The Influence of Refining Heterogeneity on Paper Properties

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This paper studies the impact of refining heterogeneity on paper property development and pressability. Three trials were performed in different refining equipment. The results showed that the strength development was due mostly to the water retention value (WRV) and the fiber straightness. Curly fibers require more energy to reach a given strength property. A heterogeneous refining, which in this case was performed by mixing less refined and highly refined pulps in different proportions, increased the energy requirement to reach a given tensile index or tensile stiffness index. The pressability of the pulps was not affected by the refining heterogeneity. At a given WRV, the pulp had the same solids content after dynamic pressing independent of the degree of heterogeneity.

Keywords: Refining; Pressing; Heterogeneity; Paper Properties

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INTRODUCTION

Pulp refining is one of the most important unit operations in papermaking. The purpose is to modify the fibers to obtain desired paper properties, for instance, tensile strength or surface smoothness. The mechanical treatment in a refiner makes the fibers more flexible by internal fibrillation as the fibril layers in the fiber wall separate and pores are created. This leads to increased water holding capacity of the fiber wall. Fibrils on the fiber surface are loosened and extend from the surface, producing external fibrillation. Some of the fibrils are entirely separated from the fiber, either as single fibrils or in entire flakes, giving rise to secondary fines. Refining also affects the fiber shape, either by straightening them or increasing curl. The mechanical treatment can also lead to fiber shortening as fibers are cut by the refining segments. However, as the pulp passes through the refiner, not all fibers experience the same mechanical treatments. Heymer (2009) suggested that heterogeneity in refining treatment is governed by the probability of fiber capture and transports into gaps and the probability of suitable forces applied to fibers within the gaps. Several investigations indicate that only a small part of the fibers is treated during the refining (Halme 1962; Ryti and Arjas 1969; Steenberg 1963; Lidbrandt and Mohlin 1980; Page 1989; Olson *et al.* 2003; Decker 2005; Batchelor *et al.* 2006; Goosen *et al.* 2007; Heymer 2009). Decker (2005) reported that only 7 to 20% of the fibers are treated in an industrial disc refiner.

On a laboratory scale, the pulp is usually treated by multiple passages. Particular PFI-refining is believed to treat the pulps homogenously (Dillén 1980; Lidbrandt and Mohlin 1980). Lidbrandt and Mohlin (1980) showed from scanning electron microscopy that most fibers in the PFI-mill were treated, whereas most of the fibers in an industrial refiner were not.

Multidisc fillings are mainly used for pulps that cannot withstand intense refining, such as recycled fibers (De Foe and Bemler 1992), hardwood fibers (Demler and Ratnieks 1991), and post refining of mechanical pulps (Robinson *et al.* 1985). The fiber treatment during refining with multidisc fillings results in a fiber treatment resembling of PFI-refining (Mohlin and Miller 1995). Refining increases the swelling of fibers and deteriorates the dewatering capacity in the wire section and in the press section, but it also increases the energy consumption if the paper entering the dryer section has a lower solids content. A lower solids content means that a larger amount of water must be evaporated, which requires more energy than pressing. Busker and Cronin (1982) found that the water retention value (WRV) predicted the solids content after pressing for about 60 furnishes having a broad spectrum of pulp type and refining, indicating that it is the total amount of water that determines the pressability, not the location of the water. For instance, certain refiners promote external fibrillation where most water molecules are on the fiber exterior, while another promotes internal fibrillation where the water is more likely to be in the fiber wall.

This study focused on the impact of refining heterogeneity on paper properties. The influence of heterogeneity was evaluated by mixing less refined and highly refined pulps in different proportions. The work includes different types of refiners and pulps: one trial with bleached softwood pulp that was PFI-refined and two pilot refining trials using bleached birch kraft pulp and unbleached softwood kraft pulp refined in two different industrial refiners.

EXPERIMENTAL

Refining Trials

Three different trials were performed at Innventia, Stockholm. Below is a short description of each trial.

Trial 1- Bleached birch kraft pulp refined in an industrial multidisc refiner

A never-dried bleached birch pulp pilot was refined using a Beloit DD-refiner at the pilot refining facility at Innventia, Stockholm, Sweden) with a multidisc filling of 20” fillings with the bar code 1.8/3.6/1.8 corresponding to a cutting-edge length of 24.9 km/rev. The rotational speed was 750 rpm. The flow-through the refiner was 800 L/min and a single pass-mode. The refining temperature was 40 °C. The multidisc-refined pulp represented the homogeneous refining.

Heterogeneously refined pulps were prepared by mixing the pulp suspension refined with 133 kWh/t and unrefined pulps suspensions in the following ratios: 100/0, 80/20, 60/40, 40/60, 20/80, and 0/100. These proportion levels represent different levels of heterogeneous refining. The refining energy input for the mixture was calculated as the average value based on the mass proportion. Handsheets were made, and their properties were evaluated. The pressability of the pulps was evaluated to investigate if the sheet made of heterogeneously refined pulps affected the outgoing solids content after pressing.

Trial 2 - Bleached softwood pulp refined in a PFI-mill

A PFI-refined never-dried bleached softwood (mixture 50% pine, 50% spruce) pulp was used. Different revolutions of PFI-refining represented the homogeneous refining. Heterogeneously refined pulps were prepared by mixing the pulp suspensions refined at 1000 revolutions with the pulp suspensions refined at 9000 revolutions in the following proportions: 100/0, 80/20, 60/40, 40/60, 20/80, and 0/100. The refining energy input for the mixture was calculated as the average value based on the mass proportion. By using a slightly refined pulp, the fibers were straightened, and the effect of fiber shape was minimized. Handsheets were made, and their properties were evaluated.

