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FRACTURE TOUGHNESS AS A PULP CHARACTERIZATION METHOD FOR RUNNABILITY ASSESSMENT OF PAPER

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ABSTRACT

For printing paper grades, runnability in the paper machine and in the printing press is partly attributed to the ability of the paper to tolerate flaws and defects in the paper. In these operations the paper fails due to forces applied in the plane of the sheet. It is important for the papermaker to have access to a relevant test method which can characterize those pulp properties applicable to this type of failure.

Papermakers knew as early as the 1920´s that the strength of a cracked paper was a unique and useful paper property. This lead to the development of the out-of-plane tear strength test method. The tear test principle has, however, been criticized for many reasons. The most severe criticism lies in the mode in which the paper fails. The mode of fracture in most production and processing operations is seldom an out-of-plane tearing, Mode III, but rather an in-plane crack propagation, Mode I.

In this paper an in-plane fracture toughness method based on non-linear fracture mechanics was compared to traditional paper testing methods for papers containing chemical pulps with different degrees of beating, mixtures of chemical and mechanical pulps as well as mixtures of chemical pulps and filler. The light scattering coefficient of the papers was also presented in relation to the toughness methods.

The results confirmed that major differences exist between the fracture properties obtained in the in-plane and out-of-plane loading modes. Refining increased the fracture toughness and decreased the tear strength in the investigated range of refining. For the pulp mixtures, both fracture toughness and tear strength increased with increasing amount of chemical pulp. The previously observed influence of refining on the two fracture properties remained for all mixture levels.

The addition of fillers to the chemical pulp decreased both the fracture toughness and the tear strength. Once again the previously observed influence of refining on the two fracture properties was noted.

It is suggested that the runnability in a paper machine or printing press is best characterized by measuring the resistance to crack propagation in a load situation similar to that prevailing in the machine. Using a non-linear fracture toughness method the results in this study imply that refining of chemical pulps improves the runnability.

INTRODUCTION

It has become increasingly important for printing paper grades over the years to improve paper machine and printing press runnability (1, 2, 3).

There are several reasons for this including less reinforcement pulps in wood containing grades, lower grammages, higher filler contents, faster and wider paper machines and higher speed printing presses. The runnability is partly attributed to the ability of the paper to tolerate flaws and defects in the paper such as pinholes, shives, edge cracks, non-uniform grammage distribution and asymmetric elastic properties, and partly to machine related parameters such as web tension fluctuations and poor alignment of cylinders(4, 5, 6, 7, 8).

It is important for the papermaker to have access to a relevant test method which can characterize those pulp properties applicable to this type of failure. Papermakers knew as early as the 1920's that the strength of a cracked paper was a unique and useful paper property. This lead to the development of the out-of-plane tear strength test method. The tear test principle has, however, been criticized for many reasons. The most severe criticism lies in the mode in which the paper fails. The mode of fracture in most production and processing operations is seldom an out-of-plane tearing, Mode III, but rather an in-plane crack propagation, Mode I (9, 10).

In this paper an in-plane fracture toughness method based on non-linear fracture mechanics was compared to traditional paper testing methods for oriented laboratory sheets of different pulp compositions and filler contents. The results confirmed that major differences exist between the fracture properties obtained in the in-plane and out-of-plane loading modes. Refining increased the fracture toughness and decreased the tear strength in the investigated range of refining. For the pulp mixtures, both fracture toughness and tear strength increased with increasing amount of chemical pulp. The previously observed influence of refining on the two fracture properties remained for all mixture levels. The addition of fillers to the chemical pulp decreased both the fracture toughness and the tear strength. Once again the previously observed influence of refining on the two fracture properties was noted.

It is suggested that the runnability in a paper machine or printing press is best characterized by measuring the resistance to crack propagation in a load situation similar to that prevailing in the machine. Using a non-linear fracture toughness method the results in this study imply that refining of chemical pulps improves runnability.

