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WET WEB RHEOLOGY ON A PAPER MACHINE

Atsushi Tanaka, Jaakko Asikainen and Jukka A. Ketoja

KCL Science and Consulting, P.O. Box 70, FI-02151 Espoo, Finland
Current address: VTT, PL 1000, 02044 VTT, Finland

ABSTRACT

The runnability of a wet web is the sum of many factors, ranging from furnish variables to papermaking running parameters (speed, draws, distance from wet pressing etc). The relative importance of these factors was studied using several different experimental methods. The dynamic stress-strain relationship was determined *in situ* by measuring it on a *wet web winder* installed on a pilot paper machine. It was then compared with values obtained by testing the wet rolls on a separate running device. The comparison suggests that tensile strength is a more fundamental characteristic of the stress-strain curve than the dynamic stiffness affected by creep. Tensile strength is dominated by moisture content in a transition region where free water enters the fiber network. Its sensitivity to moisture content weakens as the paper becomes very wet. The location of the transition region depends on the fiber saturation point. This leads to complex changes in ranking when different pulps are compared at different moisture contents. The fines content of the furnish has a significant impact on wet web strength, whereas the fiber stiffness affects the measured dynamic stiffness but not tensile strength.

INTRODUCTION

The rheology of the wet paper web is important, even on the most modern paper machines with very short open draws after wet pressing. Some tension is always needed to detach the web from a press roll [1]. The necessary draw to build up this tension introduces not only elastic but also creep deformations in the web. The initial creep rate is extremely high [2]. Irrespective of the draw length, there is significant creep, which influences paper properties.

On most current paper machines a compromise has to be found between runnability, quality and speed [3]. Poor dynamic stiffness can lead to web fluttering that can trigger web breaks, especially at high speeds. There is always a significant creep component associated with dynamic stiffness.

In this paper, we examine the rheological behavior of wet webs for various furnishes and moisture contents. Moreover, we study the effect of the delay from wet pressing by measuring the web rheology both on a pilot paper machine and a couple of hours later on a separate running device. We find important changes in the ranking of different pulps depending on the moisture content. Moreover, the delay from wet pressing appears to have an effect on dynamic tensile stiffness.

EXPERIMENTAL

Measurement devices

We have explored several methodologies to evaluate wet web strength. One is based on a *wet web winder* (**Fig.1a**) installed right after the press section of a pilot (Fourdrinier) paper machine. With this setup, winding speed and tension can be controlled and monitored, allowing the dynamic stress-strain relationship to be determined. A big advantage of this method is that it measures the wet web strength *in situ*, without the need to transport the wet

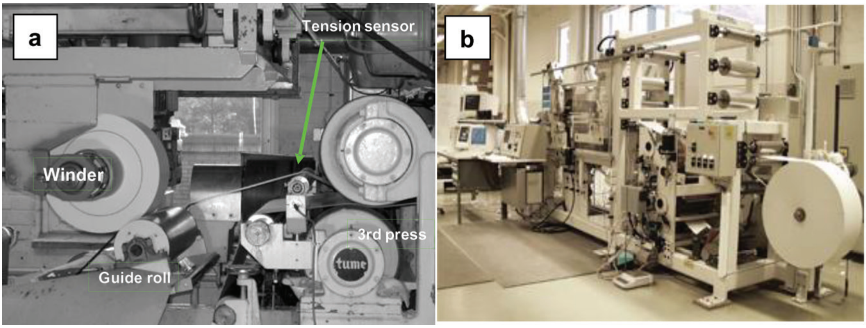


Figure 1. Tools for measuring wet web rheology at pilot scale: The *wet web winder* on a pilot paper machine (**a**) and *KCL AHMA* (**b**).

rolls for separate measurements. The possibility to vary the running conditions on the pilot machine makes it possible to separate the relative importance of furnish and running parameters. Using the winder, wet rolls at very high moisture content (50–60%) can be tested.

Another pilot device, *KCL AHMA* (**Fig.1b**), enables the study of web rheology in a wider moisture content range than on the pilot paper machine [4]. *AHMA* also has the advantage of providing detailed information on web break statistics [5], since a large number of breaks can be produced in a short period. In this study, wet and slightly dried rolls with different moisture contents were prepared. They were transported and tested within 1–2 hours after winding them on the pilot paper machine.

To evaluate the rheology of wet paper at laboratory scale, we used the *KCL Elviira* apparatus (**Fig.2**), which is composed of an environment chamber and a magnet for creating a sinusoidal oscillating force [6]. With this device, the creep and tensile stiffness of wet paper can be measured in a controlled way. Two samples are placed inside the chamber. One is attached to a pair of jaws for stress-strain measurements, while another is attached to a sample holder for weighing the mass change. The moisture content of paper is calculated from the mass change.

The moisture content of the sample can be controlled by the moistening system, i.e. heating water in a container attached to the lid of the chamber.

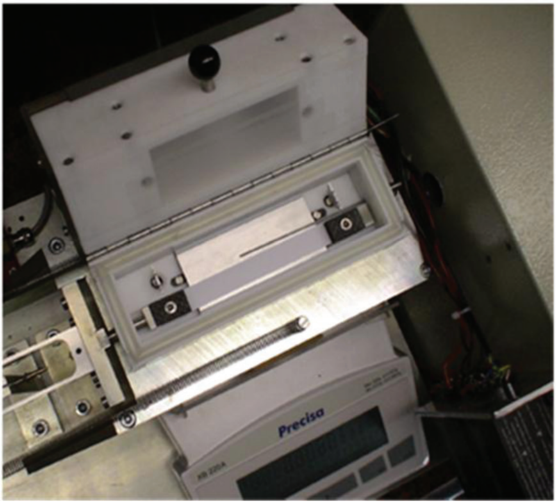


Figure 2. Sample chamber of *KCL Elviira*.

