7 Study of fibre-fibre contacts and verification of the model for number of fibre-fibre contacts and expressions for relative bonded area *(RBA)*

7.1 Introduction

In Chapter 3, we have presented a new model for the number of fibre-fibre contacts (Equation 3.11). This model has been further extended to derive expressions for Relative Bonded Area (RBA). In this chapter, we will present the experimental verification of the model.

Chapter 2 has reviewed that no technique is available for measuring the number of fibre-fibre contacts directly in paper. For the first time a new technique that can measure fibre-fibre contacts directly in paper has been developed in this project. The new technique involves resin embedding and confocal laser scanning microscopy and has been detailed in Chapter 4. Using the new technique, we obtained high quality cross-sectional images of the samples in which some fibres or fibre segments were imaged along their long axes. These fibres were chosen as fibres of interest for the measurements of fibre-fibre contacts. The measured results, including the nature of each fibre contact, the number of fibre-fibre contacts, the lengths of the free fibre segments and the out-of-plane angle of each free fibre segment, will be discussed in this chapter. The effects of fibre length and fibre cross-sectional shape on the properties of fibre fibre contacts are also studied. It is shown that a two parameter Weibull probability density function provides a good fit to the measured distribution of free fibre length. The measured number of fibre-fibre contacts will be used to verify the model for number of fibre-fibre contacts presented in Chapter 3.

Chapter 2 has also reviewed that measurement of RBA is always problematic. In this chapter, we will present two methods for measuring RBA, viz. by measuring the BET area of the sheets by nitrogen adsorption technique (RBA_{N_2}) and by measuring scattering coefficients of the sheet (RBA_{sc}). The measured results of RBA will be used to further check the correctness of the model for the number of fibre-fibre contacts.

7.2 Sample used in this study

The low kappa pulp (see Appendix A2) was used in this study. Sets of handsheets were made from pulps that had been made from the starting pulp either by hydrocyclone fractionation (see subsection 5.2.2) or by forming sheets, wet cutting them and reslushing (see subsection 5.2.3). For each set of handsheets the density was changed by wet pressing (see subsection 5.2.1).

7.3 Results and discussion

7.3.1 Average results for fibre-fibre contacts

Table 7-1 summarizes the average results of the measured fibre-fibre contacts. As shown in Table 7-1, for the accepts and rejects, as the pressing pressure increases the number of fibre-fibre contacts per unit fibre length increases. This means new contacts of fibres are formed in wet pressing. Associated with this is a reduction in the free fibre length. It also shows that the percentage of full contacts increases as the pressing pressure is increased. For a given pressing level, the sample of the accepts and that of the rejects have almost the same values of the average free fibre length and number of fibre-fibre contacts per unit fibre length. As discussed in 5.2.2, the accepts and the rejects have different fibre cross-sectional dimensions (different AD factor). However, the two sets of handsheets made from these pulps have almost the same properties of fibre-fibre contacts, for a given level of wet pressing, although handsheets from the accepts always have higher density than the rejects. It should be emphasised that the above results do not necessarily mean that fibre shape has no effect on fibre-fibre contacts because, as indicated in our model (Equation 3.11), number of fibre-fibre contacts is affect by the fill factor, fibre width, fibre density and sheet density. At this stage it is still difficult to make paper with fibres with different shapes while still keeping the other factors constant. Further study is needed for drawing a conclusion on the effect of fibre shape on number of fibre-fibre contacts.

Table 7-1 also shows that sample $AccP_1$ has higher percentage of full contacts than sample $RejP_1$. This is because the accept fibres, which are thin walled fibres, are more flexible than the reject fibres, the thick walled fibres, therefore show a higher ability for bonding. After wet pressing, full contacts in samples from both fractions are increased dramatically, indicating, in another aspect, the increase in the degree of fibre bonding. We should also note that each full contact in the accept samples has higher contact area in average than that of a full contact in the reject samples.

Table 7-1 Summary of the average results of the geometrical parameters of paper structure

Sample	N_c * (no./mm)	Full contact (%)	Partial contact (%)	Free fibre length* (μm)	Out-of-Plane angle* (degree)	Total length of fibre segment measured (μm)	Fibre width** (μm)	Fibre height** (μm)	Sheet Density (kg/m³)
$AccP_1$	13.0±1.5	24	76	73.8±7.7	4.39±0.67	10563	31.6±1.3	13.7±0.7	218
$AccP_3$	20.8±2.0	35	65	45.4±5.1	5.36±0.71	9594	34.3±1.4	11.9±0.6	392
$AccP_5$	27.7±2.1	47	53	35.7±3.0	5.76±0.56	9504	36.6±1.5	9.7±0.4	651
$RejP_1$	12.9±4.8	18	82	82.6±11.9	7.41±1.30	9225	29.5±1.2	15.8±0.8	193
$RejP_3$	19.5±2.0	34	66	50.3±5.5	6.07±0.86	9281	32.7±1.3	14.0±0.7	306
$RejP_5$	28.8±2.6	44	56	35.8±4.1	6.75±0.96	6862	34.9±1.3	11.2±0.4	510
***L_0P_3	23.4±2.4	48	52	42.1±4.2	4.30±0.63	8794	31.0±1.2	11.2±0.5	522
L_1P_3	22.2±1.9	53	47	45.6±5.2	4.62±0.65	7528	31.8±1.2	12.3±0.6	535
L_2P_3	22.5±2.1	50	50	45.4±5.0	6.35±2.27	8212	33.2±1.3	10.2±0.4	434

* ± is 95% confidence interval. ** fibre width and height were measured in sheets and fibre width has been corrected by the angle that the fibre sitting to the cross-sectional surface of the sample. ***these samples were statically pressed.

For samples with different fibre length but pressed at the same pressing pressure (samples L_0P_3, L_1P_3, and L_2P_3), the number of fibre-fibre contacts, the percentage of the full contacts and the free fibre length are almost the same. This indicates that fibre length has no effect on the properties of fibre-fibre contacts.

