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EFFECT OF LONG-FIBRED REINFORCEMENT PULP ON MECHANICAL PROPERTIES OF SHORT FIBRED-BASED PAPER

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ABSTRACT

The purpose of long-fibred reinforcement pulp in printing paper furnish is to improve the runnability of paper. Here the dry web runnability was evaluated primarily based on flaw-resisting ability of paper and secondarily based on in-plane tensile properties. Flaw-resisting ability was measured as tear strength and, more importantly, as fracture toughness. We modified the fibre length and bonding potential of chemical softwood pulp–mechanical pulp mixture. Fibre length was manipulated by proportion of pulps and interfibre bonding potential by beating level and cooking conditions of chemical pulp. Results clearly showed that higher average fibre length improved the flaw-resisting ability of dry paper. As expected, beating of reinforcement pulp and sulfite cooking (*vs.* kraft) increased the interfibre bonding of pulp mixtures. However, contrary to our expectation, improved bonding increased the flaw-resisting ability only a little. According to our analysis, low-freeness mechanical pulp has, as such, rather good interfibre bonding. Other factor is that beating of chemical pulp improves specific elastic modulus largely due to increased fibre segment activation, and only to smaller part due to bonding. The flaw-resisting ability of reinforced paper can be best controlled by modifying the average fibre length of the furnish - controlling the bonding ability seems not as critical. On the other hand, tensile properties like elastic modulus are not dependent on fibre length, instead they depend on fibre segment activation, interfibre bonding and fibre strength.

INTRODUCTION

The runnability of the dry paper web is a critical factor in paper manufacturing, in finishing and converting operations and in printing. Several studies have indicated that web breaks are often initiated by small flaws in paper (shives, holes, etc.) (Sears, 1965; Palsanen, 1979; Page, 1982; Roisum, 1990; Moilanen, 1996; Linna, 2001; Koskinen, 2001). This being the case, fracture mechanics should give useful information about the flaw-resisting ability and therefore runnability of the paper web. On the other hand, it seems logical that paper with high specific elastic modulus is easier to control in reel-to-reel process, as required tension can be achieved with low straining (e.g. low speed difference).

Because of certain practical problems (e.g. web breaks are very infrequent), extensive statistical data have been presented only in few cases in the literature to show what, if any, strength property actually correlates with paper runnability. The clear exception with extensive data for pressroom runnability has been published by Uesaka (2005). Some studies show a certain correlation between in-plane fracture parameters and press room runnability, like the classical paper by Page and Seth (1982). Swinehart and Broek (1996) reported a correlation between fracture toughness and coater runnability, and Moilanen and Lindqvist (1996) reported a correlation between fracture energy and printing press runnability. In other studies tensile strength correlated with coater runnability (Palsanen, 1979; Swinehart, 1996) and press room runnability (Palsanen, 1979; Uesaka, 2005). In most cases the correlation to any average strength property has been weak. Especially when analysing the correlation between out-of-plane tear (e.g. Elmendorf) and breaks, the results have shown little correlation (Palsanen, 1979; Page, 1982; Uesaka, 2005). In addition to the experimental results, out-of-plane tear is considered irrelevant from the logical point of view that the paper web is almost always subjected to in-plane loads (Seth, 1975; Page, 1982; Niskanen, 1998a).

Uesaka *et. al.* (1999, 2001) have criticized some of the pilot studies of the flaw-effect because in them web tension is increased until a break occurs, and because there is no quantitative data from pressrooms indicating such a strong effect of shives or flaws. On the contrary, some studies show that only a small fraction of breaks start from holes (Frye, 1994; Moilanen, 1996; Uesaka, 2005). Pressroom studies show that the tension values at printing presses are at much smaller levels; with the exception of short tension peaks during roll changes, etc. Therefore, pilot experiments done at high web tension levels may not simulate the relevant phenomenon at the printing

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press (Uesaka, 1999). It is also known that because of formation variations small enough flaws or holes do not affect the average strength of paper (critical defect size is about 1-5 mm) (Donner, 1997; Rosti, 2001).

