Preliminary development of a laboratory former for oriented sheets.

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SUMMARY

The production of paper in the laboratory where controlled forming conditions result in an anisotropic sheet of predictable properties, which match those of papers made on a commercial paper machines, is a long desired instrument for many researchers. A laboratory sheet former based on a novel interpretation of the flow in the forming region is being developed to meet this challenge. The key sheet characteristics for a given fibre stock were identified to be formation and fibre orientation. The ability of the laboratory former developed to simulate commercial paper was assessed by a number of standard tests. The sheets formed on the initial proto-type (MkI) confirmed that the conceptual design was worth pursuing, and that improvements to the control and operation were required. The design improvements made to the former resulted in a second device (Mk II) which produced oriented laboratory sheets in a repeatable manner with sheet characteristics comparable to commercially made paper. The practical difficulties encountered in the development of this device are discussed along with the solutions which were found.

INTRODUCTION

This paper addresses the preliminary developments of a laboratory paper former and highlights the approach taken to produce paper sheets with controlled anisotropy. The laboratory production of paper sheets which simulate paper made on a commercial machine in a way which is usefully predictive has been a long desired goal for both researchers and development engineers alike. The ability to predict the papermaking potential of particular fibre sources with a degree of precision which approximates the achievements of pilot paper machines, but without the expense and logistical complexity of a pilot scale trial has been a worthwhile but elusive goal. To date the devices available to form sheets in the laboratory are quite varied in their design and operation (*1-15*). The fine structure of sheets produced on many of these laboratory formers differs quite markedly from paper which has been made on a commercial paper machine (*10-12*). Further problems with grammage profiles and fibre fractionation have also been reported (*6-8, 16*). The devices which have produced paper similar to a commercial machine have been reported to be bulky, difficult to operate and hard to control (9). None of these devices has been deemed to be a truly satisfactory predictor of what may be expected on a commercial machine from a given fibre stock.
At the outset of this research a number of practical constraints and targets were imposed on the design in order to overcome the deficiencies of earlier laboratory formers. The specifications included:

1. To occupy a space of less than 3 x 3 x 3 m^3.
2. Capable of producing paper sheets of at least A4 size repeatably.
3. Use minimal amounts of pulp, (1-2kg).
4. Require a single operator.
5. Relatively inexpensive to construct.
6. Form at speeds of 0.01 - 1m/s.
7. Sheet to have a controlled basis weight range of ~20-200 gsm.
8. Simulate properties of a commercially made sheet in a usefully predictive manner.
9. A simple relation between laboratory operating parameters and measurable commercial operating parameters.
10. Device to facilitate an investigation of the forming phenomena.

The approach taken in the development of this former was to conceptually model the forming process and then to build a device which would allow test sheets to be formed, which could be used subsequently to validate the modelling perspective. Once this was achieved, further refinement of the device to improve the operability was envisaged.

THEORY

A sheet may be partially characterised by its formation and the distribution of fibre orientations present. It is likely that these sheet characteristics are interrelated (*17*).

The fibre orienting effect of the rush/drag ratio is well documented (*18*). Reports of investigations into sheet anisotropy, and specifically MD/CD fibre orientation have repeatedly stressed that the rush/drag ratio (*19*) is a key determinant of the degree of fibre orientation[✍]. The cause of fibre orientation has been re-interpreted to be more accurately expressed as arising from the velocity difference between the jet emerging from the headbox and the velocity of the wire (*20*). This observation formed the basis for the conceptual design of the current apparatus.

In order to comply with specifications 4 and 5 above, a design in which stock flows over a stationary wire was adopted. This approach reduced the modelling complexity involved in simulating a commercial paper machine whilst still permitting the most important features of wet end operations to be incorporated. The key wet-end features included were: a velocity profile above the wire, similar suspension characteristics, (similar consistency range), and

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[✍] Note, the consistency or concentration of species prior to forming is also an important factor influencing anisotropy, and there are many other factors not considered directly here.

a similar pressure profile. This conceptual approach is similar to the “moving with the flow” type analogy often used in fluid dynamics where a frame of reference having a mean velocity is used to convert a spatial domain into a temporal one. The mean velocity applied in this case is the speed of the wire, v_w (m/s). The analogy used for the design of the laboratory model is depicted below in figure 1.