The out-of-plane deflection angles of all the fractions used in this study show no regular trend with the pressing intensity (Table 7-1). It can also be shown that the distributions of the out-of-plane deflection angle of samples made from the same pulp fraction but pressed at different pressing levels are very similar and show no regular trends with pressing intensity. These results are consistent with the results shown in Table 6-1, where the out-of-plane deflection angles were measured in a different way, but are inconsistent with what was assumed in a Gorres and Luner's study (Gorres and Luner 1992), in which they assumed that the fibre deflection increases with increasing pressing pressure. If the out-of-plane deflection angle of the fibre segment stays constant, the deflecting distance of the fibre segment will be reduced as the pressing intensity is increased because the free fibre segment length has been reduced as the pressing intensity is increased. This movement provides a densification effect for the paper structure in wet pressing (for details see Chapter 6).

7.3.2 Frequency distribution of free fibre length

Different quantities have been defined as the free fibre length. The free fibre length has been defined as the distance between the centres of fibre crossings (Kallmes and Corte 1960); as the intercrossing distance represented by the distance between the centres of bonded crossings (Kallmes 1963); as the projected interbond distance, which is the distance between the projection of the bonds on the fibre axis (Page 1962). Kallmes and Bernier (Kallmes 1963) have shown that these three definitions of free fibre length will have different absolute values but will produce the same distribution of the free fibre length. In this study we define the free fibre length as the distance between the centers of two neighbouring contacts or bonds, which is the same definition as that used in (Kallmes 1963).

Kallmes et al (Kallmes and Corte 1960; Kallmes 1963) proposed that the free fibre length of a random sheet has a negative exponential distribution as $f(g) = (1/\bar{g})e^{g/\bar{g}}$, where g is the free fibre length and $\bar{g}$ is the mean of the free fibre length. They found this equation to hold for 2-dimensional sheets that are almost completely bonded, but bias arises for normal sheets (Kallmes 1963).

In this thesis we used a two-parameter Weibull probability density function (PDF), as shown by equation 7.1, to describe the distribution of the free fibre length.

$$f(g) = \frac{c}{b}\left[g/b\right]^{c-1}\exp\left[-(g/b)^{c}\right] \qquad \textbf{7. 1}$$

where b and c are constants, and $b, c > 0$, and $g \geq 0$.

The Weibull parameter b is scale parameter, and c is the shape parameter. The Weibull parameter is more general than the negative exponential distribution. When the shape parameter, c, is equal to 1, the Weibull PDF becomes negative exponential distribution. In this thesis, the values of b and c for different samples were determined through the best-fit by non-linear least-squares curve fitting.

Different fit lines with different values of c for sample $AccP_3$ are shown in Figure 7-1. As can be seen in Equation 7.1, when c is equal to 1, the Weibull PDF becomes negative exponential distribution and does not fit the experimental results in Figure 7.1 well. This indicates that the free fibre length does not take the negative exponential form proposed by Kallmes and Bernier (Kallmes and Corte 1960; Kallmes 1963). The distributions of free fibre length measured in this study, as shown in Figure 7.1 and in later figures, are very similar in shape to the measurements reported by Page et al (Page 1962).

Dent (Dent 2001) showed, about the same time as this part of work was being carried out, that a random sheet of fibres of finite length has a general gamma distribution of the free fibre length. Dent has also provided good theoretical basis for using the general gamma distribution to describe the free fibre length distribution. It is recommended to use the data in this thesis to test the gamma distribution proposed by Dent in the future work.

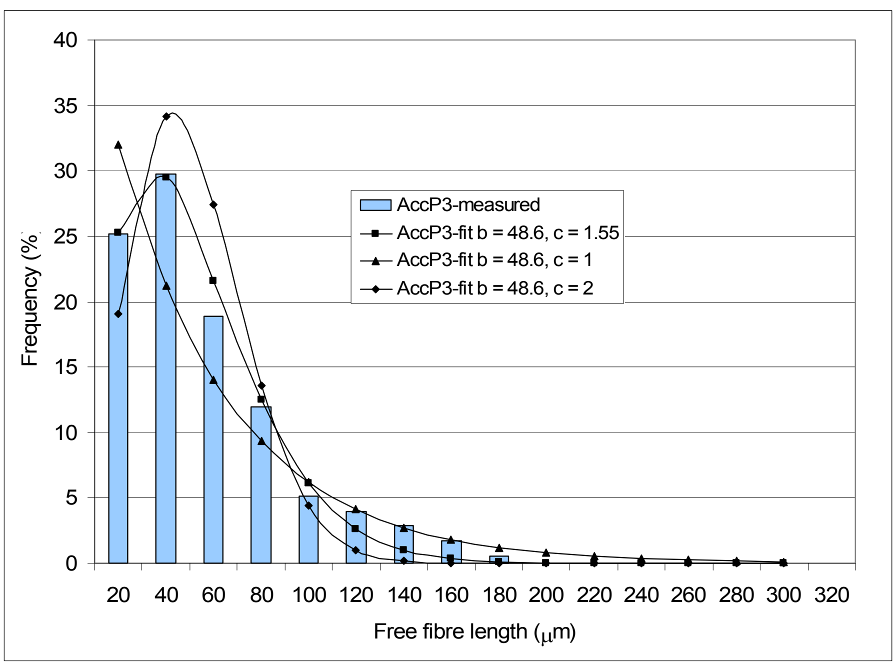


Figure 7-1 Fit lines with constant b value but different c values for sample $AccP_3$

The distributions of free fibre length of the samples made from the accepts and the rejects are given in Figure 7-2 and 7-3 respectively. The lines shown in these figures are the best fit of the Weibull PDF. The values of parameters of b and c are also given in these figures. The values of b are each about 10µm higher than the corresponding mean values of the free fibre length (see Table 7-1) The best-fit lines of Weibull PDF for these samples have values of c greater than 1, and the values of c for these samples except $RejP_1$ decrease as the wet pressing intensity is increased. We believe that the value of c for a normal sheet is in the range of 1 to 2.

