The effect of wet-pressing on paper quality
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8.1 Introduction

The mechanical behaviour of the wet web determines the maximum outgoing dryness and the degree of compaction of the wet web. The degree of compaction correlates strongly with various paper properties. Therefore, a thorough insight in the mechanical behaviour of wet web is essential to predict the wet-pressing performance of the combination of a specific furnish with a specific paper machine. Nevertheless, the mechanical behaviour of a wet web during wet pressing is still poorly understood.

The essence of wet-pressing is compaction of the wet web, and removal of water due to the application of a load. The Terzaghi principle states that the reaction force to the application of a load on a porous medium equals the sum of the stress causing the net deformation of the porous medium and the hydraulic pressure related to flow resistance during the removal of water. The first to apply this principle to paper was Campbell (Campbell 1947). Nevertheless, he based his dewatering model on the assumption that during wet-pressing all pressure was counteracted by the flow resistance between the water and the fibre walls. Therefore, he neglected the mechanical behaviour of the web, and based his model completely on the Kozeny equation. A similar approach was followed by Kerekes and McDonald (Kerekes and McDonald 1991).

Nilsson and Larsson acknowledged the importance of the mechanical behaviour of the wet web and incorporated an empirical relation describing the deformation stress as a function of the void fraction, the so-called structural pressure curve (Nilsson and Larsson 1968). This approach was developed some years earlier (Wilder 1960). Riepen and Mulder basically used the same approach, apart from some restrictions that were added to account for the plastic deformation during expansion of the wet web (Mulder and Riepen 1994).

A wet-pressing project was carried out between 1978 and 1984 at the University of Maine, Ontario (UMO), the so-called UMO wet-pressing project. This yielded an equation describing the deformation stress using two elements: an elastic and a plastic part, each as a function of the void fraction (Jewett 1984).
Both the structural pressure curve and the approach used in the UMO wet-pressing project described the mechanical behaviour by an empirical relation without connection with deformation physics. Furthermore, these equations described the lumpsum of the mechanical behaviour of the fibres and the network, and they did not consider the deformation of the fibres separately from the deformation of the network and vice versa. This means that implicitly the assumption was made that fibres are solid and that all water has to overcome the same flow resistance.

However, Carlsson (Carlsson et al. 1977) pointed out that if the outgoing dry content after wet-pressing is higher than the water retention value (WRV), fibre dewatering has to have occurred during wet pressing. According to reports by Busker this was a common situation during commercial papermaking at the time (Busker and Cronin 1982), implying that fibre dewatering is possible within a roll press nip. However, care should be taken with the interpretation of these results since Busker and Cronin most likely used a lower G-force than Carlsson to determine the WRV. Consequently there experiments yielded significantly higher WRVs.

Dynamical pressing tests carried out in the laboratory by Jantunen showed however, that for some furnishes fibre dewatering in a 2.5 millisecond pressure pulse is possible. His experiments showed an increase in dry content from 40% to 44% dry content due to a 2.5 millisecond press impulse on a 80% bleached pine kraft and a 20% bleached birch kraft mixture, cf. figure 8-1 (Jantunen 1985). A time scale of 2.5 milliseconds is of the same order as the time scale in a press nip. Carlsson reported fibre saturation points for bleached kraft pulps between 5% and 0% dry content, implying that a significant degree of fibre dewatering occurred to allow for this increase in dry content (Carlsson et al. 1977).

There are indications that fibre wall collapse is proportional to fibre dewatering (Jang and Seth 1998). When parts of the fibre wall are forced to intimate contact, chemical bonds may be formed (Nissan et al. 1985). The expansion of fibres after wet-pressing is being questioned. Maloney reported that wet-pressing irreversibly closed intra-fibre wall pores, causing hornification of the fibre wall (Maloney et al. 1997). However, the reported results did not directly support this, as they only showed the combined effect of pressing and drying.

