Vainio, A., Kangas, J. and Paulapuro, H. The role of TMP fines in interfibre bonding and fibre segment activation.


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The Role of TMP Fines in Interfibre Bonding and Fibre-Segment Activation

A. VAINIO, J. KANGAS and H. PAULAPURO

The effect of fines on interfibre bonding and fibre-segment activation was investigated with the help of drying experiments. Thermomechanical pulp (TMP) fines increase the tensile strength of the test sheets, independent of the amount of drying strain introduced into the sheets. When the sheets are strained more at the beginning of drying, tensile stiffness increases considerably. Increasing the amount of fines in the furnish leads to increasing tensile stiffness, or activation. One explanation is that fines are deposited near the bonded areas and their corners so that the lengths of free segments shorten, making the segments easier to activate. Fines have greater shrinkage potential, which leads to greater stress, forcing the free segments to straighten and activate during drying. As the amount of fines in the test sheets increases, bond strength increases significantly. No amount of fines together with long fibres can raise the level of bond strength to that of unfractionated TMP sheets.

Nous avons procédé à des essais de séchage afin d’analyser l’effet des fines sur la cohésion interfibres et l’activation des segments des fibres. Les fines de pâte thermomécanique (PTM) accroissent la résistance à la traction des feuilles d’essai, peu importe la contrainte de séchage appliquée aux feuilles. Lorsque les feuilles sont soumises à la contrainte au début du séchage, la résistance à la traction s’accroît considérablement. L’augmentation de la quantité de fines dans la composition de fabrication entraîne une plus grande résistance à la traction, ou activation. Une explication est que les fines sont déposées près des zones de cohésion et leurs coins, et la longueur des segments libres raccourcissent, ce qui rend les segments plus faciles à activer. Les fines rétrécissent plus facilement, ce qui entraîne une plus grande contraction et force les segments libres à se redresser et à s’activer pendant le séchage. À mesure que la quantité de fines dans les feuilles d’essai s’accroît, la cohésion interne des fibres s’accroît de façon importante. Aucune agglomération de fines avec les fibres longues ne peut atteindre le niveau de cohésion des fibres des feuilles de PTM non fractionnées.

INTRODUCTION

The mechanical properties of interfibre bonds and bonded fibre segments are related closely to the drying stresses that act across every interfibre bond [1]. 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 are removed of their slackness [2,3]. Once the segments are activated, the axial elastic modulus of fibres increases, which leads to a further increase in drying stress. Thereafter, both the free segments and the bonded areas are capable of bearing load. Activation of the fibre network is affected mainly by the swelling potential of pulp fibres and the paper-drying strategy.

In mechanical pulps, fines have a strong influence on the structure and properties of the fibre network. Their role in improving bonding and the mechanism in which they contribute to improving the z direction strength properties of paper have been recognized and explained quite extensively in the literature [4–8]. The primary effect of fines is an increase in density, which results in an increased number of interfibre bonds and improved tensile-strength properties of the sheet [4]. During the wet state of sheet formation, Campbell forces are increased by fines filling free spaces and expanding the volume of bound water between fibrils of neighbouring fibres [5]. Fines act as a bridge between fibres, contributing to the formation of a coherent paper network. In this way, the local stress concentrations, evolved in the network during straining, are reduced or evened out, which leads to more uniform stress distributions and improved strength properties [6]. The structural functions of fines have been divided into four separate roles, according to the type of fines [7]:

- Fibre fragments with an intact circumference and ray cells act as (short) fibres.
- Pieces of fibres (axially split fragments) fill small voids and gaps between fibres and form bridges in the fibre network.
Laminar fragments of the primary wall and ribbon-like fragments of the secondary wall act as a filling and form bonds between the fibres.

The same particles can also be deposited onto the fibre surfaces as a coating layer and, in that way, facilitate bonding.

According to Luukko and Paulapuro [8], flakes (fibre-wall fragments, thick lamellae and ray cells) do not contribute to bonding or form bonds of their own because of their non-conformability, stiff structure and compact shape, although they can increase sheet density slightly by filling and bridging the network. On the other hand, fibrils (ribbons, fibrils and thin lamellae particles), while also acting as filling and bridging agents, affect sheet density dramatically: thin and flexible particles do not block the network, but the increase in density is caused by the extensive formation of bonds. This results in high sheet strength and, at the same time, in a decreased light-scattering coefficient.

