

EFFECT OF DRYING CONDITIONS ON THE TENSILE PROPERTIES OF PAPER

Petri Mäkelä

Innventia AB (former STFI-Packforsk AB),
Box 5604, SE-114 86 Stockholm, Sweden,
petri.makela@innventia.com

ABSTRACT

Results in the literature disagree regarding the effect of drying temperature, final drying time, and drying constraint history, respectively, on the in-plane tensile properties of paper materials. Furthermore, it is debated whether the in-plane tensile properties are controlled by the final drying stress or by the total strain during drying.

In this work, the drying mechanics of a pilot machine-made paper grade was studied. Wet paper sheets were collected after the wet press section. The sheets were dried in a laboratory dryer using different drying constraints. The supplied heating power, the ambient climate, and the ventilation of the paper sheets were controlled during the drying trials, which made it possible to independently alter the drying temperature and the final drying time. The dried sheets were conditioned in 23°C and 50% RH before tensile testing.

The results showed that the tensile stiffness, tensile strength, strain at break, and tensile energy absorption of the dried sheets, respectively, were linearly related to the total strain during drying of the sheets. These linear relations were shown to be unaffected by drying temperature, final drying time, and drying constraint history. On the other hand, the corresponding relations between the in-plane tensile properties and final drying stress were found to be both non-linear and greatly dependent on the drying constraint history.

INTRODUCTION

Htun and de Ruvo [1] report results from drying experiments performed for laboratory handsheets that were produced from a bleached softwood kraft pulp. The sheets were dried under restraint and the drying temperature and final drying time were controlled and altered independently in the trials. The results in their work show that the in-plane tensile stiffness, *Figure 1*, and tensile strength of the dried papers were improved by short final drying times and low drying temperatures.

Investigations of paper drying that involve independent control of the drying temperature and final drying time are rare in the literature. Two additional studies in this field have been reported by Östlund *et al.* [2] for a bleached softwood kraft pulp, and by Wahlström [3] for an unbleached softwood sulphate pulp. Both these investigations were performed using basis weight series as an indirect method to achieve different final drying times without altering the supplied heating power. The sheets with different basis weight were dried under restraint using different drying temperatures in

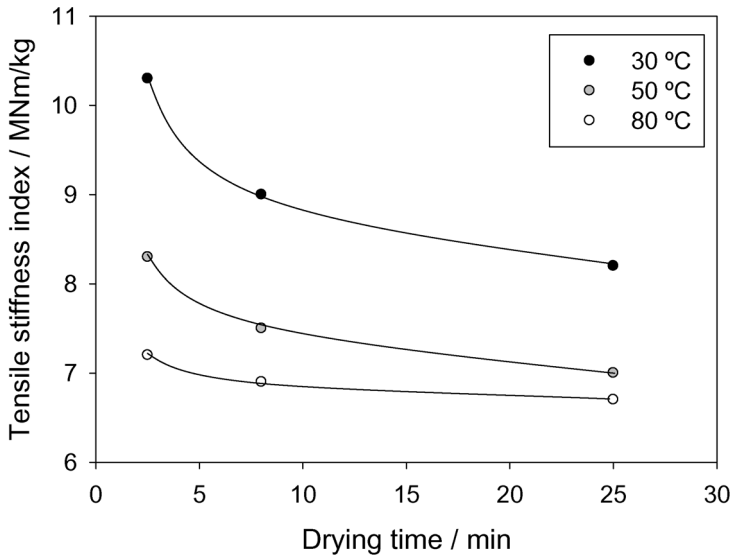


Figure 1. Results extracted from the work by Htun and de Ruvo [1], showing the effect of final drying time and drying temperature on the tensile stiffness of paper sheets dried under restraint.

both these studies. The results by Östlund *et al.* [2] confirm the previously reported results by Htun and de Ruvo [1] by showing that short final drying times and low drying temperatures improve the tensile stiffness. However, the results by Wahlström [3] show that the tensile stiffness is independent of the drying temperature and final drying time. Other similar studies in the literature (e.g. [4–6]), which were performed without controlling the drying temperature and final drying time independently, generally support the findings by Wahlström.

Htun and de Ruvo further report that the in-plane tensile stiffness and strength, respectively, are linearly related to the final drying stress [7], and that the relationship between strain at break and total strain during drying is non-linear and greatly dependent on the drying constraint history [8]. However, Wahlström *et al.* [9] show that the tensile stiffness, tensile strength and strain at break, respectively, are linearly dependent on the total strain during drying, independently of whether the drying constraint is applied in terms of prescribed strain or prescribed stress.

Clearly, the literature contains conflicting results regarding the drying mechanics of paper materials. The aim of this work was to clarify the effect of drying conditions on the resulting in-plane tensile properties of the dried paper material. This task was approached by performing carefully designed drying experiments, where the drying temperature, final drying time and drying constraint history were controlled and altered independently.

