixing the slurry using a Toyoseiki disintegrator. Handsheets prepared with the unscreened pulp were labeled A, while those prepared with R200 were labeled B. Samples containing blends of R200 with 12% of fines: R200+P200/R250, R200+P250/R300, and R200+P300/R400, were labeled B250, B300, and B400, respectively. The fines proportion was selected based on the 10 to 30% range of fillers used in commercial papers. The selected lower level was also to ensure utilization of fines generated per batch of pulping and to rule out the need to run pulping specifically to generate fines.

Five different sets of handsheets with 10 to 15 sheets per set were prepared and tested for their mechanical properties in accordance to TAPPI Test Method T 511 for folding endurance, T 414 for tearing resistance, T 403 for burst index, and T 494 for tensile index. Optical properties were examined by TAPPI test method T452. All density values are measured as sheet weight per volume of handsheet, where volume is the multiplication product of sheet area and sheet thickness.

Microscopy and Fiber Analysis

Fines were examined qualitatively using a light microscope with four lenses fixed at the rotating nosepiece. All slides were labeled accordingly and analysis of fibers was performed without staining. Transmission light microscope interfaced with an image analyzer was then run to analyze the fibers. SEM or scanning electron microscopy was run on the 30 nm gold-coated handsheet samples using a Carl Zeiss Leo Supra 50VP to check for evidence of fines entrapped in the pulp network.

Fibre dimensional characteristics were acquired from Sherwood FAS-3000 Fibre Analysis System (USA), and this analysis was performed on pulp suspensions (pulp and fines) as recommended by the instrument manufacturer. Quantitative proportion of the fines was also obtained from this analysis.

RESULTS AND DISCUSSION

Fibres and fines differ in structural properties (Gorres *et al*. 1996) and morphology. While fibres making up the accepts are pulp mass retained on the 200-mesh screen, fines are the fibrous particles passing a 200-mesh sieve. The ability of long fines structures to escape the aperture also reflects their degree of flexibility (Subramanian *et al*. 2008).

Characterization of Fines in Screened Pulp

The refined EFB mass collected as 200-mesh pulp fraction, or "accepts" denoted as R200, show the presence of fiber and fiber bundles. Fiber bundles, which occurred as a result of EFB segmentation rather than lubricated shearing of EFB vascular bundle, were found in lengths of 400 μm (Fig. 1a) and 1000 μm (Fig 1b) and of about 200 μm width, by direct two-dimensional micrographic measurement. Also predominant in the R200 mass were the long tube-like and tapered vessels in the form of bordered pits (Figs. 1c and 1e) and besides the segments of 260 μm (Fig 1c) and 420 μm (Fig 1d), vessels elements up to approximately 600 μm was also encountered as a result of segmentation

