Effects of fiber deformations on pulp sheet properties and fiber strength

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Keywords:
softwood, kraft pulping, reinforcement, strength properties, fiber strength, fiber deformation

ABSTRACT

Intact fibers were deformed by homogenization after beating. The homogenization increased the amounts of deformations (kinks and curl) in the fibers. The fibers retained their highly swollen nature during the deformation. The influence of the fiber deformations on the strength properties of the softwood kraft pulp fiber network was significant. The fiber deformations decreased fiber segment activation in the fiber network compared to undeformed fibers. The decreased fiber segment activation resulted in decreased tensile and tensile stiffness indices but in increased tear and fracture toughness indices of the pulp sheets. The results also indicated that the zero-span fiber strength measurement was not dependent on fiber curl and kinks, but is likely dependent on the load distribution uniformity of the 3-dimensional fiber wall structure.

TIIVISTELMÄ

Ehjiä kuituja deformoitiin homogenoimalla jauhatuksen jälkeen. Homogenointi lisäsi deformaatioiden määrää kuiduissa (kinkkejä ja kiharuutta). Kuitujen korkea turvonneisuus säilyi deformoinnissa. Kuitujen deformaatioiden vaikutus havupuusulfaattiselluloosan kuituverkoston ominaisuuksiin oli huomattava. Kuitudeformaatiot alensivat kuitusegmenttien aktivoitumista kuituverkostossa verrattuna deformoimattomiin kuituihin. Alentunut kuitusegmenttien aktivoituminen kuituverkostossa johti massa-arkkien alentuneisiin vetolujuus- ja vetojäykkyysarvoihin, mutta samalla kasvaneisiin repäisylujuus- ja murtositkeysarvoihin. Tulokset viittaavat myös siihen, että zero-span kuidun lujuusmittaus ei ole riippuvainen kuitujen kiharuudesta tai kinkkien lukumäärästä, vaan todennäköisimmin kuorman jakautumisen tasaisuudesta kuituseinämän 3-dimensionaalisessa rakenteessa.

INTRODUCTION

Fiber strength and undamaged fibers are highly valued in the production of reinforcement pulp, which is used to improve the runnability of the paper web on the paper machine and in the following converting processes. The strength delivery and fiber damage studies have been motivated by the fact that the strength potential of softwood kraft pulps is not usually attained in full mill-scale processes /1-8/. On the other hand, it is not even clear what strength property correlates with web runnability as discussed widely by Niskanen /9/and Uesaka /10/. Actually it seem that the desired paper properties vary in different converting operations.

The strength delivery for softwoods from industrial fiber line is reported to be 60-75% compared to the pulp produced in the laboratory from the same raw material /4-8/. Carrying out the right measurements from the pulp to find out which properties of the pulps are changed during pulp production are of great importance. It is also essential to understand which pulp sheet properties are affected by single fiber properties and which are also influenced by network properties. It is important to notice that one of the single fiber properties as also its' ability to form desired fiber networks. These considerations are essential when one needs to draw conclusions concerning the pulp quality.

The relation between fiber deformations and fiber network strength loss in the industrial cooking systems and along the fiber line has been reported by many researchers /11-16/. Pulp and fiber defects are defined by various types of deformations e.g. fiber curl, kinks and dislocations. These deformations can appear in the cell wall of a wood fiber. Fiber deformations can arise in the tree as a result of growth stresses, or they can be induced in numerous ways during processing, for example in chipping, fiberization or medium consistency unit operations /17, 18/. The fiber deformations are considered usually undesired and should be avoided when possible.

The most typical way of presenting fiber curl is the curl index given by Jordan and Page as the relationship between the fiber contour length and the ‘longest dimension’. Longest dimension is the distance between those points within the fiber which are furthest apart /19/. Dislocations are a deformation type, which consists of microcompressions and misaligned zones /20, 21, 22/. Page /13/ et.al. described microcompressions as a region where the alignment of the microfibrils is locally disturbed and according to Hartler /23/ they are developed by subjecting fiber structure to a compressive strain above the elastic limit, where local failure will result and a microcompression will develop. The dislocated fiber wall has been proposed to be changed so that the microfibrils are turned within a very small volume with the simultaneous breaking of hydrogen bonds. In such regions there has been proposed to be higher accessibility of the cellulose in subsequent chemical reactions /21/. Savolainen /6/ has suggested that dislocated regions in the fibers enhance polysaccharide degradation by enhanced diffusion of harmful radicals into fiber wall segements, which eventually leads to decreased fiber strength. A feature of somewhat larger magnitude compared to dislocation is the node or crimp. A node is essentially a region of compressive failure, with a highly localized compressive strain, often associated with delamination of the cell wall, Page /24/. Nodes were shown by Forgacs /25/ to be prefentially sited adjacent to ray crossings, presumable because of the tendency for the bends to originate there during defibering /19/. Under some circumstances, fibers will develop kinks at these nodes, so that the direction of the fiber axis changes abruptly at this point /26/.