MATERIALS AND METHODS

Materials

A pulp consisting of a mixture of previously dried bleached softwood pulp (20%) and never-dried bleached hardwood pulp (80%) was studied. The pulp was refined to 22.7° SR (WRV 1.55) and the paper material was produced in the EuroFEX pilot paper machine at Innventia as a three-layered structure. Each layer had equal pulp composition and target basis weight. Roll forming was used and each layer was produced using a lip opening of 4 mm, a forming concentration of 5.8 g/l, and a jet speed of 643 m/min. The machine speed was 600 m/min. Standard fine paper fabrics and felts were used. The wet pressing was performed in three steps; a first double-felted roll press nip (60 kN/m) followed by two single-felted shoe press nips (500 kN/m and 700 kN/m).

The wet paper web was wound up after the wet press section. Square paper sheets, 20 cm by 20 cm, were cut-out from the wet paper web. The collected wet paper sheets were placed in a tight-fitting plastic bag, which was sealed

and placed in a cold storage room pending the drying trials. The plastic bag with the paper samples was stored in a climate of 23°C and 50% RH for 24 hours, in order to let the sheets reach temperature equilibrium, before the drying trials were initiated.

Drying trials

The STFI BiaxialDryer [9], an advanced laboratory drying equipment allowing for studies of user-defined biaxially constrained drying strategies, was used for drying the paper samples. The STFI BiaxialDryer was equipped with a fan (a 12" three-bladed table fan, Wormanco, 55 W) and the drying trials were performed in a climate room (Troëdsson climate chamber). These arrangements made it possible to independently control the final drying time and drying temperature by altering the ambient climate, the ventilation of the sheet during drying, and the heating plate temperature of the STFI BiaxialDryer.

Different drying constraints, in terms of a constant magnitude of either prescribed strain or prescribed stress, were applied to the paper sheets during the drying trials. The constraining was applied to the wet paper sheet immediately after the drying process had been initiated. The applied constraining was then retained during the remainder of the drying trial. The initial wet configuration of the sheet was used as the reference configuration for evaluating strains. The strains and stresses of the sheet were measured continuously during the drying trial. The sheet was dried until no further increase in drying stress (prescribed strain conditions) or no further sheet shrinkage (prescribed stress conditions) could be detected. The final drying time was evaluated as the drying time needed to reach this equilibrium drying state.

The drying strategies were carefully planned in order to secure that all sheets were "over-dried" beyond their equilibrium moisture ratio at 23°C and 50% RH. In this way, moisture sorption hysteresis effects were avoided by ensuring that all sheets reached moisture equilibrium through adsorption during the subsequent conditioning.

A pre-study was performed in order to study the effect of different heating plate temperatures, ambient climates, and ventilations on the final drying time. The pre-study resulted in that the following settings were selected for the main study:

- Heating plate temperature: 23°C (heating plate turned off) or 150°C.
- Ambient temperature: 23°C.
- Ambient relative humidity: 15% RH or 90% RH.
- Ventilation: Fan at full speed or turned off.

Table 1 summarises the different strategies that were used in the drying trials, i.e. the different combinations of heating plate temperatures, ambient climates, ventilations, and loading types, and the resulting final drying times for each of these strategies.

Four different degrees of prescribed strain (−1, 0, 1, or 2% strain) and five different degrees of prescribed linear load (100, 200, 300, 400, and 500 N/m) were used in the drying experiments. Moreover, a free drying trial was conducted within each drying strategy using a prescribed linear load of 10 N/m. This small linear load was adopted to ensure that the paper sheet remained reasonably flat during the drying process. This small load had negligible effect on the free shrinkage potential as well as on the in-plane tensile properties of the dried paper, as compared with papers dried using a low-friction anti-buckling guide. All drying constraints were applied in the MD, while free drying was applied in the CD throughout the drying trials.

The total strain during drying and the final drying stress were evaluated as the measured strain and stress of the paper sheet in MD at the final drying time. The total strain during drying was corrected for the released elastic strain caused by the removal of the drying constraints from the paper sheets.

Table 1. Summary of used drying strategies and the resulting final drying times.

<i>Drying strategy</i>	<i>Temp. °C</i>	<i>RH%</i>	<i>Fan</i>	<i>Drying constraint</i>	<i>Final drying time / min</i>
High temp fast drying	150	15	ON	Prescribed strain	3.7
Low temp fast drying	23	15	ON	Prescribed strain	6.3
High temp slow drying	150	90	OFF	Prescribed strain	7.5
Low temp slow drying	23	15	OFF	Prescribed strain	15.8
Prescribed stress	150	15	OFF	Prescribed stress	5.8

Physical testing

The dried paper sheets were conditioned in 23°C and 50% RH for 24 hours before further actions were taken. The grammage of the sheets was evaluated and found to be linearly related to the total strain during drying. The evaluated grammage was 86.4 g/m² for the freely dried sheets and 85.1 g/m² for the sheets that were dried using 2% prescribed strain in MD.

