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# The effect of wet pressing and drying on bonding and activation in paper

Anna Vainio and Hannu Paulapuro, Helsinki University of Technology, TKK, Espoo, Finland

**KEYWORDS:** Bonding, Activation, Drying stress, Wet pressing, Wet densification, Strength, Paper strength properties

**SUMMARY:** The aim of this study was to examine the effect of wet pressing and drying stress on interfibre bonding and fibre segment activation in paper. The phenomena were studied through determination of various strength characteristics of paper, including Scott bond strength and tensile properties. Different pulps, mildly beaten chemical (kraft) pulp, thermomechanical pulp (TMP) and a 50-50% mixture of the two were used to investigate the effect of fibre type. As expected, wet pressing pressure affected paper density and z-directional bond strength positively. The effect on density was similar in all of the three types of sheets, and the effect on bonding was greatest in the TMP sheets. At the same time, increasing drying stress affected density negatively only in the kraft sheets.

Bonding decreased to the largest extent in the TMP sheets. Tensile strength was increased by wet pressing pressure in kraft sheets and in the mixture sheets, but due to relatively high variation in the measurements, the differences were not statistically significant between most of the test points. Also drying stress affected tensile strength, especially in the kraft sheets: higher strain in the beginning of the drying lead to increased tensile strength. Wet pressing seemed to have an effect on the development of drying stress during drying. The pulp type and the level of the initial strain applied to the sheets prior to drying also had an influence on this development. The highest drying stresses were observed in sheets made of kraft pulp.

Activation was not affected by wet pressing of the TMP or mixture sheets, but it appeared that for kraft sheets, increasing wet pressing pressure resulted in improved activation. Chemical pulp fibres have properties that are favourable for activation, and it seems that wet pressing further develops network properties that are advantageous to activation: consolidation of the network increases the relative bonded area and number of bonds, which in turn leads to shorter free fibre segment length. This may make it easier for the drying stresses to be transferred through the fibre network. Larger bond areas also develop higher shrinkage forces which are then transmitted to the segments, activating them efficiently.

**ADDRESS OF THE AUTHORS:** Anna Vainio

(anna.vainio@tkk.fi) and Hannu Paulapuro  
(hannu.paulapuro@tkk.fi): Helsinki University of Technology, TKK, Laboratory of Paper and Printing Technology, P.O. Box 6300, FI-02015 TKK, Finland.

**Corresponding author:** Anna Vainio

In papermaking, wet pressing serves as a means to consolidate fibre network structure and to remove water from the paper web (Szikla 1992). Wet pressing forces the fibres into close contact and enables hydrogen bonding as water is removed from the structure and, hence, can be described as a process that contributes to the strengthening of the paper web by bringing the fibres and fibre cell walls into closer contact and by collapsing

(chemical pulp) fibres, thus promoting bonding potential (Pikulik et al. 1995, Paulapuro 2001). Wet pressing densifies the sheet structure, creates favourable conditions for interfibre bonding, and hence leads to increased density (Szikla 1992, Paulapuro 2001). The furnish type affects the relationship of wet pressing pressure and density quite a lot: if mechanical pulp is the dominant component of the furnish, density increases only a little with increasing wet pressing pressure whereas papers made of chemical pulps display an extensive increase in density (Szikla 1992). Wet pressing increases also the tensile strength of paper by improving bonding: fibres will have more contacts and the bonded areas are larger (Pikulik et al. 1995).

