

Implications of the single-ply Elmendorf tear strength test for characterizing pulps

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The discrepancy between single- and multi-ply tear indices can be linked to the pulp itself and can vary with the degree of bonding in the sheet.

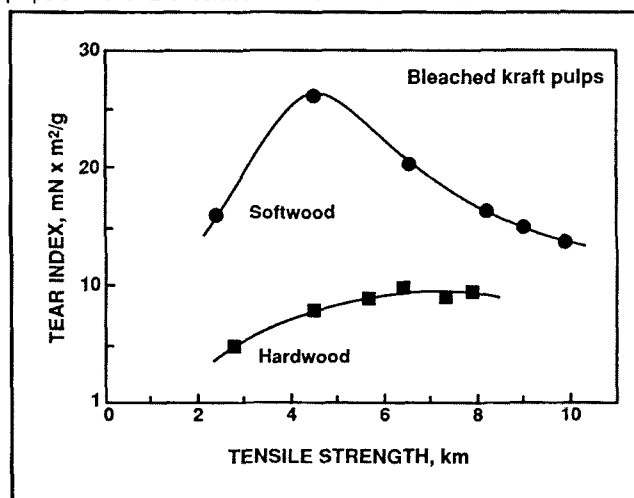
When the degree of bonding between fibers in a paper sheet is increased, both tensile strength and tear index initially increase. Bonding is increased if the pulp is beaten or refined, or the sheet is consolidated more by increased wet pressing, or if a bonding agent is added to the furnish. In sheets made from short fibers, such as those of hardwood chemical pulps or softwood mechanical pulps, the tear index eventually reaches a plateau or drops slightly, even though further increase in bonding results in increased tensile strength. However, the pattern is different for sheets made from long fibers, such as those of softwood chemical pulps. After passing through an early maximum, the tear index appears to decrease sharply with increased bonding.

Tear index-tensile strength plots for two typical commercial pulps are shown in Fig. 1. The pulps were beaten in a PFI mill. The properties were measured according to the standard procedures of the CPPA (Technical Section). Unless indicated, the handsheet grammage in all experiments was 60 g/m². Such plots are often used to characterize the strength properties of pulps. At a given refining level, a papermaker desires both high tensile strength and tear index in the furnish.

In North America and in many countries in other parts of the world, the tear strength is commonly measured with the Elmendorf tear tester. A paper sample is clamped in split jaws. A cut is made in the sample between the jaws with a sharp blade, leaving a segment across which the tear is propagated. Samples are torn by applying an impact load through a swinging pendulum. According to the procedure recommended by the CPPA (Technical Section) (1), four plies of paper are clamped together and torn simultaneously in each test. Pendulums of different capacity are used, depending on the sample strength.

The procedure recommended by TAPPI is somewhat different. While the capacity of the pendulum is fixed, the number of plies torn simultaneously is varied, so as to obtain readings within a certain range on the tester scale

1. Tear index-tensile strength plots for commercial dried bleached kraft pulps of interior B.C. softwoods and Scandinavian birch



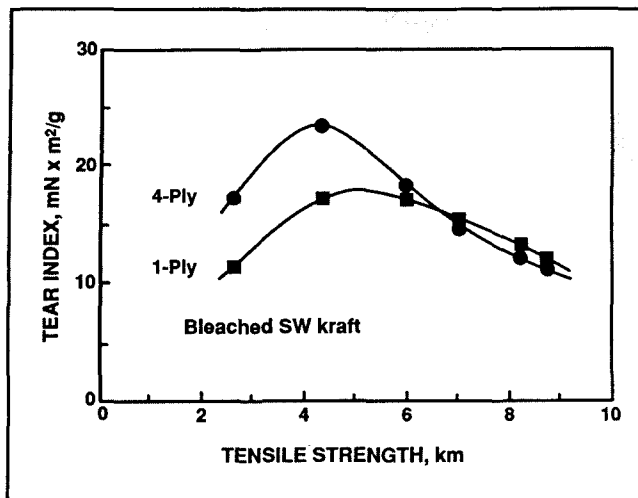
(2). With both procedures, the test instrument provides the average amount of work consumed to tear each sheet per unit tear length (gf × cm/cm or mN × m/m), which is numerically equivalent to the average force required to continue to tear a single sheet (gf or mN). The work is mostly consumed either in breaking the fibers or in pulling them out of the sheet structure at the tear zone where the stress is concentrated. The tear index is calculated by dividing the tear work by the sheet grammage.

