Preferred citation: H. Paulapuro. Wet Pressing – Present Understanding and Future Challenges. In **The science of papermaking**, *Trans. of the XIIth Fund. Res. Symp. Oxford, 2001*, (C.F. Baker, ed.), pp 639–678, FRC, Manchester, 2018. DOI: 10.15376/frc.2001.1.639.

WET PRESSING – PRESENT UNDERSTANDING AND FUTURE CHALLENGES

Hannu Paulapuro

Helsinki University of Technology, Espoo, Finland

ABSTRACT

The essential scientific problems in wet pressing are concerned with water removal from the wet web, its runnability and the effect of pressing on the quality of the web and the paper produced from it. This paper briefly reviews the present understanding of the effect of wet pressing on the web and paper quality and discusses some questions concerning the runnability of the web through the press section. The main emphasis is placed on water removal. A short historical review of the development of our present understanding of wet pressing fundamentals is presented. The modelling of wet pressing is also discussed.

The water removal from the fibre cell wall starts at fairly low solids contents of the web, in the range of 20–25%. In modern press sections, the solids content of the web after pressing is about 45–50%. At this solids content, most of the water is in the fibre wall. Thus, when trying to enhance water removal further, it is necessary to understand the mechanisms and controlling factors in cell wall dewatering. Present scientific efforts should therefore be focused on finding as invariant and quantitative knowledge as possible on the behaviour of the cell wall under wet pressing conditions.

Recent research on cell wall dewatering is reviewed in the paper. Advanced measuring methods such as NMR, solute exclusion, WRV(CCV) and DSC techniques have produced new and to a

certain extent invariant information on the cell wall structure and dewatering. As a result, a clearer picture of the differences in the behaviour of mechanical and chemical pulps, softwood and hardwood pulps and different types of fines material has emerged. The effect of hornification and beating has also been clarified. Further development of measuring techniques such as DSC-based thermoporosimetry is most likely to improve our understanding in this area, helping to make it more accurate and invariant.

INTRODUCTION

The theme of this symposium is "The Science of Papermaking". To ensure that this review is relevant to the theme, we would first need to define what is meant by "Science". There are several definitions of science to be found from different sources. One which I consider very good is "Science is a search for invariances". I will use this as a guideline in this review.

When discussing technical sciences, which the science of papermaking also belongs to, it is important first to examine the objectives of the scientific discussion of papermaking. They should to a certain extent be relevant to the general objectives of papermaking. Papermaking is a technical undertaking whose purpose is to produce, at minimum cost, paper or board, which fulfils the customer's needs in the best possible way. There are then two important considerations:

- manufacturing cost;
- quality of paper.

The manufacturing cost depends on the capital costs, i.e., the investment, and on the operating costs. The required quality of paper essentially depends on the paper or board grade to be produced. In the following discussion, I will exclude such factors as operating procedures, stability of operation and mostly also controllability aspects, though they are very important factors affecting costs and quality. In discussing the science of wet pressing, I will concentrate on the technology itself. For further analysis I will define the process of wet pressing as shown in Figure 1 according to the general concept of a process unit.

In the wet pressing process a moist fibre web is taken from the forming unit, water is squeezed out of the web in nips usually formed by two rolls or a roll and a shoe. At the same time, changes are produced in the properties of

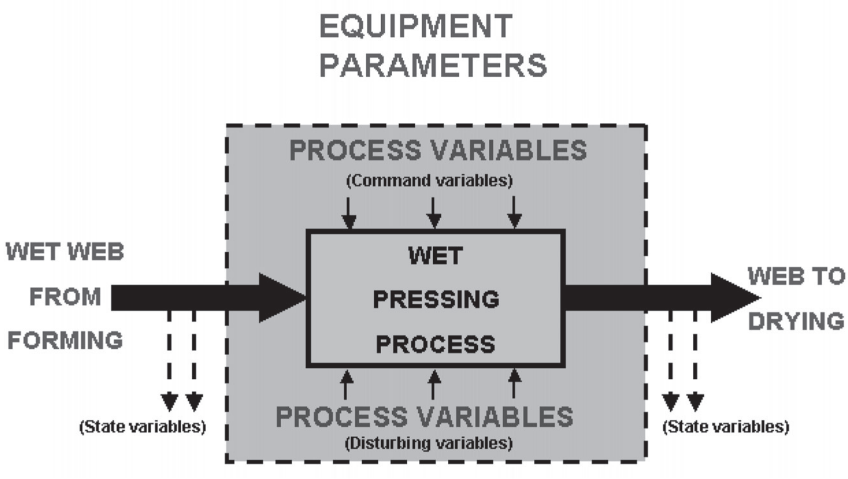

Figure 1 Conceptual process scheme of wet pressing.

the web which affect the final quality of paper. After the press section, the web is transferred for further processing to the dryer section. In order to fulfil the objectives of papermaking, the web should have as high a solids content as possible after the press section and properties which enable the required final paper or board quality to be achieved. It should also have a state (combination of state variables), which is beneficial for further water removal in drying. In addition, the web should run easily without breaks through the press section. Water removal used to be the most important consideration in wet pressing, but during the past few decades the quality aspect has grown in importance, being today as important as or even more important than water removal for many paper and board grades. The requirement for troublefree runnability has also become more important when the speed and scale of the paper machine have increased.

A typical configuration of a modern press section for printing papers is shown in Figure 2.

The capital costs of wet pressing are mainly dependent on the **equipment parameters**, which are:

– nip types;
– roll parameters;
– felt parameters;
– press section configuration.

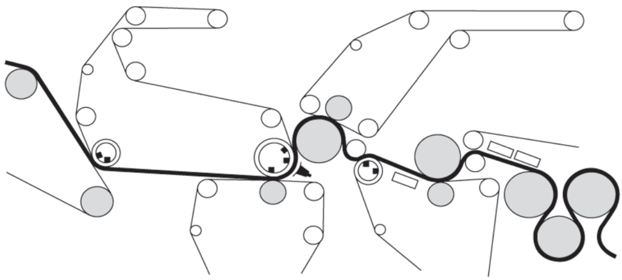

Figure 2 A four-nip press section of a printing paper machine.

The equipment parameters also have an effect on operating costs and paper quality. In addition, they determine the variables included in the process and their operating ranges. The equipment parameters are discussed here only implicitly through their influence on the process variables and operating mechanisms.

The main **process variables** of wet pressing are:

<table>
<tr><td>– nip pressure
– nip residence time</td><td>}</td><td>pressure distribution as a
function of residence time</td><td>}</td><td>press impulse;</td></tr>
</table>

– temperature;
– ingoing moisture content of the web;
– properties of the ingoing web.

The operating costs of wet pressing are influenced by two main components:

– web moisture content after pressing (water removal);
– runnability of the web through the press section.

The scope of the discussion in the review of “the science of wet pressing” can now be defined in the following way: We should find such invariant knowledge of wet pressing which could be used to:

– enhance water removal;
– improve runnability;
– improve paper quality;

in practical papermaking.

If we understand the mechanisms and fundamentals of wet pressing as invariably as possible, especially the effects of equipment parameters and process variables, it will be possible to develop wet pressing in accordance with the objectives of papermaking.

Even after the above definition, the scope of the subject is vast, so I will only briefly discuss paper quality and runnability and instead concentrate on water removal. However, to begin with, let us first review how the understanding of the fundamentals of wet pressing has developed. The fairly new and to a certain extent innovative pressing/drying or web consolidation techniques such as press drying, impulse drying and the Condebelt process are not discussed in this paper.

FUNDAMENTALS OF WET PRESSING – AN HISTORICAL PERSPECTIVE

In the 1930s, the water-retaining capacity and compressibility of wet pulps of different origins and different degrees of beating, and their dependence on the duration of load application were examined in various studies. However, the available equipment only allowed tests to be carried out under essentially static conditions [1]. For this reason, the relationships between the duration, pressure and rate of water removal could not be experimentally established in the time regime encountered in the press nip. An attempt was made in the 1940s to develop an approximate model for the increase in dryness obtained under definite pressure in a given time [2]. It was found that the increment in dryness was proportional to the pressure and the duration of pressure application and inversely proportional to the square of the basis weight, the square of the specific surface area of the pulp and the viscosity of water at the prevailing temperature. The presence of both hydraulic and mechanical pressure components and the generation of density gradients in the compressed sheet were also pointed out.

An attempt to explain dewatering in the nip was made by Nissan in the 1950s [3]. He attributed the extrusion of water in the ingoing part of the nip entirely to the compression of the felt. The expansion of the saturated paper and felt after mid-nip caused a partition of the water between the web and the felt. The transfer of water from the web to the felt thus took place on the outgoing side of the nip and was entirely caused by suction created by the expanding felt and surface tension.

In laboratory tests using a press simulator for rapid load application and removal, Bergström was unable to confirm Nissan's theory [4]. The results indicated that during compression, water is squeezed from the web into the felt and from the felt out of the system through the permeable felt support. In the recovery cycle some water is re-absorbed into the paper, mainly by capillary suction or expansion suction.

The next attempt to reach a general understanding of water removal under pressure was made by Börje Wahlström in 1960 [5,6]. Our present understanding of the wet pressing mechanism is largely based on his work. He stated that the main driving force of water removal is the hydraulic pressure created in the web due to its compression in the press nip. The compressive force (P_t) in the converging nip was balanced in each point of the nip by the sum of the structural pressure (P_s) and the hydraulic pressure (P_h) created by the flow resistance of water in the fibre network according to Equation 1. This so-called Terzaghi's principle was introduced to papermaking by Campbell [2].

$$P_t = P_h + P_s \tag{1}$$

The structural pressure balanced by the mechanical stiffness of the solid structure dominates as long as the web is not saturated. When the web becomes saturated, the hydraulic pressure starts to rise and water flows into the felt, where its movements are determined by the press design and roll surface structure. In the outgoing nip, there is a reverse flow from the roll structure into the felt and from the felt into the web. The reverse water flow from the felt to the web is called rewetting. A more precise analysis of the flow conditions in the nip was presented by Nilsson and Larsson [7], who divided the nip into four phases. Their almost classical view of the pressure distributions in the press nip is shown in Figure 3.

Wahlström also [8] defined the distinction between pressure-controlled and flow-controlled pressing according to the relative magnitude of the components in Equation 1. These concepts turned out to be instrumental for the development of practical pressing technology.

Several investigations have produced experimental data that suggest modifications to Wahlström's original theory, specifically with regard to the definition of the structural pressure and the significance of rewetting [9–13]. In the late 1970s, Carlsson et al. [10] revealed the important role of water held within fibres in wet pressing. They found that water is already expelled from fibre walls at 20–25% solids content and, as the compression progresses, the proportion of water expelled from fibres makes an increasing contribution to the total amount of water removed from the web. Consequently, flows within fibres must make a significant contribution to the structural pressure. The hydraulic pressure cannot be defined simply as the pressure counteracted by flow resistance: the location of the flow taking part in the generation of hydraulic pressure must also be determined. The flows in the inter-fibre voids

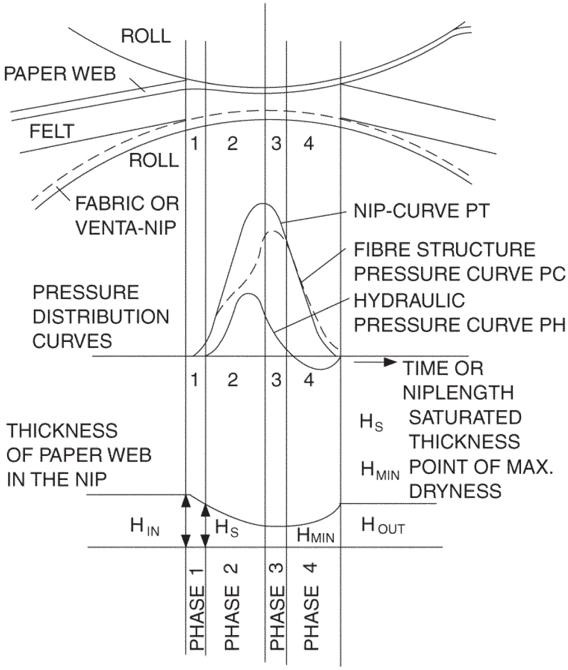

Figure 3 The four phases of the nip process according to Nilsson and Larsson [7].

would be responsible for the hydraulic pressure. The flows within fibres would thus account for part of the structural pressure. The rest of the structural pressure is the result of mechanical stiffness.

