Estimating limits of wet pressing on paper machines

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ABSTRACT: Water removal by wet pressing on paper machines depends on many factors such as press impulse, pressure, basis weight, equilibrium moisture, rewet, furnish, and fabric properties. These factors must be considered together to estimate wet pressing limits, such as the possibility of attaining 65% solids content on commercial paper machines. We have made such estimates employing the Decreasing Permeability Model (DPM) of wet pressing. This paper describes the utility of this approach and discusses some findings, such as the large dependence of low basis weight grades on equilibrium moisture content, maximum nip pressure, and rewet. The model also estimates the impact of basis weight, web temperature, double-felting, and incoming web solids on water removed.

Application: This study applied the DPM to quantify the factors that determine water removal in wet pressing, and in particular, factors to achieve high solids content. More generally, the DPM can be used to optimize existing presses and guide research and development towards the most cost effective ways to improve water removal.

State-of-the-art press sections using shoe presses and high web temperatures are able to achieve web solids in excess of 50%. In contrast, wet pressing laboratory experiments at high pressures and long times have shown that it is possible to obtain solids contents over 60% [1-5] and, in one case, as high as 71% [2]. These results have encouraged the papermaking community to optimize the wet pressing process and develop new technologies in order to approach these values.

In the United States alone, 400 million GJ/year of energy is required to dry paper at a cost of $1.5 billion [6]. Agenda 2020 has identified drier webs leaving the press section as a high priority area and has set the ambitious goal of reaching 65% solids entering the dryer section. They have formed a group of suppliers, papermakers, and researchers to understand the potential for much drier webs and devise possible solutions.

In the laboratory, a wet web can be pressed for seconds, minutes, and even days. However, in a modern, high-speed paper machine, even with a shoe press, the web is only pressed for several milliseconds. During this time, a significant amount of water must flow not only between fibers, but also through lumens and pores of individual fibers. Given the differences between laboratory conditions to reach equilibrium and commercial conditions, what are the practical limits to water removal?

More than 30 years ago, Busker and Cronin [1] made a comprehensive review of the importance of wet pressing variables. They identified eight primary wet press variables which they defined as those that could affect sheet dryness by four percentage points or more: post-nip rewet, ingoing web moisture, grammage, furnish, double-felting, web temperature, press impulse, and felt pressure uniformity.

To estimate the limits of wet pressing on paper machines, all of the previously mentioned factors must be considered together. To accomplish this, we recently extended the Decreasing Permeability Model (DPM) of wet pressing to limiting conditions by including an equilibrium term to represent the maximum dryness [5,7]. In this paper, we employ this model to quantify the effect of pressing parameters and conditions affecting the limits to water removal in commercial operations.

THE DECREASING PERMEABILITY MODEL

The DPM was derived from equations for fluid flow through porous media [5,7] on the premise that the rate of water removal diminishes as pressing proceeds because of decreasing permeability faced by the remaining water as it is progressively expelled from between fibers and from the lumens and pores of fibers. The DPM assumes the following: unidirectional flow; negligible flow resistance from the felt in comparison to the web; a vented press; and rewet affected primarily by felt design.

$$m = (m_0 - m_e)\left(1 + \frac{An(m_0 - m_e)^n I}{\nu W^2}\right)^{\frac{-1}{n}} + m_e + \frac{R}{W} \qquad (1)$$

where:

m_0 = moisture ratio before pressing

m_e = equilibrium moisture ratio

I = press impulse (nip load divided by speed), kPa.s

W = basis weight, kg/m²

υ = kinematic viscosity of water, m²/s

A = specific permeability, g/m
n = compressibility factor
R = rewet, kg/m²

The first of the 3 terms on the right hand side of Eq. (1) represents the "dewatering term." This gives the moisture left in the web after water has been expelled by pressure exerted over time to overcome resistance to flow. The second term is the equilibrium moisture content at the maximum pressing pressure. This moisture can be lowered by increasing this pressure. The third term, rewet, is described in the following paragraph.