Trial 3 - pilot paper machine trial

A never-dried unbleached softwood (mixture 50% pine, 50% spruce) pulp was used. The pulp was refined in two parallel conical JC-00 refiners with AA fillings. Table 1 lists the data for the fillings and the no-load power used in the calculation of the net specific energy. The rotational speed of the refiner was 1000 rpm. The temperature was approximately 30 °C. The pulp consistency during refining was 3%.

Table 1. Filling Designs and No-Load Power

Filling	Bar Width (mm)	Groove Width (mm)	Bar Angle (°)	Cutting Length (km/rev)	No-load Power (kW)
AA	4.0	6.0	18	1.8	23

Four different refining strategies were applied, where the total specific refining energy was 100 kWh/t (Table 2). The energy was distributed in four ways to simulate different degrees of heterogeneous refining. The power input was 68 kW in all cases. In the reference sample representing homogeneous refining, the two refiners were run in parallel with the same flow (nomination 50:50 in Table 2) resulting in the most homogeneous pulp suspension possible under the given circumstances.

Table 2. Experimental Design, Refining Energy Inputs, and Flow-Rates for the Four Refining Strategies in the JC-00

Refining nomination	Layout	Refining energy input, refiner 1 (kWh/t)	Refining energy input, refiner 2 (kWh/t)	Flow 1 (L/min)	Flow 2 (L/min)	Total Specific Refining Energy input "SRE" (kWh/t)
Homogeneous 50:50	Parallel	100	100	250	250	100
Heterogeneous 60:40	Parallel	77	143	325	175	100
Heterogeneous 80:20	Parallel	62	250	403	100	100
Heterogeneous 100:0	Series (50% of the pulp not refined)	100	100	250		100*

Note: 50% of the pulp going to the paper machine was unrefined. The total energy input of the pulp delivered to the paper machine was 100 kWh/t, while the refining energy input to the refined pulp stream was 200 kWh/t.

In other cases, the flow was varied between the two parallel connected refiners with 60:40 and 80:20 ratios. One additional heterogeneously refined pulp was produced by mixing refined pulp and unrefined pulp. Only 50% of the pulp fed to the paper machine was refined by two refiners connected in series, with a refining energy input of 200 kWh/t, while the other half of the pulp was fed to the paper machine unrefined.

Paper was produced on the FEX pilot paper machine (Innventia, Stockholm, Sweden) using the roll former unit with headbox (Valmet 7-row), slice openings at 14 mm, and a machine speed of 600 m/min. The jet speed was 680 m/min. The grammage was 75 g/m^2. The paper was dried under restrain on a one-cylinder dryer.

Dynamic MTS-pressing

To simulate a dynamic pressing situation, material testing system (MTS) equipment was used, where different press pulses can be generated and dynamic pressing studies can be performed (Lucisano and Vomhoff 2009). The pressing unit was also constructed to incorporate rewetting studies by allowing a controlled contact time between the felt and the paper after the press pulps. In the MTS pressing device, a circular paper sample with a diameter of 80 mm was pressed in a press nip (Fig. 1). The press nip could be configured either as a double-felted or single-felted press nip. The shape, peak stress, and duration of the press pulse could be controlled.

For this study the MTS was configured to replicate a double-felted press nip, with two fine felts (FF), and 1300 g/m² of a mixture of 17 µm/20 µm (3.1 dtex/4.2 dtex) batt fibers in the surface layer. The felt moisture content was held constant during the trial by holding the weight of the wet felt constant before each pressing. The felt moisture ratio was 0.2.

The MTS was programmed to generate a 20 ms shoe-press pulse (Metso type, with plateau) with a peak pressure of 6.2 MPa. The pressing was performed in a standard climate of 50% RH and 23 °C.

The rewetting study was performed by letting one of the felts contact the paper sample at no pressure for 200 ms.

Individual paper samples were punched out from the handsheets. The samples were weighed before pressing, after pressing, and after drying to determine the solids content after pressing. For each test, 8 circular papers samples were pressed.

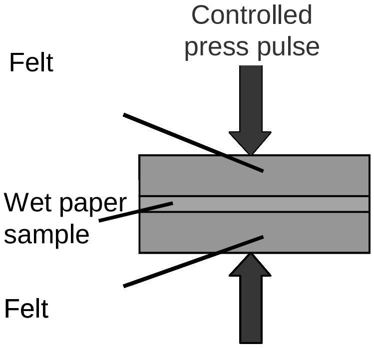

Fig. 1. Working principle of the MTS pressing simulator

Analyses

Handsheets were prepared according to ISO 5269:1 (2005) when mechanical properties were evaluated. To evaluate the pressability of the pulp, the preparation of laboratory sheets was made according to ISO 5269:1 (2005), but no pressing was included. After couching and using between 2 and 6 blotter papers to obtain a given solids content, the wet handsheets were stored in sealed plastic bags and refrigerated. PFI-refining was done according to ISO 5264-2 (2011), determination of SR-number according to ISO 5267-1 (1999), and WRV according to SCAN-C 62:00 (2000). The structural density on the handsheet was determined according to SCAN-P 88:01 (2001) and the tensile properties according to ISO1924-3 (2005). A FiberTester (L&W, Stockholm, Sweden) was used to analyse the pulp samples. The primary data from the physical testing of the handsheets were treated as recommended in SCAN-G 2:63 (2007), within a 95% confidence interval.