Interfibre bonding is essential to sheet strength. Bonds hold fibres together and therefore contribute to the internal cohesion of paper. In addition to mechanical properties, fibre bonds affect optical properties, electrical properties and dimensional properties of paper (Retulainen 1997). The structure of interfibre bonds is influenced by beating, pressing and drying. Other important factors affecting the bond structure include fibre morphology and the pulping procedure. Fines play a significant role in bonding (Retulainen et al. 1993). The mechanical properties of interfibre bonds and bonded fibre segments are closely related to the drying stresses that act across every interfibre bond (Retulainen et al. 1998). Bonding is affected by pulp properties such as the beating of kraft pulp, the amount of kraft pulp in a mixture, the characteristics of fines, and dry strength chemicals. Drying activates the fibre network, when lateral shrinkage of fibres is converted into axial shrinkage of the neighbouring fibres in bonded areas. If this shrinkage is restrained, the free fibre segments dry under stress and therefore their slackness is removed (Giertz and Rødland 1979, Lobben 1975). Thereafter, both the free segments and the bonded areas are capable of bearing load. Activation of the fibre network is mainly affected by the swelling potential of pulp fibres and the paper drying strategy. The mechanical properties of dried paper have been shown to correlate strongly with the final drying stress developed during restrained drying (Htun 1980).

The objective of this study was to examine the interaction of wet pressing and drying stress on the strength properties of paper and through these, the effect of wet pressing on bonding and activation in paper.

## Materials and Methods

The sheets used in this study were made from bleached kraft pulp (Finnish commercial kraft pulp made from Scotch pine (*Pinus sylvestris*)), bleached TMP (Finnish

commercial thermomechanical pulp made from Norway spruce (*Picea abies*) and a 50-50% mixture of the kraft (SR° 14) and TMP. The kraft pulp was disintegrated in a Valley hollander for 30 minutes and then beaten for 15 minutes (corresponding SR number 17), according to SCAN-C 25:76. The thermo-mechanical pulp (CSF 44) was hot disintegrated according to SCAN-M 10:7. 60 g/m<sup>2</sup> laboratory handsheets were made with a sheet mould producing 240x290 mm<sup>2</sup> test sheets. Apart from the size of the sheets produced, the mould and sheet forming complied with SCAN-C 26. The TMP and mixture sheets were made using circulation water.

Wet pressing was carried out with a MTS-810 material testing device (MTS Systems Corporation, Eden Prairie, MN, USA) with specially constructed pressing plates (Fig 1). The goal was to reach different wet pressing pressures while trying to keep the solids content of the sheets constant to minimise variation caused by differences in moisture content in the sheets prior to drying and straining (Fig 2). This was achieved by varying the number of dry blotters on each side of the sheet that was being pressed (Fig 3). Wet pressing pressures varied between 0.05 and 1.3 MPa and pressing time was 30 s. Due to the weight of the pressing plates, wet pressing had to be performed relatively slowly and no pressing impulses could be used. The solids content of the test sheets after wet pressing was quite low compared to that of an industrial wet pressing process. Furthermore, there was a small level of variation in the solids content of the test sheets, which may have affected the development of density and drying stresses to some extent. Since the pressing was done in quasi-static conditions and the dryness levels after the pressing were not as high as after an industrial wet pressing process, the experimental process of wet pressing could be termed densification or wet densification, but for the sake of simplicity, the term 'wet pressing' is used throughout this article.

Drying of the sheets was carried out with the PDR (Paper Drying Rheometer) device enabling biaxial straining, with 6x500 W halogen lamps for drying (see Vainio et al. 2006 for more information). First, the sheets were attached to the drying device and a preliminary straining was done to obtain a 'zero' stress level. Drying was then commenced immediately after this. In order to reach different drying stresses, the sheets were strained or allowed to relax directly after wet pressing: solids contents of the test sheets varied between 38-40% (kraft sheets); 30-36% (TMP sheets); and 28-34% (mixture sheets). Strain levels of -2%, 0% and +2%, on both of the in-plane directions of the test sheet, were used. The final, maximum drying stresses reached in the drying experiments were calculated afterwards from the sheet dimensional changes and loads of individual measuring sensors recorded with the PDR device during drying, by dividing the final maximum drying force by the cross-sectional area of the dried sheet. Sheet thickness was measured separately according to SCAN-P 7:75.