Fiber curliness affects mostly the tensile strength and the bonding ability of fibers in a fiber network. The high fiber curl e.g. according to Page /19/ affects the tensile index so that a sheet formed with curled fibers has low tensile index but can have high tear strength. This has been explained by uneven distribution of stress along the length of a curled fiber in a fracture zone, curly fibers transferring therefore larger stresses to the bonds, which in breaking consume greater energy /27/. The curly fibers tend to form a sheet that has a lower elastic modulus and higher stretch than a sheet made of straight fibers /28/.

The low tensile index of curled fibers has been also explained with low fiber segment activation /29/. The concept of activation was suggested by Giertz /30/, according to him, fiber in the dried sheets can be divided into two zones: compressed, bonded fiber segments, and more or less strained, unbonded fiber segments. The activation is used as a synonym for tightening of the unbonded fiber segments during sheet drying.

The fiber curl, in absence of other effects, raises bulk and porosity of the pulp sheet. The curliness of the fibers reduces the drainage resistance of pulps, which is seen as higher CSF values as the fibers become curlier /19/. The curly fibred pulp is reported to dewater further under given pressure and vapour is lost easier on drying /19, 31/.

According to Page /28/ and Kibblewhite /26/ the pulp sheets containing straight fibers have low extensibility both as wet web and in dry state. The greater degree of fiber curl also results in more scattering of reflected light, resulting in a matte appearance and slightly higher brightness and opacity /31/.

The effect of fiber kinks has been reported to affect the wet strength of the pulp. The more kinked the fibers are the higher the wet rupture energy. It is suggested that chlorine-caustic and chlorine dioxide bleaching causes kinks present to bleached fibers. On the other hand, fiber kinking is unaffected by pulp drying stresses /16/.

In a dislocated part of the cell wall the alignment of the microfibrills are locally disturbed /19/. A fiber with no dislocations is extremely stiff. A small number of dislocations suffice to reduce the stiffness remarkably. Some delamination occurs in the dislocated regions, which at least partly explains the decrease in the tensile stiffness. As a fiber containing dislocations bends it forms a polygon rather than a continuous curve /21, 22/. Like curl, the presence of dislocations lowers the elastic modulus of the sheet /28/. They can become weak sites of the fibers, which reduces the breaking strength of the individual fibers and the average fiber length /21, 22, 32/. As a result the strength properties of the pulp, folding endurance and bursting strength in particular decrease /22/. It is also suggested that the increase in dislocations increases tear strength and stretch. Moreover dislocations decrease bonding strength by creating discontinuities that are points of bond failure in stressed fibre networks /33/.

Most of fiber deformations, curl, kinks and dislocations vanish during beating of the pulp. This is recognized by e.g. Kibblewhite /33/, Mohlin /34/, Seth /14/, so that the strength properties return to the level of undeformed pulp. Mohlin /34/ defined the terms irreversible damage and reversible deformation. Reversible deformation can be removed by PFI beating, where the main effect is the straightening of the fibers. Mohlin /35/ also suggested that the irreversible damage could be defined as the difference in zero-span tensile index between an undamaged and damaged fibre when both are straight and it could come mainly from chemical degradation during pulping, but it is possible that it also includes mechanical damage.

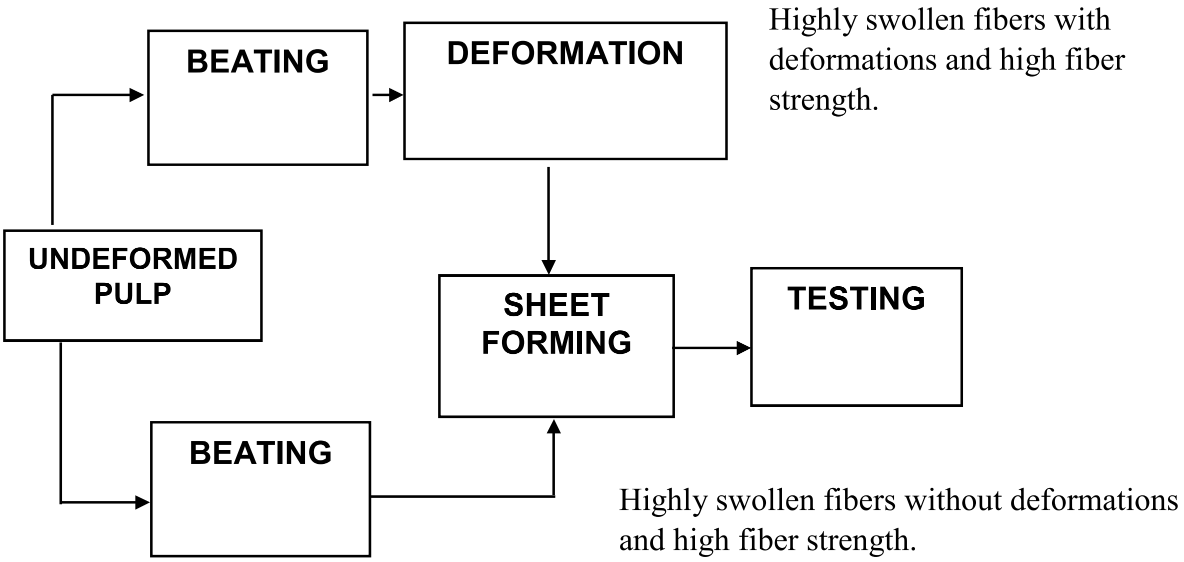
The effect of beating on the increase of fiber swelling has been attributed to internal fibrillation of the fiber wall. The increased fiber swelling increases drying stresses which are reported to be beneficial to tensile index and elastic modulus of the fiber restraint dried fiber network /36/. Gierz /30/ has argued that the increase in tensile strength during restraint drying is caused by increased fiber segment activation. During drying fibers shrink and through the microcompression effect (suggested by Page and Tydeman) create drying stresses in the network. Theses stresses straighten slack fiber segments enabling them to carry load so that it increases the whole fiber networks load carrying capacity.

