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EFFECT OF FIBRE SHAPE AND FIBRE DISTORTIONS ON CREEP PROPERTIES OF KRAFT PAPER IN CONSTANT AND CYCLIC HUMIDITY

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ABSTRACT

The purpose of this investigation was to study the effect of fibre shape and fibre distortions on the creep properties in constant and cyclic humidity and compare these data to other standard paper properties. The fibre shape and magnitude of fibre distortions were varied by low consistency beating and high consistency treatment of the pulp. The term *virgin* were used for these pulps. Furthermore the effect of drying history was investigated where papers from straight fibres were dried under restrained- and freely-dried followed by reslushing. The term *re-dried* were used for these pulps.

Fibre shape and fibre distortions of the virgin pulps had different effects on the creep stiffness. Straight fibres with few distortions had the highest stiffness values. By making the fibres curlier, the creep stiffness decreased significantly. The presence of fibre distortions in the straight fibres had no effect on the creep stiffness.

The creep stiffness of papers from re-dried pulps depended on the drying method that produced the fibres. Without beating, fibres of the freely-dried paper gave a lower stiffness than fibres of the restrained-dried paper. The fibres had a memory of the distortions that were introduced by the free drying. After beating, the difference due to the drying method disappeared.

INTRODUCTION

An important property of packaging material is their ability to protect the content in the packages against outer mechanical damage during extended storage. For the corrugated board components, linerboard and corrugated medium, it is particularly important to provide this protection both in dry and high humidity atmosphere, particularly an atmosphere where temperature and moisture vary with time.

When paper is loaded in a constant humidity, it will deform with time, as other construction materials. The phenomenon is called creep. After a sufficiently long time, the paper will reach a strain at which the material will break. This time is usually called the lifetime of the material. Since compression is the dominate mode of loading for packaging materials, it is necessary to optimize the compression properties. Creep in compression of linerboard and corrugated medium at constant humidity has previously been treated in the literature and is reviewed by Haraldsson et al. [1, 2].

In practice, packages seldom experience constant humidity, but a varying humidity with variation of amplitude and frequency. Under those circumstances, creep is accelerated as compared with creep at the constant humidity. The phenomenon exists for a number of different materials besides paper, and is described by the term mechano-sorptive creep or accelerated creep [3, 4]. Creep in compression for paper in cyclic humidity is treated by Söremark et al. [5–7]. They also review the literature on this subject.

To judge the ability of packaging materials to withstand compressive loads, the compressive strength is typically used. The two most frequently used methods are SCT, ISO 9895 and RCT, ISO 12192. Testing according to these standard methods are used in production control and product specifications. They give an indication of the maximum load a paper can take during short times at the given humidity but do not give any information on the long-term loading, particularly not in non-standardised climate.

To evaluate the ability of packaging materials to withstand long-term loading, STFI-Packforsk has developed equipment and methodology based on measurements of creep properties in constant and cyclic humidity [1, 2, 8].

The creep properties are described in terms of an equation that gives the relation between stress, strain and time or number of cycles. Creep at small stresses can be described by the creep stiffness index, which can be used to rank materials and gives a first order approximation of the load bearing ability of the box. The full non-linear description of the creep would be of use in more detailed calculations.

It is known that fibre shape, such as curl, and magnitude of local fibre distortions, such as crimps, kinks and microcompressions, have a significant influence on mechanical properties [9]. The term microcompressions is used to describe the fibre distortions produced upon drying. The terms crimps and kinks are used to describe more severe distortions produced by different fibre treatments, such as high consistency mixing. In this paper, we use the term *fibre distortions* to include all types of local distortions.

There are only a limited number of publications that deal with the effect of recycling on creep properties [10–13]. The fibre properties will be affected by the initial drying of the paper to be recycled and by the processing of the paper to repulp the fibres and produce recycled paper. Drying introduces microcompressions in the fibres, which are already known to have a significant effect on the paper properties [14]. However, the effect of these microcompressions after recycling are less known although a memory of the drying has been reported [15]. Often the recycled fibres are subjected to high-consistency treatment during processing. High-consistency treatment can cause a change in the fibre shape and number of fibre distortions [16–18]. Another significant effect on kraft fibres due to recycling is hornification, i.e. a reduction in swelling and subsequent loss in density and strength [19]. The fibres can regain their swelling potential, density, and strength by low-consistency beating [15, 19].

The purpose of this investigation was to study the effect of fibre shape and fibre distortions on the creep of laboratory made kraft paper. The creep stiffness in compression was measured in both constant and cyclic humidity. In addition, standard compression-, tensile-, and hygroexpansion properties were evaluated. The fibre shape and number of distortions were varied by low consistency beating, high consistency treatment, and by drying of pulps with and without restraint. To study the effects of fibre state on paper properties, we have chosen to compare properties at the highest density, i.e. the highest degree of bonding, where the indexed properties are expected to have levelled off.

MATERIALS AND METHODS

Materials

The starting pulp for the trials was a dried, industrially made unbleached softwood pulp with kappa number 44. This particular pulp was chosen because it had a large amount of straight fibres with few fibre distortions. The pulp was subjected to PFI beating and high consistency (HC) treatment to form modified pulps for further evaluations. The term *virgin* were used for these pulps.

