"Effect of temperature and moisture content on paper behaviour in the nip"

D.W. Kawka[1], R.H. Crotogino[2], W.J.M. Douglas
Pulp and Paper Research Center
Department of Chemical Engineering
McGill University
Montreal, Quebec, Canada

1 – now with DuPont Advanced Fiber Systems – Nomex® Paper, Richmond, VA USA
2 – Pulp and Paper Research Institute of Canada (PAPRICAN), Pointe-Claire, Quebec, Canada

Dariusz W Kawka, Ph.D.
DuPont AFS
5400 Jefferson Davis Hwy.
Richmond VA 23261
Phone: (804) 383-4194
e-mail: Dariusz.W.Kawka-1@usa.dupont.com

Abstract

Effect of temperature and moisture content on the behaviour of paper in the nip of a calender was measured using an environment controlled calendering facility reproducing all industrially relevant calendering conditions except width. Paper temperature and moisture content were investigated over the wide range of 20 to 80 °C and 1 to 14% moisture. Nip load was varied from 15 to 210 kN/m, sheet speed from 90 to 950 m/min, while two sets of calender roll were used, 202 and 355 mm radius. Sheet width was 70 mm.

The experimental determination of the stress-strain behaviour of paper included documenting the effect of initial temperature and moisture content as well as process parameters, and was expressed as the in-nip calendering equation. Uncalendered paper thickness was found to be dependent on both paper temperature and moisture content. The rheological behaviour of commercial newsprint made from thermomechanical pulp was found to be a strong nonlinear function of temperature and moisture content over the wide range of temperature and moisture content investigated.

INTRODUCTION

Uniformity of paper thickness and surface properties is a key factor determining the end-use performance of paper. Thickness nonuniformity causes problems in the high speed printing presses. Variation in surface properties reduces the quality of printed images. Calendering is for many grades of paper the final papermaking operation, and thus the last processing step where uniformity of paper properties can be controlled.

Reduction in nonuniformity of paper thickness in the CD dimension is accomplished by adjustment in local roll radius, and consequently the CD profile of local nip load on the paper by manipulating the CD profile of local roll temperature. Arrays of locally adjustable impinging air jets, induction coils or infrared heaters are used as the control actuators to change local roll temperature, thereby changing local nip load and the extent of compression of the paper.

The permanent and in-nip versions of the calendering equation allow calculation of the desired local load distribution, corresponding to a local roll deformation. Availability of an in-nip calendering equation enables calculation of the control response to a local change in paper thickness as a function of local thermal deformation of the calender roll. However, in order that this can be done over the range of industrially relevant conditions requires that the in-nip calendering equation incorporate the effects of paper temperature and moisture content.

The objective of the present study is to determine the effect of paper temperature and moisture content on the in-nip behaviour of paper enabling an introduction of comprehensive dynamic model for use in the CD model predictive control of calendering. Achieving this objective involved the design and construction of a controlled environment calendering facility. An extensive experimental program was required for the measurement of in-nip paper thickness under wide ranging calendering conditions.

BACKGROUND

Paper thickness reduction in the nip of a calender is affected primarily by nip load, machine speed, roll diameter, paper and calender roll temperature, paper moisture content and initial bulk.

Chapman and Peel [5] investigated the effect of a pressure pulse on paper thickness using a platen press. They derived empirical relationships, the master creep equations, for compressed and recovered paper thickness as functions of maximum pressure and pulse duration. The work was extended by Colley and Peel [6] to include the effect of paper temperature and moisture content. Kerekes et al. [13] modified these relationships to predict directly the thickness reduction in a calender in terms of the more easily measured nip load, roll radius and machine speed rather than maximum pressure and pulse duration. Finally Haglund and Robertson [12] modified the master creep equations to include the effect of initial density, ρ_i, on permanent and in-nip paper strain:

$$\varepsilon_{n,p} = 0.5\ (1- \rho_i\ /\rho_{n,p\_max})\ [1 + \tanh\ (\ \mu_{n,p})]$$

for which μ_p and μ_n, are defined as: [1]

$$\mu_{n,p} = a_{0\ n,p}\ + a_{L\ n,p}\ \log_{10}L + a_{S\ n,p}\ \log_{10}S + a_{R\ n,p}\ \log_{10}R + a_{M\ n,p}\ M + a_{\Theta n,p}\ \Theta$$

where ρ_{n_max} and ρ_{p_max} are the maximum density obtainable either in or after the nip.

Crotogino et al. [7, 8] proposed a comprehensive calendering equation defining the fractional reduction in permanent bulk as the strain, ε_p:

$$\varepsilon_p = \frac{B_i - B_p}{B_i} \qquad [2]$$

where B_i and B_p are initial and permanent recovered bulks. Since the CD and MD paper dimensional changes in calendering were shown to be negligible [1, 11] an empirical relationship for permanent bulk reduction in terms of web speed, roll radius, nip load and the initial paper properties: initial bulk, sheet temperature and sheet moisture content can be used to compute the strain, positive for thickness reduction:

$$\varepsilon_p = A_p + \mu_p\ B_i$$

for which μ_p is defined as [3]

$$\mu_p = a_{0p} + a_{Lp}\ \log_{10}L + a_{Sp}\log_{10}S + a_{Rp}\log_{10}R + a_{Mp}\ M + a_{\Theta p}\ \Theta$$

This calendering equation has been used extensively to calculate the cross-direction average thickness reduction as a function of CD average calendering variables [9].

Browne et al. [3, 4] determined a calendering equation for in-nip conditions, thereby providing also a quantitative description of the viscoelastic behaviour of paper in and immediately after the nip in calendering. Their results established the validity of the calendering equation for quantitative description of in-nip strain ε_n as:

$\varepsilon_n = A_n + \mu_n B_i$

where: [4]

$\mu_n = a_{0n} + a_{Ln} \log_{10}L + a_{Sn}\log_{10}S + a_{Rn}\log_{10}R$

The dependence of in-nip strain on sheet temperature and moisture content was not determined by Browne et al. as all experiments were made at ambient conditions.

Equations 3 and 4 are valid between the limits:

$$-A_{p,n} / \mu_{p,n} \leq B_i \geq (1 - A_{p,n}) / 2\mu_{p,n} \quad [5]$$

Outside these limits a new set of equations must be used:

$$\varepsilon_{p,n} = 0 \text{ if } B_i < A_{p,n} / \mu_{p,n} \quad [6]$$

$$\varepsilon_{p,n} = (1 - A_{p,n})^2 / 4B_i \mu_{p,n} \text{ if } B_i > (1 - A_{p,n}) / 2\mu_{p,n} \quad [7]$$

The lower limit is the point below which, for the specific calendering nip intensities $\mu_{p,n}$, no further bulk reduction will occur. The upper limit of applicability of the calendering equations is the point beyond which an increase in initial bulk has no measurable effect on bulk reduction.

Coefficients for the permanent and in- nip equations are different and must be determined experimentally. These coefficients are dependent on the furnish used and to some extent on the papermaking operations before calendering. Because both the permanent and in-nip versions of the calendering equation express strain relative to initial bulk, the calendering equation treatment may be applied successively for multiple nips.