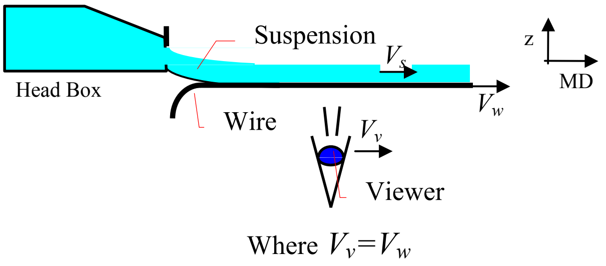

Fig 1: **The model’s analogy, (where V = velocity (m/s) and subscripts, s = suspension, w = wire, and v = viewer).**

This conceptualisation allows a simple relation between the commercial process operating parameters and the laboratory control parameters. These relationships and the justification will be presented in detail in a later paper.

For a laboratory device to be usefully predictive, the repeatability of its operation and product must first be assessed. Repeatability involves the precision of the same operator, with the same apparatus, usually on the same day, and with test specimens from the same sample of material (*21*). Repeatability may be used as a measure by which to assess:
1). the ability of an operator to repeat their measurements,
2). the stability of an apparatus, and,
3). the homogeneity of an amount of material.

In this study assessments the first and third types will be made which imply the stability of the apparatus. The stability of the device will be discussed in detail in a later paper. Further, it is necessary to establish the repeatability of a process if an effect due to a small change in the process conditions is to be detected. The repeatability establishes an expected limit for the variation in a measure.

Repeatability, expressed as a percentage, can be defined as (*21*) :

$$Repeatability,\% = \frac{100(2.77s_e)}{\bar{x}m^{0.5}} \quad \text{Eq 1}$$

where,

s_e, standard deviation,
m, number of test specimens,
$\bar{x}$, average.

THE LABORATORY FORMING DEVICE

The principle components of the sheet former include:

1. a novel multi slice headbox (CD_y width 400mm),
2. a large single pulse vacuum box (MD_x forming length 500mm, CD_y width 400mm),
3. a 110L head tank,
4. a 110L receiver tank
5. a customised reducing diameter bifurcated distributor,
6. a large vacuum reservoir, and,
7. a centripetal pump.

The components were assembled as shown in Figure 2 below, to establish a re-circulating flow loop.

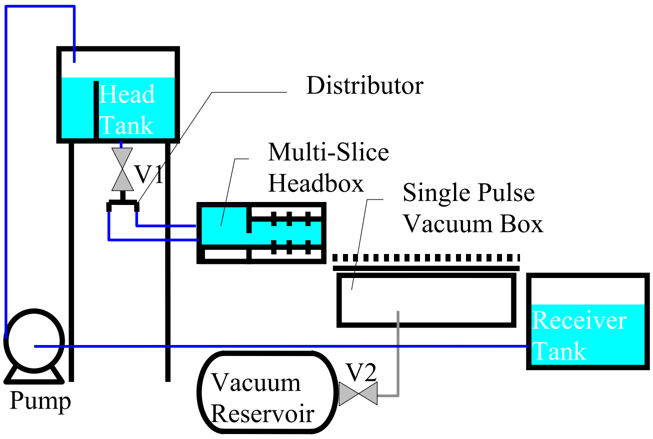

Fig 2: **Schematic diagram of the basic components and the configuration of the laboratory former.**

The system shown in Figure 2 represents the basis for the former and during the development two different schemes of flow support and control were employed. The first, Mk I, was a manual system to allow sheet formation and to test that the conceptual design was successful for achieving an oriented sheet. The second scheme, used in Mk II, overcame some areas of concern identified on the Mk I device, where it failed to achieve the project aims and failed to achieve repeatability.

Formation of sheets on the Mk I device required two operators and so did not comply with Specification 4 above. Measurements of the basis weight profile of paper sheets formed on the Mk I device revealed an unacceptable degree of variation. The sheets did, however, display MD/CD anisotropy and their formation, by visual inspection was comparable to that of papers made on full size paper machines. In view of these encouraging results the Mk I device was modified to include the following additional features:

8. a plate to support the flow prior to forming arranged in a manner so that the support could be withdrawn rapidly,
9. a self supporting flow receiver with fixed transparent walls which extended right up to the headbox,
10. a fast closing gate valve to halt the flow,
11. a more rugged means of levelling, and
12. an automated control system to initiate forming and thus eliminate the need for a second operator.