On the other hand, it seems that other reasons like paper strength non-uniformity (Uesaka, 1999; Uesaka, 2001; Uesaka, 2005), variations in the press room tension (Uesaka, 1999; Uesaka, 2001; Larsson, 1984) and variations in the tension profile of paper (in CD) (Linna, 2001; Parola, 2000; Moilanen, 2001) can cause breaks. Air humidity variations between winter and summer affect breaks, so that there are more breaks during low humidity (Page, 1982). It seems that different reasons cause breaks at pressroom: press room conditions, reel condition, variation of paper properties (Roisum, 1990) and the average level of paper strength. Therefore, it seems understandable that a selected average paper strength property can, at best, have a limited correlation with pressroom breaks.

A laboratory study is, however, limited to the average level of paper strength. In this study it is assumed that the flaw-resisting ability of dry paper correlates with runnability in certain converting operations, like coating. Furthermore, it is assumed that the flaw-resisting ability can be described by in-plane fracture properties of paper, especially by fracture toughness. On the other hand it is considered that tensile strength, specific elastic modulus and elastic breaking strain correlate, e.g., with printing press runnability. Wet web runnability is a separate phenomenon which was not touched in this study.

According to the linear elastic fracture mechanics, *fracture toughness*, K_C, (material property) can be calculated from fracture energy (G_C) and elastic modulus (E) (Niskanen, 1998a):

$$K_C = \sqrt{G_C E}$$

Fracture toughness is directly proportional to the critical web tension or the apparent breaking stress of a flawed paper web (Niskanen, 1998). Fracture energy may also have a direct bearing on sudden disturbances in web tension, e.g. during printing.

In order to characterize the strength of the paper web in press rooms, Uesaka *et.al*. (1999, 2001) considered the tensile index and elastic stretch (tensile strength divided by elastic modulus). These two rheological factors are crucial for web breaks if web breaks are not initiated by flaws in the paper, but, instead, by "random" tension peaks that in most cases occur on unflawed paper. Then, the stress-strain behavior of paper controls the maximum tension peak that the web can endure without a break. In this study, instead of the term elastic stretch the term elastic breaking strain is used (Niskanen, 1998a; Tanaka, 2001).

The specific modulus of elasticity or modulus divided by density is often appropriate for thin materials like paper because no thickness measurement is necessary (Niskanen, 1998a). Specific elastic modulus has been considered to depend mostly on elastic modulus of component fibres (~fibre strength), fibre segment activation, and only a minor effect is due to increased interfibre bonding (Niskanen, 1998b; Hiltunen, 2003).

Target of this study was to find out the effect of fibre length and improved interfibre bonding and activation on flaw-resisting ability and tensile properties of TMP-reinforcement pulp mixture sheets.

MATERIALS AND METHODS

TMP was in all cases industrial never-dried (freezer stored) pulp from a Finnish mill and made from Norway spruce (*Picea abies*). Peroxide bleached TMP had CSF value of 35 (SCAN-C 21:65). The length-weighted average fibre length was 1.68 mm and coarseness (fines removed, R200) was 0.180 mg/m.

Chemical softwood reinforcement pulps were pilot-scale never-dried bleached pulps from a single raw material batch of Norway spruce (*Picea abies*). Three different cooking methods were used: conventional batch kraft, modified batch kraft and neutral sulfite, details in (25). Chemical pulps were bleached to the target brightness of 88% ISO with the same sequence: O-D-E-D. **Table 1** lists the FSP, kappa number, fibre length (unbeaten) and zero-span values of the chemical pulps. Pulp coarseness was 0.191 mg/m in all cases. FSP was measured by the solute exclusion technique (Stone, 1968). For the Aalto University FSP method, 0.03 g/g is considered to be a significant difference. Higher FSP is assumed to mean higher fibre swelling and thus higher internal fibrillation. Thus, high FSP means high bonding and activation potential.