The papers made from one of the pulps were dried both under restraint and freely to get variations in the magnitude of fibre distortions. After reslushing of these two types of papers, new pulps were made for further evaluation. The term *re-dried* were used for these pulps.

Fines have a significant effect on paper properties [20]. Since the purpose of the investigation was to study effects of fibre properties, fines were removed from the pulps because they could mask effects of the fibre treatments. The effect of fines was beyond the scope of this investigation.

Table 1 lists the methods used for manufacturing procedures and evaluation of the properties of fibres, pulps, and papers.

Figure 1 shows the overview of the pulp treatments. The symbols illustrate the fibre shape and degree of fibre distortions. Based on measured fibre shape and classification of fibre distortion, pulps that followed the intended classifications were selected for testing. The shape factors of the different pulps are shown in Figures 2–4. The fibre swelling, in terms of WRV, is shown in Figure 5.

Virgin pulps

- <u>Group A</u>. Pulps 1–4 were beaten at low consistency for 0 to 4000 PFI revolutions. **PFI beating straightened the fibres and increased the fibre swelling. Pulps 3 and 4 were selected because they were straight and had few fibre distortions.**
- <u>Group B</u>. Each of pulps 1–4 were subjected to high consistency (HC) treatment. **HC treatment made the fibres curly and decreased the fibre swelling. The pulps in this group were curly and had many fibre distortions. Pulps 3h1, and 4h1 were chosen for further characterization.**
- <u>Group C</u>. Pulp 8 was PFI beaten at 0–4000 PFI revolutions. **PFI beating straightened the fibres and increased the fibre swelling. The selected pulps 1h3 and 1h4 were straight and had many fibre distortions.**

Table 1 Manufacturing procedures and methods for property evaluation.

Manufacturing procedures and properties	Methods
Fibre length and shape factor	STFI FibreMaster Shape factor is the ratio of projected fibre length and the true fibre length. Length weighted average values are reported. Perfectly straight fibres = 100 % [21].
Relative amount of fibre distortions. Class 1) few fibre distortions Class 2) many fibre distortions.	Fibres were examined in polarized light based on a method described by Page [22]. A judgment of the relative amount of fibre distortions was made subjectively by a trained technician.
WRV	SCAN-C62:00
PFI beating	PFI mill according to SCAN C 24:67
High consistency (HC) treatment	Electrolux, 12 litre, kitchen mixer for 4 hours at 15% consistency.
Fines removal	Laboratory filter using 200 μm nylon cloth.
Reslushing	SCAN C 18:65.
Restrained dried papers, 140 g/m^2	ISO 5269/1–1979 with deionized water using a concentration of 0.2 g/litre.
Freely dried papers, 140 g/m^2	Same papermaking procedure as above except that the papers were allowed to shrink freely. The papers were kept flat during drying between two permeable flat plates separated by a distance of one mm.
Papers for physical testing	Same procedure as for restrained dried papers described above.
Grammage	SCAN P 6:75
Structural density	Density has been used as a quantification of the degree of bonding [24, 25]. The density was be calculated based on the paper's intrinsic thickness, where the effect of surface structure is minimized [26] For our work, SCAN-P88:01 was used.
Compression strength (SCT)	ISO-9895
Tensile properties	SCAN-P67:93
Hygroexpansion	ISO 8226/1 with a custom-made apparatus described in [23]. The results are expressed as coefficient of hygroexpansion, hygroscopic strain in % divided by the difference in RH between 33 to 66 % RH

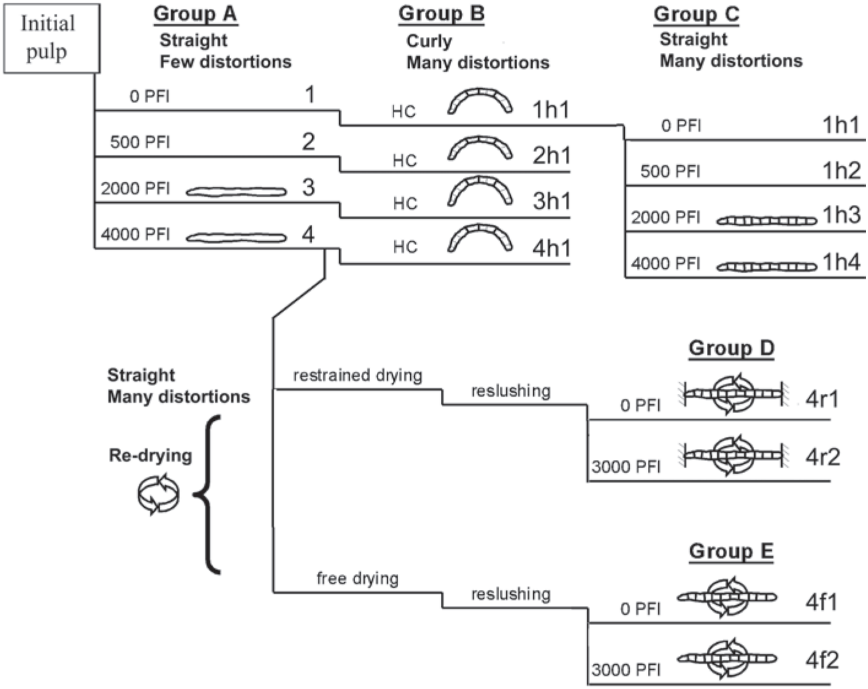

Figure 1 Schematic of the fibre treatment.