Van der Akker /37/ has offered an explanation were the increased fiber swelling after beating would increase the axial elastic modulus of fibers via ‘Jentzen effect’. Jentzen /38/ has shown that when single fibers are dried under straining their elastic modulus increases. According to Page /19/ the increase in the tensile index cannot be explained with activation on the contrary with straightening of the fibers during beating. Fiber and fiber segment straightening improves the load carrying ability and improves the stress distribution in the fiber network and therefore both the elastic modulus and the tensile strength increase /19/.

Niskanen /39/ suggests that the increased swelling straightens the fiber segments, thus enhancing their activation. In addition, according to Niskanen, the activation also increases the axial elastic modulus of single fiber segments through the ‘Jenzen effect’.

The objective of this study was to separate the effects of fiber deformations (kinks and curl) from the effects of fiber swelling on the activation of fibers in the fiber network. For example refining of the industrial pulps changes these both and the effect of one cannot be separated from the effect of another. The effects of fiber deformations on the fracture energy are discussed.

Another goal was to study the effects of fiber deformations on fiber strength and to identify the fiber wall structure properties, which contribute to fiber strength and via activation to fiber network properties. The hypothesis is illustrated in Fig. 1.



Highly swollen fibers with deformations and high fiber strength.

Highly swollen fibers without deformations and high fiber strength.

Fig. 1. The hypothesis is that the deformation itself does not decrease fiber strength.

EXPERIMENTAL

Raw material

The wood raw material used in this study was Norway spruce (*Picea abies*). The spruce logs were industrially chipped and screened. The chips were stored fresh but were not screened in the laboratory.

Cooking

The cooking experiment was performed in a 30 l forced circulation laboratory digester. Table 1 summarizes the cooking procedure used in this study. The cooking liquor was prepared in the laboratory from NaOH and industrial grade Na_2S. Deionized water was used in all experimental steps. The liquor to wood ratio was 4/1 in cooking experiment. The effective alkali charge in each cook was 4.5 mol NaOH/kg dry wood and the sulfidity 35 %.

The following temperature profile was used in all experiments: heating from room temperature to 80 ^{o}C in 30 minutes; heating from 80^{o}C to 170 ^{o}C in 90 minutes; cooking at 170 ^{o}C for 2 hours.

Table 1. Cooking results.

RAW MATERIAL	YIELD, %, TOTAL	KAPPA NUMBER	VISCOSITY, ml/g	BRIGHTNESS, %	REST. EA, g/l
Spruce	51.6	28.4	1220	28.0	5.0

Pulp treatment and testing

The spruce pulp was produced according to the cooking procedure presented. After cooking the pulp was washed with deionized water over night and disintegrated (short time) and screened. The screening was carried out using plane screen with slot size of 0.25 mm. The pulp was never spin dried or homogenized during the processing described above and the drysolids content of the pulp never exceeded 12%. The pulp was beaten in PFI beater 2000 revolutions according to standard ISO 5264-2. Directly after beating the pulp suspension was homogenized (in the beating water (not to loose fines)) in Hobart kitchen mixer. Homogenization was carried out at room temperature 25 ^{o}C and consistency of 9% with homogenization speed of 285 rpm for 15 and 45 minutes. After homogenization fiber curl and amount of fiber kinks were measured from the fibers in the pulp suspension using PulpExpert fiber analyzer. Pulp sheets were prepared for testing according to standard ISO 5269-1. Testing of the pulps and pulp sheets were done according to standards or methods:

- kappa number SCAN C-1:77
- viscosity SCAN-CM 15:99
- Fiber curl and kink index measured with a FiberExpert
- apparent bulk density EN ISO 5270.
- tensile properties EN ISO 5270
- tear index ISO 5270
- zero-span tensile index (from rewetted sheets, Pulmac) ISO 15361.
- Scott bond TAPPI T833 modif.
- water retention value (WRV) SCAN-C62.
- fracture toughness SCAN-P 77 modif..

The size of the fracture process zone was measured by 'damage analysis' from silicone-impregnated samples according to Kettunen /41, 42/.

RESULTS AND DISCUSSION

The effects of fiber deformations (kinks and curl) and fiber swelling on fiber strength and strength properties of fiber network were studied. Most of fiber deformations, curl, kinks and dislocations vanish during beating of the pulp. In this study, the fibers were beaten first and the fiber deformations were generated on the fibers after beating to be able to separate the effects of beating and fiber deformations on the fiber strength, fiber segment activation and fiber network properties.