Rewet is a poorly defined concept in the pressing literature. We have defined it in a rigorous manner in conformity with our model as water expelled by hydrodynamic force overcoming flow resistance in the web but which remains with the web upon separation from the felt. We do not specifically speculate on the mechanism as to whether it is due to some back-flow from the felt or simply surface water held by surface tension during film splitting from the felt. Whatever the mechanism, rewet is water remaining with the web that must be removed in subsequent drying.

For extremely long pressing times as in a laboratory press, $I \rightarrow \infty$, and therefore:

$$m_\infty = m_e + \frac{R_\infty}{W} \tag{2}$$

where m_∞ is the moisture content after a very long time of pressing. In the absence of rewet, this moisture equals the equilibrium moisture:

$$m_\infty = m_e \tag{3}$$

The rewet term depends on furnish and fabric properties as well as factors such as speed and the available water, $m_O — m_e$, shown in Eq. (4) [5], but is independent of the total water content of the felt [8].

$$R = k(m_O - m_e)^q \tag{4}$$

Clearly, there is no rewet when the ingoing moisture content equals the equilibrium moisture content.

Press nips are efficient in removing water when the initial moisture (m_O) is large, but this may be offset by more water available for rewetting. However, there is a practical upper limit to m_0 because, if excessive, the nip will be saturated and crushing will result.

The equilibrium moisture ratios of wet webs have been measured in many laboratory studies [1-4] and are summarized in [5]. These studies have shown equilibrium moisture to depend on applied pressure, p, in the form of Eq. (5), where c and a are furnish-dependent constants:

$$m_e = cp^{-a} \tag{5}$$

Equation (5) is an empirical equation fitted in [5] to experimental data from the literature [1-4] for long pressing times. Constants c and a are for specific furnishes and the equation is valid up to the maximum pressure tested. These pressures were 6.3 MPa for TMP giving a web solids of 71% [2] and 53.4 MPa for kraft giving a web solids of 63% [4]. The highest peak pressures exerted in commercial wet presses are on the order of 10 MPa, and the simulated pressures in this paper are less than those measured in the laboratory experiments.

For practical convenience, this equation may be approximated by an analogous expression in line loading, P (kN/m):

$$m_e = gP^{-h} \tag{6}$$

It should be noted, however, that this equation is only valid for a specific nip geometry determined by felt design, press roll diameters, and cover or belt compressibility. Accordingly, it can only be used with caution as a first order approximation in modeling different pressing conditions.

In summary, press impulse overcoming flow resistance determines the amount of water expelled from the web between the limits of initial moisture and equilibrium moisture, while maximum pressure determines the level of the equilibrium moisture.

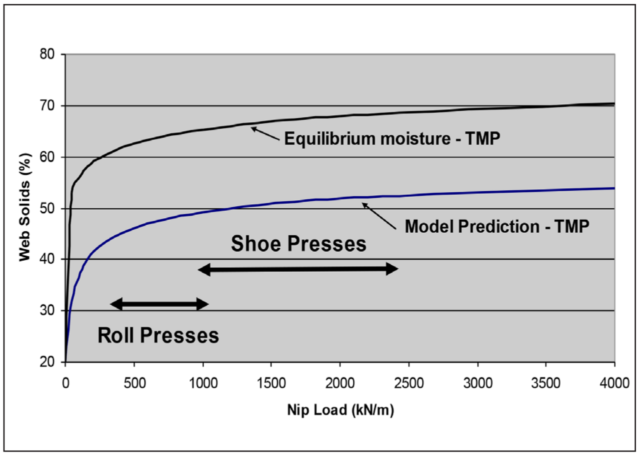
ESTIMATES FROM THE DPM

Furnish-dependent coefficients (A and n) have been measured by fitting the DPM equation to commercial paper machine measurements [5,7,9-11] and data from pilot pressing trials [5,7,9-12] (**Table I**). In this paper, we employ the DPM to examine the relative importance of the press operating condi-

