CELLULOSE REFINING FOR FIBRE CEMENT: PART 2

LENGTH REDUCTION AND OTHER EFFECTS OF REFINING, TYING EVERYTHING TOGETHER

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ABSTRACT

Having established that Freeness is proportional to the square of the specific surface area of the fibres we now proceed to analyse in detail the response of the pulp to effective refining energy and refining intensity. We have 3 sets of data available for this purpose. The first was derived from a study to determine conditions under which cutting of the fibres could be limited to a specified minimum fraction of the original length and was reported at IIBCC 2016. The second comprised data from normal operation of a conical refiner set that was operating in a factory and as noted in Part 1, the motivation for collecting this data was to compare the performance of the double disc refiner set with the conical refiner. The third set of data was provided by OJI Fibre Solutions and comprises a comprehensive study of the refining response of P Radiata pulp primarily aimed for manufacture of Fibre Cement. The freeness in the first two sets of data was measured by the SR method and the third set was measured by the CSF method.

It is confirmed that there is a relationship between the Freeness and Effective Refining Energy but that this is moderated by the intensity of refining. It is also demonstrated that refiners become choked at high refining intensity and their effectiveness in developing freeness is reduced at high intensity.

KEYWORDS:

Cellulose refining, SR, CSF, Freeness, Refining Intensity

INTRODUCTION

We first consider the effect of refining on the change in length of fibres as well a changes in width, curl and kink.

Change in Length, Width, Curl and Kink with Refining

We examine the change in length, width, curl and kink using the datasets from the previous parts of this paper.

Length

It is well recognised that refining of pulp results in a reduction in the fibre length and this is significant for fibre cement strength as the length and bonding of the fibre determines whether a specific fibre bridging a matrix crack will pull out or break under load.

Measurement of Length

In paper technology fibre length may be measured in three ways by arithmetic mean (l_n), a length weighted mean (l_l) or as a weight weighted mean (l_w). In every case, the fibres are separated either by screen and measured in groups according to the screen size or separated and individually measured and classified. The various measures of average length are calculated as follows where n = number of fibres and l is the length of the group of fibres.

$$l_n = \frac{\Sigma_i n_i l_i}{\Sigma n_i} \qquad l_l = \frac{\Sigma_i n_i l_i^2}{\Sigma n_i} \qquad l_w = \frac{\Sigma_i n_i l_i^3}{\Sigma n_i^2} \qquad 9$$

Fibre lengths are weighted average on the basis that the longer fibres contribute more to the paper properties than short fibres. The suppliers of fibres for fibre cement usually quote the length weighted average length which means that the length of softwood fibres will be quoted at around 2 to 3mm. An equivalent arithmetic mean length will be about 1 to 2 mm.

Results of the Double Disc Refining and discussion.

We first examine the distribution of the fibre lengths during refining. The following table and graph show a typical result for refining the at 1.75J/m intensity and 3 different flow rates used in the investigation.

Table 9 Length, Percentage Fraction, Cumulative Fraction of Fibres refined in Double Disc Refiner (described in Part 1)

Length mm	550 l/m	550 cum	450 l/m	450 cum	350 l/m	350 cum
0		0		0		0
0.15	16.7	16.7	20.4	20.4	26.4	26.4
0.4	17.2	33.9	21.5	41.9	20.4	46.8
0.65	14.3	48.2	16.4	58.3	15.4	62.2
1.1	16.3	64.5	15.5	73.8	15.3	77.5
1.8	16	80.5	13.5	87.3	12	89.5
5	19.5	100	12.7	100	10.5	100

The table shows the length in the left column, followed by the individual percentages of fibres of that length, the cumulative percentage of fibres up to that length for each flowrate through the refiner set.

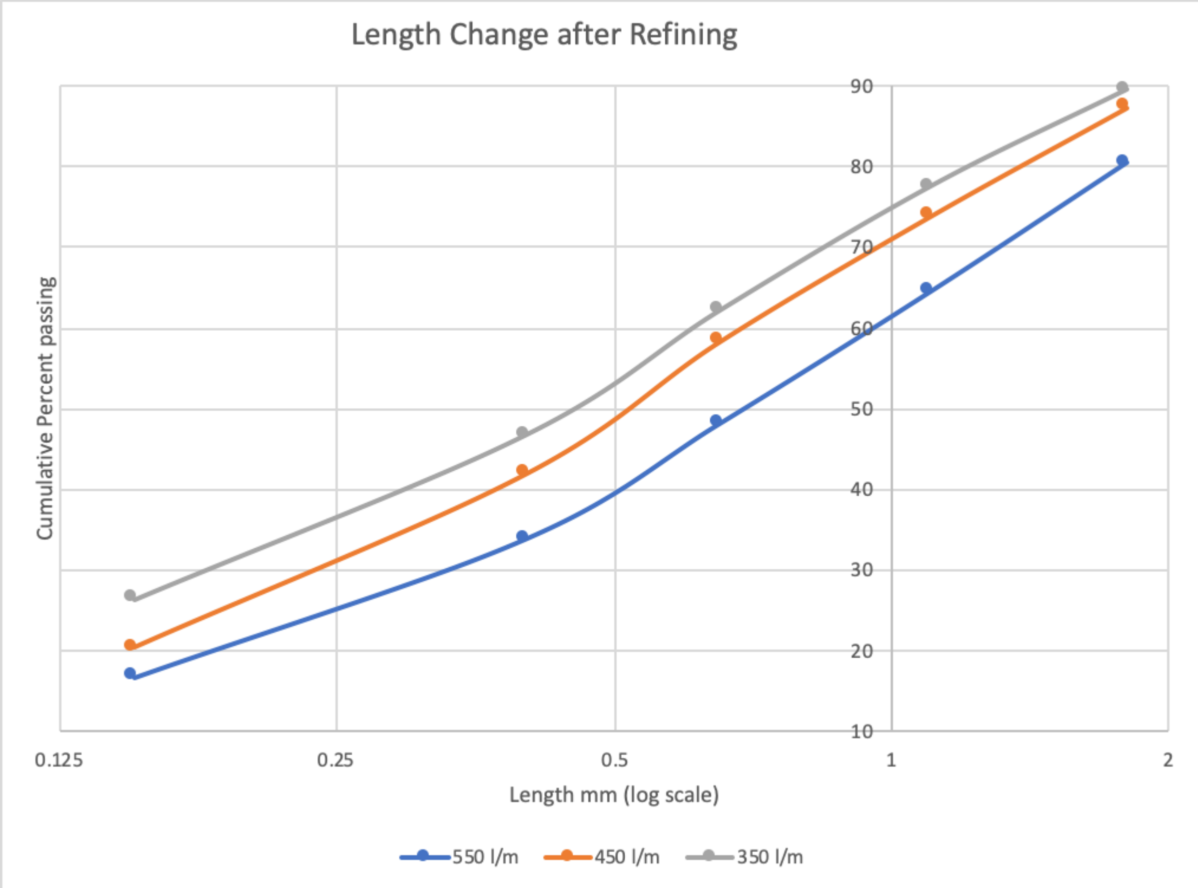


Figure 19: Cumulative percentages of fibre after various levels of refining in double disk refiner