Fiber deformations and fiber segment activation

The gently produced spruce kraft pulp fibers were beaten with PFI beater 2000 revs and deformed in Hobart kitchen mixer for 0, 15 and 45 minutes. The aim was to introduce fiber deformations without changing fiber swelling. In Figs 2 and 3 are shown fiber curl and kinks after 0, 15 and 45 minutes treating time in the mixer.

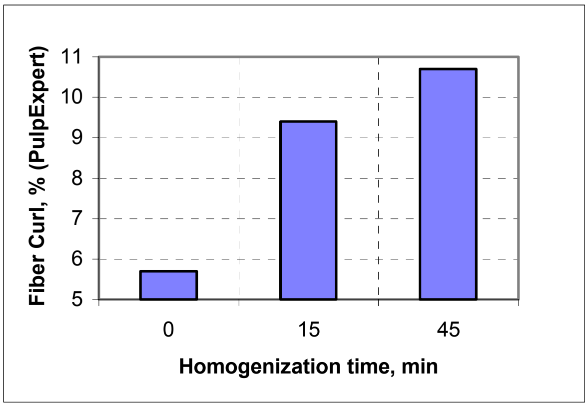


Fig. 2. The development of fiber curl as a function of homogenization time.

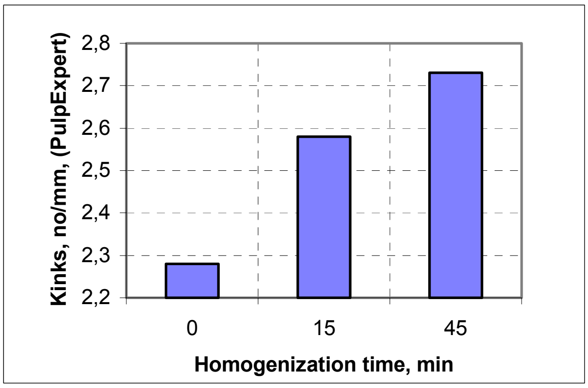


Fig. 3. The development of number of fiber kinks as a function of homogenization time.

Figs. 2 and 3 show that the homogenization increases fiber curl and number of kinks in the fibers. The CSF (Canadian Standard Freeness) and WRV (Water Retention Value) were measured from the homogenized pulps, shown in Figs. 4 and 5.

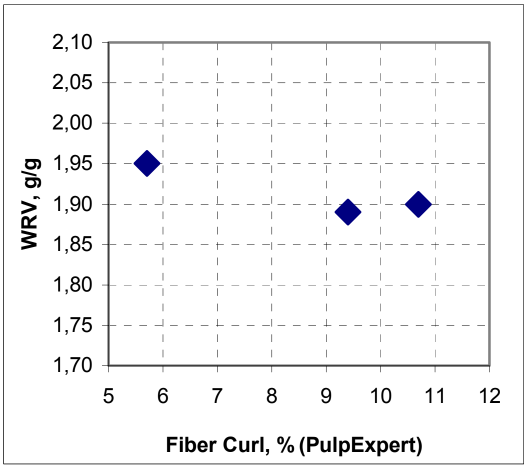


Fig. 4. The effect of homogenization on WRV as a function of fiber curl.

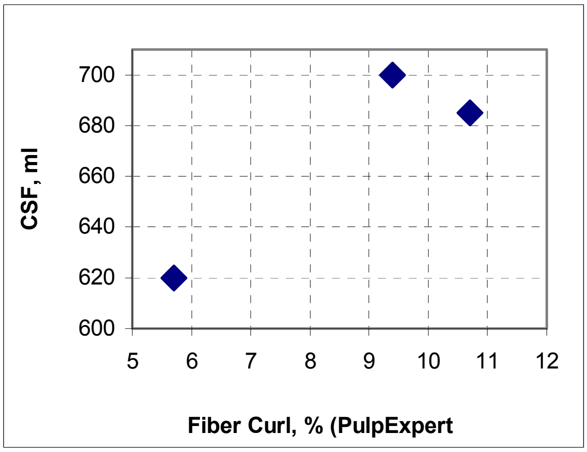


Fig. 5. The development of CSF as a function of fiber curl.

From Fig. 4 can be seen that the homogenization did not significantly modify the fiber wall of the treated fibers, which is seen as only sligtly decreased WRV values. The observed increase in CSF values (Fig. 5) may partly be due to differences in the formation of the pulp sheet because of the fiber deformations.

