Effect of grammage and concentration on paper sheet formation of *Pinus radiata* kraft pulps

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A research program has been instigated to examine the relationships among paper sheet formation, and flocculation (fibre entanglement), and fibre flexibility, using a single-fibre resource, *Pinus radiata*. Pulps having a range of coarseness levels (mass per unit length of fibre) and fibre lengths were tested. Standard paper handsheets were made at six different grammages and from suspensions at six different stock concentrations to investigate the formation potential of various fibres. Formation data were obtained using two light transmittance methods and two beta radiographic techniques.

Significant differences in formation data were obtained for paper sheets made from the four pine pulps, a spruce pulp, and a eucalypt pulp. Formation index correlated well with selected fibre properties such as relative fibre number, fibre length, width/thickness ratio, and wall thickness. For the same grammage, the formation index decreased as the suspension volume increased. Formation index decreased when either the forming stock concentration or the grammage decreased. Increasing tank level, and thus forming pressure, and delayed drainage had no significant effect on sheet formation index levels.

The normalised formation index values for sheets made from suspensions at the same concentration remained constant for each pulp class from 40 to 120 g/m^2, even though the forming volume changed from 6.67 to 20 L. Between classes the normalised formation index increased with increasing fibre coarseness for the pine pulps. Eucalypt pulp handsheets clearly had the lowest normalised formation index. The formation index for handsheets made from spruce, having the longer fibre length, corresponded with the two lower-fibre-length pine handsheet levels. The light transmittance methods gave the opposite result; the formation index decreased with both increasing grammage and forming volume. These methods may match visual sensing but clearly fail to reveal the true mass distribution. When the suspension volume and grammage increased, certain paper properties such as tensile index and light scattering coefficient remained almost constant except at the lowest grammage (40 g/m^2). Tear index increased as grammage and forming volume increased.

Keywords
Formation, fibre, grammage, concentration, fibre properties, formation index

Paper is made from a wide range of wood pulp fibres, which are asymmetric, flexible particles. In a sheared suspension fibres flex, bend, translate, collide and entangle to produce secondary entities called flocs. In effect, these are non-uniform distributions of mass, which, if not dispersed in the paper forming process, produce localised variations that can affect paper sheet quality and strength. The formation of paper therefore not only depends on the type of fibres and their pretreatment but also on the fluid mechanics of the forming process. The wide variety of forming methods and the application of shearing mechanisms can sometimes mask the inherent flocculating nature of the fibres themselves.

Beghello and Eklund (*1*) examined the role of several basic factors in the flocculation process. Various fibres with three different fibre lengths were refined at three different levels and sheets were formed at three different stock concentrations. They showed that there is a strong effect of fibre length on floc size, with the longer fibres producing larger flocs. A small increment in stock concentration also resulted in increased floc size for both long and medium fibre lengths, while the shortest fibre length furnish was unaffected.

Seth et al. (*2*) and Sampson et al. (*3*) both found that formation improved as grammage increased for the same pulp. Seth et al. used a laboratory sheet former for their investigations. Sampson et al. did not specify their experimental conditions for either real or random sheets and comparisons are therefore difficult to make. Norman et al. (*4*) analysed this work and pointed out that increased grammage leads to improved formation due to localised dewatering. They also pointed out that the optical transmission methods used by both groups to quantify formation had intrinsic calibration problems.

In an earlier study of paper formation (*5*) it was found that various formation instruments using different measuring methods produced similar trends in formation index data with changes in fibre properties. Four kraft pine pulps, with different coarseness values, were used together with a spruce pulp for comparison. Pulp refining only marginally improved the formation over the range of handsheets made from radiata pine and spruce pulps. For kraft/TMP mixtures, it was found that formation index was relatively constant and was independent of the type of kraft fibre used when the kraft fibre content was below 40 per cent. It was also found that formation measurements on handsheets, made from mechanical pulp furnishes, employing light transmittance were suspect due to a masking effect of light scattering.

The work reported in this paper is a continuation of a study (*5*) using the same species, radiata pine, rather than choosing different species to obtain different fibre lengths. In this study handsheet forming conditions were varied (grammage, and stock concentration and thus tank volume/level) to examine their effects on formation. Handsheets were also made from spruce and eucalypt fibres for comparison. The main objective in this research was to compare the differences in formation index among sheets formed from fibres of different flexibility and other properties: the aim was to study formation potential without the additive effects of various forming methods. Consequently a 'standard' handsheet former was used to

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ensure that the fibres were subjected to the same forming process conditions every time. This would be virtually impossible with machine-made papers and the limited supplies of the standard pulps.

Paper handsheet formation data were obtained by four different methods that are currently used either commercially or in research environments. Two of the formation instruments use beta radiography (Ambertec and STFI formation testers), and two testers are based on light transmittance methods (Toyo Seiki, Japan, and PFI Norway).

This study is part of an extensive research program that aims to relate paper sheet formation, fibre suspension flocculation, and fibre flexibility, for one fibre resource, *Pinus radiata*.

FORMATION TEST INSTRUMENTS

Traditionally formation was measured by visual examination of paper using transmitted light. Many formation instruments were developed based on this method and also on other methods such as beta radiation, mono-energetic electron beams, and soft X-rays. However, only the first two methods are used commercially.