Another way to control the moisture content is to bring wet samples into the *Elviira* apparatus and let them air dry for some time.

In this work, we used only the mechanical testing part of the device and made the moisture chamber smaller by covering the empty space inside the lid with tape. Because of the small size of the remaining chamber, the relative humidity reached almost 100% very quickly after putting a wet paper sample inside the chamber. This stabilized the moisture content of paper during the creep measurement.

Paper machine trials

KCL's pilot paper machine has a short circulation that enables fast stabilization. Thus, trials can be conducted effectively using a small amount of pulp. In this study, the speed of the pilot paper machine was fixed at 80 m/min and different furnishes were compared. TMP, kraft pulp (KP) and groundwood pulp (GW) were supplied from Finnish paper mills. The pulp properties are listed in **Table 1**. PCC filler was added for some test points, but no added chemicals were used (**Table 2**).

In addition to measuring the wet web properties, the *wet web winder* produces wet paper rolls for the *KCL AHMA* trials. Thus, the wet web's rheology can be measured either on-line or off-line. The standard web width is 600 mm for the pilot paper machine (*wet web winder*) and 250 mm for *KCL AHMA*.

In order to check the effect of moisture content, a series of paper rolls representing a wide range of moisture contents were prepared by passing the

Table 1. Pulp properties. TMP-b is the long fraction after fractionation of TMP-a. KP-a and KP-b are from pine (different refining levels). KP-c is from birch.

Pulp	*TMP-a*	*TMP-b*	*TMP-c*	*KP-a*	*KP-b*	*KP-c*	*GW*
Freeness (CSF), ml	47	130	46	510	250	350	62
Length weighted average fibre length, mm	1,66	1,80	1,64	2,24	2,08	0,88	0,75
Fibre fractionation in the McNett apparatus							
> 14, %	17,7	43,4	25,3	46,5	46,0	0,2	2,3
14–28, %	28,5	14,1	16,9	34,6	25,9	5,7	15,6
28–48, %	14,7	12,0	13,8	11,5	11,4	68,8	18,6
48–200, %	17,3	14,7	16,4	6,5	7,7	22,6	29,7
< 200, %	21,8	15,8	27,8	0,9	9,0	2,7	34,0

Table 2. Test points. Paper machine variables were kept the same unless otherwise noted.

	Pulp component	*Trial with*	*notes*
TP1	80%TMP-a + 10%KP-a + 10%Filler	PM, AHMA	250mm width
TP2	80%TMP-a + 10%KP-b + 10%Filler	PM, AHMA	250mm width
TP3	80%KP-c + 20%Filler	PM, AHMA	250mm width
TP4	100% TMP-b	PM, AHMA	250mm width
TP5	100% TMP-b	PM, AHMA	150mm width
TP6	100% TMP-b	PM, AHMA	600mm width
TP7	100% TMP-c	AHMA	various moisture levels (around 5–50% mc)
TP8	100% GW	AHMA	various moisture levels (around 5–50% mc)
TP9	100% KP	AHMA	various moisture levels (around 5–50% mc)

web through the dryer section. Their rheological properties were measured by *KCL AHMA* and in the laboratory by *KCL Elviira*.

STRESS-STRAIN BEHAVIOR OF RUNNING WET WEBS

A typical example of dynamic stress-strain measurement with the *wet web winder* is shown in **Fig.3**. Several speed difference variation cycles produce very similar stress-strain behavior (in the speed difference range of 1.5–6.0%), which indicates very good reproducibility of the measurement. This gives a reliable value for the dynamic tensile stiffness that is a critical factor for wet web runnability, in addition to tensile strength. Although wet web strength is estimated based on a single break, the strength value is still quite accurate because of the strong bending of the stress-strain curve near the break, allowing an estimate based on several tension measurements.

Effect of delay from wet pressing

When comparing the measurements obtained with the *wet web winder* right after wet pressing with those obtained with *AHMA* 1–2 hours later, we can see changes in the stress-strain curve, as shown in **Fig.3**. The stress-strain

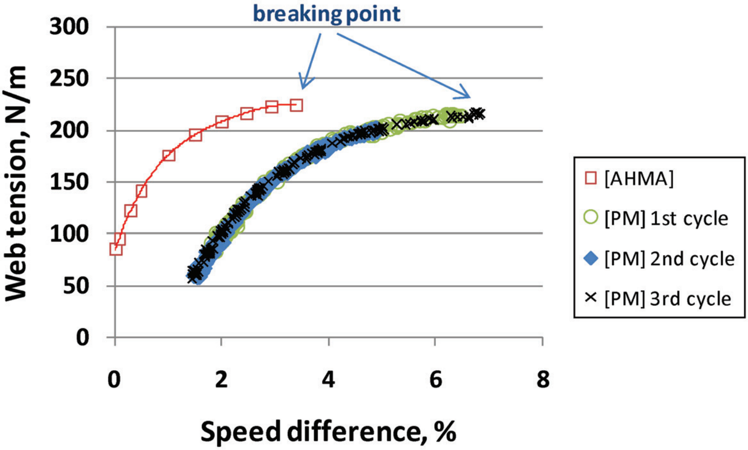


Figure 3. Stress-strain curve on the pilot paper machine (*wet web winder*) and *KCL AHMA* (**TP4** 100%TMP). Before the web break on the paper machine, the measurement was repeated three times in the speed difference range of 1.5–6.0%. The stress-strain curve starts from a higher tension value for *AHMA* because of the pre-tension of 82 N/m. The measured dynamic tensile stiffness was higher on *AHMA* than on the winder. The moisture content was 58% in both cases.

curve starts from a higher tension value for *AHMA* because of the 82 N/m pre-tension on *AHMA*. Dynamic tensile stiffness is obtained from the initial slope of the curve. We observed systematically higher dynamic tensile stiffness on *AHMA* with the longer delay from the wet pressing. On the other hand, wet tensile strength (tension at breaking) was on the same level in both cases (**Fig.4**).

