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INTERFIBER BONDING AND FIBER SEGMENT ACTIVATION IN PAPER

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Bonding and activation in paper were studied with the help of laboratory test sheets and common paper strength tests. Different papermaking furnishes and raw material treatments were used to examine the effects they have on bonding and activation. Furthermore, various boundary conditions during drying were included to single out the influence of bonding and activation on paper properties. It was found that bonding is clearly increased by beating of kraft pulp, starch addition, and thermomechanical pulp fines, whereas activation benefited most from beating and addition of reinforcement fibers to mechanical pulp based furnishes. Subjecting test sheets to increasing amounts of drying stress affected activation positively, and bonding negatively. The increase in activation did not seem to be dependent on the beating degree of chemical pulp fibers. Bonding, on the other hand, deteriorated more significantly in sheets made of extensively beaten kraft fibers, i.e. in sheets where the initial bonding potential was higher. Commonly used paper strength measurements provide dependable and accurate tools for assessing the effect of different variables on both bonding and activation. A short literature survey of bonding and activation is also provided.

Keywords: Bonding, Activation, Paper strength properties, Fines, Beating, Drying, Drying stress

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INTRODUCTION

Traditionally, the mechanical properties of paper, i.e. the strength of fiber networks, has been thought to arise from interfiber bonding – the strength of individual bonds and all the bonds within the network – and from the (axial) strength of individual papermaking fibers (Robinson 1980; Stratton 1991). More recently, the behavior of fibers in the paper network during the papermaking process has been added to this relationship (Niskanen 1993; Kettunen 2000; Tanaka *et al.* 2001a; Hiltunen 2003). The area of bonds and the strength of the bonds are important factors influencing the mechanical properties for most of the paper grades (Retulainen 1997). Bonding affects the structure of paper – both the development of structure and the final structure of the paper web.

Fiber segment activation is not a new idea; it was first put forward by Giertz (1964), and the idea of an increment in load-bearing capacity of fibers taking place in the network, of something happening to the unbonded lengths of fibers, during processing can be found in several sources (van den Akker *et al.* 1966; Lobben 1975 and 1976; Giertz and Rødland 1979; Niskanen 1993; Retulainen 1997; Wahlström 1999; Hiltunen 2003; Wathen 2006).

Interfiber Bonding

Interfiber bonding is essential to sheet strength, which, according to Stratton (1991), is a function of two factors, the strength of an individual fiber and the strength of the

interfiber bonds. An interfiber bond can be defined as the zone where two fibers are so close to each others that chemical bonding, van der Waals' interaction, or molecular entanglement can occur (Retulainen *et al.* 1998). Bonds hold fibers together and therefore contribute to the internal cohesion of paper. In addition to mechanical properties, fiber bonds affect optical properties, electrical properties, and dimensional properties of paper (Retulainen 1997).

Formation of interfiber bonds begins as solid content increases during the papermaking process. At first, bonding happens through surface tension forces pulling fibers together when water is removed. This mechanism of fiber bonding was first explained in detail by Campbell (1959), and it is known as the *Campbell Effect*. The Campbell effect changes gradually to other types of bonding, so the solids content at which actual interfiber bonding starts to happen is not known exactly. An estimate for the start of bonding can be derived from the elastic modulus of paper during drying: the change in the modulus must happen because of bond formation since wet fibers have higher rigidity than wet bonds (otherwise the fibers would disintegrate into the solution). In kraft pulp, the elastic modulus starts to increase significantly at 50 % solids content (Retulainen *et al.* 1998).

During drying, pulp fibers shrink laterally, which causes shear stresses in the bond area, because of the discrepancy between the tendency for lateral and longitudinal shrinkage of fibers. The amount of shrinkage depends on the swelling degree of the wet fiber wall, which in turn is affected by internal fibrillation and chemical composition of the fiber wall. Shrinkage forces are largest at the peripheral area of the bond, and when the system is loaded, bond edges will take the load first. Shrinkage stresses generate axial compressive forces on the crossing fibers and may cause deformations in bonded fiber segments (microcompressions) in freely dried sheets. Stresses at bond area and fiber walls, as well as the microcompressions, modify the mechanical properties of the bonded segments, so that the properties of bonded fibers will differ from those of freely dried fibers. Mechanical properties of fibers in a network are therefore related to interfiber bonds (Retulainen 1997; Retulainen *et al.* 1998).

The structure of interfiber bonds is influenced by beating, pressing and drying. Other important factors affecting bond structure include fiber morphology, pulping procedure, beating equipment and the mode of drying (free versus restrained). The final structure of a fiber-fiber bond of two chemical pulp fibers is a combination of S1-S1, S1-S2 or S2-S2 layers. Flexible fibers can form wrap-around type of bonds and fibrils, and fines form bridges between fibers. On a microscopic scale, fibrils also form entanglements (Uesaka 1984). The structure of fiber bonds between chemical pulp fibers was studied by Nanko and Ohsawa (1989), who presented the following structural features in their work: an amorphous bonding layer is formed between the S1 layer of two beaten fibers by external fibrils, and probably polymer chains as well. The more beaten the fibers are, the thicker the bonding layer and the better the contact between two fibers will be, partly because of the increased amount of fines. According to Nanko and Ohsawa (1989), the skirt is an elongated part of the S1 layer extending from bond edges, and the covering layer consists of external fibrils and fines covering smooth edges.