EQUIPMENT AND PROCEDURE

The calendering equipment of Browne et al. [2, 4], designed to reproduce industrial conditions of nip load, roll radius, and machine speed while allowing accurate measurement of the separation distance between the rolls, was modified to provide a unique controlled environment calendering facility. The new experimental calendering equipment consists of three basic elements: (1) a facility for bringing a complete roll of paper to a specific temperature and moisture content in advance of calendering, (2) the controlled environment calender, (3) a facility for producing air conditioned to a temperature and humidity independently controllable over a wide range for use in both the preconditioning chamber and the controlled environment hoods of the calender. With this facility the web temperature and web moisture content are independently controllable over a quite extended range, 20 to 80 ^{o}C, 1% to 14% moisture. Measurable error due to roll bending or bearing deflection was eliminated through use of a face width of calender rolls of only 75 mm, with maximum paper width of 70 mm.

The experimental work focused on measurements of the in-nip and permanent paper strain as paper was calendered under wide selection of industrially relevant conditions. This program involved over 22 combinations of paper temperature and moisture content (30 sets of experiments with combinations of calendering load, speed and roll radius). All experiments were performed using Eastern Canadian TMP newsprint, 48.8 g/m^2, supplied by the Abitibi-Price Company mill at Stephenville, Newfoundland. Three master rolls of paper, each 1.492 m wide and 1.09 m diameter, were slit into 64 narrow rolls of width 70 mm. Each test roll was first preconditioned to a specific paper moisture content and temperature, then maintained at these conditions while run in the environment controlled calendering facility. Experimental conditions are shown in Table I.

Initial thickness (bulk) of the uncalendered paper was measured just before and after each experiment at specific temperature and moisture content investigated. Permanent paper caliper was measured after conditioning for 24 hours at 23 ^{o}C and 50% relative humidity.

EXPERIMENTAL RESULTS AND DISCUSSION

The whole set of 760 data points was used to calculate the coefficients of both the permanent and the in-nip versions of the calendering equation. As all six calendering variables were investigated, the full version of the equation was used:

$$\varepsilon_{p,n} = A_{p,n} + \mu_{p,n} B_{i},$$

where μ_n and μ_p are: [8]

$$\mu_{p,n} = a_{0p,n} + a_{Lp,n} \log_{10}L + a_{Sp,n}\log_{10}S + a_{Rp,n}\log_{10}R + a_{Mp,n} M + a_{\Theta p,n} \Theta$$

As the measured strains, in-nip and permanent, were always greater than zero, the lower limit is not relevant. Thus only the calendering equations and appropriate upper limits were used as elements of the data processing program. All experimental data were processed using the direct search procedure of the SYSTAT Simplex method for non-linear function minimisation [14].

The coefficients for the calendering equations, along with the asymptotic standard error are presented in Tables II and III. Figure 1 shows the data for permanent and in-nip strain obtained for a single combination of all experimental variables plotted along with the calendering equation predictions and the corresponding 95% confidence limits.

The coefficients of the in-nip calendering equation from the present study compare well with those obtained by Browne et al. [3, 4], with an exception for the in-nip coefficient a_{0n}. In the Browne et al. study effect of temperature and moisture content was not measured and is included in the intercept coefficient a_{0n}. If the ambient conditions of Browne et al. were approximated as paper temperature Θ = 20 ^{o}C and paper moisture content M = 5%, the corrected value of a_{0n} coefficient ($a_{0n\text{-corr}}$=0.0605) is within the 95% confidence limits of the Browne et al. data (a_{0n}= 0.0247, S.E.= 0.0194).

The in-nip temperature and moisture content coefficients of the calendering equation, $a_{\square n}$ and a_{Tn}, presented in Table III have never previously been determined.

The permanent calendering coefficients as determined in the Crotogino et al. [7, 8] and Browne et al. [3, 4] studies are comparable with the results reported in the present study except the a_{0p} coefficient obtained by Browne et al. Again, after approximating the ambient conditions of Browne et al., as in the in-nip case, the corrected value of this coefficient ($a_{0p\text{-corr}}$= 0.1140) is seen to be comparable with their coefficient (a_{0p}= 0.1256, S.E.= 0.0101).

All calculated in-nip coefficients are statistically different from zero except for the in-nip intercept coefficient a_{0n} for which the coefficient of variation is about 50%, and thus the 95% confidence limits for a_{0n} just barely exclude the a_{0n}= 0 possibility. For the permanent case, all coefficients are statistically non-zero as all standard errors are at least one order of magnitude smaller than the corresponding estimates.

The finding of Browne et al. [3, 4] that the logarithmic relation between in-nip paper deformation and line load is strongly nonlinear, especially at lower loads, was confirmed in the present study. The regression analysis of the pieced-together form of the calendering equation attempts to fit a linear part of this equation through data at the lowest loads. The result of this procedure is that for different ranges of line loads, the linear part of the calendering equation is applied to different sets of in-nip strain data indicating that different calendering coefficients can be estimated. This can explain the small difference between the in-nip load coefficient reported here and that of Browne et al. [3, 4], as a narrower range of load was investigated in the present study.

Analysis of the in-nip data based on which part of the calendering equation is applied to fit those data shows that the calendering equation predicts that virtually all of the in-nip strain data (759 out of 760) fall above their upper limits. This finding agrees well with Browne et al. [4] report that 95% of their in-nip strains are over the upper limit and a very low nip load is required to obtain in-nip strain which fall below this upper limit. For the industrially relevant range of line load therefore, virtually all in-nip data are fitted only with the nonlinear part of the calendering equation.

Examination of the residual error computed from the full set of data implied that the forms of the calendering equation proposed in this study do not adequately predicted the moisture and temperature effects for in-nip strain, the moisture effect for permanent strain.

Effect of moisture content and temperature on uncalendered paper thickness

As the thickness of uncalendered paper varied with paper temperature and moisture content, thickness was measured at the exact conditions. Uncalendered paper thickness caused by swelling of the wood pulp fibers is found to linearly increase with both moisture content and temperature as shown on Figure 2, with a comparable sensitivity of paper thickness to its temperature and moisture content; 0.7 μm per 1% moisture, 0.9 μm per 10 ^{o}C.

The Forseth and Helle [10] investigation of the effect of moisture content on thickness of calendered paper showed that an increase in thickness with moisture content is caused of two factors: the cross-sectional expansion of compressed mechanical pulp fibers, and the development of interfibre voids and pores in the paper structure. The two factors are interrelated, as cross-sectional expansion of fibers pushes surrounding fibers up, and thus creates voids between them.

Effect of moisture content and temperature on paper strain

Both moisture content and temperature are important parameters for calendering; their importance lies in the corresponding effect of the fibers becoming more pliable and plastically deformable. The effect of paper moisture content on both permanent and in-nip strain was determined in the present study for several paper temperatures. With other calendering conditions fixed, the slope of the deformation-moisture content relation is shown to decrease with increasing paper moisture content, in some cases even vanishing, as can be seen on Figures 3 and 4. Such behaviour is caused by a conflict between two phenomena encountered when paper moisture content is increased: with the sorption of water, wood pulp fibers both swell and become more pliable.

For paper at low temperature and at lower moisture contents, the sensitive increase in permanent strain with increasing moisture content indicates that the effect from the fibers becoming more pliable is so strong that it more than compensates for the additional resistance to deformation coming from the increased amount of water in the fibers. However at higher moisture content the situation is reversed, with a now smaller increase in fiber pliability being insufficient to compensate for the restriction on paper deformation coming from the larger amount of water in the fibers.

