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Properties of *Gigantochloa scortechinii* Paper Enhancement by Beating Revolution

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Abstract

The effect of bamboo portions and beating revolution on paper made from *Gigantochloa scortechinii* was determined. The bamboo was pulped using soda-anthraquinone (AQ) pulping comparing two pulping conditions (alkali 15 & 20%, temperature 160 & 170°C) for different bamboo portions consisted of top, middle and bottom. Hand sheets from unbeaten bamboo paper were made and the tensile index, tearing index, bursting index and folding endurance ranged from 16.35 - 32.54 Nm/g, 9.6 - 13.45 mN.m^2/g, 0.81 - 1.54 kPa.m^2/g and 3 - 9 double folds respectively. After that the bamboo pulp went through beating process and the tensile, tearing and bursting index and folding endurance for bamboo paper rose tremendously from 41.23 - 83.9 Nm/g, 16.64 - 27.13 mN.m^2/g, 2.58 - 6.67 kPa.m^2/g and 48 - 1769 double folds respectively. This revealed that bamboo paper strength can be enhanced by beating process without adding any additives.

1. Introduction

Pulp and paper is one of the most important industries in the world. The consumer for pulp and paper products involved all stage of society. Historically the first paper was made from non-wood material by Tsai Lun in China. In 20th century, wood has been dominant to be the main source for pulp and paper material, due to its availability, low cost and good paper properties.

Recently, due to the shortage of wood supplies and the environmental concern related to deforestation, alternative raw material is needed to supplement or replace wood source to maintain the pulp and paper production industry. Many research and development have been done towards this issue. Most of the countries still depend on the imported raw material for their pulp and paper production, including Malaysia.

Gigantochloa scortechinii (*Semantan* bamboo) is the most common type of bamboo and the most abundant bamboo found wild in the Peninsular Malaysia forest and globally. It is also one of the most easily available resources to supplement local wood demand (Azmy & Abd. Razak, 1991; Norul Hisham *et al.*, 2006). Latest study by Nazlin & Mohd Nazip (2011) in Kuala Keniam, Pahang National Park, they found that *Semantan* bamboo has the highest relative density, up to 58.8%, in comparing with other species such as *Lemang* bamboo (*Schizostachyum*

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brachycladum), *Nipis* bamboo (*S. latifolium*), *Semeliang* bamboo (*S. grande*) and *Aur* bamboo (*Bambusa vulgaris*) at 27.5, 3.9, 7.8, 2% respectively. Relative density describes the species richness in a specific area.

Unmodified cellulose fibres, as obtained directly from pulping and bleaching processes, are generally not suitable for paper making. They must first be refined by refining or beating process, conducted mechanically in refiners or beaters. Fibres are abraded and fibrillated by the knife-edges or bars in the refiner or beater. Mechanical squeezing and pounding of cellulose fibre permits water to penetrate its structure, causing swelling of the fibre and making it more flexible. During refining or beating, the pulp fibres are separated, crushed, frayed, fibrillated, and cut. They imbibe water and swell, become more flexible and more pliable. Their capacity to bond with one another on drying is greatly enhanced, partly through modification of the fibre surfaces and partly because of the creation of new surface area and thus increased the fibre to fibre bonding during paper making process (Davison *et al*., 1957).

Jimenez *et al.* (2009) studied the effect of pulping conditions and beating on oil palm empty fruit bunches (EFB) and found that beating of the pulp is interesting because it influences on various pulp properties such as freeness, specific surface area, specific volume, surface charge, total charge and elastic modulus, that they really improve the stretch properties of paper sheets, and concluded that the stretch properties of these pulp beaten are higher than those of others non-wood pulps, as wheat straw and olive wood. Wan Rosli *et al.* (2005) mixed old corrugated board with only 20% of unbeaten EFB virgin soda pulp, or with only 10% of beaten EFB virgin pulp is sufficient enough to completely restore and improve the tensile index of the paper sheets made from the recycled fiber. The major mechanism of strength improvement is probably due to increase of inter fiber bonding as a result of substitution of inactive secondary fibers with active virgin fibers. With the addition of beaten pulps, the effect is even more remarkable. The enhancement is ascribed to the increase in the bonded area of the sheet resulting from internal and external fibrillation that occurs during beating (Jimenez *et al*., 2009).