Studies carried out at STFI [14] and at the University of Maine (UMO) [15] have revealed many important details regarding hydraulic pressure generation. They have shown that hydraulic pressure is often a decisive factor in balancing compression pressure. A higher hydraulic pressure is generated when the basis weight or the compression rate is higher, or if the beating of chemical pulp is increased.

A comprehensive review of the wet pressing research and fundamentals up to the 1990s was presented by MacGregor in the 1989 Fundamental research symposium [16]. In 1990 Wahlström summarized the work on cell wall dewatering in the context of his pressing theory. Wahlström proposed that in pressure-controlled situations the solids content after pressing is limited by the rate at which water can be removed from the cell wall. In flow-controlled pressing he suggested that increased fibre swelling influences press dewatering by facilitating the formation of a dense impermeable exit layer.

In developing their decreasing permeability model of pressing, Kerekes and McDonald [17,18] took a somewhat different view compared to the above when examining the pressure generation and water removal in a press nip. They did not support the paralleled and separable role of hydraulic pressure and structural pressure components. According to their view, all of the pressure is rather applied to remove water from the web and water removal is governed by the decreasing permeability of the web. This approach seems to be a good starting point for deriving models for water removal in wet pressing, especially in the range of practically occurring solids contents in today's presses.

However, measurements of hydraulic pressure in wet pressing simulators, e.g., in [19] have shown that the structural or "network" pressure component can be quite high and varies greatly with the fibre material of the web. In dynamic pressing conditions the rheology of the fibre network is also rate-dependent, as discussed, e.g., in [19–21]. This is at least partly attributed to the flow of the intra-fibre water within and out of the fibre walls, which is a viscous phenomenon. Therefore, it is advisable to think that the network pressure component or "the structural stress" should account for the mechanical stiffness and the flow resistance inside the fibres. When we examine and try to understand wet pressing in the solids content range of the last presses and beyond, where water removal from the cell wall pores plays a major role, the "decreasing permeability" approach may not be so fruitful. In these conditions, the main question for water removal is the rigidity of the cell wall, the question how easily the pores in the cell wall collapse and how the different water fractions[1] are to be removed from the cell wall.

Rewetting is one of the most controversial issues in wet pressing. Extensive rewetting due to capillary forces was anticipated in Wahlström's wet pressing theory [5,6]. During the past four decades, there have been many indirect observations for and against this view. Some researchers [22,23] have suggested that a considerable backflow of water from felt to paper occurs in the outgoing part of the nip. Others [11,13,14,24,25] have supported the view that rewetting is an insignificant factor in wet pressing, unless the paper web

[1]The water in the cell wall can be divided into three main fractions: "nonfreezing water", "freezing bound water" and "bulk" or "free water" [100,106]. Water within sufficiently small pores does not freeze or has a depressed melting temperature. These pores are referred to as "micropores". Water in sufficiently large pores is detected as bulk water and the pores are referred to as "macropores" [84].

and felt are kept together for a long period (tens of milliseconds) after the nip.

Norman classified rewetting into three different types: internal, external and separation rewetting [26]. The internal and external rewettings occur when water flows directly from the felt into the paper. The differentiation between them is based on the location of the water redistribution. The rewetting is called internal if it takes place within the nip and external if it occurs outside the nip. In separation rewetting, the water adheres to the surface of the web as the web separates from the felt and is transported after separation inside the structure. It has been shown that only a small amount of water can move inside the paper web on the expanding side of the nip owing to capillary [11,13] or other [9] forces, i.e., that internal rewetting is likely to be insignificant. External rewetting can take place if the paper is not separated from the felt immediately after the nip. Little information is available about the role of separation rewetting. This type of mechanism was already suggested by Wrist [27]. There are indications that under some conditions, the water around the felt-paper boundary layer can split unfavourably at the moment the paper separates from the felt [28]. Obviously, the vacuum created in the felt during web and felt separation has an effect on separation rewetting [29].

McDonald and Kerekes also made [30] experiments on a pilot machine and found that especially at low basis weights (<100 g/m^2) rewetting is a significant factor affecting the moisture content of the web after pressing. Accordingly, they added a term describing rewetting in their decreasing permeability model. They also found quite a high amount of rewet, 22.8 g/m^2 for low-basis-weight webs (<40 g/m^2), comparing with the figures found in the literature. McDonald and Kerekes did not specify the mechanism of rewetting but seemed to agree that the mechanism of rewet remains a subject of controversy.

A subject related to wet pressing mechanisms which has also created different opinions is the effect of the uniformity of pressure application (UOPA). This discussion is most often related to felt uniformity and the interactions in the felt-paper interface. It has been observed that felts made of thinner batt fibres remove more water than felts made of thicker fibres. Smart [31] and Fekete [32] systematically studied the effect of different felt components on water removal. They showed that the thickness of batt fibres on the paper side has the greatest effect on water removal. They also concluded that the differences in the micro-scale pressure nonuniformity created by the felts are the main source of the differences in water removal. Oliver and Wiseman [33] and Yamamoto [34] tried to evaluate the effect of felt roughness on the water removal through mathematical modelling. Both came to the conclusion that small-scale pressure uniformity plays a significant role for the end dryness

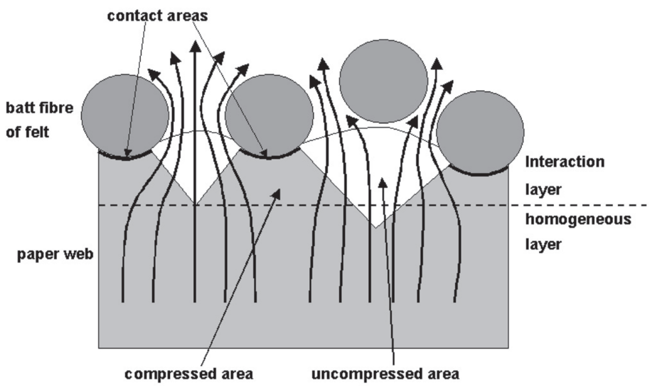

Figure 4 Hypothesis on the interaction between the felt and the web and its influence on the water flow inside the web [21].

obtained by wet pressing. Similar results have been reported by other researchers [35,36].

Vomhoff also studied the influence of local stress variations caused by nonuniform compression on water removal [21]. He concluded that interactions between the web and the rough surface, especially at low basis weights, have a large influence on the flow through the compressed fibre network. The stress variations due to uneven pressure application resulted in highly permeable areas inside the web close to the permeable surface, Figure 4. The effect of this boundary phenomenon diminished for higher basis weight and the permeability approached a constant value. This phenomenon has later been examined by Stephen l'Anson and Tim Ashworth [37]. They state that a completely even press felt would not produce good dewatering, but would allow the surface layer in the sheet to remain at a low permeability, not allowing passage of water from the sheet to the felt and resulting in very poor dryness. l'Anson and Ashworth also suggest that the differences in the sheet moisture content exiting the press nip, which are usually thought to be caused by "rewetting", can be explained by surface contact. This is an interesting new hypothesis, but more evidence is needed for verification or falsification.

The gradually increasing understanding of the water removal mechanisms and the new approaches and concepts have been instrumental for the practical development of wet pressing. In my opinion, major challenges when pursuing "scientific" knowledge, which would allow further progress to be made in wet pressing lie in the following areas:

– the water removal from the fibre wall and the rheological behaviour of the fibre network related to this;
– the role and mechanisms of rewetting;
– the role and mechanisms of the uniformity of pressure application, especially at higher solids contents.

SHEET STRUCTURE AND PAPER QUALITY

Another important consideration, in addition to water removal, when trying to understand the basic mechanisms of wet pressing, is the change in the sheet structure during pressing. Wet pressing, in principle, can affect sheet structure through the following mechanisms:

– The fibres are flattened and brought closer together, so the conditions for fibre bonding are improved. This can contribute to a permanent densification of the fibre network.
– Some pores in the fibre wall are closed, causing fibre hornification. Hornification in wet pressing has also been called "wet hornification" [38,39].
– The viscous drag of flowing water tends to create movement in the network material. Consequently, water flow compresses the fibre network. The faster the flow, the higher the compression force. In wet pressing, the flow velocity increases in the direction of the flow, which means that the compression pressure also increases. This can cause a permanent z-direction density gradient in the web.
– The bonds between the network elements are not yet well developed under wet pressing conditions. The flowing water can separate particles from each other and transport the separated particles to new positions or right out of the web. The material composition may thus change in the z-direction of the web.
– The different sides of the web, which are partly in a plastic state during wet pressing, are pressed against surfaces of different roughness. The topography of the web can thus change differently on the two sides.

The information available on the significance and probability of the occurrence of the above mechanisms has been scarce and to some extent conflicting [40–46]. Based on the work of Szikla and his co-workers [19,47–53], the following conclusions about the changes in sheet structure and properties seem valid.

Water removed from the paper web during pressing contains particles originating from the web. However, in general, wet pressing has no capacity to change the z-direction materials distribution in paper to such an extent that it would have a significant effect on paper properties. This is indicated by many investigations, which show that filler and fines distributions are unlikely to be significantly affected by wet pressing under normal conditions [40,48,54,55].

Wet pressing plays an important role for the final density of paper. It yields an increase in the average density and can change the distribution of density in the z-direction. In compression, the fibre surfaces approach each other within the web and can be deformed permanently. This deformation can improve the conditions for the bonding taking place in the next phase of consolidation, i.e., drying. At each point in the web, the effect of wet pressing on the increase in final density depends on the maximum density obtained at this point during the complete pressing process. The effect is independent of the condition of the other parts of the web during pressing. The change in density induced by pressing is greatly affected by the furnish. Pulps of lower bonding capability and/or higher springback yield a lower density.

The increase in sheet density in wet pressing affects many of the paper's end-use properties. Web consolidation improves fibre bonding and thus many strength properties, such as tensile strength, burst strength, and z-strength. On the other hand, the opacity, stiffness, and compressibility of the paper deteriorate.

In many paper and board grades, the loss of stiffness and compressibility caused by increased pressing is considered critical. However, it seems that very little can be done to optimize the pressing variables or press configuration for a minimum density increase and subsequent loss of stiffness and compressibility when aiming at a given web solids content after pressing [47]. At the same outgoing solids content, the various press configurations may, however, result in a different increase in the final average density in the following cases:

– The amounts of water redistributed from the felt to the paper web are different in the various press configurations.
– The relationship between the web density during wet pressing and the final density of the paper is not linear and the various press configurations yield different z-direction density gradients in the web.