Since the role of fibre water had not been studied in relation to the mechanical behaviour of the wet web, we found it necessary to repeat the structural pressure experiments as described in chapter 4 in combination with the test determining the
fibre water content as described in chapter 6. In addition the effect of saturation was taken into account to have an indication of the effect of water on the mechanical behaviour of the wet web.

The models found in literature described the mechanical behaviour by empirical relations obtained under equilibrium conditions (Jewett 1984; Mulder and Riepen 1994; Nilsson and Larsson 1968; Riepen 2000). However, the equilibrium situation will never be reached in the dynamic situation of a commercial press nip. The question is, what is the relevance of these relations in the dynamic situation?

Therefore we studied reports of some dynamical compaction studies. Jantunen (Jantunen 1985) and Vomhoff (Vomhoff 1998) studied the mechanical behaviour of wet webs under dynamic circumstances. Jantunen found that stress relaxation occurred within 100 milliseconds, independent of furnish type. He also reported that the degree of relaxation increased with increasing strain. Vomhoff reported less compaction and more plastic deformation at high strain rates. From these results we concluded that the degree of plasticity of compaction of a wet web is rate-dependent.

Based on Vomhoff’s experimental work Lobasco developed a mechanical model in which he described the strain as visco-elastic plastic strain (Lobasco and Kaul 2001a; Lobasco and Kaul 2001b). The model used an empirical relation to describe the plastic strain as a function of the strain rate. Nevertheless, this model significantly improved the current understanding of the mechanical behaviour of wet web. The wet-pressing model presented by Gustafsson incorporated Lobosco’s mechanical model (Gustafsson et al. 2001). Gustafsson’s model did not distinguish between fibres and network. Therefore, it is not suitable for explicitly modelling fibre dewatering.

Since we expected that fibre dewatering is key to understanding the difference in compaction that may occur between a roll nip and an extended nip press (ENP) or shoe-press nip, we aimed to develop a mechanical model of the wet web distinguishing between the stress caused by the deformation of the individual fibres and the stress caused by the deformation of the network consisting of these fibres.

The aim of this chapter is to develop this model for the mechanical behaviour based on the mechanical tests carried out by Jantunen and Vomhoff and the static experimental tests that are presented in the remaining part of this chapter. Before we present the experiments, methods to express mechanical behaviour in terms of mathematical equations are discussed in the following paragraph.
8.2 Modelling of mechanical properties

The mechanical behaviour of a wet web determines the reaction of a wet web to a pressure pulse. Models exist to describe observations of mechanical behaviour of a material in mathematical terms. Although such models do not necessarily explain the phenomena causing the mechanical behaviour, they are helpful in quantifying observations of mechanical behaviour.

According to deformation theory, stress is the reaction force per area in a material. The following equations describe different types of stress in a wet web. Depending on the type of mechanical behaviour the stress is a function of different parameters. Two main types of mechanical behaviour are distinguished: elastic and viscous deformation. In principle the deformation stress of any type of material can be modelled by these two or a combination of them.

For elastic bodies the deformation stress is linearly related to the strain resulting from the applied load.

$$\sigma = E \varepsilon$$  \hspace{1cm} \textit{equation 8-1}

In which $\sigma$ represents the deformation stress in the body resulting from the applied load [N/m$^2$], $E$ the elastic- or Young’s-modulus [N/m$^2$], $\varepsilon$ the strain resulting from the load on the structure.

The strain is a measure for the change in dimensions due to the applied load. The generally applicable relation for strain is described as follows (Ludwik 1909).

$$\varepsilon = \int_{h_0}^{h} \frac{1}{h} \, dh = \ln \left( \frac{h}{h_0} \right)$$  \hspace{1cm} \textit{equation 8-2}

In which $h$ represents the characteristic dimension of the sample under tension, while $h_0$ represents the characteristic dimension before applying a load.

For small deformations this equation reduces to Hooke’s law, i.e.

$$\varepsilon = \int_{h_0}^{h} \frac{1}{h} \, dh \approx \frac{\Delta h}{h_0}$$  \hspace{1cm} \textit{equation 8-3}

From these equations it becomes clear that the deformation stress and strain of an elastic material are supposed to occur immediately upon the application of a load,
and to disappear immediately upon removing the load. Therefore, the symbol for such a material is a spring, cf. figure 8-2 and figure 8-3.

