Evaluation of furnishes for tissue manufacturing; wet pressing

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KEYWORDS: Tissue, Wet Pressing, Water Removal, Solids Content, Beating, Pore Structure, Water Retention Value, Thermoporosimetry

SUMMARY: Wet pressing is the last operation on the tissue machine in which water can be removed prior to the expensive evaporative drying of the web. An increase in dryness at this stage can lead to major savings during the manufacturing process. A higher solids content can be achieved by suitable selection of raw materials and by optimizing the treatment of the fibres in the furnish. In this work, wet pressing was evaluated with four pulps beaten to different levels in a PFI mill. Wet pressing was done in a dynamic press simulator and conditions representative of tissue machines with regard to nip pressures and dwell times were chosen. Water retention and thermoporosimetry were used to determine the pore structure of the fibres. Thickness measurements were made to determine the permanent deformation of the sheets after the pressure pulse.

Wet pressing in tissue manufacturing is shown to be affected by the choice of pulp, which can be explained by differences in pore structure of the fibres and consequently differences in ability to retain water. More water available before pressing leads to more water that can be removed. Beating has a negative impact on the solids contents reached after pressing, which is believed to be an effect of both internal and external fibrillation. These effects of beating seem mainly to affect the dryness after vacuum dewatering, which is also reflected after pressing. Beating delaminates macropores in the fibre wall but has a minor effect on micropores. Both water between the fibres and water in macropores are removed during pressing. These results give knowledge of how the furnish should be prepared in order to reduce energy consumption in the process.

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In a saturated web of fibres, water is located in the pores between fibres, in the fibre lumen and in the porous structure of the fibre wall, Laivins and Scallan (1994). In the fibre wall, the water is classified as non-freezing and freezing water in micropores and bulk water in macropores. Only micropores are originally present in wood fibres while macropores are formed by the dissolution of lignin and hemicelluloses in chemical pulping, Maloney and Paulapuro (1999).

The pore structure of fibres and its influence on wet pressing has gained a lot of attention in the past. Maloney et al. (1998b) investigated the role of fibre swelling and pore structure in press dewatering and showed that nearly all the water that is removed from the cell wall comes from the macropores under ordinary press conditions, i.e. < 50% solids content. Beating was thought to have a very large detrimental impact on the solids content after pressing due to a decrease in sheet permeability which increases the hydraulic pressure between the fibres. Wahlstrom (1990) proposed that the solids content after pressing is limited by the rate at which water can be removed from the cell wall in pressure controlled situations when the resistance to flow through the structure is insignificant. Laivins and Scallan (1994) separated the water leaving a pad of pulp into the fraction leaving the porous structure of the cell wall (intra-wall water) and that leaving the spaces external to the wall (inter-wall water). They found that both the inter-wall and intra-wall water start leaving the pad at the lowest applied pressure. However, removal of inter-wall water is almost complete at about 2 MPa, leaving the cell water as the predominant form of water remaining at higher pressures. They identified this water as the factor that both controls the process and limits the extent of dewatering in a press. Moreover, they claimed that a paper web could be rendered almost completely dry in the press section if no water existed inside the fibres.

Rousu et al. (2010) studied the wet pressing of paper sheets containing various proportions of modified non-wood pulps. Dried common reed pulp increased the water removal while wheat straw pulp retarded it. The drying of the pulp sample, the cooking method and fines removal had strong effects on the dewatering properties. The water retention value (WRV) was found to be a good indicator to predict the behaviour of non-wood pulp during wet pressing. Moreover, they suggested that the initial moisture content strongly affects the outgoing moisture content in wet pressing. The same relationship was found by Busker (1980) who reported a difference in outgoing sheet dryness of 5% when the ingoing sheet dryness was varied from 24 to 38%. Busker and Cronin (1984) also found the WRV to be an excellent indicator of the dryness after pressing of wood pulp.