The distribution seen in Figure 19 above is cumulative percentage of fibre length graphed on a log scale and as can be seen, is more or less linear; this is typical of length or diameter distributions of particulate systems. The mean diameter can be determined from the graph by determining the intersection of the 50% line with each of the cumulated lines on the graph. The fibres are reduced in proportion to the flow rate with slower flow rates associated with shorter average fibre length. By inspection we can see that the average length of the fibre processed at 550 l/min is about 0.65mm, at 450 l/min it is about 0.55mm and at 350 l/min it has dropped to about 0.4mm. (it is a log scale).

The lines are also parallel and this indicates that all the fibres are being cut equally irrespective of length. This should be expected and confirms mechanism of cutting that the amount of cutting is proportional to the processing time for any particular refining intensity i.e. the number of bar crossings compared to the flow rate.

We now examine the reduction in fibre length with refining. We will consider the change in the arithmetic mean and the length weighted mean.

The investigation was undertaken over two days using separate batches of pulp with different settings for the refining intensity. As will be seen in the data there is a significant difference between the lengths of the two batches of pulp and therefore the relative lengths of the pulp were used rather than the absolute values of length.

Table 10 below shows the intensity of refining, the flow rates through the refiner system, the SR measured, the change in SR, the square root of the change in SR, the lengths as defined above and their relative change in length.

J/m	L/min	Eeff	SR	△SR	△SR^0.5	L(n)	L(n)/L(N)o	L(L)	L(L)/L(L)o
0.00		0.000	12		0	1.81	100.00%	2.71	100.00%
1.50	550	0.196	16	4	2	1.35	74.59%	2.30	84.87%
1.50	450	0.222	23	11	3	1.17	64.64%	2.10	77.34%
1.50	350	0.295	27	15	4	1.02	56.35%	1.91	70.48%
		0.000			0		100.00%		
1.75	550	0.201	22	10	3	1.26	69.61%	2.24	82.66%
1.75	450	0.261	25	13	4	1.03	56.91%	1.93	71.22%
1.75	350	0.337	34	22	5	0.92	50.83%	1.74	64.21%
0.00		0.000	12		0	1.45	100.00%	2.41	100.00%
2.00	550	0.254	16	4	2	0.89	61.38%	2.48	102.90%
2.00	450	0.321	29	17	4	0.76	52.41%	1.39	57.68%
2.00	350	0.406	47	35	6	0.62	42.76%	1.08	44.81%
		0.000			0		100.00%		
2.25	550	0.295	18	6	2	0.84	57.93%	2.31	95.85%
2.25	450	0.369	39	27	5	0.72	49.66%	1.56	64.73%
2.25	350	0.468	56	44	7	0.59	40.69%	1.68	69.71%

Table 10: Fibre Cutting Data and related information

We first examine the relationship between flowrate through the refiner system and the change in relative fibre length at different intensities. Figure 20 shows the results.

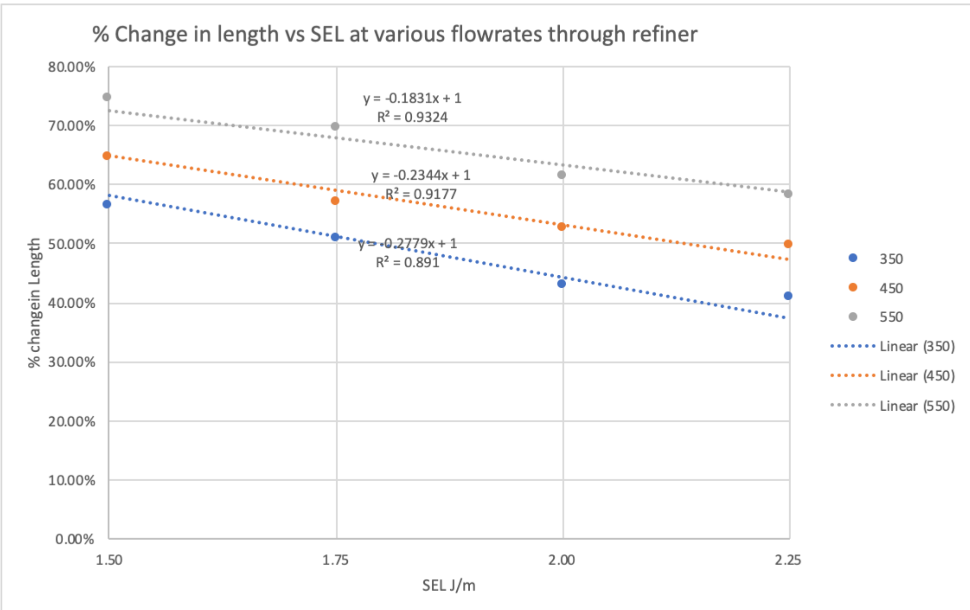


Figure 20: Change in length related to refining intensity

As there is a clear linear relationship between the flowrate through the system and the change in length modified by refining intensity, we can conclude that longer processing of the fibre reduces its length proportionately. This prompts us to examine the relationship between effective refining energy and the change in length. Figure 19 graph shows the result where we have shown the effect of effective refining energy and we have also separated out the changes according to the SEL.