The effect of moisture content is smaller on in-nip than permanent strain, which is reasonable considering the high compression of paper in the nip, with the relation between in-nip strain and paper moisture content either reaching a plateau or, most often, passing through a maximum. Figure 3 shows that for in-nip strain not exceeding about 0.4 to 0.5, i.e. at the lowest calendering loads, the in-nip strain dependence on moisture content is similar to that for permanent strain. However at heavier calendering loads, when the in-nip paper thickness is as little as 30 to 40 μm, the in-nip strains pass through a maximum which occurs at approximately 7 to 9% moisture content.

At any paper moisture content, pulp fibers are more pliable at higher temperature. Thus at higher paper temperature the fibers are already more pliable at low moisture content, hence there is less scope for increase of fiber pliability with increasing moisture content. Results obtained in the present study indicate that as paper temperature is increased the maximum in the deformation-moisture content relation shifts to lower lever of moisture content, Figure 4.

The sensitivity of paper strain, both in-nip and permanent, is naturally less at the higher level of moisture content for which the levels of strain are higher. At the high levels of in-nip deformation existing for temperatures above 50 ^{o}C, especially at the higher moisture content, there is little increase in in-nip strain with further increase in paper temperature. The present work supports the findings of Colley and

Peel [6] that at high moisture content the effect of increase of temperature is very small above 50 ^oC for groundwood furnish paper and above 70 ^oC for cotton paper.

Modified calendering equation

The strong nonlinear effect of moisture content on in-nip paper deformation indicates that the present form of the calendering equation, which is linear with moisture content, could be improved by an addition of a second order term for this calendering variable:

$$\varepsilon_n = A_n + \mu_n B_i$$

where: [9]

$$\mu_n = a_{0n} + a_{Ln}\, log_{10}L + a_{Sn} log_{10}S + a_{Rn} log_{10}R + a_{Mn}\, M + a_{M2n}\, M^2 + a_{\Theta n}\, \Theta$$

This equation is valid within the limits defined for the standard calendering equation. Estimates of the coefficients for Equation 9, along with their asymptotic standard errors are presented in Table IV.

Compared with results obtained for the standard calendering equation, Table II, the coefficients which are changed the most are those for the intercept and moisture content, a_{0n} and a_{Mn}, changed by 45 and 76%. The other coefficients change by less than 8%, except 14% change for the intercept coefficient A_n. Inspection of Figure 5 indicates that the curves generated with Equation 9 better predict the nonlinear behaviour of in-nip strain with moisture content.

As the in-nip moisture effect has been seen to be a function of in-nip strain, the alternative of including line load and paper temperature, which affect in-nip strain the most, with the moisture coefficient a_{M2n} is also investigated:

$$a_{M2n} = a_{M2o} + a_{ML}\, log_{10} L + a_{M\Theta}\, \Theta \qquad [10]$$

However, there is insufficient data available at low line load and high paper temperature to be able to extract a statistically meaningful relationship involving those variables. Thereby fitting Equations 9 and 10 to the set of in-nip strain data provided only a small improvement, Figure 5 and Table V.

As none of the modified versions of a calendering equation adequately predicts the nonlinear effect of increased moisture content on in-nip strain, a lower value of the in-nip moisture coefficient could be expected. On the other hand, the value of the in-nip temperature coefficient is much higher than the permanent temperature coefficient despite the fact that the experimental data indicate otherwise. It seems that the inadequate prediction of the in-nip moisture effect is compensated by the value of the in-nip temperature coefficient being too high.

Master creep equation

The SYSTAT statistical software was also used to fit the modified version of the master creep equation, Equation 1, exactly as with the calendering equation. As SYSTAT does not have a built-in hyperbolic tangent function the exponential definition of this function was used.

The permanent and in-nip calendering coefficients, along with the asymptotic standard error are presented in Tables VI and VII. The experimental data and regression curves with the master creep equation are plotted in Figure 6 with, for comparison, prediction curves from the calendering equation.

The limiting density obtainable after the nip is higher in the present study, ρ_{p_max}= 0.80 g/cm^3, than that reported by Browne et al. [3, 4], ρ_{p_max}= 0.59 g/cm^3. This difference is attributed to the higher paper temperatures and moisture contents used in the present study. Application of the extreme calendering conditions, high load plus high temperature or moisture content, resulted after just one heavily loaded nip in the final bulk as low as 1.39 to 1.43 cm^3/g, or paper density of 0.70 to 0.72 g/cm^3. When nips more heavily loaded yet are used, final paper density can approach the limiting value of 0.80 g/cm^3.

The limiting in-nip density is 1.41 g/cm^3, which is higher than that reported by Browne et al. [3, 4]. The in-nip data obtained here showed that a combination of high nip load with high paper temperature produces in-nip paper compression approaching 70%. At this point the actual in-nip paper density was 1.40 g/cm^3, very close to the reported limiting density obtainable in the nip. As accepted value for the density of the component fibers is 1.50 g/cm^3, this implies that in-nip strain of 0.72 to 0.75 is the highest possible compression the paper can experience in the nip.

The in-nip moisture coefficient is slightly higher than the corresponding moisture coefficient of Colley and Peel [6], but is within the 95% confidence limits. On the other hand the in-nip temperature coefficient found here is one order of magnitude higher in the present work than that reported previously. This difference can be attributed to the different combinations of paper temperature and moisture content used in the two studies. The temperature effect investigated here was over nearly the same range of paper temperature, 20 to 74 ^{o}C, but only for a moisture content of 2%, whereas in Colly and Peel study moisture content was varied from 2.3 to 12.6%.

Overall the fit of the master creep equation is similar to the calendering equation. Thus the continuous form of the master creep equation is an attractive alternative to the pieced-together form of the calendering equation with its lower and upper limits.

Relationship between permanent and in-nip strain

Browne et al. [3, 4] proposed a convenient logarithmic relationship between permanent and in-nip strain. However, their permanent and in-nip strains were measured at ambient conditions only. Present study shows that an application of different combinations of nip load, temperature and moisture content can result in paper being compressed to the same or even a lower in-nip strain, while its permanent strain would be higher. This suggests that the relationship between in-nip and permanent strain is a function of these calendering variables. Thus a modified version of ε_n-ε_p relationship is proposed:

$$\varepsilon_n = \varepsilon_o + c \log_{10} \varepsilon_p$$

where c_0 is defined as:

[11]

$$c_0 = c_0 + c_L \log_{10}L + c_M M + c_\Theta \Theta$$

The coefficients defined in Equation 11 are listed in Table VIII and the prediction curve is plotted on Figure 7.

The overall fit of Equation 11 (R-sq.= 0.76) is comparable with the in-nip versions of the calendering and master creep equations. Taking into account the continuous and linear form of this equation, with respect to the calendering variables, it is a very attractive alternative for estimating in-nip strain from permanent strain, especially for implementing in a model for a cross-direction control of calendering.

CONCLUSIONS

In-nip and permanent paper strain was determined in a controlled environment calender for paper temperature and moisture content covering the range 22 to 75 ^{o}C and 1 to 14 % moisture.

The calendering and master creep equations are shown to provide almost identical descriptions of permanent paper deformation after a calender nip for industrially relevant line loads.

The in-nip version of the calendering equation, proposed by Browne et al., is now verified to give a satisfactory description of paper deformation in the calender nip over the wide range of paper temperature and moisture content.