The interval size at which the measured free fibre length was grouped significantly influences the "smoothness" of its frequency distribution. The greater the interval size, the smoother the distribution, but this will also reduce the points available for the comparison with the predictions made by Equation 7.1. In this study we chose arbitrarily a 5µm interval to group the measured free fibre lengths to do the fit with the Equation 7.1. A 20µm interval was used when the distributions were plotted in order to smooth the lines. As shown in Figure 7-2 and 7-3, Equation 7.1 can fit distributions of the free fibre lengths well

At a given pressing level, the free fibre length of the accepts sample shows a very similar distribution to that of the corresponding sample of the rejects fraction. This further suggests that for the sheets made from these pulps, the cross-sectional dimensions of the fibres have no effect on the frequency distribution of the free fibre length and the number of fibre-fibre contacts per unit fibre length. Kallmes and Bernier (Kallmes 1963) have shown that the free fibre length distribution is independent of fibre width, which is in agreement with the results obtained in this study. Page et al (Page 1962) claimed that the free fibre length and the frequency of bonding are highly sensitive to the fibre width and to the fibre flexibility, but no particular experimental data were provided to support these claims. The main reason for the apparent discrepancy is that the definition used in this study, which completely ignores the influence of fibre width on the free fibre length, is different from the definition used by Page et al (Page 1962), which considers the free fibre length as the lengths of fibre not covered by bonds. We believe that the fibre width and fibre flexibility mainly affects the bonded area of each bond. However, it is necessary to perform further experiments to draw a final conclusion.