Re-dried pulps

- Group D. Papers from pulp 4 was dried under restraint, reslushed, and PFI beaten at 0–3000 PFI revolutions. **The selected pulps, 4r1 and 4r2, were straight and had many fibre distortions.**
- Group E. Papers from pulp 4 was dried freely, reslushed, and PFI beaten at 0–3000 PFI revolutions. **The selected pulps, 4f1 and 4f2, were straight and had many fibre distortions.**

Comment: Re-drying reduced the WRV, but it was recovered by additional beating. Restrained dried papers gave slightly higher straightness than freely dried papers due to straightening of fibre segments during drying.

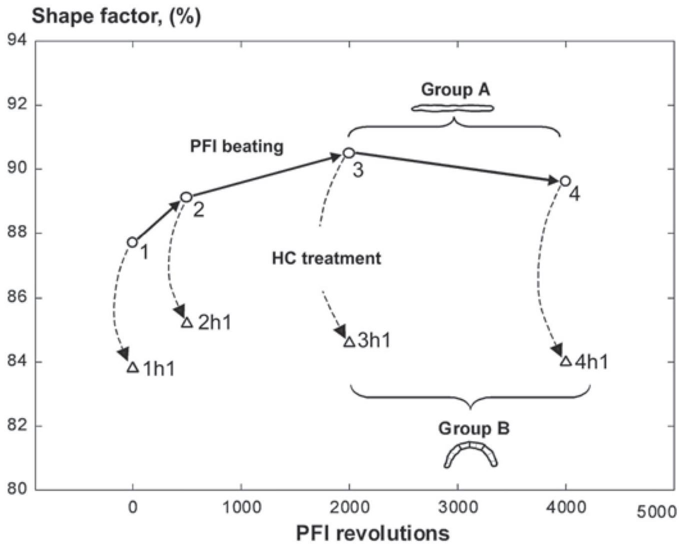

Figure 2 Shape factor with PFI beating and HC treatment for groups A and B.

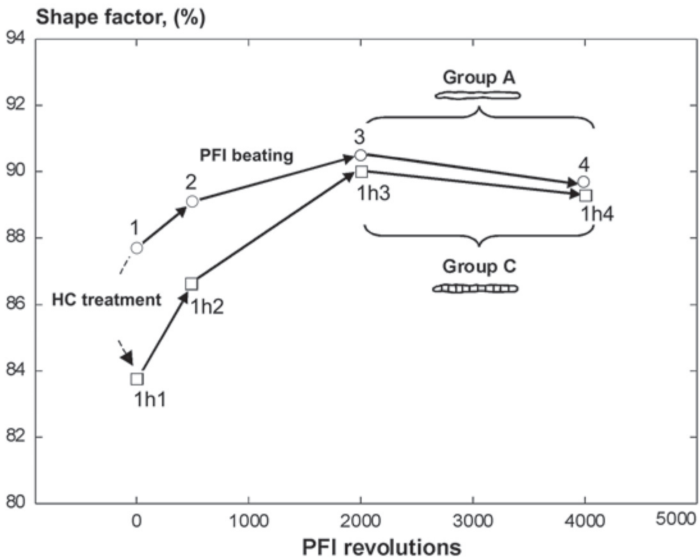

Figure 3 Shape factor with with PFI beating and HC treatment for groups A and C.

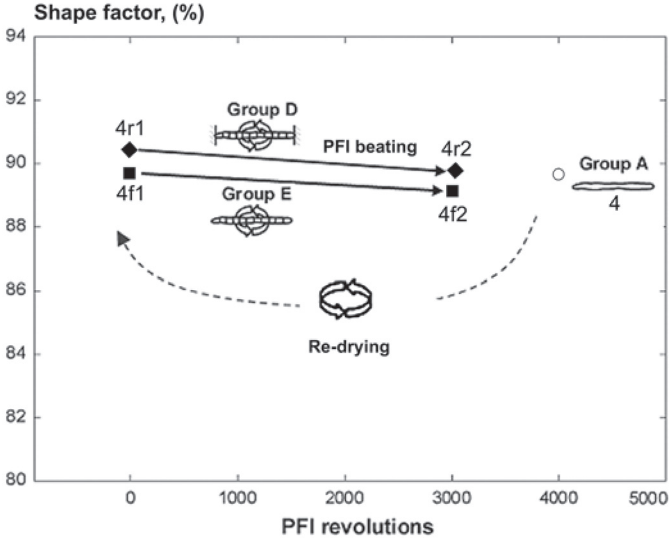

Figure 4 Shape factor with re-drying and PFI beating for groups D and E.