Formation measurements based on light transmission correlate very well with human visual perception. However, light transmission measurements cannot be used effectively to evaluate mass distribution of sheets made from various fibrous and filler components with different optical properties. Local variations in the light scattering coefficient make the correlation between light transmission and local grammage ambiguous in cases such as with filled or calendered sheets.

The most accurate commercially available method for measuring localised mass variations is based on beta radiography. Although the spatial distribution of fibre mass can be determined the distribution of floc sizes cannot as the sensor moves stepwise over a predetermined distance from test point to test point irrespective of the paper being examined. In addition, the resolution of 1 mm (the maximum resolution for the Ambertec instrument) prevents the resolution of mass variations smaller than this size. However it is a fast and accurate means of measuring local point mass variations, hence its wide use in the industry.

A contact beta-radiographic image-analysis method has been developed at the Swedish Forest Research Laboratory (STFI), which gives information on the scale and distribution of floc size, but this instrument is available only in a research environment. The paper sample is placed between X-ray film and a weak C_{14} beta-ray source uniformly dispersed in a perspex plate. The transmittance of beta rays through a material is dependent on its mass and hence local mass variations can be imaged as local exposure variations. A calibration strip consisting of areas of known grammage is used to calibrate the system. The developed film is scanned optically and power spectral density versus wavelength (floc size) data are obtained.

A brief summary highlighting the differences among the four formation instruments is presented in Table 1. A detailed description of the STFI method can be found in (*6*) and (*7*) and more details of the other instruments in reference (*5*).

Table 1
Comparison of the four formation testers.

	STFI	Ambertec Beta	Toyo Seiki	PFI
Method	β radiography	β transmission	Laser light	Image processing
Sheet Area (mm²)	105 x 178	70 x 70	220 x 220	110 x 80
Formation index	STFI Formation Number	Standard deviation	Total variation	Spectrum total energy
Time	2 hours	7 minutes	2 minutes	4 seconds

EXPERIMENTAL

Pulps

Fibre characteristics and dimensions for the pulps (*5*) used to make handsheets for formation measurements are presented in Table 2. The following pulps were used:

- High (Hi), Low (Lo) and Ultra Low (ULo) coarseness New Zealand radiata pine bleached market kraft pulp, with fibre length being the important difference between pulps.
- Bleached Canadian spruce (Sp) market kraft pulp for benchmark comparison.
- Bleached eucalypt (Eu) kraft pulp.

Handsheets

A rectangular handsheet former modelled on the PFI (Norwegian Pulp and Paper Institute) former was used to make handsheets ensuring that all fibres were subjected to the same standard forming process conditions (*14*).

The load applied during pulp refining in the PFI mill was 3.4 N/mm. Pulps were refined at 10 per cent stock concentration for 1,000 beating revs. Handsheets were made without white water recirculation except for the eucalypt sheets. No handsheets were made at the 20 L suspension volume for eucalypt furnishes.

Table 2
Pulp fibre dimensions (*5*).

Pulp category	FS 200 Fibre length* (mm)	Fibre cross-section dimensions: Width + thickness (μm)	Fibre wall area (μm²)	Fibre wall thickness (μm)	Width / thickness	Relative fibre number
High (Hi)	2.60	40.9	202	3.57	3.12	76
Low (Lo)	2.08	39.7	174	3.05	3.56	110
Ultra Low (ULo)	1.88	39.4	169	2.96	3.63	125
Spruce (Sp)	2.49	34.0	130	2.57	3.04	123
Eucalypt (Eu)#	0.74	19.6	58	2.48	1.92	924

* Length-weighted fibre length.
# Data for the bleached kraft eucalypt were obtained from (*8*).

Table 3
Matrix of handsheet sets.

	20 L	10 L	6.67 L	5 L	3.3 L
180 g/m^2	1.5X	3X	4.5X	6X	-
120 g/m^2	**X**	2X	-	4.5X(4.44 L)*	6X
90 g/m^2	-	1.5X	-	3X	4.5X
60 g/m^2	2/3X(15 L)*	**X**	-	2X	3X
40 g/m^2	1/3X	2/3X	**X**	1.5X(4.44 L)*	2X
30 g/m^2	-	-	1/3X	**X**	1.5X

Note: X = 0.018% suspension stock concentration.
* The adjusted suspension volume for that particular grammage to achieve comparable concentration.

Twelve sheets were made for each set of forming conditions; six for formation testing, and six for physical testing (optical, tensile, tear, burst and Gurley). Sheets made at 30, 90 and 180 g/m^2 were excluded from physical properties testing (except sheets made from 5 L and 10 L suspension volumes). The combination of conditions for making the handsheet sets is presented in Table 3. The two variables were grammage and stock concentration (by varying the suspension volume).

RESULTS AND DISCUSSION

The beta-radiographic methods were found to be the most accurate for measuring the local mass variations in the paper sheets (*5,9*). The results for all four formation instruments are discussed below.

Ambertec beta formation index

Formation data are presented in Figure 1 for 60 g/m^2 handsheets made from the five pulps to show how fibre concentration and therefore suspension volume affect paper sheet formation. The formation stock concentrations for 60 g/m^2 corresponding to the tank volumes are: 0.054% (3.33 L); 0.036% (5 L); 0.018% (10 L); 0.012% (15 L). The Ambertec formation index is reported as the coefficient of variation, **n**.