We can only speculate on the cause of differences in the observed tensile behavior on *KCL AHMA* as compared to the pilot paper machine. First, the speed difference over the open draw at web break is different. This may arise partly from the different straining histories in the two cases. About 2.5% strain has already been applied to the web on the winder before the web is tested on *AHMA*. Moreover, the pre-tension on *AHMA* causes a minor additional strain. For wet webs, the elastic strain component is much smaller than the plastic one. Thus, a part of the straining "potential" has already been used before the stress-strain curve is measured on *AHMA*. It would be tempting to assume that the total strain at break (i.e. summing up the whole straining history) is roughly equal in the two cases. If this were the case, the

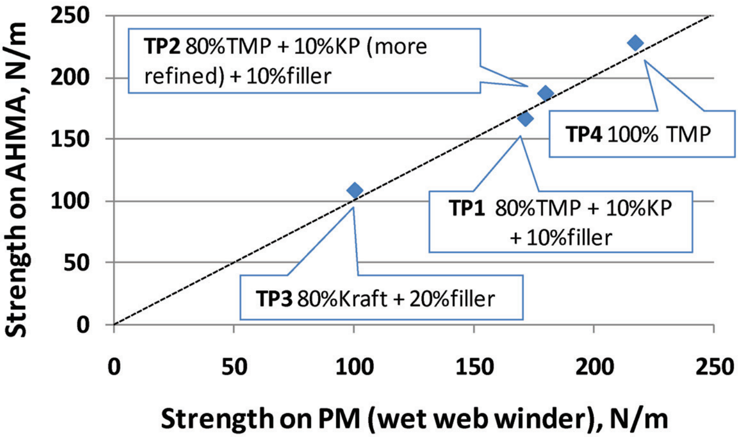


Figure 4. Comparison of wet tensile strength on pilot paper machine (*wet web winder*) and on *KCL AHMA* (**TP1–4**).

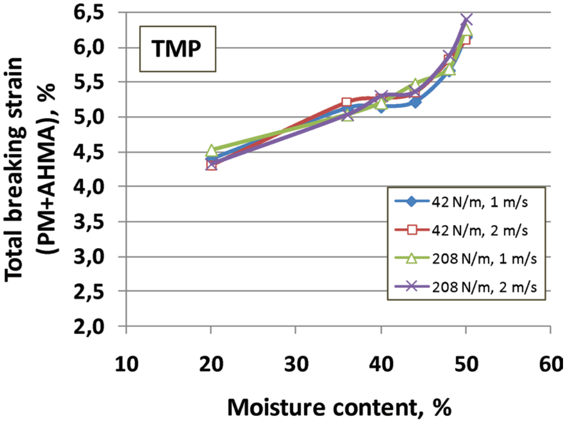
breaking speed difference on *AHMA* would be smaller and therefore also the stress-strain curve would have a steeper slope in order to reach roughly the same strength level as on the pilot paper machine. Thus, the measured dynamic stiffness would be higher on *AHMA* than on the pilot paper machine.

We tested the idea by recording the total strain for webs that were transported through the whole pilot paper machine and tested on *AHMA* with varied pre-tension, running speed and moisture content. The strain over the paper machine was obtained from speeds at the couch roll and the jumbo reel. In *AHMA* testing, we measured pre-strain and the strain in the last open draw. The sum of all the above three strains is called the total strain. At a certain moisture content, we found the total breaking strain to be quite independent of the pre-tension and running speed on *AHMA*, as shown in **Fig.5**. However, the result may be limited to this particular case. In general, the breaking strain and its dependence on history may be sensitive to e.g. moisture content during straining.

Effect of web width

Other possible reasons for the difference in stress-strain behavior between the pilot paper machine (PM) and *AHMA* are:

- Global moisture variations across the width



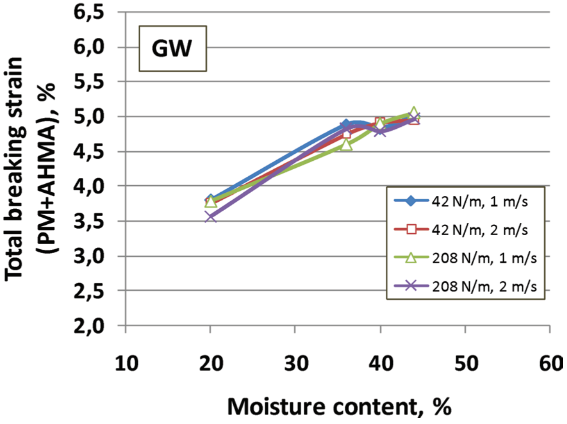


Figure 5. Total breaking strain as obtained by summing up the strain over the paper machine, the pre-strain on *KCL AHMA*, and the strain in the last open draw where the stress-strain curve in *AHMA* is measured (**TP7–8**). Different levels of pre-tension (42 or 208 N/m) and speeds (1 or 2 m/s) were tested.

- Scaling effect
- Other loading conditions
  - Pressure from the supporting roller of the *wet web winder*
  - Adhesion
  - Time effect (different bound water distribution and relaxation immediately after wet pressing as compared to longer delay times)

In order to narrow down the reasons, we checked the effect of web width on stress-strain behavior with TMP paper. If the results obtained on the PM change with a change in web width, and the corresponding results obtained with *AHMA* do not, we could suspect the global variation in moisture to be important. The comparison was made in the web width range of 250–600 mm for the PM and 150–250mm for *AHMA*. These ranges were chosen because they represent the upper/lower limit for each device. As a result, in these ranges, web width turned out to have a minor impact on the strength. Moreover, there was no effect on tensile stiffness arising from variations in the web width (**Fig.6**). Therefore, the straining history or some other loading conditions cause the difference in stress-strain behavior between the PM and *AHMA*.