Fiber Segment Activation

Activation is one of the relevant properties of fibers within a network. It means that originally kinky, curly or otherwise deformed fiber segments, unable to carry load in the

network, can be modified into active components of the network (Fig. 1). Activation of the fiber network occurs during drying, when lateral shrinkage of fibers is transmitted to axial shrinkage of the neighboring fibers at bonded areas. If this shrinkage is restrained, the free fiber segments dry under stress and are therefore removed of their slackness (Giertz and Rødland 1979; Lobben 1975). Once the segments are activated the axial elastic modulus of fibers increases, which leads to further increment of the drying stress and both the segments and bonded areas are capable of bearing load. Interfiber bonding and shrinkage of fibers are prerequisites for activation. The amount of drying stress needed to activate free segments depends on the morphology of the fibers (Retulainen 1997).

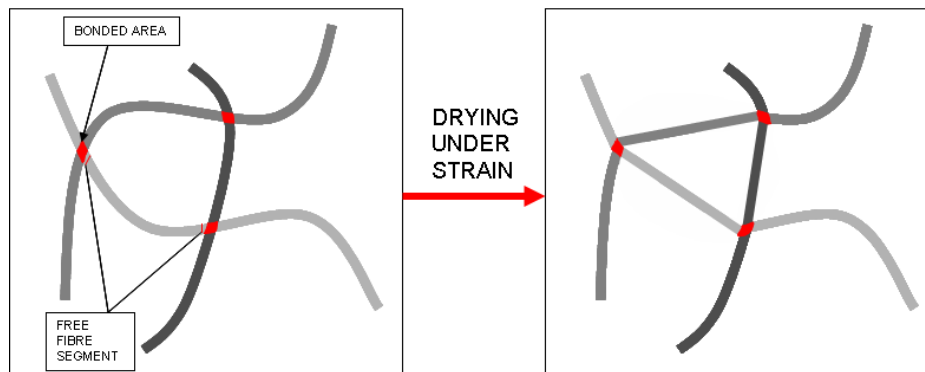


Fig. 1. A schematic illustration of activation.

During restrained drying of handsheets, the lateral shrinkage tendency of fibers is converted to axial compression of bonded fibers. Activation in bonded segments evens out larger stress concentrations at the fiber interfaces and inside the fiber wall by rearranging the lamellae and fibrils. The whole fiber is capable of bearing load more evenly. Activation of the free segments not only makes the segment straighter and fibrils more capable of bearing load, but it also may increase the order of cellulose and hemicelluloses inside the fibrils and decrease the fibril angle (Retulainen 1997).

Activation takes place during drying, and as drying shrinkage is restricted, and the fiber network is unable to contract and shrink, the level of activation becomes higher (Retulainen 1997; Tanaka *et al.* 2001). Straightening of initially slack free fiber segments leads to an increase in the elastic modulus of paper (Htun 1980). The tensile properties of paper are generally improved by increasing drying stress; especially the elastic modulus is favorably affected (Htun and de Ruvo 1978; Wahlström *et al.* 2000; Zhang *et al.* 2001). Tensile stiffness values five times the original have been reached with increasing strains (Wahlström 1999).

Activation can be improved by maximizing the bonded area and total fiber length. Pulp with low coarseness and large fiber width are favorable for both chemical and mechanical pulp. Strength of the blend can be improved by beating chemical pulp, which increases fiber flexibility and therefore bonded area can be increased. Beating increases also the number of bonds and the number of free segments and decreases the length of the free segments (Lobben 1976). The amount of fines in mechanical pulp should be high enough to tolerate reduction of fines-fiber ratio without reaching the limiting state (a function of sheet density and amount of chemical pulp fibers). The activity of chemical

pulp fibers can be improved by using pulp that has smaller fracture elongation and fewer micro-compressions and kinks in fibers.

Factors Affecting Bonding and Activation

Unbeaten fibers cannot form strong paper, at least if not mixed with other pulps. The concept of fiber bonding, ever since the beginning of papermaking history, is related to development of strength properties (Page 1989). Beating clearly promotes interfiber bonding, but has also other effects on the fiber network, for example, the effect of beating on fiber flexibility affects subsequent fiber segment activation during drying. Contact between fibers increases, and the surface of fibers changes physically. In addition to increasing RBA, refining increases bond strength (Retulainen 1997). According to Robinson (1980), the most significant effect of beating is the increment of flexibility through delamination, swelling, and dislocation within individual fibers. This permits adjacent wall segments and fibers to mould and conform to one another during pressing and drying (Robinson 1980; Retulainen 1997). Beating has been found to increase activation (Giertz and Lobben 1967; Page 1989; Hiltunen *et al.* 1998; Hiltunen 2003). Fiber swelling and increase in elastic modulus of fibers increases paper strength through the Jentzen effect, i.e., the primary strength-enhancing effect of beating comes from enhanced bonding in the wet web, which is then put to effect by drying stresses (Niskanen 1998).

Commonly, the fines fraction is defined as the fraction of pulp that passes the 200 Bauer-McNett mesh (Hiltunen 1999). The properties of fines differ considerably from the properties of the fiber fraction. The particle size is small and surface area large, which means that fines are able to bind more water and hence swell more than fibers (chemical pulp fines swell more than mechanical, since mechanical pulp fines contain more extractives and hydrophobic lignin). In mechanical pulps, the fines content has a strong influence on the structure and properties of the fiber network (Retulainen 1997; Retulainen *et al.* 1998). The primary effect of fines on the paper network is an increase in density, which results in an increased number of bonds and in that way, improves tensile strength properties of the sheet. During the wet state of sheet formation, Campbell forces are increased by fines filling free spaces and extending the volume of bound water between fibrils of neighboring fibers. Fines can also behave as loosely bonded filler material, creating new light scattering surfaces and open structures (Luukko 1999). This effect seems to be valid for mechanical pulp fines, which contain both fibrillar and flake-like material, but not for chemical pulp fines. They contain mostly fibrillar material, which have such a high bonding ability that light-scattering coefficient is not improved (Luukko and Paulapuro 1999). Fines act as a bridge between fibers, thus contributing to coherent paper network formation. 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 (Luukko 1998).