Because essentially all the in-nip strain data falls above the upper limit of the calendering equation, only the nonlinear part of the calendering equation can be used to fit this in-nip data obtained for industrially relevant calendering variables.

The in-nip master creep equation provides a similar description of paper deformation in a calender nip. Initial paper thickness is found to be a linear function of both paper temperature and moisture content.

Increased moisture content is seen to have a strong nonlinear effect on in-nip paper strain.

The relationship between permanent and in-nip strain is a function of paper temperature and moisture content as well as line load. This relationship is advantageous for estimating local in-nip strain for a given local permanent strain, but another calendering equation must be used to estimate the local value of line load.

NOMENCLATURE

a_{M2n}, a_{M20}, a_{ML}, $a_{M\Theta}$	Coefficients for modified calendering equation
A_{ij}, a_{ij}	Calendering equation coefficients Subscript: *i*: O offset, L load, S speed, R radius, Θ temperature, M moisture content, P pressure, t time *j*: n in-nip, p permanent
$B_{p,i}$	Permanent and initial bulk, cm^3/g
B_p	Permanent bulk, cm^3/g
c	Curve fitting coefficient
L	Line load, kN/m
M	Paper moisture content, %
P_{line}	In-nip applied line pressure, MPa
R	Average roll radius, m
S	Calendering speed, m/min
$\varepsilon_{p,n}$	Permanent and in-nip strain
ε_0	Curve fitting coefficient
Θ	Temperature, ^oC
$\mu_{p,n}$	Permanent and n-nip calendering intensity
ρ_i	Initial paper density, q/cm^3
ρ_{n,p_max}	Maximum in-nip and permanent paper density, q/cm^3

REFERENCES

1. BAUMGARTEN, H.L., "Changes of web dimensions during calendering and supercalendering", Symp. On Calendering and Supercalendering, UMIST, Manchester, England (1975).
2. BROWNE, T.C., CROTOGINO, R.H., and DOUGLAS, W.J.M., "An experimental calender for in-nip paper caliper measurements", JPPS 19(2):J92-96 (1992).
3. BROWNE, T.C., CROTOGINO, R.H., and DOUGLAS, W.J.M., "Measurement of paper strain in the nip of an experimental calender", JPPS 20(9):J266-271 (1994).
4. BROWNE, T.C., "Viscoelastic properties of paper in a calender nip", Ph.D. thesis, McGill University, Montreal, 1995.
5. CHAPMAN, D.L.T., PEEL, J.D., "Calendering processes and the compressibility of paper (part one)", Paper Technol. 10(2):T116-T124 (1969).
6. COLLEY, J., PEEL, J.D., "Calendering processes and the compressibility of paper (part two)", Paper Technol. 13(5):T166-T173 (1972).

7. CROTOGINO, R.H., "Towards a comprehensive calendering equation", Trans. Tech. Sect.CPPA 6(4):TR89-TR94 (1980).
8. CROTOGINO, R.H., "Machine calendering - recent advances in theory and practice", Trans. Tech. Sect. CPPA, 7(4): TR75-TR87 (1981).
9. CROTOGINO, R.H., HUSSAIN, S.M. and McDONALD, J.D., "Mill application of the calendering equation", JPPS 9(5):TR128-TR133 (1983).
10. FORSETH, T., HELLE, T., "Effect of moistening on cross-sectional details of calendered paper containing mechanical pulp", JPPS 23(3): J95-J100 (1997).
11. GRATTON, M.F., "Three-dimensional web deformations from calendering in a hard nip", TAPPI 80(4): 210-218 (1997).
12. HAGLUND, L., ROBERTSON, G., "Local Thickness Reduction in a Calender Nip - An Experimental Study", Svensk Papperstidning 77(14):521-530 (1974).
13. KEREKES, R.J., PYE, I.T., "Newsprint calendering: an experimental comparison of temperature and loading effects", Pulp and Paper Canada 75(11):65-72 (1974).
14. O'NEILL, R., "Function minimization using a simplex procedure", AS47, Applied Statistics Algorithms (P. Griffiths and L.D. Hill, eds.), Ellis Horwood Limited for a Royal Statistical Society, London (1985).