RESULTS AND DISCUSSION

Three trials were performed to clarify the importance of refining heterogeneity. Both hardwood and softwood pulps were included as well as different types of refiners to cover different refining fiber treatments.

Trial 1 - Bleached Birch Kraft Pulp Refined in an Industrial Multidisc Refiner

Multidisc fillings are mainly used for pulps that cannot withstand intense refining, such as recycled fibers (De Foe and Bemler 1992), hardwood fibers (Demler and Ratnieks 1991), and post refining of mechanical pulps (Robinson *et al.* 1985). The fiber treatment during refining with multidisc fillings results in a fiber treatment resembling PFI-refining (Miller and Mohlin 1996). Multidisc refining strongly reduces the specific edge load at a specific energy input with unaffected production. Multidisc fillings mean that the rotor is replaced by three rotors and two stator plates so that the refining gap is increased from two to six.

Heterogeneous pulp mixtures were prepared by mixing a highly refined birch pulp with an unrefined birch pulp in different proportions. The water retention value (WRV) measure the water content in the pulp and can be considered as a measurement of the bonding ability. The WRV for the mixtures were approximately the same as the homogeneous refined pulp at a given calculated refining energy input (Fig. 2). The water holding capacity (WRV) for the mixtures follows the same correlation as the refined pulp. This result indicated that the heterogeneity in the refined pulp resembles that of the mixed pulp.

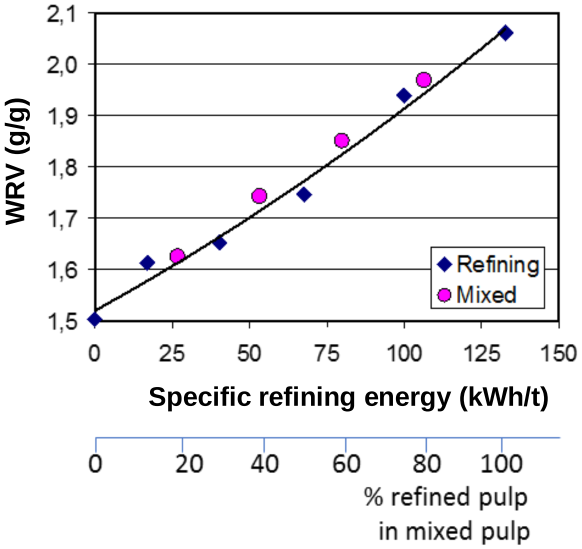

Fig. 2. WRV as a function of specific refining energy input for refining bleached birch pulp in multi disc refiners (nominated Refining) and pulp mixtures (nominated Mixed) of highly refined and unrefined pulp

The paper properties of handsheets made from refined pulps and heterogeneous pulp mixtures at a given WRV are shown in Fig. 3. The refined pulp had a higher tensile index and tensile stiffness index than the heterogeneous pulp mixtures.

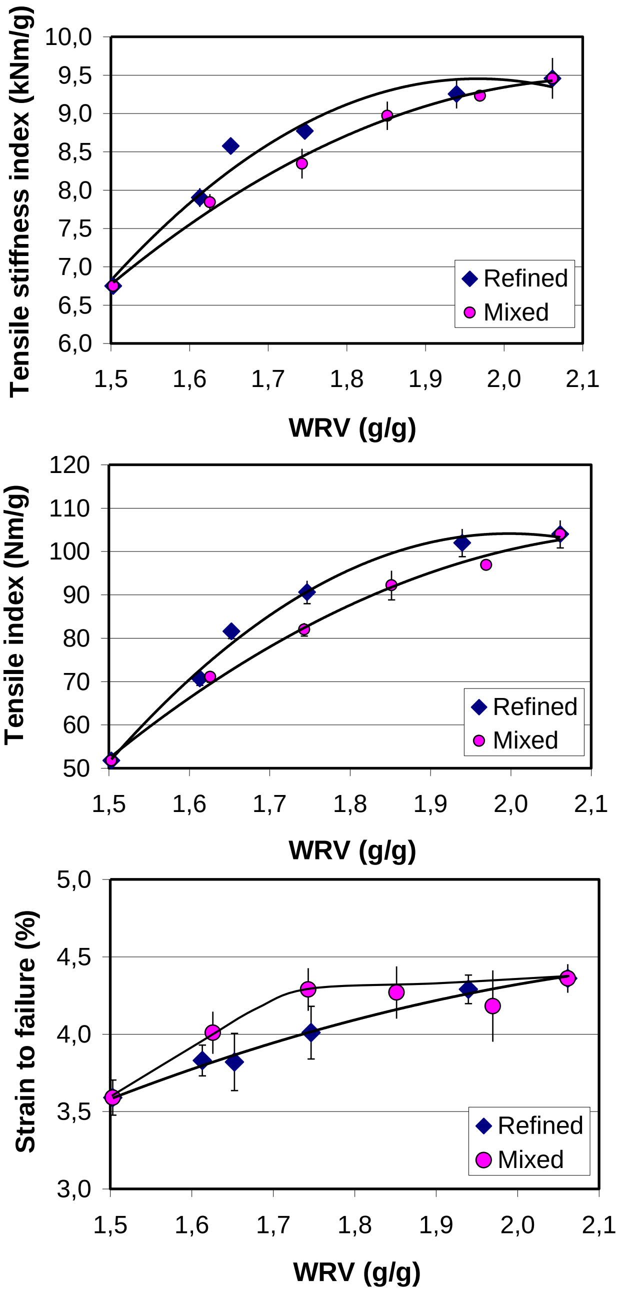

Fig. 3. The tensile index, tensile stiffness index, and strain to failure *versus* WRV for the refined pulp (nominated Refined) and pulp mixtures (nominated Mixed) of highly refined and unrefined pulp. The 95% confidence interval is shown in the figure.