EFFECT OF MOISTURE CONTENT

Pure tensile stiffness vs. dynamic stiffness for a running web

Tensile stiffness was measured at laboratory scale by creating a sinusoidal force around an appropriate base force in *KCL Elviira* [6]. The base force was typically 1N and the amplitude of the sinusoidal oscillation 0.5N. The frequency was 1Hz. Ten cycles were applied, after which the force was lowered back to the zero level. The small creep during the measurement was subtracted from the strain. Thus, the "pure" tensile stiffness obtained in this way was not affected by any inelastic creep deformations, which usually would be

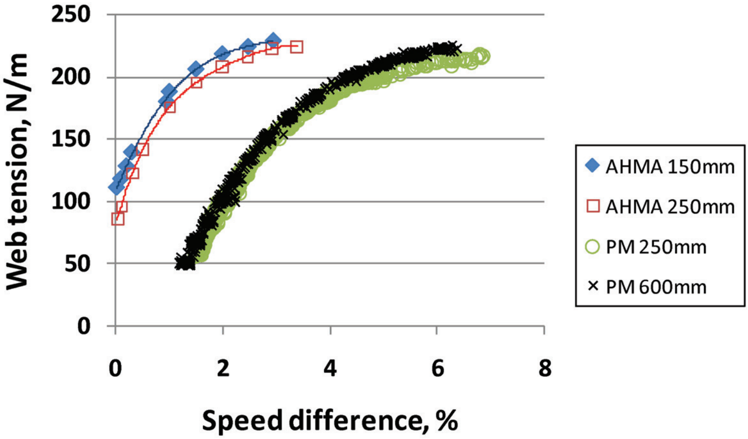


Figure 6. Effect of web width on stress-strain behavior (**TP4–6**, 100%TMP).

present in a standard tensile test. The resulting stress-strain relationship was quite linear with practically vanishing viscous loop effects, which was somewhat surprising, taking into account the high moisture content (**Fig.7**).

The pure tensile stiffness of paper decreases exponentially as a function of moisture content over a wide moisture content window from 10% to 50%, as shown in **Fig.8**. The exponents obtained, –0.049 for TMP and –0.058 for GW, are close to the "universal" value –0.067 obtained earlier by Zauscher *et al.* [7] for many paper grades (see also ref. 3). However, this universal value was obtained in a much more limited moisture-content interval using the definition of moisture content based on the so-called dry basis (often called "water fraction"). Thus, **Fig.8** suggests the earlier "universality" can be extended to wet papers by using the standard moisture content definition instead of the dry-basis one.

In contrast to "pure" tensile stiffness, the "dynamic" tensile stiffness obtained with *AHMA* is much smaller. This derives from the creep of wet paper during running over an open draw [8].

Creep properties

Typical creep behavior of wet paper in laboratory conditions is shown in **Fig.9**. The reproducibility of creep behavior was usually quite good, as seen

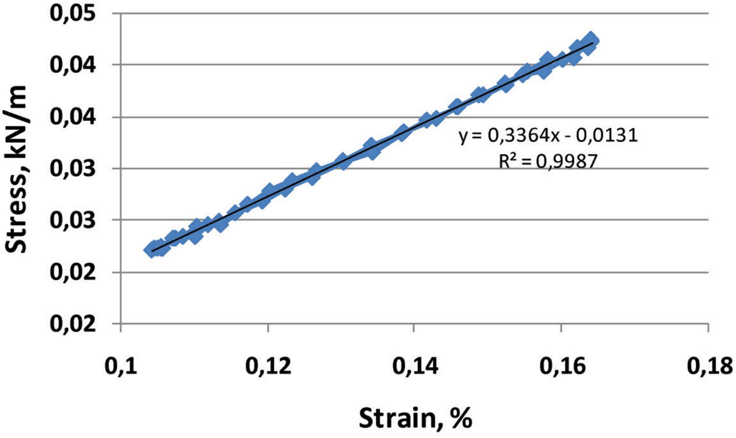


Figure 7. Typical stress-strain relationship measured with *KCL Elviira* by applying a small-amplitude sinusoidal force on paper [**TP4**, TMP paper, moisture content 56%]. The slope gives the tensile stiffness value of 33.6kN/m.

