# Kraft pulp viscosity as a predictor of paper strength: Its uses and abuses

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**ABSTRACT:** For bleached kraft pulps, two factors govern paper strength: the individual fiber strength, and the bond strength that adheres the individual fibers together in the paper matrix. Inherent fiber strength is related to the length of the carbohydrate polymers, also known as the degree of polymerization (DP). Average DP ($\overline{DP}$) is inferred by performing pulp viscosity measurements. Under certain circumstances during kraft pulping and bleaching, the average polymer lengths can be shortened, resulting in lower pulp viscosity, and may indicate fiber damage. Fiber damage typically manifests itself as a reduction in tear strength for well-bonded handsheets.

This paper will review the literature on how pulp viscosity can predict paper/fiber strength and how it can be used as a diagnostic tool. It can be a means to monitor pulp quality during pulping and bleaching, as well as to alert when such operations approach a critical threshold. However, viscosity losses must be carefully and judiciously analyzed. Like most diagnostic tools, viscosity measurements can be misused and abused, which can lead to incorrect inferences about intrinsic fiber strength. This review will also cover these misuses. The overall goal is to provide the papermaker a better understanding of what pulp viscosity is, how it correlates to potential sheet strength, and what its limitations are. It will be illustrated that when pulp viscosity drops below a critical value, it will indicate an appreciable deterioration in the paper's tear and tensile strength.

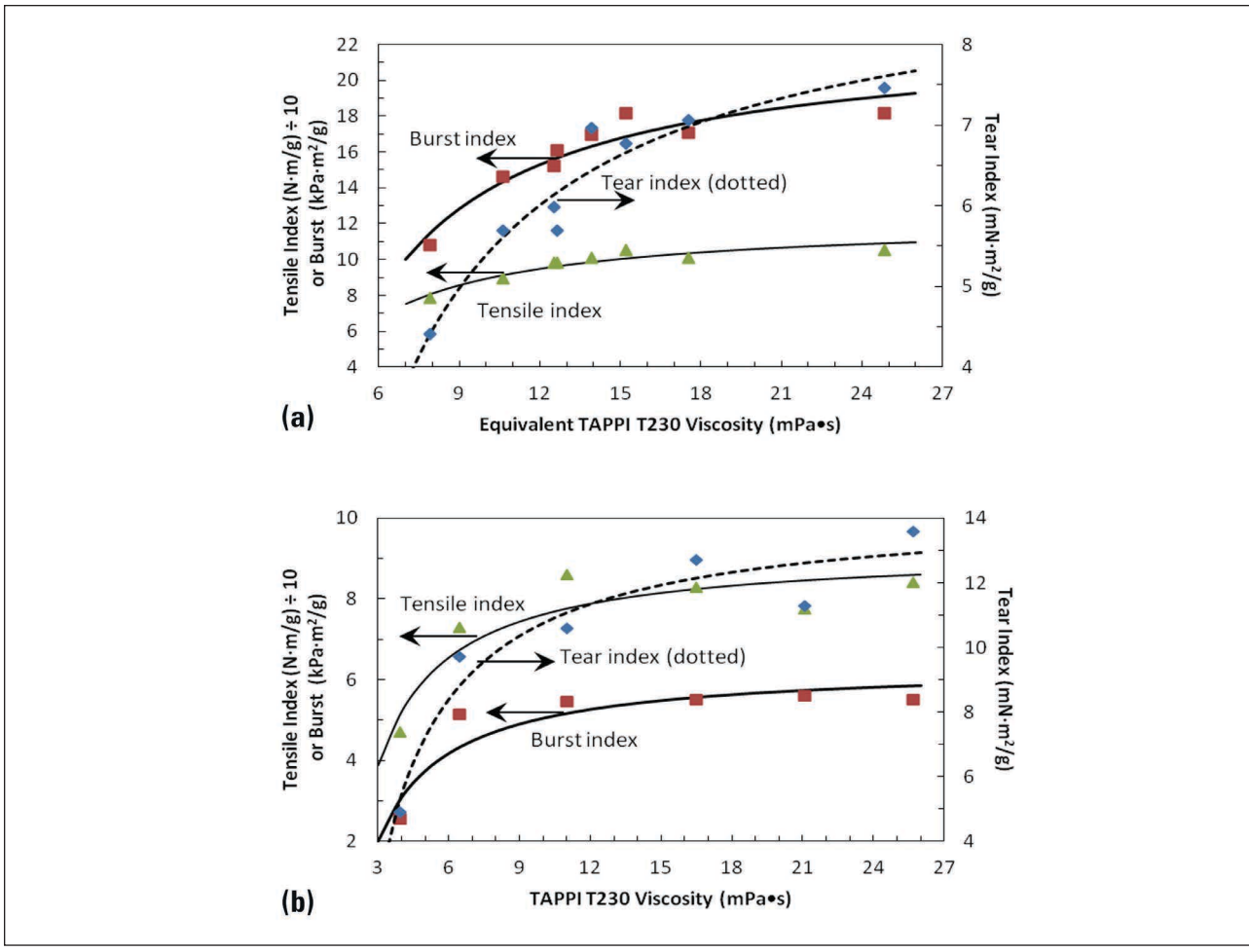
***Application:*** This paper attempts to reconcile the disparaging inferences made with kraft softwoods and hardwoods with regard to intrinsic pulp viscosity (as measured by TAPPI Standard Test Method T 230) and pulp strength, specifically in regards to tensile and tear index.

The paper industry has used pulp viscosity measurements to characterize chemical pulps since around the 1940s [1-11]. Such measurements are reported in the pulping and bleaching literature. These measurements quantify how much cellulose degradation has occurred in the fibers as the wood is converted to pulp. Viscosity data are often coupled with kappa number or brightness data. Analysis of these data sets can quantify how selective unit operations are at delignification or brightening vs. damaging the carbohydrates.

Mills have routinely conducted viscosity tests to monitor pulping and bleaching operations. Pulp samples are taken at several points, particularly where appreciable strength losses can occur. Such points can include after the digester and the bleach plant. Additional sampling may be required following certain bleaching stages. Historically, this included hypochlorite (H) and extraction ($E_1$) stages for bleach plants that used chlorination (C) stages [1-7]. Nowadays, this test may be done on pulps after oxygen (O) and ozone (Z) stages. In these cases, the viscosity test is used as a surrogate for pulp strength tests. Although this test takes a few hours to conduct, it is considerably quicker to perform than physical handsheet testing. Substantial time is required to convert the unbeaten samples into conditioned handsheets, which are then subjected to the appropriate mechanical tests (e.g., burst, tensile, and tear).

The viscosity test has been mistrusted by scientists as to how it relates to pulp strength [8,9,11-14]. Oglesby and coworkers [11] reported that there were no discernible relationships between handsheet strength properties of bleach plant pulps and their cupriethylenediamine (CED) viscosities as measured by TAPPI Standard Test Method T 230-om13 "Viscosity of pulp (capillary viscometer method)." Seth and Chan [12] stalwartly stated that pulp viscosity is a very poor predictor of fiber strength based on their work with bleached market kraft pulps. Gurnagul et al. [13] concluded that there was no correlation between the dry or wet zero-span tensile strength of softwood kraft pulps and their SCAN intrinsic viscosities over the 690 to 1180 mL/g range, as measured by SCAN Standard C15:62, "Viscosity of cellulose in cupriethylenediamine solution (CED)." Earlier, Gurnagul and Page [14] examined the tensile strength, as well as dry and wet zero-span tensile, of several unbleached and bleached kraft pulps; these authors did not note any apparent relationships between tensile measurements and SCAN intrinsic viscosity.