The structure of fibre bonds in chemical pulp fibre networks was studied by Nanko and Ohsawa [9], who found that an amorphous bonding layer is formed between two fibres. Skirt structures are elongated parts of the fibre-wall layers extending from bond edges, and covering layers consist of external fibrils and fines covering the edges of the bonds. The skirt and covering layer structures have an important role in strengthening the bond. The bonding layer is formed when external fibrils and secondary fines come close during dewatering and couching, and become pressed and packed between fibres. As the web dries, external fibrils and fine material form the bonding layer [9]. The structure of bonded areas in mechanical pulp fibre networks and their behaviour may be similar or comparable to this, at least to a certain extent.

The effect of fines on activation is not known equally well. However, the results of recent test series conducted at the Laboratory of Paper Technology of Helsinki University of Technology indicate that thermomechanical pulp (TMP) fines do have some sort of role in activation. The present work was designed to examine this role more closely with the help of drying experiments to draw some conclusions about the mechanism by which mechanical pulp fines influence activation and the strength properties of paper.

The aim of this work was to examine the effect of TMP fines on both interfibre bonding and fibre-segment activation. The main purpose was to find out whether fines really affect activation and to study the mechanism by which they contribute to improving it.

MATERIALS AND METHODS

Fractionation of TMP

The TMP used in the experiments was a commercial bleached TMP (made from Norway spruce, Picea abies). The pulp was sampled after the post-bleaching wash press from a Finnish pulp mill. The TMP was stored in a freezer and latency was removed by hot disintegrating the pulp according to SCAN-M 10:77 [10]. The freeness of the pulp was 44 ml Canadian Standard Freeness. The percentages of various fibre fractions are shown in Table 1. The fines and long-fibre fraction were separated with a Bauer McNett apparatus so that the R30 and R50 fractions were collected as long fibres and the P200 fraction as fines. The fractionation was done according to SCAN-M 6:69 [11] with some modifications: no filter papers were used but the fractions were collected into buckets. The two fractions were thickened by letting the fibres/fines settle and then removing the excess water. The sedimentation of long fibres took ~30 min and that of fines 48 h.

Test Sheet Preparation and Drying Experiments

To examine the effect of fines on paper-strength properties, various mixtures of long fibres and fines were used for sheet preparation. Five levels of fines were used: 0, 10, 20, 30 and 40% of the dry weight of the long-fibre fraction. In addition, reference sheets were made from unfractonated TMP. The 60 g/m2 sheets were made with two different sheet moulds, both utilizing circulation water. Sheets containing fines and those made from unfractonated TMP were made using a special sheet mould producing 240 x 290 mm sheets that could be fitted onto the paper drying rheometer (PDR) [12] drying device later. Sheets made from 100% long fibres were prepared with a standard sheet mould according to SCAN-M 5:76 [13], using gloss plates for restricted drying and propylene sheets to ensure free drying stress. All sheets were pressed for 4 min with 400 kPa pressure, after which the sheets containing fines were placed in plastic bags and stored in a cold storage room before drying. The sheet piles were turned at regular intervals to ensure an even moisture distribution within the pile.

Drying of the sheets was carried out with the PDR device, enabling biaxial straining, with 6 x 500 W halogen lamps for drying (see [12] for more information). First, the sheets were attached to the drying device and a preliminary straining was done to obtain a zero stress level. Then, drying was commenced. To reach various drying stresses, the sheets were strained at the solids content of ~30% immediately after wet pressing. 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 (Fig. 1) were calculated afterwards from the data showing the sheet-dimensional changes and the 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

![Fig. 1. Final drying stresses of the various test points. The strains used to stretch sheets made of unfractonated TMP can be seen next to the corresponding test points (crosses). CD = cross-machine direction; MD = machine direction.](image)

<table>
<thead>
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<th>Fraction</th>
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<tr>
<td>R30 - long fibres</td>
<td>17.3</td>
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<tr>
<td>R50 - long fibres</td>
<td>18.7</td>
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<tr>
<td>R100</td>
<td>18.3</td>
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<td>R200</td>
<td>18.6</td>
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<tr>
<td>P200 - fines</td>
<td>27.1</td>
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TABLE I

TMP FRACTIONS

<table>
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<tr>
<th>Fraction</th>
<th>%</th>
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thickness was measured separately according to SCAN-P 7:75 [14].

Sheets made from 100% long fibres could not be dried with the PDR device, since their wet strength was very low and they could not have withstood any kind of straining prior to or during drying. Gloss plates were used for restricted drying, corresponding roughly to 0% strain in the PDR device. Propylene films (Mili- lipore, Billerica, MA, USA, polypropylene prefilter, type 2.5 μm AN25) were used to enable the sheets to shrink completely freely during drying, corresponding up to a point to the negative strains of the PDR device. The fines-free sheets were dried in a conditioned room (23°C, 50% RH) for at least 24 h.