The aim of this study is to investigate the effect of bamboo portion on paper properties and also to determine the suitability of bamboo for paper making and the enhancement process to improve the bamboo paper strength by using beating process. This will reveal the unbeaten and beaten paper properties of *Semantan* bamboo.

2. Material and Methods

2.1 Soda-AQ Pulping

Soda-Anthraquinone (AQ) pulping was conducted with 4L MK-digester unit. For each batch of pulping, 250 g oven dried (o.d.) of bamboo sample was used. The fixed pulping conditions for each batch were as follows:

Time to reach pulping temperature	:	90 min
Time at pulping temperature	:	90 min
Bamboo to liquor ratio	:	1 to 4
Anthraquinone	:	0.1%

The pulping process was to produce pulp from the wood chips for paper making. In this study, the pulping was conducted to according to bamboo portions that consist of top, middle and bottom portion as listed in the Table 1. The bamboo culm were harvested 30cm from the ground and it was divided into three sections with four feet length for each section and labelled as top, middle and bottom. Only two stages of alkali percentage (15 & 20%) and pulping temperature (160 & 170°C) were used in this study in comparing the lower value and upper value of pulping conditions.

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Table 1: Soda-AQ pulping variables (bamboo by portion)

Treatment	Sample	Alkali (%)	Temperature (ºC)
TC1	Top	15	160
TC2	Top	20	170
TC3	Middle	15	160
TC4	Middle	20	170
TC5	Bottom	15	160
TC6	Bottom	20	170

After the pulping process, the pulp was placed inside a hydrapulper to disperse the fibres into individual fibres. Then the pulp was washed thoroughly under running water to remove all the liquor from the fibres. Continuously, the pulp went into the Sommerville screener with 0.15 mm slot size to separate the fibre from the rejected or uncooked bamboo, and only fibres that can go through the screener will be used in the paper making process.

2.2 Beating Process

Beating process was conducted according to TAPPI standard T248 sp-00 by using the PFI beater for the bamboo pulping from minimum of 1,000 revolutions until maximum of 24,000 revolutions for the top part of the bamboo sample which undergo 20% alkali and 170ºC temperature pulping condition. This was to find the optimum beating revolutions for the bamboo pulp. Details of beating process conducted were shown in Table 2.

Table 2: Beating process for bamboo sample

Sample	Beating Revolutions
T20-1	1000
T20-2	2000
T20-3	3000
T20-4	4000
T20-5	5000
T20-6	6000
T20-8	8000
T20-16	16000
T20-24	24000

2.3 Paper Making

The 60 g/m^2 laboratory paper making process was based on TAPPI standard T205 cm-88. The tearing test was based on TAPPI standard T414 om-88 by using 4 sheets of 31 cm^2 paper area with 4 replications for each testing. Tensile test was conducted according to TAPPI standard T404 cm-92 also to the 15 mm width of paper sample using Horizontal Tensile Tester machine, with 7 replications for each paper sample. Burst test was based on TAPPI standard T403 om-91 using Frank Prufgerate GmbH machine with 8 replications for each paper sample. Folding test was based on TAPPI standard T511 om-88 to 15 mm width of paper sample with 8 replications for each paper sample.

3. Results and Discussion

For results and discussion, alkali will be used for referring to pulping conditions with alkali and temperature variables, since they were varied together, i.e. when alkali is 15%, the temperature will be at 160ºC and whenever alkali is 20%, the temperature will be at 170ºC. Thus, only alkali 15% or alkali 20% will be used to represent the pulping conditions. Table 3 shows the paper properties for unbeaten *Semantan* bamboo pulp according to bamboo portion that consisted of paper mechanical properties such as tearing, tensile and bursting index, and also the folding endurance of the paper sheet.