He et al. (2003) examined the behaviour of fibres in wet pressing and quantified the density increase as an effect of gap closure, fibre collapse and fibre twist. They found that the three mechanisms occur simultaneously at low pressures (less than 0.5 MPa), and that gap closure is the predominant mechanism in paper structure densification. Increasing pressure only slightly increased the apparent density, and was believed to be due to additional twist and collapse of the fibres. Springer et al. (1991) examined the influence of fibre and sheet structural properties on wet pressing. Fines creation and fibrillation induced by beating had a large negative impact on press performance. Sheet structure properties such as formation and fibre length had no influence on the dryness, but a decrease in the void volume between the fibres led to an increase in the hydraulic pressure generated in the sheet.

Although the influence of pore structure and fibre properties on wet pressing has been investigated in the past, most of this research was done on higher grammage papers not representative of tissue grades. The present work was therefore focused on investigating these aspects further including pulp types, degrees of beating and press conditions typically used in tissue production. Both virgin and recycled fibres are used in tissue production but virgin fibres are easier to characterize. The pulps used in tissue production are normally mildly beaten so that the bulk and softness of the end product is preserved. Depending on the end product the grammage of tissue products varies between 12-50 g/m^2.

Materials and methods

Four once-dried commercial bleached kraft pulps were used in this study; pine, spruce, birch and eucalyptus (*E. globulus*). The target °SR of the pulps was determined based on personal communication with the suppliers so as to produce refined pulp in fair agreement with that of pulp used in industrial tissue production. The softwood pulps were beaten at 1000 and 2000 revolutions and the hardwood pulps at 500 and 1000 revolutions. The dewatering resistances and characterization of the pulps can be found in Kullander et al. (2012). The pulps were used without pre-conditioning. The conductivity of the stocks varied between 1.9-2.4 μS/cm^3 and the pH between 7.4-7.7 during the trials.

Isotropic sheets were formed assisted by vacuum on a wire to a grammage of 20 g/m^2 at a constant dwell time of 20 s to reach an initial solids content of 15-25%. These are the levels reached in earlier work focused on suction box dewatering, Kullander et al. (2012). Constant parameters during vacuum dewatering were also desirable to facilitate a comparison. The pressure level was 10 kPa in the vacuum tank during the trials. The sheets were carefully peeled off and placed on a press felt (EcoMaster 2522, Metso fabric) prior to pressing. The air permeability of the felt is 11 cfm. The pressing was performed in a material test system (MTS) at three different nip pressures; 2, 4 and 6 MPa. The dwell time was set as short as possible during the trials, i.e. 25 ms. The contact time between the press felt and the sheet after pressing was typically 10-20 s, which implies that complete rewetting occurred. The solids content was determined according to ISO 638.

The thickness was measured in a STFI thickness tester. WRV measurements were conducted according to ISO 23714:2007. Pore size measurements were made with thermoporosimetry in a differential scanning calorimeter (DSC Q2000, TA instruments). Pulp samples were prepared by centrifuging at 900 g for 30 min to reach a moisture ratio of 1-3 g/g. After centrifuging, 8-12 mg of the pulp pad was sealed in a preweighed hermetic aluminium pan. In this study, the following thermal sequence was used: Cooling to -45°C, heating at 5°C/min to -30°C and holding for 5 minutes and then cooling to -45°C. The cycle was repeated with the isothermal melting set point at -8, -5, -3, -2, -1, -0.6, -0.4, -0.2 and -0.1°C with 15 minutes for the melting transition to complete. Temperature calibration was done with deionized water. Further details of the method used can be found in Maloney et al. (1998a).