MATERIALS AND METHODS

Pulp preparation

The dried bleached softwood kraft pulp was refined in an Escher-Wyss laboratory refiner, R1L, at 2.5 % consistency to 20 , 25 and 30 °SR. In the pulp mixture and filler trials chemical pulps manufactured at different times were used. The groundwood pulp was obtained from a commercial plant. It had a brightness of 78.5 % ISO and a freeness of 63 ml CSF. The filler was calcium carbonate, $CaCO_3$, with the trade name DX-50 (OMYA). A two-component retention aid system, Hydrocol (AB CDM), was used in the filler trials. Hydrocol consists of alkali swollen montmorillonite microparticles and a cationic high molecular weight polyacrylamide.

Sheetmaking

Oriented laboratory sheets at a grammage of 100 g/m2 were made on the Formette Dynamique former (11). The sheets were pressed in a laboratory press according to SCAN-standard (12) except that the pressure was 311 kPa and the sheets were pressed only once. The sheets were dried under restraint in MD and CD in the STFI plate drier by using a technique similar to that described by Htun and Fellers (13). During drying the sheet was in contact with a heated plate. The drying time was on the order of five minutes. After drying the sheets were placed in the testing climate according to SCAN-standard (14).

Evaluation.

Tensile, tear and light scattering were evaluated according to SCAN-standards (15, 16, 17).

The fracture toughness was determined using the Liebowitz method for J integral evaluation as described by Fellers, Fredlund et. al. (18). The tensile stiffness was evaluated from the maximum slope of the force elongation curve. The rate of elongation for these two tests was 1.7 %/s.

The geometric mean value of MD and CD values (13) was used in the presentations of the results.

RESULTS

In this paper an in-plane fracture toughness method based on non-linear fracture mechanics was compared to traditional paper testing methods for oriented laboratory sheets of different pulp compositions and filler contents.

Pulp mixture trials

In the pulp mixture trials, chemical pulps of different degrees of beating were mixed with a groundwood pulp. The fracture toughness increased with the chemical pulp content as shown in Figure 1. Although increased refining had a positive effect on this pulp, the effect was small, especially at low chemical pulp contents.

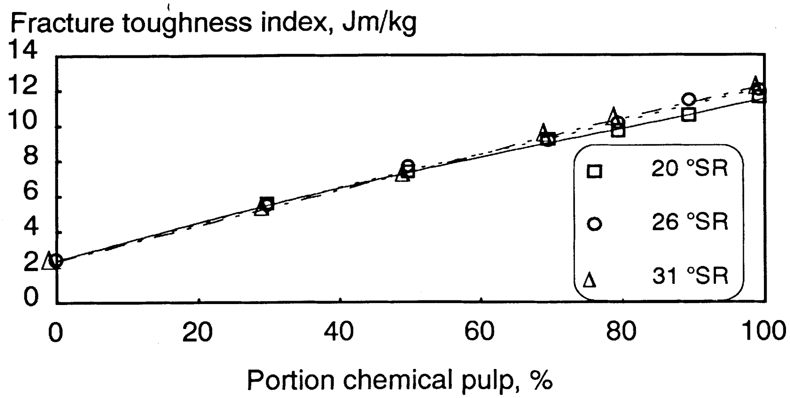

Figure 1. Fracture toughness increases as the amount of softwood kraft pulp increases in a SGW-furnish. The lowest values at a given mixture are observed at the lowest degree of refining.

In Figure 2 the tear index also increased with the chemical pulp content. An increase in the degree of beating of the chemical pulp resulted in lower tear index values.

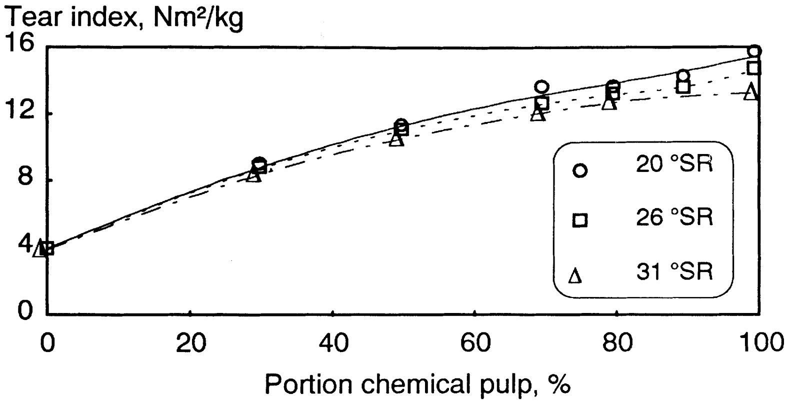

Figure 2. Tear strength increases with increasing amount of softwood kraft pulp in a SGW-furnish. The lowest values at a given mixture are observed at the highest degree of refining.