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Table 3: Unbeaten *Semantan* bamboo paper properties

Sample	Tear Index ($mN.m^2/g$)	Tensile Index (Nm/g)	Burst Index ($kPa.m^2/g$)	Folding (double folds)
T 15%	12.26	29.21	1.38	6
T 20%	13.45	32.54	1.54	6
M 15%	12.22	27.60	1.36	5
M 20%	12.08	30.22	1.52	9
B 15%	9.60	16.53	0.81	3
B 20%	10.95	25.38	1.19	5

Figure 1 shows the linear relationship between tearing and tensile index for unbeaten *Semantan* bamboo pulp. The tearing index varied in range of 9.60 to 13.45 $mN.m^2/g$ (Table 3). Tearing phenomena involved pulling out fibre from the paper and fibre breaking. Tearing index depends on the fibre length in a paper. Fibre length average in a raw material may not change during the pulping process. The degree of hydrogen bonding might depends on the fibre properties and the severity level of chemical treatment on the fibre (Zhao *et al*., 2002). This was observed in this study, due to bamboo has longer fibre length compared to wood fibre, thus it produced paper of better mechanical properties.

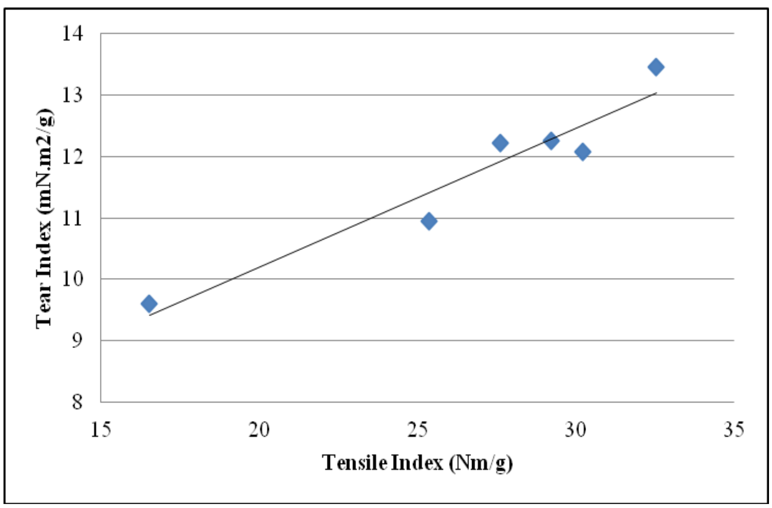

Figure 1: Tear index and tensile index for unbeaten pulp

In this study, the tensile index varied from 16.53 to 32.54 Nm/g (Table 3). For tensile index, top bamboo portion with 20% of alkali, again, produced the highest tensile strength compared to the other bamboo portion. Fibre strength properties depend on the individual fibre strength and bonding strength between fibres. The bonding strength between fibres occurs from the physical contact with hydrogen bonding between hydroxyl groups on the fibre surface area.

Folding endurance is an empirical testing that measures numbers of folds a paper can stand before its tensile strength falls under standard value. The paper was folded backwards and fronts repeatedly between two rollers that rolling at 120 double folds per minute (Casey, 1981). As shown in Table 3, the unbeaten *Semantan* bamboo paper has a very low folding endurance i.e. between 3 and 9 double folds. In this

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result, middle portion with 20% of alkali gave the highest double folds, but its lowest and highest double folds, 3 and 9 respectively, has no significant effects and irrelevant to be used for paper strength determination.

Bursting index for unbeaten *Semantan* bamboo paper was found to be from 0.81 to 1.54 kPa.m^2/g. It is considered as a relatively low reading to be considered as raw material for structural paper. The highest bursting index also was produced from the top portion with 20% alkali concentration. Bursting index is closely related with H-bonding between fibres. Higher H-bonding between fibres will increase the bursting index due to more forces are needed to break the surface of the sample. This happened on a paper with high strength fibre bonding.

Analysis of variance and Duncan's Multiple Range Test were done by using the SPSS software to show the significant difference between portion and alkali for unbeaten *Semantan* bamboo paper. Table 4 shows that the F-value of all paper mechanical properties are highly significant between the bamboo portion and alkali percentage applied, except for tearing index that was only affected by bamboo portion but not alkali percentage. It showed that bamboo portion affect the paper sheets produced and proved that bamboo is a hygroscopic material similar to wood that has different properties along the culm. The alkali percentage and pulping temperature also have significant effect on unbeaten *Semantan* bamboo paper properties. In this study, higher pulping condition produced higher unbeaten bamboo paper. This might due to more lignin was dissolved during pulping and thus improve the fiber to fiber bonding during paper formation. When the fiber is closed to each other, more bonding will be produced and this will increase the paper durability during paper testing.