Additives that affect interfiber bonding positively are high molecular weight, hydrophilic colloids, either natural or synthetic, such as starch, proteins, vegetable gums and water-soluble resins (particularly polymers of acrylamide) (Robinson 1980; Ketola and Andersson 1999). They act by adsorption onto fiber surfaces, where fiber-to-binder-to-fiber bonds can evolve and contribute to bond and sheet strength. Addition of dry strength chemicals (e.g. starch, carboxymethyl cellulose,) is an ideal way of improving interfiber bonding and tensile strength of paper: they cause no increment in

sheet density or deterioration of light scattering coefficient. The strengthening ability of starch is related to the degree of substitution in starch, and it is not very effective if fibers are stiff and the bonded area small to begin with (Retulainen 1997). The increment in tensile strength with starch addition is largely due to improved specific bond strength and increased stiffness of bonded areas. The rupture process of interfiber bonds is also affected by starch addition: it does not seem to change the starting point of the rupture (stress or strain at which rupture starts is not increased), but the rate of bond ruptures is decreased considerably. For example, Lindström *et al.* (2005) and Hubbe (2006) have written extensive reviews on the relationship between dry strength chemicals and bonding.

The mechanical properties of bonds and bonded fiber segments are closely coupled by the drying stresses that act across every interfiber bond (Retulainen *et al.* 1998). During drying, the shrinkage of component fibers causes contraction of the whole fiber network and creates internal stresses in the paper. Fiber shrinkage influences various properties of paper, such as sheet structure, mechanical properties, and hygroscopic behavior (Nanko *et al.* 1991). Drying of previously undried virgin pulp fibers under axial tension increases considerably the tensile strength and decreases the breaking strain. Laboratory experiments have even shown that an 8 % increase in strain from -4 % (shrinkage) to +4 % (stretch) can yield a tensile stiffness five times the original (Wahlström 1999).

Drying and wet straining during drying affect fiber strength. Jentzen (1964) studied the effect of free drying and drying under load on the properties of individual fibers. Drying under axial tension can considerably increase the tensile strength and decrease breaking strain of single fibers. According to Jentzen (1964), the changes in mechanical properties are brought about by two factors: an increase in crystallite orientation and, secondly, by a more even distribution of stress within the fiber (among fibrils). An increase in crystalline orientation, taking place due to drying under load, leads to increasing tensile strength and Young's modulus (also, the ultimate fiber elongation decreases). Drying under load also induces a redistribution of stress within the fiber.

Objectives

The objective of this work was to examine interfiber bonding and fiber segment activation as basic phenomena with the help of laboratory scale analyses: how different papermaking processes affect bonding and activation, and in turn, how bonding and activation relate to the end properties of paper, especially to different mechanical properties. Investigating the effect of drying and drying stress and their usefulness in examining bonding and activation was our special interest. At first, only two different drying modes were used (preliminary test series): free drying, where the test sheets were allowed to shrink freely during drying, and restricted drying where drying shrinkage was completely inhibited. Later on, a special drying frame construction (the Paper Drying Rheometer, PDR) enabling biaxial straining of test sheets was used to introduce different levels of drying stresses to the sheets at the beginning of drying.

Furthermore, the objective was to use common, widely used paper strength tests and analyses, and to study how well these can be used in examining bonding and activation. The goal was to establish testing procedures that would be comprehensive enough to yield feasible information on the phenomena, but at the same time, keep the testing so simple that it could be performed without very laborious or difficult analyses, with the equipment available for most paper mills and research facilities.

EXPERIMENTAL

Materials

ECF bleached TMP [Finnish commercial thermomechanical pulp made from Norway spruce (*Picea abies*)] was used in the experiments. The pulp was collected from the mill post-bleaching wash press before latency removal, and stored in a freezer. Before sheet forming, the TMP was hot-disintegrated according to SCAN-M 10:7. Freeness of the pulp, 44 ml CSF, was measured according to SCAN-C 21:65. For examining the effect of fines on TMP based paper properties, the mechanical pulp was fractionated, and the long fiber and middle fractions separated with a Bauer-McNett apparatus so that the R30 and R50 fractions were collected, and the R100, R200 and P200 fraction discarded. The fractionation was done according to SCAN-M 6:69 with some modifications: no filter papers were used but the fractions to be used were collected into buckets.

The chemical pulp used in these experiments was bleached kraft pulp [Finnish commercial kraft pulp made from Scotch pine (*Pinus sylvestris*)]. The pulp was disintegrated and beaten in a Valley beater according to SCAN-C 25:76. In this work, four different beating levels were used: SR° 14, 17, 22 and 34, as well as an unbeaten pulp (SR° 12).

The cationic starch used in the experiments was commercial potato starch from Kemira Oyj, and it was added to the furnish prior to sheet forming. Four different addition levels were used for both 100% kraft pulp and 100% TMP pulp sheets: 0, 2, 5 and 10%. The starch was adsorbed onto fibers that had been first washed into sodium form (Swerin and Wågberg 1994). The consistency in the adsorption experiments was 5 g/L, ionic strength 0.5 mM NaHCO₃ and reaction time under magnetic stirring 30 min.

Methods

The laboratory sheets were formed with a semi-automatic sheet mould, producing 165 mm x 165 mm handsheets, according to the standard SCAN-C 26. White water filtrate was circulated in order to balance the amount of fines, when sheets containing TMP were made. For those test series in which the sheets were dried with the PDR device, a different sheet mould, producing 240 mm x 290 mm laboratory sheets, was used. Apart from the size of the sheets produced, the mould and sheet forming complied with SCAN-C 26.