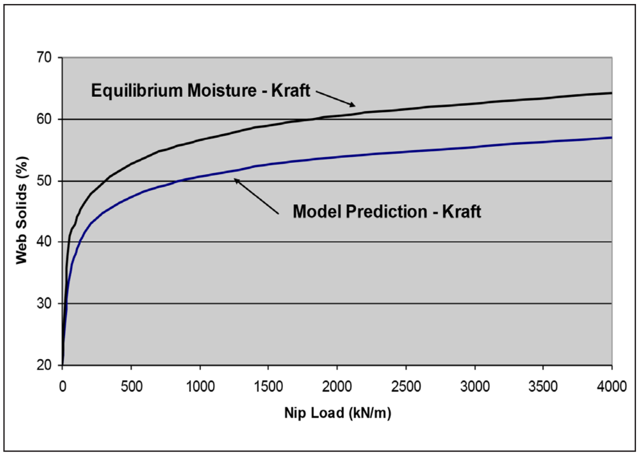
Furnish	A*, g/m	n	g	h	c	a	References
Thermomechanical pulp	5.24×10^{-10}	1.290	1.72	0.17	0.682	0.20	[5,7]
Kraft	1.61×10^{-9}	0.738	1.94	0.27	1.30	0.23	[5,7]

* at 20°C.

I. Furnish coefficients for the decreasing permeability model.



1. Press dewatering of thermomechanical pulp (TMP) furnish assuming machine speed of 1500 m/min, web temperature of 50ºC, basis weight of 50 g/m², incoming web solids of 20%, and rewet of 20 g/m². The equilibrium web solids content was calculated using Eq. (6) with the coefficients in Table I.



2. Press dewatering of kraft furnish assuming machine speed of 1500 m/min, web temperature of 50ºC, basis weight of 60 g/m², incoming web solids of 20%, and rewet of 10 g/m². The equilibrium web solids content was calculated using Eq. (5) and the coefficients in Table I.

tions (press impulse, maximum pressure, basis weight, and temperature), furnish (specific permeability and compressibility), and felt design (rewet) to estimate the highest attainable web solids contents in paper machine press sections.

Line load and press impulse

A primary variable for expelling water from a web in pressing is the press impulse, defined as the product of pressure and time of pressing. It can also be expressed as the line loading divided by the machine speed. Generally, given the decreasing permeability faced by water in interstices of compacted webs, and within lumens and cell wall pores, as well as the short residence time in nips and rewet, the resulting dryness after pressing is often far from its equilibrium moisture content (m_e).

In earlier work, we simulated pressing for infinite time in a pilot press having roll diameters of 0.75 m by placing the wet handsheets on the felt and passing them through the nip between the two rolls. The sheets stuck to the roll surface and were captured after passage through the nip. Multiple passes were made until sheet moisture content no longer changed [7].

The data for a TMP furnish were fitted to Eq. (6) and extrapolated to line loads (P) beyond the levels of current pressing technology to show the limit for water removal (**Fig. 1**). For example, at a line loading of 1000 kN/m and an infinite time of pressing, it would be possible to reach 65% solids. This finding is supported by a comparison to laboratory pressing results of Maloney et al. [2] for TMP by fitting Eq. (5) to their data, which gave c=0.682 and a=0.2. For Maloney's maximum pressure of 6.3 MPa, Eq. (5) gives a solids content of 68%. This level was also measured experimentally. In short, our result is reasonable.

From these findings and Eq. (1), for a press load of 1000 kN/m and speed of 1500 m/min, the water remaining in the web is comprised of 54% equilibrium moisture and 40 % rewet (R). Thus, only 6% of the remaining water could be removed by a longer pressing time. On the other hand, a larger pressure would increase both the press impulse and decrease the equilibrium moisture. If pressure were increased by a factor of 1.6 to 10 MPa in Eq. (5), the result would be a 70% solids content. In comparison, increasing line loading in Eq. (6) by the same factor would give P=1600 kN/m, which from Eq. (6) gives about 68% solids content.

In summary, these results show that pressing under these conditions reaches a plateau solids content near 1000 kN/m. Further increases in loading produces little additional dewatering. The limiting factor is equilibrium moisture content. In actual paper machine presses, the solids contents are much lower, as shown in Fig. 1. The likely cause is rewet.