The dried sheets were conditioned (23°C, 50% RH) and tested for density (SCAN-P 7:75), tensile properties

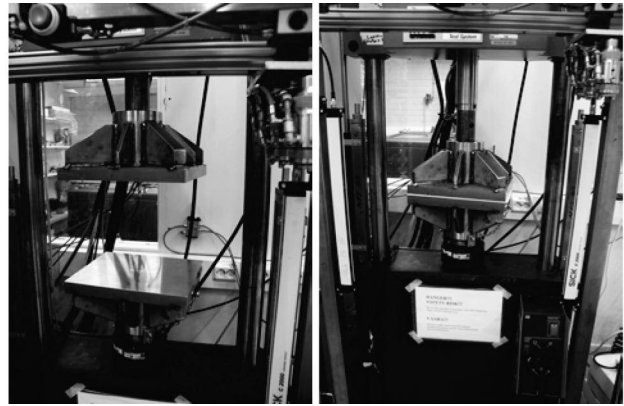


Fig 1. MTS-810 with the wet pressing plates attached.

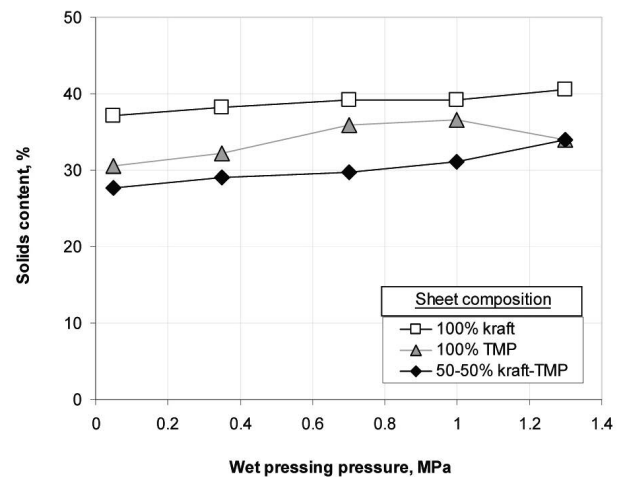


Fig 2. Development of sheet solids content as a function of wet pressing pressure.

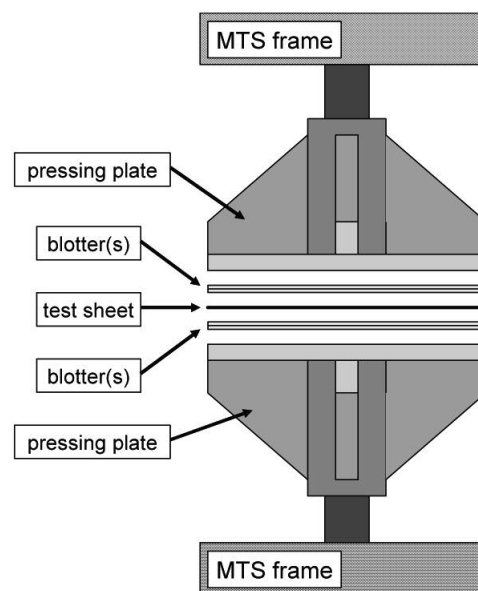


Fig 3. A schematic illustration of the pressing plate-test sheet arrangement.

(SCAN-P 38:80), bond strength (Scott bond strength, TAPPI T833) and in-plane tear strength, which was measured with an MTS 400 tensile tester according to the procedure described by Kettunen and Niskanen (2000a). Also damage analysis was carried out. It yields two parameters, damage width and pull-out width: damage width measures the extent of damage or fibre de-bonding from the actual crack line, and pull-out width describes the extending of fibre ends from the crack line (Kettunen and

Niskanen 2000b). Damage width indicates how far a fracture will progress perpendicular to the fracture line in a paper network, and its extent depends on bond strength and fibre strength in the fibre network. In these experiments, damage width was used to calculate a separate variable – in-plane tear index divided by damage width – which is assumed to represent the overall bonding (z-directional bond strength and in-plane directional shear strength of bonds), at least to a certain extent. Tensile stiffness or elastic modulus is used in the following as an indicator of the level of activation in the sheets.