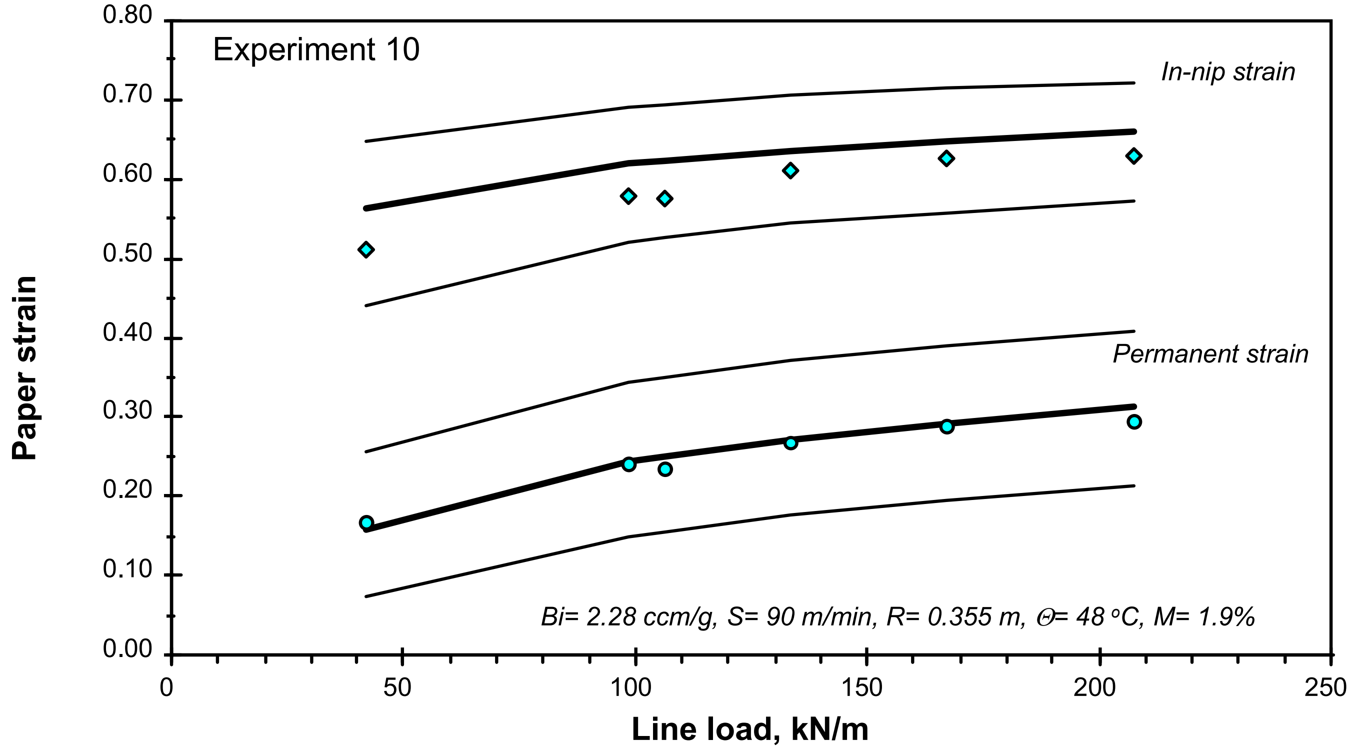
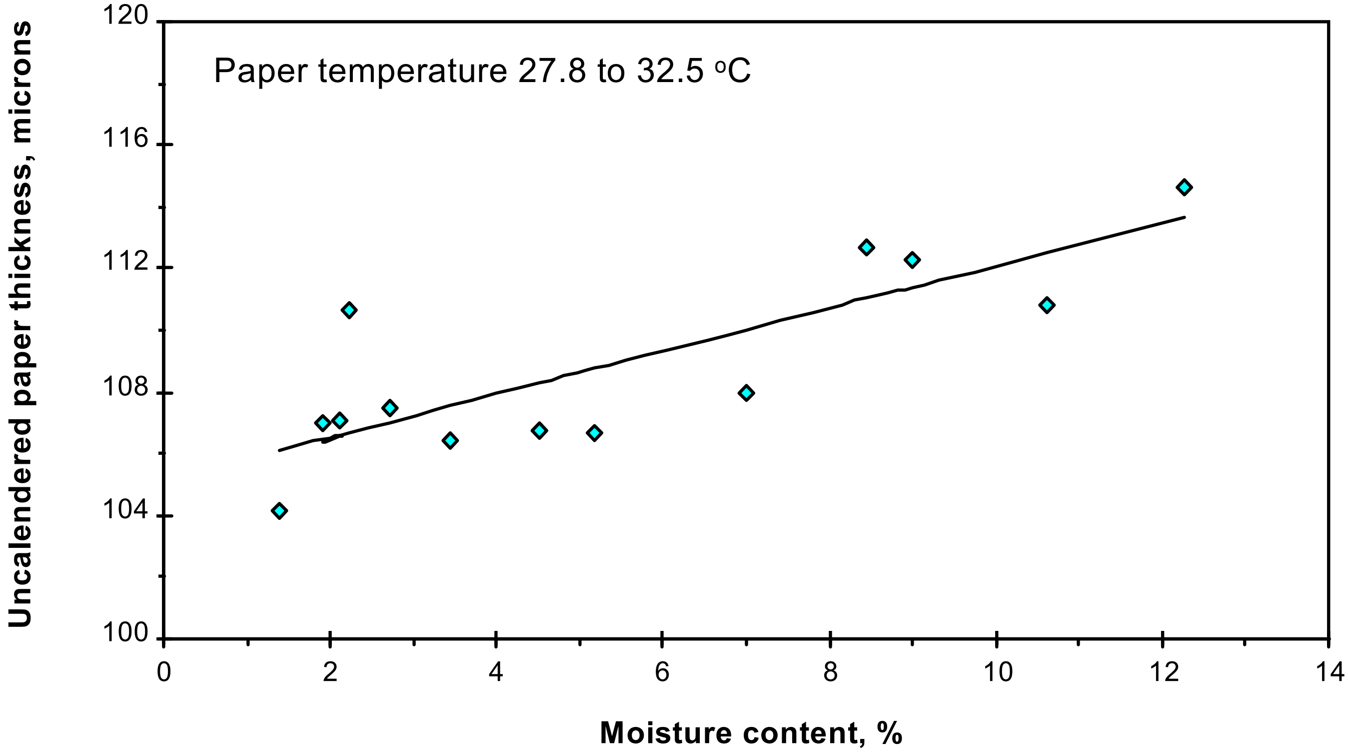


Figure 1: Effect of load on strain.
Best fit lines with upper and lower 95% confidence limits



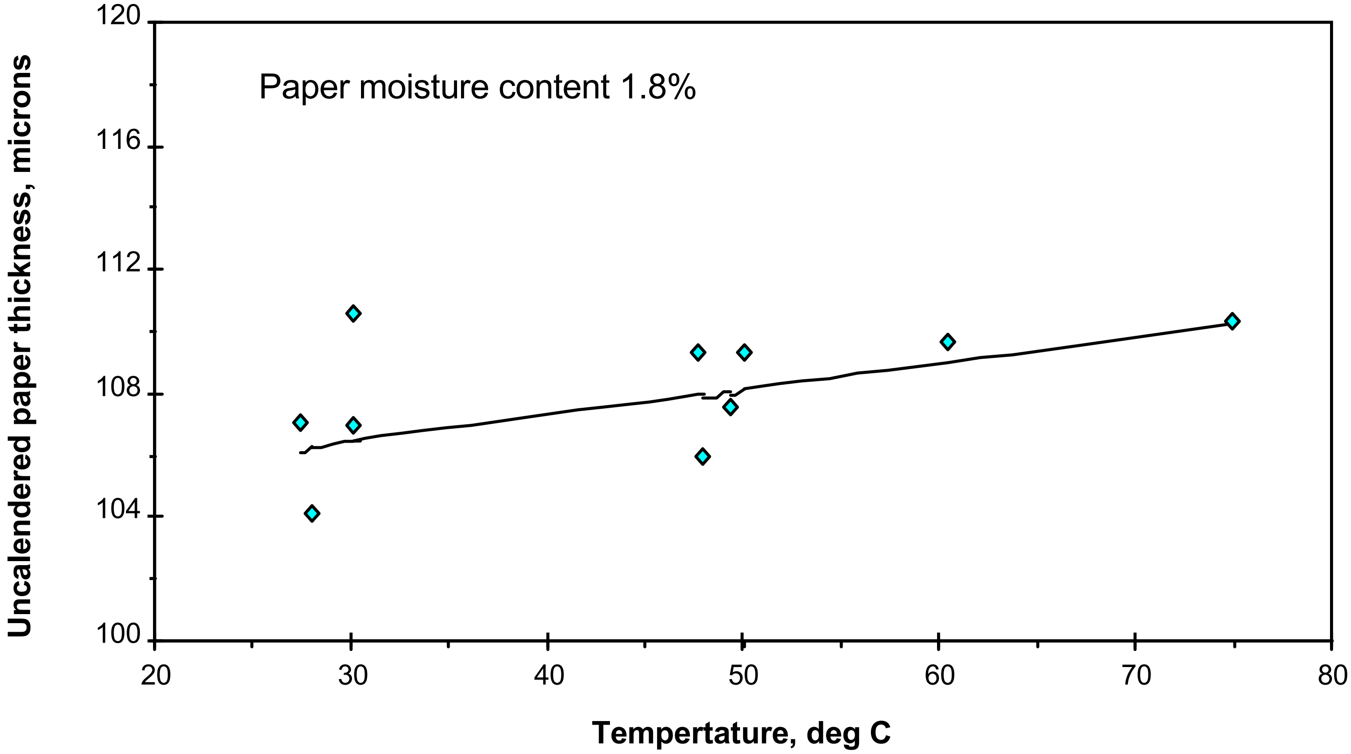
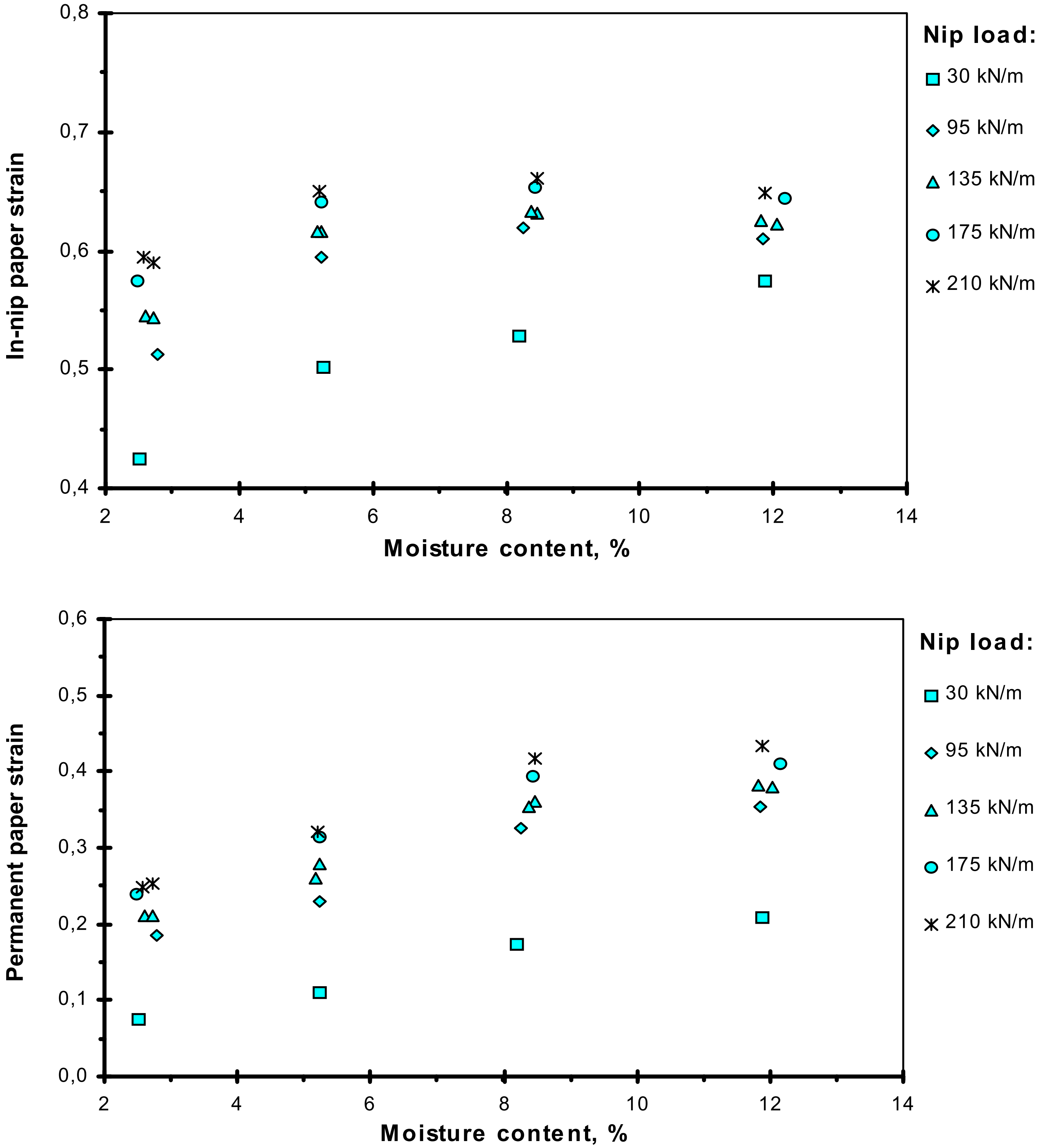