The laboratory sheets were wet pressed right after sheet forming and couching, according to the standard SCAN-C 26:27. Ordinary 165 mm x 165 mm laboratory sheets formed with the normal sheet mould were then dried; it was necessary to obtain different levels of drying stress with the help of a simple method. Gloss plates (squares the size of laboratory handsheets, cut from thin, laminated board) were used to restrict the shrinkage of test sheets during drying. This would correspond roughly to 0% strain. Propylene films (Millipore polypropylene prefilter, type 2.5 µm AN25) were used to allow the sheets to shrink completely freely during drying, corresponding up to a point with the negative strains of the PDR device. These sheets were dried in a conditioned room (23°C, 50 % RH) for at least 24 hours. Apart for using the propylene films in free drying, these methods of drying comply with the standard SCAN-C 26:27. The larger sheets, bound to PDR drying, were stored in a cold storage room after wet pressing prior to drying. These sheets were wrapped in double plastic bags, stacked and turned regularly to ensure even moisture distribution within the stacks.

PDR is a construction with 6-7 separate clamps for each side of the paper sample (Fig. 2). Each clamp is connected to high-precision sensor that measure position and force throughout the experiment. The drying procedure is controlled with a computer, and the measurements from the sensors are recorded on-line with special computer software. The PDR device utilizes both hydraulic and pneumatic drives for moving beams onto which the clamp-sensor constructions are attached. By controlling the beam movement, the paper sample can be for example subjected to different controlled strains during drying. Drying is achieved by six 500 W halogen lamps.

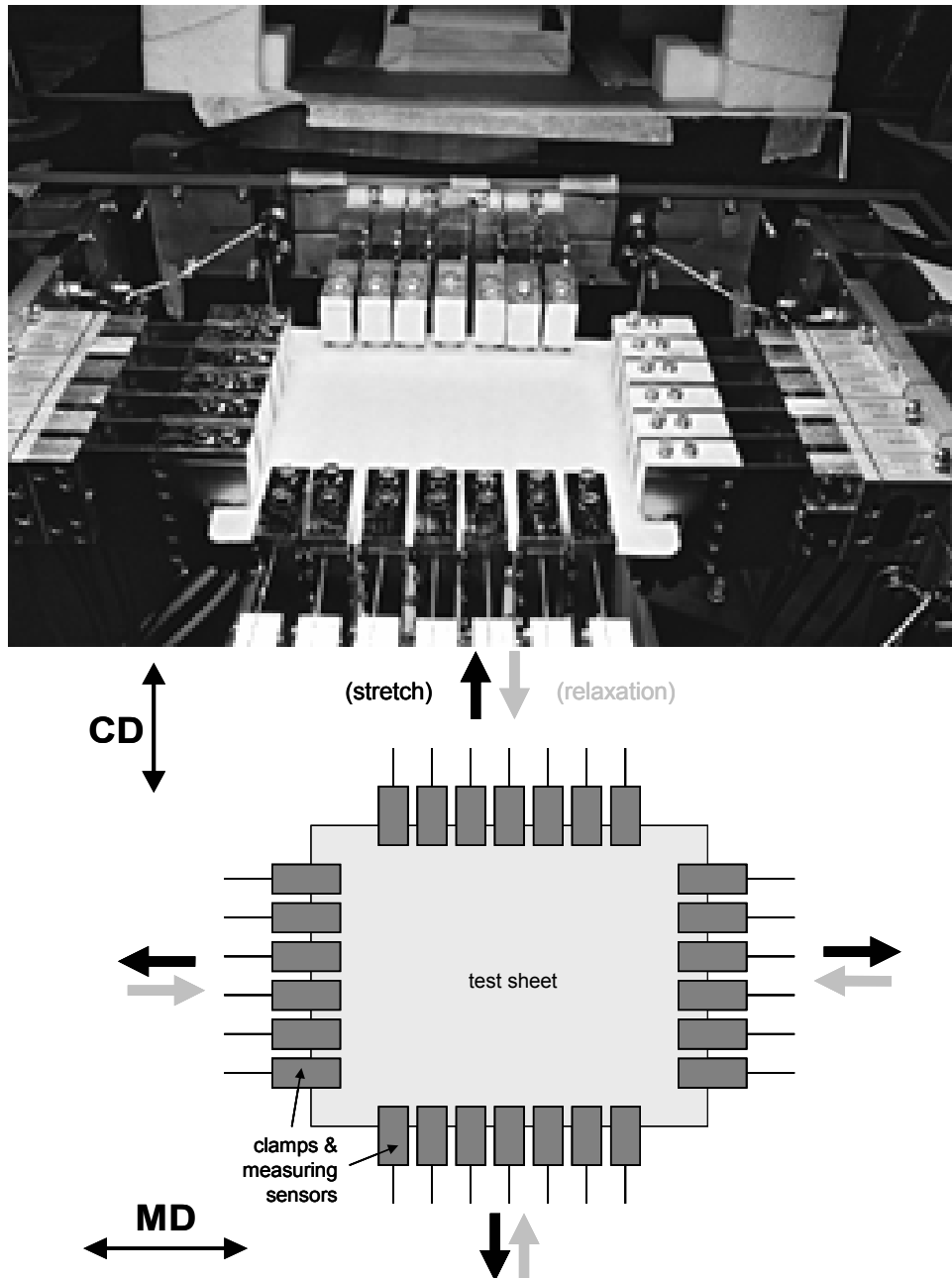


Fig. 2. Above: Paper Drying Rheometer (PDR) with an attached test sheet (right), and **Below:** A schematic illustration of the PDR test setup.