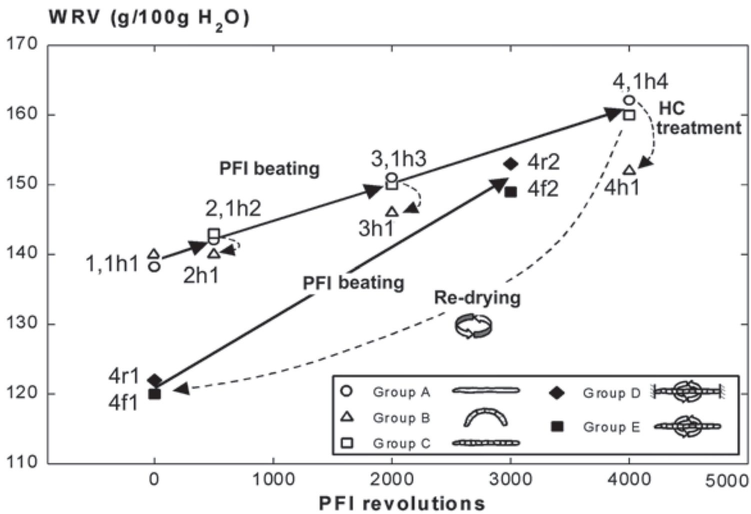

Figure 5 WRV as a function of PFI revolution for the different treatments of the pulps.

Evaluation of creep properties

The principles of evaluation are described in a separate publication [8]. Creep stiffness index can be understood as the force per unit width per unit grammage, for small forces, divided by the strain after a given number of cycles or a given time. If the material should be insensitive to moisture and time, the value would be equal to the tensile stiffness index. A summary is given below.

A test piece was loaded in compression. The applied stress was chosen in such a way that the strain did not exceed 0.2 % during the creep. The strain was recorded as a function of number of cycles or time.

The term **Isocyclic Creep Stiffness Index** was used for the creep behaviour when the paper was exposed to a cyclic humidity between 50 and 90% RH with a cycle time of 7 hours. For small strains, the isocyclic creep stiffness after N cycles, $E^{cr,w}(N)$, is given by Equation (1). The samples were tested for 3 cycles. The strain values at the end of each cycle, at 50 % RH, were used to determine the stiffness and the parameters. Finally, the isocyclic creep stiffness after 10 cycles was predicted.

$$E^{cr,w}(N) = \frac{\sigma^w}{\varepsilon(N)} = a_2 \cdot N^{-p} \tag{1}$$

where

$E^{cr,w}(N)$ is the isocyclic creep stiffness index after N cycles, Nm/kg
σ^w is the stress expressed as force per unit width per unit grammage, Nm/kg
N is the number of cycles
$\varepsilon(N)$ is the strain at the end of each cycle, at 50%RH
a_2 and p are material parameters.

The term **Isochronous Creep Stiffness Index**, was used for the creep behaviour when the paper was exposed to a constant humidity either at 50% RH or at 90% RH. For small strains, the isochronous creep stiffness is given by Equation (2). The strain values during three minutes loading were used to calculate the stiffness and material parameters. Finally the isochronous creep stiffness after 24 hours was predicted.

$$E^{cr,w}(t) = \frac{\sigma^w}{\varepsilon(t)} = a_2 \cdot \left(\frac{t}{t_0}\right)^{-p} \tag{2}$$

where

$E^{cr,w}(t)$ is the isochronous creep stiffness index at time t, Nm/kg
σ^w is the stress expressed as force per unit width per unit grammage, Nm/kg

t_0 is the reference time, equal to one second.
$\varepsilon(t)$ is the strain at time t
a_2 and p are material parameters

Note that the values of the material parameters, a_2 and p, for the isocyclic equation will be different than the values for the isochronous equation.

Creep apparatus

The apparatus used for compressive creep tests has been previously described [8]. Important factors for the design of this apparatus include that buckling of test piece under axial compression was prevented by sets of columns and that forces due to movement of the columns and clamp were negligible. The paper width was 25 mm, the initial distance between clamps was 54 mm and the gap between the columns was 0.6 mm. The gage length for the strain measurement was 43 mm.

Preconditioning

When paper is exposed to changing humidity, the paper dimensions permanently change. To describe the phenomena, the term *release of internal stresses* is used [27]. Since different papers might have been exposed to different number of cycles, a comparison without preconditioning may be misleading. Furthermore, the evaluation procedure of isocyclic stiffness requires that the strains are reversible after moisture cycling at zero load. A release of the internal stresses was used by cycling the samples between 50 and 90% RH at least 10 times before physical testing.

Statistical treatment of data

95 % confidence limits are shown in the figures.