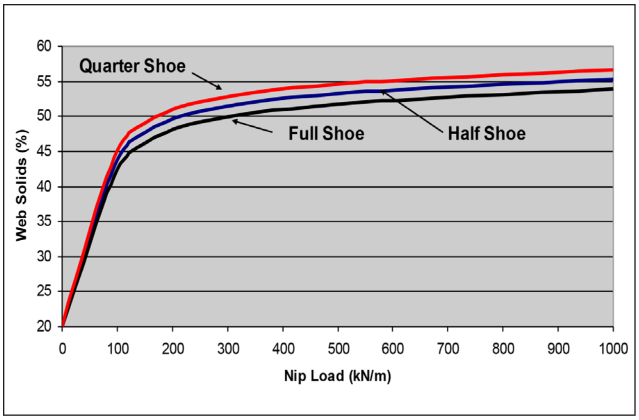
Similar results to those previously mentioned were found for a kraft softwood furnish shown in **Fig. 2**. Here, an equilibrium solids content of 65% was attained around 4000 kN/m. This same equilibrium solids content was experimentally measured by Maloney et al. [2] at about 6.3 MPa. Laivins and Scallan [4] measured this level of solids content in their experiments at about at about 20 MPa. Interestingly, in this latter case, doubling the pressure to 53 MPa only raised the solids content to 66%.

Pressure

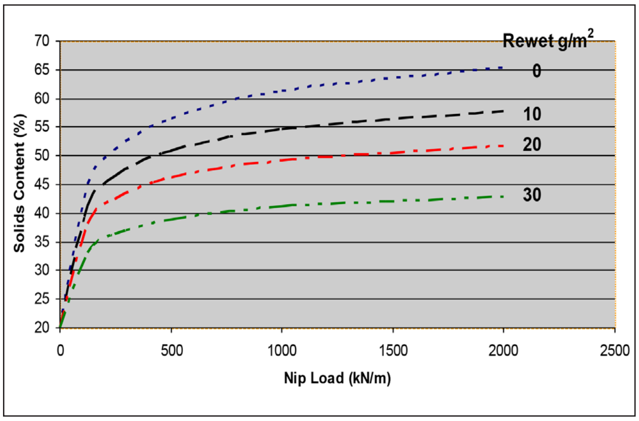
Shortening the length of the shoe-press nip at the same nip load increases maximum applied pressure. Although the press impulse is constant, the higher pressure lowers the equilibrium moisture (m_e) as shown in **Fig. 3**.

Furnish

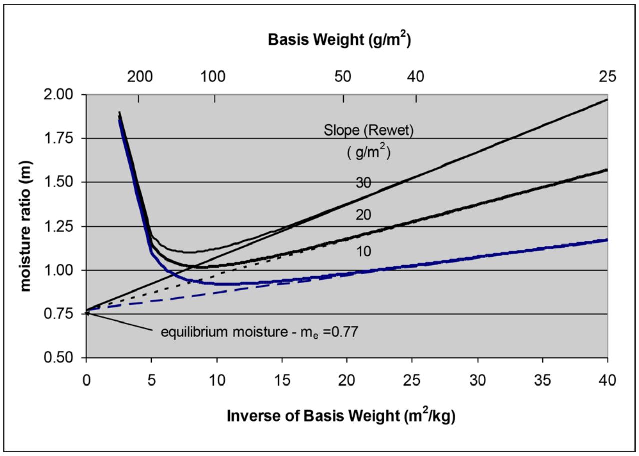
In a previous study [13], a "pressability index" was developed to evaluate press dewatering of several furnishes refined to different levels. This work confirmed that: previously-dried



3. Applying greater pressure at the same press impulse gives higher press solids for a TMP furnish. The operating conditions are: machine speed of 1500 m/min, web temperature of 50°C, basis weight of 50 g/m², incoming web solids of 20%, and rewet of 20 g/m².



4. Effect of rewet for a TMP furnish assuming machine speed of 1500 m/min, web temperature of 50°C, basis weight of 50 g/m², and incoming web solids of 20%. The equilibrium web solids content was calculated using Eq. (6) with the coefficients in Table I.



5. Pressed moisture ratios of a kraft furnish assuming machine speed of 1500 m/min, nip load of 1000 kN/m, incoming web solids of 20%, a web temperature of 50°C, and three levels of rewet. The equilibrium web solids content was calculated using Eq. (5) with the coefficients in Table I.

pulps were easier to dewater than never-dried pulps; higher pressed solids can be obtained by adding fillers that do not swell in water; and refining makes the furnish more difficult to dewater.