In the test series of this work, the idea was to achieve different levels of drying stress by straining the sheets before drying. The sheets were strained immediately after wet pressing at approximately 30% solids. 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 straight after this. Strain levels between -2 (negative strain, i.e. the sheets were let to relax) and +2% on both of the in-plane directions (MD and CD) of the test sheet, were used. The principle of PDR drying and straining of test sheets can be seen in Fig. 2. Unfortunately, the actual final (maximum) drying stresses could not be examined due to unexpected data losses on the PDR measuring system. Based on the results of other similar drying experiments performed with the PDR, it can be said with confidence that the different strains will produce statistically significantly different drying stress levels.

The dried sheets were conditioned (23°C, 50 % RH) and tested for tensile properties, bond strength (Scott bond strength and elastic breaking strain) and in-plane tear strength, which was measured with MTS 400 tensile tester according to the procedure described by Kettunen and Niskanen (2000a). Also damage analysis was carried out. It produces two parameters, damage width and pull-out width: damage width measures the extent of damage or fiber de-bonding from the actual crack line, and pull-out width describes the extending of fiber ends from the crack line (Kettunen and Niskanen 2000b). Certain assumptions were made when assessing the results of this study. Tensile stiffness or elastic modulus is an indicator of the level of activation in the sheets. Scott bond strength represents the z-directional bond strength, whereas elastic breaking strain, calculated from tensile index divided by tensile stiffness index, gives an indication of bonding in the in-plane direction. 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. Damage width indicates how far a fracture will progress perpendicular to the fracture line in a paper network, and its extent depends of bond strength and fiber strength in the fiber network.

RESULTS AND DISCUSSION

Using Paper Strength Properties to Examine Bonding and Activation

During this work, cause-effect relationships between the different paper properties and bonding/activation were closely investigated. Tables 1 and 2 were designed for examining the relationships between different strength properties and bonding and activation. These tables can be utilized in clarifying the effects of for example drying, beating or different fiber surface treatments on bonding and activation. Different strength property pairs and combinations, such as in-plane tear strength and damage width or tensile strength and density, can be then used to examine the effect of different variables on bonding and activation. The tables, when correctly modified, are applicable to all possible variations of processes (beating, wet pressing, drying) and raw materials (pulp type, amount of fines, additives, fiber surface treatments). In Table 1, activation is divided into two different categories: in one, activation is increased through increasing fiber swelling and in the other, by increased straining during drying. In Table 2, interfiber bonding is divided into two categories, in which bonding is thought to be increased either by dry strength additives or by fines. Activation is thought to be affected mainly by drying stress.

Table 1. Chemical Pulp Paper Properties and Bonding/Activation

<i>Property</i>	<i>Interfiber bonding</i> conventional dry strength additives	<i>Fiber segment activation</i>	
		fiber swelling (e.g. low-intensity beating)	drying stress
Density	0	++	0
Tensile strength	++	++	++
Elastic modulus	0 or +	++(+)	+++
Elastic breaking strain	++	+	--
Z-directional strength	+++	++	--
In-plane tear strength	+ or -	+ or -	--
Damage width	--	--	--

Table 2. Mechanical pulp paper properties and Bonding/Activation

<i>Property</i>	<i>Interfiber bonding</i>		<i>Fiber segment activation</i>
	conventional dry strength additives	TMP fines	drying stress
Density	0	++	0
Tensile strength	+	++	+(+)
Elastic modulus	0	++	++
Elastic breaking strain	0	++	-(-)
Z-directional strength	++	+++	--
In-plane tear strength	-	++	--
Damage width	-	-	+

Key for both tables: + positive correlation, - negative and 0 no significant effect, the amount of signs indicates the strength of the correlation).

Results from Preliminary Test Series

Adding starch to the TMP or kraft furnish prior to sheet forming did not affect tensile stiffness, as could be expected, since tensile stiffness or elastic modulus largely depends on the axial strength of fibers (or fiber segments in the network). These are governed by beating, wet pressing and the properties of the pulp mixture components. Drying stresses influence the elastic modulus as well (the elastic modulus increases if drying shrinkage is limited) (Niskanen and Kärenlampi 1998). In other words, activation of fiber segments influences the elastic modulus. This can be seen in Fig. 3: tensile stiffness of the restrictedly dried sheets were significantly higher than that of the freely dried sheets. Restricting the drying shrinkage resulted in significantly higher tensile stiffness values than what was observed in the freely dried sheets.

The effect of beating on activation in 100 % kraft sheets can be seen in Fig. 3. Beating increased tensile stiffness significantly, although the most significant changes seemed to take place already with quite small beating intensity increment. Beating clearly promoted interfiber bonding (Fig. 4, right), but had also other effects on the fiber network, for example, the effect of beating on fiber flexibility affected subsequent fiber segment activation during drying. As can be seen in Fig. 3, increasing the drying stress by restricted drying led to higher tensile stiffness – and activation in the kraft test sheets. Again, starch addition had no effect on tensile stiffness/activation.

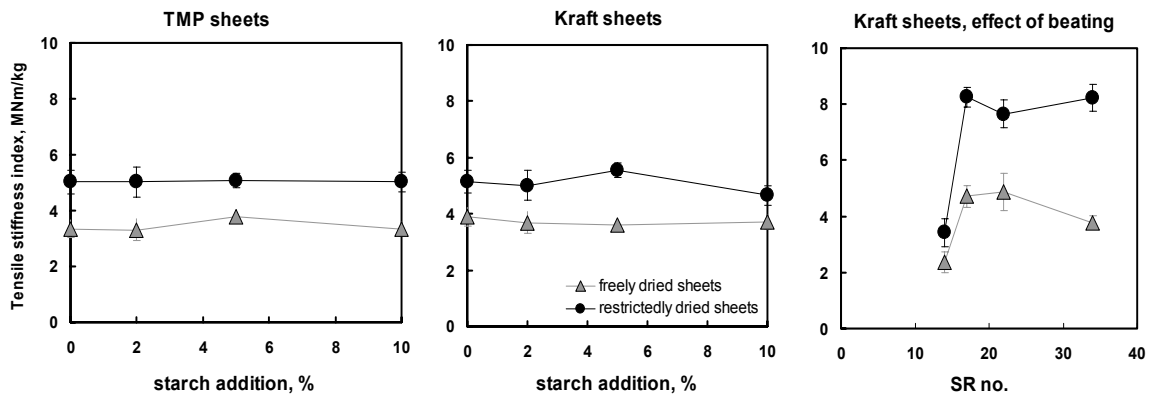


Fig. 3. Effect of starch addition and kraft pulp beating on activation in TMP and kraft sheets