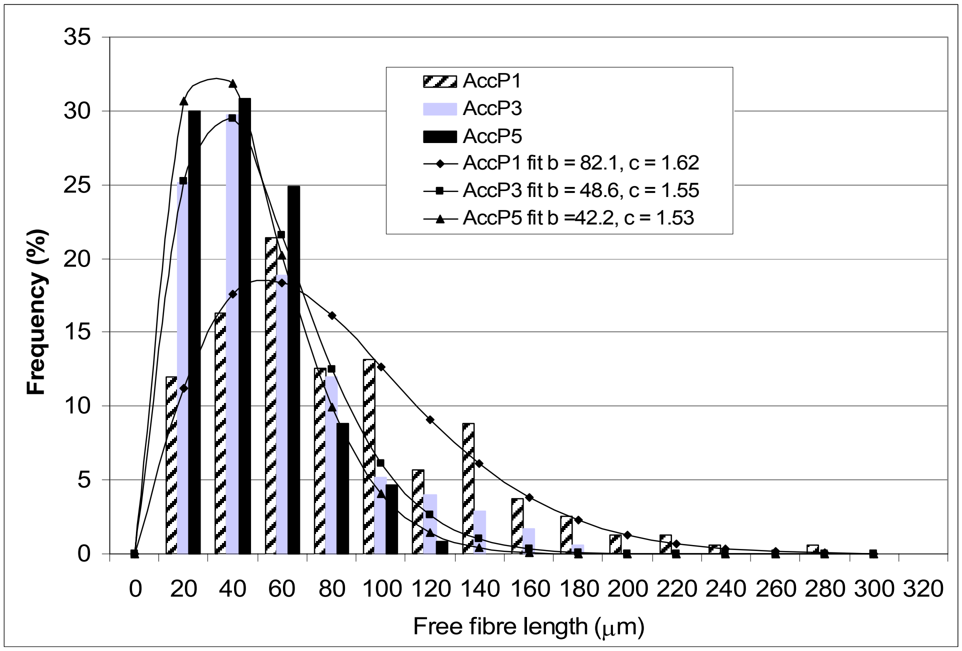


Figure 7-2 Frequency distribution of free fibre length of samples of the accepts

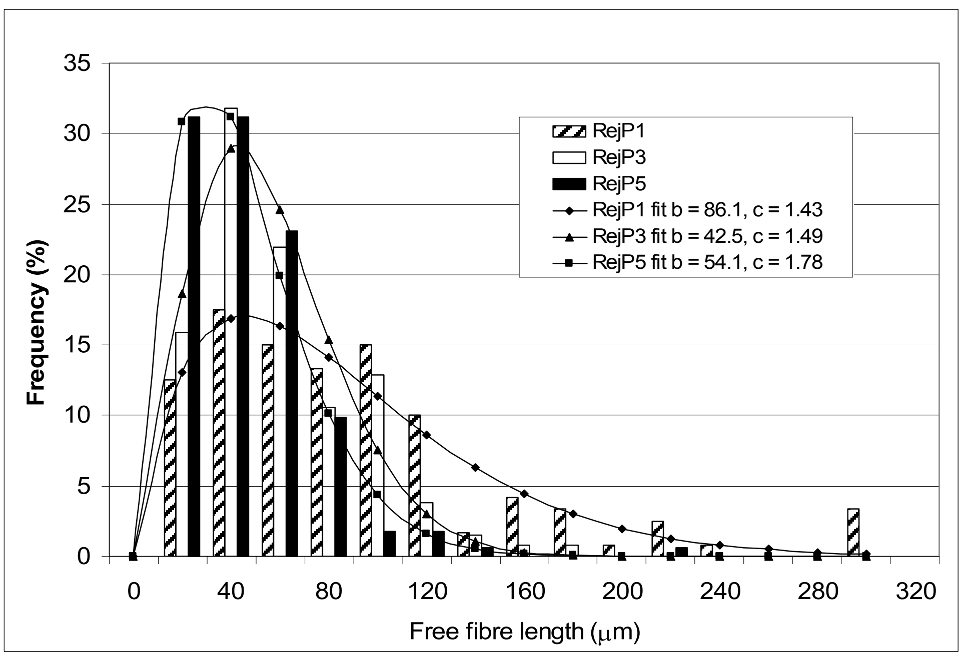


Figure 7-3 Frequency distribution of free fibre length of samples of the rejects

Both the accepts and rejects reponse to wet pressing in a similar manner. The free fibre length distributions were skewed to a lower value range and narrowed when the samples were pressed (see Figure 7-2 and 7-3), resulting in decreases in the mean value of free fibre length and increases in the number of fibre-fibre contacts per unit length of fibre (Table 7-1). The broad distributions of free fibre length in $AccP_1$ and $RejP_1$ imply that the bonding structure along fibres in these sheets is non-uniform, which will produce a non-uniform load distribution along the fibres and will lead to less efficient load transfer between fibres when the sheet is loaded. Wet pressing can narrow the distribution of free fibre length in the sheet, which therefore improves the uniformity of load transfer between fibres when the sheet is loaded.

The distributions of the free fibre length of the samples made from fractions with different fibre lengths are also almost the same as each other, indicating that the fibre length has no effect on the distribution of free fibre length in a sheet (see Figure 7-4). As discussed before, the mean values of the free fibre length and the number of fibre-fibre contacts per unit length of fibre are also independent of fibre length (see Table 7-1). Page (Page 1962) believed that fibre length would have strong influence on the frequency of fibre bonding, but no evidence was given. Kallmes and Bernier's (Kallmes and Corte 1960) theory was based on fibres with infinite length, but their theory was partial verified with data obtained with normal sheets.

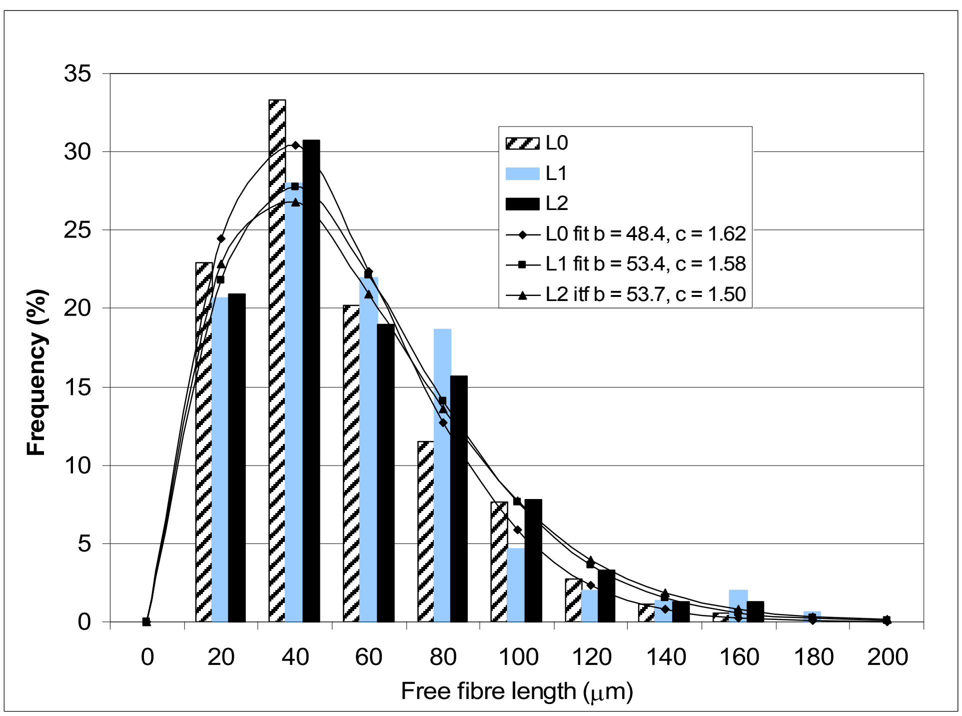


Figure 7-4 Frequency distribution of free fibre length of samples of fractions with different fibre length (these samples were pressed statically at P_3)