There is a systematic lowering of the formation index as the tank volume increases for all four pulps although the percentage reductions vary. For the pine pulps there is a 37 per cent decrease for the Hi, a 35 per cent decrease for the Lo, but only a 29 per cent decrease for the ULo. The spruce pulp exhibits a 37 per cent lowering in formation index (identical to the Hi) as the tank volume increases from 3.33 L to 15 L. Spruce fibres (2.49 mm long) are slightly shorter that the 2.60 mm Hi pulp fibres yet the absolute formation indices of the corresponding paper sheets are much lower at comparable forming concentrations. Spruce fibres have a smaller wall thickness and coarseness and hence their increased flexibility and conformability would also assist in lowering the formation index across the range. This shows that sheet uniformity or formation is more that just a fibre length phenomenon (*10*).

The magnitudes of formation indices for papers made from eucalypt pulp are much smaller (41 per cent lower) than values for sheets made from the shortest pine fibres ULo. There is only 17 per cent reduction in formation index on dilution from 3.33 to 10 L for the eucalypt pulp. Compared to ULo the magnitude of reduction due to dilution from 3.33 to 10 L is only 12 per cent. However with the very low fibre aspect ratio for a typical hardwood pulp with a mean fibre length of only 0.74 mm, it would be expected that the propensity to flocculate would be almost independent of the volume change (4.5 times) in these experiments. These results confirm this.

The results show that the formation stock concentration has a very significant effect on sheet formation. In practice a properly designed flowbox and twin-wire forming section can apply additional controlled shear to minimise some of these effects. In contrast these results obtained in a standard sheet former show the natural propensity of various fibres to flocculate and the effect of selected fibre variables on formation.

Another factor affecting the results could be the concomitant increase in tank level and therefore the suspension forming head as tank volume increases. Forming sheets from a larger stock volume also increases the forming time. Some additional experiments were performed to ascertain the significance of forming pressure and delayed drainage on forming and subsequently on the sheet formation index. Fortunately at the fibre concentrations used in these experiments neither tank head nor fibre concentration were significant variables. (In hindsight a factorial experimental design would have been more appropriate to extend the range of test conditions).

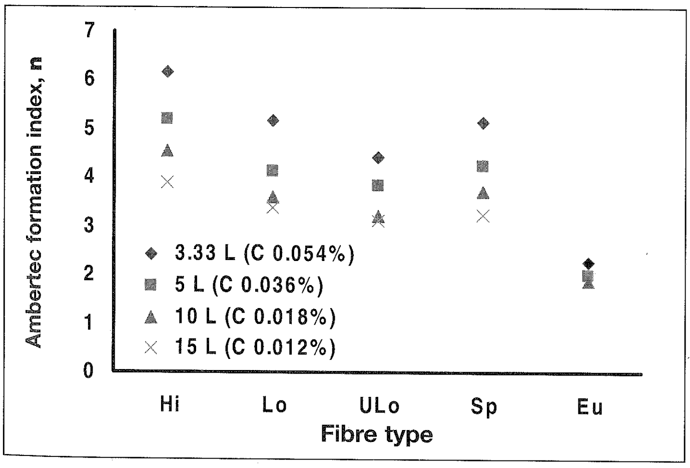

Fig. 1 The effect of suspension volume on 60 g/m^2 papersheet formation index n for the five pulps.

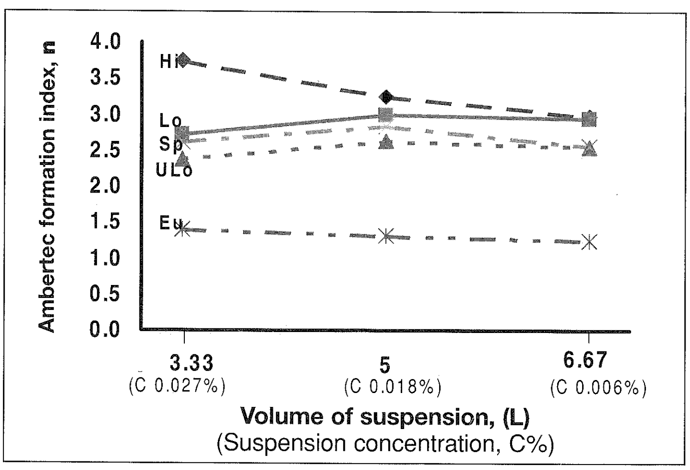

Fig. 2 Ambertec formation index n versus increasing suspension volume at 30 g/m^2. Forming suspension concentration is shown in brackets.