For viscous materials the deformation stress is a function of the rate of strain, i.e. the speed at which the material deforms as a function of the applied load. The strain of a viscous material remains at it’s final value when the load is removed. The symbol for such a material is a dash-pot filled with a viscous fluid, cf. figure 8-2 and figure 8-3.

The deformation stress of a viscously behaving material can be calculated using Newton’s flow equation.

\[ \sigma = \eta \frac{\partial \varepsilon}{\partial t} \]  

\textit{equation 8-4}

In which \( \sigma \) represents the deformation stress in the body resulting from the applied load to the structure [N/m\(^2\)], \( \eta \) the viscosity in [Ns/m\(^2\)], and \( \partial \varepsilon / \partial t \) the time derivative of the strain [1/s].

As mentioned before the mechanical behaviour of a material may fit a combination of these basic types of mechanical behaviour. The most elementary combinations are the Maxwell element and the Kelvin-Voigt element.

The mechanical behaviour of a Maxwell element is represented by a spring and a dashpot in series, because it is the sum of the behaviour of a spring and a dashpot, resulting in a partly viscous and partly elastic reaction to the application of a load. This mechanical behaviour is described by the following equations.

The spring and the dashpot are in series thus the stresses are the same for both the elastic and the viscous element of the material:

\[ \sigma = \sigma_{el} = \sigma_{v} = \varepsilon_{el} E = \eta \frac{\partial \varepsilon_{v}}{\partial t} \]  

\textit{equation 8-5}

In which the subscripts \( el \) and \( v \) refer to the elastic and the viscous parts of both the stress and the strain.

The strain rate however equals the sum of the individual rates of strain of the elastic and the viscous element of the material, respectively.
For a constant strain this results in the following equation describing the stress relaxation:

\[
\frac{d\sigma}{\sigma} = -\frac{E}{\eta} \frac{dt}{dt}
\]  

\textit{equation 8-7}

If \( \sigma = \sigma_0 \) at \( t = 0 \), integration results in the following equation describing stress relaxation:

\[
\sigma = \sigma_0 e^{-\frac{\tau}{\eta}} = \sigma_0 e^{-\frac{t}{\tau}}
\]

\textit{equation 8-8}

In which \( \tau \) represents the so-called relaxation time \([s]\), i.e. the time required to relax the stress to the level \(1/e\) of the initial level \(\sigma_0\). This equation implies that the stress will disappear if one waits long enough, i.e. \( \sigma \to 0 \) if \( t \to \infty \).

The mechanical behaviour of a Kelvin-Voigt element is represented by a spring and a dashpot in parallel, because it is the product of the behaviour of a spring and a dashpot, resulting in a partly viscous and partly elastic reaction to the application of a load. Therefore, during compaction, the mechanical behaviour may be the same as for a dashpot, but during expansion the spring forces the dashpot to return to its initial position, causing a significantly different behaviour. This is described by the following equation describing the strain.

\[
\frac{\dot{\epsilon}}{\dot{t}} = \frac{\sigma}{E} - \frac{\epsilon E}{\eta} \frac{dt}{dt}
\]

\textit{equation 8-9}

This differential equation yields the following expression to describe the strain during creep, i.e. when the stress is maintained at the constant value \(\sigma_0\),

\[
\epsilon = \frac{\sigma_0}{E} \left( 1 - e^{-\frac{E}{\eta} t} \right) = \frac{\sigma_0}{E} \left( 1 - e^{-\frac{t}{\tau}} \right)
\]

\textit{equation 8-10}

Implying that the strain will approach the value \(\sigma_0/E\), when a constant stress, \(\sigma_0\), is applied to a Kelvin-Voigt element for a very long period of time, \( t \to \infty \).
8.3 Experimental

All tests were carried out on hand sheets made of two different types of virgin fibres: thermo-mechanical pulp (TMP) and bleached kraft hard wood (BKHW). The TMP was produced at the Norske Skog-Parenco newsprint mill and air dried at TNO, the BKHW was obtained as dry bales. After dispersing, the BKHW was beaten for 1500 rounds at minimum pressure in an Imset differential Mühle für Imitationsmahlung (Imset differential laboratory refiner).