RESULTS

Isocyclic and isochronous creep

Figure 6 shows the isocyclic creep stiffness index as a function of structural density for the investigated pulps. Looking first at the virgin pulps at the highest density, the general trend is that Group B (curly, with many fibre distortions) had a much lower stiffness than Group A (straight, with few fibre distortions) and Group C (straight, with many fibre distortions). There was

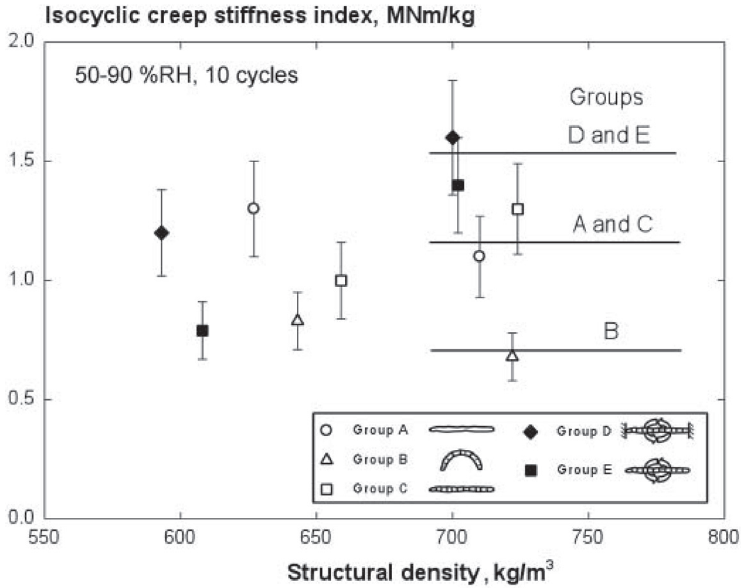

Figure 6 The isocyclic creep stiffness index after 3 cycles in a cyclic relative humidity (50–90–50 % RH, 7 hours) as a function of structural density.

no significant difference between Groups A and C. Apparently, the fibre distortions in C had an insignificant effect.

Before additional beating, both re-dried pulps showed a significantly decrease in density. The freely dried pulp (Group E) showed a significantly lower stiffness than both the restrained dried pulp (Group D) and the virgin pulps with straight fibres (Groups A and C). Additional beating increased both the density and the stiffness to the same levels as the virgin pulps and minimized the differences between the drying methods.

Figures 7 and 8 show the isochronous creep stiffness index, at 50 and at 90% RH respectively, versus structural density. These results show the same trends as for the creep stiffness index in cyclic humidity.

Tensile properties

The results for tensile properties are shown in the Figures 9–11. For the straight fibre pulps, all properties increased with structural density. At the highest density, there was no difference in stiffness and strength for the

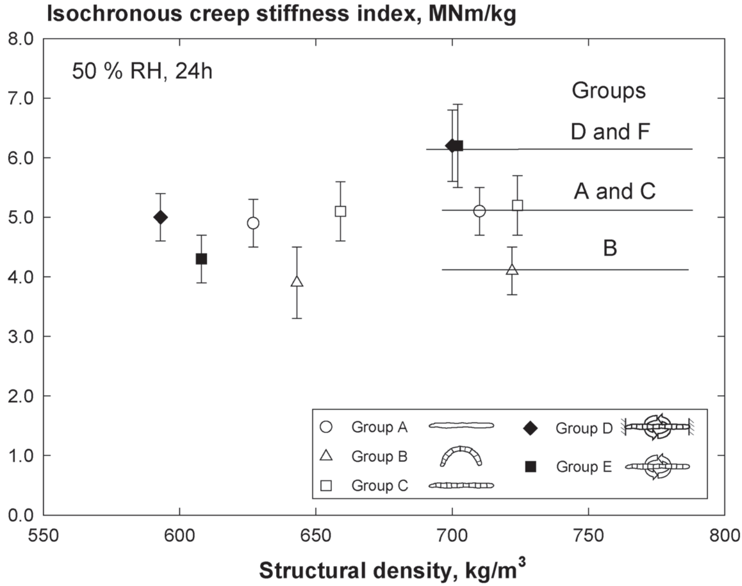

Figure 7 Creep stiffness index in 50% RH constant humidity after 24 hours, as a function of structural density.

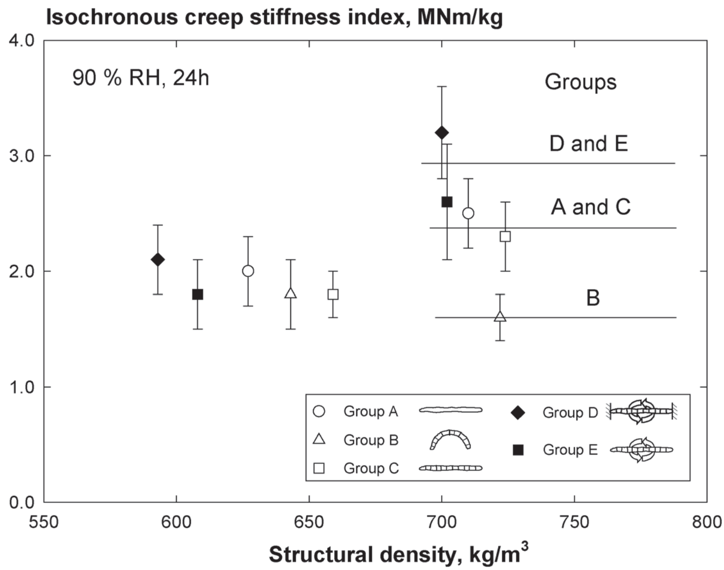

Figure 8 Creep stiffness index in 90% RH constant humidity after 24 hours, as a function of structural density.