All in-plane tensile testing was performed in MD, i.e. in the principal material direction that had been subjected to different degrees of drying constraints in the drying trials. The tensile testing was performed using the L&W tensile tester in an ambient climate of 23°C and 50% RH. The tensile stiffness, tensile strength, strain at break, and tensile energy absorption in MD, were evaluated in accordance with ISO 1924-3:2005. The specific tensile properties for the dried and conditioned paper sheets were evaluated using the individual grammage of each sheet.

RESULTS

Relation between in-plane tensile properties and total strain during drying

Figure 2 shows the evaluated tensile stiffness versus the total strain during drying for each of the four drying strategies that involved prescribed strain. The concerned sheets were either freely dried or dried using a prescribed strain of -1, 0, 1, or 2%, respectively. The lines in the figure (one line for each drying strategy) were determined by linear regression analysis and the error bars denote the 95% confidential interval. A negative total strain during drying indicates that the sheet shrunk during the drying trial, while a positive total strain during drying means that the sheet did expand. The corresponding results for tensile strength, strain at break, and tensile energy absorption, respectively, are shown in *Figures 3–5*.

The results show that each of the investigated in-plane tensile properties exhibited a linear relation to the total strain during drying. Furthermore, the results show that neither the drying temperature nor the final drying time had any statistically significant influence on the in-plane mechanical properties of the studied paper sheets.

Effect of drying constraint history on drying mechanics

Figure 6 shows the strain history during drying for the sheets that were dried using the “fast drying at high temperature”-strategy. The concerned five sheets were either freely dried or dried using a prescribed strain of -1, 0,

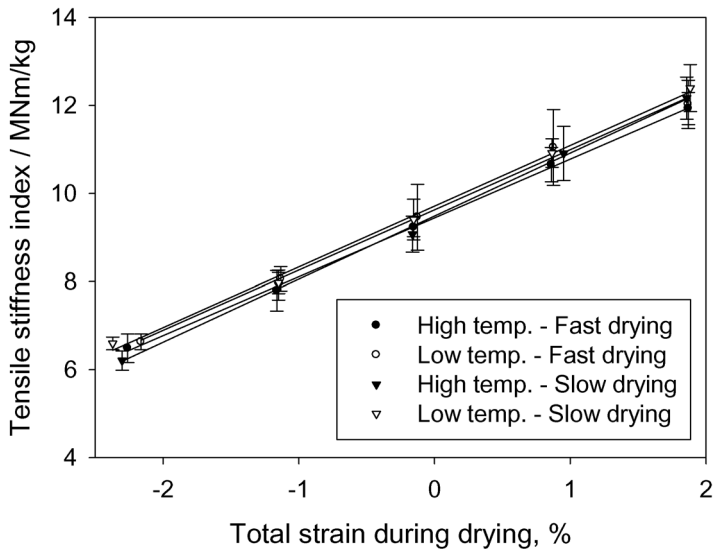


Figure 2. Tensile stiffness index in MD versus total strain during drying in MD for the sheets that were dried using the four different prescribed strain strategies.

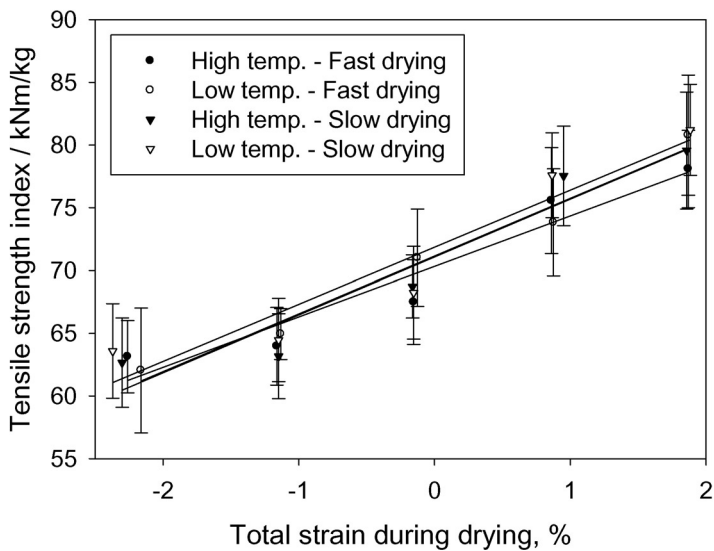


Figure 3. Tensile strength index in MD versus total strain during drying in MD for the sheets that were dried using the four different prescribed strain strategies.