The pulp was divided in two portions. Half of the pulp was used directly to make hand sheets. The other half was first washed over a sieve (mesh 50 micron) before the pulp was used to make hand sheets. The aim of the washing was to remove a significant part of the fines present in the pulp.

Hand sheets were made using a Rapid Köthen sheet former. The sheets were made of the fresh pulps shortly before the tests and stored in a refrigerator until the test. Just before the test circular samples were cut from the hand sheets, using the Zwick Kniehebelpresse in combination with a circular knife of 79.8 mm diameter. The aim of the experiments was to determine the mechanical behaviour of the solid parts of the wet web during loading.

Therefore, we registered the compaction and expansion, the water content, and the water retention value (WRV) after compaction of wet samples. The samples of known ingoing moisture content were pressed to completion. After being pressed to completion the samples were allowed to expand. During compaction and expansion the thickness of the samples was continuously recorded. After expansion the samples were weighed and centrifuged to determine the outgoing moisture content and the WRV.

To determine the effect of moisture on the expansion, samples expanded with and without rewet. Additionally, some samples were pressed several times in a row to test whether the equilibrium moisture content remained constant.

Compaction without rewet was realised by pressing the sample between solid plates, while all excess water was removed by absorption (tissue) before the sample was allowed to expand. The dewatering had to occur in the xy-plane of the sample, this type of dewatering is also referred to as lateral dewatering. The samples that were tested while rewet could occur were pressed against a porous plate, allowing the water to flow out of the sample across the whole sample surface.
In this type of dewatering the water flowed in the z-direction. Therefore, this type of dewatering is referred to as transversal dewatering. The water was not removed after flowing into the porous plate, it could also flow back into the sample during expansion, causing rewet. However, not all the water removed during compaction flowed back into the sample, this caused a difference in sheet dryness before and after compaction.

8.4 Results

8.4.1 Expansion and rewet

The outgoing dry content correlates strongly to the apparent density of the sheet (Busker 1985). To understand more of this relation we measured the actual wet apparent density after expansion and we also calculated the wet apparent density based on the assumption that the samples remained saturated during compaction. Figure 8-4 shows the calculated wet apparent density plotted against the measured wet apparent density of BKHW samples. The points at which the calculated density equalled the measured density were connected by a line, points on this line represent the samples that remained fully saturated.

Most of the samples lay well below this line, implying that air had flow into the samples. From this we concluded that the samples expanded due to an inner force, causing air or water to flow into the samples. The samples marked z in the legend expanded with rewet. These samples lay close to the line of saturation. Apparently water flew preferably into these samples keeping them saturated during expansion.

In all figures the samples marked by a yellow circle were made of unfractionated pulp. For BKHW the fractionation was not expected to have effect on the apparent density, because of the low initial fines content. Even for TMP the fractionation did not significantly affect the final wet apparent density, cf. figure 8-5.

After compaction the fibre water content was estimated by measuring the WRV. Figure 8-6 shows the WRVs measured on TMP.

The solid line is the line at which the WRV equalled the outgoing moisture ratio, i.e. the points on this line represent samples in which all the water was bound to the fibres. The samples that were expanded without rewet (green symbols) coincide
with the solid line, indicating that after expansion all the water was located within the fibre walls. The WRV of the samples pressed to 4.0 MPa and expanded without rewet lay well below values reported by Carlsson for unpressed TMP, indicating significant fibre dewatering. Fibre dewatering of the samples pressed to 0.5 MPa was insignificant. This confirms the conclusion of chapter 6 that under static conditions fibre dewatering occurs, if the applied pressure is sufficiently high.