On the other hand, there are several investigators who have reported a linear or curvilinear relationships between a pulp's wet zero-span tensile or other strength properties and its TAPPI T 230 viscosity over the 8 to 24 mPa·s gamut [1,3,5-7,15-22]. Rydholm [1] examined the 1940s to 1960s literature for softwood kraft pulps. He noted that tensile indices have a somewhat positive correlation with its cuprammoniumhydroxide (cuoxam) falling-ball viscosities below 30 mPa·s; tear indices have a stronger positive correlation with cuoxam viscosities below 50 mPa·s (around




***1. Correlations of physical handsheet strength properties to pulp viscosity: (a) data from Valeur [16] that examined a bleached softwood kraft pulp with chlorination-extraction-hypochlorite-chlorine dioxide (CEHD) sequence; and (b) data from Otero D'Almeida study [17] that examined a eucalypt pulp bleached with CEHD sequence. Data from Valeur was converted to equivalent TAPPI T 230 viscosity using the Sihtola et al. procedure [10].***

12 and 19 mPa·s TAPPI T 230, respectively [10]). Rydholm advised that pulp viscosities greater than these levels exhibit no relationships to pulp strength. In 1951, Valeur [16] examined the tensile, burst, and tear of bleached softwood pulps vs. cuoxam viscosity. Examination of the raw data from this study (**Fig. 1a**), when converted [10] to TAPPI T 230 viscosity, showed correlations between pulp strength and viscosity, particularly for values below 15 mPa·s. Otero D'Almeida [17] observed similar trends with a bleached eucalypt pulp (Fig. 1b), mostly for values lower than 9 mPa·s. Still, many others [5-7,19-22] have seen a nonlinear relationship between pulp viscosity measurements and tear for well-bonded sheets (at constant tensile).

This cursory overview suggests that there are inconsistent interpretations of pulp viscosity data. A better holistic comprehension is needed for what this test exactly communicates. Many paper mills and market pulp customers stipulate a floor-level (e.g., ≥ 16 mPa·s for bleached softwood kraft), expecting that this parameter accurately reflects pulp strength [23]. The objective of this study is to re-analyze some of the historical data to provide a clearer understanding of how the viscosity relates to pulp strength, as well as what are some of the inherent weaknesses and limitations of this test. It is hoped that this review will dispel some of the myths surrounding the pulp viscosity test, as well as point out how the test may be misapplied.

## OVERVIEW OF VISCOSITY, MOLECULAR WEIGHT, AND DEGREE OF POLYMERIZATION

The degree of polymerization (DP) or the molecular weight (M) of a pulp sample can be ascertained from the intrinsic viscosity, $[\eta]$ (mL/g), of the sample when dissolved in a solvent [8,9,24-31]. Cellulose solvents used include CED, cuprammonium hydroxide (cuam), cadmium ethylenediamine (cadoxen), and iron sodium tartaric acid (EWNN) solutions. The most commonly used solvent is CED. A series of pulp solutions are made at low concentrations, and the viscosity, $\eta$, of these individual solutions is measured. These values are then the ratio to that of the pure cellulose solvent, $\eta_0$. The $[\eta]$ is calculated from $\eta/\eta_0$ values by taking

the limit as the pulp concentration, $c$ (g/mL), approaches zero:

$$[\eta] = \lim_{c \to 0} \left( \frac{\frac{\eta}{\eta_0} - 1}{c} \right) \quad (1)$$

The average molecular weight of the sample, $\overline{M}$ (g/mol), is related to [$\eta$] by the Mark-Houwink expression [1,7,24-29]:

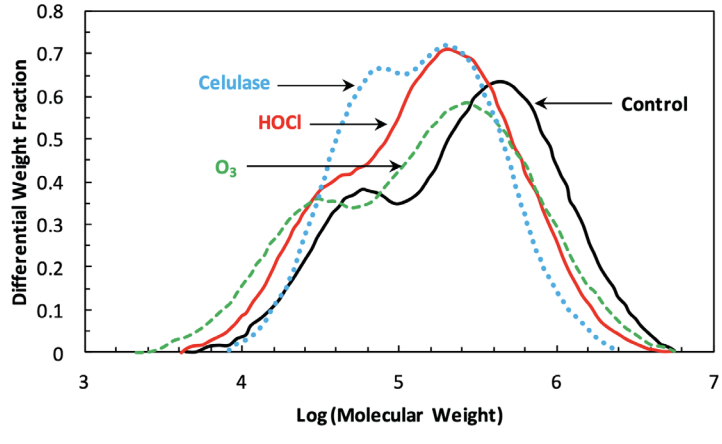
$$[\eta] = K\overline{M}^a = K'\overline{DP}^a \quad (2)$$

Empirical parameters $K$ and $a$ vary depending on what pulp solvent is used and how $\overline{M}$ is determined by other external test with appropriate cellulose or Pulman standards [7-10,13,24-30]. The average DP ($\overline{DP}$) calculated from Eq. 2 can be can be determined by using the appropriate $K'$ value. Historically, the SCAN intrinsic viscosity procedure simplifies the above process. It measures $\eta$ for a single solute concentration $c$ such that the value of the $c$·[$\eta$] product is near 3.0. The cellulose solvent used is 1 M CED.

Alternative methods for measuring pulp viscosity [3,4,10], $\eta$ (mPa·s), include the TAPPI Standard Test Methods T 230 om-13, T 254-cm10 "Cupriethylenediamine disperse viscosity of pulp (falling ball method)," and T 206-os62 "Cuprammonium disperse viscosity of pulp." The TAPPI T 230 test measures the viscosity of 0.5% pulp solution in 0.5 M CED using an Ostwald viscometer. Viscosity is calculated from the time it takes the cellulose solution to pass through a capillary at a fixed distance. The TAPPI T 254 test measures the viscosity of a 1% pulp solution in a 1 M CED solution that is saturated with cupric hydroxide. Viscosity is determined by how long it takes for an aluminum sphere to drop through the solution over a fixed distance. The TAPPI T 206 test, which was withdrawn in 1972, is similar to TAPPI T 254 but uses cuoxam instead of CED as the cellulose solvent.

Sihtola et al. [10] compared various viscosity tests with one another. The authors established equations that could convert the TAPPI T 230 viscosity $\eta$ to [$\eta$] and vice versa. This provided a means to approximate ($\overline{DP}$) and $\overline{M}$ if the SCAN protocol was not employed. The SCAN method uses $K'$ of 1.33 and $a$ of 0.905 in the Mark-Houwink equation (Eq. 2) to approximate a number-average DP ($\overline{DP}_n$). Technically, the $\overline{DP}_n$ values derived from [$\eta$] are viscosity-average ($\overline{DP}_v$) values [27,28].

Measurements of viscosity yield limited information about the average chain length of the carbohydrates. It is just a parameter. It cannot provide any information about the size distribution of the carbohydrate chains in the pulp. Chemical pulps can have the same intrinsic or TAPPI viscosity, but have entirely different molecular weight distributions. **Figure 2** illustrates this with data from Montet's study [32], which subjected a hardwood pulp from a bleach plant to additional carbohydrate degradation. The initial bleached pulp had an [$\eta$] of approximately 895 mL/g ($\overline{DP}_v$ of 1370). Montet treated the pulp with ozone ($O_3$), hypochlorous acid (HOCl), or cellulase enzyme to induce carbohydrate damage. Montet manipulated each treatment to bring about an [$\eta$] of around 582 mL/g ($\overline{DP}_v$ around 850). Despite the similarity in [$\eta$], the various molecular weight distributions ($M$) of the pulps are dissimilar. Overall log($M$) distributions are commonly bimodal. For the initial pulp, the lesser than 5 log($M$) peak is assigned to hemicelluloses, whereas the greater than 5 log($M$) peak is attributed to cellulose. The $O_3$ treatment results in a distribution analogous to the starting pulp, albeit uniformly displaced to lower values. The cellulase treatment has the most pronounced effect on the distribution. It appreciably diminished its bimodality when compared to the control and shifts the main peak to lower levels. Finally, the HOCl degradation results in an intermediate distribution that is between the others.