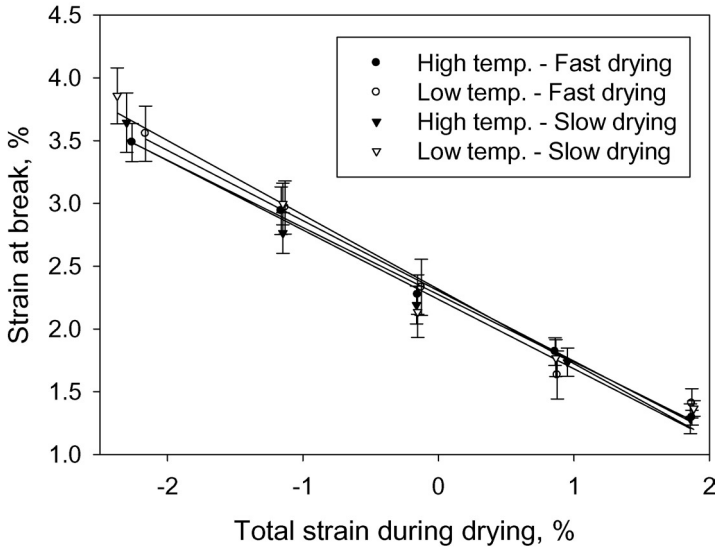


Figure 4. Strain at break in MD versus total strain during drying in MD for the sheets that were dried using the four different prescribed strain strategies.

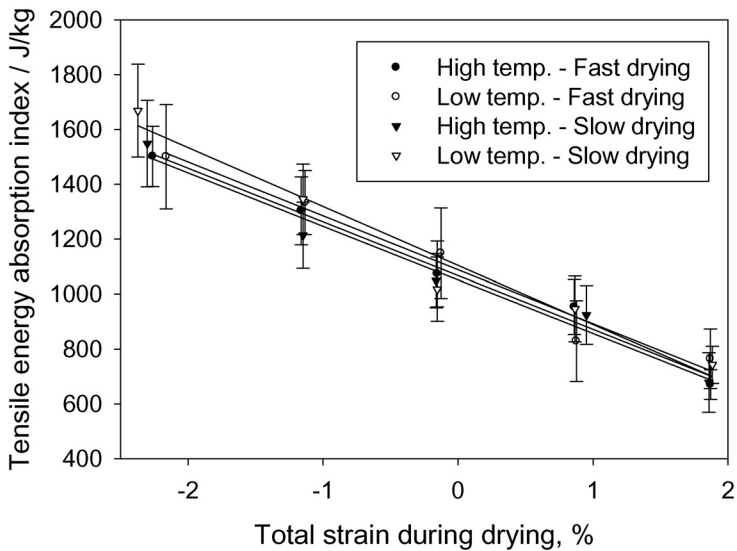


Figure 5. Tensile energy absorption index in MD versus total strain during drying in MD for the sheets that were dried using the four different prescribed strain strategies.

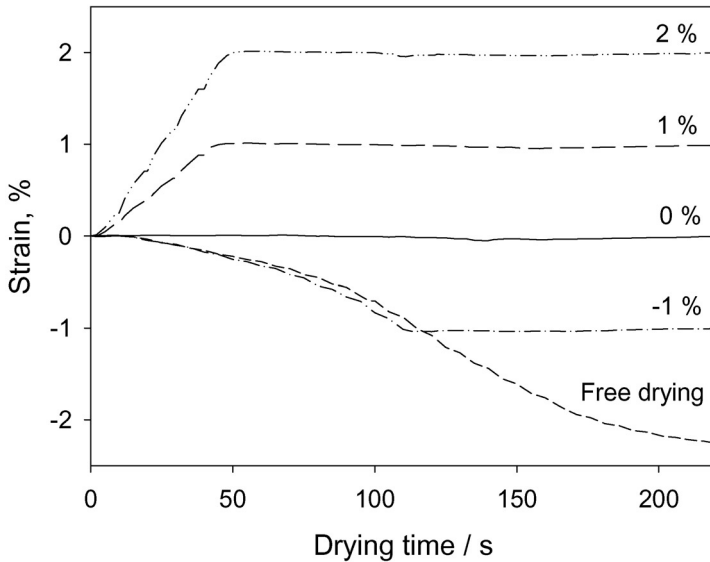


Figure 6. Strain history in MD during drying for the sheets that were dried using the “fast drying at high temperature”-strategy.

1, or 2%, respectively. The corresponding stress history is shown in *Figure 7*.