In more recent work, the furnish-dependent coefficients A and n were determined for a number of different furnishes using a pilot roll press [11,12]. These coefficients were used with the DPM in proprietary applications to evaluate existing press operating conditions, recommend changes to optimize dewatering, and evaluate investments in press rebuilds [12].

As shown in Figs. 1 and 2, the kraft furnish reported in [5,7] dewatered more easily than the TMP furnish and the equilibrium solids content reached 65% at extreme nip loads.

Rewet

As described earlier, we define rewet as water that has been expelled from the web by hydrodynamic force overcoming flow resistance in the web but which remains with the web upon separation from the felt. It is noteworthy that such “separation” rewet also takes place in the absence of a pressurized nip when a paper web separates from a forming fabric on a paper machine [14]. Rewet levels as high as 1000 g/m² have been reported for coarse fabrics used in two roll pulp dewatering presses [15]. Such high levels may be “post-nip rewet” that occurs if the felt remains in contact with the web after the nip and increases with contact time [16]. For lightweight paper grades, rewet is probably between 5 and 35 g/m², which is still significant [10,11]. The effect of various levels of rewet are shown in **Fig. 4**.

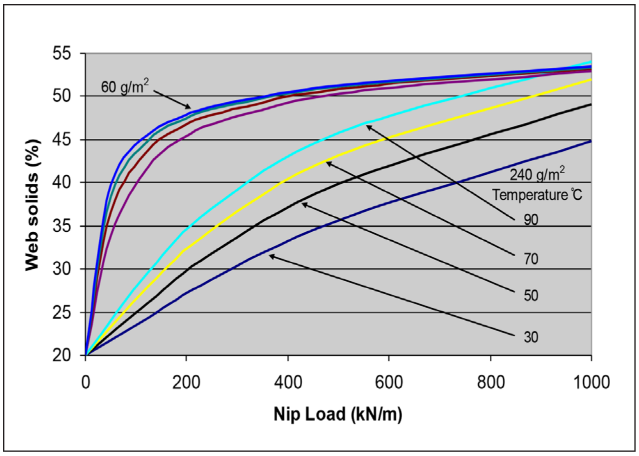
Basis weight

The nonlinear nature of press dewatering is most apparent when considering the effect of basis weight. With decreasing basis weight, pressed solids content may increase or decrease depending on the amount of rewet and the shape of the dewatering curve (**Fig. 5**). Low basis weight reduces the moisture ratio of the pressed sheet as a result of decreased flow path length. However, this is countered by rewet, which becomes a larger fraction of the web mass. This is illustrated for the kraft furnish at three different rewet levels plotted as the inverse of basis weight in Fig. 5. The straight lines are Eq. (2) with intercept m_e = 0.77. As basis weight is reduced (i.e., as 1/W is increased), the dewatering curve asymptotically approaches a straight line with R as the slope.

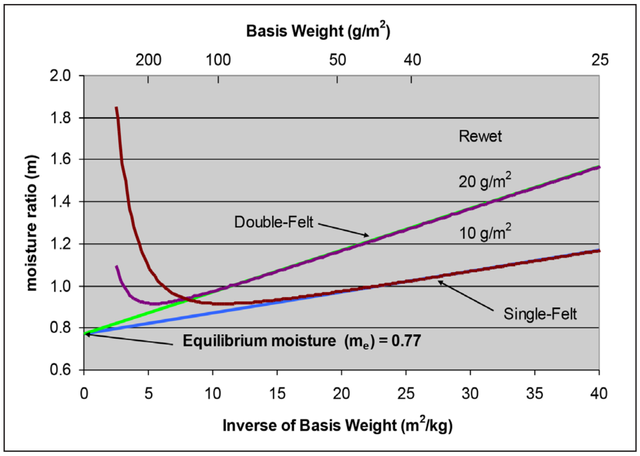
Comparisons of the straight lines with the curves in Fig. 5 reveal an important finding. For basis weights below 50 g/m² (1/W> 20 m²/kg), solids content after pressing is entirely determined by equilibrium moisture (y-axis intercept) and rewet (slope of the line).