Table 4: Summary of ANOVA for unbeaten *Semantan* bamboo paper properties

Variables	df	F-value (tensile index)	F-value (folding endurance)	F-value (bursting index)	F-value (tearing index)
Portion	2	145.76**	25.242**	127.542**	17.517**
Alkali	1	95.687**	29.959**	79.574**	4.852*
Portion X Alkali	2	15.256**	5.852*	8.020*	1.655ns

Note: **-highly significant; *-significant; ns-not significant

Table 5 shows the tear, tensile and burst index and folding endurance for beaten *Semantan* bamboo paper. Top portion of the bamboo with pulping conditions 20% alkali and 170ºC temperature was chosen to go through beating process to enhance the paper strength, as the beating process will make the fibre more flexible and increase the fibre to fibre bonding.

Major effects of refining of fibers that result in changes in fiber structure are categorized by many researchers (Loijas, 2010; Oksanen *et al.*, 1997; Page, 1989; Rene *et al.*, 2006). These are listed as: fibrillation (external fibrillation, internal fibrillation (swelling)), fines formation, fiber shortening and fiber straightening (Jimenez *et al*., 2009). When the fiber was beaten, the external and internal fibrillation will cause the fiber become more flexible and conformable, and thus also increased the surface contact area between fiber to fiber bonding during paper formation.

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Table 5: Beaten *Semantan* bamboo paper properties

Sample	Tear Index (mN.m^2/g)	Tensile Index (Nm/g)	Burst Index (kPa.m^2/g)	Folding (double folds)
T20 1000	23.03	41.23	2.58	48
T20 2000	27.13	49.36	3.51	283
T20 3000	25.66	55.75	4.27	618
T20 4000	24.01	62.22	4.79	1161
T20 5000	22.38	64.37	5.22	1201
T20 6000	21.58	69.05	5.41	1273
T20 8000	17.97	75.54	5.88	1294
T20 16000	17.33	82.66	6.84	1494
T20 24000	16.64	83.90	6.67	1769

Figure 2 shows the tear and tensile index for beaten *Semantan* bamboo paper. As can be seen, the tear index increased from 1000 revolutions to 2000 revolutions from 23.03 to 27.13 mN.m^2/g, but as early as 3000 beating revolutions, the tear index was started to decreased and the tearing index decreasing was continuously dropped until 24000 beating revolutions to only 16.64 mN.m^2/g. This results was slightly higher than reported by Yusoff, *et al.* (1992), that the tear strength of 3 years old tropical bamboo *Gigantochloa scortechinii*) soda pulp was 13.2 – 25.2 mN.m^2/g at 0 to 10000 revolutions.

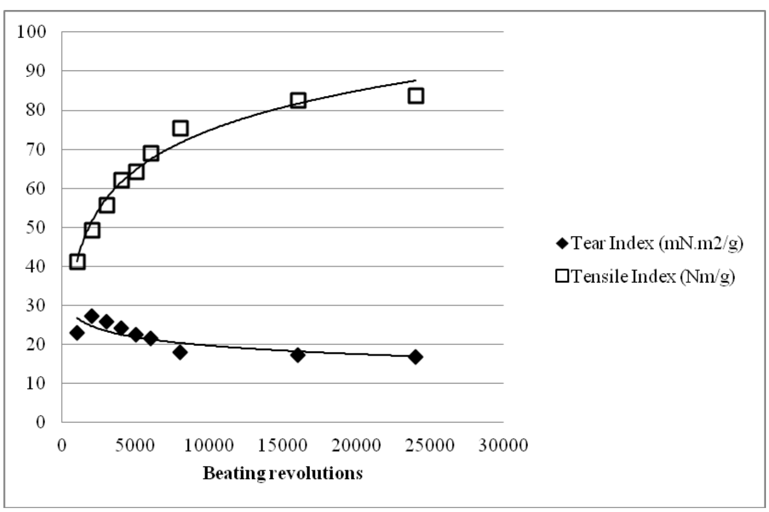

Figure 2: Tear and tensile index for beaten *Semantan* bamboo paper

The maximum in tear resistance is due to the fibre to fibre bonding which develops as beating proceeds. The tear resistance of paper made from unbeaten pulp is low because there is essentially no bonding to hold the fibres together. A slight amount of beating greatly improves tear resistance by providing some bonding between the fibres. However, as beating proceeds further, increased fibre to fibre bonding eventually tends to reduce sheet flexibility and thus localized any external stress applied to the paper, so that tearing can now proceed more easily.