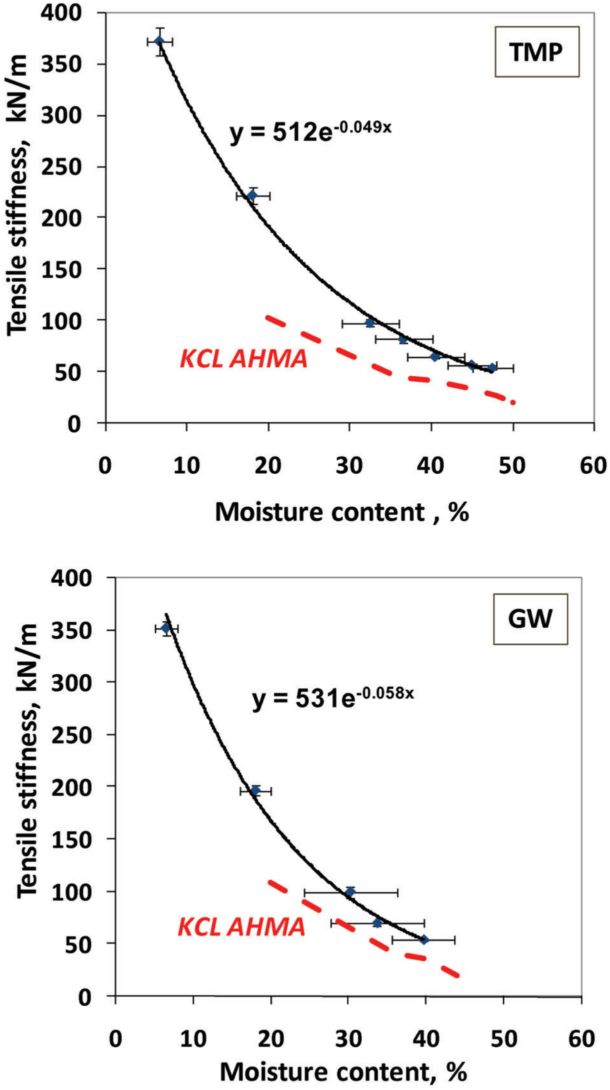


Figure 8. Pure tensile stiffness as a function of moisture content for pilot paper measured with *KCL Elviira* (**TP7–8**). The dashed line indicates the much lower dynamic stiffness obtained when running the same paper on *KCL AHMA*.

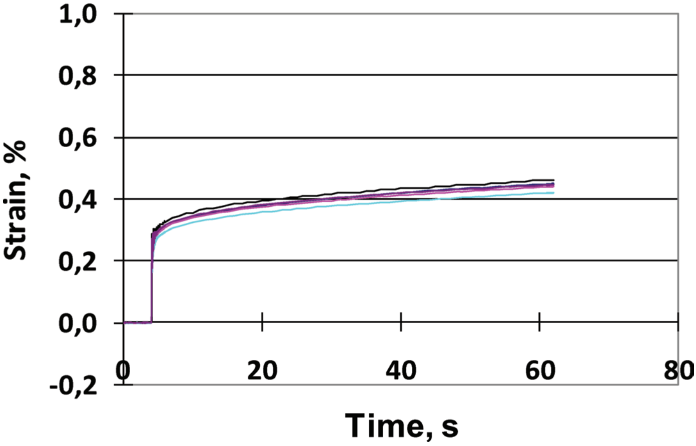


Figure 9. Typical creep behavior of wet paper (five parallel tests) measured by *KCL Elviira*. The picture shows the measured total strain in creep experiments for wet TMP paper (**TP4**, 53% mc). The tension is 67 N/m.

in this figure. The major part of the creep strain was obtained almost immediately after the beginning of the test.

One would expect the creep behavior to differ quite a lot, depending on whether there is free water [9] in the fiber network or not. The free water prevents chemical bonding at some of the inter-fiber contacts under stress. Indeed, the creep measurements suggest a transition around 36–40% moisture content for the TMP and GW pilot papers. The increase in creep rates at high moisture contents can be seen directly as an increase in the total breaking strain for running webs, as shown earlier in **Fig.5**.

A more sophisticated way to see the transition is to plot the master curve by shifting each creep curve in time so that we obtain the best possible overlap with the other curves [8]. Doing this for the pilot paper made from TMP (**Fig.10a**), one obtains an almost perfect match for the curves with 33% and 37% moisture content, but these curves do not overlap with the rest of the curves [8]. Instead, the moisture contents 41%, 45% and 48% form their own creep master curve. This indicates a change in creep dynamics in the 37–41% moisture interval. **Fig.10b** shows similar master curves for GW pulp. It has similar characteristics as the master curve for the TMP: a transition in creep properties seems to take place in the interval 34–40%.

We found the same kind of transition in dynamic tensile strength at a moisture content of 35–40% for both TMP and GW papers (**Fig.11**). The curve of birch KP paper ends near the transition point when the moisture

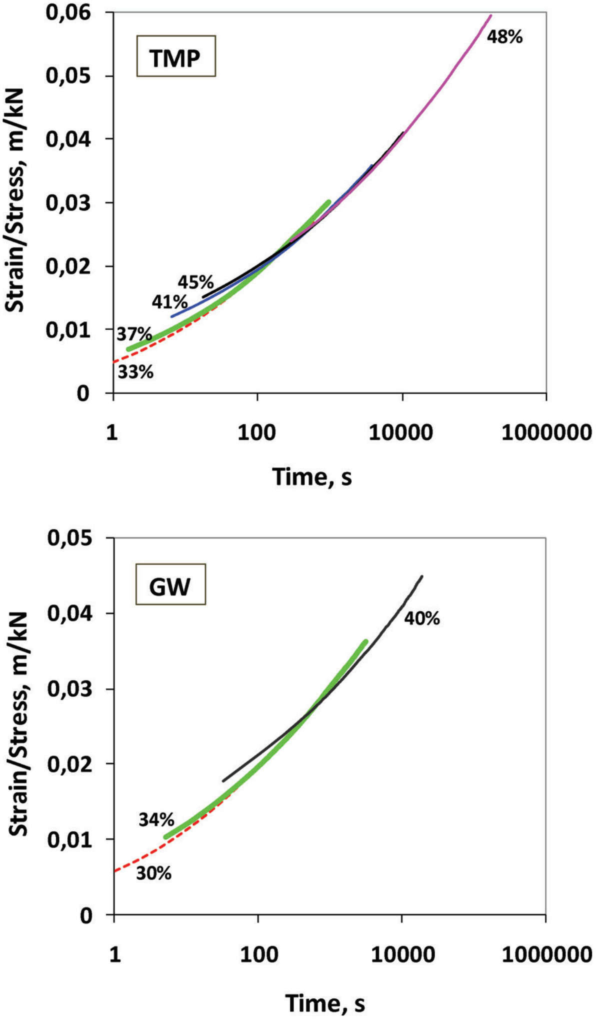


Figure 10. Master creep curves with varied moisture content. **TMP:** Curves for 33% and 37% mc overlap with one another, but they do not overlap with the rest. Instead, curves for 41%, 45% and 48% form their own master curve. **GW:** Curves for 30% and 34% mc overlap with one another, but not with the 40% curve [8].