*2. Logarithmic molecular weight distributions of the carbohydrates from a bleached hardwood kraft pulp (control) treated with ozone ($O_3$), hypochlorous acid (HOCl), or cellulase enzyme [10]. Data is from Montet's Ph.D. dissertation [32]. Treatments were conducted to result in yield intrinsic viscosity value of around 582 mL/g. Data on various average degree of polymerization, $\overline{DP}$, and average molecular weight, $\overline{M}$, values are listed in Table I.*

| Treatment | Intrinsic Viscosity, mL/g | Estimated TAPPI T 230 Viscosity, mPa·s | Average Molecular Weight, g/mole | | | Average DP | | | Wet Zero-Span Tensile, N·m/g |
|---|---|---|---|---|---|---|---|---|---|
| | | | $M_v$ | $M_n$ | $M_w$ | $DP_v$ | $DP_n$ | $DP_w$ | |
| Control (none) | 895 | 19.0 | 222,000 | 90,700 | 536,000 | 1370 | 560 | 3310 | 34.9 |
| $O_3$ | 587 | 9.0 | 139,000 | 50,200 | 410,000 | 860 | 310 | 2530 | 31.4 |
| HOCl | 570 | 8.6 | 134,000 | 81,000 | 290,000 | 830 | 500 | 1790 | 32.0 |
| Cellulase | 593 | 9.2 | 141,000 | 89,100 | 277,000 | 870 | 550 | 1710 | 21.3 |

***I. Average molecular weight ($\overline{M}$) and degree of polymerization ($\overline{DP}$) of the carbohydrates from a bleached hardwood kraft pulp (control) treated with ozone ($O_3$), hypochlorous acid (HOCl), or cellulase enzyme [10]. Data is from Montet's Ph.D. dissertation [32]. Treatments were conducted to result in yield intrinsic viscosity value of ca. 582 mL/g. The molecular weight distributions for these pulps are given in Fig. 2.***

**Table I** displays the various $\overline{DP}$ and $\overline{M}$ values from Montet's investigation [32].

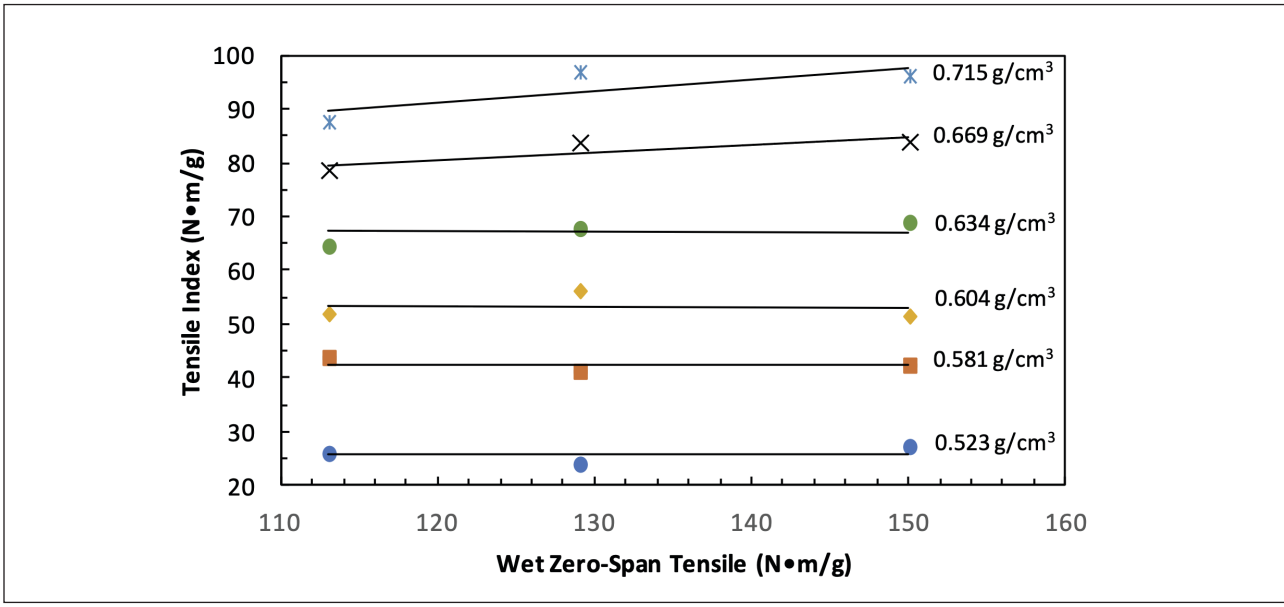
## RELATIONSHIP OF PULP VISCOSITY TO PULP AND INHERANT FIBER STRENGTH

Paper strength made from chemical pulps is governed by two global factors. These fundamental aspects are inherent fiber strength and fiber-fiber adhesion [5,7,33-37]. For tensile strength, the simplified Page equation [33] illustrates this for tensile strength ($T$):

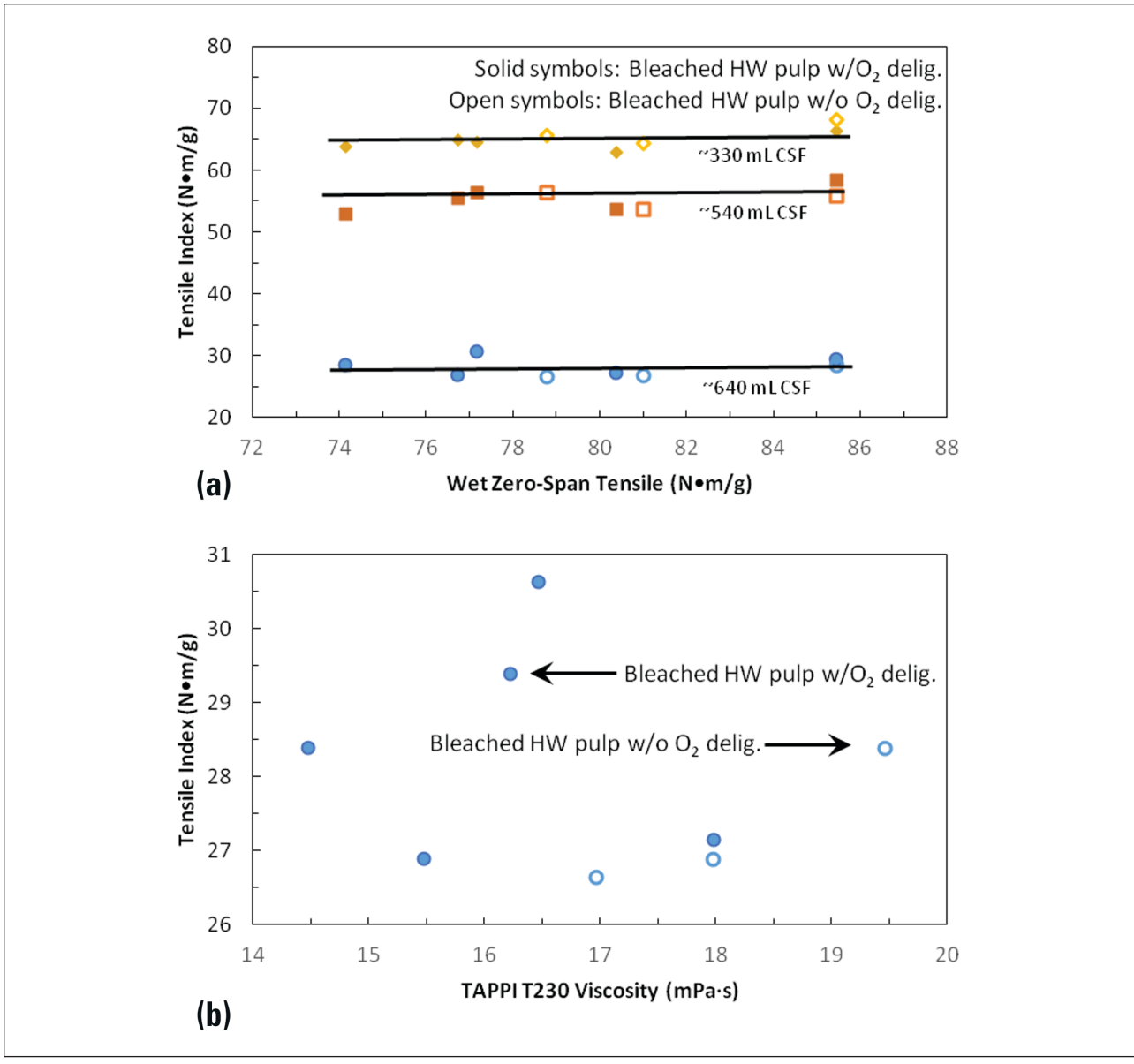
$$\frac{1}{T} = \frac{9}{8Z} + \frac{1}{B} \qquad (3)$$