The Mk II assembly had the benefits of an instantaneous vacuum application to the entire forming area, a tighter control of the forming width (402mm +/- 1mm), allowing a non-intrusive measurement of the flow depth for the entire forming length, and allowing the former to be arranged so that the flow receiver was self-supporting. These modifications, whilst improving the repeatability of machine set up and operation, also significantly reduced the time involved in re-assembling the device and so increased productivity. A modification to the method by which a sheet was couched from the wire was also made. The couching technique was altered to include a nylon/muslin cloth between the blotting paper and the sheet allowing an easier separation of the sheet from the blotter.

In Mk II, forming was initiated by an electronically timed pneumatic actuator. The actuator had three tasks, (figure 4):
1). halting the flow,
2). removing the flow support, and
3). applying the vacuum.
The pressure differential profile within the suction box was recorded by a pressure transducer located within a side port which was logged to a computer. The software was set to log the pressure data every 10ms over a 3s interval from the point of initiation[✎] .

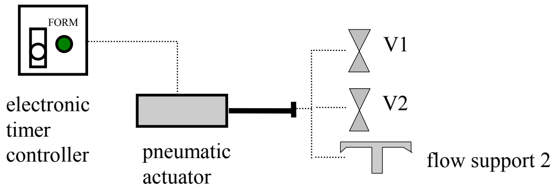

Fig 4: MkII Automated Control Scheme

Mk II Former Procedure

A Mk II forming experiment involved the establishment of a stable flow loop, followed by subsequent sampling and recording of the process variables. Typical former settings were as shown in Table 1.

Table 1: Mk II Former Parameters.

Parameter	Value	Precision
Slice Height	10 mm	± 0.25 mm
System Head	1 m-stock	± 0.01 m
Vacuum Time	0.6 s	± 0.02 s
Reservoir Vacuum	50 kPa (gauge)	± 0.5 kPa
Mass of Stock	1 kg	± 0.010 kg
System Volume	200 L	± 5 L

The Mk II former settings in table 1 resulted in the following forming conditions; mean velocity, $v_s = 0.5$ m/s, consistency $x_c = 4.9$ g/l, Vacuum peak $\Delta P_{max} = 7.2$ kPa, and a height over wire, $h = 10$ mm.

PROCEDURE

The stocks used in this investigation were prepared by suspending measured quantities of air dried, un-refined, dry lapped, bleached eucalypt kraft pulp (Brightness 88% ISO) from Amcor's Maryvale Mill in measured volumes of tap water. A small amount of commercial Sodium hypochlorite was added to prevent bacterial growth, (10 ml into the 200L system).

Stock consistencies were measured gravimetrically by sampling directly from the flow receiver and filtering through pre-weighed, oven dry, analytical filter paper, (Whatman No. 541). The filter cake was then oven dried (110°C) for 12 hrs before subsequent weighing.

Sheets were formed using the apparatus (Mk I and Mk II) described above. The wet sheets were couched on to sheets of blotting paper (~200 gsm, 42 x 57 cm^2). Further dewatering was achieved by pressing manually against additional dry blotting paper with a hand roller. No other pressing was used. A layer of thin woven nylon mesh was interposed between the wet sheet and the blotting paper to facilitate separation of the sample and the blotting paper after drying for the sheets formed on the Mk II device.

The sheets were allowed to dry freely in open conditions. This method of drying occasionally resulted in some creasing within the sheet if the sheet was restrained to the blotter in a particular region. The creases in the sheet which were introduced during couching and drying caused problems for the ultrasonic test. The creases need only be short (~2cm) and well defined for the test to fail or produce defective results. This represents a sample handling problem which is outside the focus of this study. The problem was largely overcome by the end of this investigation through more careful extraction and handling of samples.

The test methods employed on the Mk II Former were used to establish the repeatability of the sheets formed on the device.