On the other hand, tensile index was determined by pulling out the fibres from the paper sheet. As the beating revolution increased, the fibre to fibre bonding became closer to each other and high strength of stress was needed to break the paper sheet, thus increased the tensile index with the increasing of

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the beating revolutions. This study agreed with tearing and tensile index theory as the *Semantan* bamboo paper tearing index also decreased with the increased of beating revolutions and tensile index increased with the increased of beating revolution.

Figure 3 shows the burst index for beaten *Semantan* bamboo paper. The burst index kept increasing from 1000 beating revolutions to 16000 beating revolution and produced bursting index from 2.58 to 6.82 kPa.m2/g. At 24000 beating revolutions, the bursting index slightly drop to 6.67 kPa.m2/g. This is where the beating revolutions for this research was limited at 24000 revolutions due to the optimum beating revolutions of the paper had been found in bursting index, even though the tensile index and folding endurance keep increasing.

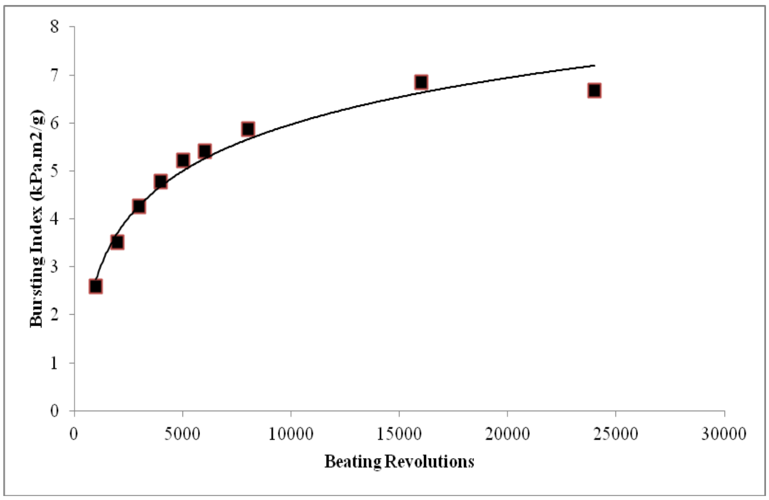

Figure 3: Burst index for beaten *Semantan* bamboo paper

Yusoff, *et al.* (1992) reported that burst strength for 3 years old tropical bamboo *Gigantochloa scortechinii* soda pulp was 4.5 to 4.7 kPa.m2/g. Sadawarte (1982) revealed the highest burst index of unbleached bamboo kraft pulp was occurred at 3500 revolutions was 5 kPa.m2/g.

Figure 4 shows the folding endurance for beaten *Semantan* bamboo paper. The folding endurance rose linearly with the increasing of beating revolutions, starting at 48 double folds at 1000 beating, up to 1769 double folds at 24000 beating. This finding was much higher than reported by Suphat (2007) that folding endurance for unbleached sweet bamboo alkali sulfite pulping with anthraquinone (AS-AQ) and conventional kraft pulping were 405 and 492 double folds respectively.

Similarly to tensile and bursting indexes, the increasing of folding endurance also influenced by fibre to fibre bonding and the fibre strength in the paper sheet. Whenever the fibre to fibre bonding increased with the beating revolution increased, the paper folding endurance become higher due to more double folds action were needed to be broken up the paper sheets. Furthermore, the improvement of the fibre flexibility due to mechanical treatment by beating process, produced fibres to be easily collapses during paper making process and this also contributed to higher fibre to fibre bonding in the paper sheet.