where $Z$ is the zero-span tensile strength, and $B$ is the fiber-fiber bonding index, which incorporates relative bonding area (RBA), shear bonding strength ($b$), and fiber morphology and conformability. The 9/8Z term accounts for the contribution of inherent fiber strength to the overall sheet tensile strength, whereas the 1/$B$ term represents the contribution of inter-fiber bonds to hold. Usually, the first term is the one most affected by pulping and bleaching operations [5]. The fibers are chemically attacked, which causes cellulose chains to shorten and/or the fibers to experience excessive mechanical treatment, which leads to fiber wall defects. To a lesser extent, pulping and bleaching can alter inter-fiber bonding by modifying the hemicellulose content, coarseness, and conformability of the fibers. Fiber morphology, which is set by wood species used to produce the pulp, affects the 1/$B$ term. Several of these issues are covered in more detail in other literature reviews [5,7,35].

In most cases, the adhesion of the fibers ($B$ term) rather



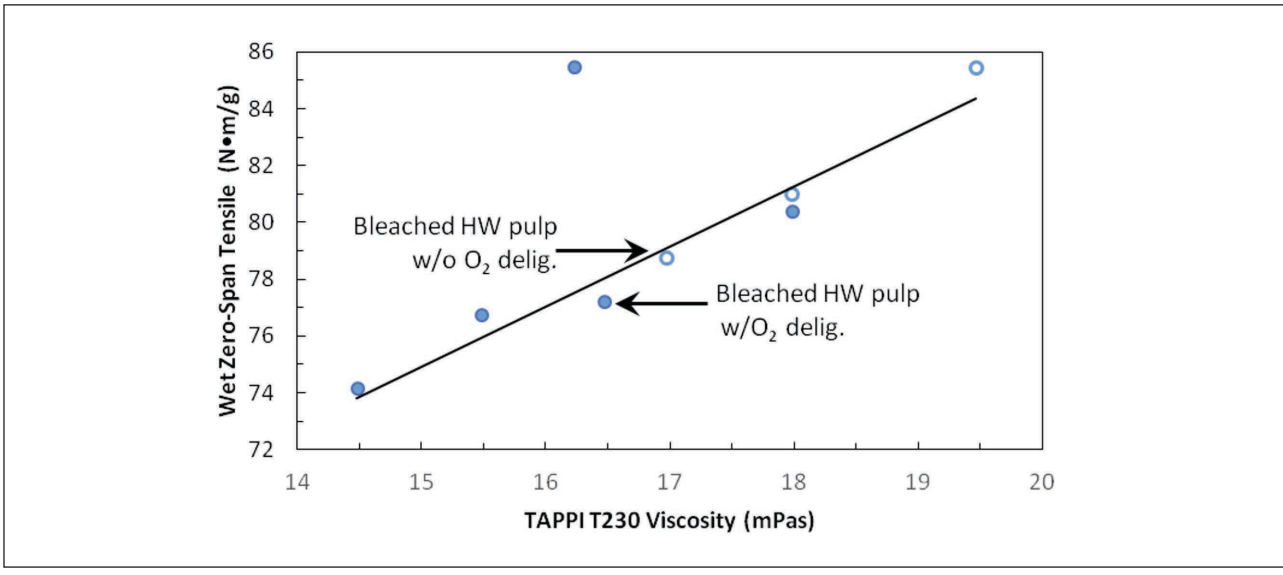

***3. Wet zero-span tensile strength (N·m/g) vs. tensile index (N·m/g) for McKenzie softwood kraft pulp data [35] at different fiber bonding levels as denoted by apparent sheet density (g/cm³). Untreated control had wet zero-span strength of 150 N·m/g. Controls treated with cold liquid hydrochloric acid (HCl) at two levels obtained weakened fibers with wet zero-spans of 129 and 113 N·m/g. Lower fiber strength did not affect the tensile index. It was only with the most severe acid treatment and highest sheet densification (i.e., 0.715 g/cm³) that fiber strength becomes apparent.***



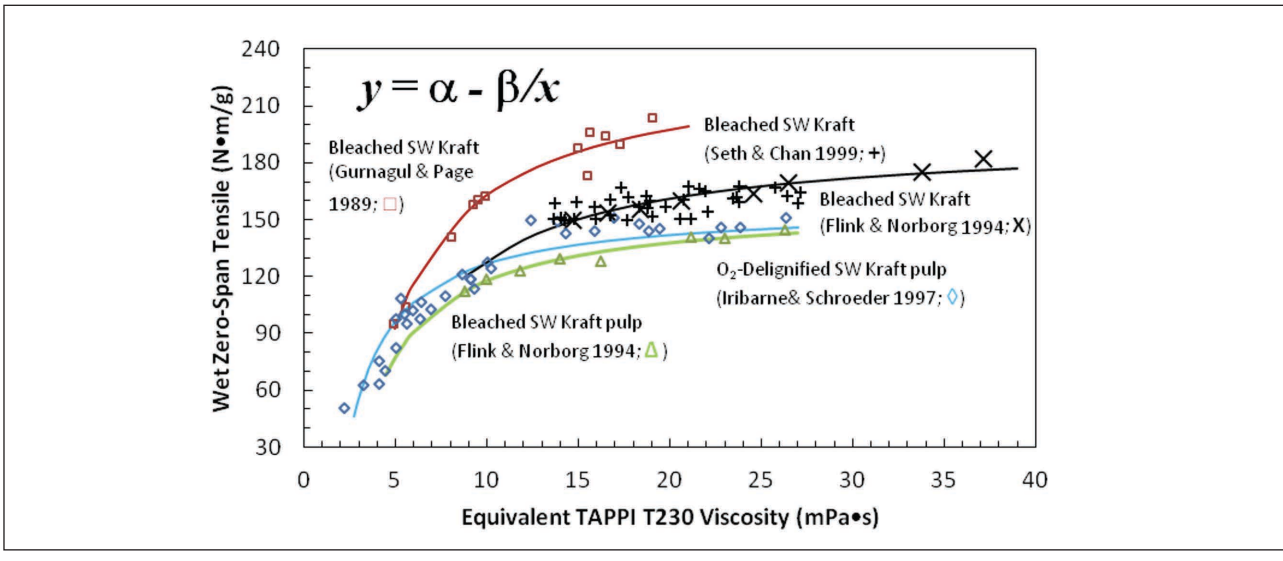

*4. Wet zero-span tensile strength (a) or pulp viscosity (b) vs. tensile index for Oglesby et al. bleached hardwood (HW) kraft pulp data [11] at different fiber bonding levels, as denoted by Canadian standard freeness (CSF). Tensile index was unaffected by intrinsic fiber strength measured by wet zero-span strength or pulp viscosity.*

than fiber strength (*Z* term) dominates tensile strength (*T*). It is only where *B* becomes very large in the Page equation that the effects of *Z* become noticeable. This is illustrated with McKenzie's data [35] of pine kraft pulps (**Fig. 3**). McKenzie degraded fiber strength with cold hydrochloric acid treatment of the pulp at two levels. The fiber bonding index was manipulated by increasing wet fiber conformability by PFI beating. Increases in apparent sheet density improve RBA, which magnifies *B*. The *T* is enhanced as sheet density increases. However, *T* is invariant for fixed density levels as *Z* declines. It is only at high sheet densification, hence high *B*, where lower *Z* becomes perceptible on *T*.