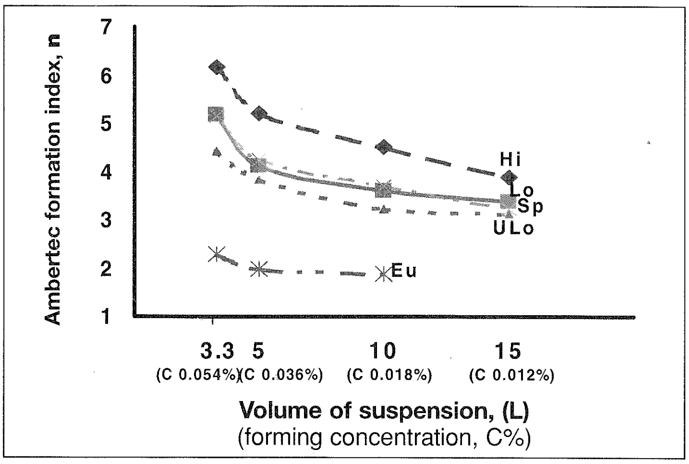

Fig. 3 **Ambertec formation index n versus increasing suspension volume at 60 g/m². Forming suspension concentration is shown in brackets.**

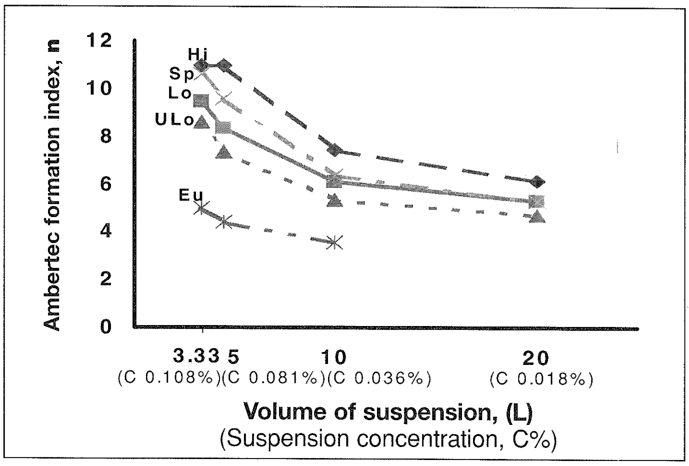

Fig. 4 **Ambertec formation index n versus increasing suspension volume at 120 g/m². Forming suspension concentration is shown in brackets.**

Plots of formation index **n** against the suspension volume (Fig. 2 – 4) show the sensitivity to fibre length, and volume change (concentration) for handsheets made at 30, 60 and 120 g/m².

No significant changes in Ambertec formation index **n** were observed with decreasing concentrations (or increasing suspension volume) for 30 g/m² handsheets, except for the Hi kraft pulp (Fig. 2). The similarity of formation index **n** values at decreasing concentrations is mainly due to the low number of fibres in the suspension. The formation indices for handsheets made from spruce pulp are between the values for Lo and ULo coarseness pulps.

For the 60 g/m² handsheets, the change of slope in the formation index versus dilution relationship from 3.33 L to 5 L clearly points to some forming 'difficulties' either due to concentration or inadequate mixing in the tank (Fig. 3). The linear trends in the data as tank volume increases from 5 to 15 L (dilution) shows a systematic reduction in slope or index/dilution sensitivity as fibre length decreases. Compared to Figure 2, the spruce pulp shows similar values of formation index to Lo over the dilution range.

As the grammage increases to 120 g/m², the formation index for spruce handsheets moves closer to the formation values for Hi and are higher than the values for Lo across the dilution range (Fig. 4). The slope for each type of pulp becomes more significant compared to those at lower grammages. The gradual relative increase of formation index for spruce shows the increasing influence of fibre length as the grammage increases.

Results for Ambertec formation index **N** at different grammages are presented in Figure 5. The coefficient of variation **n** should not be used for formation comparisons particularly if sheets have different grammages (*11*). There is no linear physical correspondence between the mean and standard deviation of a set of formation data. Thus the normalised index of formation, Ambertec formation index **N**, is used instead of coefficient of variation **n** as in Figure 1 (data apply to sheets made at the same 60 g/m² grammage). The Ambertec normalised formation index **N** is defined as the standard deviation **n** divided by the square root of the grammage.

The formation index **N** for all handsheets made from each pulp increases as the sheet grammage increases (i.e. forming concentration increases) when the suspension volume remains constant (Fig. 5). As the required fibre quantity per unit volume increases with grammage, the flocculation tendency will also increase. In addition the lower grammage sheets form more rapidly as there is less fibre per unit area of screen. Also as the deposited fibre layer builds on the wire the filtration resistance increases which can also affect the fibre mass distribution. At the lower formation concentrations used in this

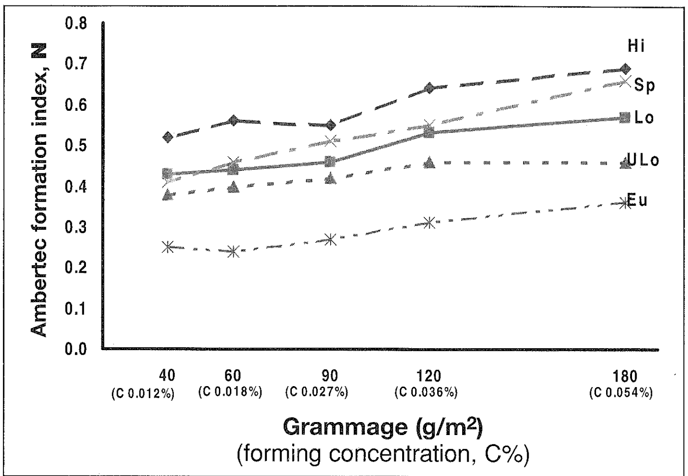

Fig. 5 **The effect of grammage and forming concentration on the Ambertec normalised formation index N for the five pulps.**