A large effect of stress relaxation on the drying mechanics was observed in the results, which may be exemplified by the sheet that was dried using 2% prescribed strain in *Figure 7*. This sheet responded with decreasing stress immediately after the prescribed constant strain had been reached. A continued increase of the stress could have been expected, since the constraining situation becomes gradually more severe as the sheet strives to shrink during the continued drying process. Clearly, the stress relaxation of the paper material counteracted and initially managed to suppress the increasing constraint severity. Furthermore, all constrained sheets ended up with a fairly similar final drying stress, although one of these sheets was allowed to shrink 1%, while another one was wet strained 2%.

Figure 8 shows the stress history during drying for the sheets that were dried using the prescribed stress strategy. The concerned six sheets were either freely dried or dried using a prescribed linear load of 10, 100, 200, 300, 400, or 500 N/m, respectively. The corresponding strain history is shown in *Figure 9*.

A large effect of creep on the drying mechanics was observed in the results,

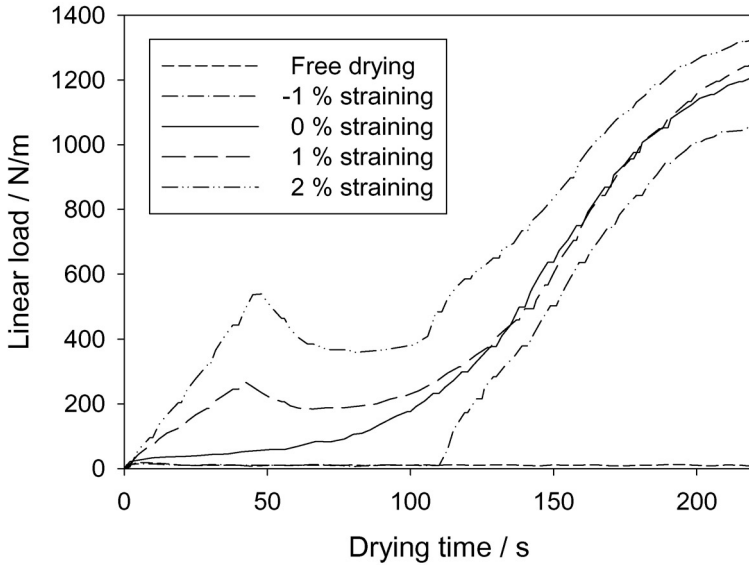


Figure 7. Stress history in MD during drying for the sheets that were dried using the “fast drying at high temperature”-strategy.

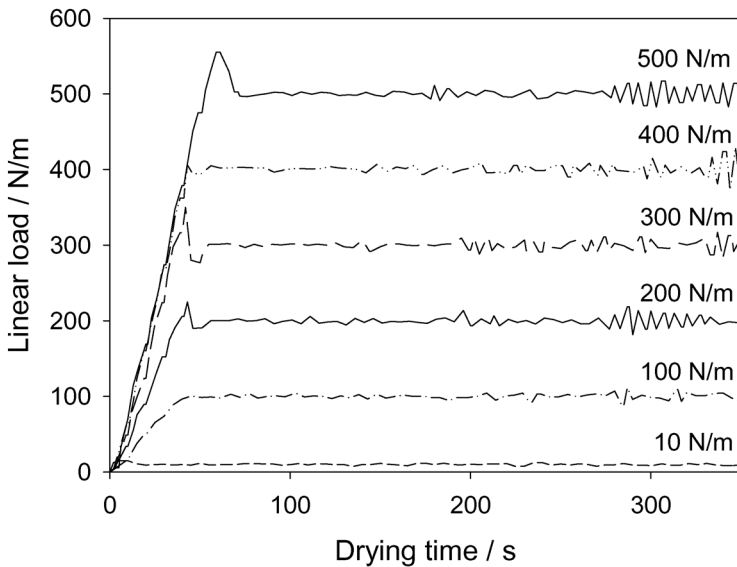


Figure 8. Stress history in MD during drying for the sheets that were dried using the prescribed stress strategy.

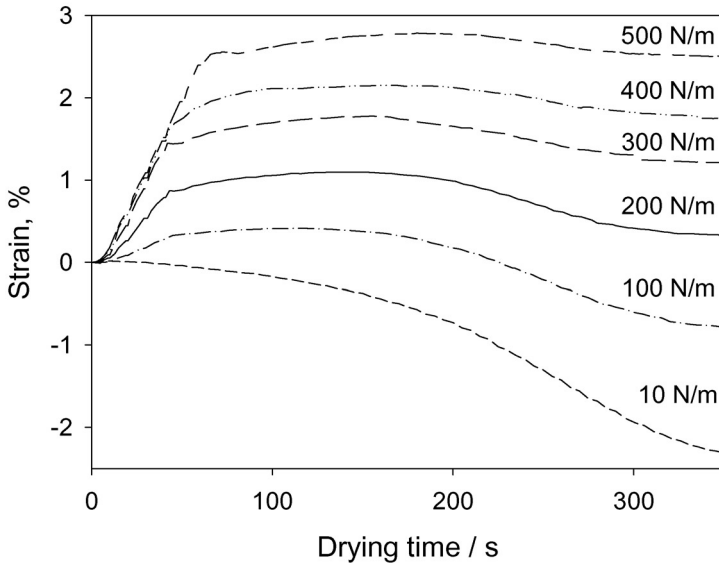


Figure 9. Strain history in MD during drying for the sheets that were dried using the prescribed stress strategy.