Likewise, data from the Oglesby et al. [11] bleached hardwood study shows a similar phenomenon (**Fig. 4a**). Although the wet zero-span tensile (*Z*) varies, the *T* value remains constant at given levels of pulp freeness. Lower freeness leads to higher RBA, which in turns leads to larger *B*. However, the changes in *B* are not appreciably high enough to observe how lower *Z* affects *T*. The corresponding viscosity data (**Fig. 5**) shows a strong a linear correlation with *Z* but no relationship to *T* (Fig. 4b). Both the viscosity and wet zero-span data suggest that the lower values show lower inherent fiber strength, but this lower strength is a minor contributor to overall tensile strength when compared to the fiber bonding index in the Page equation. Here, the carbohydrate chemical damage is not severe enough to affect tensile strength. In fact, the wet zero-span tensile strength would have to decrease to below 62 N·m/g




*5. Pulp viscosity vs. wet zero-span tensile strength for Oglesby et al. bleached hardwood (HW) kraft pulp data [11].*




*6. Pulp viscosities over a wider range vs. wet zero-span tensile strength indices for oxygen delignified or bleached softwood (SW) kraft pulps. The relationship between viscosity and wet zero-span follows Eq. 4, which is a similar nonlinear behavior observed for intrinsic viscosity-tensile strength for polymeric materials.*

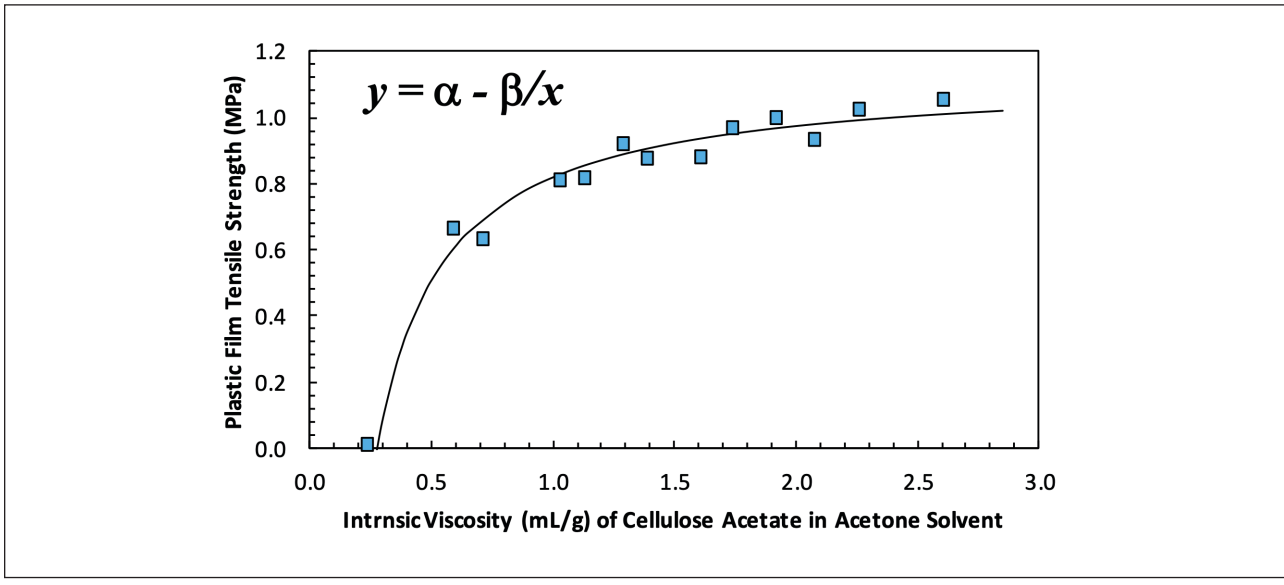
(9 mPa·s TAPPI T230 viscosity) before it began to affect the tensile index for the 330 mL CSF pulp. This value is similar to the Otero D'Almeida study [17] for bleached eucalypt pulps.

**Figure 6** compares wet zero-span tensile data from several softwood studies where the investigators also reported pulp viscosity values. In these cases, there is a curvilinear relationship between pulp viscosity and wet zero-span tensile when a broader range is examined. Typically, a small decrease in TAPPI viscosity (approximately Δ1 mPa·s) in the 5 to 15 mPa·s range results in large reductions of wet zero-span tensile, whereas above 15 mPa·s results in small to negligible changes to wet zero-span tensile. This transition occurs at around 885 $\overline{DP}_v$, ($\overline{M}_v$ around 143,000). This nonlinear behavior is not unusual when compared to other polymeric materials.

Correlations of intrinsic polymer viscosity, $\overline{DP}$, or $\overline{M}$ values to various polymer strength properties, such as tensile or tear strength, are frequently nonlinear [38-43]. Often, these empirical trends take the form:

$$y = \alpha - \frac{\beta}{x} \tag{4}$$

where $y$ is the strength property of interest; $\alpha$ is the plateau value of the property; $\beta$ is some positive constant; and $x$ is the polymer's intrinsic viscosity in an organic solvent (or $\overline{DP}$ or $\overline{M}$ values). In the 1940s, Flory [39,40] arrived at this




***7. Intrinsic viscosity vs. tensile for polymeric cellulose acetate films. Data is from Sookne and Harris study [38]. Nonlinear trend line follows Eq. 4.***

expression for the tensile strength versus the $\overline{M}_n$ of the polymer. He showed that the unfractionated polymer tensile strength could be deduced from the individual tensile strengths of fractionated polymers as long as the molecular weight distribution of the unfractionated sample is known. Similar findings were reported by Sookne and Harris [1,38] for cast films made from cellulose acetate (**Fig. 7**).

The shapes of wet or dry *Z* vs. pulp viscosity curves follow similar tendencies when examining a wide viscosity range (Fig. 6). The broader trends probably explain why there are so many disparate observations in the literature regarding pulp viscosity. For example, Seth and Chan [12] stated that pulp viscosity *does not* predict zero-span tensile, whether wet or dry. However, the viscosity range examined, approximately 12 to 25 mPa·s, is at or past the transition zone where wet zero-span value plateaus. In other examples [5,7,15,36,44] investigators examined the 9 to 14 mPa·s range where wet zero-span incrementally grows as viscosity increases.