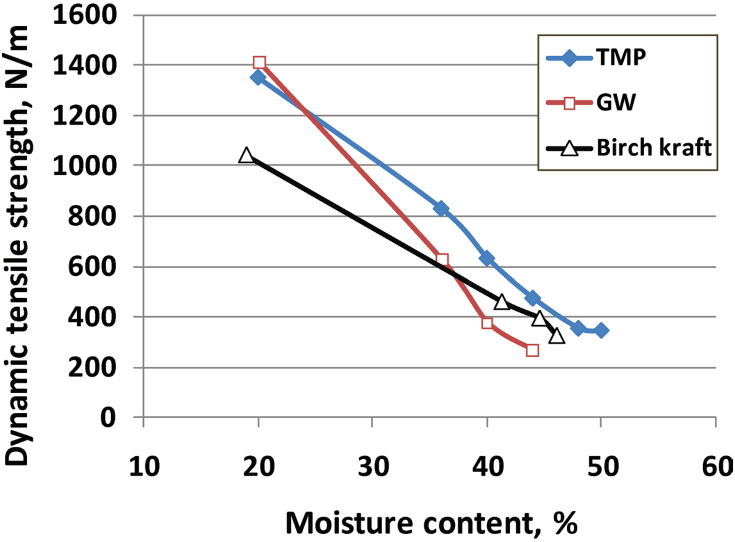


Figure 11. Tensile strength for TMP, GW, and KP at varied moisture level (trials with *KCL AHMA*).

content is 48%. For reference, the fiber saturation point (FSP) of the tested birch KP was 1.1g/g, which means free water is expected to appear around a moisture content of 50%. These transitions at different locations cause intriguing changes in the ranking of different pulps when the moisture content is varied, as shown in **Fig.11**.

For running webs, the transition in creep behavior becomes very clear when we plot the slope (i.e. derivative) of the stress-strain curve at the breaking strain as a function of moisture content, as shown in **Fig.12**. This slope decreases almost linearly below 40% moisture content and practically vanishes (within experimental accuracy) at higher moisture contents for both TMP and GW. This behavior probably reflects the fast sliding of fibers in relation to one another just before the web breaks.

By combining and interpreting the results of the *AHMA* trials and laboratory experiments, we have found three regions where tensile properties develop in different ways. In the following, we summarize the main features of each region:

- Low or moderate moisture content:
  - no free water in the fiber network
  - tensile strength and stiffness decrease with increasing moisture content

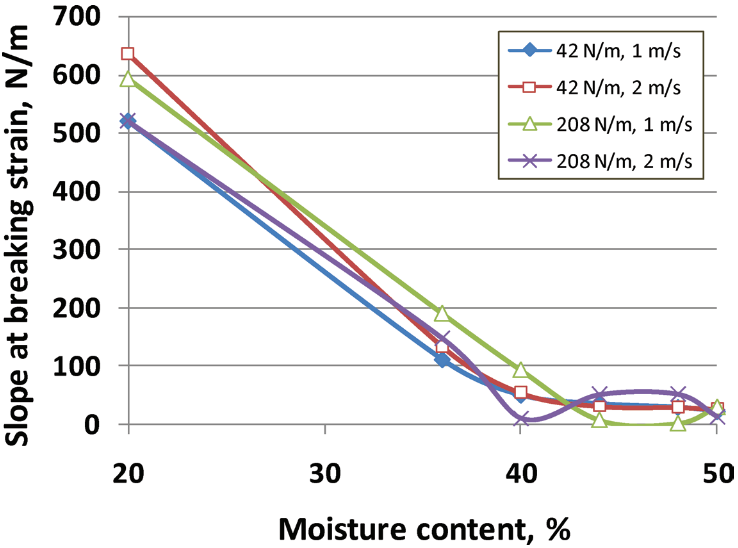


Figure 12. Slope (or derivative) of the dynamical stress-strain curve at the breaking strain for varied moisture content. Within experimental accuracy, this slope vanishes above 40% moisture content, which suggests the existence of an underlying "sliding" transition when free water enters the fiber network. The results include different pre-tensions and web speeds for the same TMP as in Fig.11.

  - dynamic tensile stiffness is strongly affected by creep deformations (relaxation)
- Transition:
  - free water appears in the fiber network
  - tensile strength decays fast with increasing moisture content
  - dynamic tensile stiffness is only little affected by variation in the moisture content within this region
- High moisture content:
  - plenty of free water in the fiber network
  - tensile strength becomes independent of straining history and is less sensitive to moisture content
  - dynamic tensile stiffness begins to decay fast with increasing moisture content (affected by creep deformations)

EFFECT OF FURNISH

Difference in stress-strain behavior between mechanical paper and fine paper

It is commonly known that mechanical papers (see **Fig.13**) have higher wet strength (better runnability) than fine papers. Also in this study, TMP papers (**TP1–3**) were found to have higher dynamic tensile strength than kraft paper (**TP4**), as shown in **Fig.4**.

The stress-strain behavior of fine paper showed a clear difference between PM and *AHMA* trials. The stress-strain relationship looks quite linear even close to the breaking point on the PM (**Fig.14**). An exceptional shape of the stress-strain curve is possible if the creep rate is very high already at low tensions but slows down strongly when higher creep strains are achieved (at high tension values). Note that the dynamic tensile stiffness on *AHMA* for fine paper responds very strongly to straining on the pilot PM.