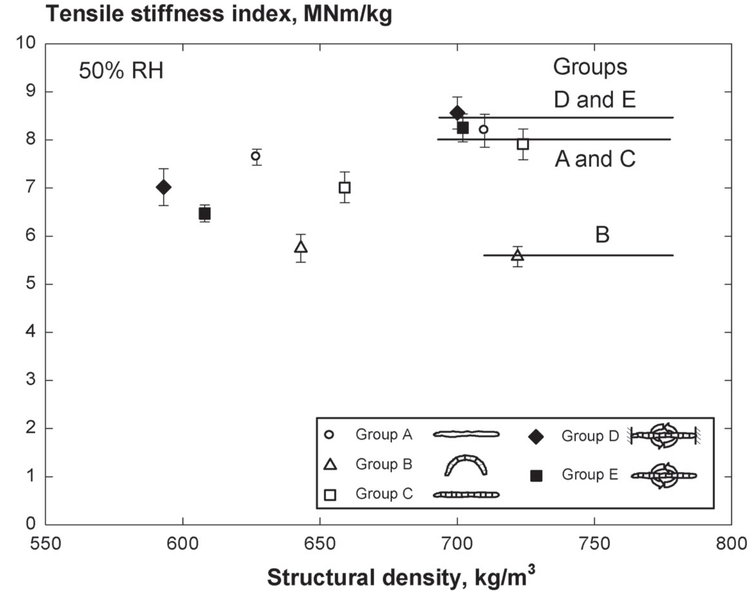

Figure 9 Tensile stiffness index at 50 % RH as a function of structural density.

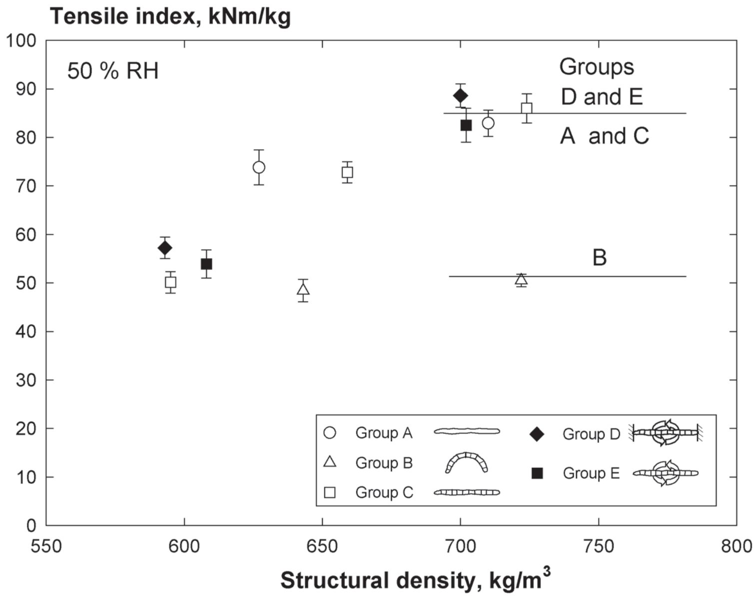

Figure 10 Tensile index at 50 % RH as a function of structural density.

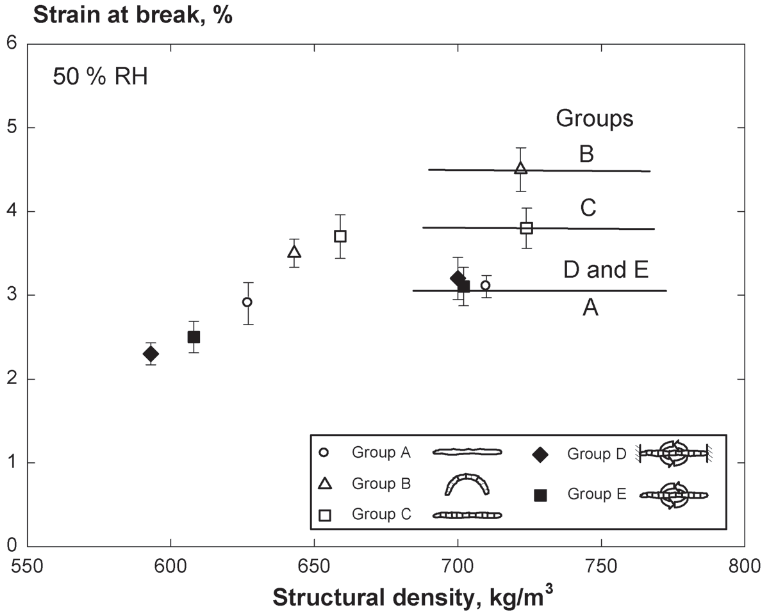

Figure 11 Strain at break in tension at 50 % RH as a function of structural density.

different pulps with straight fibres. Group B (curly, with many fibre distortions) had significantly lower stiffness and strength. The strain at break was highest for Group B (curly, with many fibre distortions) followed by Group C (straight, with many fibre distortions) and Group A (straight, with few fibre distortions). Once-drying reduced the strain at break, but it was recovered by additional PFI beating.

Compression index

The compression index versus structural density is shown in Figure 12. The compression index increased with density for all the papers and there was no significant difference between the pulps with the exception of Group B (curly, with many fibre distortions), which gave lower values.