Formation was measured using an Ambertec beta-ray absorption apparatus (Model No. BFT-1), which employs equations which treat the data in a statistical manner by utilising the two-dimensional power spectrum S(k), (where k is a spatial frequency vector), of the scan area. These are as follows:

Variation:

$$\sigma^2 = \int_{-\infty}^{\infty} S(k)dk \qquad \text{Eq 2.}$$

Normalised Standard Deviation:

$$N = \sigma / \sqrt{<m>} \qquad \text{Eq 3.}$$

Coefficient of Variation:

$$C.o.V. = \sigma / <m> \qquad \text{Eq 4.}$$

[✎] the typical forming time was of the order of 0.2s as determined by image analysis.

The Ambertec beta-ray method of formation analysis was selected as it provides a thorough non-destructive assessment of the microscale basis weight variations. An aperture size of 1mm with a scanning region of 69 x 69 mm^2 was employed. Kajanto *et al* (*22*) reported the error associated with this method of analysis to be 0.25 gsm. This device is the most accurate (*23*) and it is reported to correlate well with standard homogenous sheets of other materials (*24*).

Sonic velocity measurements were performed using a Nomura Shoji (Model No. FST 3000) on A4 samples cut from the region of higher uniformity regions of the Mk I and Mk II sheets. Methods used were as described in the Nomura- Shoji Manual (*25*). The Nomura Shoji ultrasonic velocity anisotropy test was chosen as it provides a very quick non-destructive indication of the fibre orientation and anisotropy of a sheet. This test measures the speed of an ultrasonic pulse through the sheet in all directions in the plane of the sheet. The resulting anisotropy indices are the ratios between the of the MD and CD sonic velocities, or the of the maximum and minimum sonic velocities.

A mean stock velocity over the wire was determined by measuring the time taken for a neutrally buoyant particle to traverse the forming region (0.5m).

MK II FORMER RESULTS

Representative results for the tests performed on the sheets made on the Mk II former are shown below in Figures 5a-9 inclusive.

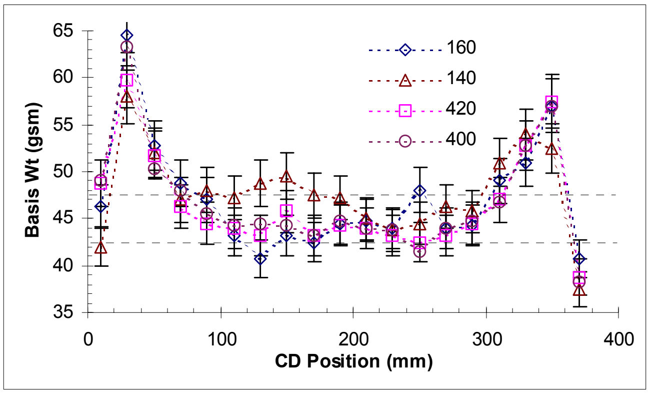

Fig 5a: **CD Basis weight profile for the Mk II Former, (07121998-01, Sheet No. 4), the key refers to the distance from the slice at which the coarse CD basis weight profile was analysed.**

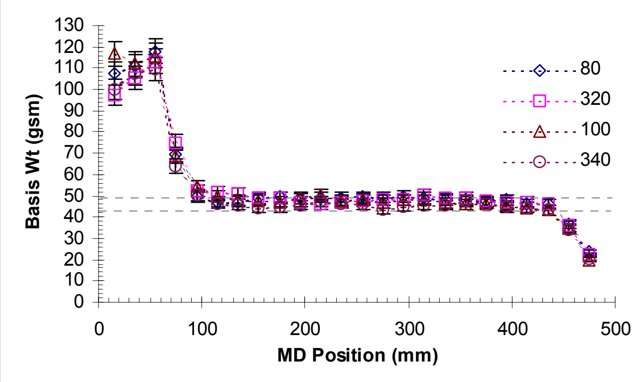

Fig 5b: **MD Basis weight profile for the Mk II Former, (07121998-01), the key refers to the distance from the left hand side wall where the coarse MD basis weight profile was analysed.**