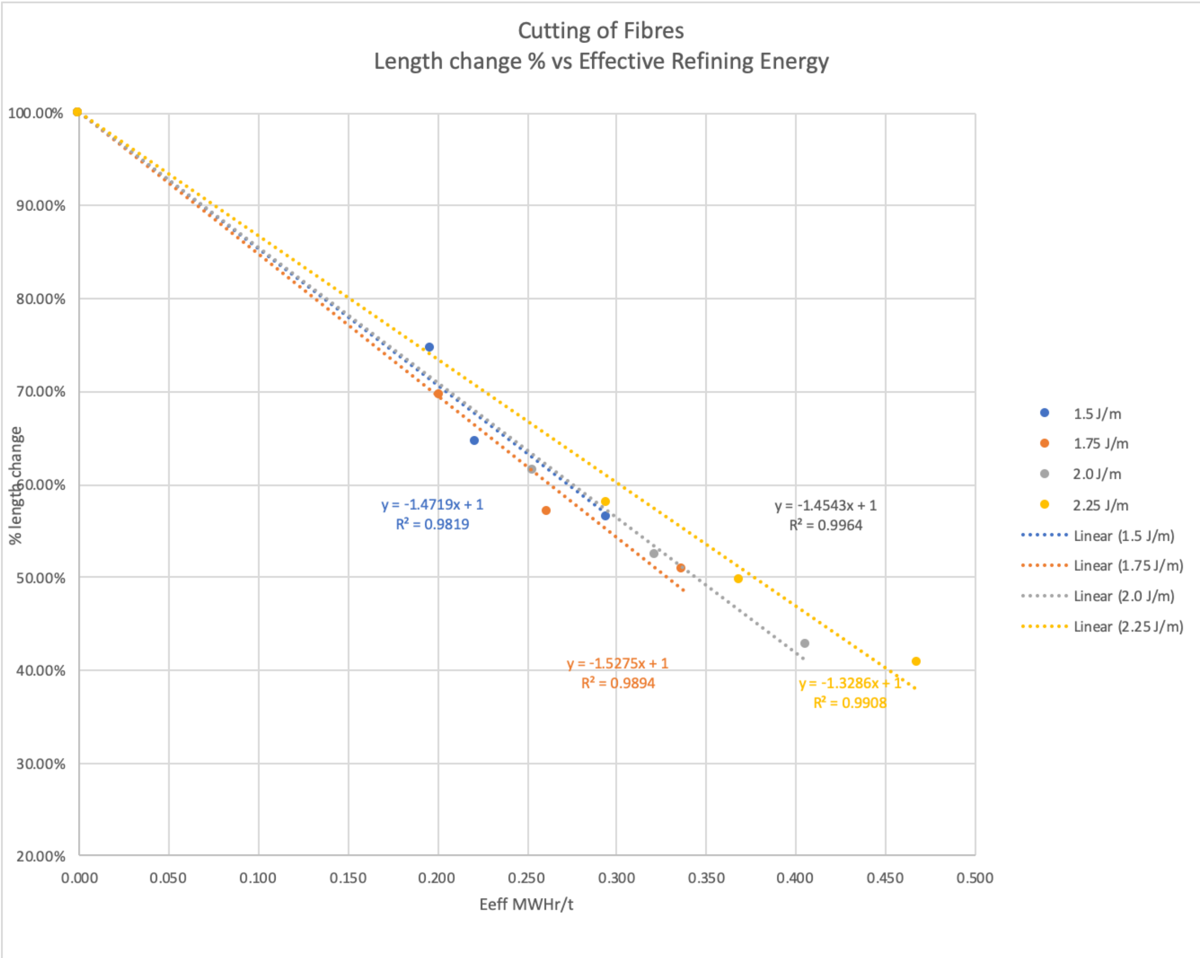


Figure 21: Length reduction according to Effective Refining Energy and Refining Intensity

As we can see there is a strong linear relationship between the effective refining energy and the reduction in length and that this relationship is modified by the intensity of refining. If we now take the coefficients of reduction of length we find that the coefficients first rise and then fall.

SEL J/m	Reduction Coefficient
1.5	1.4712
1.75	1.5275
2	1.4534
2.25	1.3286

Table 10: Fibre Length Reduction Coefficients vs Intensity

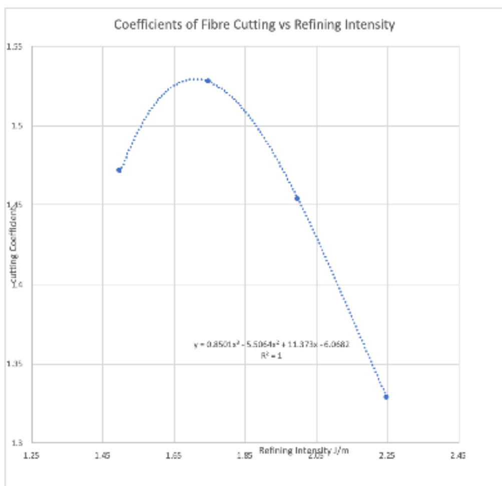


Figure 22: Coefficients graphed

. The relationship between the coefficients follows the same cubic polynomial pattern as we observed for the effects of refining energy on freeness and points to our previous conclusion that beyond a certain intensity i.e. below a specific clearance between the blades of the refiner, passage of fibres between the rotating surfaces of the refiner is restricted and flow within the refiner occurs mainly in the grooves between the blades. In other words the efficiency of the refiner in producing cutting (or freeness or specific surface area of the fibres) is reduced at high intensities.

It will be noted that the coefficients do not differ much with changing SEL and from a pragmatic point of view the coefficients can be ignored as will be seen from Figure 23 where the total data is graphed.