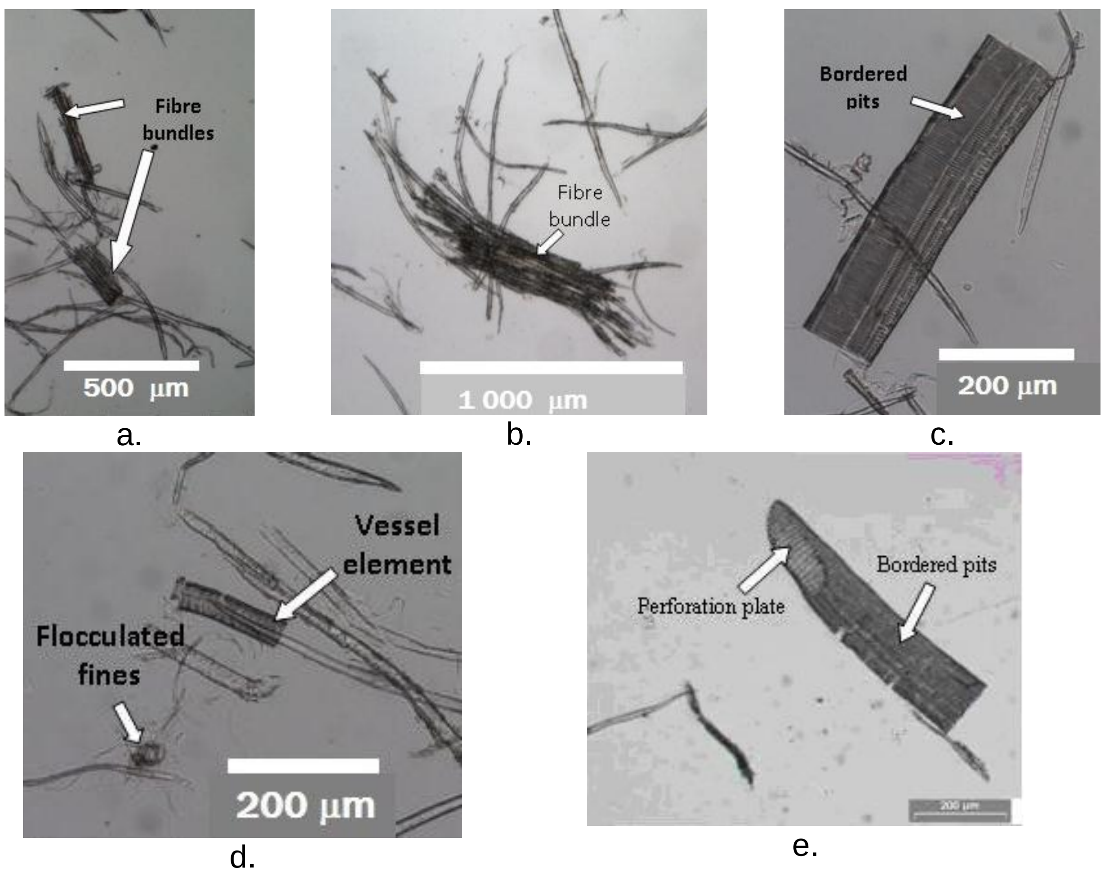


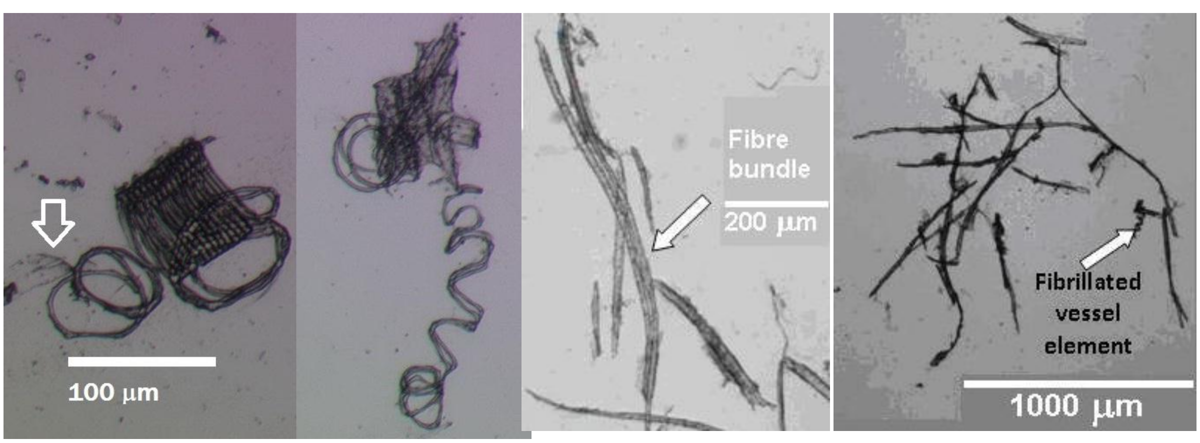
Fig. 1. Fines collected together with R200 fraction a) Fibre bundle and fibers, b) Larger fiber bundle (resemble fiber if sheared to single strands of 1 mm fiber) c) vessel elements showing bordered pit d) Flocculated fines e) Bordered pit and perforation plates encountered on vessel element.

of the vessel in the internal structure of EFB vascular bundles. These are the unfibrillated elements in the fibrous mass, marking the failure of vessel and fiber fractions to fibrillate extensively.

Evidence of an intact perforation plate in Fig. 1e is also indicative of poor fibrillation. The smorgasbord of structures suggests the kind of EFB pulp mass passing between the refining plates (Peel 1999), which is believed to be the consequence of refining action (Chevalier-Billosta *et al*. 2007). The abundance of the unfibrillated materials including intact vessel fragments shown in Fig. 1 reflects the rigidity of the lignin-carbohydrate matrix and the inadequacy of biomass softening allowed by the adopted conditions.