Temperature

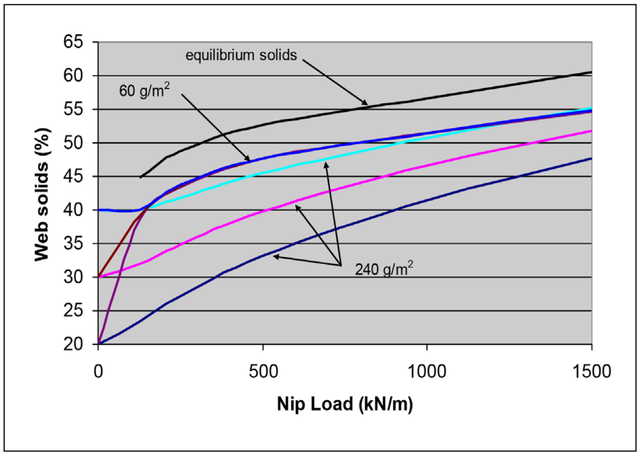
Increased temperature is known to reduce web moisture content after pressing [1]. Although they did not describe their



6. Effect of temperature on dewatering of kraft furnish assuming machine speed of 1500 m/min, incoming web solids of 20%, and rewet of 10 g/m² for basis weights of 60 g/m² and 240 g/m². The equilibrium web solids content was calculated using Eq. (5) with the coefficients in Table I.



7. Kraft furnish 1500 m/min, 1000 kN/m nip load, 50°C, m_0 = 4, assuming rewet of 10 g/m² for a single-felted nip and 20 g/m² for a double-felted nip.



8. The pressed solids content of a kraft furnish after a simulated second shoe-press at differing levels of incoming solids content (20%, 30%, and 40%) and basis weights (60 g/m² and 240 g/m²). The other conditions are: machine speed of 1500 m/min, web temperature of 50°C, and rewet of 10 g/m². The equilibrium web solids content was calculated using Eq. (5) with the coefficients in Table I.

method, Busker and Cronin reported that web solids increased from 0.5% to 1.3% per 10°C increase in web temperature [1]. A value of 1%/10°C was found for press simulator experiments with 120 g/m² pads [17], as well as pilot machine trials with 127 g/m² linerboard [18] and 40-55 g/m² newsprint [19]. These values were obtained under controlled conditions with extensive instrumentation, so they are probably the most reliable. Measurements on commercial paper machines gave values of 2.5%/10°C for 127 g/m² linerboard [20], 1.5%/10°C for 67 g/m² fine paper [20], 1.5%/10°C for 48 g/m² newsprint [21], and 0.7%/10°C for 120 g/m² fluting grade [21].

In our earlier application of the DPM [9], we showed that the effect of temperature on viscosity in the dewatering term of Eq. (1) accounted for an increase in solids in the range from 0.5% to 2.5 % per 10°C increase in temperature.

The effect of temperature also depends upon pressing conditions and basis weight. For a heavy web of 240 g/m² where the first term in Eq. (1) dominates, the solids content is increased by 1% for every 10°C increase in temperature (**Fig. 6**). In contrast, for a light web (60 g/m²) where the equilibrium and rewet terms dominate, the effect of temperature is of the order of 0.5%/10°C at press nip loadings representative of typical roll presses (Fig. 6).

Another potential effect of temperature may be its influence on equilibrium moisture content under pressing conditions. Here, the effect of temperature is no longer on the rate of dewatering caused by viscosity change, but rather on web permeability through changed pore structure. For example, increased pliability may lead to more pore closure under pressure, or the opposite, easier pressure-forced opening of new pathways. This subject clearly requires further study.

Single versus double felting

Double felting of the first press reduces the flow path by allowing water to flow from both surfaces of the web. Water flows outward from a neutral plane in the middle of the web, so in effect it behaves as if it is half the basis weight. Double felting is beneficial for heavier grades > 100 g/m² (<10 m²/kg). For example, at 200 g/m², double felting gives 5% higher solids content than single felting. However, because of rewetting on both the top and bottom sides of the web, it is less effective for lighter grades (<100 g/m²) as shown in **Fig. 7**.