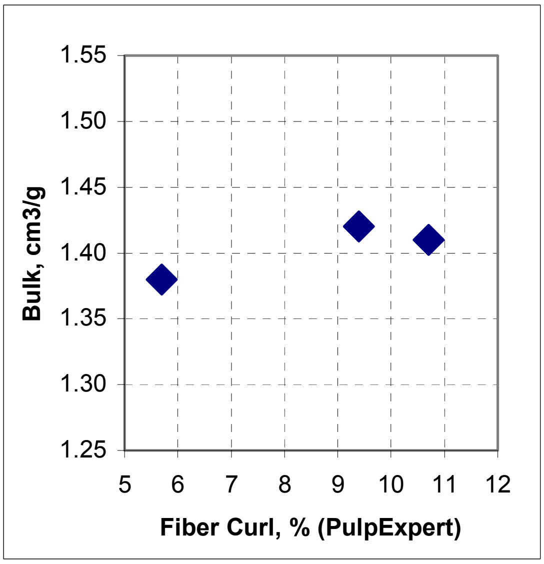


Fig. 6. The effect of fiber curl on the bulk of the pulp sheet. Error bars 95% confidence interval of the mean of the measurement is inside the symbols.

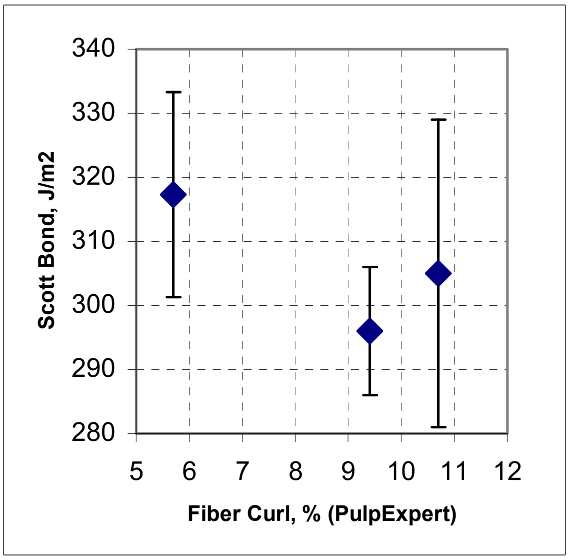


Fig. 7. The development of Scott Bond as a function of fiber curl. Error bars 95% confidence interval of the mean of the measurement.

From Fig. 6 can be seen that there is no or very little difference in the bulk of the pulp sheets. In addition, the differences in the Scott Bond measurements between the pulp samples are quite small (Fig. 7). In Figs. 8 and 9, stretch and tensile stiffness index results from tensile test are presented. From Fig. 8 and 9 can be seen that when the amount of fiber deformations increases, the stretch of the pulp sheet increases and tensile stiffness index decreases. This phenomenon can be explained so that the deformed fibers (fiber curl, and kinks) form a fiber network where the load distribution is nonuniform (fiber activation is not uniform) compared to situation with straight and undeformed fibers. The nonuniform load distribution causes local stress points, which break when fiber network is drawn, which results in low tensile stiffness and tensile index values. The stretch increases in such fiber network because of the slack fiber segments, which have to be straighten before they are able to carry load compared to fiber network of straight fibers /19, 27, 28/.

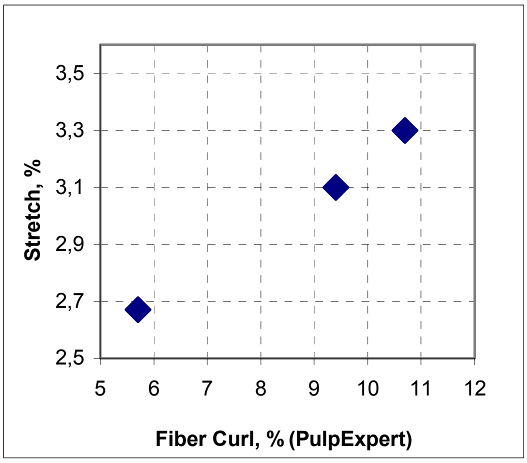


Fig. 8. The effect fiber curl on stretch of the pulp sheet as a function of fiber curl. Error bars 95% confidence interval of the mean of the measurement is inside the symbols.

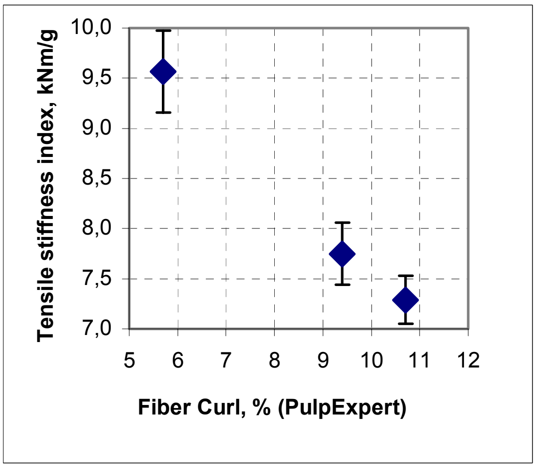


Fig. 9. The development of tensile stiffness index as a function of fiber curl. Error bars 95% confidence interval of the mean of the measurement.

Figs. 8 and 9 also show that, when the fiber swelling is kept approximately constant, the only factor contributing to fiber activation in the fiber network is the fiber deformations i.e. geometrical factors. The uneven load distribution during drawing of the pulp sheet can be also clearly seen from the tensile index of the pulp sheets, shown in Fig. 10. When fibers are straight, the tensile stiffness and tensile index are much higher compared to deformed fibers, due to higher fiber segment activation.