as may be exemplified by the sheet that was dried using a prescribed linear load of 500 N/m in *Figure 9*. This sheet reached a strain of roughly 2.5% immediately after the prescribed linear load had been applied. Thereafter, the strain of the sheet initially continued to increase, although sheet shrinkage associated with water removal during drying could have been expected. Finally, the sheet ended up with a total strain during drying of roughly 2.5%, meaning that after the prescribed stress had been applied, the sheet shrinkage was counteracted and finally balanced by the creep strain.

It is obvious from *Figures 6–9* that prescribed strain conditions cause completely different stress and strain histories during drying than prescribed stress conditions.

Effect of drying constraint history on in-plane tensile properties

Figure 10 shows a comparison of the evaluated tensile stiffness between the sheets that were dried under prescribed strain and prescribed stress, respectively, versus the total strain during drying. *Figures 11* and *12* show the corresponding results for the tensile strength and strain at break, respectively. These

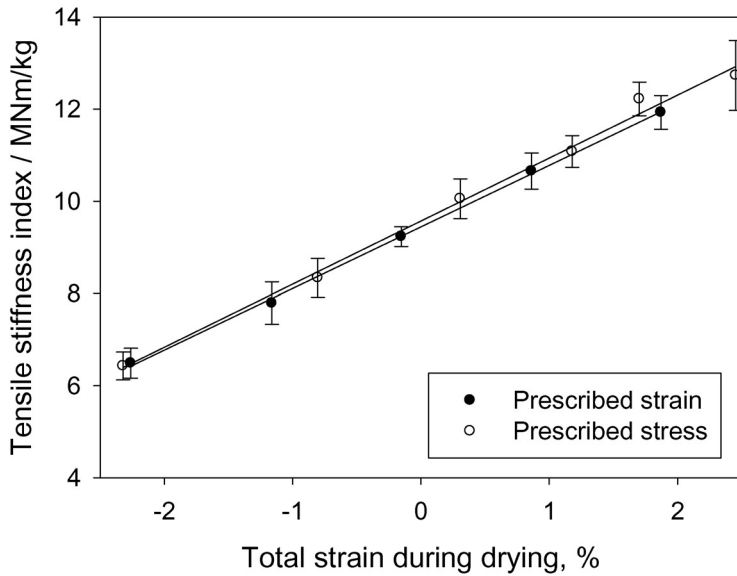


Figure 10. Tensile stiffness index in MD versus total strain during drying in MD for sheets dried under prescribed strain and prescribed stress, respectively.

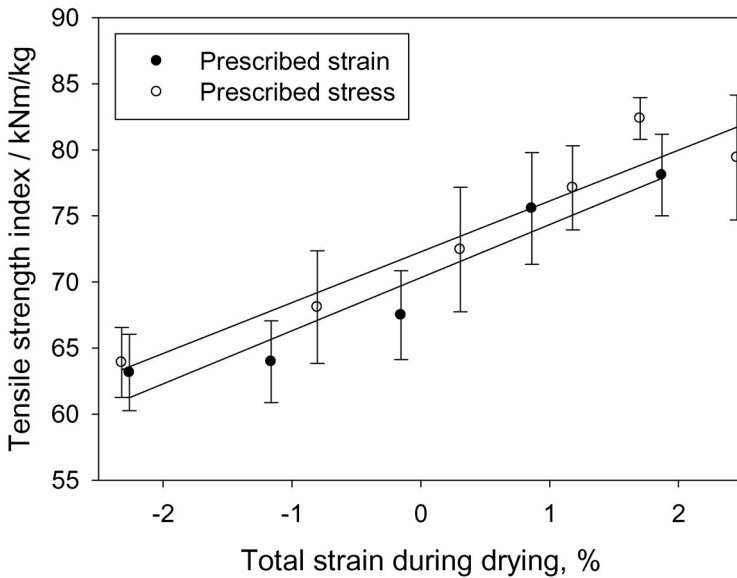


Figure 11. Tensile strength index in MD versus total strain during drying in MD for sheets dried under prescribed strain and prescribed stress, respectively.