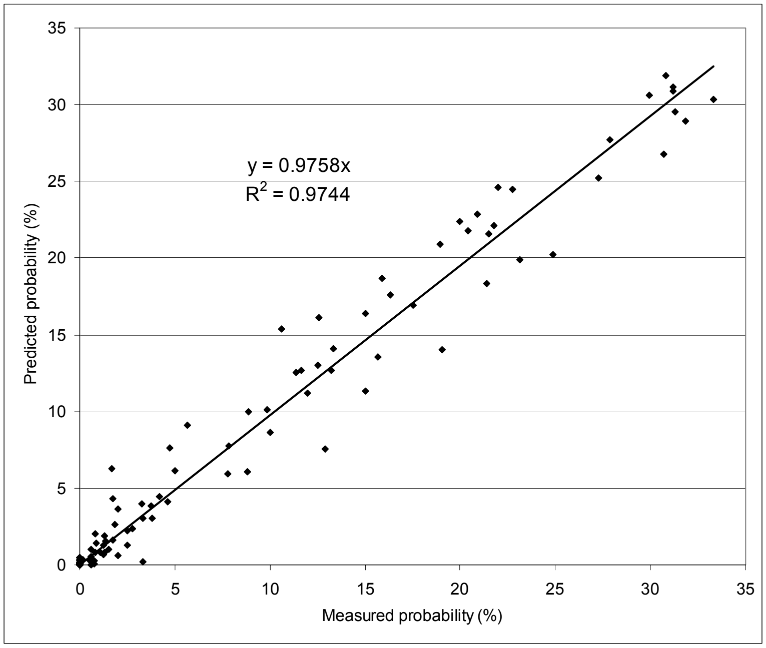


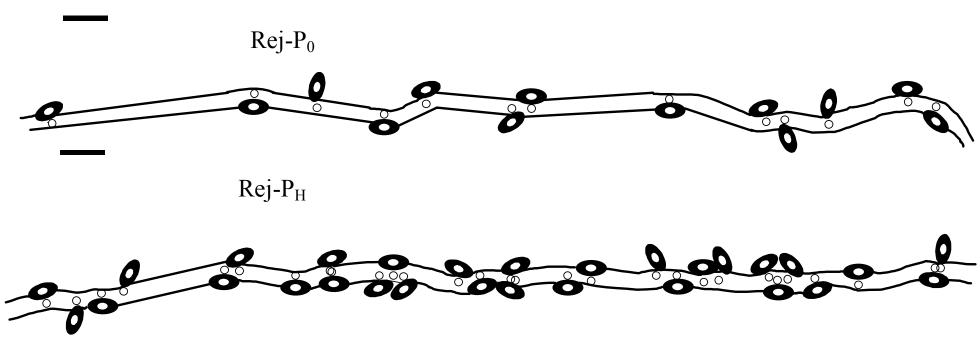
Figure 7-5 The correlation plot of all of the samples used in this study

The measured probability in each interval (interval size is 20μm) for all of the samples used in this study is plotted against the corresponding predicted probability in Figure 7-5. As shown in Figure 7-5, the measured values and predicted values show very good correlation with a correlation equation of $y = 0.97x$. This means that Equation 7.1 can describe the distribution of the free fibre length very well.

Although we can not justify theoretically the use of the two-parameter Weibull PDF to fit to the experimental data, both the graphic comparison and the check of correlation between the experimental results and the predictions show that the two Weibull PDF can fit the distribution of the free fibre length well and will be used to build model structures of fibre-fibre contacts in simulations of load distributions in fibres in Chapter 8.

7.3.3 Reconstruction of the fibre-fibre contacts

Based on the experimental results of the distribution of the free fibre length, the number of fibre-fibre contacts per unit length of fibre, the nature of the contacts and the distribution of the out-of-plane angle, a model structure of fibre-fibre contacts for a fibre segment of any of these samples can be reconstructed. Examples of such model structures for samples $RejP_1$ and $RejP_5$ are illustrated in Figure 7.6, in which the small circles along the fibre axes represent points between which the free fibre lengths were measured. The drawing here is to scale. The position of each contact and the out-of-plane angle of each free segment were calculated using their frequency distributions, respectively. The nature of the contacts was randomly assigned to each contact according to the percentage of fully and partial contacts for each fibre sample. The fibre segments shown in Figure 7-6 are 1mm in length. Clearly, in sample $RejP_1$, the arrangement of fibre-fibre contacts along the fibre segment is not uniform. There are some long free fibre segments. After it was pressed, the number of fibre-fibre contacts increased and arrangement of the contacts become more uniform. The number of long free fibre segments was reduced dramatically. These model structures provide a direct view and better understanding of the structure of fibre-fibre contacts in paper, and these data can also provide important information for simulation studies of the load distribution along a fibre.



*** the size bar is 50µm.**

Figure 7-6 Model structure of fibre-fibre contacts

7.4 Verification of the model for number of fibre-fibre contacts

7.4.1 Direct comparison between measured number of fibre-fibre contacts and predictions by Equation 3.11

As discussed above, the number of fibre-fibre contacts has been measured directly in the cross-section of paper. The measured data is now ready for comparison with the predictions made by the new model for number of fibre-fibre contacts given by Equation 3.11 in Chapter 3.

Several points need to be clarified here. Firstly, Equation 3.11 assumed that all of the contacts in paper are identical and are full contacts. However, as shown in Subsection 4.4.2, the fibre-fibre contacts measured in the handsheets can be divided into two types, viz. full contacts and partial contacts. There is no theoretical basis for determining how many partial contacts are equivalent to one full contact. However, the 'converting factor' is most likely to be within the range between 1 and 2. Secondly, to use Equation 3.11, we need first of all to determine the value of the packing factor, β, in the Equation. By using data from literature, we have shown in Subsection 3.3.3 that the packing factor appears to be a constant. In this study, we allowed the 'converting factor' to be adjustable between 1 and 2, and then calculated the values of β for each sample by bringing the converted number of fibre-fibre contacts and other parameters into Equation 3.11. The best value for the converting factor was determined by assessing how close to each other the calculated values of β are. It was found that the value of such a 'converting factor' was 1.5. The calculated values of β are given in Table 7-2. As shown in Table 7-2, the calculated β by equation 3.11 is constant within errors for all samples. In all following calculations, we used an average value of $\beta = -0.29$.

Table 7-2 Determination of β using the measured results of fibre-fibre contacts in paper (converting factor was 1.5)

Sample	D_w (μm)	f_h	N_{cm} (No./m)	β
L_0P_3	30.68	0.55	19375±4008	-0.31±0.14
L_1P_3	34.45	0.52	18710±4215	-0.31±0.15
L_2P_3	33.11	0.55	18725±4074	-0.33±0.15
$AccP_1$	30.19	0.43	9743±1710	-0.36±0.17
$AccP_3$	34.08	0.45	16309±2509	-0.31±0.12
$AccP_5$	36.38	0.51	22784±3521	-0.29±0.12
$RejP_1$	28.03	0.46	9377±1992	-0.31±0.16
$RejP_3$	32.22	0.49	15757±3141	-0.16±0.20
$RejP_5$	34.71	0.54	23482±4584	-0.21±0.14

A comparison between the measured number of fibre-fibre contacts and the prediction made by the new model are shown in Figure 7-7. When the trend line is forced to pass the origin, the slope (0.99) is very close to 1 and the correlation coefficient R^2 is 0.93. This means that the predictions made by the new model and the measurements are very close to each other indicating the model with best fit parameters can predict number of fibre-fibre contacts very well.