Starch addition and beating increased the bond strength of kraft hand sheets (Fig. 4), although here as well, the increment seems to have been most significant already at a relatively low increase in beating intensity (from SR°14 to SR°17), and with the lowest starch addition (2%). There were no differences between the two drying modes in the differently beaten kraft handsheets, but in the starch-treated handsheets there were statistically significant differences between freely and restrictedly dried sheets, suggesting that the mechanism in which these two treatments affect bonding and bond strength is different. According to Retulainen (1997), the increment in tensile strength with starch addition is largely due to improved specific bond strength and increased stiffness of bonded areas. Starch affects bond strength directly by increasing the actual strength of bonds, whereas beating increases both bond strength and the bonded area in the fiber network. Drying stress decreases bonding in starch-treated sheets. Beating, on the other hand, affects fiber swelling, flexibility, conformability and bonding potential of chemical pulp fibers by creating external fibrillation and secondary fines (Robinson 1980; Page 1989; Niskanen 1998; Hiltunen 2003). External fibrillation increases the strength of interfiber bonds and enhances sheet consolidation (Retulainen *et al.* 1998). It provides a mechanism by which cellulosic surfaces can attain the close contact, without which the formation of hydrogen bonds would not take place. Beating not only increases the specific bond strength, but also the area of bonds.

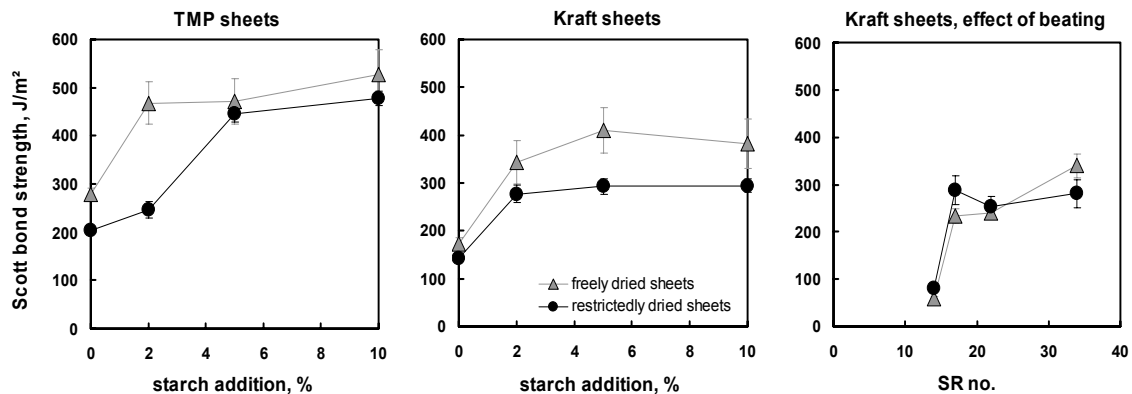


Fig. 4. Effect of starch addition and beating of kraft pulp on bonding in TMP and kraft sheets.

Figure 5 depicts the relationship between tensile stiffness index and a calculated variable in-plane tear index/damage width, and also the relationship of bonding and activation. In the kraft sheets (Fig. 5, left), beating seems to have affected both bonding and activation, whereas starch addition influenced only bonding. The effect of starch addition on bonding and activation in TMP sheets was either non-existent (restrictedly dried sheets) or ambiguous (freely dried sheets) (Fig. 5, right). On the other hand, removal of fines decreased both bonding and activation. The role of fines in bonding is widely recognized. But contrary to previous beliefs, their role in activation seems to be quite important as well. The role of fines in the development of activation in mechanical pulp sheets appears quite vital. Originally, the TMP fines were thought to affect only bonding. TMP fines and their influence on activation have been discussed in more detail by Vainio *et al.* (2007).