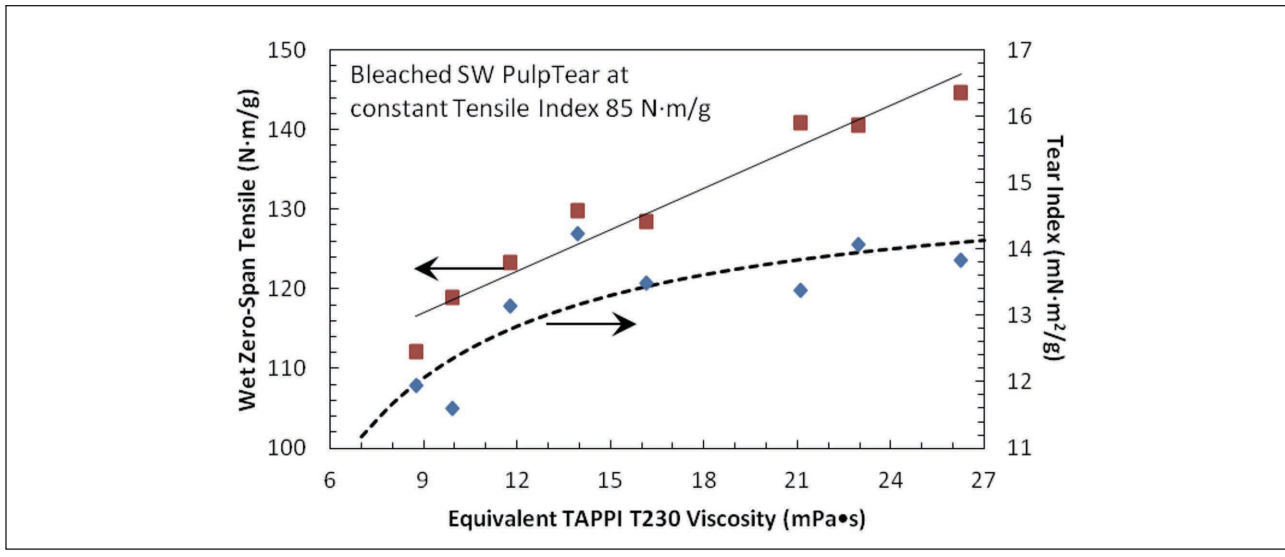
As mentioned earlier, pulp viscosity only provides information about the molecular weight or DP distribution. For example, the treated pulps [32] shown in Fig. 2 and Table I have nearly identical pulp viscosity. However, the distributions are distinct. The wet zero-span values for the treated pulps are not the same. The $O_3$ and HOCl treatments afford pulps with similar wet zero-span, whereas the cellulase treatment results in a wet *Z* that is 33% lower. These viscosity values of the treated pulps, at first glance, would have implied that they should all have the same wet zero-span tensile strength. The log(*M*) distributions of the cellulase-treated pulp show it has more cellulose of lower *M*, 25,000 to 63,000 g/mol, than the other pulps. The greater proportion of these weaker and smaller chains results in the pulp having a reduced wet zero-span tensile. Pulps treated with $O_3$ or HOCl have a greater fraction of *M* in the 100,000 to 250,000 g/mol range that are stronger. Hence, caution should be exercised when making inferences about fiber strength strictly based on viscosity data. This proviso has been stated in numerous studies, particularly regarding the effects of oxygen and ozone in pulp bleaching [32,45-47]. Knowledge of *M* or log(*M*) distributions are needed to draw valid conclusions from viscosity data, particularly if the pulp process conditions are vastly different, such as comparing elemental chlorine free (ECF) and totally chlorine-free (TCF) bleached pulps.

The previous examples have focused on how pulp viscosity related to a pulp's tensile strength. In most cases, during pulping and/or bleaching, a reduction in tear resistance manifests itself as a result of fiber damage [5,35]. Tear failure of well-bonded softwood sheets involves fiber breakage and is therefore dominated by fiber strength and fiber length [5,48,49]. Tensile failure, on the other hand, usually involves fiber pullout and is typically dominated by fiber-to-fiber bond strength. Page and MacLeod have shown that the work of tear (*W*) for softwood kraft pulps is related to both tensile and zero-span tensile:

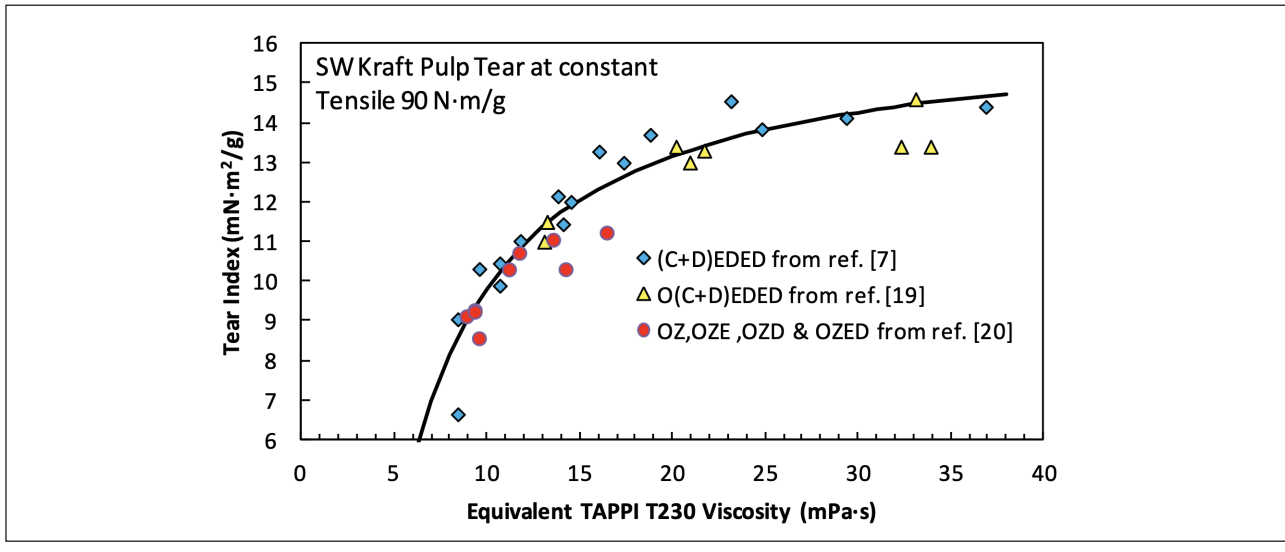
$$W \propto \frac{Z^n}{T} \tag{5}$$

where *n* is an exponent value that is typically between 2.5 and 3.0. For a given *T* level for well-bonded sheets, tear is expected to vary in accordance to zero-span tensile to the $n^{th}$ power. This means that if the *Z* value drops a small amount, for instance 5%, then the tear strength could be reduced by 12% to 15%.

**Figure 8** shows the relationships of pulp viscosity to tear index and wet zero-span tensile strength for bleached




*8. Relationships of pulp viscosity vs. tear index and wet zero-span tensile strength for softwood (SW) kraft pulp bleached with different sequences. Data from Flink and Norborg study [15], where reported SCAN intrinsic viscosities converted to equivalent TAPPI T 230 viscosities [10].*




*9. Relationships of pulp viscosity over a wide range vs. wet zero-span tensile strength for softwood (SW) kraft pulp bleached with different sequences. Data from Sjostrom and Brolin [7], Fossum and Marklund [19], and Lindholm [20] studies, where reported SCAN intrinsic viscosities converted to equivalent TAPPI T 230 viscosities [10].*

softwood kraft pulps using data from Flink and Norborg [7,15]. Pulp viscosity varies linearly with wet zero-span tensile over the 9 to 27 mPa·s (600 to 1000 mL/g) range. Tear strength seems relatively stable for viscosity levels above 13 mPa·s (750 mL/g) or wet zero-span values above 125 N·m/g. However, tear precipitously decreases below these threshold levels. Similar nonlinear correlations of tear index vs. pulp viscosity are given in **Fig. 9** for softwood pulps treated with different bleaching sequences. In these cases, this threshold occurs around 13 to 16 mPa·s.

Oglesby et al. [11] did not see any relationships between tear and pulp viscosity for hardwood kraft pulps. However, the Otero D'Almeida [17] study of bleached eucalypt pulps shows a correlation for viscosities for values below 9 mPa·s (Fig. 1b). Re-examination of the Oglesby et al. [11] study also revealed there were no discernible relationships between tear index and wet zero-span tensile (not shown). All of these hardwood observations at first glance seem inconsistent with softwood pulps. It should be noted that tear is also a function of fiber length [35,48]. Tear mechanics differ more for short fibers than for long fibers. In the former, the work to pull the short fiber out is much less than it is to break the fiber, whereas the opposite is true for long fibers. It is only when there is substantial damage to the short fiber strength that its tear resistance is affected. This probably explains why tear strength for hardwoods does not depend as strongly on inherent fiber strength as for softwoods, unless the carbohydrate damage is excessively severe.