Softwood reinforcement pulp refining was done with an Escher-Wyss conical laboratory refiner at intensity 2.0 J/m (SEL) – a typical value for softwood pulp. Refining consistency was 4%. 60 g/m^2 handheets were made according to SCAN 26:76 (with restraint drying). TMP containing sheets were made with a white water circulation in order to retain fines

Table 1. Some properties of spruce softwood pulps

	Fibre Saturation Point (**FSP**) (g_{H2O}/g_{fibre})	**Kappa number** (before bleaching) SCAN-C 1:77	Length- weighted **fibre length** (mm) Kajaani	Wet **zero span** (Nm/g) Tappi-273 pm/95
Conventional kraft	1.02	24.7	2.29	95.9
Modified kraft	1.06	25.4	2.27	88.5
Neutral sulfite	1.40	25.6	2.27	85.6

in the sheet. Fracture energy has been evaluated by using the in-plane tear (IPT) test (Kettunen, 2000a) with an ordinary tensile testing machine (MTS 400/M). Tensile properties were measured according to SCAN-P 38:80.

The size of the fracture process zone was measured by "damage analysis" from silicone-impregnated samples (Kettunen 2000a; Kettunen, 2000b; Kettunen, 2000c). The damage analysis gives "damage width", which is a measure of the size of damage zone (fracture process zone). The fracture process zone is the area where plastic deformation during paper fracture occurs (Seth, 1993). Plastic deformation in the damage zone consists of fibre and bond breakages and other microscopic ruptures during the fracture of paper. Silicone enhances the contrast of newly revealed fibre surfaces enough to allow the interfibre bond openings and fibre breakage to be detected (Korteoja, 1996). Examples of images of siliconized samples can be seen at Zhang (2002).

Silicone impregnation has only a minor effect on the interfibre debonding process (Kettunen, 2000c). After in-plane tearing the samples were scanned with an ordinary desktop scanner (Mustek). The images were analyzed using an appropriate program (Kettunen, 2000a). Main parameter measured: damage width (w_d), characterizes the extent of fibre debonding from the crack line. Independent thermographic measurement of the damage zone agrees with damage analysis results (Kettunen, 2000c).

RESULTS AND DISCUSSION

According to **Figure 1**, the highest out-of-plane tear strength is achieved with unbeaten pure chemical pulps. Increasing bonding and activation by refining of chemical pulp or by modifying cooking method decreases tear strength. Thus, it seems that the average fibre length is the dominating factor for traditional out-of-plane tear strength (fibre length of TMP 1.7 mm and of chemical pulps 2.3mm).

Because fracture energy is measured in different mode compared to traditional tear strength (in-plane *vs.* out-plane), the microscopic mechanism of fracture process is different. Thus, it is logical that is has been shown for chemical pulps that fracture energy (and in-plane tear) reach their maximum value at higher level of interfibre bonding than traditional out-of-plane tear (Seth, 1975). Here we study if the same holds true for mixtures of mechanical pulp and reinforcement pulp.

Fracture energy is strongly dependent on effective fibre length, **Figure 2b**. Damage width (w_d) measures the effective fibre length, **Figure 2a**. The dependency is linear with "reasonably well-bonded" sheets with varying fibre raw materials (Kettunen, 2000c).

When interfibre bonding is varied, the fracture energy of pure chemical pulps depends to some extent both on beating and cooking method, **Figure 3.** However, the effect on the mixture sheet fracture energy is significantly smaller – all of the mixture sheet data points are situated close to each other and at clearly separate level between pure TMP and pure chemical pulps. Average fibre length seems to have a dominating effect.