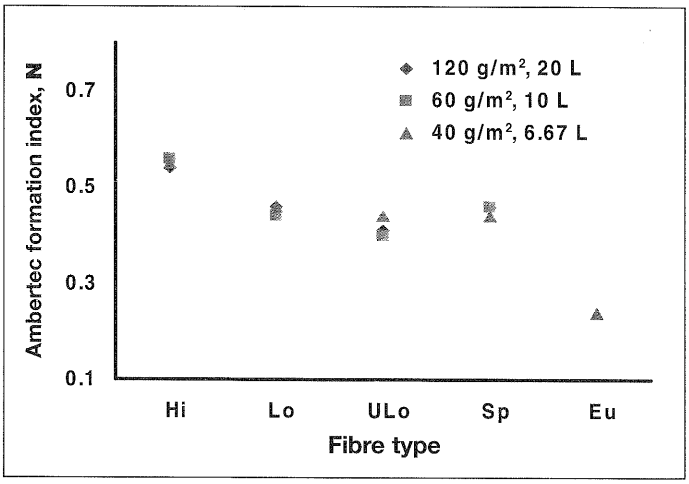

Fig. 6 **The effect of grammage and suspension volume on paper sheet formation index N for the five pulps.**

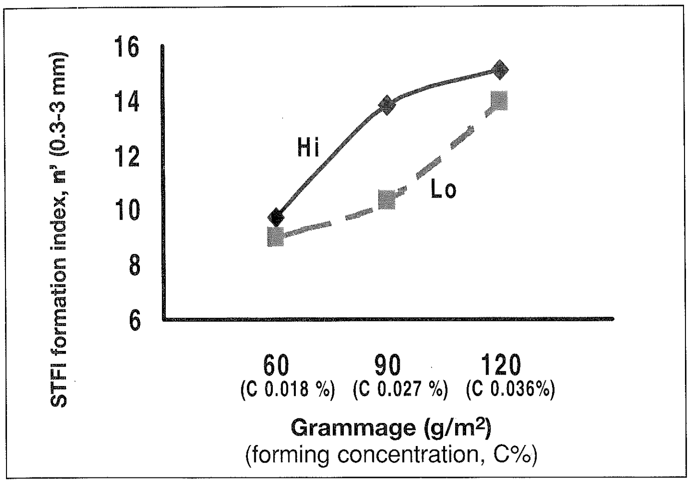

Fig. 7 **STFI formation index n' micro-scale (0.3 to 3 mm) for handsheets made from a 10 L suspension. Forming suspension concentration is shown in bracket as C%.**

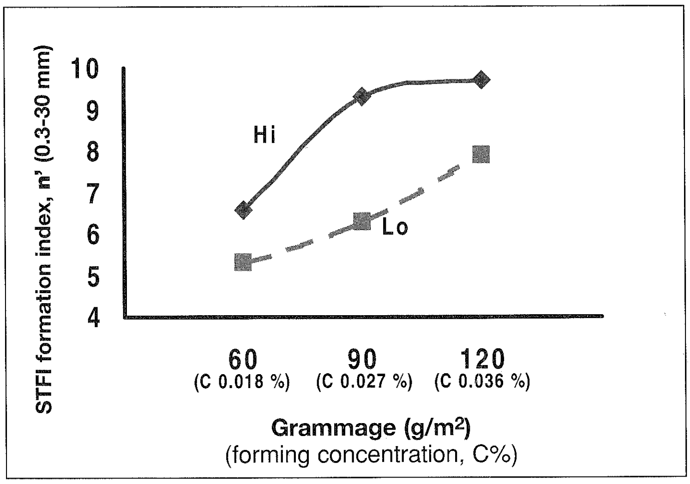

Fig. 8 **STFI macro-scale formation index n' (3 to 30 mm) for handsheets made from a 10 L suspension. Forming suspension concentration is shown in bracket as C%.**

study the differences in formation index values are not significantly large (from 0.11 to 0.17 $\sqrt{g/m^2}$). The overall differences are the lowest for ULo and the highest for spruce.

Using the formation data in the range from 40 to 120 g/m^2, the various indice ranges are: Hi 19%, Lo 19%, ULo 17%, Sp 25%, Eu 19%. The data range for eucalypt handsheets is similar to those of radiata pine athough the mean levels in magnitude are much lower. It is interesting to observe that the formation indices of papers made from Hi and spruce fibres at 180 g/m^2 are similar. However as the grammage decreases sequentially to 40 g/m^2 and the forming concentration reduces simultaneously, the formation index **N** values for the spruce sheets decrease more rapidly and to a lower value than for the sheets made from the Hi pulp (mean fibre length of the Hi fibres is 2.60 mm and the spruces is 2.49 mm). This suggests that fibre length has more influence at the higher grammage forming conditions (180 g/m^2) and fibre flexibility is the important factor at the lower grammages (40 g/m^2 conditions).

The normalised formation indices **N** (normalised standard deviation) for sheets made at the same concentration are presented in Figure 6. The grammage and suspension volume were adjusted to obtain the same concentration of 0.018 per cent. As expected, the sheets made at the same forming concentration had the same or similar formation values. The results again show that although tank level varied extensively as tank volume ranged from 6.67 to 20 L in order to make sheets from the same fibre concentration, the head or pressure differences dictating the forming process had no significant effect on formation. In addition the extra forming time required to make the higher grammages had no significant effect.