Results and discussion

Impact of pulp

Fig 1 shows the results of the press trials. The error bars plotted in the graphs show the standard deviations based on five dryness measurements at each dwell time. The solids content after pressing was between 30 and 43% and increased with increasing nip pressure. For the unbeaten grades, the highest solids contents were achieved with the two softwood pulps and the birch pulp. 2-4 percentage points lower solids content was achieved with the eucalyptus pulp. No significant differences were seen between the pulps at the same number of revolutions in the PFI mill. The initial solids content was higher for the hardwood pulps, probably due to the relatively long dwell time during forming. The denser fibre mat created by hardwood pulps leads to a higher pressure level in the vacuum tank and consequently a higher solids content. For sheets with a grammage of 100 g/m^2, this effect was demonstrated with a basic pressure transducer. The pressure level was 9-10 kPa for sheets made of softwood pulps and 12-14 kPa for birch and eucalyptus sheets.

The effect of pressing is generally expressed as solids content or moisture content after pressing. Since the solids content of the sheet entering the press section clearly affects the outgoing solids content, it may be more relevant to consider the increase in solids content during pressing. The solids content increase was 1-3 percentage points less for the birch pulp and 4-6 percentage points less for the eucalyptus pulp than for the softwood pulps. The total available water before pressing (TAW) was 3.5-5.5 g/g fibre of which 1.5-4 g/g was removed during pressing. A clear correlation was found between the total available water and the amount of water removed, *Fig 2.* More available water before pressing leads to more water that can be pressed out. In pressing studies, two limiting cases are often identified. In a compression-controlled press nip, the outgoing dryness is constant regardless of ingoing conditions. In a flow-controlled press nip, on the other hand, the amount of water removed is constant regardless of the ingoing dryness. Compression-controlled conditions typically arise with thin webs with a low moisture content, whereas a combination of thick webs and high moisture content makes flow-controlled conditions more likely. The pressure nip in the present experiments was probably close to compression-controlled since the relation between the amount of pressed out water and the amount of total available water is linear with a gradient close to one.

Even though the total available water seems to control the amount of water that can be removed during pressing, the location of the water is believed to be important. The water allocation before pressing based on DSC-measurements is listed in *Table 1.*