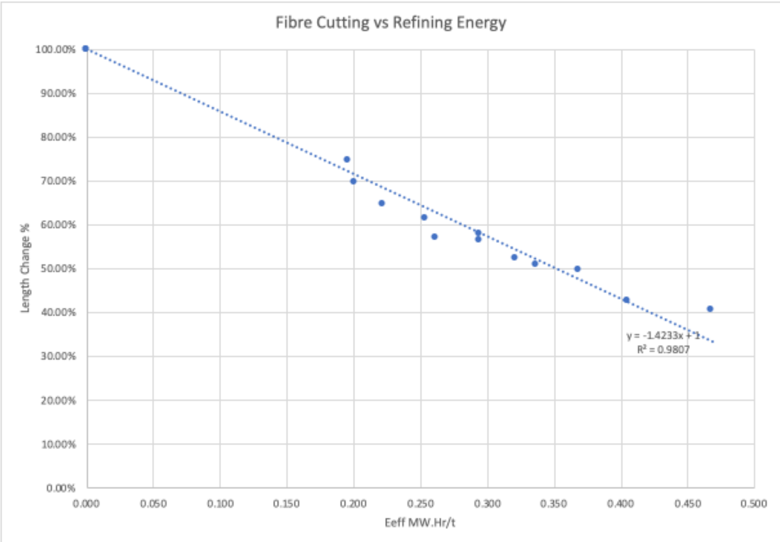


Figure 23: Fibre cutting vs Effective Refining Energy

It will be seen that the aggregate data represents the relationship very well and the effect of SEL on the reduction in fibre length is not very large. There is a greater divergence of the points from the regression line where the intensity is highest but this divergence is small.

We now repeat the analysis using the length weighted average length. Figures 24 and 25 illustrate.

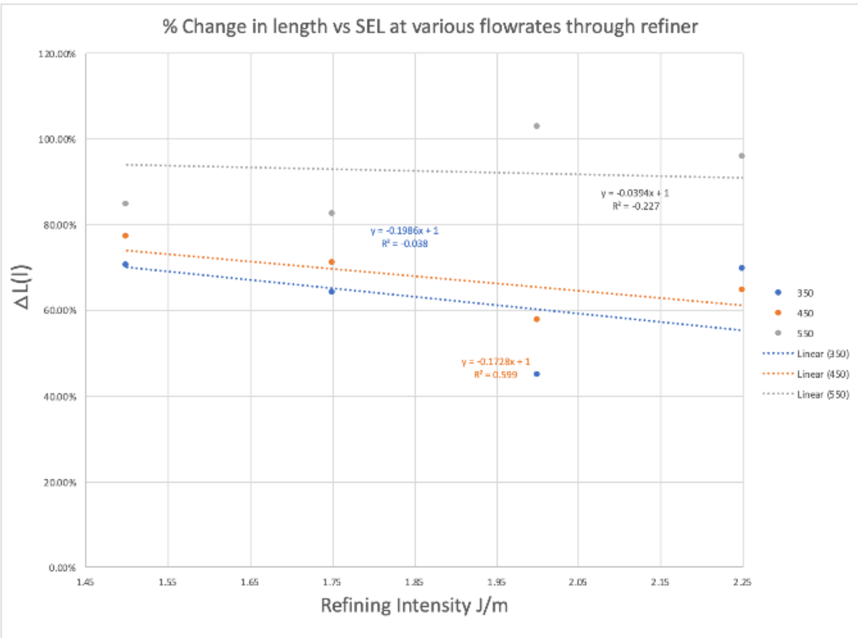


Figure 24: Length weighted Length reduction versus Refining Intensity

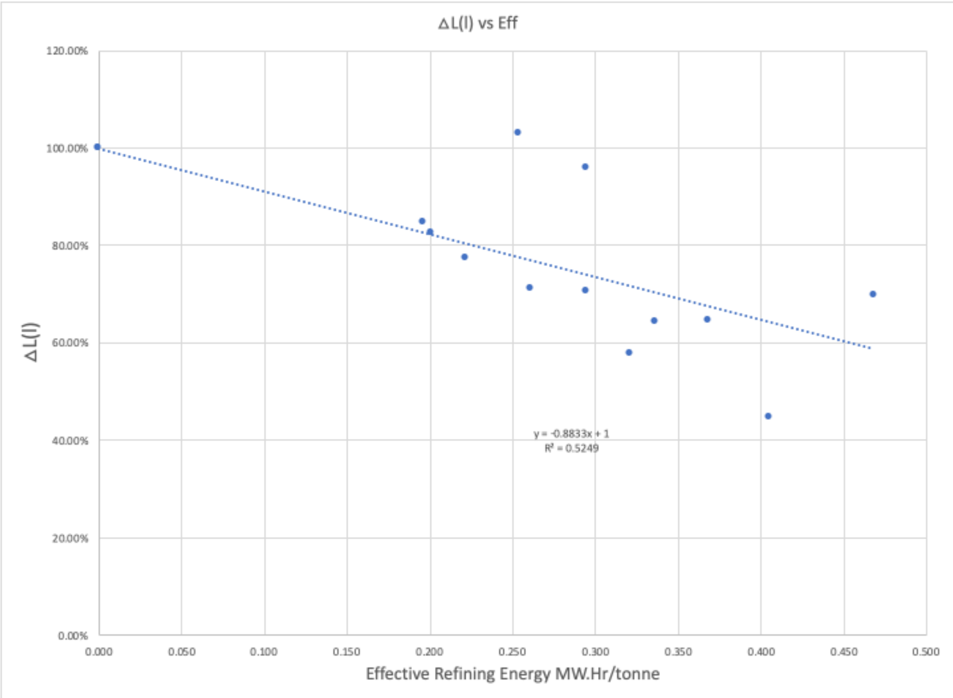


Fig 25: Length weighted Length reduction versus Effective Refining Energy

It is immediately apparent in Figure 24, that the simple relationships derived for the unweighted average length do not apply to the length weighted results as the regression coefficients for the linear relationships are quite low with R^2 ranging from -0.227 to 0.599 by comparison with those of the unweighted data where R^2 is uniformly close to 0.99.

This reflects the fact as demonstrated in figure 19 that cutting of fibres occurs uniformly across all of the fibres presented to the refiner bars and that shorter fibres are equally likely to be cut as the longer fibres. When the Length weighted Length is used to characterise the fibre lengths, the longer fibres are emphasised relative to the shorter fibres and it is inevitable that this will distort the change in actual length of the fibres during refining.

In anticipation of later discussions I conclude that the length weighted measure of fibre length and its change with refining are of little value for the prediction of fibre cement behaviour.