Figure 3 shows that tensile index followed the same trend as the fracture toughness. The light scattering coefficient, as plotted in Figure 4, decreased with the chemical pulp content. The scattering coefficient was not significantly affected by the degree of beating with the exception of the 100 % chemical pulp where higher degree of beating gave lower scattering values.

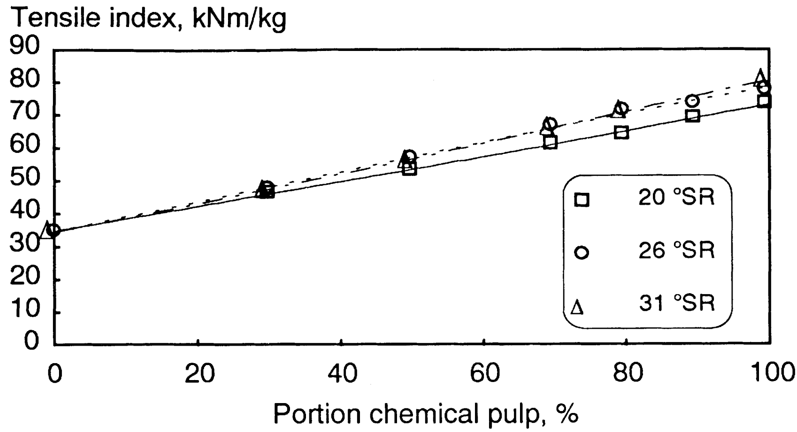

Figure 3. Tensile strength increases as the amount of softwood kraft pulp increases in a SGW-furnish.

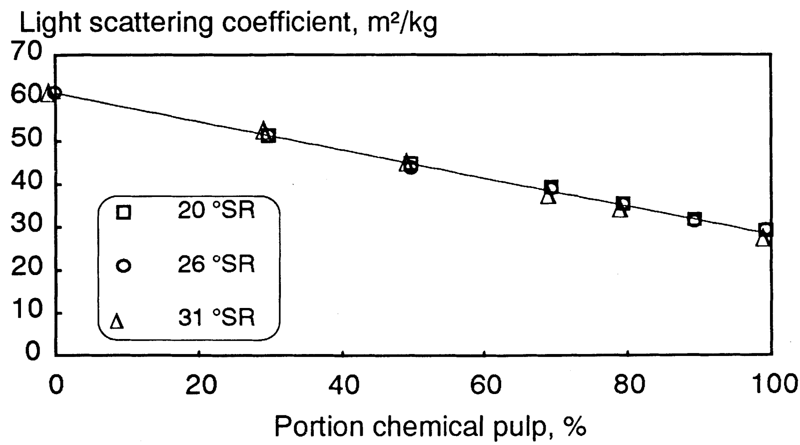

Figure 4. Light scattering decreases with increasing amount of softwood kraft pulp in a SGW-furnish. The influence of refining is negligible.

Filler trials

In the filler trials, a filler was added to softwood kraft of different degrees of beating. Figure 5 shows how fracture toughness decreased with filler content. At a given filler content it was advantageous to increase the degree of beating from 20 to 25 °SR. However, increasing the degree of beating above 25 °SR the fracture toughness did not improve further.

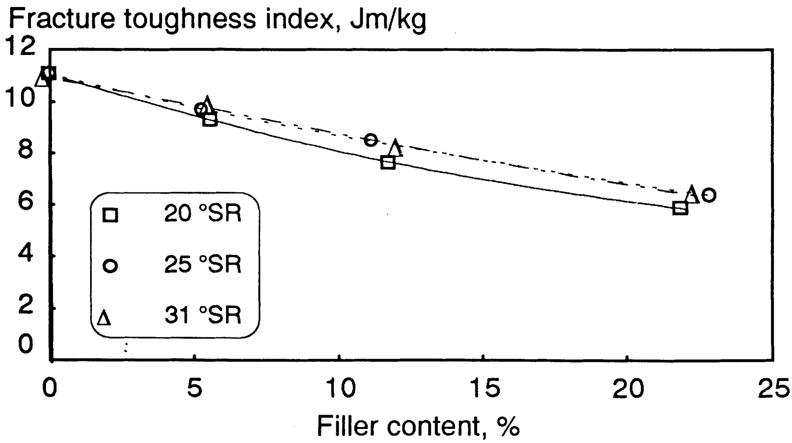

Figure 5. Fracture toughness decreases with increasing filler amount. The lowest refined pulp shows a faster decline.