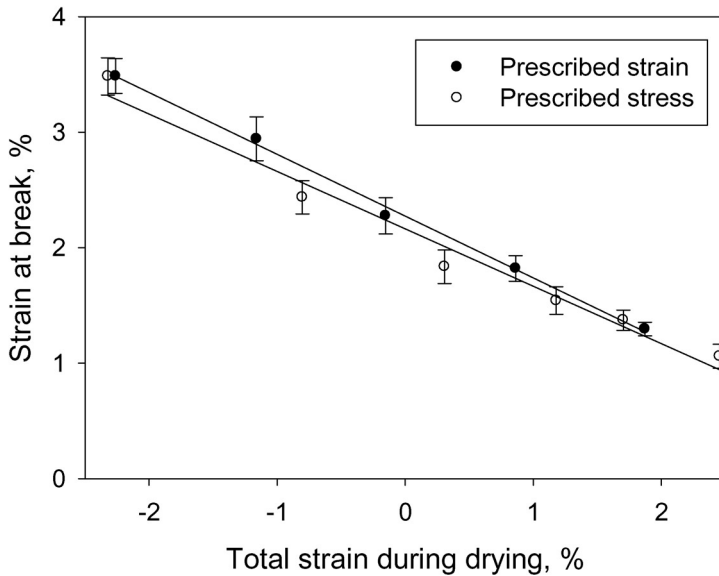


Figure 12. Strain at break in MD versus total strain during drying in MD for sheets dried under prescribed strain and prescribed stress, respectively.

results show that the linear relations between the in-plane tensile properties and the total strain during drying were unaffected by the drying constraint history.

Relation between in-plane tensile properties and final drying stress

Figure 13 shows a comparison of the tensile stiffness between the sheets that were dried under prescribed strain and prescribed stress, respectively, versus the final drying stress. The lines in the figure simply connect the mean values of the evaluated tensile stiffness for each drying strategy. The corresponding results for tensile strength and strain at break are shown in *Figures 14–15*. These results clearly show that the relations between the in-plane tensile properties and final drying stress were non-linear and greatly dependent on the drying constraint history.

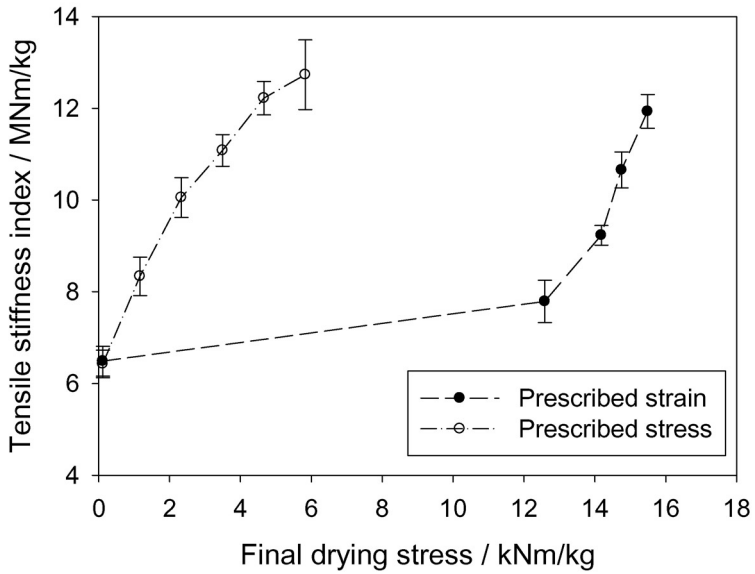


Figure 13. Tensile stiffness index in MD versus final drying stress in MD for sheets dried under prescribed strain and prescribed stress, respectively.

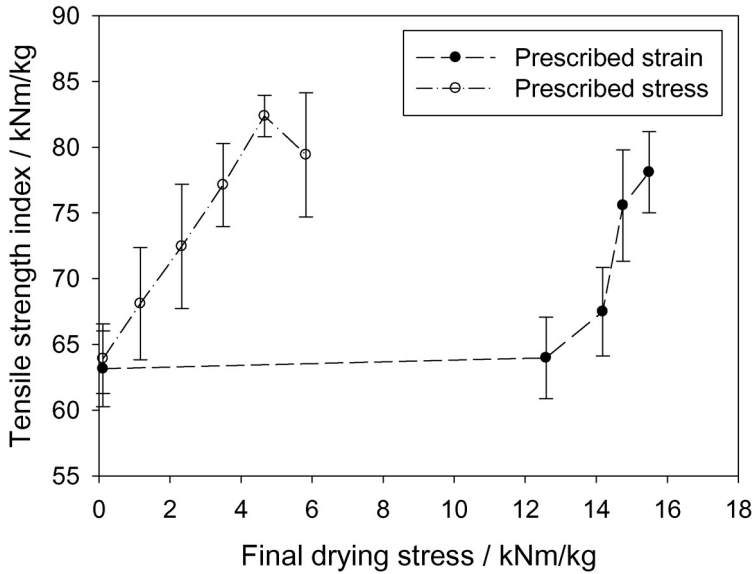


Figure 14. Tensile strength index in MD versus final drying stress in MD for sheets dried under prescribed strain and prescribed stress, respectively.