STFI formation index

The Ambertec Beta instrument has a maximum resolution of 1 mm, which prevents the resolution of mass variations smaller than this size. This means that it is necessary to use the STFI method to obtain floc size or scale information.

The total formation indices **n'** (0.3 - 30 mm) obtained from the STFI method show similar overall trends to the Ambertec values. In the micro-scale range (0.3 to 3.0 mm), the formation indices for both Hi and Lo decrease with decreasing grammage (Fig. 7). The data are limited as only a small number of sheets from the total number were tested.

Macro-scale (3 to 30 mm) formation data and trends are presented in Figure 8.

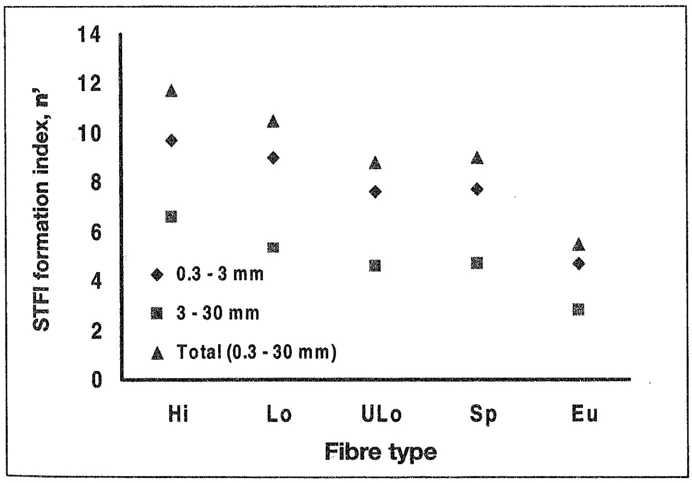

Fig. 9 **Formation indices n' for handsheets made at 60 g/m2 from 10 L suspension volume for the five pulps.**

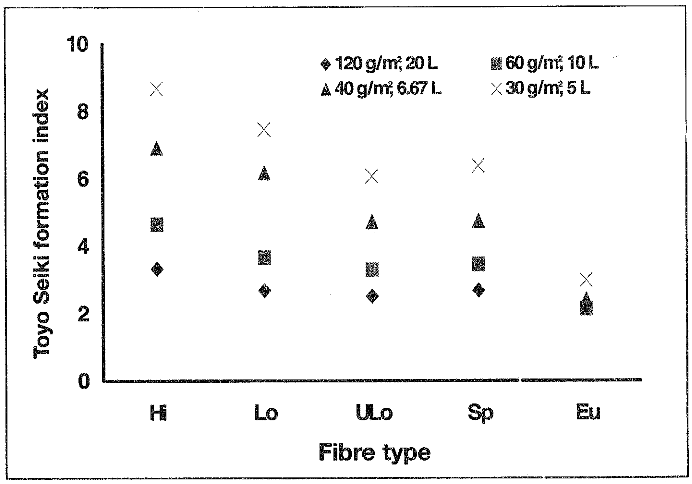

Fig. 10 **Toyo Seiki formation index for handsheets made at the same forming concentration by varying the grammage and suspension volume.**

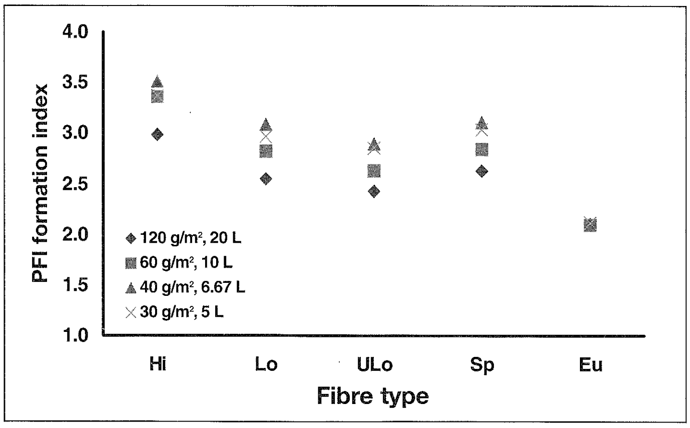

Fig. 11 PFI formation index for handsheets made at the same forming concentration by varying the grammage and suspension volume.

Table 4
Interaction between pulp and concentration at a fixed grammage.

Grammage (g/m^2)	F value Pr > F	Note
30	0.1000	Not significant
40	0.0564	Not significant
60	0.0021	Significant
90	0.0107	Significant
120	0.0189	Significant
180	0.0427	Significant

The general trends in the data are similar to the micro-scale data (Fig. 7) where the higher formation index values occur at 120 g/m^2. The magnitude of the differences between the formation indices of the papers made from the Hi and Lo coarseness pulps is greater in the macro-scale range. This is probably due to the longer Hi pulp fibres, which increase the chance of collision and entanglement when forming. Hence the floc size distribution for Hi is larger than for the Lo.