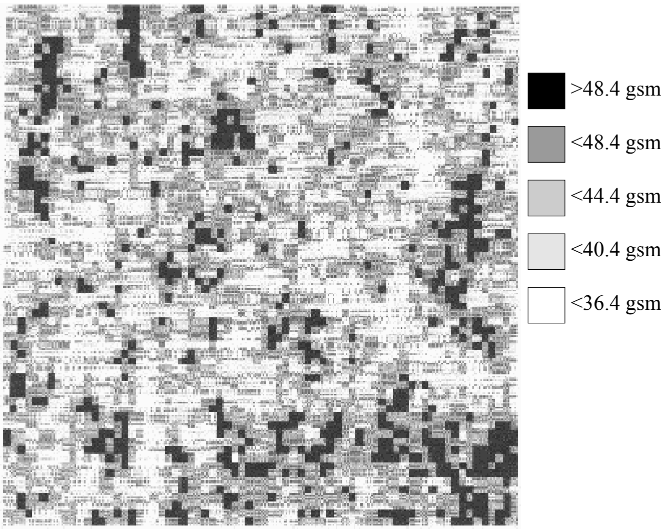

Fig. 6: **Basis weight distribution map (07121998-01).**

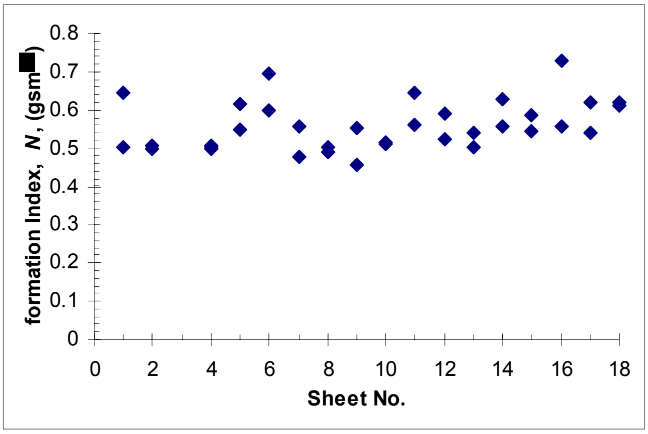

Fig 7: **Formation indices of the sheets produced on the Mk II Former, (sheet 3 was destroyed during couching)✍ .**

✍ Note that sheet No.'s 1,6,11 and 16 are outliers. Sheets 1 and 16 were formed at consistences outside of an acceptable range (0.49 $^{w}/_{w}$% ± 2%), sheet 6 was formed with a control failure, and 11 suffered from splash after forming.

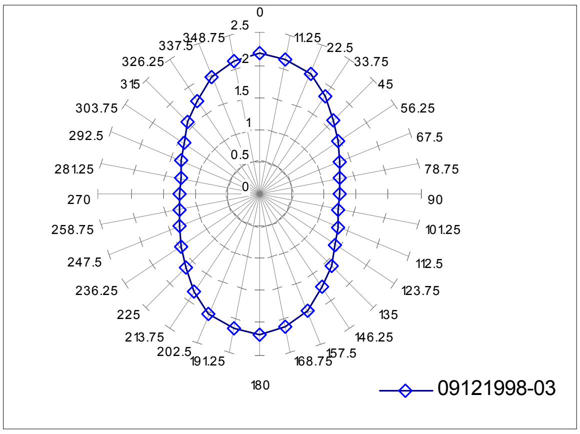

Fig 8: **Typical polar plot of the Nomura Shoji TSI for the Mk II former.**

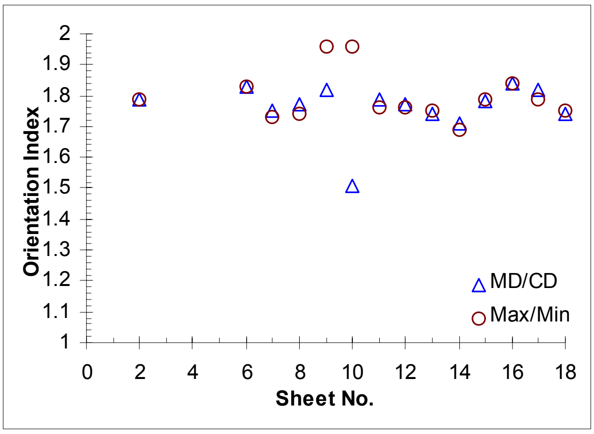

Fig 9: **Tensile Stiffness Indices (Nomura Shoji) of the sheets produced on the Mk II Former, (Sheet No.s 1, 4, 5 & 9,10 were creased).**