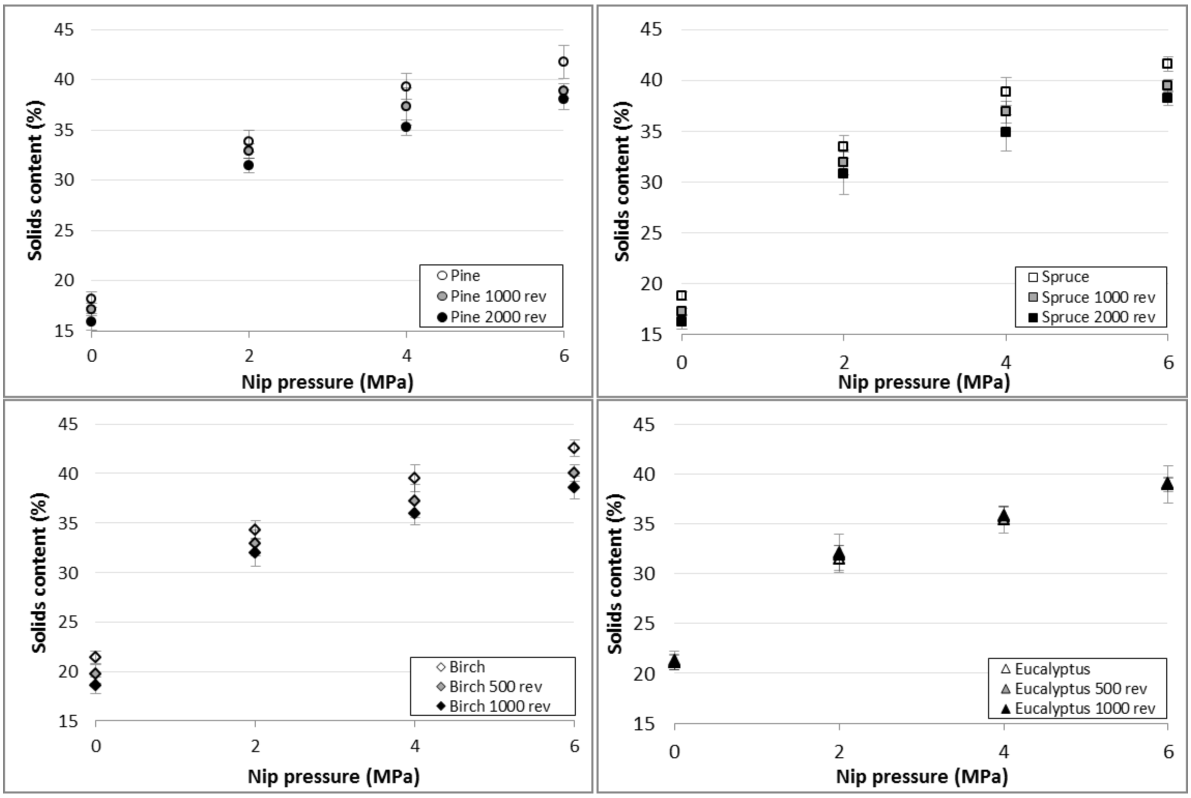

Fig 1. Solids content as a function of nip pressure at different degrees of beating.

Table 1. Water allocation before pressing (g water / g fibre).

Pulp	NFW	Micropores	Macropores	WRV	Water between fibres	TAW
Pine	0.42	0.67	0.42	1.09	3.43	4.52
Pine 1000 rev				1.53	3.32	4.85
Pine 2000 rev	0.45	0.74	1.04	1.78	3.51	5.29
Spruce	0.43	0.71	0.36	1.07	3.25	4.32
Spruce 1000 rev				1.52	3.30	4.82
Spruce 2000 rev	0.45	0.79	0.93	1.72	3.45	5.17
Birch	0.28	0.54	0.58	1.12	2.55	3.67
Birch 500 rev				1.43	2.62	4.06
Birch 1000 rev	0.29	0.59	1.06	1.65	2.72	4.37
Eucalyptus	0.13	0.46	0.84	1.30	2.43	3.73
Eucalyptus 500 rev				1.63	2.12	3.74
Eucalyptus 1000 rev	0.14	0.52	1.29	1.81	1.90	3.71

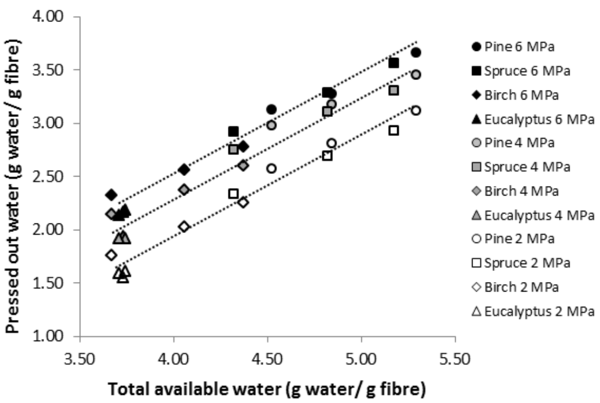

Fig 2. Water removed by pressing as a function of total available water.

Micropores are defined as all pores containing water with a depressed melting temperature, i.e. ≤ -1°C or water that does not change phase at all, i.e. non-freezing water. Of the total available water, 1-2 g/g is held in the fibre wall. Water not associated with the fibre wall is held between the fibres and in the lumen. This water would be the first to be removed from the sheet under ordinary pressing conditions. Capillaries in the cell wall are finer than the capillaries between the fibres and the fibre wall water is thus hold more strongly. The average pore size is of the order 10^{-9} to 10^{-8} m in the fibre wall and 10^{-6} to 10^{-4} m between fibres in a wet web, Wahlstrom (1990). Since the amount of water between fibres is higher in softwood pulps, a higher rate of water removal would be expected. The straight pores between the fibres have also been shown to be larger in sheets made of softwood pulps and this might enhance removal of this water in pressing just as in suction box dewatering, Kullander et al. (2012).