The heterogeneously pulp mixtures required more energy to reach a certain tensile or tensile stiffness index. Thus, at a given tensile index, refining results in "better strength enhancing fiber treatment" than heterogeneously mixing, which can be interpreted as a homogeneous refining, is beneficial from a strength standpoint. This study did not analyze the degree of external and internal fibrillation or amounts of fines at a given WRV value. However, it is most likely that the refined pulps and the heterogenous pulp mixtures have different degrees of external and internal fibrillation.

At low and medium WRV levels, the strain to failure was slightly higher for the heterogeneous pulp mixtures. The difference in tensile stiffness index and strain to failure may depend upon differences in fiber shape, as unrefined pulp with a lower shape factor was mixed with refined pulp with a straighter fiber.

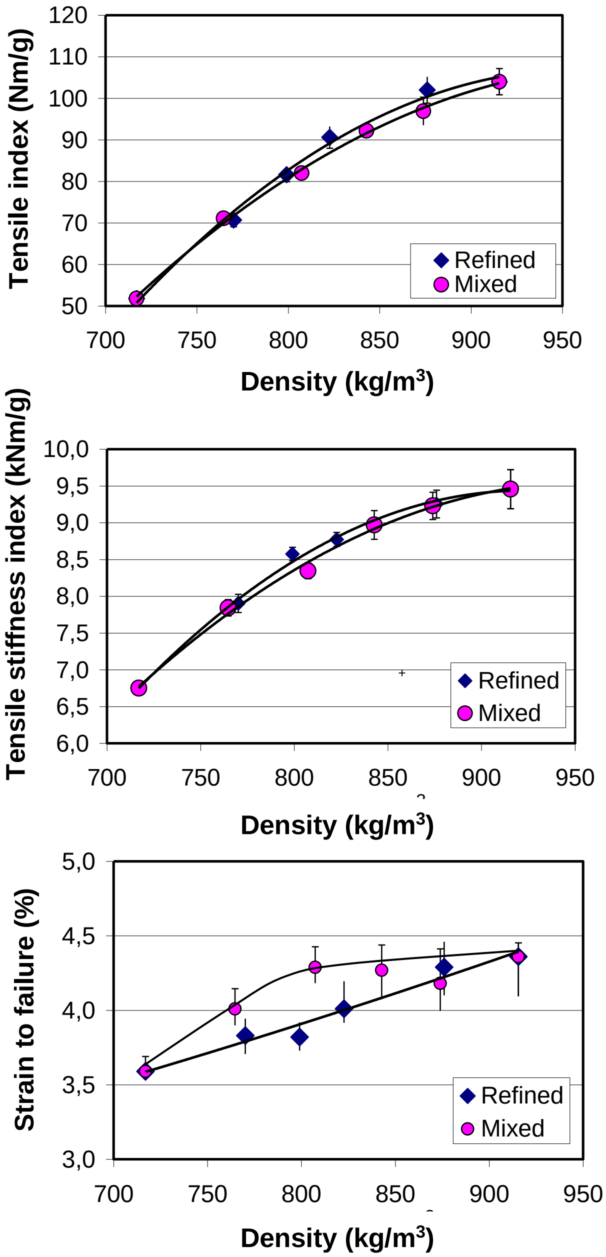

Fig. 4. The tensile index, tensile stiffness index, and strain to failure versus density for the refined pulp (nominated Refined) and pulp mixtures (nominated Mixed) of highly refined and unrefined pulp. The 95% confidence interval is shown in the figure.

The tensile index, tensile stiffness index, and strain to failure, as a function of density for the refined pulp and the pulp mixtures of unrefined and highly refined pulp are shown in Fig. 4. The deteriorating effect on tensile properties of unrefined fibers can be amended by the addition of highly refined fibers. Mixing unrefined pulp fibers with a lower shape factor with refined pulp with straighter fibers increased the strain to failure of the sheets. This might be useful in products where high stretch properties are desired, for instance, sack paper.

The water retention value is a measure of how much water the pulp contained, but it does not distinguish where the water is located. A highly externally fibrillated fiber can have the same WRV as a fiber that has little external fibrillation. Kang (2007) found that an increase in external fibrillation while keeping the internal fibrillation (measured as fiber saturation point [FSP]) constant increased the tensile strength by 20%, whereas the light scattering was slightly decreased which indicates that a densification of the paper occurred. Kang (2007) suggested that the increase in tensile strength at a given FSP might imply a better combination of dewatering and paper strength.