## Results and Discussion

The increased density brought about by web consolidation could be observed in all of the test sheets of this study, independent of the furnish composition (Fig 4). The kraft sheets were prepared from chemical pulp beaten to some extent, and their density was the highest. Their structure is consolidated by fines, internal fibrillation and by the shrinkage potential and conformability of the fibres (Robinson 1980, Hiltunen 2003). In TMP sheets, density is affected by fines, too, but since the long fibres of mechanical pulp are relatively stiff and unconfortable (Tyrväinen 1995, Retulainen et al. 1998), density remains at a lower level. The fines fill network voids between fibres, and the higher the wet pressing pressure, the more efficient this packing becomes, reflected in increasing density, although it has been shown that the distribution of small particles does not change further during wet pressing (Szikla 1992, Pikulik et al. 1992). The sheets made of kraft-TMP mixture had the lowest density. Mixture sheets do not necessarily behave in an additive manner (Mohlin and Wennberg 1984). As a generalisation, it can be said that restricting the fibre network shrinkage during drying also leads to a less dense structure. In this study, this seemed to happen only with the conformable kraft pulp fibres that had the largest shrinkage potential (and, hence, were prone to become more activated and straightened during drying): the density of sheets dried under higher drying stress was considerably lower at 0.35-1.3 MPa wet pressing pressures.

As density increases with increasing wet pressing pressure, z-directional bond strength also increases (Fig 5). Density and bond strength have been connected in several studies (Retulainen and Ebeling 1993, Retulainen et al. 1998); improvements in bonding are caused by increasing relative bonded area and number of bonds. The effect was biggest in the TMP sheets that contained a high amount of fines to enhance bonding. The effect of drying stress on bond strength was also clearest in the TMP sheets – different strains at the beginning of drying lead to statistically significant differences between the test points. In the kraft sheets, increasing wet pressing pressure influenced bond strength only slightly. Also the effect of drying stress was considerably smaller than in the TMP sheets. In the mixture sheets, increasing wet pressing pressure hardly improved bonding at all.

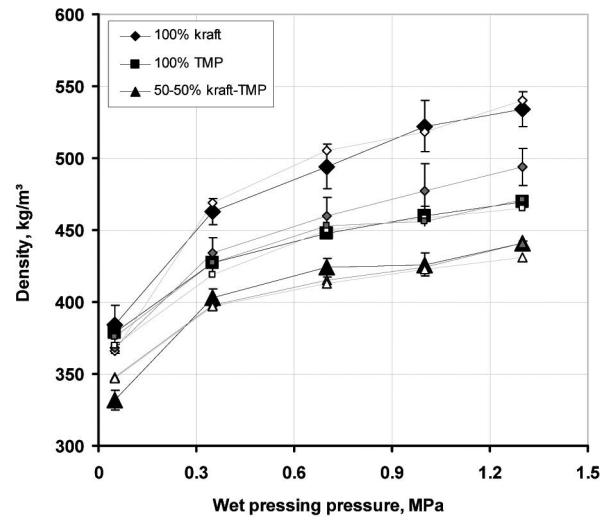


Fig 4. The development of apparent sheet density with increasing wet pressing pressure and drying stress. Black markers are for 0% strain before drying; open markers for -2%, and grey markers for +1% (this applies in Figs 5 and 6 as well).

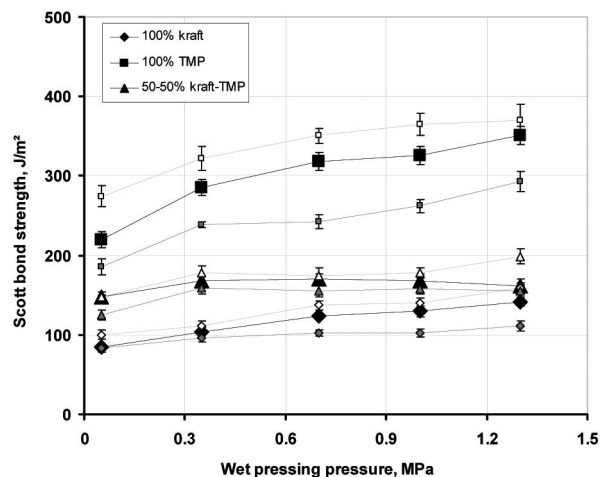


Fig 5. The development of bond strength (Scott bond strength) with increasing wet pressing pressure and drying stress.