Apart from the noted unfibrillated elements, flocculated fines (Fig. 1d) were also present in the R200 mass, plausibly originating from the detachment of long fibrils of EFB vascular bundles, analogous to the fibrillar end of the vessel element in Fig. 1c. This was attributable to the friction between vessel elements and the refining plates, resulting in shear instead of segmentation, due to the presence of residual alkaline peroxide. Although resembling fibrils, the coiling conformation of about 60 μm with surrounding fine web attributable to external fibrillation had apparently denied successful passage through the 107 μm diagonal of the aperture of the 200-mesh sieve

Unlike the R200 pulp fraction, which is insignificantly different from the P200/R250 fractions, both Fig. 2a and Fig. 2b show fines characteristic of xylem vessel elements of the P250/R300 fines fraction, demonstrating extensive fibrillation. Evidence of a broom-end structure in Fig. 2a is one demonstration of fibrillation of the fibril (vessel strand) arising from 'splitting' along vessel pits. This resulted in pulp mass in the form of a fiber or single strand, insufficiently thin (75 μm x 75 μm unfibrillated vessel and 500 μm x 10 μm fibril) to escape or long enough to tangle and thus, retained on the 300-mesh screen of 53 μm x 53 μm aperture with 75 μm diagonal. Noteworthy, however, is the fact that fiber bundles encountered in this mesh fraction contained a lower count of fiber in a bundle, suggesting lower-width mass with more flexibility to escape the 250-mesh sieve.



a. b. c.

Fig. 2: Fines of P250/R300 consisting of a) semi-split xylem vessel with broom-end (arrow) and a more pronounced splitting of vessel resembling fibre of spiral conformation (x10) on the right, b) two semi-detached stands of fiber in a bundle and c) segmented spiral fibril hooked to long fibers (x4).

Intact vessel elements were also scarce, except for those dangling with long spiral fibrils (Fig. 2a) possessing length typical of EFB chemical pulp fiber. Figure 2c shows the relative sizes of fibers and fines in the form of segmented vessel fibril. Spiral conformation increases the possibility of hooking to fibers and retention in the R300/P250 fines fraction. Under the influence of their length, these are unlikely to fill up micro-voids but likely to promote good paper formation by creating sites for gluing onto multiple fibers.

Fibrous mass of reduced dimensions were commonly encountered in the P300/R400 fines fractions (Fig. 3). These are segments of vessels, fibers, fibre bundles, and fibrils. Segmentation of fibrils of the vessel elements left behind vessel flakes of 74 µm x 76 µm dimensions (insert in Fig. 3) that may have adequate curving capacity to escape 300-mesh sieve of 75 µm diagonal aperture. On handsheets, flakes were observed to adhere onto fibre surfaces, visible as patches of vessel element (Figs. 4c and 4d), and likely to impose high picking tendency in the offset lithographic printing (Colley 1973). As in the case of flakes, likewise the liberated fibrils that have undergone severe rupture apparent from the web-like appearance, as indicated by circles in Fig. 3c, are unhelpful in promoting sheet strength. These are elements responsible to the acclaimed 'fiber coalescence' commonly encountered on the surface of EFB pulp handsheets of tensile index above 15 Nm/g (Ghazali *et al*. 2011; Dermawan and Ghazali 2011). By masking of individual fiber strands and promoting sheet cohesion, the pulp network appears smoother. Finer materials with broom-end features of submicron fibrils that are signs of severe shearing forces or segmentation upon shearing of individual fiber and vessels also promote inter-fiber bonding due to their chances of clinging onto adjacent fibers.