In this study, the refined pulp fibers and fibers in mixtures of unrefined and highly refined pulps have different fibrillation patterns (external and internal fibrillation) and thus water at different locations. Pulp fibers with a high degree of external fibrillation have more water at the exterior while pulp fibers with a high degree of internal fibrillation have water more at the interior. Do these differences have an influence on the dry solids content after wet pressing as suggested by Kang (2007)? Wet handsheets of the refined pulps and the pulp mixtures were pressed in a dynamic pressing device (Lucisano and Vomhoff 2009). The solids content was investigated after pressing and after a rewetting time of 200 ms. There was no difference in solids content between the refined pulp and pulp mixtures after pressing, nor in rewetting behavior (Fig. 5).

Obviously, the heterogeneity of the raw materials did not affect the solids content after pressing. Clearly there was an inhomogeneity of the pulp because the mixtures contained pulps with a WRV of 1.5 g/g and nearly 2.1 g/g and different proportions of external and internal fibrillation on a fiber level as well as different amounts of fines. The results indicated that there was no sensitivity in the pressing response to where the water was located.

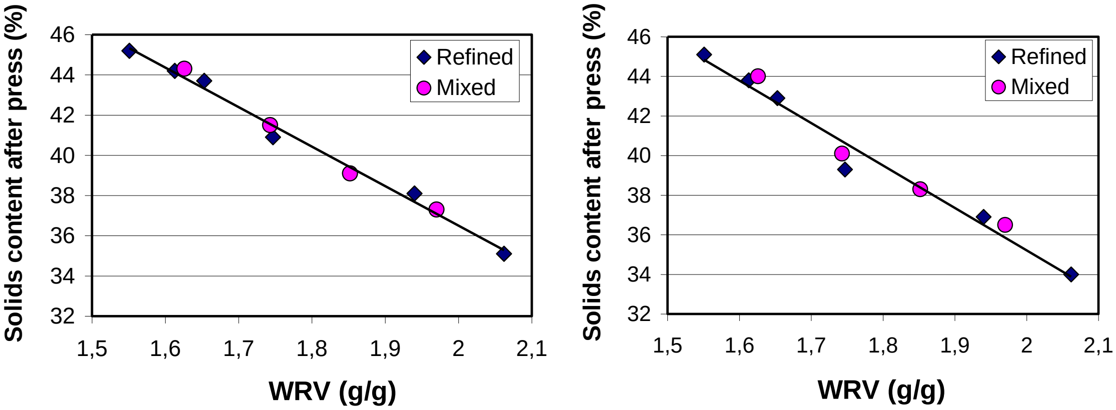

Fig. 5. Solids content after press as a function of WRV for a homogeneous (nominated Refined) and a heterogeneous (nominated Mixed) pulp mixture. The left diagram shows with no rewetting and the right with re-wetting time of 200 ms.

Trial 2 - Bleached Softwood Pulp Refined in a PFI-mill

Fiber shape affects the mechanical properties of paper, as straighter fibers can take on load. An effect of refining heterogeneity can be the differences in shape between the pulp fibers. In the second trial, the effect of refining heterogeneity was studied by eliminating the influence of fiber shape by mixing a highly refined pulp in varied proportions with a slightly refined pulp, both pulps had approximately same fiber shape. The two PFI-refined pulps chosen are shown in Fig. 6.