Hygroexpansion

The coefficient of hygroexpansion versus structural density is shown in Figure 13. Group B (curly, with many fibre distortions) produced papers with the highest coefficient of hygroexpansion followed by Group C (straight, with

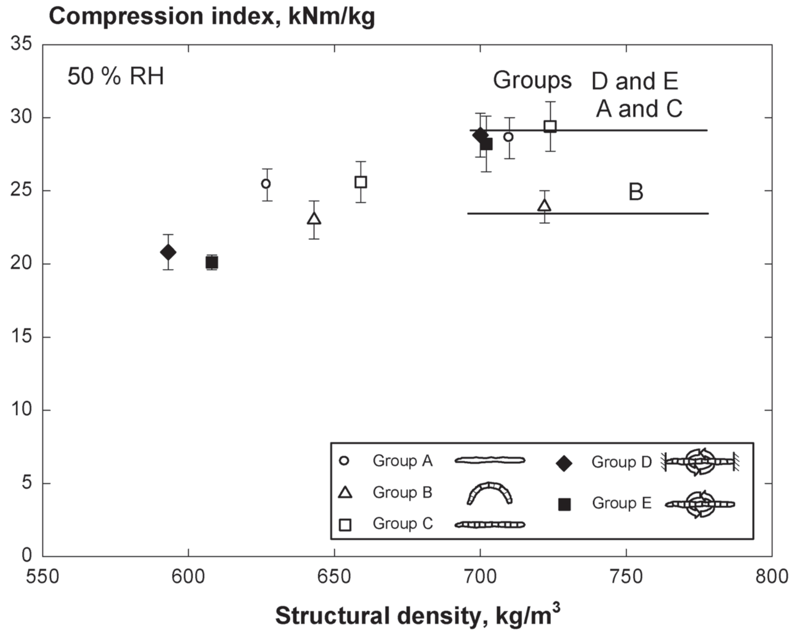

Figure 12 Compression index at 50 % RH as a function of structural density.

many fibre distortions). There was no significant difference between the other pulps.

DISCUSSION

The purpose of this investigation was to study the effect of fibre shape and fibre distortions on the creep properties in constant and cyclic humidity and compare these data to other standard paper properties. The fibre shape and magnitude of fibre distortions were varied by low consistency beating and high consistency treatment of the pulp. The term *virgin* were used for these pulps. Furthermore the effect of drying history was investigated where papers from straight fibres were dried under restraint and dried freely followed by reslushing. The term *re-dried* were used for these pulps.

In order to isolate the effects of fibre shape and fibre distortions from structural features of the paper, it is necessary to compare properties where the structural features are expected to be constant. Page and Seth's theory for the elastic modulus of paper enables us to discuss the conditions under which

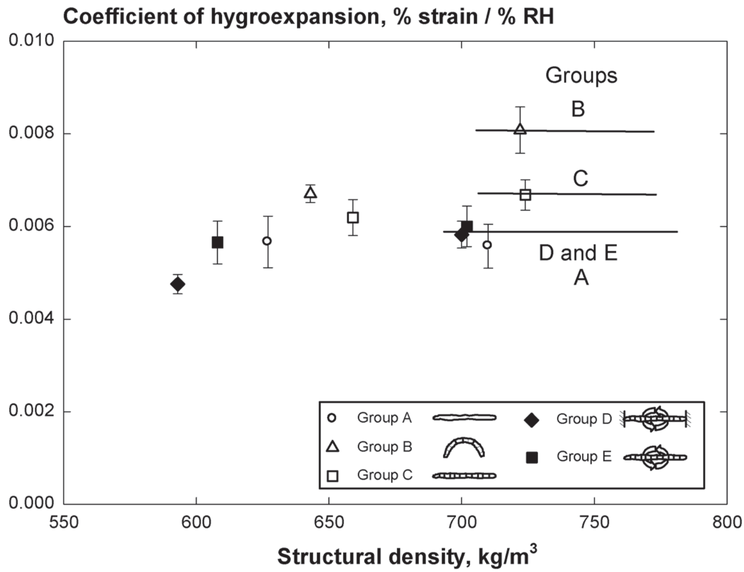

Figure 13 Coefficient of hygroexpansion as a function of structural density. The moisture ratio was 4.7% at 33%RH and 8.5% at 66%RH.

bonding can be considered constant [28]. For a given pulp this theory states that the tensile stiffness index of the paper is determined from the bonding of the paper and the fibre state, e.g. fibre shape and fibre distortions. As bonding increases, the stiffness index initially increases then levels off to a finite value. The maximum stiffness index is 1/3 of the fibre stiffness for straight fibres with few fibre distortions and decreases from this maximum as the fibres become curlier and as the magnitude of fibre distortions becomes greater.

To study the effects of fibre state on paper properties, we have chosen to compare properties at the highest density, i.e. the highest degree of bonding, where the indexed properties are expected to have levelled off.