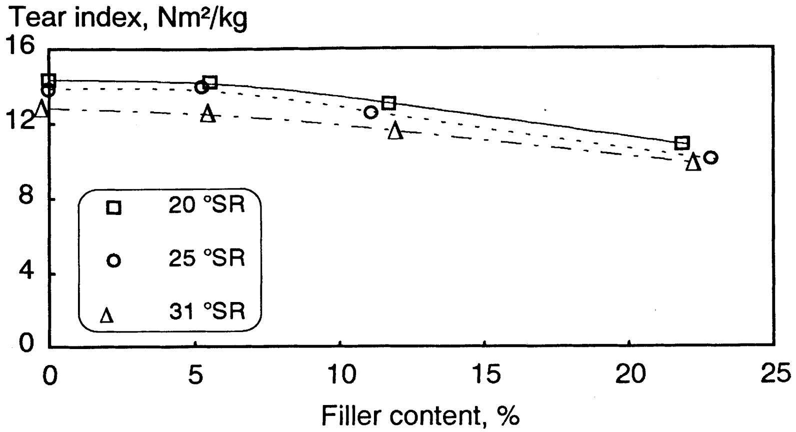

Figure 6. Tear strength decreases with increasing filler amount. The degree of refining has considerable influence at all filler levels.

In Figure 6 tear index also decreased with a higher filler content. However, at low filler content there was no significant influence of filler addition. Increasing the degree of beating decreased the tear index at all levels of filler addition. Figure 7 shows that tensile index decreased with filler content and increased with higher degrees of beating at all filler contents.

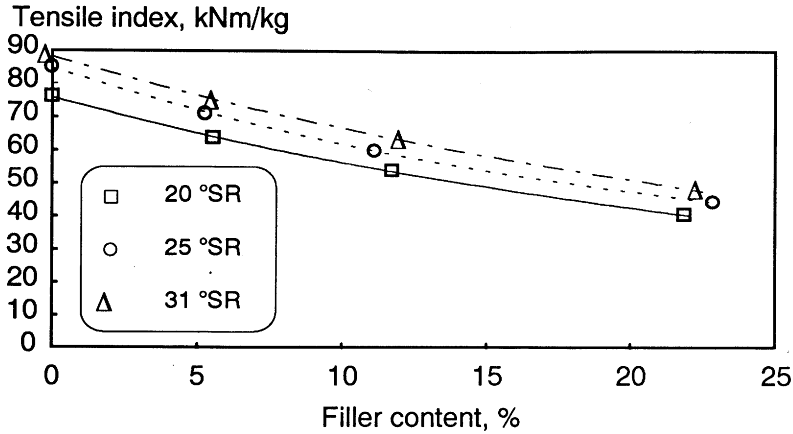

Figure 7. The decrease in tensile strength with filler addition is approximately linear at the different levels of refining.

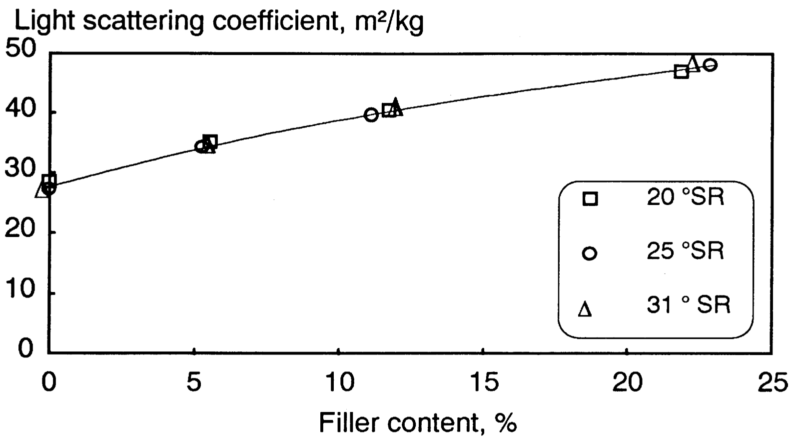

Figure 8. Light scattering increases with addition of filler. In the investigated interval of refining there is no significant effect on light scattering.