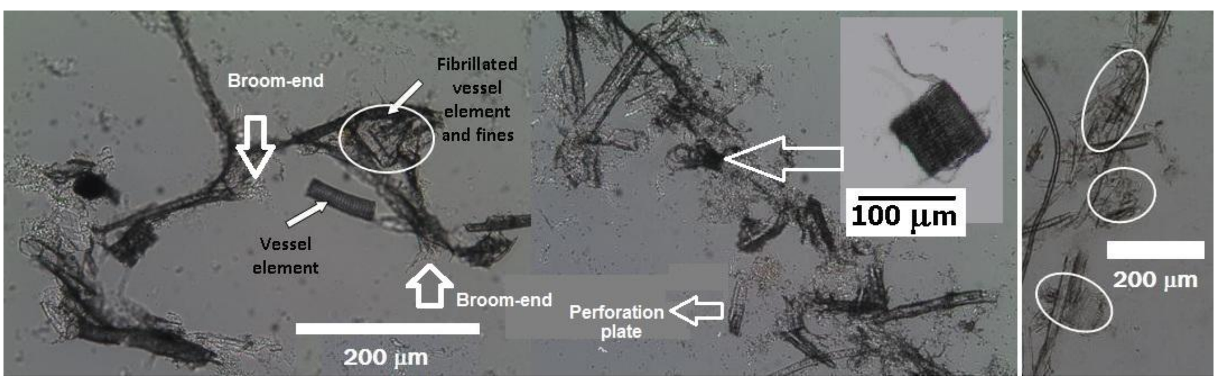


Fig. 3: Fines collected as 400-mesh fractions showing mixture of completely 'split' xylem vessel, fiber bundle and fibre fragments (insert)(x4).

Table 1 sums up the approximate size of the vessel elements in the respective mesh fractions. Although the relative sizes of the unfibrillated and fibrillated elements correlate with the predicted shearing severity undergone by the biomass, the relative sizes of micro-gaps are more influential in determining the more desirable fines dimension. Despite being most slender, for instance, P250/R300 fractions offer less of filling effect in comparison to the P300/R400 fraction but served more as a binder due to the presence of long fibrils (Fig. 2a) and more binding sites. These are even enhanced by the existence of submicron fibrillated fibrils evident as a broom-end structure in Fig. 2a.

Table 1. Approximate Dimensions of Vessel Elements in Fines Fractions

Fines Fraction	Predominant Vessel Dimension					
	Unfibrillated		Fibrillated			
	Length, µm (±10 µm)	Width, µm (±10 µm)	Length, µm (±50 µm)	Width, µm (±5 µm)	Approximate Slenderness	
					Min	Max
200-mesh	100-600	20-150	200-1000	5-20 µm	10	200
300-mesh	60-75	50-75	400-1500	7-10 µm	40	214
400-mesh	65-80 50	15-73 50	100-300	5-7 µm	14	60

Diagonal of stainless steel square mesh aperture:
200-mesh (76 µm x 76 µm): 107 µm
250-mesh (63 µm x 63 µm): 89 µm
300-mesh (53 µm x 53 µm): 75 µm
400-mesh (37 µm x 37 µm): 52 µm

NB: Nature of Fibrils
200-mesh: very uncommon
250–mesh: partially detached to vessel
300-mesh: partially attached to vessel
400-mesh: detached from vessel & segmented.