The general trend due to curly fibre state as stated by Page and Seth also holds for our tensile stiffness data in Figure 9. Increased bonding increased the stiffness and curly fibres decreased the stiffness. In our data, the presence of fibre distortions seemed to have less importance. At the highest density, the only obvious effect of fibre distortions was on the strain at break. This indicates that the type of fibre distortion introduced by high consistency beating became active only at higher strains.

The same general discussions also apply for tensile strength and for compression index. Compression index was surprisingly unaffected by the fibre state with the exception of the curly fibres which gave slightly lower values. Strain at break behaved as expected and so did hygroexpansion in accordance with previous findings [29] where curly fibres were found to increase hygroexpansion.

The properties of papers from re-dried pulps depended on the method that produced the pulps. Re-drying the fibres without beating resulted in sheets with decreased density; the density was recovered by further low-consistency beating. Without beating, papers made from fibres of the freely-dried paper had a lower stiffness than papers made from fibres of the restrained-dried paper. Obviously, the fibres had a memory of the fibre distortions that were introduced by the free drying, an effect previously found for tensile properties [15]. After beating, this difference due to the drying method disappeared. Further, the difference between papers from virgin and re-dried fibres disappeared after beating of the re-dried pulps, which agrees with previous results [13, 15, 19]. In fact, in some cases the re-dried pulps gave higher values than the virgin pulps.

Relation between creep properties and tensile stiffness

In a previous publication [8] it was suggested that certain stiffness ratios could be used to explore whether creep stiffness could be related to a standardized paper property. Two of these are analysed in this paper. *Mechano-Sorptive Factor (MSF)* is the isocyclic creep stiffness after 10 cycles between 50 and 90%RH (50–90,10c) divided by the isochronous creep stiffness at 90%RH after 24 hours. *Total Creep Effect (TCE)* is the isocyclic creep stiffness (50–90,10c) divided by the tensile stiffness at 50%RH. The correlation between isocyclic creep stiffness and tensile stiffness at 50% RH is shown in Figure 14, from which *TCE* can be evaluated.

For the variables studied in this investigation, the conditions that affect the tensile stiffness also seem to affect the creep stiffness at any given RH environment. Note that these results apply for these types of fibres and testing variables and we do not imply that the same interpretation will be universal to all papermaking variables.

MSF and *TCE* were not significantly affected by the fibre variables in this investigation. The calculated values of *MSF* = 0.44 and *TCE* = 0.16 are somewhat higher than previously published values for machine-made papers [8]. These differences may be due to many factors such as fines content, fibre orientation and drying restraints. This warrants further investigation.

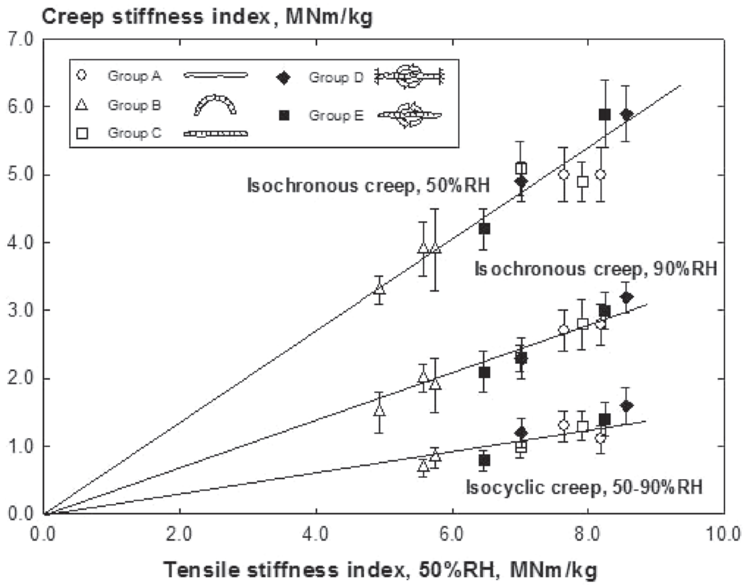

Figure 14 Creep stiffness index for isochronous and isocyclic creep as compared with the tensile stiffness index at 50% RH.

CONCLUSIONS

The effect of fibre shape and fibre distortions on creep stiffness followed the same trends as for tensile stiffness, thus it is concluded that the highest creep stiffness is achieved with well-bonded sheets containing straight fibres. The presence of fibre distortions in straight fibres had no detrimental effect on well-bonded sheets; the type of fibre distortion introduced by high consistency treatment became active only at higher strains. Re-drying decreased both the creep stiffness and tensile stiffness by reducing the density and introducing fibre distortions. Low consistency beating of the re-dried fibres restored the properties.

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Transcription of Discussion

EFFECT OF FIBRE SHAPE AND FIBRE DISTORTIONS ON CREEP PROPERTIES OF KRAFT PAPER IN CONSTANT AND CYCLIC HUMIDITY

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Gary Baum

You showed in the beginning of your talk stacks of boxes and you talked about the need for both appearance and survival. This may not be a fair question, but how do you interpret the contribution your results to the end goal of creating a stack of boxes looking good?

Joel Panek

It would be a matter of looking at the out-of-plane deflection of a corrugated wall. The amount of out-of-plane deflection under a load would be based on the components and based on the environment it is under. You should look at this deflection in addition to whether the panel fails.