STFI formation data for paper handsheets made from all five pulps are compared in Figure 9. All sheets were made at 60 g/m^2 from a 10 L volume of suspension. The micro-scale, macro-scale, and total formation indices **n'** obtained from the STFI method are presented. The formation index increases from micro-scale to macro-scale, to the overall value for each handsheet for each pulp class. Fibres and small fibre bundles cause formation micro-scale variations, whereas the macro-scale reveals the contribution of the main spectrum of floc sizes. Handsheets made from the shorter fibre eucalypt clearly have the lowest formation indices. The ULo short fibre length pine pulp handsheets had similar values to the handsheets made from the longer but more flexible spruce fibres.

Toyo Seiki and PFI formation indices

Both light transmittance methods gave disparate formation values especially with regard to the grammage effect. Formation appears better as handsheet thickness increases, even to the naked eye. Light scattering appears to unify the distribution of transmitted light and the results often do not agree with the beta radiographic data.

The Toyo Seiki and PFI formation indices for handsheets made at the same concentration are presented in Figures 10 and 11 respectively. Toyo Seiki and PFI both give the opposite formation results to the Ambertec results for sheets made at the same forming concentration. Even though the suspension volume was adjusted to achieve the same forming concentration, the grammage still determined the formation index for both light transmittance instruments. The effect of grammage was more significant for Toyo Seiki than PFI. Figure 10 shows that the formation index increases as the grammage decreases, i.e. the formation of the sheet appears to be better. The effect of grammage was less when using the PFI formation tester as seen in Figure 11. However, the formation index for sheets made at the highest grammage (120 g/m^2) is still lower than for those made at lower grammage. These results show that light transmittance formation instruments should not be used to measure sheets made at different grammages.

Statistical analysis

The experiment results were analysed using the general linear model in the SAS statistical software package. Only regression analyses were performed on paper properties and some preliminary results are presented in Table 4. This is the first part of a more extensive investigation not reported here. The results for the prediction of formation index from fibre dimensions are presented in Table 5. Even though only five types of kraft pulp were included in the analysis, the predictions give a reasonably good indication of how grammage and suspension concentration affect the Ambertec formation indices for radiata pine and spruce pulps. As the grammage range is very large, it would be of interest to observe the effect of varying concentration at a fixed grammage. It is shown in Table 4 that the effect of concentration is insignificant below 40 g/m^2 and independent of pulp type. Suspension concentration becomes more significant on Ambertec formation indices at higher grammages. In Table 4, F is the type of testing hypothesis (Fisher Test) and Pr is the probability of error. F values should be less than 0.05 (95% confidence level) for the variable to be significant in the interaction. For example, when $P = 0.05$ there is a 5% chance that the relation between the variables is a 'fluke'.

Influence of fibre and sheet properties on paper formation

Pulp category Hi has the highest coarseness and longest fibre of the radiata pine pulps (Table 2). It would be expected that handsheets made from the shorter length and lower coarseness Lo and ULo pulps would have improved formation over Hi. Spruce fibres are slender compared to the radiata pine fibres as indicated by their smaller wall area (lower coarseness), fibre wall thickness, and width/thickness ratio. However, the formation indices for spruce are only slightly higher than for ULo because of its longer fibre length (similar to Hi). The eucalypt fibres are much shorter (0.74 mm), slender and of low wall area (coarseness) compared to the softwood fibres. Hence in suspension the

Table 5
Formation index prediction from fibre dimensions for the four long fibre pulps.

Dependent variable	Independent variables	r^2
Ambertec (60 g/m^2 sheets) (10 L volume)	Relative fibre number	0.931
	Fibre thickness	0.910
	Fibre length	0.863
	Width / fibre thickness	0.696
	Wall thickness	0.695
	(Width x fibre thickness)	0.571
	Wall area	0.542
	Width	0.062

fibre network strength would be lower and the propensity to flocculate greatly reduced.

The various correlations among the handsheet formation indices and specific fibre dimensions or properties are presented in Table 5. These were obtained by linear regression analyses and the coefficient of determination r^2 is used as the indicator of best correlation for comparative assessment.

Excluding the eucalypt pulp, most fibre and handsheet properties correlate quite strongly with the respective values of formation index for radiata pine and spruce. The relative number of fibres per unit mass of pulp is by far the best single predictor of formation index ($r^2 = 0.93$) with fibre thickness and length also being important (r^2 values about 0.91 and 0.86 respectively). Fibre wall area, which is a measure of fibre coarseness (fibre mass/unit length), is an important fibre parameter (*12*) but it only gives an r^2 value of 0.54 in this study.

INFLUENCE OF GRAMMAGE ON SHEET PROPERTIES

Light scattering coefficient

Figure 12 shows that the scattering coefficient of the sheets increases initially with increasing grammage from 40 to 60 g/m^2 and also with increasing forming concentration from 0.012% to 0.018%. It then levels off to a constant value (i.e. scattering coefficient is independent of grammage). The sheets made from eucalypt have the highest values of scattering coefficient, while the radiata pine and spruce have similar values.