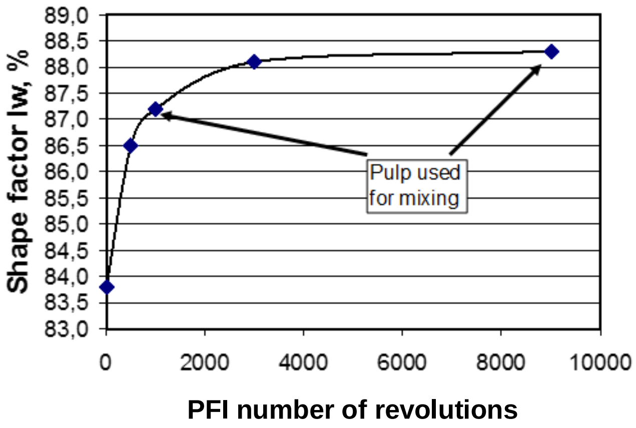

Fig. 6. Fiber shape (length-weighted) versus number of revolutions in a PFI-mill

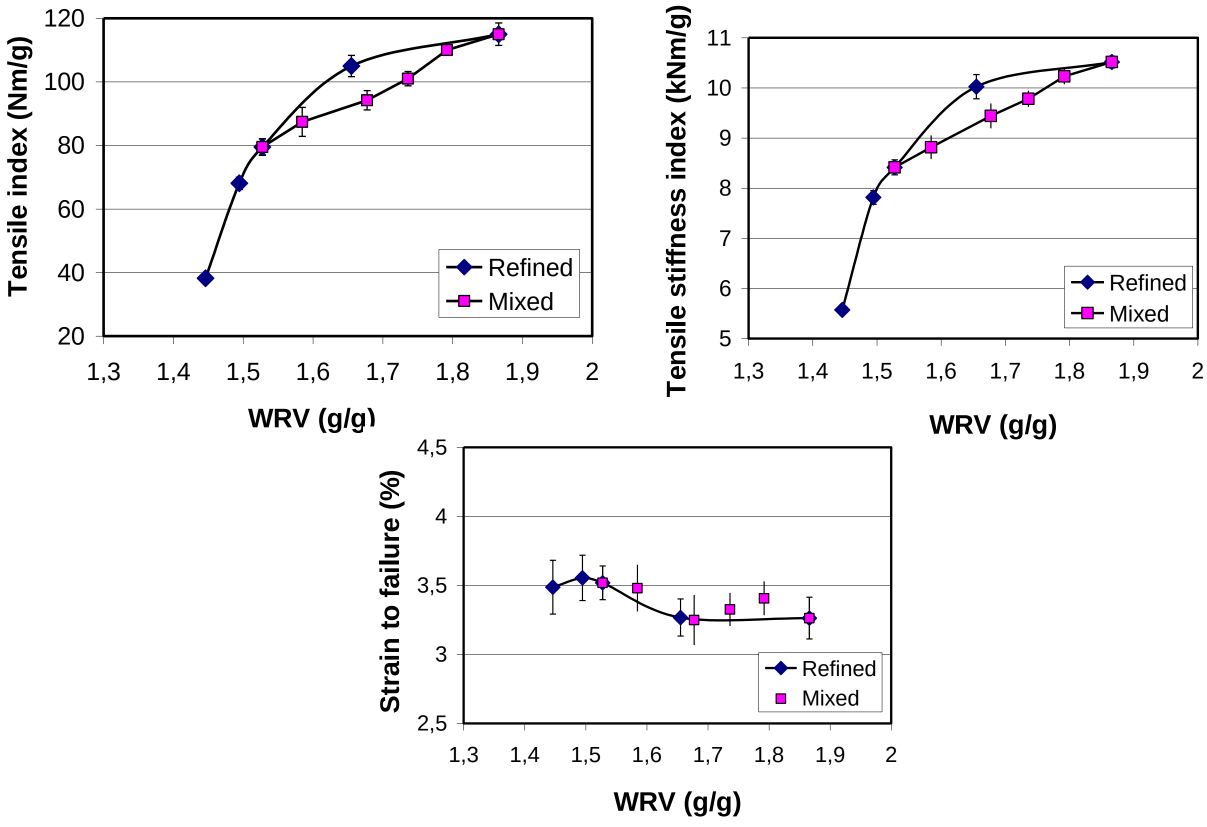

Fig. 7. The tensile index, tensile stiffness index, and strain to failure versus WRV for the refined pulp (nominated Refined) and pulp mixtures (nominated Mixed) of highly refined and unrefined pulp. The 95% confidence interval is shown in the figure.

As in the case of multidisc refining of bleached birch pulp, the PFI-refined softwood pulp obtained higher tensile index and tensile stiffness index than the pulp mixtures at a given WRV (Fig. 7). Similarly, the difference seemed to be highest at the highest degree of heterogeneity in the pulp mixture, not when the percentage of slightly refined pulp was highest. Interestingly, there was no difference in the strain to failure in this trial which indicates the differences between the refined pulp and the heterogenous pulp mixture observed in Fig. 3 solely depended upon the fiber shape.

Contrary to the first trial studying multidisc refining of birch pulp and mixtures of highly refined and unrefined pulps with different shape factors, the second trial in which the effect of the shape factor was eliminated showed differences in the relationship between tensile properties and sheet density (Fig. 8). The refined pulp had at a given density a slightly higher tensile index and a higher tensile stiffness index than the pulp mixtures. This indicates that PFI refining gives a more homogeneous treatment of pulp fibers than multidisc refining

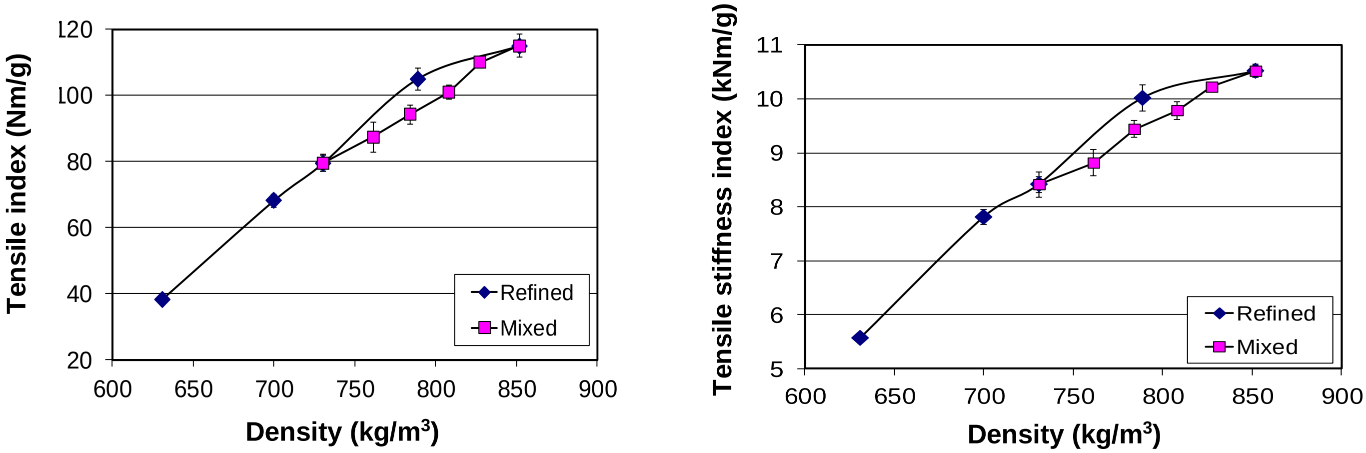

Fig. 8. The tensile index and tensile stiffness index versus WRV for the refined pulp (nominated Refined) and pulp mixtures (nominated Mixed) of highly refined and unrefined pulp. The 95% confidence interval is shown in the figure.