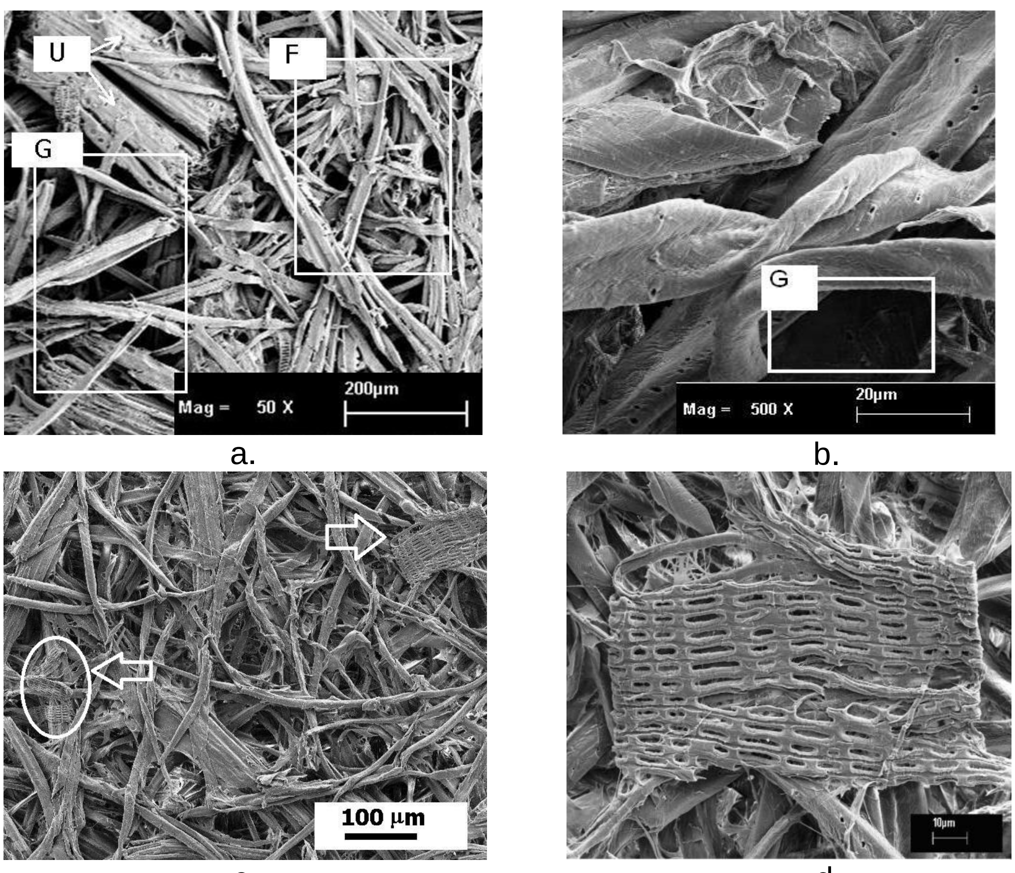
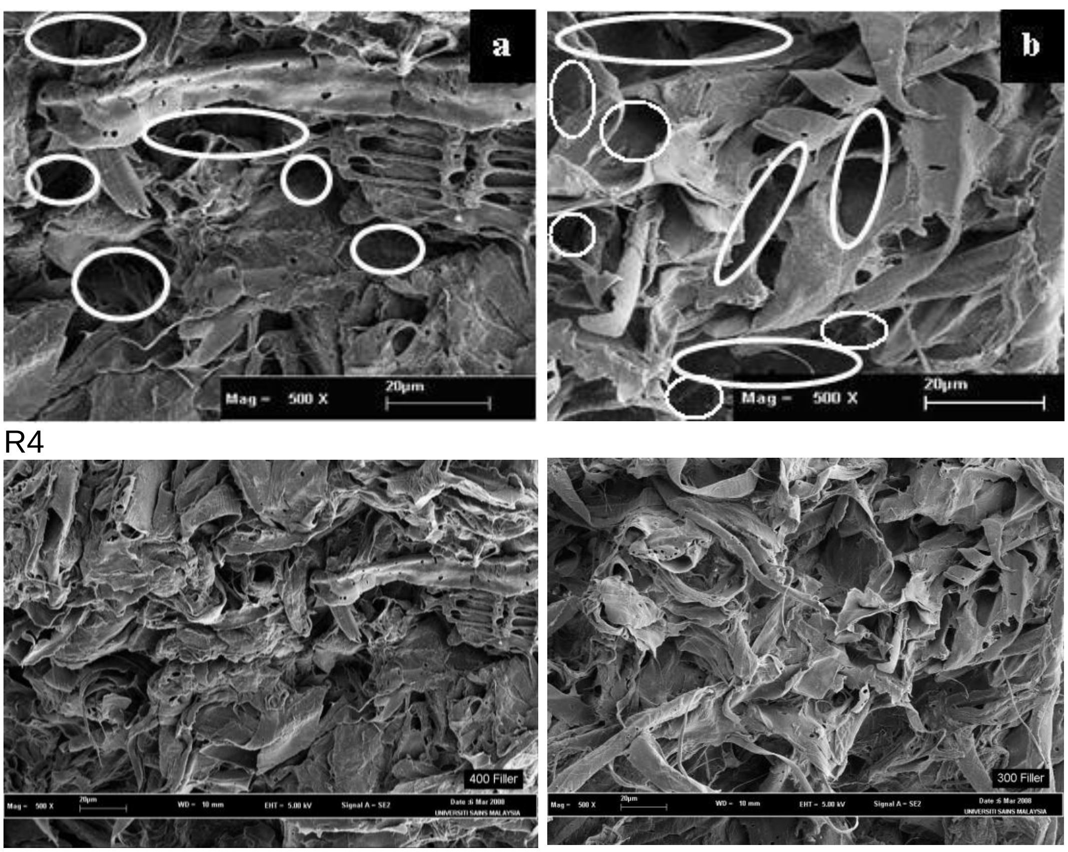


Fig. 4. Micro--void (G) and filled gaps (F) in the studied pulp network a) G, F and unfibrillated bundles (U), b) close up of smaller gaps, which is less likely to accommodate fines c) vessel on surface of pulp network d) close-up of vessel on pulp network marked by circle and arrows in c.