Fibre wall water can be divided into water in macropores and water in micropores, where micropores contain both freezing and non-freezing water. The total amount of water in the fibre wall is quite accurately represented by the WRV of the pulps. The WRV is in the order: pine, spruce < birch < eucalyptus for both the unbeaten and beaten pulps. A higher WRV means that more water is retained within the fibres (swelling). Hardwood pulps have a higher ability to sorb water in the cell wall and this water is more difficult to dewater than free water between the fibres. At the same time, hardwood pulps have more water allocated in macropores and less in micropores than is the case in softwood pulps. Maloney et al. (1998b) found that the water which is removed from the cell wall comes almost entirely from macropores under ordinary press conditions. Water from micropores and non-freezing water is removed only when the pulp is pressed to a low moisture content. Fibre wall water should thus be more easily removed from hardwood than from softwood pulps.

The thickness of the sheets was measured at the different pressure levels, *Fig 3*. The permanent deformation is reported as $(t_0-t_1) / t_0$ where t_0 is the thickness before pressing and t_1 is the thickness after pressing. As seen in the figure, pressing introduces a permanent deformation in the sheets, which varies with the fibre species. The order remains the same for the three pressures used in this study. A lower permanent deformation can be observed for the eucalyptus sheets, which certainly contributes to the lower solids contents achieved. The deformation was highest for birch sheets, which may be a cause to the relative high solids contents reached after pressing. It is remarkable that the eucalyptus shows a propensity to deform more than the other pulps when the nip pressure is increased. The higher deformation of sheets made of eucalyptus may indicate that these fibres collapse more easily. Gap closure is believed to be the predominant mechanism at low pressures while fibre collapse or fibre twist gain importance in the additional deformation introduced at higher pressures.

Influence of beating

The solids content after pressing decreased with increasing beating for the softwood pulps and the birch pulp. *Fig 4* shows that the solids content decreased with increasing WRV for the pulps, with the exception of the eucalyptus pulp where the solids content was unaffected by beating and independent of WRV. This may be due to a lower rigidity of the fibres, Maloney et al. (1998b). If a fibre is not sufficiently rigid, an increase in swelling may be overcome by compression since the pores are easily collapsed. The lower rigidity of some hardwood pulps is considered to be due to a high hemicellulose content and a high swelling capacity. Both these criteria apply to eucalyptus. Birch pulps have high hemicellulose content as well but the fibres have a lower swelling capacity compared to eucalyptus fibres and at the same time thicker cell walls. The rigidity is consequently believed to be higher of these fibres.

The same trend has been shown with respect to the dryness after water removal by suction, regardless of whether vacuum dewatering occurs with dynamics close to that of the industrial process, Kullander et al. (2012), or whether the dryness is measured after a long suction time. The effect of beating on pressing may therefore better be evaluated if the increase in solids content during pressing is considered. Even though small changes can be seen as a result of the beating of the pulps, no significant differences were observed. An increase in dryness after pressing might consequently be due to a better dewatering in the forming section. The DSC measurements show that beating affects the volume of macropores but that the effect on micropores is small, *Fig 5*. This is in agreement with the work of Maloney and Paulapuro (1999). The increase in WRV with beating is thus due to an opening of the macropores in the fibre wall. The amount of water between the fibres is however unaffected except in the case of eucalyptus. Since the amount of water pressed out increases linearly as the beating is increased, both water between fibres and water in macropores are removed at all the pressure levels investigated in this study.

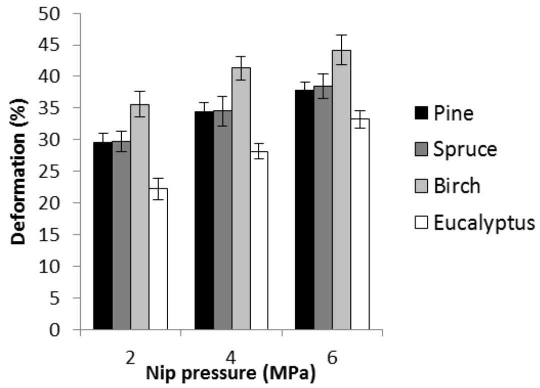

Fig 3. Permanent deformation after pressing as a function of nip pressure.