**Measurement of Paper Strength Properties**

The dried sheets were conditioned (23°C, 50% RH). Formation was measured with an Ambertec, β-formation meter (Ambertec, Espoo, Finland). The sheets were tested for density (SCAN-P 7:75), tensile properties (SCAN-P 38:80) [15], bond strength (Scott bond strength, TAPPI T 833) [16] and in-plane tear strength, which was measured with an MTS (MTS Systems Corp., Eden Prairie, MN, USA) 400 tensile tester according to the procedure described in [17]. Damage analysis was also carried out. It produces two parameters, damage width and pull-out width, of which damage width was used in this study. Damage width measures the extent of damage or fibre debonding from the actual crack line [18]. It indicates how far a fracture will progress in a paper network, and its extent depends on the bond strength and fibre strength of the fibre network.

Certain assumptions were made when assessing the results of this study. The tensile strength of paper is assumed to reflect both bonding and activation. Tensile stiffness or elastic modulus is an indicator of the level of activation in the sheets [19]. Scott bond strength represents the z direction bond strength. A calculated variable (in-plane tear index divided by damage width) is assumed to combine these two aspects of bonding, at least to a certain extent. It has been used previously to shed light on bonding in paper [20,21].

**RESULTS AND DISCUSSION**

The TMP fines increased the tensile strength of the test sheets up to a fines content of 30%, independent of the amount of drying strain introduced into the sheets (Fig. 2). With 20–40% fines in the furnish, the sheets’ tensile index reached almost the level of the sheets made from unfractonated TMP, at least in the sheets that were strained +2% before drying. The difference in tensile strength between the three drying modes was quite small, although a slight increase was seen as the drying stress increases. The tensile properties of paper were improved generally by increased drying stress. Especially the elastic modulus was affected favourably [22,23]. Since drying stress affects bonding negatively and at the same time leads to increased activation, the overall effect of drying stress on tensile strength should be min-
imal. However, in these sheets, tensile strength did increase slightly with increasing drying stress, which might mean that bonding did not deteriorate too much, while activation increased during wet straining of the sheets. The fines content seemed to affect tensile strength more than drying stress. This suggests that TMP fines have a positive effect on both bonding and activation.

As for the tensile stiffness index, which reflects activation, the increases in fines content and drying stress clearly increased it (Fig. 3). When the sheets were strained more at the beginning of the drying procedure, tensile stiffness increased considerably. The positive effect of drying stress on tensile stiffness/activation has been recognized in earlier studies (e.g., Htun [24]), who reported that the straightening of initially slack fibre segments leads to an increase in the elastic modulus of the paper web. Tensile stiffness values five times the original can be reached with increasing strain [25]. Increasing the amount of fines in the furnish also leads to increased tensile stiffness and activation. Tensile stiffness increased linearly up to a fines content of 20%, after which the effect levels off.

One possible explanation for the mechanism in which fines affect activation is presented in Fig. 4. Fines are deposited in the fibre network near the bonded areas and their corners in such a way that the effective length of free segments shortens, making them easier to activate. The characteristics of fines may also explain their working mechanism: mechanical fines influence the way in which moisture is removed from the fibre network, affect the structure of the bonded area and even out local stress concentrations in the network [5]. The increase in final drying stress with increasing amount of fines can be seen in Fig. 1. Fines have a greater shrinkage potential, which leads to greater stress, forcing the free segments to straighten and activate during drying. A similar explanation was provided by Sirviö et al. [26]. Furthermore, fines affect sheet consolidation positively [1,27]: densification of sheet structure arises from an increase in the number of bonds, which could also result in the shortening of free fibre segments, making them more prone to activation.

As the amount of fines increased in the test sheets, Scott bond strength increased significantly, displaying a linear increment (Fig. 5). However, no amount of fines together with long fibres can raise Scott bond values to the level of bond strength in unfractonated TMP sheets, in which the Scott bond values are 2-3 times higher than for any of the long fibre-fines sheets.

Drying stress affected bond strength slightly negatively. Increased stress reduced the bonded area and even broke up bonds in the sheet (reflected as decreasing sheet density). Similar results have been published by Wahlström et al. [23]. However, the decrease in Scott bond strength was not very drastic, and the presence of fines seemed to affect the behaviour of the bonded areas within the paper network, resulting in a structure able to resist the negative influence of straining prior to drying. This effect could arise from the changes in bond structure and changes in water removal from the bonded area during drying.