Figure 8 shows that the light scattering coefficient increased with increasing amount of filler. At zero filler content, the light scattering coefficient decreased with the degree of beating. However, at higher filler contents there was no significant effect of refining.

DISCUSSION

Several investigations state that paper-caused web breaks can be assigned to an infrequent occurrence of weak spots in the paper web. Weak spots in the paper web may not only depend on impurities in the pulp e.g. shives in mechanical pulps or fiber bundles in chemical pulps, but also on many other defects such as "unknown, bursts, wrinkles, cracks-cuts, corrugations, holes, roll condition and miscellaneous" according to Frye (4). The sparse distribution of these weak spots makes their detection and the determination of their distribution somewhat difficult by conventional laboratory procedures.

Assuming that the paper contains a given number of those defects, it is the ability of the paper to tolerate flaws and defects that governs the web break frequency. It is thus desirable to have access to a method measuring the resistance to crack propagation in a load situation similar to that prevailing in the machine. In this paper the in-plane fracture toughness based on non-linear fracture mechanics was compared to traditional paper properties for oriented laboratory made sheets of different pulp compositions and filler contents.

The results showed that an increasing amount of softwood chemical pulp in the chemical-mechanical pulp mixture improved the fracture toughness. This is in agreement with general experience in paper manufacturing and the principal function of reinforcement pulps. By adding filler to the paper the fracture toughness decreased, also in accordance with general experience. In both of these aspects the fracture toughness behaved similarly to the tear and tensile values. Differences between fracture toughness and tear appeared when beating of the chemical pulp was considered. The data were replotted in accordance with common pulp characterization practise as fracture toughness and tear vs tensile strength in Figures 9 and 10. Fracture toughness as well as tear strength increased with increasing tensile strength (increasing amount of chemical pulp as indicated by the dotted arrow). However, for the investigated range of beating fracture toughness increased when the tensile strength was increased by refining whereas tear decreased (indicated by arrows in the graphs).

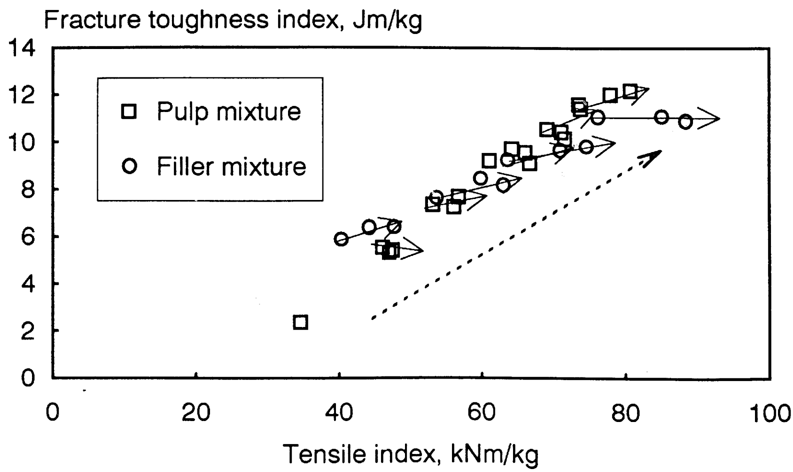

Figure 9. Fracture toughness vs. tensile strength for the collected data. Dotted arrow signifies increasing amount of chemical pulp and short arrows signify increasing refining.