OJI Fibre Services K25 Softwood Pulp for Fibre Cement - Length Reduction

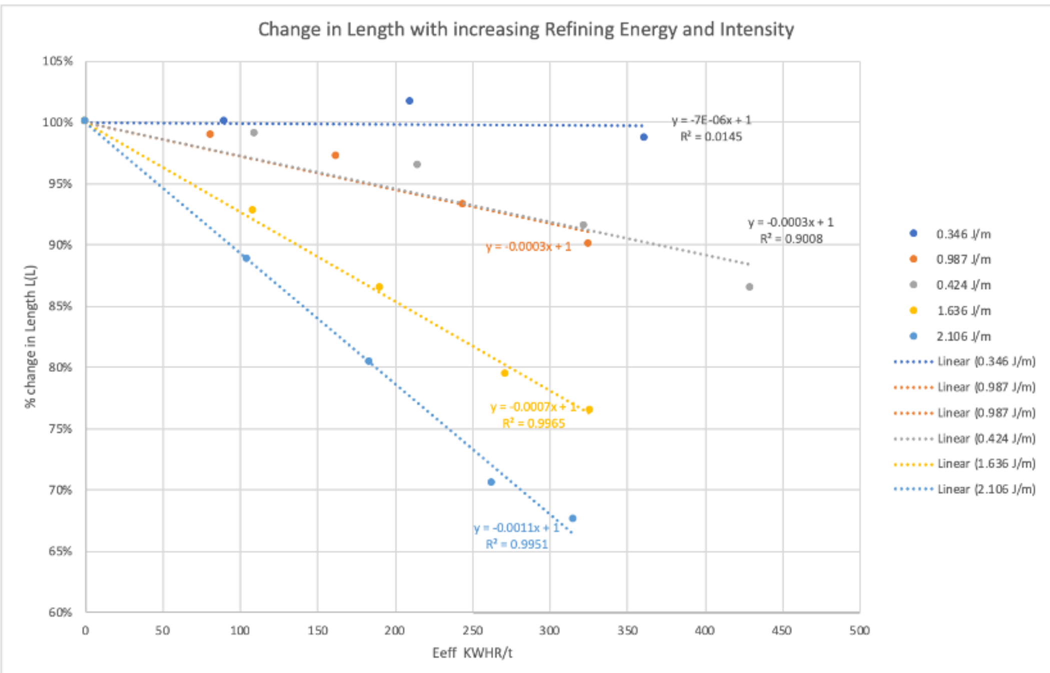
We now consider the results of refining K25 Fibre as shown in Table 11

Table 11: Results of refining K25

Run ID	Specific edge load Ws/m	Temp rise oC/min	Energy input kWhr/t	Freeness	Fibre Length	Relative Fibre Length	Fines	Coarseness	Total Fibres	Fibres Generated
160517D			0	740	3.02	100%	2.43	0.229	11181	0
160517D	0.346	1.8	90.3	727	3.02	100%	2.65	0.224	11933	752
160517D	0.346	1.8	210.5	680	3.07	102%	2.32	0.203	11670	489
160517D	0.346	1.8	361.1	675	2.98	99%	3.01	0.216	13590	2409
160517D	0.346	1.8	541.7	460	2.97	98%	3.12	0.201	15217	4036
160518D			0	760	3.04	100%	2.24	0.220	11281	0
160518D	0.987	2.07	81.4	690	3.01	99%	2.65	0.223	12180	899
160518D	0.987	2.07	162.6	610	2.95	97%	2.82	0.217	13407	2126
160518D	0.987	2.07	244.2	486	2.83	93%	3.45	0.234	14238	2957
160518D	0.987	2.07	325.1	348	2.74	90%	3.68	0.215	16645	5364
160519D			0	765	3.04	100%	2.48	0.270	9520	0
160519D	0.424	1.84	109.2	706	3.01	99%	2.66	0.230	11795	2275
160519D	0.424	1.84	215.2	621	2.93	96%	2.96	0.209	14186	4666
160519D	0.424	1.84	322.6	553	2.78	92%	3.67	0.268	12909	3389
160519D	0.424	1.84	429.9	431	2.63	86%	4.05	0.218	17598	8078
160805C			0	745	3.05	100%	2.27	0.209	11961	0
160805C	1.636	2.28	108.9	652	2.83	93%	3.06	0.228	13466	1505
160805C	1.636	2.28	190.5	512	2.64	86%	3.56	0.223	15803	3842
160805C	1.636	2.28	272.0	350	2.42	79%	4.33	0.205	20082	8121
160805C	1.636	2.28	326.3	270	2.33	76%	4.62	0.200	21716	9755
160805D			0	770	3.05	100%	2.19	0.227	11056	0
160805D	2.106	2.48	105.1	666	2.71	89%	3.11	0.226	14197	3141
160805D	2.106	2.48	184.1	500	2.45	80%	3.74	0.217	17542	6486
160805D	2.106	2.48	263.1	316	2.15	70%	4.56	0.201	22369	11313
160805D	2.106	2.48	315.5	240	2.06	68%	4.97	0.198	24158	13102

We first consider the reduction in fibre length with applied refining energy and on graphing the results separately in Figure 26 for each SEL level we obtain the following.

Fig 26: K25 Change in Length with increasing Refining Energy and Varying Refining Intensity

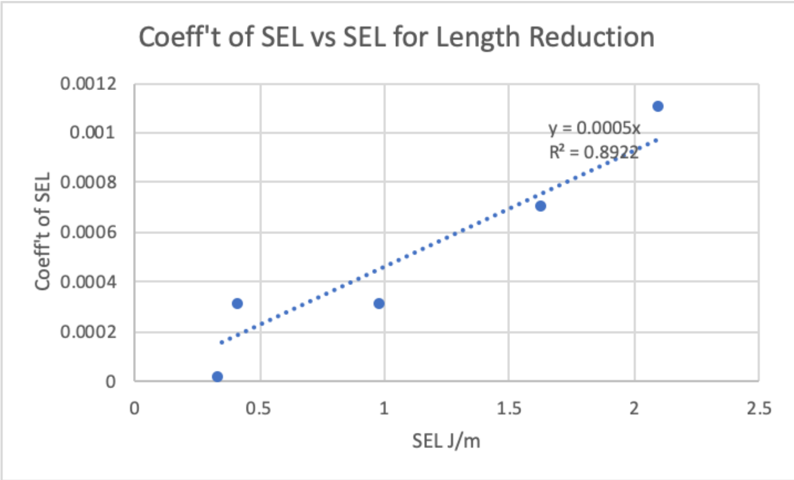


In the graph we also apply to each set of data a linear regression forced through the point 0,1 to obtain for each the relationship between the applied energy and the change in length. As can be seen there is good correlation for all of the regressions except for the lowest intensity. If we extract the coefficients for each level of SEL we obtain table 12 which is graphed in Figure 27.