When pure neutral sulfite pulp and pure kraft pulps are compared at same refining energy level 90 kWh/t it can be seen that sulfite has actually higher fracture toughness, **Figure 4**. However, corresponding mixture sheets show no difference. Fracture toughness *vs.* refining of chemical pulp shows similar behaviour – pure chemical pulp sheets show differences, but in mixture sheets practically no change is noticed (a slight increase in fracture toughness at start of the refining). It seems that the average fibre length is the dominating factor for both mixture sheet fracture energy and fracture toughness. Interfibre bonding seems to have only a smallish secondary effect.

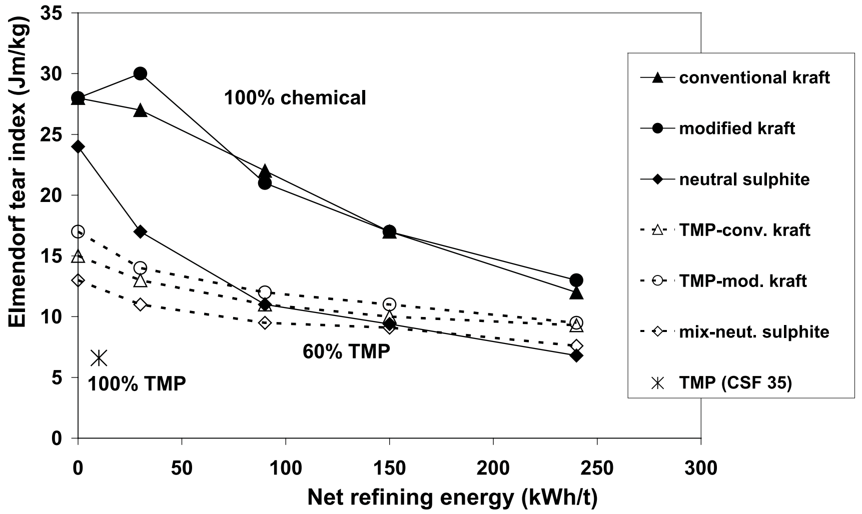

Figure 1. Out-of-plane tear (Elmendorf) *vs.* net refining energy at different refining energy levels + corresponding mixtures with TMP and pure TMP

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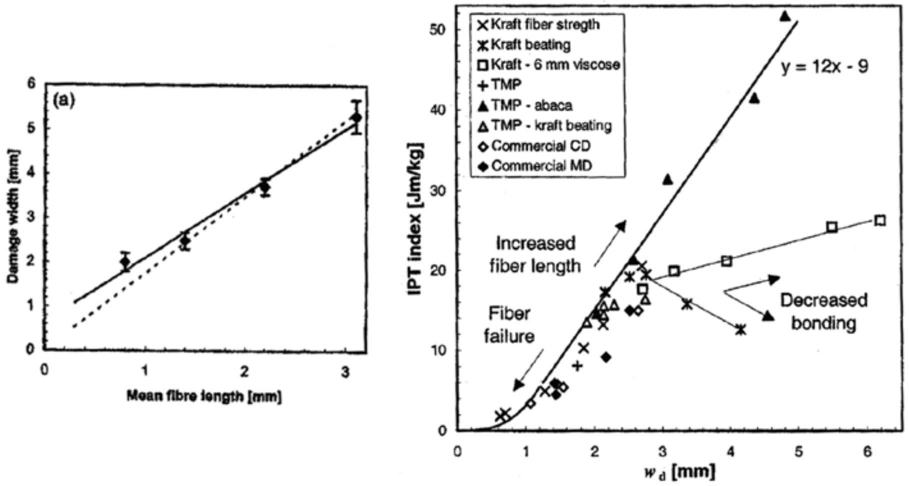


Figure 2. a) - Damage width *vs.* mean fibre length (Kettunen, 2000b). b) - Fracture energy (in-plane tear index) *vs.* effective fibre length (damage width) (Kettunen, 2000c)