Due to gradients in the hydraulic and structural pressures in the nip, the sheet becomes much denser on the side through which water is removed from the web [41,49]. The density on the other side in one-sided water removal remains almost constant. Thus, one-sided water removal in wet pressing can

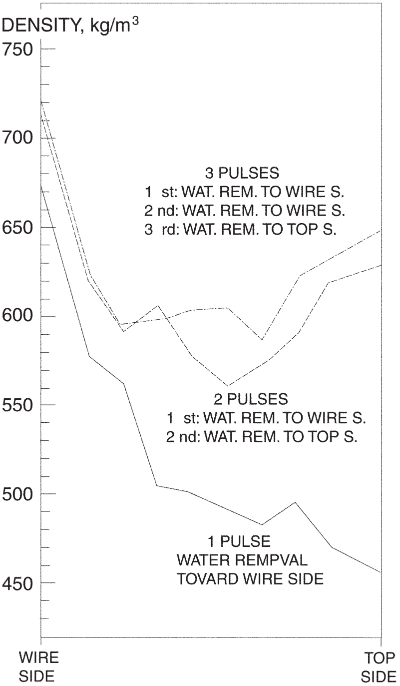

Figure 5 Z-direction density distributions in sheets when the direction of water removal is altered in subsequent wet pressings. Furnish 80% bleached birch sulphate and 20% bleached pine sulphate, basis weight 100 g/m^2 [49].

create a z-direction density gradient in the sheet. The uneven z-direction density distribution is probably the main cause of the two-sided absorption properties of the paper. Fortunately, the uneven density distribution originating from press nips can be corrected in a further nip, where the direction of the water removal is reversed, Figure 5 [49].

During wet pressing conditions, the paper surface easily forms a replica of the pressing surface. The surface fibres of today's felts are very thick compared to wood fibres, Figure 6 [56]. Thus the paper surface becomes quite uneven on the side in contact with the felt, while the side in contact with the roll becomes smoother. The total effect of wet pressing on the two-sidedness of paper depends on the configuration and types of nips of the press section.

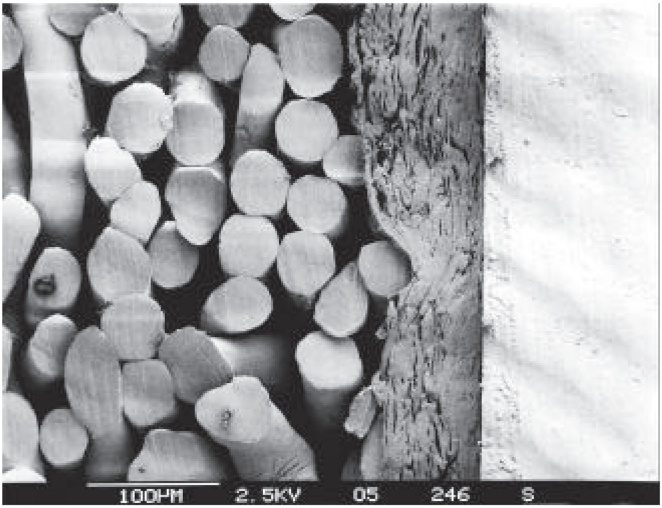

Figure 6 SEM micrograph of felt/paper interface, magnified 230× [56].

Using higher wet pressing temperatures has become common practice in modern papermaking to improve water removal. Increasing the web temperature beyond the present operating levels would further enhance water removal in pressing. However, sheet quality can become the limiting factor. As pressing temperature increases, the density increases and the brightness of the sheet decreases [57,58]. The density increase can be critical to paper stiffness, especially with low basis weight papers which have a high filler content.

Hornification of fibres is a significant phenomenon affecting their properties. However, the main hornification effects are caused by drying. Therefore, the effect of "wet hornification" is probably quite small after the fibres are dried.

To summarize, the effects of wet pressing on paper and board properties are caused by changes in the following structural characteristics of the sheet:

– density;
– density distribution in the z-direction;
– surface evenness (topography).

RUNNABILITY

The runnability of the web through the press section on modern machines is essentially related to the behaviour of the web in open draws. The most modern printing paper machines do not even have open draws between the wire and the dryer sections. However, on most paper machines the first open draw is situated after the third press nip. This is also the most critical point for runnability, since the web still has a fairly low solids content at this point. The science of wet pressing related to runnability is thus very much focused on understanding the mechanisms of the adhesion and release of the web from the centre roll, as well as the stresses applied to the moving web under these circumstances.

A comprehensive discussion of these phenomena would be beyond the scope of this review. As to the dynamics of the moving web and the forces applied to it, I would like to refer to an excellent summary of web handling given in [59]. I will only make some notes here on the web adhesion and release properties. The web adhesion to press roll materials and the rolls' release properties have recently attracted a lot of attention because of the attempts to find replacing materials for granite in the centre roll position. The web adhesion and release properties are not yet fully understood, so the recent research has been concentrated on deriving more fundamental information about the underlying factors influencing sheet release phenomena [60]. The following factors and mechanisms behind the sheet release have been proposed [61,62]:

– Liquid film thickness between the web and roll (the work of adhesion increases with decreasing film thickness).
– Liquid cavitation (microscopically sharp features in a roll exhibit excess surface energy and can serve as nucleating sites for many surface phenomena such as condensation, particle separation, and air bubble formation. All of these can reduce adhesion and promote web release).
– Surface energy (surface energies of the roll cover, its possible contaminants and sheet material are important factors in evaluating wettability and release mechanisms).

The surface energies of roll covers are important factors influencing wettability and sheet release properties. The wettability of a surface materials should be good enough to prevent sheet stealing, but weak enough to allow stable web release. Surface energy also has a great influence on the roll cover's affinity for pitch and rosin deposits. Increased wettability will also improve the doctoring of hydrophobic contaminants. Direct measurement of the surface energy of a solid surface has not been possible, but several methods can be used to evaluate it indirectly. The use of static contact angle measurements with different probe liquids has produced satisfactory results [60]. Surface energy parameters of various press roll materials are given in Table 1 [60]. The surface energy components were calculated according to the modern theory of surface energy using Lifshitz – van der Waals' and Lewis acid and base components [63].

Table 1 Surface energy parameters of various press roll materials [60].

Sample[a]	**Surface energy component**[b], **mJ/m**^{2}				
	γ^{LW}	γ^{+}	γ^{-}	γ^{AB}	γ
Gr	40.5	0.0	14.8	0.0	40.5
C1	40.8	0.0	10.6	0.0	40.8
C2	38.1	0.03	0.4	0.2	38.3
R1	23.7	0.0	3.4	0.0	23.7
R2	22.9	0.0	4.4	0.0	22.9
R3	33.0	0.12	0.0	0.0	33.0
R4	39.9	0.71	0.01	0.2	40.1
R5	35.1	0.05	0.0	0.0	35.1
R6	40.0	1.42	0.9	2.3	42.3

[a]Gr = granite, C = ceramic, and R = rubber materials
[b]γ^{LW} is Lifshitz–van der Waals' component
γ^{+} is acid component
γ^{-} is base component
$\gamma^{AB} = 2(\gamma^{+}\gamma^{-})^{1/2}$
γ is surface energy

As can be seen from the table, there are differences as well as similarities in the surface energy components between different types of press roll materials. The role of these as well as that of the surface microstructure for the web release properties is still unclear. Many questions remain to be answered on how to apply the fundamental surface chemistry knowledge on a paper machine for solving papermaking problems. However, the work to this end is continuing [64–66].

MODELLING OF WET PRESSING

Modelling of a physical phenomenon or a process is a good way to gain a better understanding of the mechanisms and thus enhance "science", especially if modelling results in reasonable invariant models which show quantitative effects of main process variables and equipment parameters. Models are very useful for predicting what happens when variables or parameters are changed and can thus be used for optimization and design purposes. In the best case, they can also indicate how the process could be made more efficient and developed further.

A great number of attempts to model wet pressing have been made. The target function of modelling has been almost solely the water removal or web solids content after pressing. A rigorous analysis of all the approaches used is not possible here, so I will only discuss a few examples of the models presented.

Walhström originally proposed a static descriptive model for web moisture ratio, MR (g_{water}/g_{solids}) after the nip (Equation 2)

$$MR = MR_{\min} + f_p + f_f + P_d + \frac{R}{W} \tag{2}$$

where $MR_{\min}$ is moisture ratio at the mid nip, when the flow resistance is zero and the pressure is evenly distributed
f_p the addition to the moisture ratio caused by the flow resistance of the web,
f_f the addition to the moisture ratio caused by the flow resistance of the felt,
P_d the addition to the moisture ratio caused by the uneven pressure distribution,
R rewet and
W the basis weight (abs. dry).

Wahlström's model cannot be used in practice to predict the final moisture ratio of the web. However, it explicitly shows the factors which were thought to have a significant effect on the water removal in the nip.

Other models suggested range from simple ones, for example, Equation 3 [67] to models based on very complex and sophisticated approaches [17,18,24,30,68–79]. Many of the models describe the flow of water in one dimension, but some include two-dimensional formulations. In a few cases air in addition to water is also considered.

$$MR = f_2 P^{-f_1} \tag{3}$$

where P is the applied pressure and
f_1, f_2 are furnish-dependent constants.

In many of the approaches, Darcy's law (Equation 4) has been utilized.

$$V = \frac{A\Delta P}{\eta W \overline{R}_w} \tag{4}$$

where	V	is flow velocity
	A	the area of filtration,
	Δp	pressure difference over the mat,
	η	dynamic viscosity of water,
	W	the basis weight of the filtering mat and
	$\overline{R}_w$	the specific filtration resistance of the mat per unit basis weight.

The specific filtration resistance is often related to the porous structure of the mat, e.g., by using the Kozeny–Carman equation [80]. According to Kozeny–Carman, the specific filtration resistance of the mat can be expressed by Equation 5:

$$\overline{R} = \frac{kS_v^2(1 - v)^2}{v^3} \tag{5}$$

where	$\overline{R}$	is the specific filtration resistance of the mat (=W$\overline{R}_w$),
	k	constant depending on the capillaries, i.e., the Kozeny constant,
	S_v	the specific surface area of the solids per unit volume of the mat and
	v	the void volume per unit volume of the mat.

Darcy's law describes the flow through the porous medium, which is incompressible. In wet pressing, the fibre mat is compressed and its filtration resistance as well as permeability thus change during pressing. Consequently, in order to apply Darcy's model rigorously, we should know the changes in permeability in wet pressing conditions. For this reason, many of the modelling approaches and theoretical work are concentrated on estimating the permeability and compressibility of water-saturated fibre webs. Some recent works in this area have been reported by Vomhoff [21,81], and Rasi et al. [82].

One of the first comprehensive models of wet pressing was developed at the University of Maine [24]. In this model, the wet web is defined as an unsaturated medium composed of three phases: solids, water and air. The equation representing the stress-strain relationship for cellulosic fibre structures has 7 coefficients identified with a special dynamic compression device

(UMO tester). The authors applied Darcy's law to the flow of water through an element of thickness of the wet sheet to obtain a differential equation in three variables: hydraulic pressure in water, water velocity and permeability to water. They also utilized the liquid material balance to relate the liquid velocity to the void volume fraction and provided expressions in terms of their void volume fractions. In this approach the structural mechanical behaviour of the wet sheet was considered to be viscoelastic. The purpose of the UMO model was to simulate flow in the thickness direction of the web.

The work done at UMO has been important for developing our understanding of wet pressing fundamentals. However, the application of the model itself has not been discussed widely in the literature, probably due to its complexity and the need for determining of several experimental coefficients.