Effect of fines

In order to understand the reasons for differences in tensile strength values between mechanical and fine papers, we studied the effect of fines. Mechanical papers generally contain 20–30% fines, whereas in fine paper the fines

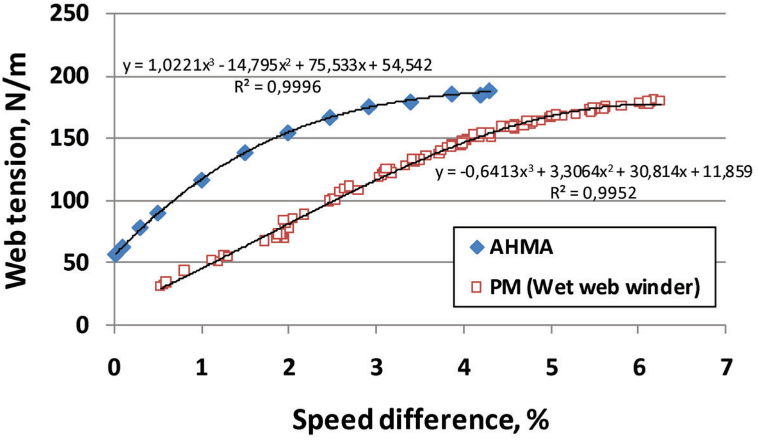


Figure 13. Relationship between wet draw and web tension on *AHMA* and the pilot paper machine (*wet web winder*). The finite web tension on *AHMA* at 0% draw was due to the pretension. Mechanical paper [**TP2**: 80%TMP + 10%KP (more refined) + 10%filler].

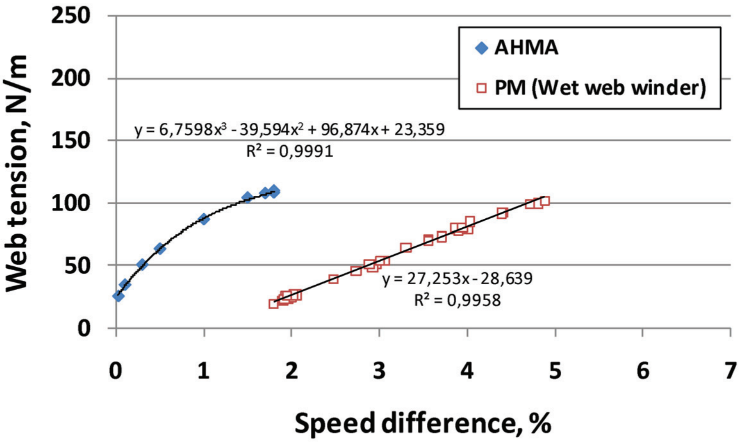


Figure 14. Relationship between wet draw and web tension on *AHMA* and the pilot paper machine (*wet web winder*). The finite web tension on *AHMA* at 0% draw was due to the pretension. Fine paper [**TP4**: Kraft pulp 80% + filler 20%].

content is below 10%. We found that by adding TMP fines to kraft pulp, the tensile strength was at the same level as for a pure TMP furnish, see **Fig.15**. On the other hand, by removing the fines fraction from the TMP furnish, the wet tensile strength dropped to the level of fine paper. Thus, we conclude that the main reason for the difference in tensile strength between mechanical and fine papers is the difference in fines content. It can be noted here that the stiffness of fibers seems to affect the dynamic tensile stiffness but not the strength. Similar findings have earlier been obtained in simulations of wet fiber networks [10]. On the other hand, fines improve not only tensile strength but also dynamic tensile stiffness and breaking strain, as seen in **Fig.15**.

CONCLUSIONS

By examining the wet web strength using several different measurement methods we obtained new information on the underlying mechanisms. For the first time, we are able to report systematic results of testing the rheology of a running wet web on a pilot paper machine. This work resulted in several interesting findings.

Firstly, it appears that tensile strength is a more fundamental characteristic of the stress-strain curve than the dynamic stiffness affected by creep.

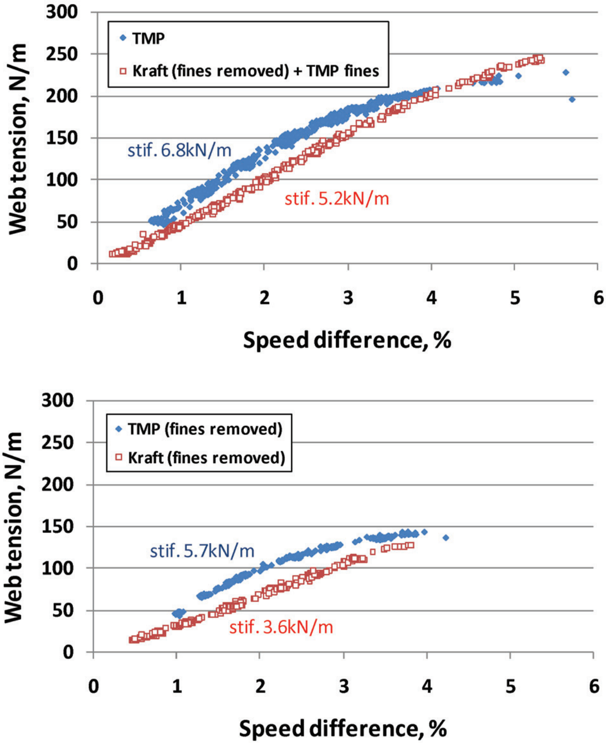


Figure 15. Relationship between wet draw and web tension on paper machine (*wet web winder*). The top figure refers to furnishes with fines, the bottom figure to furnishes from which fines have been removed.

Secondly, tensile strength is dominated by moisture content in a transition region where free water enters the fiber network. The sensitivity to moisture content weakens as the paper becomes very wet. The location of the transition region depends on the fiber saturation point. This leads to complex changes in ranking when different pulps are compared at different moisture contents.

Thirdly, our studies reveal the importance of the furnish fine structure (fines and other small particles/polymers) for wet web runnability. The fines content affects strongly not only tensile strength, but also dynamic tensile stiffness and breaking strain. This observation is important for the development of new paper structures.