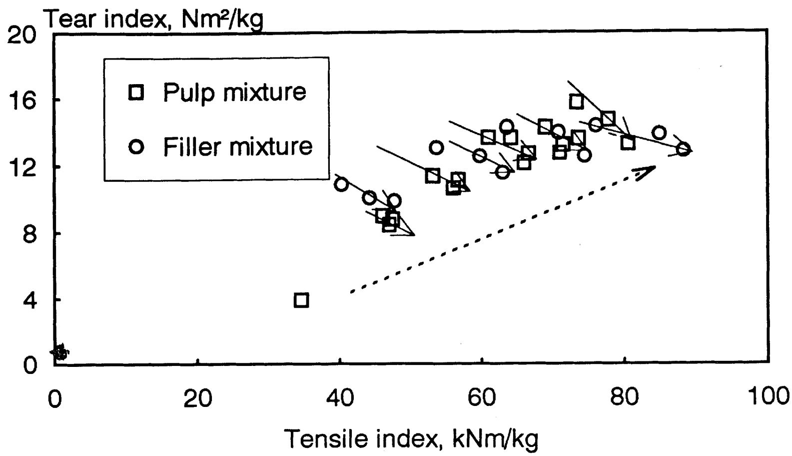

Figure 10. Tear strength vs. tensile strength for the collected data. Dotted arrow signifies increasing amount of chemical pulp and short arrows signify increasing refining.

A practical situation requires both mechanical and optical properties to be considered. As seen in Figure 11, which plots all points at all beating levels, for the range of this limited study beating did not represent a means to influence the relation between light scattering and fracture toughness.

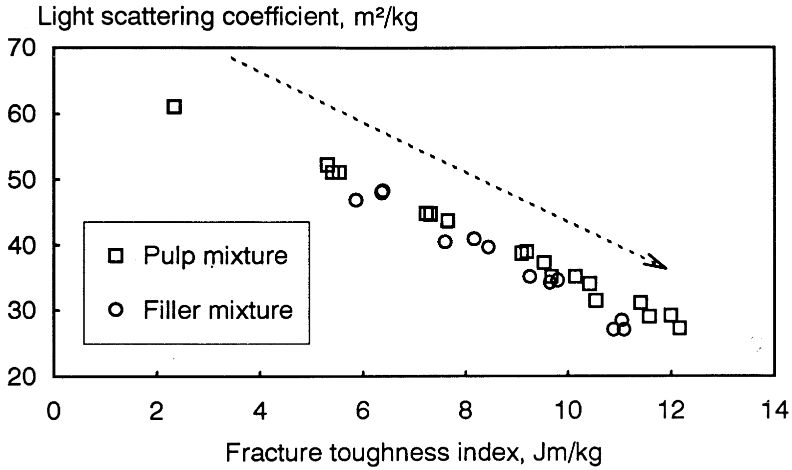

Figure 11. Light scattering decreases as fracture toughness increases for the collected data. Dotted arrow signifies increasing amount of chemical pulp.

Papermaking parameters such as pressing, drying and calendering, as well as the immediately surrounding environment are known to have a great influence on the mechanical properties of paper. Further studies are needed to show the influence of these and other parameters on fracture toughness.

It is suggested that the assessment of a pulp property related to runnability in the paper machine or the printing press is best characterized by measuring the resistance to crack propagation in a load situation similar to that prevailing in reality. Using a non-linear fracture toughness method the results in this study imply that refining of chemical pulps improves the runnability.

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Transcription of Discussion

PLANE STRESS FRACTURE TOUGHNESS AND ITS MEASUREMENT FOR PAPER

Prepared contribution

R Seth, PAPRICAN:

THE J-INTEGRAL AS A FRACTURE TOUGHNESS PARAMETER OF PAPER

T Yuhara

FRACTURE TOUGHNESS AS A PULP CHARACTERISATION METHOD FOR RUNNABILITY ASSESSMENT OF PAPER

A Astrom (Paper presented by A Nordstrom):

(EDITOR'S NOTE: WHAT FOLLOWS IS THE PROCEEDINGS OF A DISCUSSION OF ALL THREE PAPERS)

Dr F El Hosseiny, Weyerhaeuser Paper Co

This question is addressed to whoever can answer it. For the past two decades fracture mechanics of paper was introduced hoping to be able to characterise the behaviour of paper in the converting process and especially press room newsprint runnability. Seth and Page have shown that newsprint runnability is governed only by the rare event phenomena irrespective of its fracture toughness. If fracture toughness or fracture mechanics failed to do what it was supposed to be doing, that is to predict the flow carrying ability of a sheet, what hope do we have for extending this study. We could do it for another 20 years and come to the same conclusion. Why are we continuing doing work in the fracture mechanics of paper?