Table 12 K25 Length Reduction

Fibre Length Reduction	
SEL J/m	Coeff't of SEL
0.346	0.000007
0.424	0.0003
0.987	0.0003
1.636	0.0007
2.106	0.0011

Figure 27



In this case there is a reasonable linear relationship between the SEL and its coefficient again after forcing the regression through 0,0. So we could write a relationship to determine the likely length reduction as follows.

$$L = 1 - 0.0005.SEL.E_{eff} \dots\dots\dots\dots\dots\dots 10$$

Where L is the average fibre length, SEL is as previously described and E_{eff} is the applied effective refining energy in this case in kW.Hr/tonne.

Fines and Coarseness

We can also consider the development of fines is the same manner as above, except of course that fines increase with increasing refining energy. We use the same approach by determining the increase in fines from the starting point and we obtain a linear increase in fines with an increase in a refining energy and intensity.

We can also apply the same method to the coarseness of the fibre where it first appears there may be a trend to decrease the coarseness with the increase in refining energy. However this proves to be elusive and it appears that the coarseness is not consistently affected by refining.

Width, Curl and Kink[12]

The only data that we have for width, curl and kink is for the fibre that was reported for the cutting trials.

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[1] Detailed data on development of Fineness, Coarseness, With Curl and Kink have been omitted here for brevity and because they do not add to the overall conclusions in fibre cement. Details of the changes observed allow us to make the conclusions stated here.

[2] Definitions

Width – cellulose fibres are hollow tubes when in their wood, however when extracted from the wood they collapse and form essentially a flat tape. The width of this tape can be measured.

Curl – when treated at high consistency (particularly) the fibres tend to adopt a spiral conformation where they remain permanently bent and they appear similar to a woven tape that has been deliberately curled for decorative packaging

Kink – kink is similar to curl except that the fibres are creased like a piece of folded paper. Kink is measured in no of kinks per metre of fibre.

The data shows the refining intensity, the effective energy of refining and the flow rates through the refiner set along with the measured widths, kink and curl. We have also calculated the change in width, kink and curl as a percentage of the same parameter as the unrefined pulp. There is very little variation with kink and curl although the fibre width tends to increase at high refining energy and intensity. The increase in width is consistent with the suggestion that the refiners become choked at high intensity of refining i.e. the refiner gap tends to zero.

We have also calculated the mean of each parameter, its standard deviation and its coefficient of variation. The coefficient of variation of each parameter is fairly low indicating that there is little variation in the parameter with increase in effective refining energy.

PULLING IT ALL TOGETHER

We have so far shown that the effect of effective refining energy in proportion to energy imparted on the cellulose fibres is to

- increase the fibre specific surface area
- decrease the average fibre length

We now wish to determine the effect of refining on the properties of the fibre along with a simplified theory of short fibre reinforcement of brittle composites to determine the likely changes in relative strength and compare that with practice. We will use the following calculation scheme to effect this.

$$E_{EFF}^2 \Rightarrow \text{SR or CSF measurement} \Rightarrow R_f \Rightarrow SSA_v \Rightarrow l_{crit}$$

$$E_{EFF} \Rightarrow l_n \Rightarrow \%l_n > l_{crit} \Rightarrow \text{Tensile Index}$$

Specific Surface Area of Fibre

In the above scheme we start with a fibre and using the input refining energy we determine the SR or CSF freeness . From the freeness we determine R_f which is the specific resistance of the freeness filter pad and determines the specific surface of the fibre SSAv. From SSAv we determine the fibre critical length l_{crit} i.e. the length of fibre that is sufficiently embedded to break during a tensile test.

We also use the input refining energy to determine the length change in the fibre and from the length distribution we determine the percentage of fibres greater in length than l_{crit} and from this an indication of the likely tensile strength of the fibre cement composite.

It was found when the freeness was calculated using equation 1 (from Part 1) that the ratio of InvCSF/CSF is directly proportional to R_f allowing us to estimate R_f from CSF without having to make a separate measurement. A similar relationship may be inferred for SR/InvSR although the proportionality is not same. Thus starting with the SR or the CSF we determine R_f from the empirically derived relationships between R_f and the ratios InvCSF/CSF or SR/InvSR. We then use equation 2 (from Part 1) to determine the specific surface area of the fibre in terms of surface area/volume of fibre having dimensions mm^{-1}.

Critical Fibre length

We assume that a fibre bridges a crack in the matrix and then determine its behaviour when the fibre cement is put under tension. The fibre will break if it is strongly enough bonded to the matrix and the length of fibre that is sufficient to ensure fibre breaking is called the critical length (l_c). l_c will be determined by the cross-sectional area of the fibre, the fibre strength, the bond strength of the fibre to the matrix and the surface are of the embedded fibre.

Typical P. Radiata cellulose fibre strength (has been measured at approximately 500 N/mm^2. The fibre cross-sectional area can be calculated from typical values of fibre coarseness which is usually expressed in mg/m. For P. Radiata fibres, the coarseness is typically 0.24 mg/m (equivalent to $0.24*10^{-3}$ mg/mm) and is unaltered by refining. The density of cellulose is 1.5 g/cm^3 which gives a cross-sectional area of $0.24*10^{-3}/1.5 = 0.16*10^{-3}$ mm^2.

Breaking load per fibre (P_f) is therefore

$$P_f = A_f * \sigma_f = 0.16 * 10^{-3} * 500 = 0.08 \text{ N} \qquad 11$$

This load must be supported by the shear load in the fibre embedded in the matrix across the crack. We now need to determine the surface area of the fibre that is embedded from its end to the crack. From our knowledge of R_f we can determine the specific surface area of the fibre in mm^2/mm^3 i.e. 1/mm or mm^{-1} and from this we can determine the surface area per unit length of fibre (per mm). Thus the embedded area A_e is

$$A_e = l * A_f * SSA_v \text{ mm}^2 \qquad 12$$

Which becomes $A_e = A_f * SSA_v$ mm^2 when $l = 1$ mm 13

From this we can derive l_c by dividing the breaking load by the shear force necessary to break the bond between the fibre and the matrix taking into account that the shear force on the fibre varies linearly from its embedded end to the crack.

$$l_c = 4\,\frac{P_f}{A_e} = 4 * \frac{A_f * \sigma_f}{A_f * SSA_v * \tau} = 4 * \frac{\sigma_f}{SSA_v * \tau} \qquad 14$$

Where τ = bond strength of the fibre to the matrix.