In general, increasing wet pressing pressure affects tensile strength positively, mainly due to the improved bonding (Pikulik 1995, Retulainen 1997) resulting from consolidation of the network: increase in bonded area, number of bonds and bond strength. This could be seen especially clearly in the kraft sheets (Fig 6), where tensile strength increased almost linearly (up to a point, 0.75 MPa). However, the variation of tensile strength values was quite high. There were statistically significant differences only between test points at the lowest and highest wet pressing pressure; tensile strength increased about 15-20% from 0.05 MPa to 1.3 MPa independent of the strain level. Increasing drying stress had a positive effect on tensile strength. Also the TMP sheets and mixture sheets indicated this effect of drying stress, although there were no statistically significant differences. Wet pressing pressure influenced the tensile strength in these sheets as well, but the relationship was not linear, and the variation of strength measurements was quite large. The effect of wet pressing on tensile stiffness can be seen in Fig 7, and in the results discussed in the next paragraph in the context of activation.

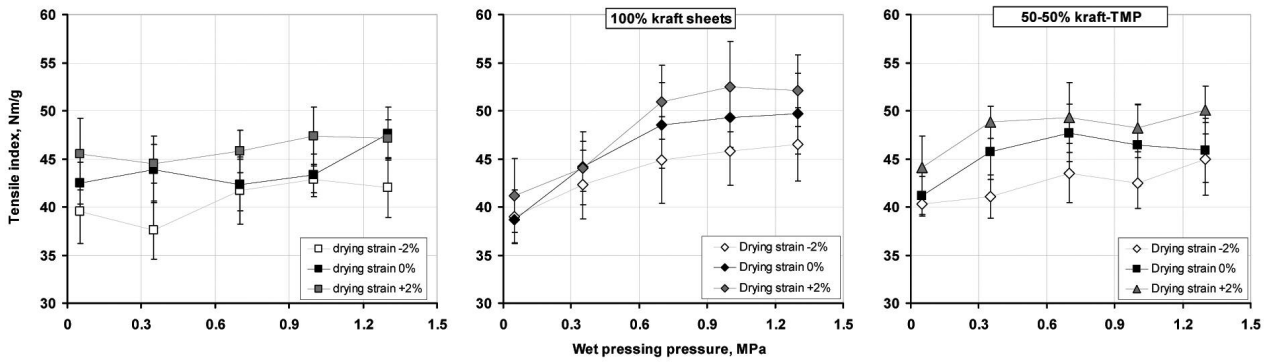


Fig 6. Tensile strength of the different test points.

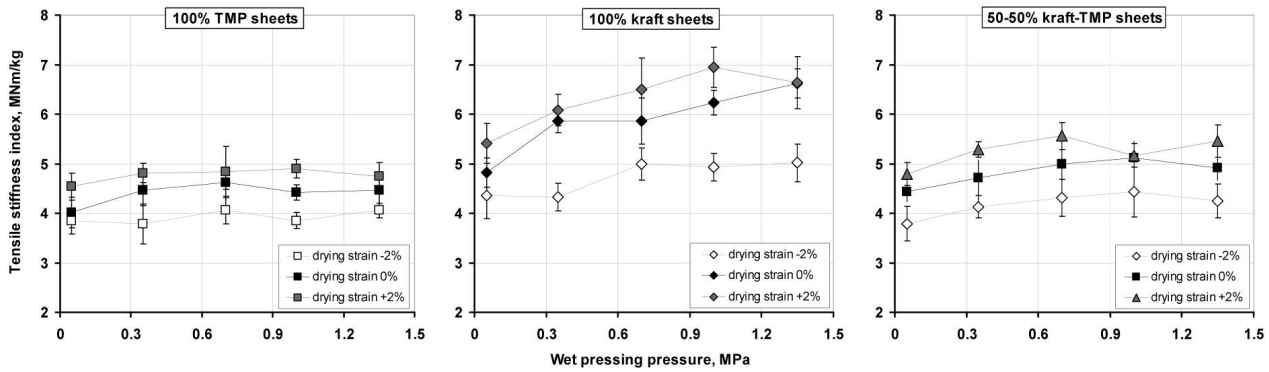


Fig 7. Tensile stiffness of the different test points.