Effect of incoming moisture

The effect of the amount of water entering the second of two shoe presses is shown in **Fig. 8**. For a heavy grade (240 g/m ²), the solids content after pressing depends on the web solids content entering that nip, even up to a nip load of 1500 kN/m. However, for a lighter grade (60 g/m²), the pressed solids are independent of the incoming solids for all but the lightest nip loads, which is in accord with measurements after the first press nip on a pilot paper machine [22]. This occurs because the web is already near equilibrium and therefore the outgoing nip moisture is simply the sum of the equilibrium solids content and rewet.

Fabric design

Felts with batt fibers having small diameters have been shown to reduce the amount of rewetting [5], but the exact mechanism is unknown. Some researchers hold that non-uniform distribution of pressure exerted by the felt creates uncompressed zones in the web that become pockets of higher moisture and that this "unpressed" water is interpreted as rewet [23]. However, measurements by Beck [24] in an instrumented pilot press nip indicated that a rough felt (with larger diameter batt fibers) gave a higher mid-nip web solids content but more rewet than the smooth felt. The net result at the nip exit was a lower web solids content from the rough felt than from the smooth felt because of rewetting. This observation has been corroborated by pilot pressing experiments on market pulp where rough felts gave better water removal than smooth felts [25]. The non-uniform pressure gave lateral channels of high permeability that enhanced water removal. This is a subject worthy of further study.

CONCLUSIONS

Our calculations using the Decreasing Permeability Model (DPM) have quantified the factors that affect press section water removal. Because the equations are nonlinear, it is not possible to draw general conclusions for all grades. For heavyweight grades (> 100 g/m^2) with a state-of-the-art press section (two shoe presses), optimizing press impulse, basis weight, web temperature, and felt configuration will have a significant impact on the web solids.

For lightweight grades (< 100 g/m^2) with a modern press section, the final solids content after pressing depends only on the equilibrium moisture (m_e) and the amount of rewet (R). Our findings suggest that higher solids contents can only be achieved by lowering the equilibrium moisture and minimizing rewet. Equilibrium moisture depends on furnish and peak pressure. Temperature may be a factor, but this requires further study.

Although rewet is poorly understood, indirect evidence suggests that incoming moisture, machine speed, and felt/web structure are important. We believe that understanding the behavior of water at the felt/paper interface as the surfaces separate would suggest ways to minimize rewetting. This is another topic deserving further study.

In conclusion, equilibrium moisture and rewet need to be reduced in order to obtain a pressed web solids of 65%. **TJ**

ABOUT THE AUTHORS

This research was motivated by the goal of 65% pressed solids set by Agenda 2020 in its dryer web project. As we participated in this project, we understood that the many factors affecting pressing are not independent and had to be considered together to reach this target. We realized that our Decreasing Permeability Model (DPM) could be used to evaluate these factors in a comprehensive manner.

This research is an application of the DPM, which was initially published in *TAPPI Journal* using data from surveys of Canadian paper machine press sections (*Tappi J.* 74(12): 142,150(1991)). Later, we accounted for rewet in *Tappi J.* 78(11): 107(1995). Numerous other publications in *TAPPI Journal* and other journals applied the model to different paper grades and further developed the model to include a term to represent the equilibrium moisture — the limiting moisture that can be achieved in a specific press nip.

The DPM is based on the concept that the nip pressure is exerted on water between and within in the fibers. This differs from the conventional pressing models that are based on parallel pressures acting on water and fibers. Acceptance of the DPM has been surprisingly slow, likely due to the intuitive appeal and long history of the conventional model, despite its flaws and lack of predictive capability. We have addressed this over the years by publishing numerous successful applications of the DPM on paper machines.

What was most interesting in this research was that the three terms in the equation correspond precisely to the qualitative descriptions that have been applied for more than 50 years: the flow-controlled regime, the pressure controlled (rewet) regime, and limiting consistency. Achieving 65% solids by pressing in a commercial machine is probably not possible, but improvements to existing operations can be made.

For mills, the DPM can be used to identify the most cost effective ways to increase press section water removal. Our findings suggest two areas that need further study to open possibilities for higher solids content in wet pressing: rewet and equilibrium moisture.

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