Based on the results, bonding clearly requires factors other than only fines to be efficient. The z direction strength/delamination resistance especially is evidently also controlled by other factors, such as external fibrillation of the fibres, smaller fibre material (fibrils, pieces of fibres) and flexibility of fibres [4,8,9]. As suggested in Fig. 4 for long fibres-fines sheets, the fines are situated around the bonded area (near the corners and edges) rather than between the fibres inside the actual bond zone, probably because the middle fraction that would normally capture the fines is lacking. Therefore, fines alone cannot act as a glue-like material between two neighbouring fibres to strengthen the bond. Even if there were fines between the fibres in the bond zone, the fines material alone would not be as good in improving bond strength as it would be together with the other smaller particles (not present in the furnishes these test sheets were made from). In other words, a bonding system consisting of fibre-fines-fibre is easier to break than a system of fibre-(fines + fibrils)-fibre. The importance of small, fibril-like particles was recognized in [8].

The improvement of bond strength brought about by fines can also be witnessed as decreasing damage-width values, as the fines content of the sheets increases (Fig. 6). At lower bond strengths, the fracture process breaks up bonds and the fracture can proceed further into the fibre network. As the bond strength increases, the energy used by the fracture process changes gradually from bond breakage into fibre failure, as strong bonds are able to withstand more energy. Hence, the fracture process halts earlier without proceeding further into the network [28]. This change can also be seen in the relationship between Scott bond values and

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**Fig. 5.** Scott bond strength of test sheets.

**Fig. 6.** Damage width of the test sheets.
in-plane tear (IPT) index/damage-width values (Fig. 7). The relationship is linear at relatively low fines contents, i.e., the energy used by the fracture process is linearly proportional to bond strength but, as the bond strength increases, fracture energy is used up in phenomena other than bond breakage. Again, it can be noted that drying stress does not seem to play a major role for bond strength as long as fines are present to help the fibre network withstand the negative effects introduced into the sheets by wet straining.

The relationship between bonding and activation can be observed in Fig. 8. Ideally, one would expect a fairly linear relationship between the two characteristics: with increasing drying stress, activation increases and bonding deteriorates, and the extent of the change depends on the shrinkage potential of fibres and the network (activation) and initial bonding potential of the fibres (bonding). In these sheets, however, the relationship is different. In the sheets made from unfractionated TMP, bonding does deteriorate somewhat with increasing drying stress, but activation is not improved at all. The test sheets still contain a lot of water, which may be situated especially in the fines and fibrils concentrated in and around the bonded areas. During straining, neighbouring fibres are able to slide over each other, because the bonds have not yet reached a sufficiently dry, solid structure and are therefore able to yield to the strain. This could be a factor that inhibits activation from taking place during wet straining and the initial stages of drying.

In the sheets made from various mixtures of long fibres and fines, the relationship is drastically different. First, activation increases significantly as drying stress caused by wet straining increases. Also, the increase in fines content clearly contributes to activation. Furthermore, the more fines the sheets contain, the higher the level of activation seems to be (dashed lines in Fig. 8). On the other hand, bonding does not deteriorate with increasing drying stress and the more fines the sheets contain, the better the overall bonding gets (light arrows in Fig. 8). This would also seem to suggest that the fines are situated in the fibre network so that they contribute to bonding but do not necessarily affect moisture removal. The bond areas become solid finished structures quite early during drying, which enables drying stress to be transmitted through the network, activating free segments but not destroying bond areas irreversibly.

CONCLUSIONS

The tensile properties of the test sheets, tensile strength and tensile stiffness, are improved by increased drying stress. However, an increment in fines content affects tensile strength more than drying stress does, and the effect of fines on tensile stiffness, or activation, is considerable. Based on the results of this test series, an explanation of the mechanism in which fines influence activation is put forward: fines are situated near the corners of the bonded areas rather than inside the bonding zone between two fibres. In this way, the effective length of the free, unbonded fibre segments shortens, making them easier to activate. Fines also have greater shrinkage potential, which during drying increases the stress caused by shrinking bond areas that is then transmitted to the axis of the fibres, pulling the free segments straight.

Fines also have a favourable effect on the bonding properties of paper, although neither Scott bond strength nor elastic breaking strain values of the test sheets reach those of the sheets made from unfractionated TMP. Drying stress decreases bond strength, but its effect is less drastic in the sheets made from various combinations of long fibres and fines. The presence of fines seems to affect the behaviour of the bonded areas so that the fibre network is able to resist the negative influence of drying stress on bonding. The changes in bond structure and in water removal brought about by fines may be the reason behind this. However, bonding requires other factors than just fines to be efficient.

The results of this test series suggest that, during sheet consolidation and wet pressing, the fines become situated in the fibre network so that they can contribute to bonding up to a point, but do not necessarily affect the way moisture is removed from the bonded areas. Quite early in the drying process, the bond structures become solid enough to enable the drying stress to be transmitted through the network, activating free segments. At the same
time, the bonded areas are able to yield to the stress, preventing the bonds from breaking.

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REFERENCES