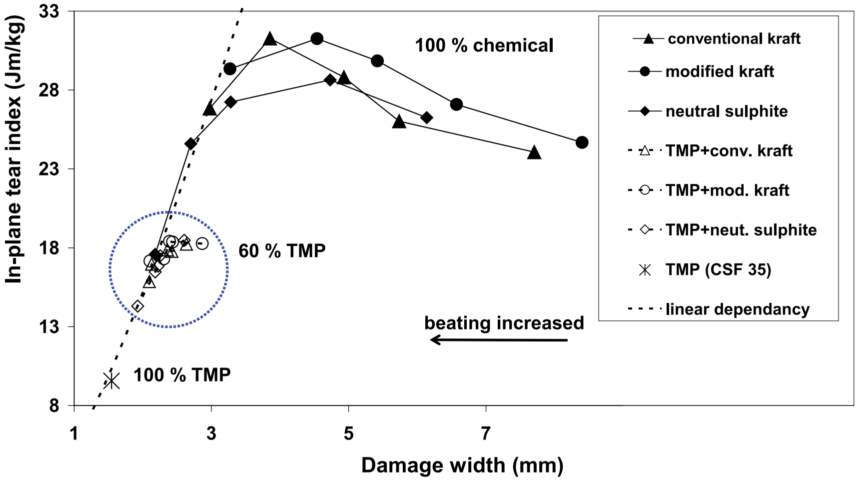


Figure 3. Fracture energy (in-plane tear index) *vs.* effective fibre length (damage width) for three chemical softwood pulps (closed symbols) at different refining energy levels + corresponding mixtures (open symbols) with TMP and pure TMP. Chemical pulp refining from 0 to 240 kWh/t

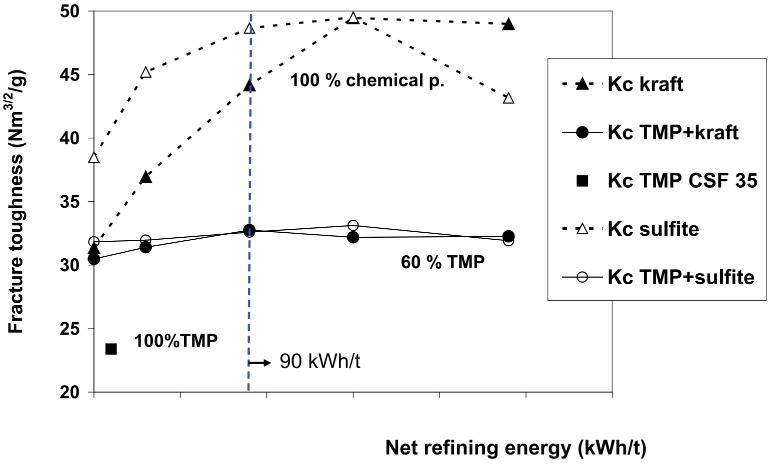


Figure 4. Fracture toughness (K_c) *vs.* chemical pulp refining energy for kraft pulp and neutral sulfite pulp, corresponding mixtures with TMP