R Seth

Yes, I was involved in that study. You are quite right. The reason for my getting back into fracture was for the softwood kraft market pulps and tear. Tear is a millstone around the necks of market kraft pulp producers. Tear goes down when you refine the pulp implying you shouldn't refine. Fracture toughness tells us now that you can refine without fear of losing tear because what matters in the end use processes is the stresses in the plane of the sheet, therefore don't be afraid to refine, and that was the purpose. If you wish I can draw curves of fracture toughness against refining and tear against refining; fracture toughness goes up and tear factor goes down. This convinces papermakers that there is a merit in refining and thus using the full potential of the fibre. We now have tear resistance also in plane stress, like tensile strength and elastic modulus, and they all increase as we refine, unlike the out-of-plane tear. That was the only reason I got into this and I think the industry does appreciate that.

Dr D Page, PAPRICAN

I guess my comment is similar to F El-Hosseiny's. There has been a lot of work on fracture mechanics and debate and how to measure fracture mechanics. But what surprises me is that fracture toughness has become a religion. When you actually look for the data to find out if it is important to runnability you will find one plot that R Seth and I published many years ago when we collected 1½ years runnability data. We measured fracture toughness of newsprints and obtained runnability data for a large press room and got a correlation which was significant but very poor between fracture toughness and runnability. It seems to me that the difficult step is to prove that in general it is worthwhile using fracture toughness as a means of evaluating pulps or sheets. That's the difficult step. The easiest step is what you three people are doing now, namely trying to devise a method for measuring it. I think the important step though has to be to show a relationship between end use and a test. I can visualise for example that you can take sheets or reels of paper which have 1% stretch to break and rereel them using 0.5% stretch they won't break, but use 1.5% stretch and they will. This will have nothing whatsoever to do with fracture toughness. What is the proper criterion for failure? I believe we don't know and I believe that's where the next step has to take place, not in a laboratory but in the workplace where the real data exist. In the absence of evidence we are at the mercy of evangelists and their beliefs.

Yuhara *(in response to El Hosseiny question)*
If we want to talk about runnability we have to cover all three factors discussed by Niskanen in the first presentation and also mentioned in my presentation. The three factors are the number of flaws present, uneven tension and finally the paper toughness. For example, Japanese newsprint does not always have high fracture toughness so the industry focuses on decreasing the number of flaws and controlling the calliper profile, especially in the cross machine direction. Not only calliper but also moisture content and of course the basis weight profile. These things influence the tension on the printing press, and the fracture toughness may not be the dominant factor. We must consider other things for good runnability.

R Seth
I agree with Dr Yuhara. We do measure tensile strength and other stress-strain properties, and write review papers on these properties. Why are we doing this; do these properties matter at

all. If we go back to basic materials science, it tells us that there are certain mechanical properties, and if they are OK, we have a hope that the material will survive and fracture toughness is one of them.

Dr K Ebeling, Kymmene Corp, Finland

Thank you for your answer to the first question Dr Seth. One comment I would like to make - it is not the papermakers, it's the pulp merchants that promote the importance of tear strength. I think they are so short minded that tear strength is the only thing they understand.

R Seth

It is unfortunate. We have to educate them.

Dr F-J Chen, Kimberly Clark Corp, USA

One of the key reasons for breaks is web non-uniformity which may be particularly sensitive to your notch method. What happens to the coefficient of variance in your measurement? Is the average value more important or is the coefficient of variance more important? Would the two numbers reported together give us better indication as to whether breaks may occur?

R Seth

I will pass this question because I am not measuring fracture toughness at present to relate to breaks. I am measuring only to evaluate pulps. So those who are doing it to predict breaks should answer this question.

Yuhara

Maybe we have to use some sort of safety assessment method for achieving the fracture toughness for high runnabilitv.

R Seth: *(Question for Yuhara)*
Let's go back to your figure 7 in the text on page 799. In each figure there are about 25-30 points. Which one of them can I call the fracture toughness value?

Yuhara: Actually as I presented in my conclusions, there is no way, so far, to evaluate the energy for crack extension. From that point of view none of those values have a physical meaning which relates to the energy available to drive the crack. Your method, the essential work of fracture cannot give the energy available for crack growth in a machine made paper.