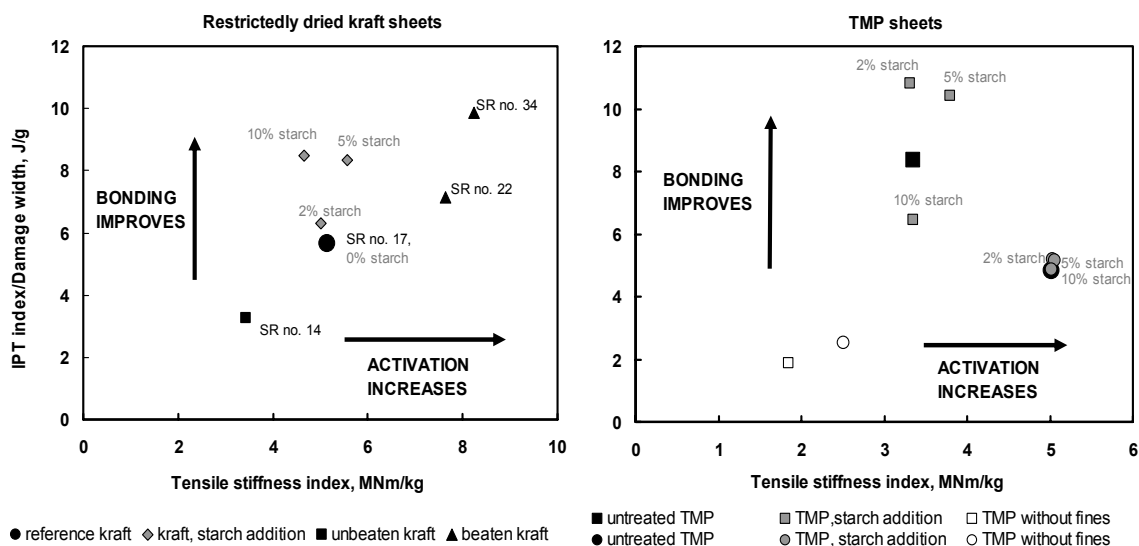


Fig. 5. Bonding and activation in restrictedly dried kraft sheets and TMP sheets. For TMP sheets, square markers represent freely dried sheets and round markers restrictedly dried sheets; open markers represent TMP without fines and black markers normal, unfractionated, untreated TMP; gray markers are for TMP sheets treated with starch.

Results from PDR Test Series

Fiber segment activation (or elastic modulus of dry paper) is affected by fiber properties, but the strategy used for drying the paper network plays a significant role for the development of activation (Htun 1980, Zhang *et al.* 2001). In most sheets, activation increases linearly with increasing drying stress. During wet straining of paper, fiber segments become permanently elongated, and if the straining of paper is relatively small, i.e., not extensive enough to cause network failure, initially unloaded, non-bonded fiber segments become activated as the segment lengths stretch and bonded areas around them rupture (Niskanen 1993).

The tensile properties of sheets made of 100% kraft were generally improved with increasing drying stress (Fig. 6), although tensile strength increased only slightly. Tensile stiffness was affected very positively. All three beating levels seemed to behave quite similarly; the increase in tensile strength or tensile stiffness was almost the same in all to the three different beating levels. The initial level of tensile strength/stiffness was naturally

higher the higher the beating degree of the kraft pulp was. Beating did not seem to have much influence on the improvement in activation (Fig. 6, right), although the fibers should have different swelling properties due to their different beating levels. The results confirm deductions made on the effect of drying on paper properties: tensile stiffness index, understood here to reflect activation, increases with drying strain. When initially slack, free fiber segments straighten during drying under strain, and the elastic modulus of paper web increases (Htun 1980, Wahlström 1999). Tensile strength is thought to reflect both activation and bonding, and therefore the overall effect of drying stress on tensile strength is not very extensive.

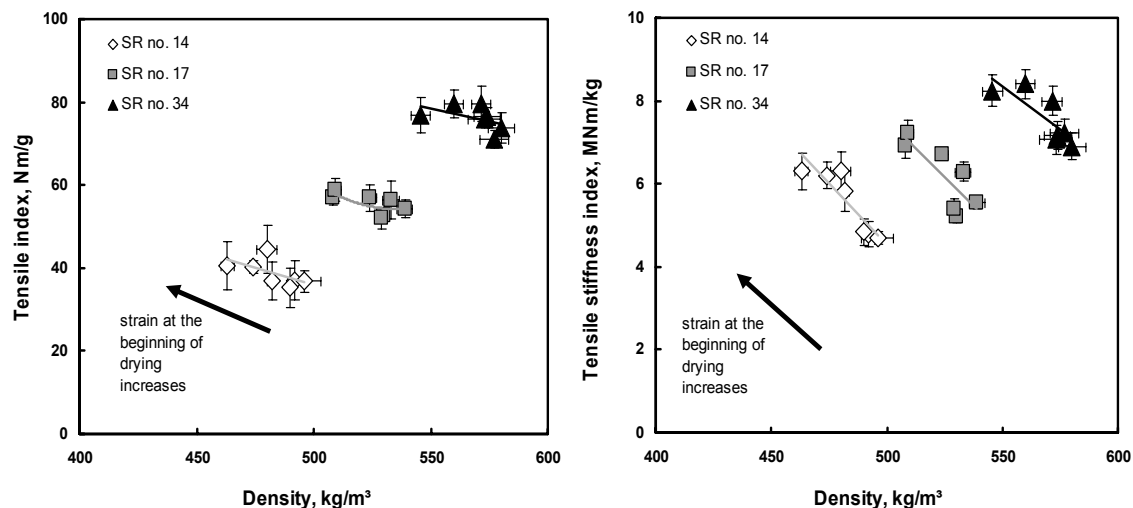


Fig. 6. The effect of drying stress on the in-plane strength properties of handsheets.

Z-directional bond strength decreased with increasing drying stress (Fig. 7, left). The decrease was most drastic in sheets made from highly beaten pulp, probably because the initial ‘capacity’ for bonding was higher than in the sheets made from less beaten kraft pulp. Beating creates fines material and external fibrillation and increases fiber flexibility, which all promote bond strength and increase the bonded area (Page 1989; Robinson 1980). A similar negative effect can be in elastic breaking strain values of the test sheets: also the in-plane directional bond strength decreased with increasing drying stress (Fig. 7, right). Here, the degree of beating did not seem to influence the extent of deterioration. Increased drying stress reduces the bonded area and can also break up bonds in the network (reflected as decreasing sheet density). Similar results have been published by Wahlström *et al.* (2000). When paper is strained or elongated, as was done in this test series prior to drying with the PDR device, microscopic failures and even smaller scale ruptures take place in the network. These failures affect not only the internal structure of paper but also fiber-to-fiber bond structures and hydrogen bonds, which deteriorate either gradually or are destroyed altogether (Niskanen 1993).