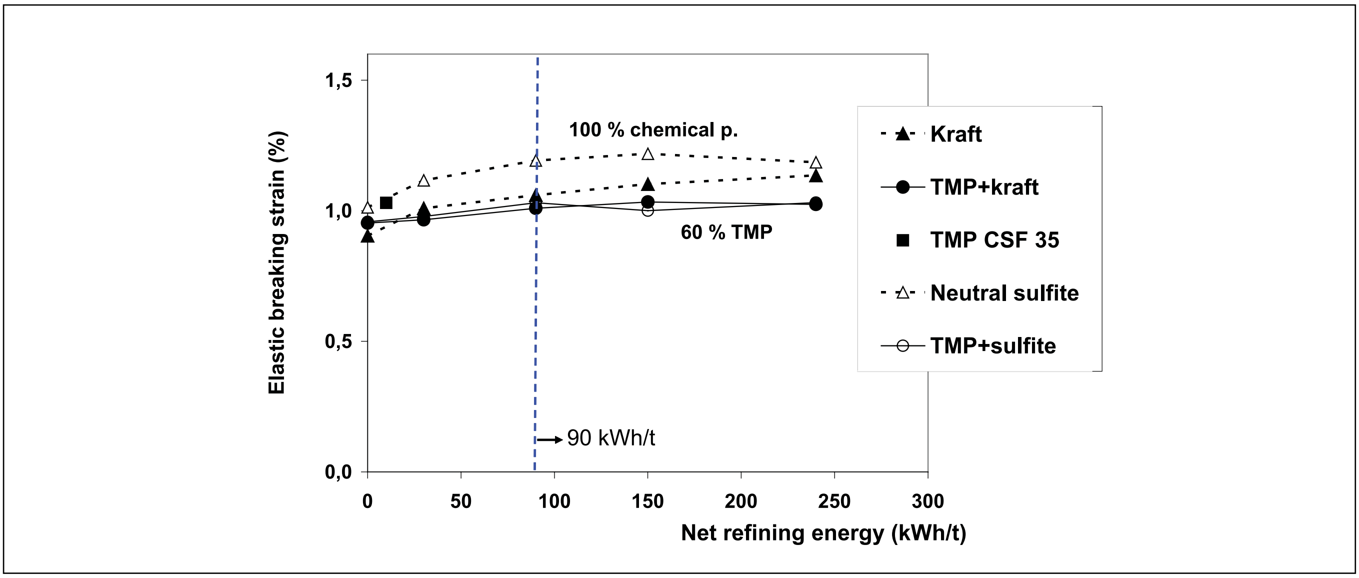
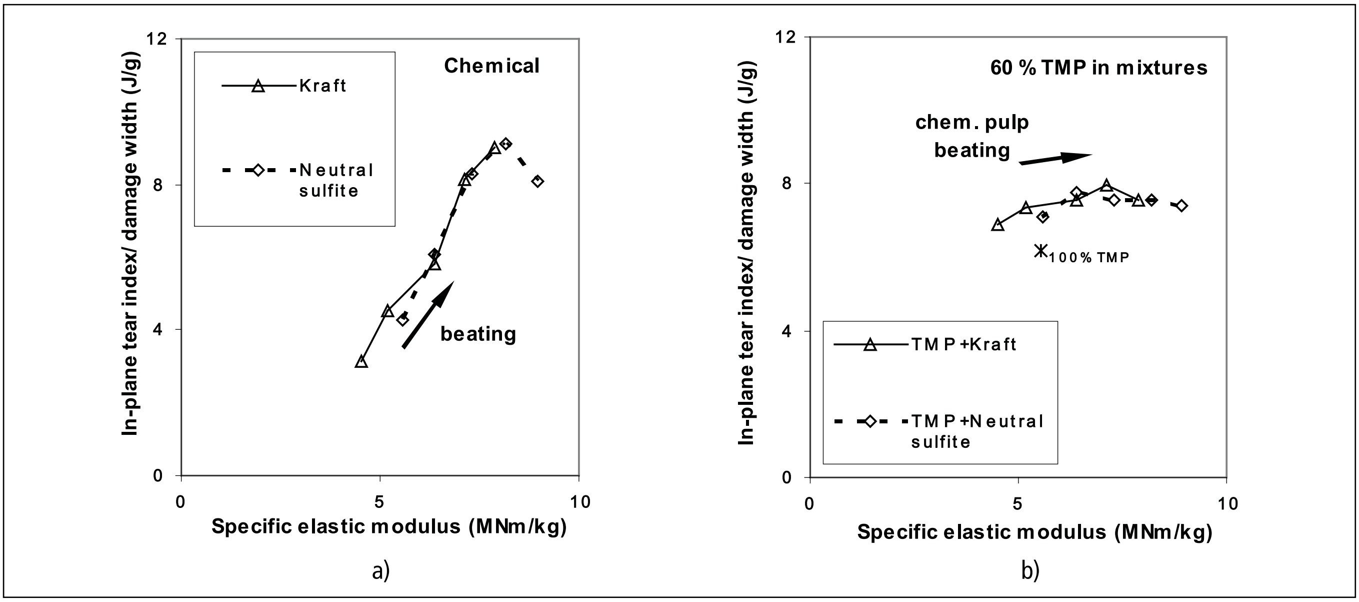