As discussed above, Kerekes and McDonald developed the so-called decreasing permeability model [17,18] based on a different view of wet pressing compared with Wahlström's original approach. They later added a rewet term to the model [30] and have recently discussed the use of their model as a design equation for paper machine press sections [79]. Since this is an interesting approach and the model obviously works well in many practical cases, it is also worth discussing here. The decreasing permeability model is based on Darcy's law and some assumptions on the dependence of permeability and compression on the moisture ratio. The model predicts the outgoing moisture ratio of the web (m) after the nip according to Equation 6:

$$m = m_0\left(1 + \frac{Anm_0^n I}{vW^2}\right)^{-1/n} + \frac{R}{W} \tag{6}$$

where	m_0	is ingoing moisture ratio
	I	press impulse
	W	basis weight
	v	kinematic viscosity
	n	compressibility factor
	A	specific permeability
	R	rewetting factor

Here the compressibility factor (n), specific permeability (A) and rewetting factor (R) are furnish-dependent. When using the decreasing permeability model, the furnish-dependent factors have to be determined by fitting Equation 6 to the experimental data. The model is thus strictly valid only in the area where the parameters have been determined.

Basically, the decreasing permeability model does not **explicitly** describe the detailed mechanism of water removal and how different furnish parameters, such as the type of fibre, affect dewatering. All these effects are embedded into the furnish-dependent factors, which have to be determined case by case. I am also inclined to think that when examining pressing effects at high solids contents, where the critical phenomenon is water removal from the cell wall, the best approach would not be the concept of decreasing permeability. However, due to its "transparency" and applicability, the descreasing permeability model has its place among the wet pressing models.

An attempt to develop a comprehensive sophisticated model of wet pressing was also made by Kataja et al. [74]. In this approach, the paper web is divided into three components: 'air' (a), 'water' (w) and 'solid' (s). The authors have used a model where the properties of the web components, e.g., pressure, velocity and density are described as continuous functions of the machine-direction and transversal locations. The flow in the nip is considered to be stationary, i.e., the properties of the web at one location in the rest frame of the machine are assumed to be constant. Further, it is assumed that the shear forces and inertial effects within the components are negligible compared to the pressure gradient and the momentum exchange between the components. It is also assumed that in the rest frame of the mat entering the nip, the flow is purely transversal. Under these assumptions the hydrodynamic equations of motion become:

$$c\partial_x(\rho_a) = -\partial_z(\rho_a v_a) + \Sigma_a^0 \tag{7}$$

$$\partial_z p_a = \Sigma_a^2 \tag{8}$$

Here the subscript α can be either a, w or s, referring to the different components of the web. The constant machine speed is denoted by c, v_α is the transversal velocity of component a, ρ_a is the density and p_a the pressure. The Σ-terms stand for interactions between the different components and for material leaving or entering the web. The symbols ∂_x and ∂_z are shorts for the partial derivatives ∂/∂_x and ∂/∂_z *where* x is the coordinate in the machine direction and z the coordinate in the transversal direction.

Equation 7 describes the conservation of mass and Equation [8] the conservation of momentum. As $\alpha = a,w,s$ Equation 7 and Equation 8 contain 6 equations. To be able to solve the Equations for the unknowns v_a and ρ_a the authors have to express also the quantities p_a , Σ_a^0 and Σ_a^2 in terms of v_a and ρ_a. In their expression for the partial structural pressure of the fibrous mat

$$p_s = p_{so}\left(\frac{(a-1)(s/s_0)}{a-(s/s_0)}\right)^b, \tag{9}$$

s is the local strain of the mat and can be calculated from the density. The authors also have introduced the parameters a, b, p_{so} and s_0 that have to be determined experimentally (in principle separately for loading and unloading). In order to include the possibility of permanent deformation in the model, the relation in Equation 9 can be modified for each layer of the paper with aid of the quantity $0 \leq \varepsilon \leq 1$ that is the permanent deformation of the layer.

In this work the authors have not considered any mass transfer from one web component to the other, i.e., they neglect phenomena like vapourization, condensation and squeezing out water from the cell wall of the fibre. This means that in Equation 7 $\Sigma_a^0 = 0$. According to the authors, it is however possible to supplement the model with these features if necessary.

The other transfer term Σ_a^2 is associated with the transfer of momentum between the different components. Using the Navier–Stokes equations, the authors construct expressions for Σ_a^2 containing two unknown parameters, namely the specific permeability

$$k_0 = \frac{1}{2S_0^2} \tag{10}$$

where S_0^2 is the pore surface area in a unit solid volume, and a parameter γ (Equation 11) which characterizes the distribution of water and air in the pores.

$$\gamma = \frac{\ln(\omega)}{\ln(\xi)}, \tag{11}$$

where ω is the relative proportion of the pore walls covered with water and ξ is the saturation.

The approach used in this model resembles to a certain degree that used in the above-mentioned UMO model.

The model of Kataja et al. seems physically well-founded, but can be computationally cumbersome. It also includes parameters which have to be determined experimentally for different furnishes. An advantage is that water removal from the fibre wall could be explicitly added to the model.

A general problem in the application of the more sophisticated models to examining wet pressing is that these models include coefficients that need to be determined empirically in each case and often with specific devices. The practical application of the models could be improved, if there were "standard"-like methods to determine the necessary coefficients, as has been proposed [83].

WATER REMOVAL FROM THE FIBRE WALL

As previously mentioned, Carlsson et al. already pointed out the important role of water within the fibres in wet pressing. They indicated that even at 20–25% solids content, water is already expelled from fibre walls. Other studies have also demonstrated this [84]. In modern press sections, the last nip operates in the solids content range of 45–50% (MR = 0.8–1.0). If we wish to understand the wet pressing in scientific terms relevant to papermaking, we should direct our efforts to analyzing what happens to water removal in this area. In the web moisture ratio 0.8–1.0, most of the water is within the fibre [85]. This is especially the case for paper grades which contain chemical pulp. So, to increase press solids beyond the current levels, more water needs to be removed from the cell wall in particular.

A number of earlier studies [86–88] have shown that there is a negative correlation between the solids content after pressing and the degree of fibre swelling. The important role of fibre swelling in press dewatering is also reflected by the fact that press performance can be improved by deswelling pulp [88], and the common observation that previously dried chemical pulp web is easier to dewater than the web containing never-dried pulp.

One way to analyze pressing phenomena further is to consider the individual components of a web's resistance to compression. According to Wahlström, the total pressure acting on a web, P_t is equal to the sum of structural pressure acting on the fibres, P_s and hydraulic pressure between the fibres, P_h, Equation 1. He also proposed [89] that it is appropriate to divide P_s into a purely mechanical component of compression, P_c and the pressure used to remove water from the fibre wall, P_f thus:

$$P_t = P_h + P_s = P_h + P_c + P_f \tag{12}$$

It seems likely that fibre swelling can affect each of the components of compressive resistance. The pressure drop across a porous membrane, such as the cell wall, depends on the size of the pores through the membrane. Since the size of the cell wall pores is related to the degree of fibre swelling [90], it is apparent that swelling should affect the hydraulic pressure in the cell wall, P_f. Swelling also influences fibre flexibility [91] which in turn affects the size of interfibre pores. Therefore P_h will probably also be influenced by the degree of fibre swelling. The effect of fibre swelling on P_c is less obvious. However, studies [92] indicate that in porous structures there is a relationship between the size and shape of the pores and the compressive strength of a material. In these studies it is usually found that the smaller the pores within a structure, the higher its compressive strength. It is also a common observation that when a porous material is compressed, the largest pores collapse first followed by sequentially smaller pores.

To be able to analyze the cell wall dewatering and pore collapse in wet pressing, it is necessary to know more about the pore size distribution of the cell wall and how water is located there. Maloney et al. [93,94] have recently measured the pore size distributions of the cell wall and examined how water is expelled from the wall. This work was based on the idea that there is a class of larger pores in the cell wall called "macropores" and a category of relatively smaller pores called "micropores" [95,96]. Macropores are believed to be gaps between the microfibrillar lamellae which are formed in pulping by dissolution of lignin and hemicelluloses from the cell wall [97–99]. The micropores are spaces within the lamellae. The macro- and micropore water can be measured with solute exclusion in combination with differential scanning calorimetry (DSC). The DSC technique can also be called thermoporosimetry, and is described by Maloney et al. [100] and further discussed by Maloney and Paulapuro in this symposium [101]. Figure 7 shows

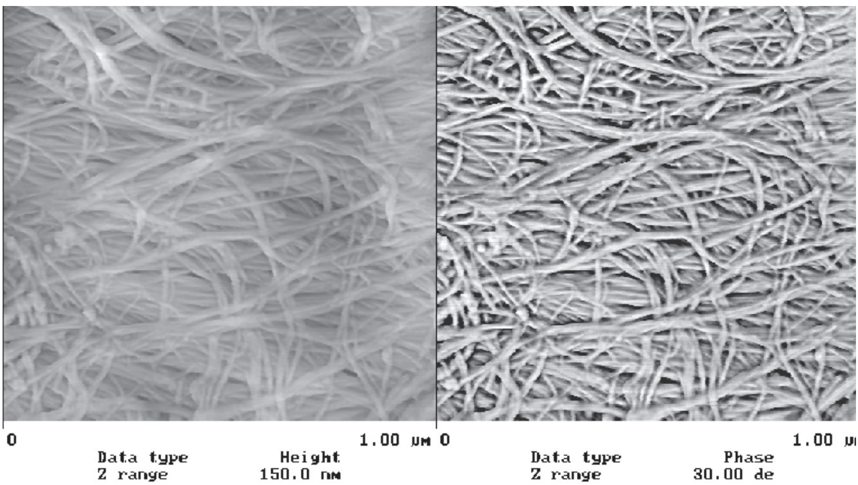

Figure 7 Topographical and phase contrast atomic force micrographs of BSW fibre dried from cyclohexane. Image sizes 1 µm × 1 µm.

topographical and phase contrast atomic force micrographs of a bleached softwood (BSW) pulp fibre wall. The fibrils are clearly to be seen in the image, but it also gives an idea of the pores within the cell wall.

To measure the balancing components for the compressive pressure in Equation 12, Maloney et al. [94] used both static and dynamic pressing experiments. For static pressing experiments a new method called the centrifugal compression value (CCV) test was developed [102]. In this method a pulp pad is placed between a press felt and brass weight and then centrifuged under controlled conditions. Achieving true static equilibrium may take hundreds of days [103], a quasi equilibrium is reached after 10–15 minutes, after which changes to the moisture content are negligible. Under static conditions, it can be assumed that P_h and P_f are 0. Therefore, the only resistance to compression is purely mechanical (P_c).

Pressing pulp pads under static conditions is a simple way to acquire a deeper understanding of how the fibre pore structure can influence dewatering and the collapse of the cell wall. Measurements of pulps [14,93] indicate that pores in the cell wall tend to collapse from the largest to the smallest as dewatering progresses in pressing. Therefore, the compression curve (amount of compression vs. applied pressure) of the water saturated pulp pad contains information about the fibre pore structure. The static pressing response is shown in Figure 8 for series of hardwood and softwood pulps, whose swelling was changed in different ways [94].

For the softwood pulps, the moisture content after pressing increases with the FSP. As the amount of pressure increases, the slope of the curves decreases. At high pressures the swelling has little influence on the pressing response. This behaviour agrees with the observations [94] that beating, hornification or changes in the osmotic pressure affect mostly the volume of larger pores in the cell wall, and that pores collapse from the largest to the smallest when the fibres are compressed.