Trial 3 - Pilot Paper Machine Trial

In the third trial, refining heterogeneity was generated by mixing unbleached softwood pulps refined to different degrees, as described in Table 2.

The refining energy input of the mixed pulp was 100 kWh/t in all trial points. Figure 9 shows the WRV and SR-numbers for the trial point. The degree of heterogeneity increases starting from the bar on the left (reference), where equal portions of pulp refined with the same amount of refining energy were mixed.

The highest degree of heterogeneity in the mixed pulp was obtained to the right (Inhomo 100:0), where an unrefined pulp was mixed with pulp refined in a two-stage process.

The lowest WRV was obtained when unrefined pulp was mixed with refined. The difference was also significant for the SR-number. As the heterogeneity increased, the SR decreased.

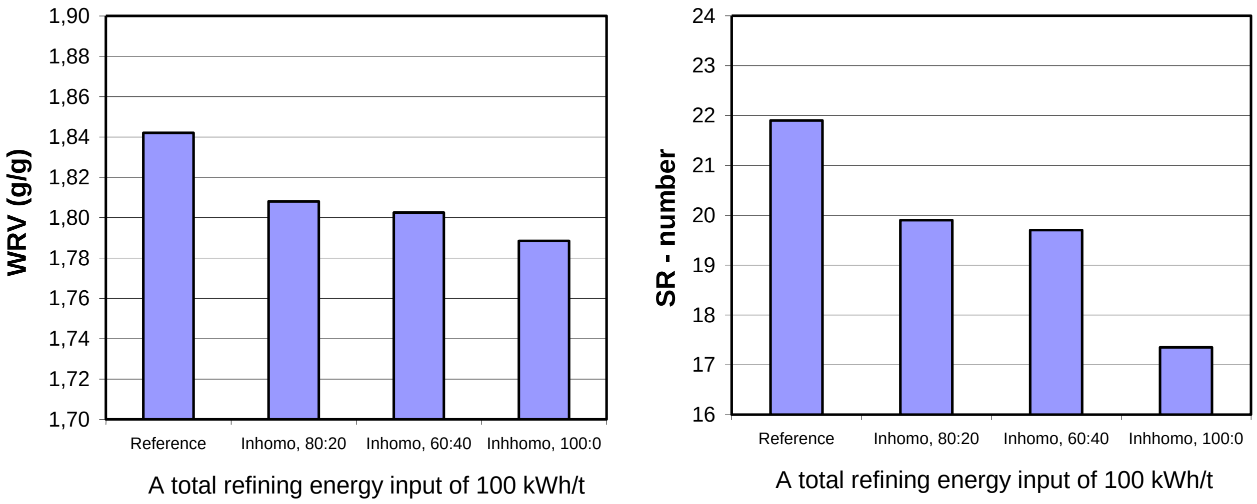

Fig. 9. WRV and SR-number for the four different refining cases representing homogeneous (reference) and heterogeneous refining

The FiberTester was used to analyse the pulp fed to the paper machine and the heterogeneously refined pulps were slightly longer than the reference refined pulp (Fig. 10). The shape factor decreased as the degree of heterogeneity increased. The curliest fibers were obtained as expected when unrefined pulp was mixed with refined pulp. The results indicated that a homogeneous fiber treatment promoted development of WRV and SR and reduced the fiber length as a result of fiber cutting.

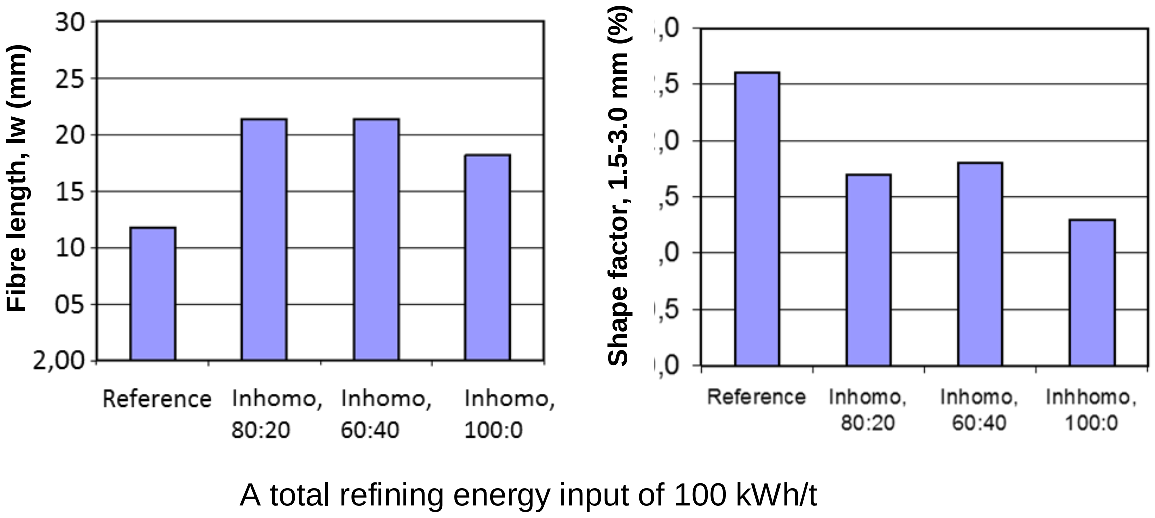

Fig. 10. Fiber length and mean shape factor (1.5 to 3.0 mm) for the four different refining cases representing homogeneous (reference) and heterogeneous refining

Figure 11 shows the tensile index, tensile stiffness index, strain to failure, and density for PM-made papers made from pulps from the four refining cases. The tensile index was constant except when unrefined pulp was mixed with refined pulp (100:0). The tensile stiffness value was slightly higher or equal to the reference case except for the last running cases when unrefined pulp was included. In this case, also a lower density was observed.