ACKNOWLEDGMENT

We would like to thank Ms. Sanna Lehti for her contribution in creep studies as well as in developing *KCL Elviira*.

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Transcription of Discussion

WET WEB RHEOLOGY ON A PAPER MACHINE

Atsushi Tanaka, Jaakko Asikainen and *Jukka A. Ketoja*

KCL Science and Consulting, P.O. Box 70, FI-02151 Espoo, Finland
Current address: VTT, PL 1000, 02044 VTT, Finland

Torbjörn Wahlström Stora Enso

Thank you, these are very interesting devices you have described, and I have a couple of questions. First, you said tensile strength was more fundamental. Do you mean that property is more important for runnability?

Atsushi Tanaka

No. What I mean is that tensile strength was not affected, for example, in this case. It was at the same level on AHMA and on the paper machine. If we changed the testing time and put some delay from the wet press, or changed some other properties for example, stiffness or strain at break will be varied but the tensile strength will stay in the same range. That is what I meant.

Torbjörn Wahlström

Okay. You had some very interesting cases here with and without fines. In the abstract you said you found changes in ranking when different pulps are compared at different moisture contents. In addition to the testing you presented, I suppose that you also did standard tensile testing. Did you find them the same relation between those furnishes?

Atsushi Tanaka

Yes, basically the same. You mean the initial wet strength, like tensile strength?

Torbjörn Wahlström

Yes.

Atsushi Tanaka

Yes, there was a good correlation and it also produces quite similar results. What I mean is that each pulp has some transition region. It is specific to the pulp, so if you are changing the mixture ratio, the transition region might vary. It will make the ranking more complicated. That is what I wanted to say in the text.

Torbjörn Wahlström

Yes, but were the same differences also seen for standard tensile testing or did you need to use the dynamic devices to find it?

Atsushi Tanaka

Well. I recommend using the dynamic, anyway.

Torbjörn Wahlström

Thank you.

John Roberts University of Manchester

I think the results with the TMP fines are very interesting. Just a point of clarification first; did you say in your summary slide that filler particles have an adverse effect on wet web strength?

Atsushi Tanaka

I cannot show the result.

John Roberts

It doesn't matter about showing the results, but did the filler particles have an adverse effect?

Atsushi Tanaka

Yes, if we increase the filler amount.

John Roberts

Yes. I just wondered if you could speculate on how you think the TMP fines are having such a dramatic effect on wet web strength?

Atsushi Tanaka

This is a good question and we are still checking the facts. One thing is that the fines particles have so many factors like fibrillar fines or particle-like fines that can affect properties. Here we show only the effect of TMP fines. For example if we change to kraft fines, that could have a different effect. So thanks for your comment.

Norayr Gurnagul FPInnovations

Just a clarification point, did you mention that the kraft pulp was refined or unrefined?

Atsushi Tanaka

Actually, it was refined. To the same level that the TMP is in the grade of newsprint and the kraft pulps are for normal fine paper, like the copy paper grade. So it was refined.

Gil Garnier Australian Pulp and Paper Institute

Interesting work, especially the part using the TMP with and without fines. A clarification: did you use a polymeric retention aid for those experiments?

Atsushi Tanaka

No, we did not.

Gil Garnier

Not at all?

Atsushi Tanaka

No. In order to make it more simple, just use only the pure fibres.

Torbjorn Wahlström Stora Enso

Was the kraft and TMP furnishes refined to the same refining degree, or to the same strength properties?

Atsushi Tanaka

The TMP was delivered from a Finnish paper mill as already refined. CSF was 53 mL. The Kraft pulp (pine) was delivered in bales. It was slushed in a pulper and refined with a conical refiner (Metso Optifiner RF-1) at 4% consistency. There were two refining stages. In each stage, the specific edge load was 2.5 J/m and the specific refining energy consumption was 90 kWh/tonne. CSF was 702 mL (before) and 408 mL (after).

Petri Mäkelä Innventia

Thank you for a good presentation, Atsushi. I would like to have a look at Figure 8 again because it puzzles me. Have you tried to do ordinary tensile tests also using a constant strain rate on the investigated paper?

Atsushi Tanaka

Yes, actually, and this data has already been presented in some other conference and was done by my colleague.

Petri Mäkelä

Anyway, I have read your work back and forth a few times and I am trying to understand this. You have quite a high strain rate in KCL AHMA. I believe that you claim in your work that the initially very high creep rate is the reason that you get such low dynamic stiffness in KCL AHMA. But then you do the testing in KCL Elviira, that is cyclic testing, right?

Atsushi Tanaka

The creep test is not by the cyclic testing but in a creep mode, just keeping a constant tension for a long time. There are two modes for the Elviira, one is just a simple creep test, the other is cyclic, which gives the pure tensile stiffness.

Petri Mäkelä

So how do you do the test which you call pure tension stiffness?

Atsushi Tanaka

It is a test with ten oscillations. Because of the creep, the strain is gradually increasing, so we just take off that effect. In the end only the pure strain and stress relationship is obtained.

Petri Mäkelä

I would call that a cyclic test since you cycled the load. If I remember it correctly, you used a mean load of 1 N and then you cycled the load 0.5 N up and down. So why doesn't the paper have time to creep more in KCL Elviira? You used 1 Hz, as I understand. The paper should have more time to creep and I would, therefore, expect that you would measure a lower stiffness value in KCL Elviira than in KCL AHMA? As far as I know if you increase the strain rate in a tensile test you get higher stiffness and strength out of the test. So it would be nice to see data from ordinary tensile tests performed with a constant strain rate as compared to the data in Figure 8.

Jukka Ketoja VTT

Just to comment on the previous discussion. I guess Atsushi already mentioned that the creep part is filtered out. We have learnt from other people in these conferences how they do it. That is why we call it pure tensile stiffness.