Compared to the USW pulps, the FSP has only a small effect on the static pressing response of UHW pulps. One cause of this is probably the relatively high swelling of these pulps, which results in a soft cell wall that is easily compressed. Further evidence that the cell wall of the UHW pulps is easily dewatered is given by the WRV experiments reported in [104].

The dynamic pressing experiments were made with the hydraulic platen press simulator [50]. The purpose of these experiments was to show how the hydraulic pressure in the fibre wall P_f influences press dewatering. This was done by pressing a series of 100 g/m^2 handsheets made of unbeaten hardwood and softwood pulps. Under these conditions, it is expected that hydraulic pressure between the fibres is small and can be neglected [47]. In Figure 9 the moisture content after dynamic pressing is shown as a function

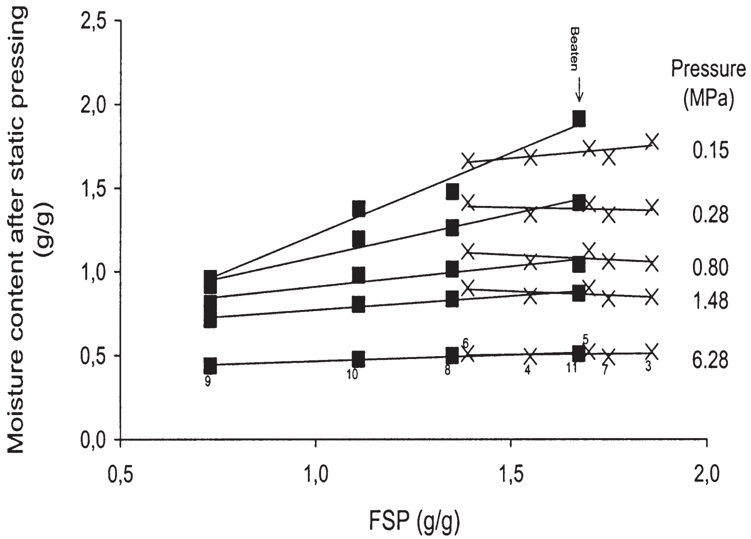

Figure 8 Moisture content after static pressing in a CCV test shown as a function of pulp swelling for USW fibres (■) and UHW whole pulp (X). The swelling was changed with different methods [94].

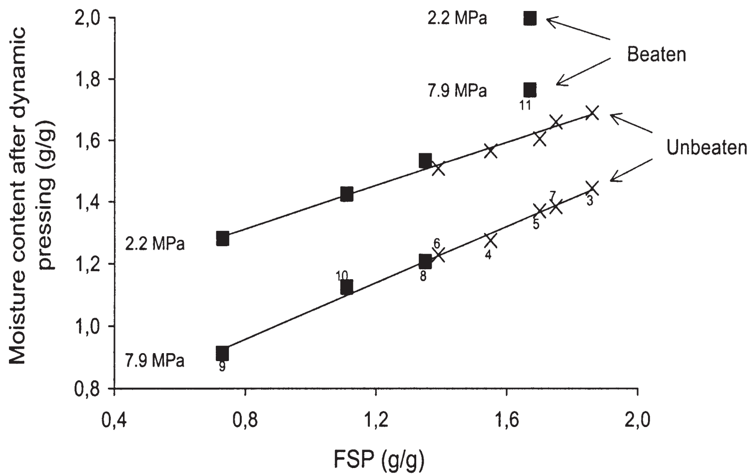

Figure 9 Moisture content after dynamic pressing (16–17 ms pulse) for the pulps used in Figure 8. USW fibres (■) and UHW whole pulp (X). All the pulps were unbeaten except the indicated points [94].

of FSP [94]. The same softwood and hardwood pulps were used as in Figure 8.

The results show that there is a great difference in the behaviour of the pulps under static and dynamic conditions. This is especially notable for the UHW pulps where the fibre swelling does not greatly affect the static pressing behaviour, but has a large effect on the dynamic press dewatering. In the dynamic pressing experiment, the pulse was 16–17 ms. This is in the time scale of an extended nip press. Already at this pulse length, it is clear that it is P_f rather than P_c that accounts for most of the compressive resistance. It is evident that when the press pulse becomes shorter, P_f and P_h increase their share of compressive resistance.

Figure 9 shows that beating has a much larger effect on dewatering than other treatments which change swelling. This is probably because significant hydraulic pressure, P_h, develops between the beaten fibres. Fines will also have a large impact on press dewatering when they are present in the sheet. The dewatering efficiency will depend on the distribution of the fines in the fibre network in relation to the direction of water removal [94].

It is well known that mechanical and chemical pulps behave differently in wet pressing. This is due to the different mechanical properties and pore structure of the fibre wall as well as the differences in the type and amount of fines. In chemical pulping the dissolution of lignin and hemicelluloses opens up relatively large pores (macropores) between the microfibrils. The category of smaller pores, called micropores, is present in both mechanical and chemical pulps. When the yield decreases, the volume of micropores increases to about 70% yield [105]. At 45% yield, about half the water in the cell wall is in macropores.

Mechanical pulp fibres are liberated from wood with a combination of thermal and mechanical energy. Mechanical pulps swell much less than chemical pulps. Figure 10 indicates differences in the behaviour of chemical and mechanical pulps in press dewatering. In this figure the water in micropores (which includes nonfreezing water) is shown as a function of pulp moisture content. The FSP marked on the curves gives a rough idea when the macropores in the cell wall start to collapse. The results show that when fibres are pressed, the water in micropores is not removed until most of the macropores are emptied (pulp moisture content = micropore water).

TMP fibres have virtually no macropores, so all the water removed from the cell wall is expelled from the microreticular system. This requires considerable time and pressure, and cell wall dewatering is unlikely to play any major role in pressing mechanical pulps under ordinary conditions. In the BSW and BSW-fines pulps, a large amount of water is removed from the

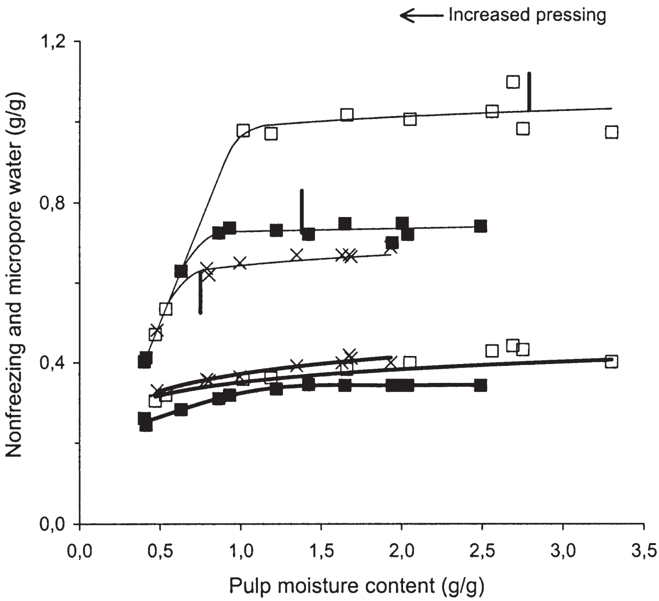

Figure 10 Water in micropores (light line) and nonfreezing water (heavy lines) vs. sample moisture content after static pressing from 0–7.4 MPa (■ unbeaten BSW fibre, □ BSW-fines, X TMP fibre: The FSP is marked with a heavy vertical line) [94].

cell wall at the moisture content which occurs in paper machine pressing (about 1 g/g).

Mechanical pulp fines can, however, behave differently from mechanical pulp fibres. Mechanical pulp fines can be classified into two types of distinct particles: flakes and fibrillar fines [107]. The proportion of flakes and fibrils depends on the processing conditions in mechanical pulping and probably on the raw material. It has been found [108] that these types of fines have very different swelling. Flakes have a low of swelling of about 0.3–0.6 g/g while fibrillar type fines have a swelling of about 1.6–1.7 g/g. This is significant for press dewatering because it is almost certain that fibrillar-type fines have poorer dewatering characteristics.

DISCUSSION

From the above review it is clear that cell wall dewatering plays an important role in wet pressing at the solids contents of the last presses of modern paper machines. Cell wall dewatering depends on the type of fibre material and naturally on the pressing conditions.

The ability of wet pulp fibres to resist compression depends partly on their pore structure. Large pores collapse easier than small ones. The different pore structures of chemical and mechanical pulps contribute to their different behaviour in wet pressing. Beating of a chemical pulp opens mostly macropores and larger delaminations in the cell wall. Hornification of chemical pulp fibres closes macropores and some micropores. The different behaviour of unbeaten, beaten and hornified chemical pulps in static pressing is shown in Figure 11 [94]. As can be seen, TMP fibres behave more like the hornified chemical pulp fibres.

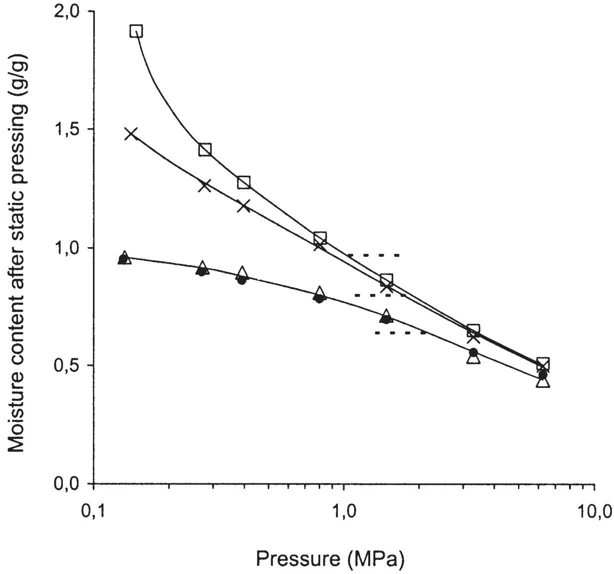

Figure 11 Static pressing response of USW never-dried unbeaten fibres (X); USW never-dried, beaten fibres (10,000× in a PFI mill) (□); USW hornified, unbeaten fibres (•); and TMP fibres (Δ). The hornified pulp was dried at 105°C. The dashed line shows the amount of micropore water for the pulps. Note that hornified USW and TMP had about the same amount of micropore water, 0.64 and 0.69 g/g, respectively [94].

The tendency of fibre walls to collapse and the water removal are also affected by the rigidity of the fibre wall. Even if the fibres have high swelling capacity, like chemical pulps in general, there are differences in this respect, e.g., between softwood and hardwood fibres.

The dynamics of the cell wall pore collapse also has implications for press dewatering. In multiple pressing the cell wall is exposed to several cycles of compression and relaxation. After the cell wall is partially dewatered in the first nip, water that re-enters the web in the rewetting phase will not necessarily re-enter the fibre wall. It has been shown [93] that some of the pores in the cell wall remain shut after pressing (wet hornification). The water from rewetting may thus be easier to displace from the web in the next nip than water from the cell wall. The dynamics of cell wall spring-back and reswelling on the fast time scale are subjects that are still poorly understood.

Fines can also have a significant role in water removal in pressing. Depending on the type of fines, they can have big differences in swellability. The distribution of fines in sheet thickness direction also affects dewatering.

One way to study cell wall dewatering is to measure the amount of the individual water fractions over the moisture range of interest. In the DSC analysis of pulp fibres, the sum of these three water fractions measured equal to the total water in the sample,

$$\mathrm{MC} = \mathrm{NFW} + \mathrm{FBW} + \mathrm{BW} \tag{13}$$

where MC is moisture content, NFW is nonfreezing water, FBW is freezing bound water and BW is bulk water. Figure 12 shows the development of these water fractions for birch kraft pulp as a function of decreasing moisture content of the web [109,110]. In this figure dewatering is divided into a series of phases that are differentiated by the disappearance of one or the other water fractions.