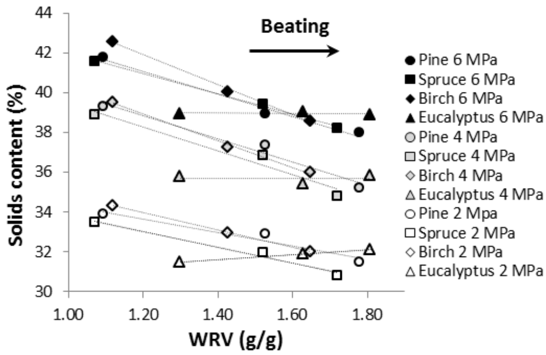

Fig 4. Solids content after pressing as a function of WRV.

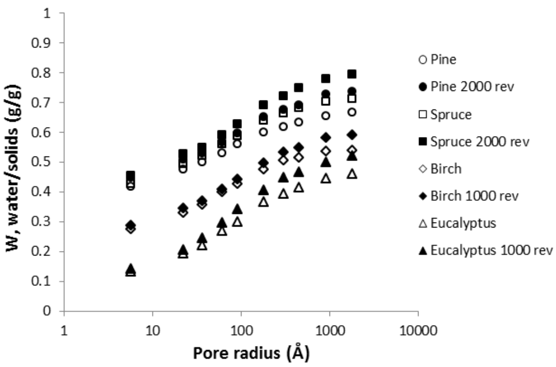

Fig 5. Amount of water (W) as a function of pore radius.

An explanation of the low influence of beating on the increase in solids content during pressing might be the low ability of the PFI mill to create fines. Fibre characterization shows that no secondary fines were created with the pulps used in this study. The PFI mill is a very low intensity refining device which imposes a higher ratio of compressive to shear forces than an industrial refiner, and this leads to a higher internal fibrillation and lower external fibrillation and fibre shortening, Kerekes (2005). Fines have much larger specific surface area per unit mass than fibres and have been shown to carry almost twice the amount of water per unit dry mass than fibres, Laivins and Scallan (1996). Due to their size, fines also block channels between fibres where water can be drained. A more pronounced effect of beating on the solids content after pressing can thus be expected in industrial applications.

Conclusions

Wet pressing of low grammage paper has been shown to be affected by the choice of pulp and by the treatment of the fibres in the furnish. The pore structure of the fibres seems to control the removal of water during pressing. Hardwood pulps have a greater ability to sorb and retain water in the fibre wall than softwood pulps. The water in the fibre wall of hardwood pulps is however expected to be more easily removed since more water is located in macropores. The removal of water during pressing is also dependent on the total amount of available water. Beating in PFI mill does not significantly affect the increase in solids content during pressing under the conditions used in this study, i.e. mild beating and low grammages. The negative effect of beating can however be seen after vacuum dewatering, an order that is maintained also after pressing. Beating mainly delaminates macropores with a small effect on the micropores. Both water between the fibres and the water in macropores in the fibre wall are removed during pressing. These results give a better understanding of how the furnish should be prepared in order to increase the press dryness in the tissue manufacturing process. The energy demand for drying will be roughly proportional to the amount of evaporated water, so that one percent increase in dryness after the last press will reduce the drying energy demand by 3-4 percent.

Acknowledgements

The tissue education and research programme TERP at Karlstad University is gratefully acknowledged for the financial support and feedback to the project. Timo Ylönen and Christian Orassaari at Aalto University are thanked for technical support during the press trials.

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Manuscript received May 14, 2012
Accepted August 21, 2012