The dotted lines indicate the WRV of unpressed TMP as reported by Carlsson (Carlsson et al. 1977). In the case of rewet the WRV of all samples laid within or close to these border lines, implying that fibre rewet occurred. Similar results were obtained on BKHW.

### 8.4.2 Compaction

To determine the compaction behaviour of purely the network we studied compaction without fibre dewatering and compared this with the compaction behaviour with fibre dewatering.

Figures 8-7 to 8-12 show the results of these experiments. When interpreting these figures the following should be taken into account. The application of a load causes a change in the wet-apparent density, so normally the load would be on the x-axis and the resulting wet-apparent density on the y-axis. Nevertheless we have chosen to plot the results the other way around. We did this because the interpretation of these figures requires comparison to stress-strain diagrams. We expected to help the reader by presenting the results in this way.

Figure 8-7 shows the compaction of wet TMP samples pressed to completion by 0.5 MPa. Figure 8-6 shows that at this load no significant fibre dewatering occurred. The solid lines in this figure show the compaction behaviour of the unpressed samples. The samples compacted proportionally to the applied load. Nevertheless, different stages in the compaction behaviour were registered.

- Initially the compaction increased significantly at low pressure. This was associated with pressing to completion.
- When a sample was pressed to completion, further density increase required a significant pressure increase.
- After the loading had become constant, the density increase continued. When the pressure was relieved, the density initially did not change significantly. However, after the applied load decreased below a certain minimum value, the density rapidly decreased.
Before we draw conclusions, we have to realise that figure 8-7 is not a stress-strain diagram, because most of the time the load does not equal the deformation stress. In most cases a significant part of the applied load was used to overcome flow resistance. To check the significance of this effect we compared the compaction behaviour of saturated samples with the compaction behaviour of unsaturated samples.

The dotted lines in figure 8-7 marked pp show the compaction behaviour of the unsaturated prepressed samples. The initial density of these samples was expected to equal the final density of the unpressed samples, because the prepressed samples started as regular samples before being pressed for a second time. A difference in density existed between a regular sample at the end of a pressure cycle and the density of the same sample at the start of a second pressure cycle. This was caused by expansion during weighing of the samples, because during weighing no pressure was applied to the samples, whereas in the nip a minimum load of 50 N was required to guarantee proper contact with the position sensor.

The first phase of the compaction of the prepressed samples, i.e. pressing to completion, occurred significantly faster than for the unpressed samples. The same results were found in case of compaction of BKHW, cf. figure 8-8. This confirmed the assumption that the first phase is pressing to completion, because the prepressed samples had a significant percentage of air in the void spaces of the sample whereas the unpressed samples were saturated with water. The density and viscosity of air were significantly lower than the density and viscosity of water therefore the compaction to completion occurred significantly faster in case of the prepressed samples.

Furthermore, the prepressed samples appeared to be compacted to a higher density than the unpressed samples. To verify this observation we compacted some samples up to four times. Figure 8-9 shows the registered straining of a representative sample. This figure clearly shows that each time a load was applied to the sample it compacted a bit further than the previous time it was pressed to completion. This means that the wet web relaxed while the load was applied to it. This is in line with observations by Jantunen that the relaxation time, $\tau$, of a wide range of furnishes is below 100 milliseconds.
Extrapolation of the data in figure 8-9 yields the mechanical behaviour of the network alone. From this extrapolation we concluded that the network tended to deform immediately proportionally to the applied load, and that it relaxed if the load was applied during a longer period. This type of behaviour is best described by a Maxwell element.

Figure 8-10 shows how the mechanical behaviour of the wet sample changed when the load was increased to 4.0 MPa. Since the only change was fibre dewatering because of the higher maximum applied load, it seems that the fibres were significantly stiffer than the network. The question is whether the fibres showed viscous or elastic behaviour. The experimental results on WRV, cf. figure 8-6, showed that fibre rewet occurred under static conditions. However the commonly held opinion is that fibre rewet does not occur on the millisecond time scale of a commercial press nip (Jang and Seth 1998; Maloney et al. 1997). Therefore we assumed that the measured fibre rewet occurred due to capillary forces, and that this process is too slow to occur on the millisecond time scale in the nip. This implies that the mechanical behaviour of fibres was regarded as fully viscous. If this assumption proofs to be wrong the model can be easily adjusted by changing the description of the fibres from viscous to Maxwell-element.