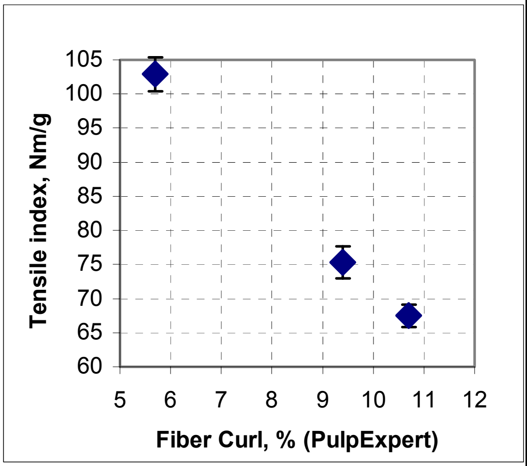


Fig. 10. The effect fiber curl on tensile index of the pulp sheet. Error bars 95% confidence interval of the mean of the measurement.

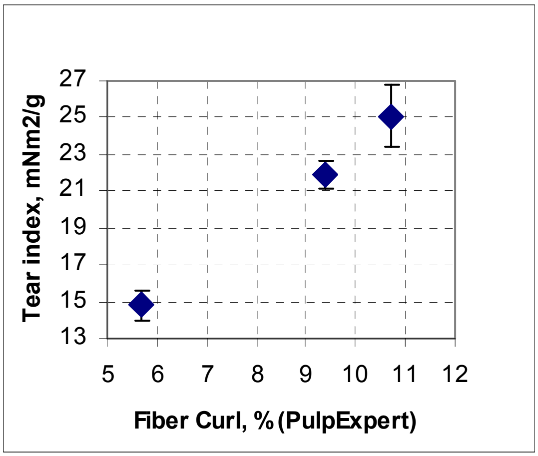


Fig. 11. The development of tear index as a function of fiber curl. Error bars 95% confidence interval of the mean of the measurement.

From Fig. 11 can be concluded that the tear index increases when the fibers in the fiber network are deformed. The deformed fibers transfer therefore stresses to larger area and to more bonds, which in breaking consume greater energy and is seen as higher tear indices /27/. The size of the fracture process zone was measured by ‘damage analysis’ from silicone-impregnated samples; results are shown in Figs. 12 and 13.

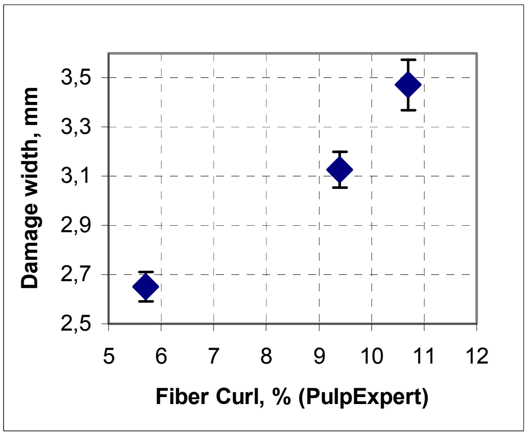


Fig. 12. The damage width as a function of fiber curl. Error bars 95% confidence interval of the mean of the measurement.

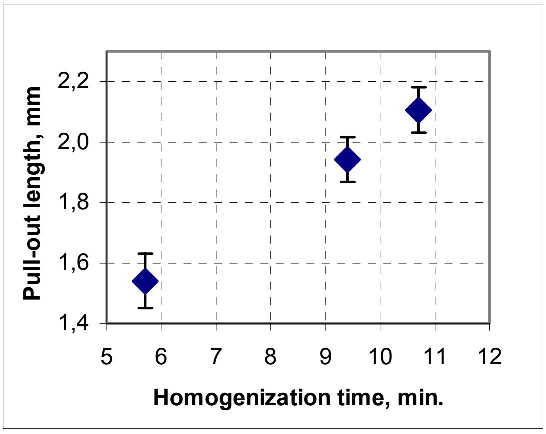


Fig. 13. The pull-out length as a function of fiber curl. Error bars 95% confidence interval of the mean of the measurement.

Figs. 12 and 13 show clearly that in the in-plain tear test, the fracture area increases when the fibers in the fiber network are deformed. The increasing pull-out width (Fig. 13) shows that the fibers are straightened during the tearing process and they remain less broken due to larger distribution of the stresses compared to fiber network of straight fibers.