Figure 2: Effect of temperature on thickness of uncalendered paper:
a) Θ = ~30 ^{o}C
b) M = 1.8%



<u>Figure 3</u>: Effect of moisture content and line load on paper strain.

R= 0.202 m, Θ= ~ 30 ^{o}C, S= 300 m/min

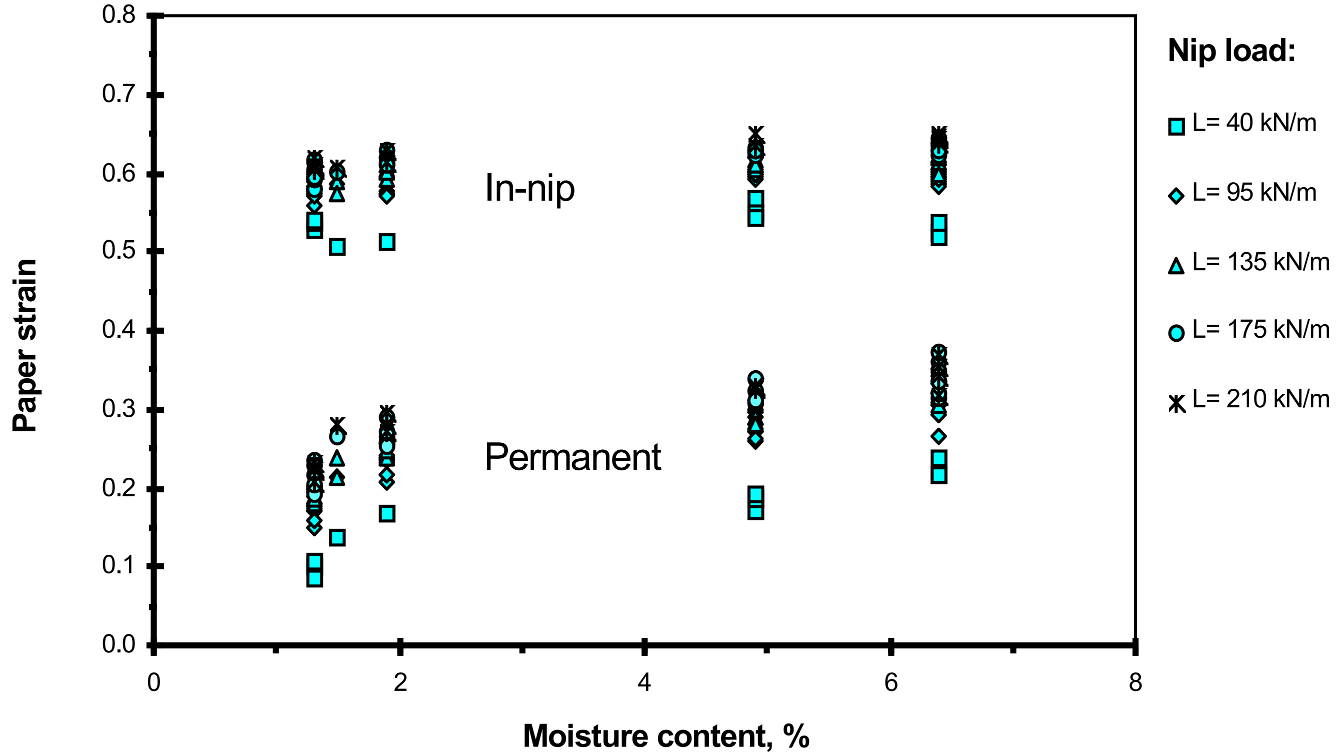


Figure. 4: Effect of moisture content and load on paper in-nip strain.
R= 0.355 m, M= ~3.8% Θ= ~48 ^{o}C, all speeds