In the first dewatering phase the bulk water between the fibres is removed. This normally happens in the wire section and early part of the press section. Here the FSP was used to separate the interfibre water removal in phase 1 from the subsequent cell wall dewatering. This is only an approximation, since some water is pressed out of the cell wall prior to complete removal of interfibre water. Another factor that blurs this transition is the redistribution of fibre water in multiple press nips.

In phase 2, macropores are dewatered and the consolidation of the microfibrils begins. This phase is relevant only for chemical pulps, since mechanical pulps lack macropores. Typically, this phase will begin within the press section. In this phase, the shrinkage of the fibre and web begins [111]. The disappearance of bulk water from the cell wall marks the onset of phase 3.

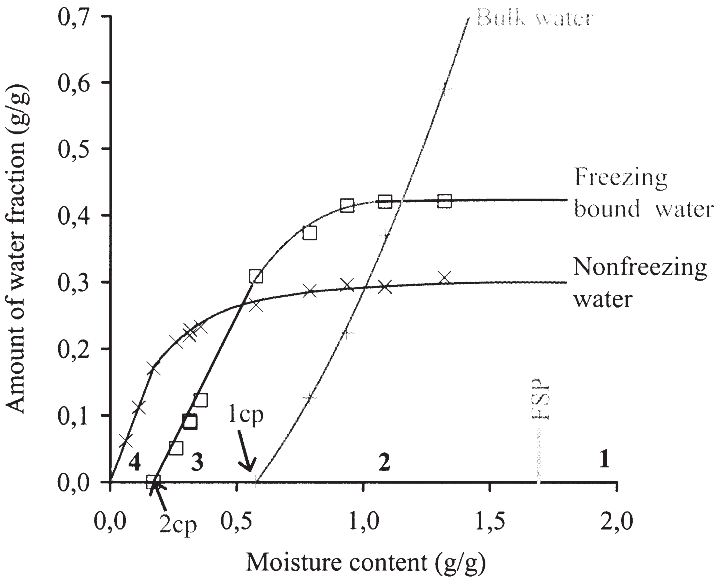

Figure 12 The dewatering phases for birch kraft pulp. The water between the fibres is removed in phase 1. Phase 2 extends from the onset of cell wall dewatering up to disappearance of bulk water. In phase 3, freezing bound water is removed. In phase 4 the more tightly bound nonfreezing water is removed. The FSP and the first and second critical points (1 cp and 2 cp) can be used to define the transition between water removal phases [110].

The transition moisture content between phases 2 and 3 will be referred to as the first critical point (1cp). In phase 2, the micropores start to collapse. It seems likely that the dewatering of the micropores starts from the relatively highly swollen hemicelluloses, which surround the microfibrils, followed by dewatering of the pores within the amorphous regions of the cellulose microfibrils. There is some removal of freezing bound water prior to the 1cp, indicating a smooth rather than discrete transition between dewatering zones. This implies that there is simultaneous dewatering of pores of different sizes (although most of the dewatering comes from the largest existing pores). It is markedly more difficult to remove the water in the cell wall after the 1cp. This is shown by the large increase in the pressure required to remove water in pressing or a drop in the evaporation rate in drying. At the second critical point (2cp), all the freezing water disappears, thus beginning the fourth and final dewatering phase. The moisture content of the 2cp is 0.18–0.28 g/g, depending on the type of pulp. The remaining water in the cell is in very small pores, less than 2–3 nm. Fibre [111,112] and web shrinkage [38] increase after the 2cp. The heat of evaporation of the water in this final stage of drying is much higher than for bulk water, because cellulose-water hydrogen bonds must be broken. There is some removal of nonfreezing water prior to the 2cp. This is consistent with the idea that the transition from one dewatering phase to the next is smooth rather than discrete.

If aiming at a more invariant scientific understanding of wet pressing, it is clear that the basics of the behaviour of different fibre materials in wet pressing conditions must be better understood also quantitatively. It would be helpful to be able to specify the essential differences in the behaviour of fibre material in wet pressing. An attempt to classify the types of fibre material according to their behaviour in wet pressing is made in Figure 13. Quantification of the behaviour as done in the experiments above is already taking our invariant understanding much farther. The next – much more more difficult – phase would be to develop wet pressing models which include explicitly the different behaviour of raw materials in the right way. In this respect, the present models need to be refined. The parameters in the present models determined experimentally include the total effect of the behaviour of the fibres (intra-fibre) and the network (inter-fibre). Thus, we have a fairly large black box in the models. To develop the understanding and quantification into a more invariant direction, it is advisable to divide this black box into smaller parts, as Wahlström [89] has proposed in Equation 12. As the above review shows, this kind of an approach is very fruitful for enhancing our understanding of wet pressing and also devising experimental methods for this purpose. Some of the present wet pressing models obviously offer good possibilities to include the necessary refinements in the basic model structure.

Against the background of this discussion, the essential questions in the "science" of wet pressing, as far as furnish-related water removal is concerned, can be summarized as follows:

To gain a more accurate and invariant understanding of:

- the fibre cell wall pore structure and swelling;
- the collapse and closure of cell wall pores under wet pressing conditions;
- the dynamics of cell wall collapse and its effect in multiple nip pressing and on rewetting;
- dewatering of different types of fines material.

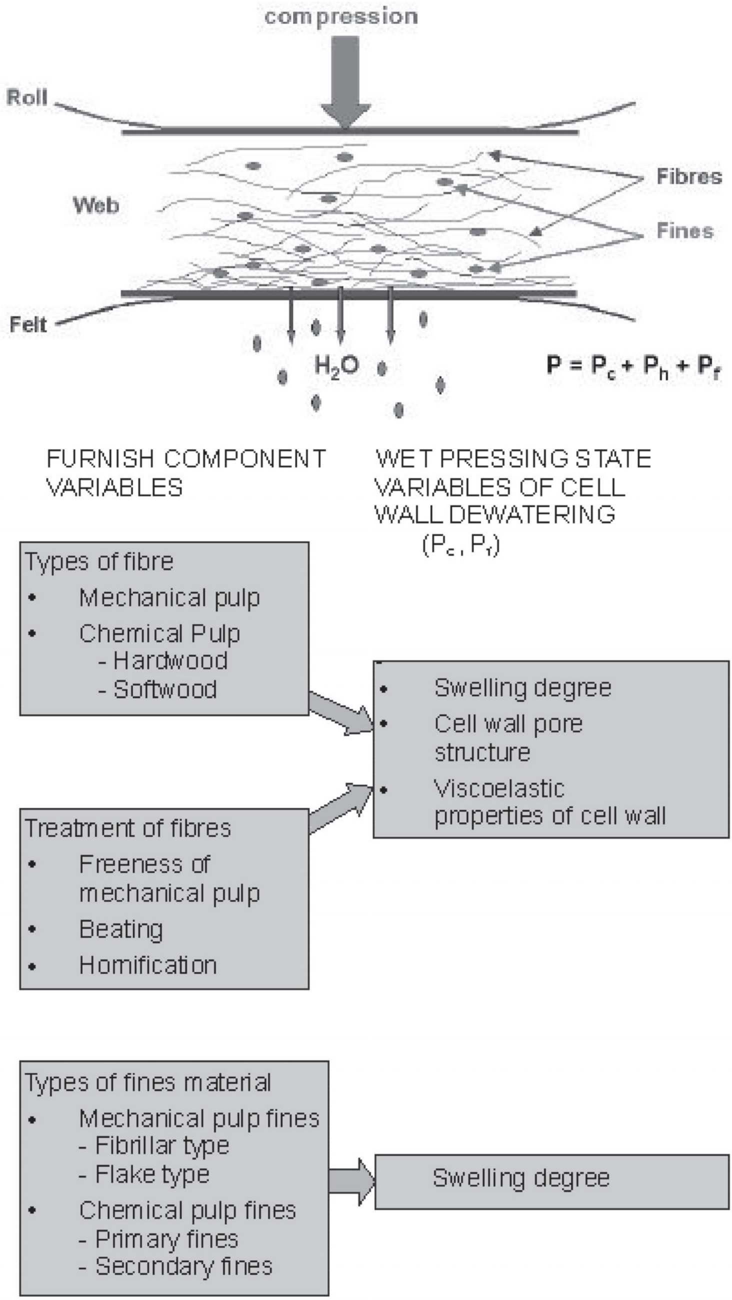

Figure 13 A schematic illustration of furnish and wet pressing state variables.

CONCLUDING REMARKS

The solids content after the press section of modern paper machines is in the range of 45–50%. Earlier research has shown that in wet pressing water is expelled from the fibre wall already at the solids content of 20–25%. The higher the solids content in the press nip the more important the fibre wall dewatering. If the solids content is to be increased from the present level, the essential questions are concerned with the water removal from the fibre wall and the fines material. Research has shown that the water in the fibre wall can be divided into three fractions, nonfreezing bound water, freezing bound water and free or bulk water. The water is located in the cell wall pores which again can be divided into “macropores” and “micropores”. The nonfreezing and freezing bound water is located mainly in micropores and free water in macropores. In wet pressing the pores collapse from the largest to the smallest.

The fibre wall pore system and the collapsing behaviour of cell walls depends essentially on the type of fibre raw material and its treatment before it reaches the paper machine. There are distinct differences between chemical and mechanical pulps and between softwood and hardwood chemical pulps. These differences can be described qualitatively invariably in relation to the water removal behaviour. Beating of fibres and hornification in drying also have a significant effect on the drainage behaviour of the fibre in wet pressing. To a certain extent, these differences can also be understood in invariant terms. However, because beating also affects the water removal between fibres, e.g., due to external fibrillation and production of fines material, it is more difficult to separate the beating effects into inter- and intrafibre dewatering.

The fines material is also playing a more important role in press dewatering, as paper webs are produced from finer and finer pulps. There are differences in this respect between chemical and mechanical pulp fines, but also within the fines material of a given pulp, especially in mechanical pulps. Mechanical pulp fines can be classified into two categories, fibrillar-type material and flake-type material. Fibrillar-type material has much higher swelling capability and therefore is more difficult to dewater than flake-type material.

When trying to advance the technology of wet pressing, the scientific problems related to water removal are focused on gaining a deeper and better quantified understanding of the behaviour of different types of raw material. Recent developments in research methodology [84,101] seem to offer good possibilities for gaining this understanding. Other questions in wet pressing which are important to the objectives of papermaking are web and paper quality and the runnability of the web through the press section. These areas also include many “scientific” questions where we need to deepen our understanding. It is obvious that research on the behaviour of fibre material in wet pressing is also fruitful, in examining web and paper quality and runnability of the web.