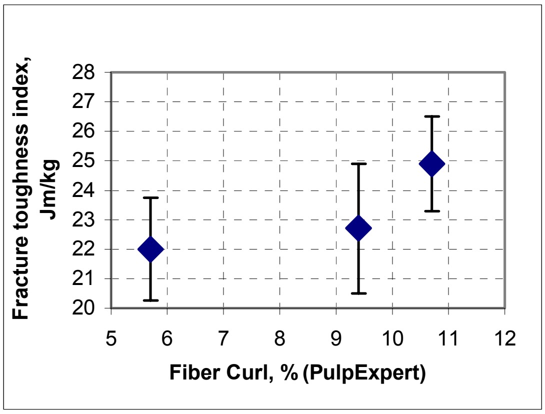
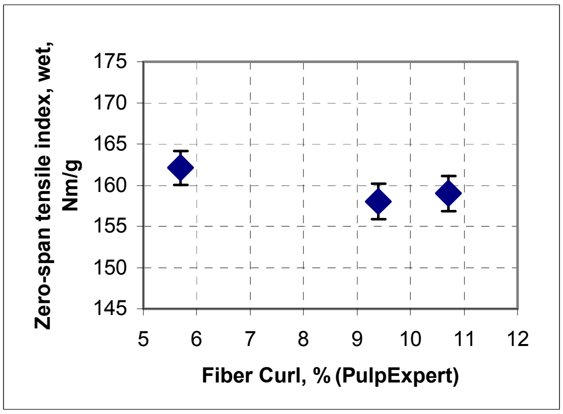
	

Fig. 14. The effect fiber curl on fracture toughness of the pulp sheet. Error bars 95% confidence interval of the mean of the measurement.	Fig. 15. The development of zero-span tensile index as a function of fiber curl. Error bars 95% confidence interval of the mean of the measurement.

The larger amount of energy absorbed by the fiber network of deformed fibers is also seen as an increase in the fracture toughness index (Fig. 14). The large variation in the fracture toughness measurement is probably due to variation between the test strips. The effects of fiber deformations on the distribution of stresses in the fiber network, discussed above, are illustrated in Fig. 16.

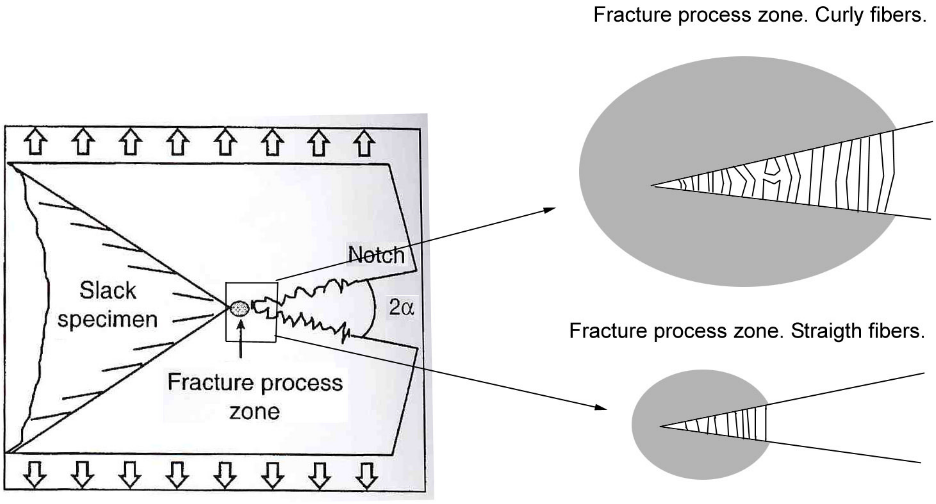


Fig. 16. The effects of fiber deformations on the distribution of stresses in the fiber network. In-plain tear test illustrated in the figure.

From Fig. 15 can be concluded that fiber curliness has no effect on the zero-span (wet) tensile measurement, therefore the zero-span indicates the average single fiber strength. According to literature /14, 34, 35/ the zero-span fiber strength should be measured from the well-beaten and straight fibers. This recommendation is mainly based on the hypothesis that curly fibers do not carry load in the measurement and they have to beaten to be straight. This hypothesis is according to our results erroneous (Fig. 15). The explanation to this difference could be that the fibers with mechanically or chemically modified fiber walls distribute load nonuniformly inside the fiber wall, meaning: very carefully handled fibers have no damage in the fiber wall and can therefore transfer more load regardless of the fiber deformation degree compared to damaged fibers. The load transfer inside undamaged, damaged and beaten damaged fiber walls is illustrated in the Fig. 17.