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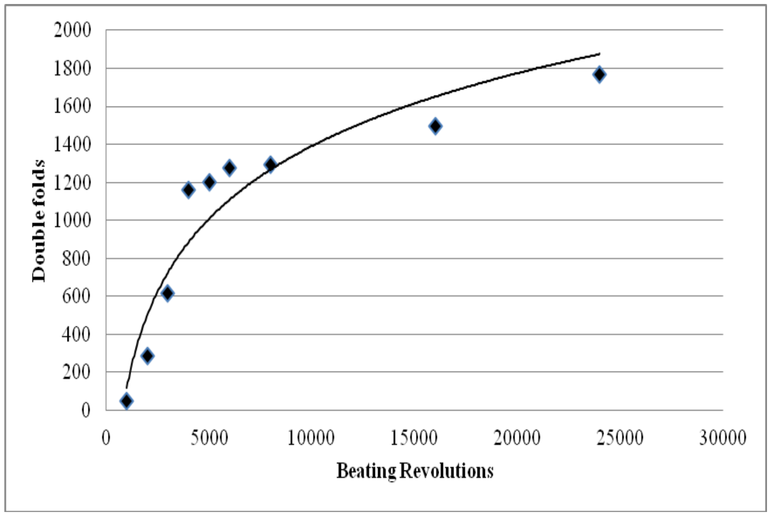

Figure 4: Folding endurance for beaten *Semantan* bamboo paper

Table 6 shows the ANOVA for beaten paper properties of top bamboo portion. It showed that every beating revolution was highly significantly different at significant level of $p \leq 0.05$ for all mechanical paper properties. This also showed that beating revolution affect the *Semantan* bamboo paper significantly in all mechanical properties tested. All paper mechanical properties increased with the increasing of the beating revolution except for tearing index due to different mechanism in determining the tearing strength. It was believed that beating process increased the fiber internal and external fibrillation and increased the surface contact area between fibers, thus produced more dense paper and higher strength properties.

Table 6: Summary of ANOVA on beaten top portion of *Semantan* bamboo paper properties

Variables	df	F-value (tensile index)	F-value (folding endurance)	F-value (bursting index)	F-value (tearing index)
Beating (rev.)	8	75.812**	10.679**	41.142**	17.575**

Note: **-highly significant; *- significant; ns-not significant

Table 7 shows the improvement of unbeaten *Semantan* bamboo paper in terms of percentage. The highest value from unbeaten paper was compared with the lowest beating revolution (1000). Mechanical properties of *Semantan* bamboo paper that consisted of tear index, tensile index, burst index and folding endurance improved by 71.23%, 26.67%, 67.53% and 433.33% respectively. This proved that *Semantan* bamboo paper properties can be enhanced by beating process and become value added material in pulp and paper industry. Furthermore the fiber has very high durability as it can received up to 24000 beating revolution before fiber failure occurred.

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Table 7: Comparison between unbeaten and beaten *Semantan* bamboo paper properties

Paper Properties	Unbeaten Paper (highest value)	Beaten Paper (1000 revolutions)	Increment (%)
Tear Index (mN.m^2/g)	13.45	23.03	71.23
Tensile Index (Nm/g)	32.54	41.22	26.67
Burst Index (kPa.m^2/g)	1.54	2.58	67.53
Folding(double folds)	9	48	433.33

4. Conclusion

Paper making for unbeaten bamboo portion that consisted of top, middle and bottom produced tensile index, tearing index, bursting index and folding endurance range from 16.52 – 32.54 Nm/g, 9.60 – 13.45 mN.m^2/g, 0.81 – 1.54 kPa.m^2/g and 3 – 9 doubles folds respectively. Top portion of *Semantan* bamboo has been chosen randomly for beating revolution optimization and the tensile index, tearing index, bursting index and folding rose tremendously to 41.23 – 83.90 Nm/g, 16.64 - 27.13 mN.m^2/g, 2.58 – 6.84 kPa.m^2/g and 48 – 1769 double folds respectively. Natural durability of bamboo fibre made them strong enough to be beaten from 1000 up to 24000 beating revolutions and most of the mechanical paper properties such as tensile, bursting and folding increased with increased beating revolutions. The increment of the paper mechanical properties at the lowest beating revolution (1000) was from 26.67% until 433.33%, thus proved that *Semantan* bamboo fiber can be good material for paper industry especially for those paper strength oriented industry.

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