These results showed some discrepancy from the results obtained in the trials where the heterogeneous pulp mixture had a lower tensile index at a given energy input. In this case, there was no negative effect of the fiber shape on strength properties, except when unrefined pulp was blended in. Despite a lower shape factor (Fig. 10), no clear negative effect of the curlier fibers was observed. The reason for this can be two-fold: 1) the amounts of fines was different for the different refining cases; and 2) the papers were produced in a paper machine at very different conditions than during laboratory sheet making. In the wire section of a paper machine the fiber suspension consists of flocs of different characteristics, which have an impact on the sheet structure, but also the pressing procedure between laboratory pressing and machine was very different.

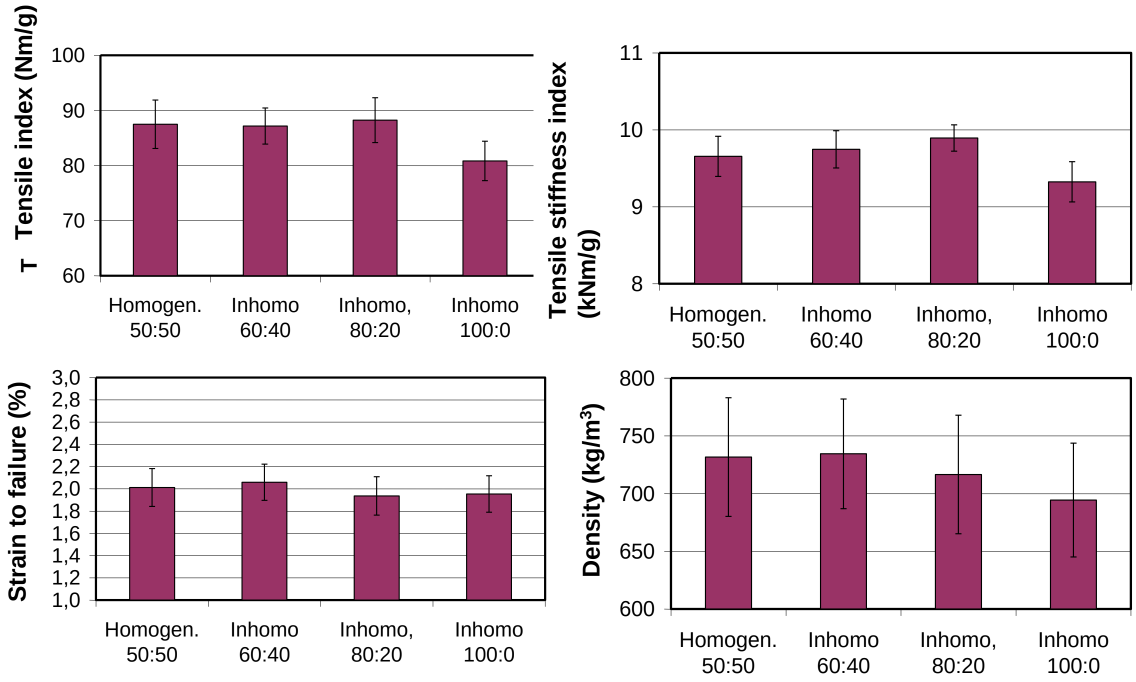

Fig. 11. Tensile index, tensile stiffness index, strain to failure (geometric mean values), and density for the four different refining cases representing homogeneous and heterogeneous refining. The 95% confidence interval is shown in the figure.

CONCLUSIONS

1. In three experimental studies, extremely heterogeneous pulp mixtures, in addition to a homogeneous mixture, were produced, and the influence of heterogeneity on paper strength and pressability were studied. The results indicated that the effect of refining heterogeneity mainly originates from fibers having different shapes and defects. There was no significant effect of heterogeneity on the relation between paper properties and density, except for strain to failure. This implies that the mills can have large freedom in refining strategies without any significant negative impact on the tensile strength properties at a given density.
2. The results also stress the importance of having a straight fiber in the sheet structure as the load-bearing element. The fiber straightening and reductions of kinks occurs within the refiner at relatively low energy inputs. This effect is important, especially when

evaluating different fibers and their refinability. A curly fiber requires more energy to reach a given strength property such as, for example, tensile index. A homogeneous refining treatment is beneficial from an energy saving aspect.

3. A maximally heterogeneous refining (performed by mixing) has an increased energy requirement to reach a given tensile index or tensile stiffness index. For the pilot paper machine trial, an effect of maximally heterogeneous refining was observed only when 50% of the stock fed to the paper machine was unrefined.
4. The pressability of the pulps was not affected by the refining heterogeneity. The pulp has at a given WRV the same solids content after dynamic pressing independent of the degree of heterogeneity.

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