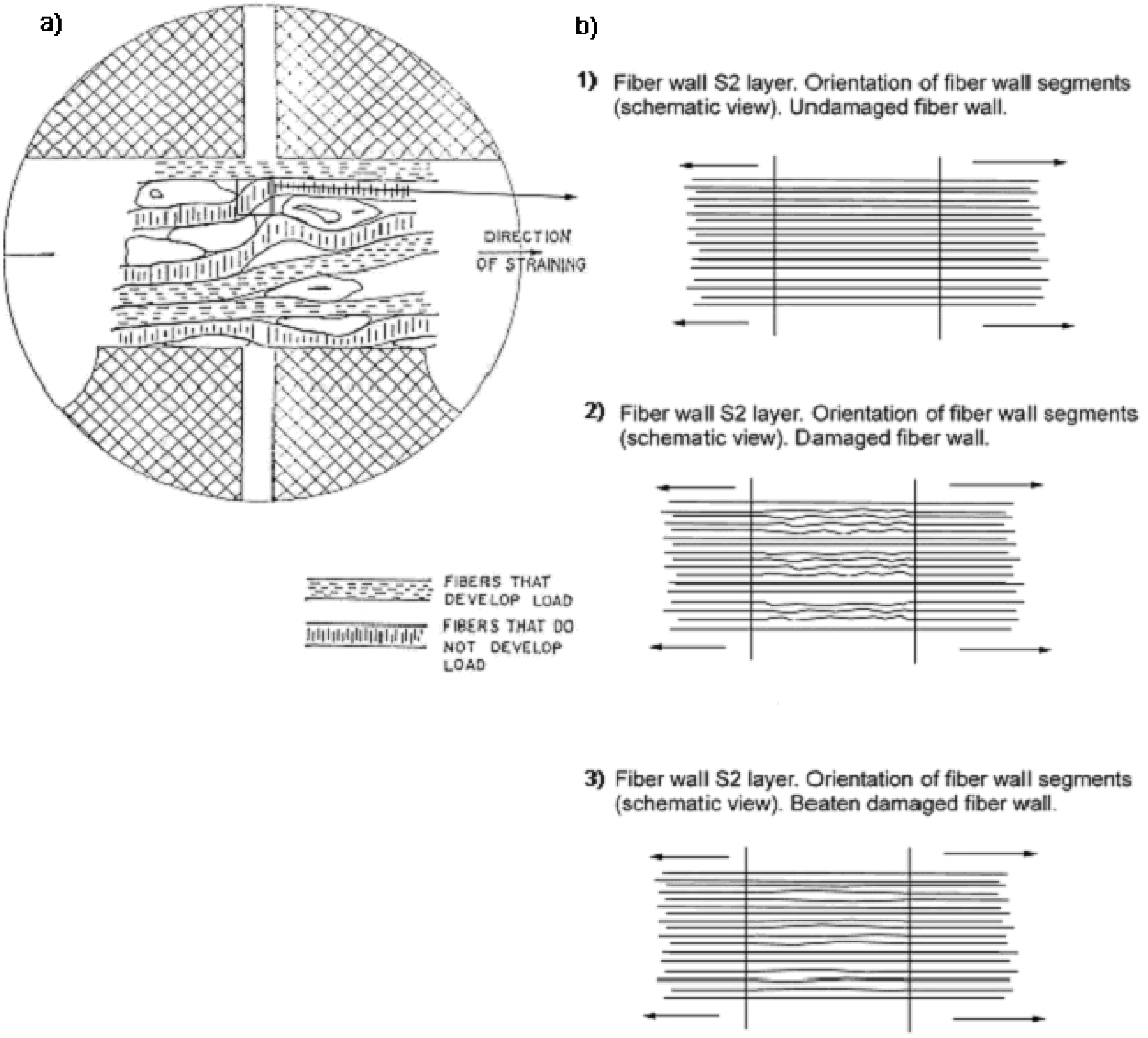


Fig. 17. a) Generally accepted hypothesis of the effect of curl on the zero-span fiber strength /34, 35/. Only straigth fibers carry load. b) The new hypothesis: all fibers carry load. Fiber wall segments carrying load in three different cases is illustrated: 1) Undamaged fiber wall stress transfer. 2) Damaged fiber wall stress transfer, 3) Beaten damaged fiber wall stress transfer.

Fig. 17 b) shows that the fibrils and fibril aggregates of the undamaged fiber wall distribute load uniformly, which leads to high fiber strength. The damaged fiber wall distributes load nonuniformly, which generates points in the fiber wall that carry most of the load. This leads eventually to lower fiber strength. When the damaged fiber wall is beaten the swelling of the fiber wall increases and through this mechanism, the fibrils and aggregates are rearranged so that the load distribution becomes more uniform and fiber strength increases. Therefore, the zero-span tensile strength describes the single fiber strength at certain arrangement structure of the fibrils and aggregates of the fiber wall.

CONCLUSIONS

The effects of fiber deformations (kinks and curl) on the activation of the fibers in the fiber network were studied. The influence of the fiber deformations on the strength properties of the softwood kraft pulp fiber network is significant, while the single fiber strength remained unchanged. The fiber deformations decreased fiber segment activation in the fiber network, which resulted in decreased tensile and tensile stiffness indices but in increased tear and fracture toughness indices. This was concluded to be caused by the deformed fibers in the fiber network, which contribute to nonuniform distribution of stress along the length of a fracture process zone. Deformed fibers transfer therefore stresses to larger area and to more bonds and greater energy is also needed in straightening and partially or totally breaking bonds between the fibers.

The zero-span fiber strength measurement was not dependent on fiber curl and kinks, but is likely dependent on the load distribution uniformity of the 3-dimensional fiber wall structure. Fibrils and aggregates of the undamaged fiber wall distribute load uniformly, which leads to high fiber strength. The damaged fiber wall distributes load nonuniformly, which generates points in the fiber wall that carry most of the load. This leads eventually to lower fiber strength. No major ‘Jenzen effect’ was detected for the undeformed fibers.

ACKNOWLEDGEMENTS

We are grateful for financial support from TEKES via the Wood Material Science Research Programme (BUNDLE, Fibre wall modelling).

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