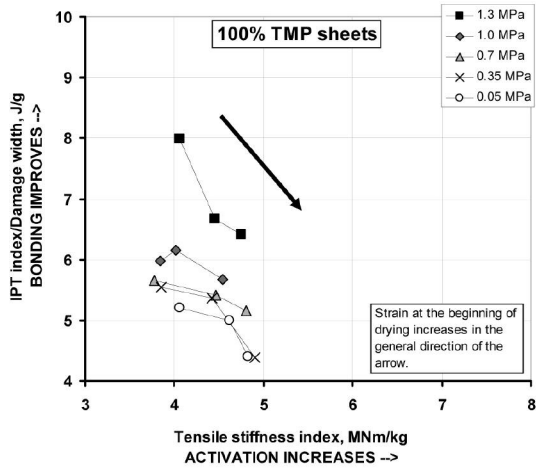


Fig 8. The relationship between bonding and activation in TMP sheets.

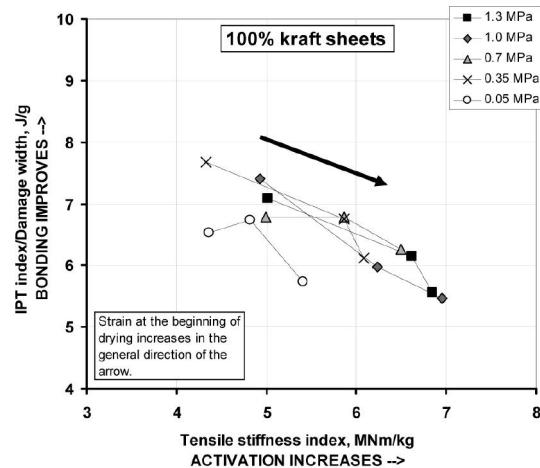


Fig 9. The relationship between bonding and activation in kraft sheets.

The relationship between bonding and activation in the test sheets is shown in Figs 8-10. The effects of wet pressing pressure and drying stress (strain at the beginning of drying) are also displayed. In the TMP sheets (Fig 8) higher wet pressing pressures lead to a clearly higher overall bonding. Especially the largest pressures increased bonding significantly. Activation, on the other hand, was not much affected. Wet pressing probably cannot influence the initially stiff, sticklike TMP long fibres favourably, as may be the case for the kraft sheets judging from their activation behaviour (Fig 9). As reported before (Vainio and Paulapuro 2005), increasing drying stress affected bonding negatively, and the higher the initial bonding potential (in this case brought about by wet pressing), the more extensive the decrease in bonding seemed to be. Activation increased

with increasing drying stress. Especially in the kraft sheets, this load-bearing capacity of fibre network was extensive (Fig 9). In the kraft sheets, or the mixture sheets (Fig 10), wet pressing did not play such a big role in improving bonding.

Wet pressing seems to have an effect on the development of drying stress during drying (Fig 11). Both the pulp type and the level of the initial strain subjected to the sheets prior to drying influence this development as well. The highest drying stresses were observed in sheets made of kraft sheets. As has been explained before, the properties of chemical pulp fibres (shrinkage potential, flexibility) are favourable to drying stress development – and activation (Giertz and Lobben 1967, Page 1989, Hiltunen et al. 1998). The effect of wet pressing is more difficult to explain, but it might arise