Tensile index

An increase in grammage does not significantly increase the tensile index (see Fig. 13). There is a small increase in tensile index as grammage increases from 40 g/m^2 to 60 g/m^2, except for the eucalypt. Above 60 g/m^2, tensile index decreases slightly. Tensile strength normally decreases as fibre length is reduced. Figure 13 reveals an anomolous result for tensile index data for handsheets made from Hi category pulp. It would normally be expected that the curve should lie just below the curve for spruce with a similar fibre length but lower cell wall thickness (Table 2). However, the curve even lies below the other lower coarseness and shorter Lo and ULo pine pulps and this could partly be caused by the low degree of beating of the fibres before the handsheets were made. The probability of a fibre crossing the network rupture line in a paper sheet is proportional to its length (*12*). Tensile strength is also determined by the bonding ability of single fibres (*13*). Even though Hi coarseness fibres are longer, the bonding ability and the collapse potential (width/ thickness) are very low. The ULo fibres have shorter length but possess a greater bonding and collapse potential. Hence papers made from them have good tensile strength even though the fibres are shorter.

Tear index

In Figure 14, tear index is seen to increase as the grammage and fibre length increase and the differences in values between each pulp type become larger above about 60 g/m^2. The tear indices for both Hi and Sp handsheets are similar over the range of grammages because their fibre lengths are similar. The data in Figure 14 confirm how the fibre length plays a major role in tear strength as expected (*2*). The tear index for the short eucalypt sheets, however, does not really increase until reaching 120 g/m^2 and then only slightly.

CONCLUSIONS

- The Ambertec formation index n decreases with increasing suspension volume at the same grammage (lowering the suspension concentration).
- At the same volume of suspension, the formation index **N** (normalised formation index) decreases as the grammage decreases. However, for the Toyo Seiki light transmittance method the trend is reversed. The PFI formation results are unsystematic.

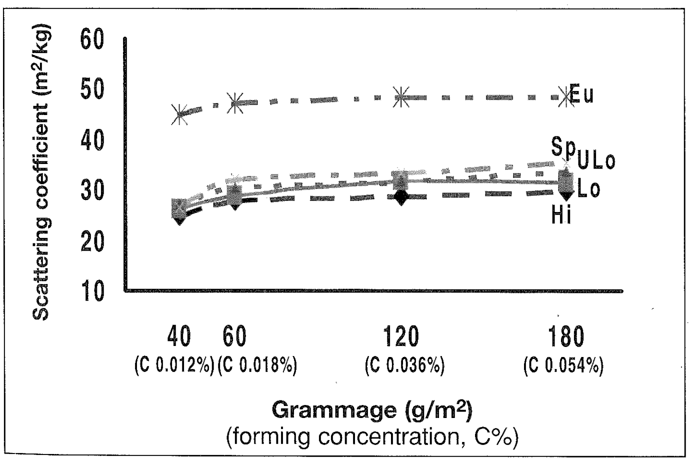

Fig. 12 Scattering coefficient versus grammage at 10 L suspension volume.

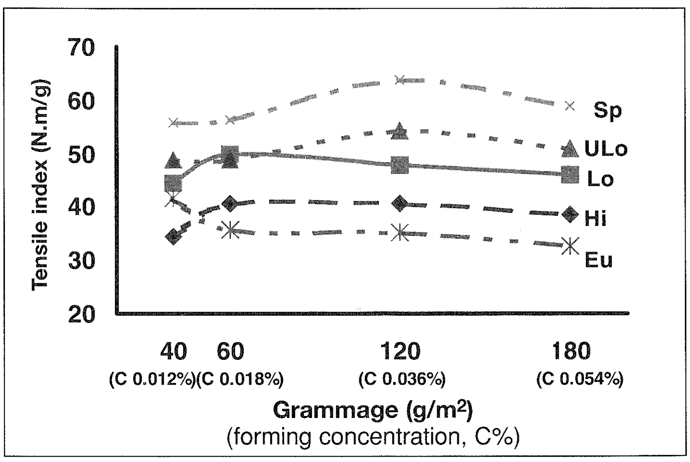

Fig. 13 Tensile index versus grammage at 10 L suspension volume.

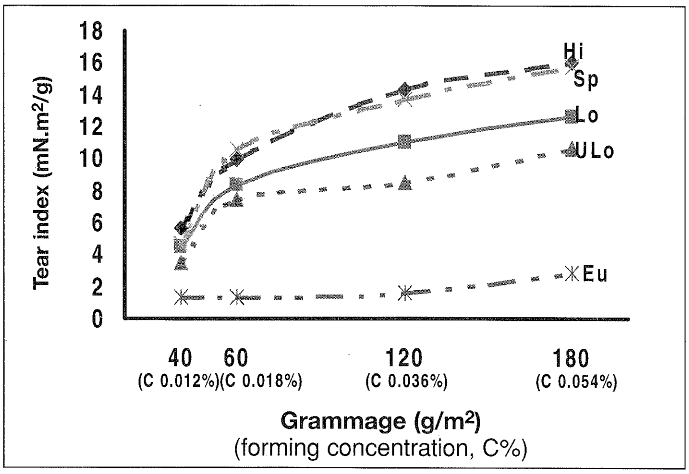

Fig. 14 Tear index versus grammage at 10 L suspension volume.

- For the Ambertec beta radiographic formation data, the normalised formation index **N** values are similar as either grammage or suspension volume is reduced (i.e. the same concentration). The data trends for the Toyo Seiki and PFI indices are the reverse, pointing to the danger of using optical formation methods.
- When forming concentration and grammage increase, both the light scattering coefficient and tensile index remain almost constant except at the lowest grammage (40 g/m^2). The tear index increases with grammage and fibre length.

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