## FINAL REMARKS

The previous sections have examined the connections between pulp viscosity measurements and pulp strength properties determined from physical handsheet testing. Pulp viscosity relates to $\overline{DP}$ (or $\overline{M}$) of the carbohydrates, and specifically to the long cellulose chains. The pulp's $\overline{DP}$ (or $\overline{M}$) is associated with inherent fiber strength. The correlation of pulp viscosity with fiber strength is nonlinear over a broad range of viscosity values. This nonlinear trend is in line with the strength-viscosity relationship of other polymeric materials. Depending on what part of the range is examined, pulp viscosity values will either have strong positive correlations or little correlations to zero-span tensile strength. This limit, where pulp viscosity becomes relevant, occurs around 10 to 15 mPa·s TAPPI T 230 viscosity or about 630 to 800 mL/g SCAN intrinsic viscosity; this corresponds to a relative SCAN $\overline{DP}_v$ value between 720 and 890.

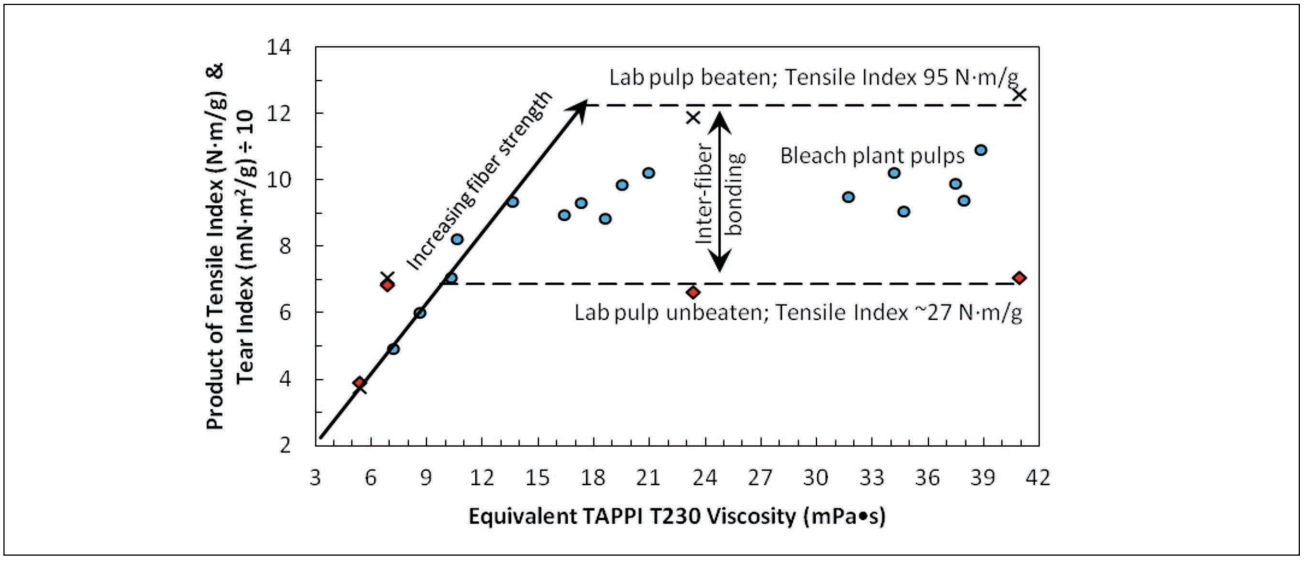
The $\overline{DP}_v$ derived from viscosity provides partial information regarding the *DP* or molecular weight distributions of the carbohydrates in the pulp. Pulps can have nearly identical viscosity values but have distinct DP or molecular weight distributions. It is the higher DP chains that have the greatest effect on zero-span tensile strength. Pulps that have a greater fraction of high DP cellulose chains will exhibit higher zero-span tensile values when compared to pulps with identical pulp viscosity but lower fraction of these chains. Therefore, caution should be exercised when drawing fiber strength inferences when comparing viscosity values for pulps from different chemical treatments. Prior knowledge of the carbohydrate molecular weight distribution is needed in order to draw conclusions from viscosity comparisons.

Tensile indices of kraft pulps are determined by two factors as generalized in the Page equation: inherent fiber strength and degree of fiber-fiber bonding. Most times, the amount of inter-fiber adhesion dominates the tensile index vs. inherent fiber strength. It is only when the fiber strength, and hence pulp viscosity, has been reduced below a critical level that this factor becomes relevant to tensile failure.

Tear resistances of kraft pulps are more sensitive to changes in inherent fiber strength and fiber length. For softwood kraft pulps, there is a nonlinear relationship between the tear index (at a fixed tensile index) and pulp viscosity, similar to wet zero-span tensile. The threshold level when softwood pulp viscosity transitions from strongly correlated to weakly correlated occurs around 15 to 20 mPa·s TAPPI T 230 viscosity, or 800 to 915 mL/g SCAN intrinsic viscosity. The viscosity-tear relationship for hardwood kraft pulp differs from that of softwoods. For hardwoods, the shorter fiber of the pulp makes fiber pull out the overriding factor in tear failure rather than fiber breakage, which is predominant for softwoods. It is only when hardwood fiber damage, and consequently pulp viscosity, drops below a critical value (≤9 mPa·s) that this factor becomes germane to tear failure.

Overall, it is emphasized that low pulp viscosity values (<10 mPa·s TAPPI T 230) denote lower inherent fiber strengths. High pulp viscosity values (>20 mPa·s TAPPI T 230) do not imply higher pulp strengths; it is only when viscosity drops below a threshold value where any further reductions will cause considerable declines in fiber strength, which affect tear and tensile. Any viscosity reductions above the critical value will not affect pulp strength.

In this context, pulp viscosity should be used to monitor pulp mill operations. It should not be used as a set-point value, such as a kappa number or brightness level, to control pulp mill operations. Instead, it should be used as a