MK II FORMER DISCUSSION

The coarse scale grammage profile results presented in Figures 5a/b show that the for the Mk II sheets had removed the basis weight bias present in the Mk I sheets. The coarse sheet produced by the Mk II former had an inner region of higher uniformity slightly larger than an A4 sheet. The dimensions of this region are provided below in Figure 10.

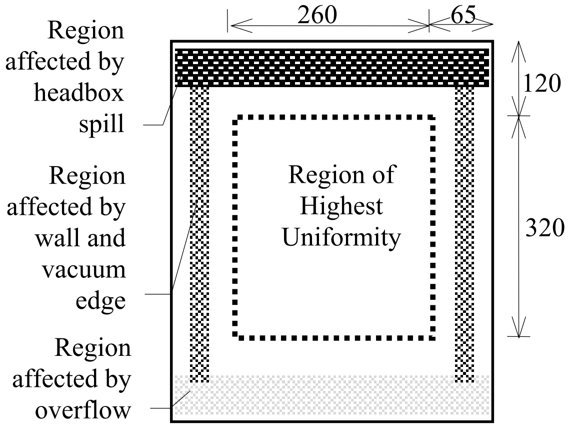

Fig 10: **Crude sheet produced on the Mk II former with the region of uniformity identified.**

The formation of these sheets was found to be repeatable (c.o.v. 8%) and consistent with commercially achievable formation at the operating consistency chosen.

Kiviranta *et al* (*26*) have developed a semi-empirical method for predicting (R^2=0.64) a formation index, *N* (for fine paper produced on a Fourdrinier paper machine) based on crowding number, n_{crowd}, , based on equations 4 and 5.

$$N = 0.29 + 0.014 n_{crowd} \qquad \text{Eq. 5.}$$

where;

$$n_{crowd} = \frac{\pi c \lambda^2}{6\delta} \qquad \text{Eq. 6.}$$

and,

c, mass of fibres per volume (g/l),
λ, length weighted mean fibre length, (m), and,
δ, mean fibre coarseness, (kg/m)

Application of Equations 5 and 6 to the Mk II system, (with typical values of λ = 1.01 mm, δ = 0.105 mg/m for bleached eucalypt kraft pulp), predicts N= 0.63, (n_{crowd} = 24.9). This prediction was found to agree only moderately with our measured formation indices, N = 0.54 ± 8%. The formation index was observed to correlate poorly with the consistency (R^2 = 0.07) in Kiviranta *et al*'s (*26*) study, yet a trend is still observable. The plot of N vs. x_c is provided below in Figure 11 to allow a comparison.

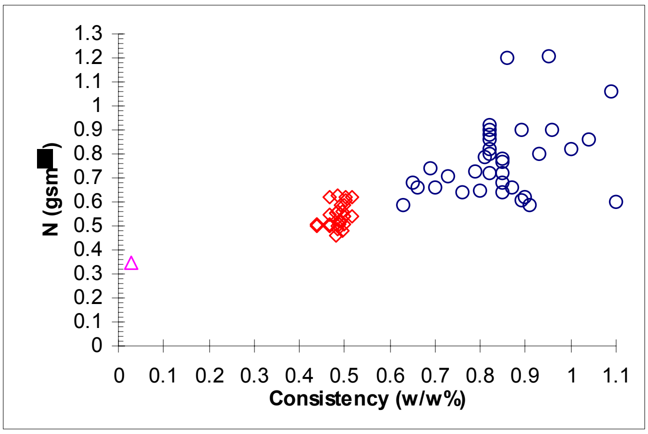

Fig. 11: Comparison of Formation Index to previously published data, (outliers removed).
○ Pilot machine data, Kiviranta et al (26).
◊ Mk II Former.
Δ Handsheet, Kiviranta et al (26).