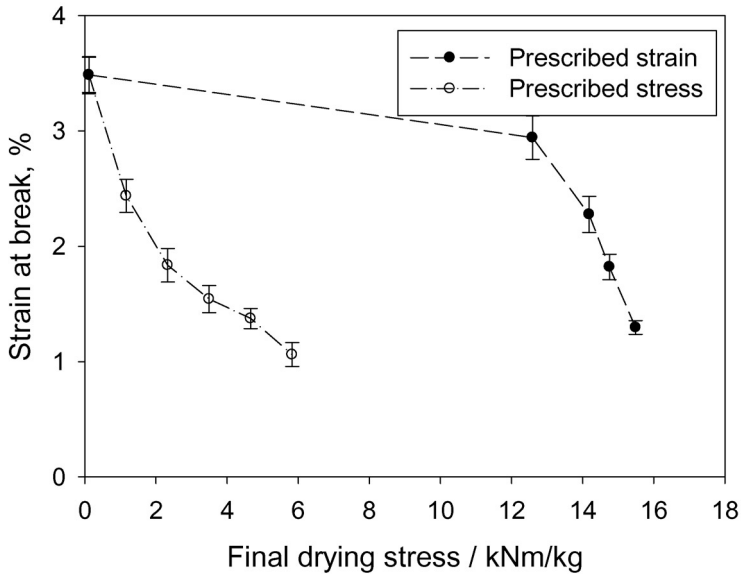


Figure 15. Strain at break in MD versus final drying stress in MD for sheets dried under prescribed strain and prescribed stress, respectively.

CONCLUSIONS

The in-plane tensile properties of a pilot machine-made paper grade were found to be linearly dependent on the total strain during drying, independently of the used drying temperature, final drying time, and drying constraint history. The drying temperature and final drying time had no or negligible effect on the in-plane tensile properties of the paper. The relations between the in-plane tensile properties and the final drying stress were found to be non-linear and greatly dependent on the drying constraint history.

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Transcription of Discussion

EFFECT OF DRYING CONDITIONS ON THE TENSILE PROPERTIES OF PAPER

Petri Mäkelä

Innventia AB (former STFI-Packforsk AB), Box 5604, SE-114
86 Stockholm, Sweden

Torbjörn Wahlström Stora Enso

For 30 years, we have been thinking that there is potential in having the right combination of drying time and temperature and now you say that this effect does not exist?

Petri Mäkelä

Our experiments clearly show that such potential does not exist. I cannot account for what people have been thinking during the last 30 years, so I would like to re-direct this question to the audience, starting with you. Have you believed in this potential?

Torbjörn Wahlström

No.

Doug Coffin Miami University

Given your understanding of time and temperature effects in drying, could you put the previous results and your results in some context that we can understand?

Discussion

Petri Mäkelä

It would just be speculation. No, I do not want to try explaining results obtained by other researchers.

Anders Åström Aylesford Newsprint

Just to clarify, you showed in several of the graphs, the strain versus the drying time. It seems that you did not apply the strain initially, the strain built up as the paper dried. Did I read the graph correctly?

Petri Mäkelä

Do you mean Figures 6 to 9 in the paper?

Anders Åström

Yes. About 50 seconds is the time when you have built up the two parameters, stress and strain.

Petri Mäkelä

The maximum strain rate of the STFI BiaxialDryer, the laboratory drying apparatus that was used in the drying trials, is limited. About 40–50 seconds was required to reach 2% straining in the equipment. All prescribed strains and stresses during the drying trials were applied as linear ramps under finite time periods rather than as steps.

Anders Åström

Do you think that it could make any difference?

Petri Mäkelä

The use of loading steps rather than loading ramps may influence the results, but I do not think that this would change the general trends or conclusions from the study.

Anders Åström

Thank you.

Torbjörn Wahlström Stora Enso

Commenting on this question just raised, that must be an extremely small difference. In one case you have shrinkage and strain at the beginning of drying and in another one you have it at the end of drying, and it gives exactly the same effect on tensile stiffness. It shows that it does not matter where you apply the strain during drying, it is just the amount of strain that governs what properties you get.

Petri Mäkelä

Thank you, Torbjörn, for expanding the question and giving me a helping hand. Of course you are right.

Gary Baum PaperFuture Technologies (from the chair)

I have a comment. I wonder if you are familiar with the work of Setterholm at the US Forest Products Laboratory? He did a very nice treatment of this topic back in the 1970s. He produced some very nice graphs relating drying restraints, shrinkage and draws but not temperature and time, however.

Petri Mäkelä

Yes, I am aware of him.