Fibre are not of uniform length and they typically range from 0 to around 5 mm in length in most softwood pulps. Therefore consider any crack that is bridged by say 100 fibres there will be some that are greater than the critical length and embedded so that they break; there will also be some that are less than the critical length and there will be some that are greater than the critical length but have one end that is embedded in the matrix such that there is insufficient length from their end to the crack that can cause them to break.

In Hatschek machine made fibre cement the fibres are typically laid at an angle to the axis of the machine that increases the length of embedment necessary to ensure breakage of the fibre. There is a further complication with very slender fibres such as cellulose that they usually do not lie straight and unbending or uncurling the fibre is necessary before that fibre can be fully loaded. There are also cranking effects in the fibre where an angled fibre emerges from the matrix at the crack. Thus the analysis of the fibre loading during a tensile or flexural test is somewhat complicated.

To overcome these problems, a simplified view of the fibres is considered. We consider fibres bridging a crack to be load bearing only if they are considerably longer than the critical length. The fibres are not all the same length so in any sample of the fibres some will be less than the critical length and some longer. Clearly there will be some fibres in the range of length $2*L_{crit} > L > 4*L_{crit}$ that will carry sufficient load to break and there will be some in this range that will also be insufficiently embedded to break and will pull out. However using only the proportion of fibres greater than twice the critical length will give some indication of the likely relative strength of similar composites. We will use this to show how the fibre distribution and degree of refining is likely to affect the strength and other mechanical properties of these composites.

Fibre Length Distributions

It is convenient to plot the cumulative percentages of the fibre up to a particular length. It is found that these percentages plot to a sigmoidal curve when plotted against the linear length. As expected this curve plots to a line when percentage is plotted against the logarithm of length and the curve is truncated at both the top and the bottom. The linear relationship between log of length and percentage of fibre less than that length is used to easily determine the proportion of fibres longer than any length. Figure 28 shows the results for the fibre length distributions where the fibre was refined at 1.5 J/m intensity. The lines from top to bottom show refining in the continuous refiner at 350, 450 and 550 l/min respectively. The equations on the chart are determined from the trendline

Figure 28: Fibre Length Distribution at 1.5 j/m refining intensity

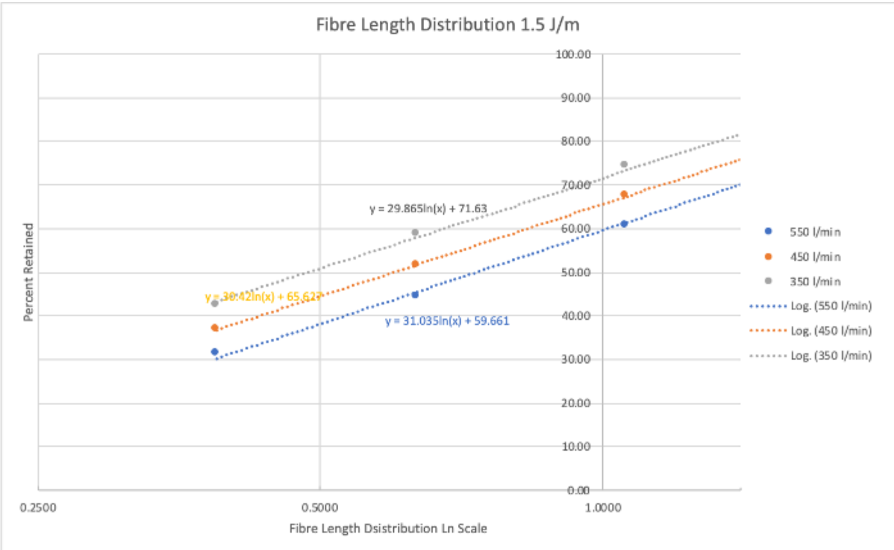


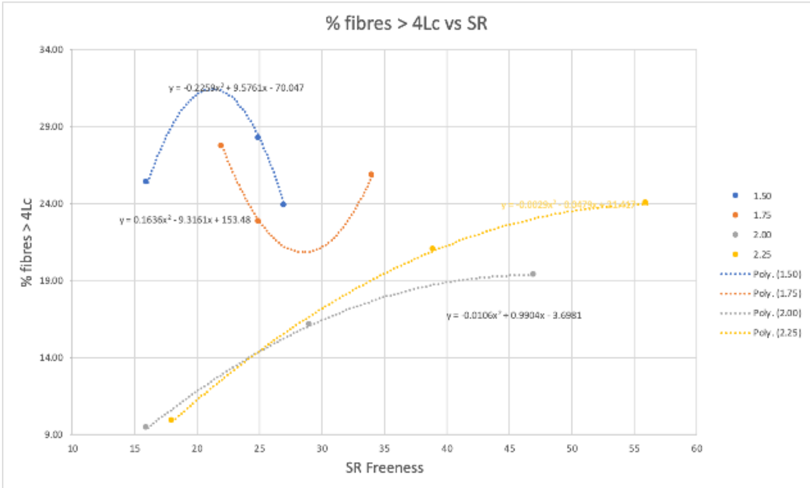
Table 13 Proportion of Fibre of X*L_{crit}

Factor	x	4			
SR	Intensity	Lcrit mm	Coefficient	Constant	%> X* Lcrit
	J/m		Ln(L)		
16	1.50	1.6209	31.035	59.661	25.35
25		1.2253	30.421	65.627	28.19
27		1.1632	29.865	71.63	23.86
22	1.75	1.3320	34.378	62.453	27.69
25		1.2253	30.102	71.0776	22.81
34		0.9856	28.399	74.592	25.82
16	2.00	1.6209	30.668	75.763	9.43
29		1.1069	29.057	80.971	16.08
47		0.7512	25.573	87.96	19.36
18	2.25	1.5099	30.47	77.574	9.87
39		0.8847	27.127	82.365	20.96
56		0.6271	25.573	87.96	23.98

Similar graphs can be drawn using the data from the other results from the continuous refiner. In each case we can derive an equation for the cumulative percentage of fibre less than a specific length. The adjoining table results where we calculate the percentage of fibres greater than the critical length as previously calculated. We have also included a factor to adjust the length of the fibres of interest so that we can experiment with the results.