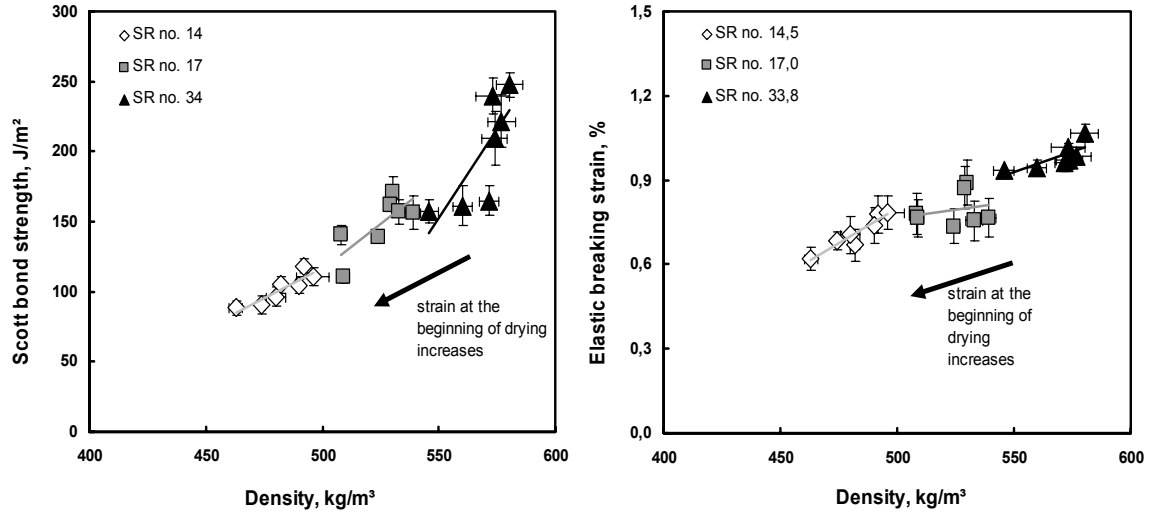


Fig. 7. The effect of drying stress on the bonding properties of handsheets.

Examining the relationship between bonding and activation in the test sheets (Fig. 8), it can be seen quite clearly that the overall bonding was affected negatively by increasing drying stress, although the extent of the decrease in bonding depended quite strongly on the degree of treatment that the kraft has been subjected to in beating. In the sheets made of very gently beaten kraft pulp, bonding almost stayed at a level independent of the drying stress, whereas in the sheets made of more beaten pulp, the effect was much more drastic. Activation, and its development with increasing drying stress, did not seem to depend on the beating level.

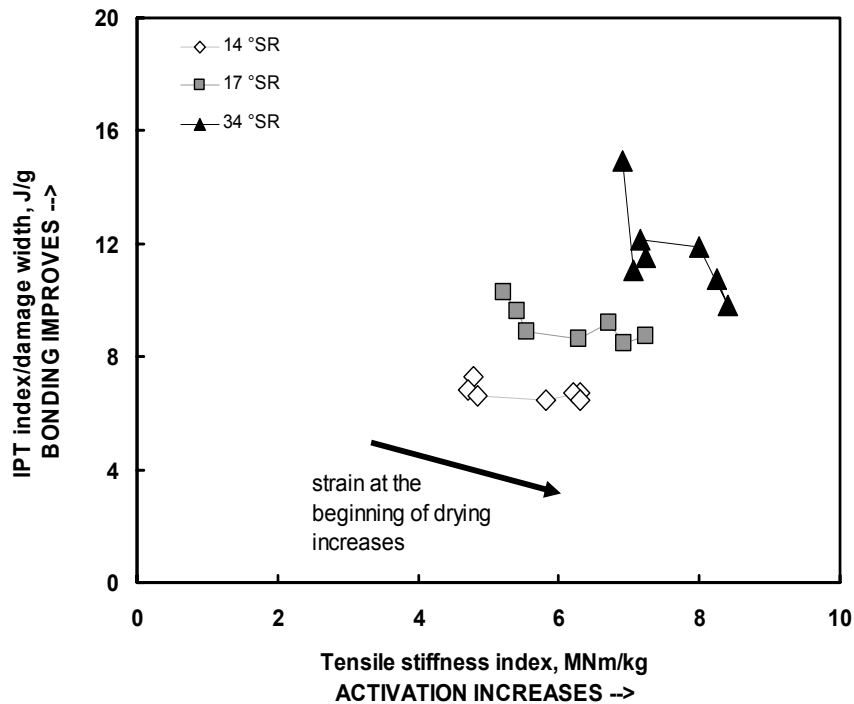


Fig. 8. Bonding and activation in handsheets made of differently beaten kraft pulp.

CONCLUSIONS

1. Bonding and activation in paper can be well described with different strength properties and their combinations (Tables 1 and 2). The relationships between bonding and activation and different paper properties in kraft sheets are quite well understood; for example, beating and dry strength chemicals improve bonding. In TMP sheets, the cause-effect relationships seem to behave somewhat differently than in kraft sheets, and require further investigation to be fully understood.
2. Straining of test sheets before or during drying has a clear effect on both in-plane and z-directional strength properties: in general, activation of network increases by straining and bonding deteriorates with increasing straining.
3. Bonding is strongly affected by variables such as beating, furnish components and strength additives. For bonding, there are clear differences between different beating levels and sheet behavior in drying. Bonding potential develops during beating and refining, and those processes also have a significant influence on the structure and strength of bonds, which in turn seem to affect how bonds and bonding in general develops during drying.
4. Activation is affected by pulp properties (chemical vs. mechanical fibers; beating of chemical fibers) to some extent, but the role of drying strategy is significant. Activation is increased by beating, independent of the actual beating intensity, which could suggest that drying and drying stresses are more significant than fiber properties in the development of activation.
5. Furthermore, TMP fines seem to have some sort of role in activation, not only in bonding. The mechanism in which fines affect activation cannot be clarified with the results of this work.

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