The found fines elements, however, are much better in reinforcement of pulp network strength in comparison to ray cells, which according to Sundberg and co-workers (2003) are of no aid to pulp network strength improvement. The vessel-rich mass from APP of EFB is likely to impose a different extent of pulp network improvement, depending on the nature of the gap created by the incompletely fibrillated mass. This is revealed in Fig. 4, which demonstrates gaps or micro-voids (G) in handsheets arising from oversized elements in the pulp mass, U, which is in close association to the partially ruptured vessel elements in the R200 pulp fraction in Fig. 1e or the unfibrillated portion of vessel in Fig 2a. From the relative sizes of gaps (Fig. 4) and fines (Table 1), it is plausible that the smaller fines stand higher probability of acting as voids filler. Present in invariable shapes, gap areas ranging from 10 μm^2 to more than 200 μm^2 are more likely to be densely filled with the P300/R400 fines fraction than the P250/R300 fines fraction. The relative compactness of the said fines is reflected in Fig. 5a and Fig 5b, with smoother and denser appearance depicted on the P300/R400 fines in comparison to the higher count and the larger size of the micro-voids within the P250/R300 fines cluster. In addition, the higher coarseness or bulk implied by the higher extension of fines-air interface in the P250/R300 fines in Fig. 5a is attributed to the loose volume caused by the long spiral structure of the vessel element previously presented as Fig. 2a.



a. b.

Fig. 5. Scanning electron micrographs emphasizing count and size of micro-voids marked by circles and ovals: a) R400/P300, b) R300/P250 fines, at x500 magnification, with close-up look at the top and larger viewing area below

Table 2 also presents changes in optical and mechanical properties of handsheets upon addition of fines. The increase in brightness as a result of adding fines is a signal of good reaction between peroxide and fines. This suggests the predominance of surface lignin, to which peroxide is prone (Asikainen *et al.* 2011). The findings therefore map surface lignin as residing in the fibrillated vessel elements and fibrils (Figs. 2a and 3). With more gaps accommodated by fines, reduction in sheet porosity and enhancement in opacity indicated in Table 3 suggest improvement in inter-fiber bonding.

Without fines, screened pulp (Sample B), however, offered the lowest tensile and tear indices due to poor inter-fiber bonding. Low extent of fibrillation, which resulted in the predominance of unfibrillated structures and fibre bundles (Fig. 1) was the key factor and this reflects the rigidity of the lignin-carbohydrate matrix and the inadequacy of biomass softening allowed by the adopted conditions. The principal reason for occurrence of these fiber bundles was inadequate reaction between alkaline peroxide and EFB that would otherwise soften the biomass and facilitate fibrillation process. One way to improve this is by applying alkaline peroxide during the refining process, similar to the concept of PRC-APMP™ (Xu, 1999b; Xu *et al*., 2000b), the results of which will be discussed elsewhere.

As far as mechanical strengths are concerned, tear index improved by 15%, and this is only 0.1 point inferior to the whole (unscreened) pulp network of Sample A, suggesting that the individual fibres were more difficult to pull from the network of native fibrous mass blended with size-specific fines fractions. The better strengths as a result of enhancement in inter-fiber bonding and reduction of sheet porosity as also implied in the higher density of handsheets prepared with fines addition. Similar behaviour was also portrayed by the highly fibrillated fines of bleached softwood kraft pulp reported by Subramanian and team (2008).

Incorporation of the P200/R250 fines fraction in Sample B250 led to 61% (relative to Sample B) enhancement of tensile index, quantitatively suggesting a positive effect of fines, although this effect is difficult to delineate from qualitative microscopic observations. This was also demonstrated by the initiation of folding resistance.