Inf Figure 29 we graph the proportion of fibres greater than x*L_{crit} against the freeness of the refined pulp to obtain an indication of the relative strength of the fibre cement as it varies with the freeness of the pulp. The following graph shows the results where x = 4 i.e. the percentage of fibres greater than 4 times L_{crit} is plotted against SR.

Figure 29: Fibres > 4*L_{crit} vs SR



Discussion

Figure 30 Strength vs Freeness

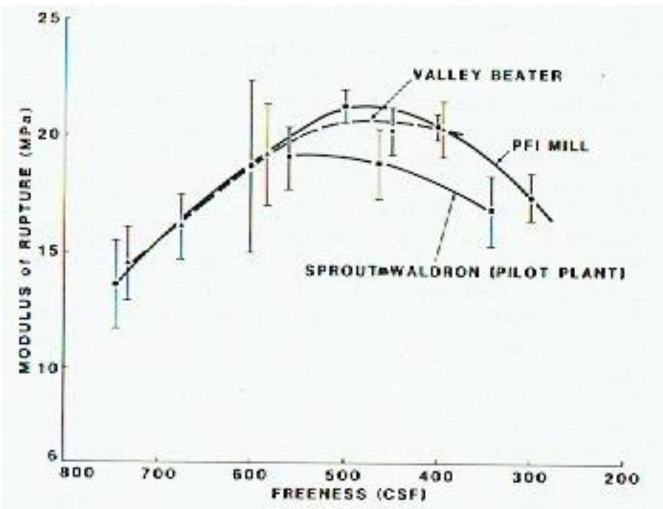


Fig. 2 — Flexural strength (oven dried) *versus* freeness.

Our expectation of the variation of strength with refining has long been known and for autoclave cured fibre cement, it has been empirically determined that fibre cement strength varies with the degree of refining first rising as the pulp is refined, peaking and then declining after the peak strength has been achieved.

Some typical results from Coutts and Ridikas, 1982[3] are illustrated in Figure 30 where the measured flexural strength of fibre cement has been graphed against the freeness of various pulps refined in different equipment.

This is the normal experience of the fibre cement industry and this is the normal expectation for flexural strength. While this may be the normal expectation this author's experience has been a little different and this seems to be reflected in the result of this study. It was the experience of this author that freeness is not a fully reliable predictor of flexural strength on a day by day basis.

In this investigation we had the luxury of knowing the size distribution of the fibres and as can be seen the pulp refined at 1.5 and 1.75 J/m respectively was considerably longer than the pulp refined at 2 and 2.25 J/m. These pulps were refined on two successive days and were of different batches. Because our investigation was intended to determine the effect of refining intensity on the length of the pulps we did not attempt to separate the strength test results for each of the differently refined pulp. Indeed it would not have been possible to do this in a busy factory because we had limited storage for refined pulp and we only refined sufficient pulp to obtain samples for fibre analysis.

Referring now to our results we see that with the exception of the results from refining at 1.75 J/m intensity the curves of % fibres greater than 4*L_{crit} are concave. This follows our expectation that as the fibres are shortened and their bond to the matrix is increased by refining there comes a point that the increase in surface area is

[3] Coutts R.S.P and Ridikas V. "Refined wood fibre-cement products", Appita Journal, Vol 35, No 5, pp395-400, March 1982

insufficient to overcome the effect of reduction in length of embedment. Thus the strength initially rises and then falls. The point of maximum strength however is also dependent on other factors and from these results the distribution of fibre lengths appears to be critical. In the example above the fibres of the first two tests were longer and had a wider distribution of fibre lengths while the fibres in the last two tests were shorter and had a narrower distribution of fibre lengths. I speculate therefore that a specification of fibres for fibre cements should also include fibre length distribution as a criterion for selection. I add a caution that this conclusion is based on the results applicable only to one species of pulp and since it is known that the internal structure of cellulose fibre is species dependent, this conclusion should not be randomly applied to all pulps.

The results from 1.75 J/m intensity refining are anomalous but it should be noted that the difference in percentage of fibres > 4* L_{crit} is quite small and this result could be just random chance.

Findings from the Investigation

We can come to the following conclusions

1) Significance of Freeness
   a) Freeness (measured either by CSF or SR) develops with the square of the effective refining energy.
   b) Freeness is proportional to the square of the specific surface area of the fibres being measured.
   c) Specific surface of the fibres is therefore developed linearly with the input of effective refining energy
2) Refining of the Fibre
   a) Refining the fibre decreases the length of individual fibres linearly with increasing effective refining energy.
   b) All fibres are reduced in length in equal proportions.
   c) The use of length weighting of fibre length is deceptive as it emphasises the proportion of longer fibres
3) Refining Intensity
   a) Higher intensity refining tends to cause a greater reduction in fibre length at the same effective refining energy
   b) Increasing refining intensity to very high levels reduces the effectiveness of refining probably because there is insufficient gap between the refiner bars to allow the fibres to pass between them and be refined. This also shows in the width of the fibre that is essentially unaltered until high intensity is used.
   c) Although there is a greater decrease in fibre length at moderate to high intensities compared to low, the use of a general relationship ignoring intensity to determine the change is length does not introduce much error.
   d) For these fibres there was no generation of kink or curl at any intensity of refining.
4) Refining and Strength
   a) While it was not possible to confirm the generally accepted relationship between fibre cement strength development and freeness, it is possible to infer from the results that there will be maximum strength at a specific freeness for a particular fibre.
   b) The freeness at the maximum strength appears to depend on the fibre length distribution and the response of the particular fibre to refining

What is next?

There are clearly several unanswered questions revealed by the above. These are

1) Confirm the models of the freeness testers that are revealed in the references and specifically determine the voidage of the filter pads produced in the test equipment.
2) Prove that the linear relationship between R_f and freeness/inverse freeness (SR/Inv SR or Inv CSF/CSF) is mathematically consistent with the models.
3) Set up a series of experiments to determine the relationship of strength to the properties of the refined fibres. This should include several different species of fibres.
4) Develop a sound model of the mechanical properties of fibre cement composites and relate that to the fibre properties

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REFERENCES