REFERENCES

1.. Sedoff, A., Holmberg, C.V., Jahn, E.C., “Water Retention of Beaten and Gelatinized Pulp”, *Paper Trade J.*, **109**: TS350–TS357 (1939).
2.. Campbell, W.B., “The Physics of Water Removal”, *Pulp Paper Mag. Can.*, **48**: Convention Issue, 103–109, 122 (1947).
3. Nissan, A.H., “The Function of the Felt in Water Removal on the Papermaking Machine”, *Tappi J.*, **37**: 597–608 (1954).
4. Bergström, J., “Något om pressfiltens roll vid våtpressning. Referat av ‘Aktuella problem rörande filtar för massa-och pappersindustrin” vid SPCI’s årsmöte i Stockholm 25 april 1959, *Svensk Papperstidn.*, **62**: (367) (1959).
5. Wahlström, P.B., “A Long Term Study of Water Removal and Moisture Distribution on a Newsprint Machine Press Section”, Part I, *Pulp Paper Mag. Can.*, **61**: T379–T401 (1960).
6. Wahlström, P.B., “A Long Term Study of Water Removal and Moisture Distribution on a Newsprint Machine Press Section”, Part II, *Pulp Paper Mag. Can.*, **61**: T418–T451 (1960).
7. Nilsson, P., Larsson, K.O., “Paper Web Performance in a Press Nip”, *Pulp Paper Mag. Can.*, **69**: T438–T445 (1968).
8. Wahlström, P.B., “Our Present Understanding of the Fundamentals of Pressing”, *Pulp Paper Mag. Can.*, **70**: T349–T369 (1969).
9. Carlsson, G., Lindström, T., Norman, B., “Some basic aspects on wet pressing of paper”, International Water Removal Symposium, Transaction of Canadian Pulp and Paper Association, with Institute of Paper Chemistry held in Vancouver: 5–12 (1982).
10. Carlsson, G., Lindström, T., Söremark, C., “Expression of water from cellulosic fibres under compressive loading”, BPBIF 6th Fundamental Research Symposium, Oxford, 5 pp + 5pp fig. (1977).
11. Bliesner, W.C., MacGregor, M.A., “How important is rewetting in wet pressing”, *Tappi J.*, **59**: 114–119 (1976).
12. Ellis, E.R., Jewett, K.B., Ceckler, W.H. and Thompson, E.V., “Dynamic compression of paper”, III, Compression equation for cellulose mats”, AIChE Symposium Series 232, 80, 1–7 (1984).
13. Thorne, J.T., “The effect of capillary rewet on pressing operations”, M.S. Thesis: University of Maine, Orono, ME (1981).
14. Carlsson, G., “Some fundamental aspects of the wet pressing of paper”, Doctoral Thesis, Royal Institute of Technology, Stockholm (1983).

15. Hoering, J.F. et al., "Dynamic compression of paper, Part ii", Compression behaviour of saturated cellulose mats, International Water Removal Symposium, Transaction of Canadian Pulp and Paper Association, with Institute of Paper Chemistry, Vancouver, 99–104 (1982).
16. MacGregor, M.A., "Wet Pressing Research in 1989, a Historical Perspective, Analysis and Commentary", Fundamentals of Papermaking, Transactions of the Ninth Fundamental Research Symposium, Cambridge, 511–586 (1989).
17. McDonald, J.D. and Kerekes, R.J., "A decreasing-permeability model of wet pressing: applications: *Tappi J.*, **74**: 142–149 (1991).
18. Kerekes, R.J. and McDonald, J.D., "A decreasing-permeability model of wet pressing: theory, *Tappi J.*, **74**: 150–156 (1991).
19. Szikla, Z. and Paulapuro, H., "Compression behaviour of fibre mats in wet pressing, Fundamentals of Papermaking, Transaction of the Ninth Fundamental Research Symposium, Cambridge", 587–624 (1989).
20. Lobosco, V., "A Rheological Model of the Paper Fibre Network in Wet Pressing", Licentiate of Science Thesis: Royal Institute of Technology, Stockholm (2000).
21. Vomhoff, H., Dynamic compressibility of water-saturated fibre networks and influence of local stress variations in wet pressing", Doctoral Thesis, Royal Institute of Technology, Stockholm (1998).
22. Wahlström, B., "New developments and new insights in water removal by pressing, Web Formation and Consolidation", EUCEPA International Conference held in London, 92–121 (1979).
23. Sweet, J.S., "A basic study of water removal at the press", *Pulp Paper Mag. Can.*, **62**: T376–T371 (1961).
24. Ceckler, N.H., Thompson, E.V., Ellis, E.R., Jewett, K.B., Hoering, J.F., Thorne, J.T., Busker, L.H., "The University of Maine Wet Pressing Project and the application of the results to optimization of press performance", Engineering Conference, San Francisco, 141–146 (1982).
25. Busker, L.H., Cronin, D.C., "The relative importance of wet press variables in water removal", International Water Removal Symposium, Transaction of Canadian Pulp and Paper Association, with Institute of Paper Chemistry, Vancouver, 25–34 (1982).
26. Norman, B., "On the Mechanisms of Dewatering in the Twin-Wire and Press Sections", *Nordic Pulp Paper Res. J.*, **2**: Special Issue, 39–46 (1987).
27. Wrist, P.E., "The present state of our knowledge of the fundamentals of wet pressing", *Pulp Paper Mag. Can.*, **65**: T284–T296 (1964).
28. Jaavidaan, Y., Ceckler, W.H., Thompson, E.V., "Rewetting in the expansion side of press nips", *Tappi J.*, **71**: 151–155 (1988).
29. Palokangas, A., "Vacuum felt increase dryness in wet pressing: Paper Technology, 24th EUCEPA Conference, Stockholm, 118–124 (1990).
30. McDonald, J.D. and Kerekes, R.J., "A decreasing-permeability model of wet pressing with a rewetting term", *Tappi J.*, **78**: 107–111 (1995).
31. Smart, F.R., "Water removal performance on a grooved second press", Part 1, CPPA Technical Section 62nd Annual Meeting, A13–A18 (1976).

32. Fekete, E.Z., “Water removal performance on a grooved second press. Part 2, Stratified felts”, *Paper Technol. and Ind.*, **16**: T177–T181 (1975).
33. Oliver, J.F. and Wiseman, N., “Water removal in wet pressing: The effect of felt roughness”, Trans. Tech. Sect. 4: *Pulp Pap. Can.*, **79**: TR104–TR109 (1978).
34. Yamamoto, H., “Effect of uniformity of pressure application on the moisture content of a wet paper sheet in pressing”, OFE (1978).
35. Fekete, E. and Wiebe, K., “The limits of pressing”, International Engineering Conference, Miami, FL, 267–277 (1998).
36. Helle, T., Forseth, T., “Influence of felt structure on water removal in a press nip”, *Tappi J.*, **77**: 171–178 (1994).
37. l’Anson, S. and Ashworth, T., “Differentiated permeability surface layer (DPSL) pressing theory”, *Tappi J.*, **83**: 70 (2000).
38. Weise, U., “Characterization and Mechanisms of Changes in Wood Pulp Fibres Caused by Water Removal”, Doctoral dissertation, Acta Polytechnica Scandinavica, Chemical Technology series No. 249, Espoo (1997).
39. Weise, U., “Hornification – mechanisms and terminology”, *Paperi ja Puu*, **80**: 110–115 (1998).
40. Pikulik, I.I., McDonald, J.D., Mentele, C.J., Lange, D.V., “The effect of refining, forming and pressing on fine paper quality”, *Tappi J.*, **81**: 122–130 (1998).
41. Wicks, L., “The influence of pressing on sheet two-sidedness”, Engineering Conference, San Francisco, 3–8 (1982).
42. McGregor, M.A., “Some effects of wet pressing on sheet structure”, Engineering Conference, San Francisco, 9–24 (1982).
43. MacLaurin, D.J., Whalen, J.F., “Effects of wet pressing on sheet properties”, *Tappi J.*, **37**: 608–613 (1954).
44. Eiderbrant, Å., Andersson, N., “The fabric press and paper quality”, *Svensk Papperstidn.*, **69**: 847–853 (1966).
45. Schiel, C., “The effect of wire and press section on the two sidedness of the printing paper”, *Das Papier*, **26**: 223–228 (1972).
46. Busker, L.H., “The effects of wet pressing on paper quality”, Engineering Conference, Atlanta, GA, 117–129 (1985).
47. Szikla, Z., “On the basic mechanism of wet pressing”, Doctoral Thesis, PCS Communication 31, KCL Paper Science Centre, Espoo (1992).
48. Szikla, Z. and Paulapuro, H., “Z-directional distribution of fines and filler material in the paper web under wet pressing condition”, *Paperi ja Puu*, **68**: 654–658 (1986).
49. Szikla, Z. and Paulapuro, H., “Changes in z-direction density distribution of paper in wet pressing”, *J. Pulp Pap. Sci.*, **15**: 11–17 (1989).
50. Szikla, Z. and Paulapuro, H., “Wet pressing laboratory simulation”, Modern Technologies in Pressing and Drying, Bournemouth, 29 pp. (1990).
51. Szikla, Z., “Role of the felt in wet pressing, Part 1, Effect of pressure uniformity on water removal”, *Paperi ja Puu*, **73**: 70–77 (1991).
52. Szikla, Z., “Role of the felt in wet pressing. Part 2, Movement of water during the separation of paper from felt”, *Paperi ja Puu*, **73**: 160–166 (1991).
53. Szikla, Z. and Palokangas, A., “Role of the felt in wet pressing, Part 3, Prop-

erties of felt and their effect on water removal", *Paperi ja Puu*, **73**: 260–266 (1991).

54. Busker, L.H., "The effect of wet pressing on paper quality", Engineering Conference, Atlanta, GA, 117–129 (1985).
55. Pikulik, I.I., Garner, R.G., Daunais, R., McDonald, J.D., "Pressing of low solids content webs", *Pulp Paper Can.*, **93**: T6–T10 (1992).
56. Paulapuro, H. and Nordman, L., "Wet pressing, History and future trends", *Pulp Paper Can.*, **92**: T1–T8 (1991).
57. Talja, R., "Press developments a big jump, or step by step change", *Paper Technol.*, **33**: 18–23 (1992).
58. Talja, R., "Experience of pressing at elevated temperature", The Helsinki Symposium on Alternate Methods of Pulp and Paper Drying, 129–152 (1991).
59. Kurki, M., Pakarinen, P., Juppi, K., Martikainen, P., "Web handling in Papermaking, Part 2, Drying", (ed. by M. Karlsson), Fapet, 374–431 (2000).
60. Alastalo, A., Neimo, L., Paulapuro, H., "Sheet adhesion on press roll materials", *Tappi J.*, **82**: 175–180 (1999).
61. Oliver, J.F., "The Surface Character of Granite Press Rolls", *J. Pulp Paper Sci.*, **8**: TR1–TR5 (1982).
62. Oliver, J.F., "Adhesive film properties affect web adhesion and release from press rolls", *Tappi J.*, **65**: 119–123 (1982).
63. Van Oss, C.J., Chaudhury, M.K., Good, R.J., "Interfacial Lifshitz-van der Waals and Polar Interactions in Macroscopic Systems", *Chem. Rev.*, **88**: 927–941 (1988).
64. Kekkonen, J., Stenius, P., Laine H., "Adhesion properties of polyamide fibres used in press felts", *Tappi J.*, **83**: 71 (2000).
65. Kekkonen, J., "Adsorption kinetics of wood materials on oxides", Doctoral Thesis, Helsinki University of Technology, to be published 2001.
66. Hättich, T., Häyrynen, P., Berg, M., "Impact of press roll adhesion on paper machine runnability and sheet quality", *Paperi ja Puu*, **82**: 393–397 (2000).
67. Chang, N.L., "Dynamic compression of handsheets", Tappi Engineering Conference, San Francisco, CA: 93–106 (1978).
68. Luey, A.T., "Pressing Recycled Paperboard, Web Formation and Consolidation", EUCEPA International Conference, London, 124–143 (1979).
69. Holstege, G.H.J., "Press dewatering; new life for an old concepts", *Tappi J.*, **81**: 115–121 (1998).
70. Westra, H.A., "New Contribution to Press Nip Analysis", *Paper Technol.*, **16**: 165–171 (1975).
71. Jönsson, K.A.-S. and Jönsson, B.T.L., "Fluid Flow in Compressible Porous Media, Steady State Conditions", *AIChE J.*, **38**: 1340–1348 (1992).
72. Jönsson, K.A.-S. and Jönsson, B.T.L., "Fluid Flow in Compressible Porous Media: Dynamic Behavior", *AIChE J.*, **38**: 1349–1356 (1992).
73. Riepen, M., Sinon, A.M., Mulder, B., "The Integrated Paper Machine Dewatering Model (IMP), Drying 96", Proceedings of the 10th International Drying Symposium (IDS'96), Krakow (1996).
74. Kataja, M., Hiltunen, K., Timonen, J., "Flow of water and air in a compressible