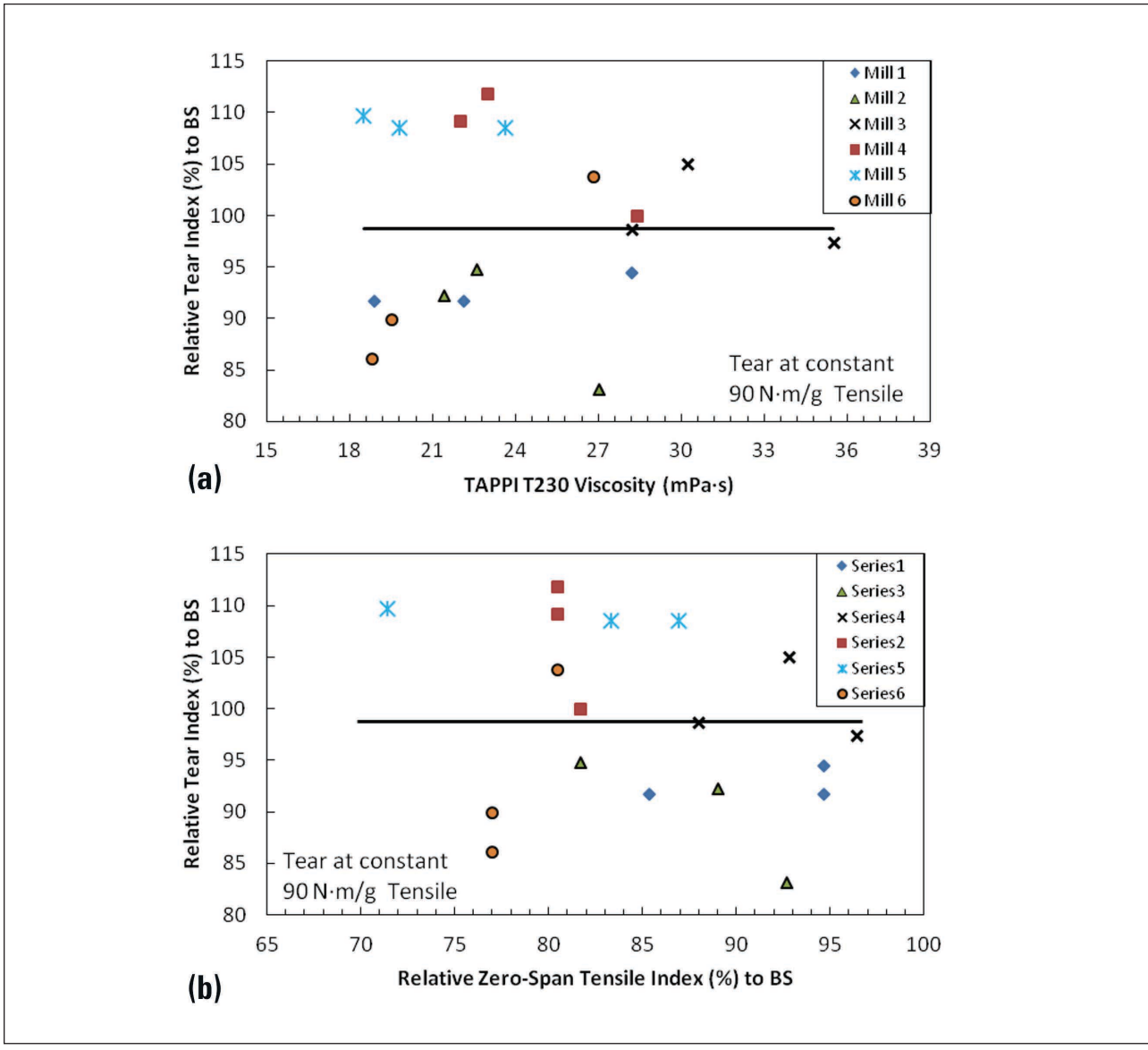



*10. Relationship of pulp viscosity to tensile-tear product for bleach plant softwood kraft pulp. Data from Dahm [18], who examined pulp viscosities of pulps after the chlorination-extraction-hypochlorite (CEH) bleach sequence and compared handsheet strength data to laboratory data. Data was converted to SI units and to equivalent TAPPI T 230 viscosity using Sihtola et al. procedure [10].*

warning gauge to alert when extensive cellulose damage is so severe that it negatively affects fiber strength.

An example of this can be seen in the 1950s data presented by Dahm [18] who investigated the chlorine-hypochlorite bleaching of a softwood pulp at a Norwegian kraft mill. Dahm examined the tensile strength, tear strength, and cuoxam falling ball viscosity of the pulp after the sodium hypochlorite (H) stage. It well known hypochlorite bleaching can cause severe drops in viscosity and fiber strength if the bleach conditions are not carefully monitored. Dahm compared the mill data to the laboratory data where the brownstock was bleached and subsequently beaten. The graphical data from the study are shown in Fig. 10, which is updated into equivalent TAPPI T 230 viscosity [10].

Dahm [18] looked at both the individual tensile and tear strengths, as well as the tensile-tear product, vs. pulp viscosity. The tear of the bleach plant pulps after the H stage uniformly decreased as the pulp viscosity decreased below 22 mPa·s (TAPPI T 230). A similar trend is observed for tensile when the pulp viscosity dipped below 14 mPa·s (TAPPI T 230). This is more compactly shown in **Fig. 10**, along with the laboratory data to show the individual effects of fiber strength and fiber-fiber bonding. The tear-




*11. Mill audit data from Marcoccia et al. [50], who examined six different North American fiber lines using generic O(C+D)$E_1D_1E_1D_2$ sequence to bleach softwood kraft pulps to full brightness. Authors examined samples after brownstock (BS) washing, oxygen delignification (O), first extraction stage ($E_1$), and final chlorine dioxide stage ($D_2$). Relative tear index is the tear index value relative to BS. As the BS goes through the bleach plant (right to left), the pulp viscosity decreases. In most cases, the decrease in viscosity does not correspond to changes in relative tear index. Viscosity values in the above cases are >15 mPa·s, the critical threshold where softwood fiber strength become noticeable. There are similar trends with relative zero-span tensile.*

tensile product helps to normalize differences in the two strength parameters for the bleach plant pulps. Including the laboratory data helps to estimate the effects of fiber-fiber bonding level. Data analysis showed that the papermaking strength of the pulps with viscosities above 14 mPa·s is similar, whereas pulps with viscosities below 14 mPa·s became weaker as viscosity decreased.

The Dahm study with the chlorine-hypochlorite bleach plant represents an extreme when compared to today's bleacheries. Modern ECF sequences use more selective bleaching agents than sodium hypochlorite, such as chlorine dioxide, which minimally attacks the carbohydrates. Marcoccia and co-workers [50] conducted softwood fiberline audits on six North American bleach plants in order to determine how bleaching affected pulp strength delivery. The authors collected samples after brownstock washing (BS), oxygen delignification (O), extraction after chlorine dioxide delignification ($D_0E_1$), and the final chlorine dioxide ($D_2$) stage. The samples were tested for viscosity and zero-span tensile, as well as beaten and made into handsheets for physical testing. **Figure 11** is a plot of the viscosity or relative zero-span against the relative tear index to the BS pulp. Viscosity values did not correlate to the relative tear index (at fixed tensile 90 N·m/g). Likewise, there was no relationship between relative zero-span tensile to relative tear (not shown). Pulp viscosity shows a somewhat linear relationship to the relative zero-span tensile over the 18 to 36 mPa·s range (not shown). The previous data analysis suggests that losses in inherent fiber strength, as measured by drops in pulp viscosity or zero-span tensile strength, are not great enough to contribute to overall pulp strength delivery. **TJ**

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## ABOUT THIS PAPER

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## ABOUT THE AUTHORS

We chose this topic after one of us handled a review for the paper by Robert Oglesby and co-workers entitled "Does kraft hardwood and softwood pulp viscosity correlate to paper properties?", which can be found in *TAPPI J.* 15(10): 643(2016). There were a few items not discussed in that review that we wanted to address in this paper. This paper is not to contradict the findings of the Oglesby et al. paper, but to expand and complement it.

In reviewing the pulp and paper literature over the past 75-plus years, we found a lot of confusion about what TAPPI Standard Test Method T 230 pulp viscosity actually means. After the review, it became clear that pulp viscosity relates to intrinsic fiber strength and not to fiber-fiber bonding. Most paper strength from kraft hardwood and softwood pulps is more related to fiber-fiber bonding. It is only when the individual fibers have been so attacked that intrinsic fiber strength begins to take over from fiber-fiber bonding (i.e., the Page equation for tensile index).

The most difficult aspect of this research was the divergence of opinion on pulp viscosity measurements and its relevance to paper strength. After looking at more than 75 years of research in the area, it became evident that pulp viscosity relates to intrinsic fiber strength once it drops below 9 to 15 mPa·s (TAPPI T 230). Above these values, pulp viscosity does not have much effect on overall paper strength. Below these values, there is a strong correlation to pulp viscosity loss vs. tear and/or tensile index loss.

***Brogdon***

***Lucia***

One particularly interesting observation we made was that various opinions on pulp viscosity have to be interpreted in proper context. None of the papers reviewed is incorrect; the conclusions drawn have to be considered within the narrow limits of the studies.

Kraft mills can use this review to justify the value of pulp viscosity measurements. It is a tool that should be used in conjunction with other physical test methods.


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