Blending the R200 pulp with P250/R300 and P300/R400 fines fractions improved tensile index by 75% and 100%, respectively. This demonstrates the strength enhancing effects of the fines collected from the APMP of EFB, which were evidently vessel elements. The sheared vessel elements splitting along the perforation lines resembled thin, long fibres [*cf*. EFB fiber: 1000 μm length, 20 μm diameter (Law *et al*. 2007)] possessing better flexibility and collapsibility, which are likely to enhance inter-fiber bonding filling of micro-voids and acting as connecting medium. This renders better pulp consolidation, enhanced sheet cohesion and thus, an increase in tensile strength. Similar observation was also reported by Sirvio and Nurminen (2004) and Rousu and Niinimaki (2005) for inter-fiber bond enhancement by wood fibrillar fines and parenchymatous and epidermal cells monocot non-wood (common reed and wheat straw) pulp fines, respectively.

Besides the well fibrillated structures (Fig. 2), other fragmented mass constituting the finer pulp mass indicated in Fig. 3 were mainly responsible for filling the gaps between the R200 pulp of EFB. This pulp mass, which is predominantly fines and short fibres, are shorter (Table 2, Pulp Fractions), resembling the more pronounced segmentation and shearing undergone by the 300-mesh fines fractions. Owing to their higher surface areas, other than acting as filler, these elements also provided contact for enhanced fibre-to-fibril and fibril-to-fibril bondability (Fig. 5) and overall pulp network strength. Considering that a CSF value of 580 to 530 mL is an acceptable range of pulp drainability, the findings point to the practicality and the high potential of fines as pulp strength reinforcement filler with acceptable practicality. The reverse effect may be imposed by higher mesh fines fractions due to challenges with pulp drainability during paper product fabrication and the natural tendency of these finer materials to adsorb unwanted materials (Ahmad *et al*. 2011) and introducing foreign materials such as leached extractives (Luukko and Paulapuro 1999) to the resultant product.

Table 2: Selected Properties of Pulp and Handsheets

	Samples				
	A	**B**	**B250**	**B300**	**B400**
CSF (ml)	710	580	564	550	530
% Pulp Fractions					
Fines	N/A	16.4	N/A	18.5	22.9
Short*	N/A	21.8	N/A	26.2	29.2
Medium**	N/A	50.8	N/A	46.8	42.9
Long***	N/A	7.7	N/A	5.6	3.7
Density (g/cm³)	0.222	0.230	0.244	0.253	0.254
Tensile Index (Nm/g)	4.3	3.6	5.8	6.3	7.2
Tearing Index (mNm²/g)	3.9	3.3	3.8	3.8	3.8
Folding Endurance	0.00	0.00	1.4	1.7	1.9
Brightness (%ISO)	44.9	44.4	46.4	46.5	46.9
Print Opacity	88.21	89.78	93.55	93.64	94.72
Tappi Opacity	81.13	83.00	89.27	90.71	90.57

Key:
A ≡ whole pulp
B ≡ screened pulp
B250 ≡ B + 12% P200/R250 fines fraction
B300 ≡ B + 12% P250/R300 fines fraction
B400 ≡ B + 12% P300/R400 fines fraction

Fines ≡ width 3-60 μm;length < 0.112 mm
*Short ≡ width 3-60 μm;length 0.112-0.448 mm
**Medium ≡ width 3-60 μm;length 0.560-1.456 mm
**Long ≡ width 3-60 μm;length 1.568-7.168 mm
N/A ≡ Not available.
*, **, *** dimensions defined by FQA data.

CONCLUSIONS

1. EFB handsheets blended with the smallest of the examined fines fractions (P300/R400) showed enhanced pulp network strength associated with tensile index and folding endurance.
2. Reinforcement fibers in the P300/R400 fines fractions were the segmented vessel fibrils characterized by their minimal length and diameter that were also the key factors enabling them to accommodate the micro-voids commonly found in the network of pulp produced by the adopted method.
3. Besides acting as filler, pulp network strength was also improved by the long fibrillated vessels in the P250/R300 fines fraction due to their high surface areas

serving as fibers bonding sites. External fibrillation of these produces submicron fibrils was also able to improve fibre network by their web structure.

4. This study identified and characterized desirable fines whose collection and utilization enable maximization of process yield and minimisation of waste from APP of EFB pulping line.

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