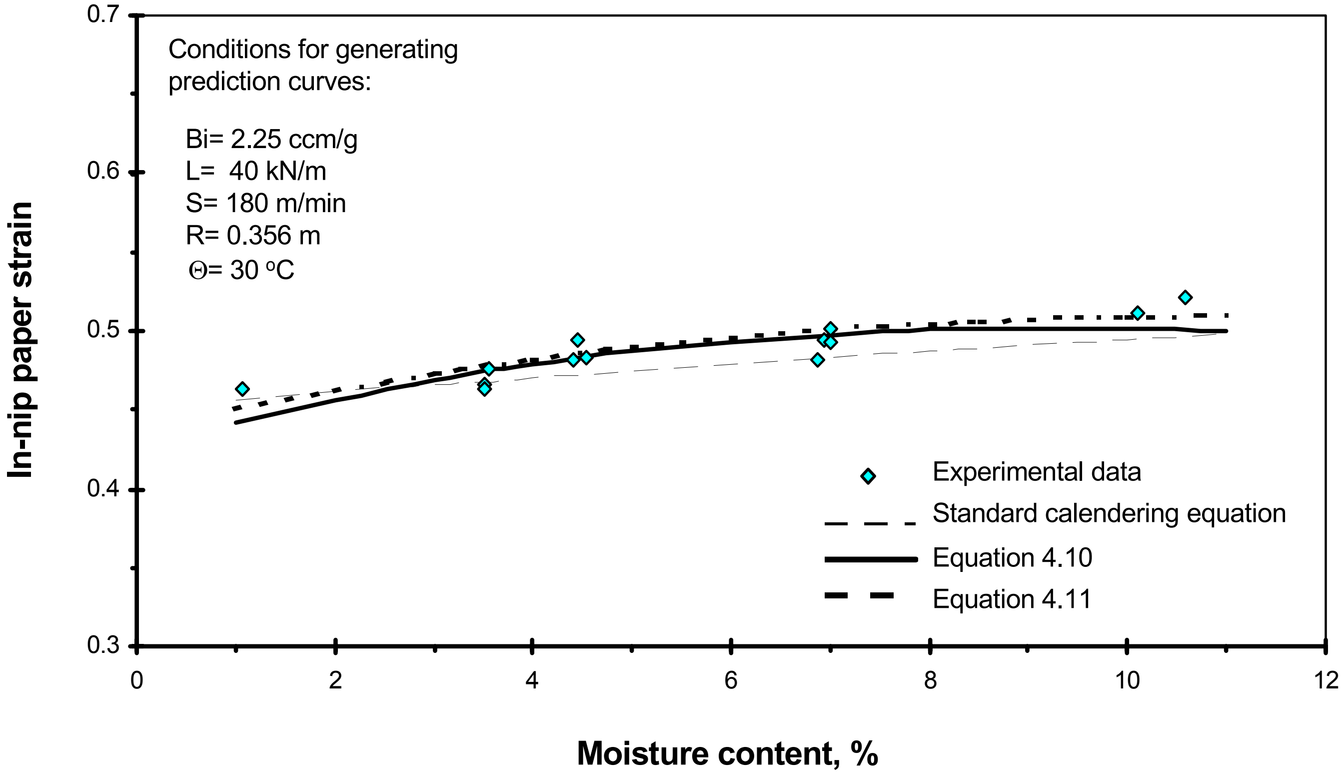


Figure 5: Effect of moisture content on in-nip strain.
R= 0.356 m, Θ= 27 to 30 ^{o}C, L= 40 kN/m, all speeds