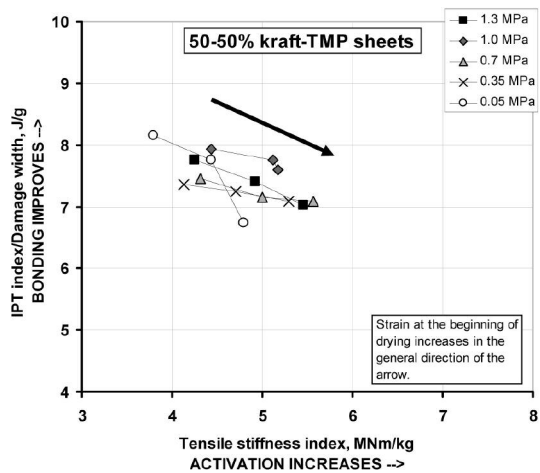


Fig 10. The relationship between bonding and activation in 50-50% kraft-TMP mixture sheets.

from the changes in bonding it brings about: larger bonded areas and an increase in the number of bonds may imply that the length of free fibre segments decreases. This way the drying stress that starts to develop at the bonded areas not only increases because there are more and larger bonds but also because the stress can be more easily transferred throughout the fibre network.

## Conclusions

Wet pressing pressure has significant effects on the strength properties of paper. Depending on the pulp type used in the test sheets, density and bonding increases: in TMP sheets, the presence of fines and their behaviour in wet pressing and, subsequently, drying increase bond strength significantly. Tensile strength is not much affected by wet pressing in TMP sheets, although one could expect the increase in bond strength to be reflected in tensile strength as well. In kraft sheets, the effect on density and bonding is not as extensive, but tensile strength behaves more or less linearly with increasing wet pressing pressure. The mixture sheets' behaviour is closer to that of kraft sheets in bonding, density and tensile strength development with increasing wet pressing pressure.

Wet pressing pressure seems to affect also activation of the fibre network in kraft sheets. Increasing wet pressing pressure lead to higher drying stress in all of the test sheets, but the effect was clearest in kraft sheets. Chemical pulp fibres have properties that are favourable for activation (high shrinkage potential, conformability), but it seems that wet pressing further develops network properties advantageous to activation: consolidation of the network leads to an increase in relative bonded area and number of bonds, which in turn leads to shorter free fibre segment length. This may make it easier for the drying stresses to be transferred through the fibre network. Larger bond areas also develop higher shrinkage forces which are then transmitted to the segments, activating them efficiently.

When comparing the effects of wet pressing and drying, the rather surprising conclusion in this work is

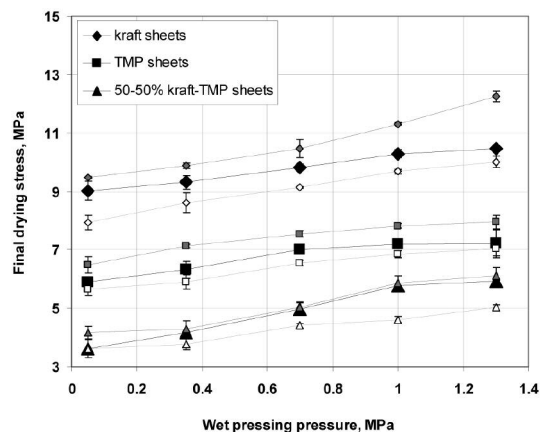


Fig 11. Final drying stress of the different test points. Black markers are for 0% strain before drying; open markers for -2%, and grey markers for +2%.

that the effect of both of the parameters on sheet density, z-directional strength (Scott bond strength) and tensile strength are of roughly the same magnitude. Commonly, the assumption is that, for example, density can be influenced mainly in the press section of a paper machine. The results of this study show some indication that the drying process may contribute to the development of density as well.

When assessing the results of this work, one should bear in mind that the wet pressing or sheet densification conditions used were far from ideal or usable for simulating an industrially realistic wet pressing process. The dynamic nature of the wet pressing can lead to non-uniform densification of the paper web in the z-direction. This could influence the development of mechanical properties of the sheets during drying. For future work, designing more industrially applicable wet pressing experiments would be essential.

## Acknowledgements

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