8.4.3 Lateral versus transversal dewatering

The experiments were carried out in two different ways:
1. Compaction between solid plates, preventing rewet. We refer to these experiments as lateral dewatering without rewet.
2. Compaction against a porous plate, these experiments are referred to as transversal dewatering. In the latter experiment rewet was not prevented.

In static experiments lateral dewatering is supposed to yield the same results as transversal dewatering, provided that the waiting time is sufficiently long (Ellis 1981; Kruf and Mulder 1994; Mulder and Riepen 1994; Nilsson and Larsson 1968; Paulapuro 2001). Therefore, one method was used to determine the mechanical behaviour without rewet and the other to determine the mechanical behaviour with rewet.

Comparison of figure 8-7 with figure 8-11 and figure 8-8 with figure 8-12 shows some significant differences that may be explained from the differences in the nature of lateral and transversal dewatering.
During transversal dewatering, the rate of strain during compaction was lower than for lateral dewatering. This was explained by the significantly shorter flow path in transversal dewatering than in lateral dewatering, causing a lower flow resistance during transversal dewatering than during lateral dewatering.

The expansion of the transversal dewatered sample started at a higher load than the expansion of the lateral dewatered sample. This may also have been a result of differences between lateral and transversal dewatering, because in transversal dewatering water and air may have flown into the sample at each point of the sample surface that is in contact with the felt or porous plate, while in case of lateral dewatering air could only flow into the sample at the perimeter of the sample. Therefore, the flow path to overcome before any part of the sample becomes saturated with air or water was significantly shorter in the case of transversal dewatering, which resulted in an equally lower flow resistance in case of transversal dewatered samples compared to lateral dewatered samples.

In addition to these expected results we also found that the maximum compaction of the samples during transversal dewatering was about 15% more than during lateral dewatering. This effect was measured both on the TMP and the BKHW samples. According to the present understanding of wet-pressing this should mean that the samples were not pressed to completion. Therefore, we pressed samples for up to 50% longer. Although the sample density increased slightly no significant density increase resulted. This means that the observed difference in maximum compaction is not caused by differences in permeability between transversal and lateral direction, otherwise the increased pressing time should have significantly reduced the difference.

Since the pressure drop is higher during transversal dewatering, a likely explanation of the observed difference in compaction is the dilatation. However, after expansion the transversally dewatered sample had a lower density than the laterally dewatered sample. This indicated that the compaction due to lateral dewatering was more plastic than the compaction due to transversal dewatering, independent of the differences related to the occurrence of rewet. Apparently there is an inherent difference in compaction between lateral and transversal dewatering.
8.5 New theory

The question is how to describe the compaction behaviour of wet webs independent of the furnish characteristics. Additionally, the description of the mechanical behaviour of the wet web has to have a physical meaning in order to provide an alternative to the empirical relations used in the currently applied dewatering models.

We suggest that the viscous effects of flow caused by the dewatering should be considered separately from the viscous effects related to the mechanical behaviour of the fibrous material.

Additionally, we want to consider the deformation of the network separately from the deformation of individual fibres. Therefore we assumed that the total structural pressure in the web is caused by deformation of the network as well as deformation of the fibres. This means that the stress due to the application of a load may be fully located in either the network or the fibres, depending on the characteristics of the wet web and the way in which the load is applied to the web.

Equation 8-11 states that we expect the deformation stress in the network to act in the same direction as the deformation stress in the fibres. In the following we derive the equations describing the structural pressure of the network and the structural pressure of the fibres from the observations made during static and dynamic tests.

\[ p_s = p_{sn} + p_{sf} \]

*equation 8-11*

In which \( p_s \) represents the structural pressure of a wet web, i.e. the total deformation stress [N/m²], \( p_{sn} \) the structural pressure of the network [N/m²], and \( p_{sf} \) the structural pressure of the fibres [N/m²].