porous medium, model of wet pressing of paper", *J. Phys. D. Appl. Phys.*, **25**: 1053–1063 (1992).
75. Jewett, K.B., Ceckler, W.H., Busker, L.H., Co, A., "Computer model of a transversal flow press nip", *AIChE Symp. Ser. 200*, **76**: 59–70 (1980).
76. Bloch, J.-F., "Transfert de masse et de chaleur dans les milieux poreux déformables non-saturés: application au presage du papier", Ph.D. Thesis: Institut National Polytechnique de Grenoble, Grenoble (1995).
77. Funquist, J., Danielsson, K., "Press nip dewatering: from data collection to model validation using grey box identification", International Engineering Conference, Miami, FL, 535–546 (1998).
78. McDonald, J.D., "Predicting the press dewatering of heavyweight grades", International Engineering Conference, Miami, FL, 563–570 (1998).
79. McDonald, J.D., Hamel, J., Kerekes, R.J., "Design Equation for Paper Machine Press Section", *J. Pulp Pap. Sci.*, **26**: 401–406 (2000).
80. Ingmanson, W.L. and Andrews, B.D., "High-Velocity Water Flow Through Fiber Mats", *Tappi J.*, **46**: 150–155 (1963).
81. Vomhoff, H., "On the in-plane permeability of water-saturated fibre webs", *Nord. Pulp Pap. Res. J.*, **15**: 200–204, 210 (2000).
82. Rasi, M., Koponen, A., Aaltosalmi, U., Timonen, J., Kataja, M., Niskanen, K.J., "Permeability of paper: Experiments and numerical simulations", Tappi International Paper Physics Conference, San Diego, CA, 297–306 (1999).
83. Jones, G., "Simulation modelling of dewatering in press nip, Engineering and Papermakers, forming bonds for better papermaking", Nashville, TN, 331–345 (1997).
84. Maloney, T.C., "On the Pore Structure and Dewatering Properties of the Pulp Fiber Cell Wall", Doctoral dissertation, Acta Polytechnica Scandinavica, Chemical Technology series No. 275: Espoo (2000).
85. Laivins, G.V., Scallan, A.M., "Removal of Water from Pulps by Pressing – Part 1: Inter- and Intra-Wall Water", Engineering Conference, Orlando, FL, 741–748 (1993).
86. Busker, L.H. and Cronin, D.C., "The relative importance of wet press variables in water removal", *Pulp Pap. Can.*, **85**: T138–T147 (1984).
87. Springer, A., Nabors, L.A. and Bhatia, O., "The influence of fiber, sheet structural properties, and chemical additives on wet pressing", *Tappi J.*, **74**: 221–228 (1991).
88. Swerin, A., Ödberg, L. and Lindström, T., "Deswelling of hardwood kraft pulp fibers by cationic polymers", *Nord. Pulp Pap. Res. J.*, **5**: 188–196 (1990).
89. Wahlström, P.B., "The Effects of Water in the Fiber Wall in Wet Pressing", Appita, 44th Appita Annual General Conference, Rotorua, Proceedings, A21.1–A21.24 (1990).
90. Stone, J.E. and Scallan, A.M., "The Effect of Component Removal Upon the Porous Structure of the Cell Wall of Wood. Part III. A Comparison between the Sulphite and Kraft Processes", *Pulp Paper Mag. Can.*, **69**: 69–74 (1968).
91. Laine, J., "The effects of cooking and bleaching on the surface chemistry and charge properties of kraft pulp fibers", Doctoral Thesis, Helsinki University of Technology, Espoo (1997).

92. Gibson, L.J., Ashby, M.F., "Cellular solids: structure and properties", Pergamon, Oxford (1988).
93. Maloney, T.C., Li, T., Weise, U. and Paulapuro, H., "Intra- and interfibre pore closure in wet pressing", *Appita J.*, **50**: 301–306 (1997).
94. Maloney, T.C., Todorovic, A., Paulapuro, H., "The effect of fiber swelling on press dewatering", *Nord. Pulp Pap. Res. J.*, **13**: 285–291 (1998).
95. Stone, J.E., Scallan, A.M., "The effect of component removal upon the porous structure of the cell wall of wood. Part II. Swelling in water and the fiber saturation point", *Tappi J.*, **50**: 496–501 (1967).
96. Alince, B and van de Ven, T.G.M., "Porosity of Swollen Pulp Fibres Evaluated by Polymer Adsorption", Fundamentals of Papermaking, Transaction of the 11th Fundamental Research Symposium, Cambridge, 771–788 (1997).
97. Stone, J.E., Scallan, A.M., "Structural model for the cell wall of water-swollen wood pulp fibers based on their accessibility to macromolecules", *Cellul. Chem. Technol.*, **2**: 343–358 (1968).
98. Kerr, A.J. and Goring, D.A.I., "The ultrastructural arrangement of the wood cell wall", *Cellul. Chem. Technol.*, **9**: 563–573 (1975).
99. Favis, B.D., Goring, D.A.I., "A model for the leaching of lignin macromolecules from pulp fibers", *J. Pulp Pap. Sci.*, **10**: J139–J143 (1984).
100. Maloney, T.C., Paulapuro, H., Stenius, P., "Hydration and swelling of pulp fibers measured with differential scanning calorimetry", *Nord. Pulp Pap. Res. J.*, **13**: 31–36 (1998).
101. Maloney, T.C., Paulapuro, H., "Thermoporosimetric techniques for pulp fibres", Fundamentals of Papermaking, Transaction of 12th Fundamental Research Symposium, Oxford (2001).
102. Maloney, T.C., Paulapuro, H., "The centrifugal compression value", *Tappi J.*, **82**: 150–154 (1999).
103. Van den Akker, J.A., Wink, W.A., Bobb, F.C., "Some experiments on the water cellulose fiber system", *Tappi J.*, **42**: 340–344 (1959).
104. Maloney, T.C., Laine, J.E., Paulapuro, H., "Comments on the measurement of cell wall water", *Tappi J.*, **82**: 125–127 (1999).
105. Maloney, T.C. and Paulapuro, H., "The formation of pores in the cell wall", *J. Pulp Pap. Sci.*, **25**: 430–436 (1999).
106. Yamauchi, T. and Murkami, K., "Differential scanning calorimetry as an aid for investigating the wet state of pulp", *J. Pulp Pap. Sci.*, **17**: J223–J226 (1991).
107. Luukko, K., "Characterization and Properties of Mechanical Pulp Fines", Doctoral dissertation, Acta Polytechnica Scandinavica, Chemical Technology series, No. 267, Espoo (1999).
108. Luukko, K., Maloney, T.C., "The swelling of mechanical pulp fines", *Cellulose*, **6**: 123–135 (1999).
109. Maloney, T.C., "How the structure of the cell wall influences press and dryer dewatering", IDS 2000, 12th International Drying Symposium, Noordwijkerhout (2000).
110. Kang, T., "Absorption of water by pulp fibers", Master's Thesis, Helsinki University of Technology, Espoo (2000).

111. Rance, H.F., “Effect of Water Removal on Sheet Properties, The Water Evaporation Phase”, *Tappi J.*, **37**: 640–654 (1954).
112. Nanko, H., Asano, S., Ohsawa, J., “Shrinkage behavior of pulp fibers during drying”, Tappi International Paper Physics Conference, Kona, Hawaii, 365–371 (1991).

Transcription of Discussion

WET PRESSING – PRESENT UNDERSTANDING AND FUTURE CHALLENGES

Hannu Paulapuro

Helsinki University of Technology

Ron Crotogino Paprican

You gave us a very nice summary of major events in the development of wet pressing theory, could you comment on how these major events affected the way press sections were designed?

Hannu Paulapuro

It would take time to go into detail, but I think there are very good examples; Wahlstrom's idea of the pressure controlled and flow controlled press nips and the ideas of temperature's role in dewatering; directly led to the development of, for example, the extended nip press, and so on. Wet pressing is a good area because the science seems to be preceding the practical development, in many other cases, it is the technology that is preceding and then later the science behind it is researched.

Derek Page Institute of Paper Science & Technology

The concept that you have put forward here of pressing water out of the cell wall is I think well accepted in view of the mountain of evidence that suggests that this is going on during wet pressing, I have been waiting for 15 or 20 years for someone to come up with an estimate of how long it takes for water to come out of the cell wall from pores of different sizes. It shouldn't be very difficult to work out. If you flatten a fibre, how long would it take for the water to come out of the lumen; we've got radii of curvature that we can use. Then you can consider the same thing for the cell wall – has all that been looked at? Pressing is an awfully fast process – why is there time for the water to come out through these extremely fine capillaries?

Discussion

Hannu Paulapuro

We have different types of wet pressing, for example, the fast presses or the roll presses and the extended type of shoe presses. The dynamics of the fibre wall relaxing and the behaviour of water removal from the fibre wall has not been analysed in depth to my knowledge. The dynamics of the cell wall collapse and its effect, for example, in multi-nip pressing is a good research area, and I have thought this as paper machines get faster. There are many other phenomena that are time dependent and I think we should include the time effect in these. So I can't answer directly what is the time effect but certainly it is an important area to research.

Dick Kerekes University of British Columbia

Congratulations on an excellent paper – I enjoyed it. I would like to comment on your proposal for further work on cell wall dewatering. I concur that this is where the work is needed. It was an issue we faced when we developed the decreasing permeability model. At that time, the Carlsson and Lindström work had been published and it was evident that structural pressure as defined was really contributing to water removal as well as the so-called hydraulic pressure. This led us to consider that the whole problem to be not one of diminishing driving force, but increasing resistance to water remaining in the paper. We also took into account that there could be structural pressure. In the original equation we have a term for true structural pressure that does not contribute to water removal, but we found that in most cases of wet pressing and rolling nips on paper machines, we didn't have to use it. In recent years, however, we are getting up to very high solids content and I agree with you that we may be in the range where there are true structural pressures. I consider this pressure to be one that cannot contribute to water removal as compared to one that can. When we get down to addressing a fibre, along the lines of what Derek suggested I think some of these concepts that we looked at should be addressed here as well. Is low dewatering rate due to a high resistance from the small pores that the water has to flow through or, in practical pressing, from the low driving force due to our inability to get pressure onto water in the fibre. We probably will get to a range where there is a discontinuous medium giving true structural pressure that cannot contribute to water removal. I think this should be sorted out in single fibre measurements, because if we don't get it right, we don't know whether we're chasing a diminishing driving force or increasing resistance. I suspect we are crossing the line between these two phenomena. You are suggesting a good area for future research I think that is where the next breakthroughs will come to get more water out of the wet web.

Hannu Paulapuro

Thank you for your comments, I agree with you. This is, in a way, a new matter that seems to be coming up just recently when we have possibilities to measure the cell wall structure in more detail. It should certainly be given more thought, as you've suggested, of what is really happening in the physics of the fibre network and what is the time effect, as Dr Page suggested.