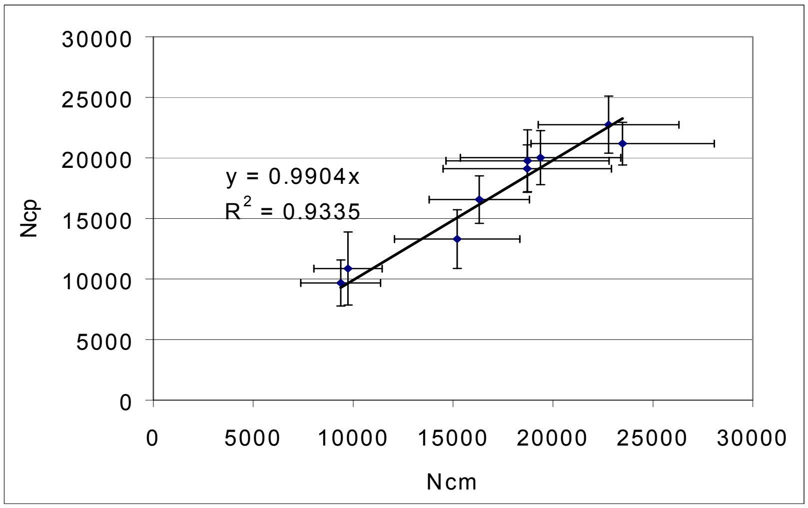


Figure 7-7 Correlation of measured equivalent number of fibre-fibre contacts per unit fibre length against the predictions made by Equation 3.11 using $\beta = -0.29$.

7.5 Verification of the expressions for RBA

7.5.1 Measurement of RBA with nitrogen adsorption

As reviewed in Chapter 2, the measurement for RBA is always problematic. In this study, the nitrogen adsorption method was used to determine RBA for all of the samples used and denoted as RBA_{N2} (see Appendix C). The surface area of unbonded sheets was determined by measuring the free surface of spray dried fibres. A fibre suspension with very low consistency (0.04%) was sprayed on a teflon surface and left to dry in the air. The dried fibres were then collected carefully avoiding losing material. Since fibres dried in this way rarely are in contact one another, no bonds should formed between fibres when they dry and the fibres should have an equivalent free fibre surface to a unbonded sheet made from the same pulp fibres. The free fibre surface area of these spray dried fibres were then measured by the nitrogen adsorption method and used as the free fibre surface area of unbonded sheets to calculate RBA by:

$$RBA = (A_u - A)/A_u \qquad \textbf{7.2}$$

where A_u is the free surface area of unbonded sheets and A is the free surface area of normal sheets.

The measured surface areas of unbonded sheets for samples L_0, L_1, L_2 and L_3 were 905m^2/kg, 920 m^2/kg, 921 m^2/kg and 927 m^2/kg respectively, and for the accepts and the rejects were 993 m^2/kg and 1063 m^2/kg, respectively. According to Braaten (Braaten 2000), if fibres are cylindrical with perfect smooth surfaces, and the fibre wall density is always 1.5g/cm^3, then the total surface area (includes the external surface and the lumen surface) per unit weight of such fibres can be estimated by $SA = 2/1.5t$, where t is the fibre wall thickness. For fibres used in this study, the wall thickness is in the range of 2μm to 3μm. The estimated SA is within 667 m^2/kg to 444 m^2/kg. These values are comparable with the measured results of the fibre surface area of unbonded sheets. The difference is reasonable because the calculation assumes that the surface of the fibres is perfectly smooth, which is not true in reality. Therefore, the measured results of the surface area of unbonded sheets are acceptable.

7.5.2 Comparison between the measured RBA_{N2} and the predicted RBA_{N2} by Equation 3.13

A comparison between the measured RBA_{N2} and the predicted RBA_{N2} is given in Figure 7.8. The predicted RBA_{N2} was calculated by Equation 3.13. The R factor in this equation considers the difference between the contact area of a real contact and an ideal contact. The factor R in Equation 3.13 was determined by fitting the measured values with predicted values of RBA_{N2} and using R as a variable. The value of R for the best fit was found to be 1.35, which is greater than 1 indicating that the actual bond width is greater than D_w. This may be true, as fibres tend to flatten when they are bonded together to form a skirt shape of bonding region (Nanko 1989). The value of 1.35 for R implies that each bond has expanded the width of the fibre by about 15%.

Figure 7-8 includes all of the data for samples used in this thesis. The best fit line, shown in Figure 7-8, shows an intercept close to zero and slope close to 1. It shows a reasonably good correlation ($R^2 = 0.88$) between the measurements and the predictions. All these indicate that Equation 3.13 can predict RBA well. This indirectly also proves that the model for the number of fibre-fibre contacts, Equation 3.11, is correct.

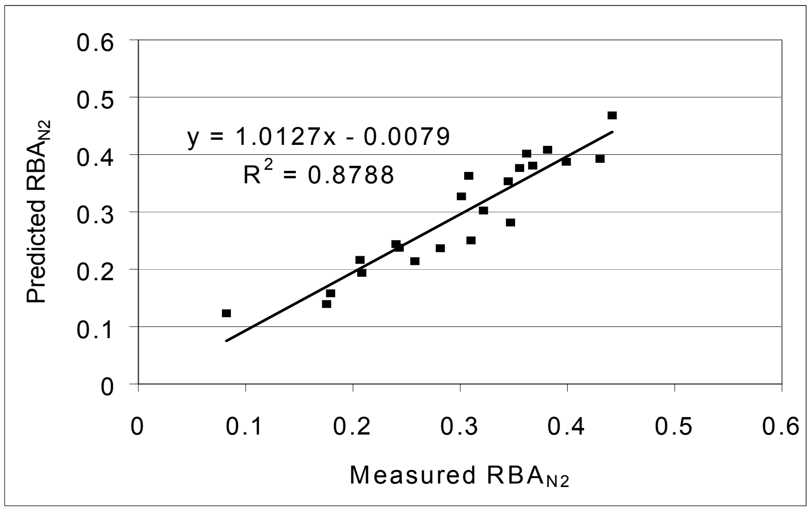


Figure 7-8 The correlation between the measured RBA by N2 adsorption and the predicted RBA by Equation 3.13.