Figure 5. Elastic breaking strain (tensile divided by specific elastic modulus) *vs.* chemical pulp refining energy for kraft pulp and neutral sulfite pulp + corresponding mixtures with TMP



a)

b)

Figure 6. Fracture energy per damage width (G_C/w_d) *vs.* specific elastic modulus during beating of chemical pulp; a) pure chemical pulps b) mixture sheets with 60% TMP

Elastic breaking strain is considered to describe in-plane bonding properties of paper (Tanaka, 2001). It seems that refining of chemical pulp improves in-plane bonding of mixture sheets only slightly, **Figure 5**.

The bonding potential of chemical pulp (sulfite *vs.* kraft) seems to have no effect to the bonding of mixture sheets. In-plane bonding of pure TMP is in this case rather close to that of pure chemical pulps. In **Figure 6** the specific elastic modulus is assumed to describe fibre segment activation. Fracture energy/damage width (G_C/w_d) is a measure for in-plane bonding (Hiltunen, 2003). According to Figure 6a, refining of chemical pulp increases both interfibre bonding and fibre segment activation in pure chemical pulp sheets. However, in mechanical pulp-containing mixture sheets (Figure 6b) only activation is increased (bonding slightly in the beginning of refining).

The higher bonding potential (higher fibre swelling) of neutral sulfite pulp enables higher activation at lower level of refining energy for mixture sheets (compare starting points of curves), but the ratio of bonding *vs.* activation does not change (Figure 6b). As elastic modulus of chemical pulp sheets and mixture sheets is in the same range, it seems clear that fibre length does not much affect elastic modulus.

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CONCLUSIONS

Here the dry web runnability was evaluated primarily based on flaw-resisting ability of paper and secondarily based on in-plane tensile properties. We modified the fibre length and bonding potential of chemical softwood pulp–mechanical pulp mixture. Fibre length was manipulated by proportion of pulps, and interfibre bonding potential by beating level and cooking conditions of chemical pulp.

Results clearly showed that higher average fibre length improved the flaw-resisting ability of dry paper. As expected, beating of reinforcement pulp and sulfite cooking (*vs.* kraft) increased the interfibre bonding of pulp mixtures somewhat. However, contrary to our expectation, improved bonding increased the flaw-resisting ability only a little. It has been reported by Yu *et al.* (1999) that even with very poorly bonding viscose fibres, fibre length dominates fracture energy.

It seems clear that the flaw-resisting ability of reinforced paper can be best controlled by modifying the average fibre length of the furnish - controlling the bonding ability seems not as critical. It is known from elsewhere that also fibre strength is important for flaw resisting ability (Kärenlampi, 1997; Yu, 2000). Chemical pulp has higher fibre strength and, thus, works better as reinforcement pulp than mechanical pulp even at the same fibre length (Lehto, 2010).

Other factor is that beating of chemical pulp improves mixture sheet elastic modulus largely due to increased fibre segment activation, and only to smaller part due to bonding. On the other hand, tensile properties like elastic modulus are not dependent on fibre length, instead, they depend on fibre segment activation, interfibre bonding and fibre strength (Hiltunen, 2003). According to our analysis, low-freeness mechanical pulp has as such rather good interfibre bonding. The bonding ability of TMP seems not to be the bottleneck for printing paper runnability (Hiltunen, 2002).

The role of long-fibred reinforcement pulp in printing papers seems to be “only” to improve flaw-resisting ability. For example, elastic modulus is not significantly affected. It is also known that average strength of paper is only one factor affecting runnability. The use of reinforcement pulp can also have negative effects on runnability because long fibres are known to make formation poorer, thus deteriorating the evenness of paper. ■

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