R Seth
Because of the experimental difficulties? I'll come to that point later. So am I correct in assuming that the J methods that you have used, (and you are using 5 of them), none of them gave you an unambiguous result. Am I right in saying this?

Yuhara
Yes, absolutely right.

R Seth
As far as difficulties with my method are concerned, first of all my method may not work for brittle papers such as newsprint because of unstable crack propagation. It was not meant for newsprint, but for ductile sheets, and I have been using it for tough handsheets, sack kraft etc; it worked very well for copying paper. Further, if you have difficulties in having the two edge cracks not connect on propagation, there is nothing in that method that stops you from using a single edge notched sample. There will be experimental difficulties of keeping the clamps from turning. There are guided

clamps which we use and I am happy to give the drawings of them to anyone who wants them. These difficulties can be met, but you have to recognise that the essential work of fracture method is for ductile materials and that is what my February 1993 paper in Tappi said.

Dr J R Parker, Messmer Instruments, UK

I seem to remember from very old data that one of the few properties of paper that had any relationship to runnability was moisture content. I wonder if this gives any pointer to the sort of toughness measurement that might be appropriate.

R Seth

A small increase in moisture content can lead to a higher fracture toughness. It's a piece of work which we did 15-16 years ago, and that was the indication. We measured fracture toughness of newsprint between 40-60% humidity at that time and 60% humidity results were higher.

J Waterhouse, IPST, USA

We need to distinguish between rare events and fracture mechanics but I think it is clear that there are a number of different areas where fracture mechanics can be applied, and obviously rare events will sometimes occur. I always remember Christer Fellers showing the beer bottles on the floor because of failed packaging in one of his presentations on fracture mechanics. There are examples of scoring, durability, perforations, and more recently die cutting, so I think as we can analyse the end use application of paper more correctly, we can see quite a number of applications of fracture mechanics. Obviously fracture toughness is key to this and ultimately what we want to know is: how the processes at the micro mechanics level relate to fracture toughness, ie what do we have to do to improve the fracture toughness of paper? Also, does fracture mechanics give us any clues as to the ultimate strength properties of paper again going back to K Niskanen's excellent review paper this morning.

Prof M Kortschot, University of Toronto, Canada

Let me defend the use of fracture toughness. I think it is still true that in spite of the rarity of breaks in a printing press and in spite of the influence of moisture and other factors, some paper does run better than others. When papermakers have problems with runnability they have to respond by adjusting the furnish. We therefore need some method of addressing the relationship between furnish parameters and the eventual runnability. Intuitively it seems that fracture toughness is the most likely means of characterising this relationship, but I agree with Dr Page that we have to explore this in much more detail.

R Seth

There was an earlier question from Dr Chen that I tried to evade and that was regarding whether I was measuring an average value and what was the spread. If we look at the test, we are measuring an average in the same way as for example tear strength; an average value along a certain path. So, what I am doing is giving an average for the material that I am testing. If you want to see what is the spread or error in that value I would suggest that you look up the Tappi paper (February 1993) which explains the method and you will see that the measurements are fairly good, and the error is comparable to the error in tensile strength etc.

Prof H Kropholler, UMIST, UK

We seem to have a very powerful technique, lots of mathematics and different ways of doing it and there was one very interesting problem which I don't think has been mentioned. There is folklore in the paper industry that some grades of strong papers are best made with a wild formation, corrugating medium is one of these and Prof Göttsching showed some 15 years ago that this was folklore and not true. Another interesting one is sack kraft where it is suggested that the fracture strength is better if you have a wild formation. I don't really believe this but surely you could prove this with fracture mechanics.

R Seth

I will think about it.

Dr K Ebeling, Kymmene Corp, Finland

I think we have to keep the testing methodology on two levels in our minds. The process engineer would like to have a simple method to follow for example if the raw material he is using has a constant quality. As scientists we should have methods that allow us to understand what really is going on and allow us to predict how a better product should be made. The fracture toughness is very important for wood containing printing paper manufacturer because when you have a machine producing 250,000 tonnes a year and if you can save 1% - unit a year in your expensive chemical pulp by using pulp that provides a better fracture toughness to your web, you have earned your salary many times.

R Seth

I agree with you.