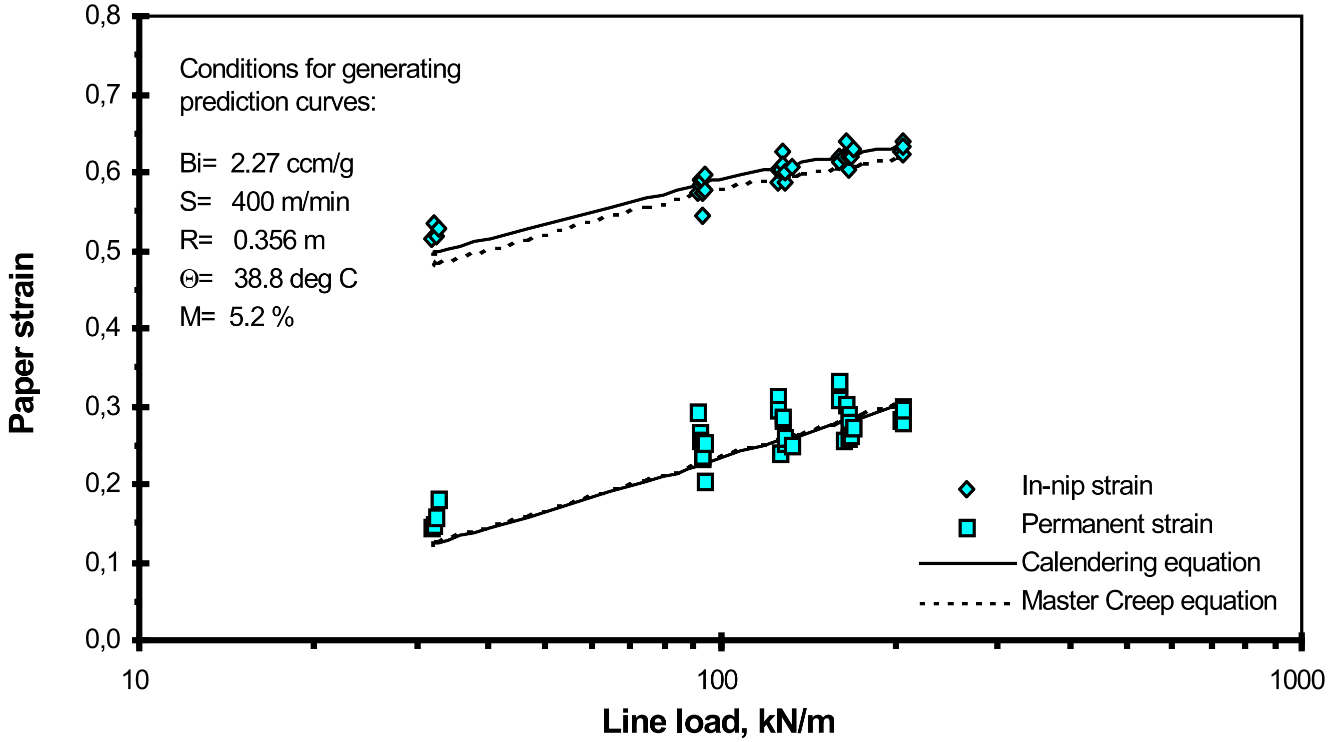


Figure 6: Effect of line load on strain, all speeds

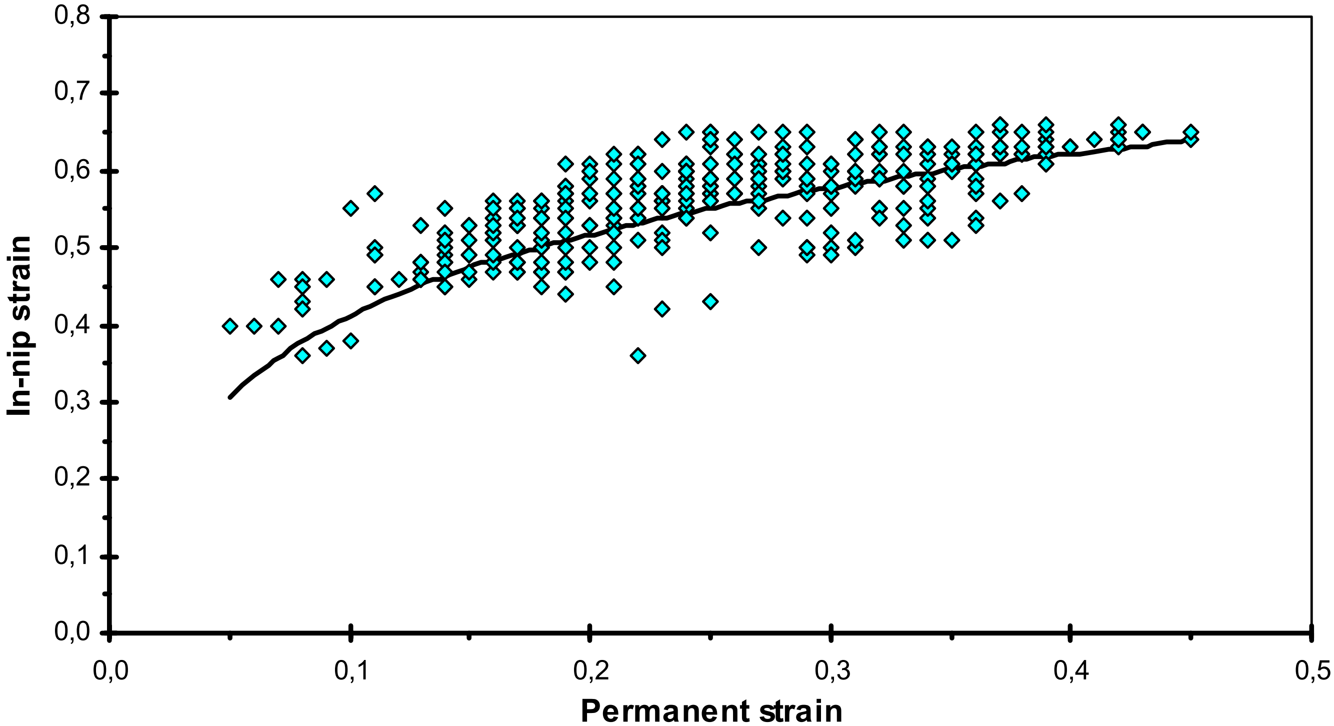


Figure 7: Relationship between permanent and in-nip strain.
Θ = 25 to 33 ^{o}C, all loads and moisture contents

Table I: Calendering conditions

Load, kN/m	15, 30, 40, 95, 135, 175 and 210
Speed, m/min	90, 180, 300, 500 and 950
Roll radius, mm	202 and 355
Temperature, ^{o}C	20, 30, 40, 50, 60 and 75
Moisture content, %	2 to 14
Initial bulk, cm^3/g	2.16 to 2.35

Table II: In-nip coefficients for the calendering equation.

PARAMETER	ESTIMATE	A.S.E. (C.V.)
A_n	-0.3172	0.02388 (7.5)
a_{0n} (g/cm^3)	-0.0239	0.01275 (53)
a_{Ln} (g/cm^3)	0.1781	0.00853 (5)
a_{Sn} (g/cm^3)	-0.0128	0.00412 (32)
a_{Rn} (g/cm^3)	-0.0413	0.01265 (31)
$a_{\Theta n}$ (g/cm^3 ^{o}C)	0.00347	0.000112 (3)
a_{Mn} (g/cm^3)	0.00299	0.000383 (13)
R-squared	0.77	

Table III: Permanent coefficients for the calendering equation.

PARAMETER	ESTIMATE	A.S.E. (C.V)
A_p	-0.4186	0.01678 (%)
a_{0p} (g/cm^3)	0.0642	0.00179 (%)
a_{Lp} (g/cm^3)	0.0973	0.00451 (%)
a_{Sp} (g/cm^3)	-0.0218	0.00124 (%)
a_{Rp} (g/cm^3)	-0.0351	0.00406 (%)
a_{Tp} (g/cm^3 °C)	0.00097	0.000053 (%)
a_{Mp} (g/cm^3)	0.00607	0.000363 (%)
R-squared	0.90	

Table IV: In-nip coefficients for Equation 9

PARAMETER	ESTIMATE	A.S.E. (C.V.)
A_n	-0.3727	0.02681 (7%)
a_{0n} (g/cm^3)	-0.0438	0.01344 (31%)
a_{Ln} (g/cm^3)	0.1926	0.00966 (5%)
a_{Sn} (g/cm^3)	-0.0141	0.00440 (31%)
a_{Rn} (g/cm^3)	-0.0440	0.01348 (31%)
$a_{\Theta n}$ (g/cm^3 ^{o}C)	0.00381	0.000125 (3%)
a_{Mn} (g/cm^3)	0.01230	0.000403 (3%)
a_{M2n} (g/cm^3)	-0.00066	0.000005 (1%)
R-squared	0.77	

Table V: In-nip coefficients for Eq. 9 modified with Eq. 10

PARAMETER	ESTIMATE	A.S.E. (C.V.)
A_n	-0.3241	0.02681 (%)
a_{0n} (g/cm^3)	-0.0252	0.00721 (%)
a_{Ln} (g/cm^3)	0.1774	0.00875 (%)
a_{Sn} (g/cm^3)	-0.0126	0.00341 (%)
a_{Rn} (g/cm^3)	-0.0323	0.01183 (%)
$a_{\Theta n}$ (g/cm^3 ^{o}C)	0.00333	0.000112 (%)
a_{Mn} (g/cm^3)	0.00946	0.000384 (%)
a_{Mo} (g/cm^3)	-0.00092	0.000005 (%)
a_{MT} (g/cm^3 ^{o}C)	0.000016	0.000004 (%)
a_{ML} (g/cm^3)	0.0000075	0.00000035 (%)
R-squared	0.78	

Table VI: Permanent coefficients for the master creep equation.

PARAMETER	ESTIMATE	A.S.E. (C.V.)
ρ_{p_max} (g/cm^3)	0.7983	0.02461 (%)
a_{0p}	-2.5126	0.09150 (%)
a_{Lp}	1.0510	0.05364 (%)
a_{Sp}	-0.2289	0.01736 (%)
a_{Rp}	-0.4397	0.04304 (%)
$a_{\Theta p}$	0.01180	0.000643 (%)
a_{Mp}	0.07597	0.004382 (%)
R-squared	0.90	

Table VII**:** In-nip coefficients for the master creep equation.

PARAMETER	ESTIMATE	A.S.E. (C.V.)
ρ_{n_max} (g/cm^3)	1.4071	0.02821 (%)
a_{0n}	-1.8394	0.11629 (%)
a_{Ln}	0.8394	0.04154 (%)
a_{Sn}	-0.0604	0.02207 (%)
a_{Rn}	-0.3106	0.07065 (%)
$a_{\Theta n}$	0.02341	0.001940 (%)
a_{Mn}	0.02305	0.002256 (%)
R-squared	0.77	

Table VIII: Coefficients for Equation 11

PARAMETER	ESTIMATE	S.E. (C.V.)
a	0.7602	0.01432 (%)
c_0	0.4956	0.02326 (%)
c_L	-0.0636	0.01474 (%)
c_Θ (1 / ^oC)	-0.0028	0.00025 (%)
c_M	0.0089	0.00142 (%)
R_squared	0.76	