In the previous paragraph we concluded that the mechanical behaviour of fibres should be regarded as fully viscous. Therefore, the structural pressure of the fibre is described by the following equation.

\[ p_{sf} = \eta_f \frac{\partial \varepsilon_f}{\partial t} \]

*equation 8-12*

In which \( p_{sf} \) represents the structural pressure of the fibres [N/m²], \( \eta_f \) the “viscosity” of the deformation of the fibres [N.s/m²], and \( \frac{\partial \varepsilon_f}{\partial t} \) the rate of strain at which the fibres (are forced to) compact [1/s].
The most general definition of strain is applied because the deformation of the fibres may be significant, due to significant fibre dewatering, cf. chapter 6. Additionally, the compressive forces were defined as positive forces. Therefore, the following equation describes the strain of the fibres in a network.

\[ \varepsilon_f = \frac{1}{h} \int \frac{\partial h}{h} = \ln \left( \frac{h_{f0}}{h_f} \right) \]

*equation 8-13*

In which \( h_f \) represents a measure of the pore volume inside the outer fibre wall, while \( h_{f0} \) represents a measure of the intra-fibre pore volume before applying a load [m].

The average intra-fibre pore volume height, \( h_f \), can be considered a measure for the intra-fibre pore volume, because we are considering the dewatering effect on a macro scale and the web width does not change significantly during wet-pressing. Thus the only variable of the intra-fibre pore volume is the average intra-fibre pore volume height.

In the previous chapter we concluded that the network as a whole behaves like a Maxwell element; the deformation of the network is partly viscous and partly elastic. This results in the following equation describing the relation between the structural pressure of the network and the network strain, in which the network strain is the strain of the wet web without the strain of the fibres:

\[ \frac{\partial \varepsilon_n}{\partial t} = \frac{1}{E_n} \frac{\partial p_{s,n}}{\partial t} + \frac{P_{s,n}}{\eta_n} \]

*equation 8-14*

In which \( \varepsilon_n \) represents the network strain [m²/m], \( p_{s,n} \) the structural pressure of the network [N/m²], \( \frac{\partial p_{s,n}}{\partial t} \) the change in the structural pressure of the network over time [N/(m²s)], \( E_n \) the modulus of elasticity of the network [N/m²], and \( \eta_n \) the viscosity of the network [Ns/m²].

From the above it follows that the model is based on a description of fibre and network deformation. Therefore we will call it in the following the fibre and network deformation (FND) model.

Figure 8-13 gives a graphical representation of the FND model. The role of the fibres is represented by the dashpot at the left hand side. The dashpot means that the deformation stress in the fibres is proportionally to the rate of strain by which the fibres compact. We assume that deformation of the cellulose strings, forming the fibres, is quite similar to the effect of shearing a twined cable. The deformation
may become plastic directly in the drying section due to chemical bonds, forming between different parts of the fibre wall that are brought in close contact in a relatively dry environment.

The mechanical behaviour of the network formed by the fibres is represented by a Maxwell element, the dashpot and spring in series, at the right side of the figure. For the structural pressure of the network we associate the viscous part of the mechanical behaviour with fibre slippage, which may occur if the part of the applied load, being diverted to shear forces exceeds the yield locus of the web at a contact point between fibres. The elastic part of the structural pressure of the network is associated with compaction and expansion of the porous structure without the fibres in the network changing position.