7.5.3 Calculation of *RBA* with scattering coefficient

Traditionally, the Ingmanson and Thode pressing/beating extrapolation method (Ingmanson and Thode 1959) is the most widely used method for RBA measurement. In this method the light scattering coefficient for an unbonded sheet is determined by extrapolating the plot between tensile strength and the light scattering coefficient to determine the scattering coefficient, S_0, corresponding to zero tensile strength of paper. RBA is then calculated from $RBA = (S_0 - S)/S_0$. In this thesis, different S_0 for samples with different fibre lengths were obtained by using this extrapolation. The values of S_0 determined by this method of extrapolation for the L_0, L_1, L_2 and L_3 are 42.0 m^2/kg, 34.1 m^2/kg, 33.1 m^2/kg and 28.6 m^2/kg (Figure 7-9). These results are unreasonable because these fibre fractions only differ in fibre length and should have almost the same S_0. The Ingmanson and Thode extrapolation may have worked for their data because they were able to obtain data over a large range of tensile strength. Their extrapolation showed a highly non-linear curve. Thus if only a limited range of tensile strength vs scattering coefficient is available, it is not surprising that the extrapolation does not work. The results suggest that this extrapolation should not be used to determine S_0 and therefore the RBA. Obviously, an alternative method should be used for determining S_0.

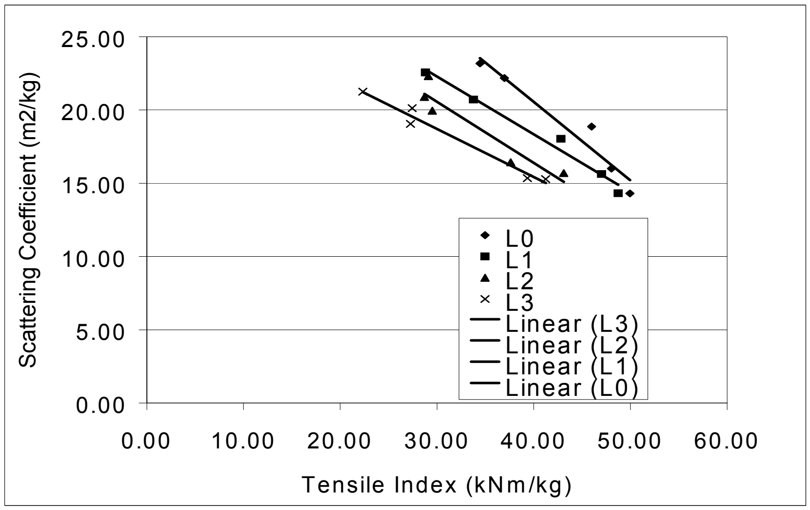


Figure 7-9 Plot between tensile index and light scattering coefficient of samples made from cut fibres pressed at different pressing levels

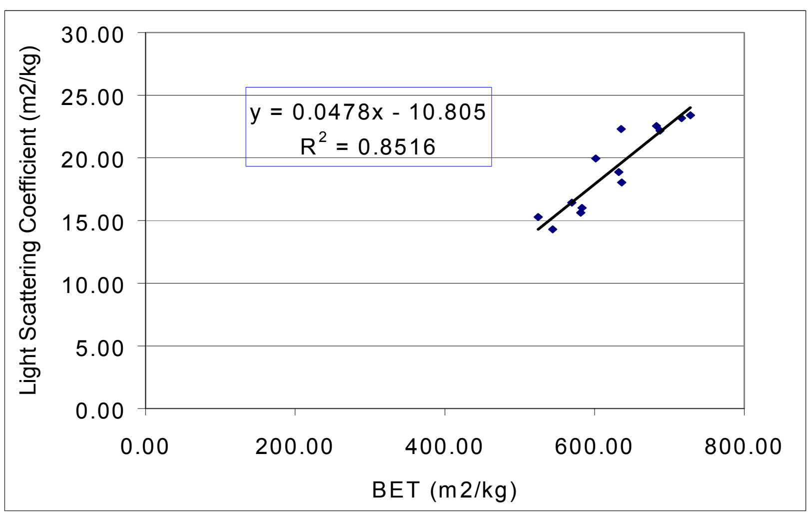


Figure 7-10 The relationship between the BET area and the light scattering coefficient for samples made from fibres with different length and pressed at different pressing levels

A linear relationship was found between the light scattering coefficient and the BET area for samples made from fibre fractions generated by cutting wet handsheets (see Figure 7-10). Similar relationships have previously been reported (Haselton 1955; Swanson 1959). S_0 was determined by using the linear equation shown in Figure 7-10 to calculate the scattering coefficient corresponding to the BET area of the spray dried sheets. The S_0 obtained using this method was 32.4 m^2/kg for L_0, 33.1 m^2/kg for L_1, 33.2 m^2/kg for L_2 and 33.5 m^2/kg for L_3. These values were then averaged and used as S_0 for RBA calculation for all of the four different fibre length fractions. It is important to note that S_0, calculated in this manner, does not change as the fibre length is decreased. This is as expected because the cutting process does not change the cross-sectional dimensions of the fibres.