Overall, the predicted and observed data are in moderate agreement. Confidence limits were not reported by Kiviranta *et al* (*26*), however, the published plots include some measured formation indices which are in good agreement with those reported here and which are predicted by Equations 4 and 5 to result from use of stock consistencies at the end of the range employed in this study (0.44 - 0.51 $^{w}/_{w}$ %).

The formation of the handsheet in Kiviranta *et al*'s study was measured to be $N_{handsheet} = 0.35$ and is typical of handsheets made from fine paper pulp stocks.

The results of ultrasonic measurement, (Figures 8, 9 and 12) confirm that significant anisotropy is present with most measured anisotropy indices lying in the range 1.7-2.0. Measured fibre orientation angles were in the range (0 ± 3^{o}) indicating a low level of cross flow on the wire of the Mk II former. These anisotropies fall within the range observed for papers made on commercial paper machines *(17)*.

The repeatability[1] (c.o.v. 2%) is illustrated below in Figure 12 where four sheets formed sequentially on the same day (9/12/1998) are superimposed upon one another, (possible re-calibration required for sheet 09121998-05).

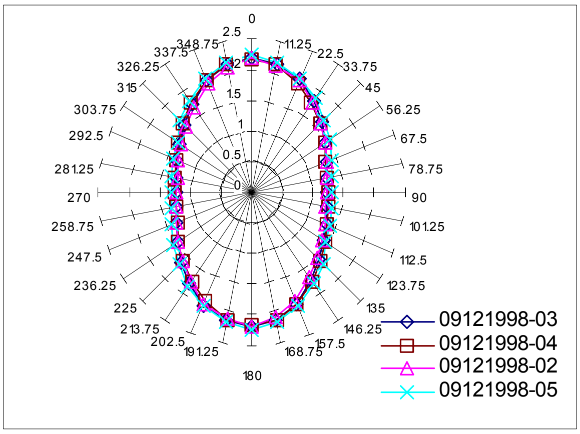

Fig 17: TSI Polar diagrams (Nomura Shoji) for 4 sheets formed on the same day which show good repeatability.

Clearly, the sheets formed on the Mk II former are more akin to the pilot scale sheets and that expected on commercial paper machines than a laboratory handsheet, in terms of both formation and fibre orientation.

The fibre orientation data and formation data presented here demonstrate that the Mk II former can be used to form sheets which match the anisotropies and formation indices of some papers made on full scale paper machines. Further work to fully explore the relationship between the "moving with the flow" forming analogy as employed here, and the operation of a commercial fourdrinier is in progress. The formation and anisotropy test indices presented here provide a meso scale assessment of the fine scale structure uniformity. They do not constitute a rigorous analysis of the relation of structural features to the forming conditions[2] . These tests are more suited to commercial applications. Future analyses will need to provide more information which is location specific if a relation between the pulp characteristics, forming conditions and sheet structure is to be established.

CONCLUSION

The sheets formed on the Mk I laboratory former confirmed that the conceptual design was worth pursuing. Subsequent improvements to the former resulted in a device (Mk II) which produced oriented laboratory sheets in a repeatable manner. These sheets were shown to exhibit similar coarse and fine scale basis weight distributions and MD/CD anisotropies to those of commercially made paper formed at similar stock consistencies.

The sheets formed under the operating conditions had, MD/CD TSI = 1.76 +/- 2%, N= 0.54 gsm$^{0.5}$ +/- 8% and a basis weight, BWt= 46.1 gsm +/- 3%.

The project target constraints of 1,2,3,4,5 were deemed to be accomplished. Further work to meet the remaining goals and effect a study of the forming phenomena is underway.

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[1] Sheet No.s 9-10 were creased and hence outliers.

[2] ie: compare the template sizes of the tests and the point/zone location of the test.

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ACKNOWLEDGMENTS

The authors wish to thank:

- Amcor Limited for use of testing equipment, library resources, provision of pulp samples, loan of experimental equipment from its Research and technology (R&T) Centre, and technical advice.
- staff of Amcor R&T for helpful advice.
- Clariant Pty Ltd for a sample of cationic dye.
- Albany for the forming wire material.
- The University of Melbourne Department of Chemical Engineering Workshop for their continual assistance during development.
- DEET for APAi funding.

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