The dashpot representing the fibres behaviour and the Maxwell element representing the behaviour of the network are in parallel connection. This means that we expect that the wet web as a whole to react like a Maxwell element and a dashpot in parallel, with the network properties determining the Maxwell element, and the fibre properties determining the dashpot. Therefore, when applying a load on the network the stresses divide between the fibres and the network. Within the network the deformation stress is the same in the viscous and the elastic parts. Substitution of this insight in equation 8-11 yields the following equation.

\[ P_S = E_n \varepsilon_n + P_{S,f} = \eta_n \frac{\partial \varepsilon_n}{\partial t} + P_{S,f} \quad \text{equation 8-15} \]

The rate of strain of the network is defined as a result of both the elastic and the viscous deformation, cf. equation 8-14. Substitution in equation 8-15 yields the following equation defining the structural pressure as a result of the structural pressure of the fibres, the structural pressure of the network and the loading rate of the network.

\[ P_S = P_{S,f} + \eta_n \frac{\partial P_{S,n}}{E_n \frac{\partial t}{} + P_{S,n}} \quad \text{equation 8-16} \]

In which \( P_S \) represents the total structural pressure in the web [N/m²], \( P_{S,f} \) the structural pressure of the fibres [N/m²], \( P_{S,n} \) the structural pressure of the network [N/m²], \( E_n \) the modulus of elasticity of the network [N/m²], and \( \eta_n \) the viscosity of the network [Ns/m²].

This equation perfectly explains the observation made by Vomhoff that a rapidly applied load compacted a wet web to a lesser extent than a slowly applied load.
The above mentioned equations constitute the FND model, describing the mechanical behaviour of the wet web. To determine the validity of this model we tried how it describes the behaviour of the wet web as a function of the applied time scale. For this aim we used the following experiment of thought:

Figure 8-14 shows the structural pressure resulting from an imaginary pressure pulse on a wet web. The time scale of this pressure pulse is variable.

Figure 8-15 visualises the three different reactions that are predicted by the FND model. The indicated time scales are estimates; the exact values can only be determined when the characteristic modulus of elasticity and the viscosity of both the network and the fibres are known.

The picture on the left of this figure shows the effect of a very fast pressure pulse, much faster than will occur in current paper machines. In this case the equation predicts that viscous forces prevent any significant deformation, implying an inherent limit to the speed at which a web can be dewatered due to wet-pressing.

The picture on the right of this figure shows the effect of a very slow pressure pulse. In this case the deformation is expected to be fully elastic. This is less realistic since, especially with a high ingoing water content, fibre slippage will always occur and therefore part of the network deformation will always be plastic. However, wet-pressing is such a dynamic process that the deviation in this limiting case seems less important.

The central picture shows the situation as it occurs on time scales between these two limiting cases. This is by definition the time scale occurring on commercial press nips, because that is the situation for which the FND model was derived.

The central picture shows that with increasing structural pressure the strain will increase more than linearly, while with decreasing pressure part of the strain will appear plastic. The faster the straining, the higher the percentage of plastic strain.

### 8.6 Conclusions

The wet-pressing performance was determined by measuring compaction and dewatering rates. The structural pressure appeared to play an important role both
in determining the flow rate from the web and in determining the final degree of compaction after wet-pressing. Therefore, proper understanding of the structural pressure seems essential if we are to optimise the wet-pressing performance.

Current equations for the structural pressure describe the compaction behaviour of the wet web, not the expansion. The role of fibres and network is lumped together. We have presented a new model, describing the mechanical behaviour of the wet web during both the compaction and the expansion. In this model the roles of fibres and network are considered separately. The network and fibres are expected to work in parallel. The contributions of the network and the fibres to the structural pressure of the wet web are described in terms of viscosity and E-modulus. These descriptions are linked to phenomena occurring during wet-pressing. Therefore the model was called the fibre and network deformation (FND) model.

Fibre rewet was measured on a long time scale. Nevertheless, no such effect has been measured on the short time scales occurring in commercial press nips. Therefore, we expect the fibres to deform as a viscous medium, whereas the network is expected to deform like a Maxwell element. It will require dynamic tests to determine the viscosity of the network and the viscosity of the fibres.

The new model for web deformation has not yet been validated. Nevertheless, it explains the following observations made in dynamic press simulations (Vomhoff 1998):

• The maximum deformation is lower at high strain rates than at low strain rates.
• The degree of plastic deformation is higher at high strain rates.

8.7 References