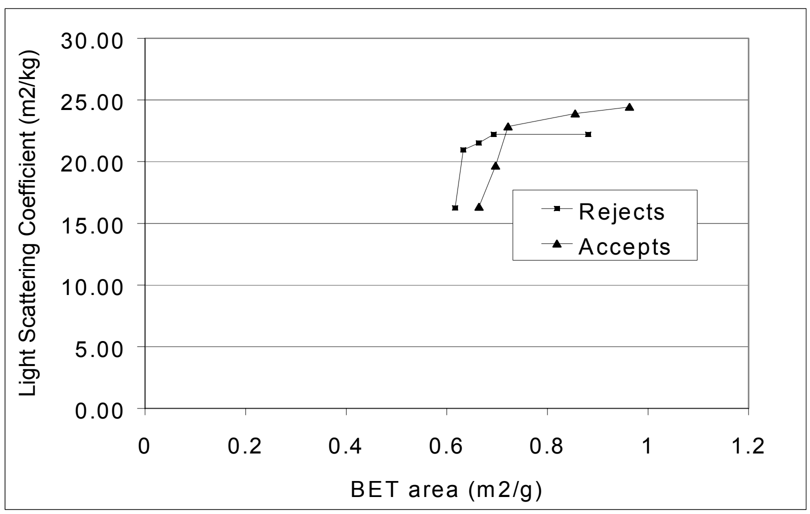


Figure 7-11 The relationship between the BET area and the light scattering coefficient for samples made from the accepts and the rejects pressed at different pressing levels

It was also found that the relationship between the BET area and the light scattering coefficient was non-linear for samples made from the rejects and also for samples made from the accepts (as shown in Figure 7-11). Currently, we have no good explanation for this non-linear relationship. A possible reason is that the accepts and the rejects were fines free pulps and formed sheets having “pin holes”, which seemed to have a significant effect on the measurement of the light scattering coefficient.

7.5.4 Comparison between the measure RBA_{sc} and the predicted RBA_{sc} by Equation 3.14

A comparison between the measured RBA_{sc} and the predicted RBA_{sc} by Equation 3.14 is shown in Figure 7-12. The value of R in Equation 3.14 was also determined by fitting the measured RBA_{sc} with the calculated RBA_{sc} using R as a fitting parameter. Interestingly, the value of R was 1.39 that is almost equal to the value of R determined in Figure 7-8. This means R is a constant as is assumed in Equations 3.13 and 3.14. As can be seen in Figure 7-12, the trend line shows an intercept very close to zero and slope close to 1 and very high R^2 statistic of 0.94 indicating that Equation 3.14 can predict RBA very well. This further proves that the new model for number of fibre-fibre contacts is valid.

It is also interesting to estimate the maximum values of RBA_{N2} and RBA_{sc} by setting ρ_a, f_h, and δ in Equations 3.13 and 3.14 to limiting values. For a sheet made from heavily refined pulp and pressed at high pressure, the reasonable maximum value for ρ_a is 750kg/m^3, for f_h is 0.6 and for δ is 1/4. When these values were brought into Equations 3.13 and 3.14, the calculated maximum values for RBA_{N2} and RBA_{sc} are 0.49 and 0.61 respectively, which are quite reasonable.

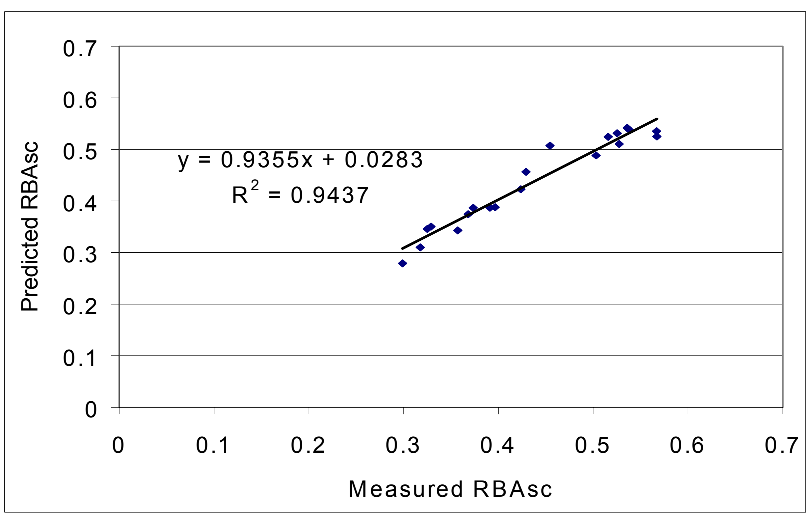


Figure 7-12 Correlation between the measured *RBA* by scattering coefficient and the predicted *RBA* by Equation 3.14 (The handsheets were made by fibres with different fibre lengths generated by cutting wet handsheets)

7.6 Conclusions

The main conclusions from this chapter are:

- A new technique for measuring the properties of fibre-fibre contacts directly in paper has been proposed and has been used successfully. It is the first technique that can determine all of the parameters associated with the fibre-fibre contacts simultaneously.
- It has been shown for the first time that fibre length seems to have no effect on the properties of fibre-fibre contacts. Fibre cross-sectional shape has no significant effect on the frequency of fibre bonding along a fibre and the distribution of the free fibre length. However, the accepts fibres (the thin walled fibres) tend to form a higher percentage of full contacts in a sheet.
- The out-of-plane deflection angles of the free fibre segments have no regular trend with the pressing intensity for both the handsheets of the accepts and of the rejects. However, the out-of-plane deflection distance has been reduced by wet pressing since the free fibre length has been reduced.
- The distribution of free fibre length for a normal sheet is not negative exponential. It seems to fit a two-parameter Weibull probability density function.
- The distribution of the free fibre length is narrowed and shifted to a lower value range by wet pressing. The bonding frequency along a fibre is increased, while the free fibre length is reduced as the pressing intensity is increased. There is no significant difference in the behavours of the fibre-fibre contacts of the handsheets made from the accepts and those made from the rejects.
- It has been demonstrated that model structures of fibre-fibre contacts can be reconstructed using the data measured by the new technique.
- The model for the number of fibre-fibre contacts per unit fibre length has been verified directly by using the data of fibre-fibre contacts measured in paper. The comparison between the measurements and the predictions made by the new model shows a very good correlation, indicating that the model is valid.
- It has been shown that both of the two expressions can predict *RBA* well. This further proves that the new model for fibre-fibre contacts is valid.