The tear index in Fig. 1 was obtained according to the CPPA procedure (1). A pendulum of 800 gf capacity was used.

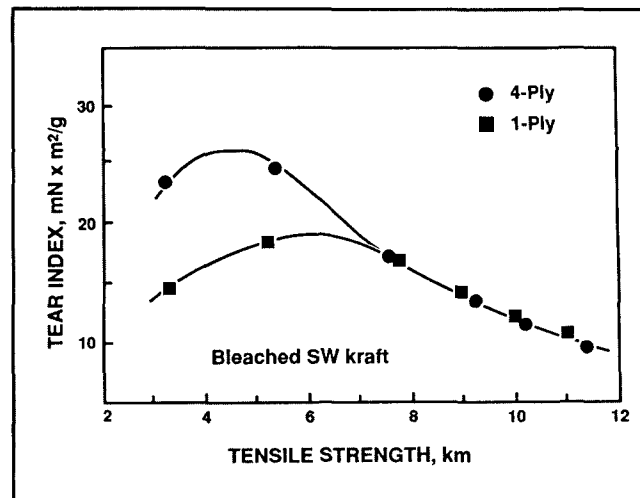
If the tear test is performed using a single ply and a pendulum of 200 gf capacity—instead of tearing four plies simultaneously as in the standard test—different results are obtained. In this investigation, the discrepancy between single- and four-ply tear indices was determined for handsheets made from various pulps. Each pulp was beaten to several different levels. Although the effect of beating a pulp on the discrepancy between single- and multi-ply tests has been examined before (3, 4), it was done for only two beating levels, not for the entire beating range.

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2. Single- and four-ply tear index-tensile strength plots for a commercial dried bleached kraft pulp of southern U.S. pines



3. Single- and four-ply tear index-tensile strength plots for a commercial dried bleached kraft pulp of eastern Canadian softwoods



This investigation showed that the discrepancy between single- and four-ply tear indices is different for different pulps; and within a pulp, the discrepancy varies with the degree of bonding in the sheet. This article points out the implications of these results for evaluating the papermaking properties of pulps by tear-tensile plots. In light of these findings, it discusses limitations of the Elmendorf test for characterizing the tearing strength of paper and discusses alternatives.

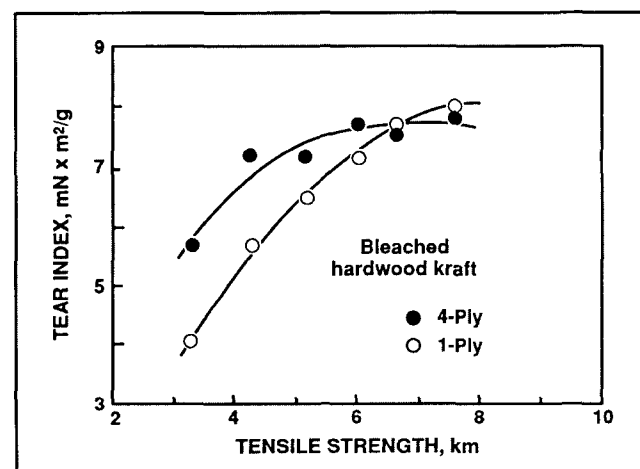
Results and discussion

Figure 2 shows tear-tensile plots for the same pulp, using four- and single-ply tests. Clearly there is a large discrepancy between the two tear indices, which changes with the degree of bonding in the sheet. The discrepancy has been confirmed for a variety of pulps. It can be as large as 50% to 60%. Figures 3 and 4 show two further examples.

For a papermaker who is selecting pulps from tear-tensile data, single-ply tear-tensile plots give a different perspective of a pulp's response to refining than do four-ply. In softwoods, the single-ply tear strength is initially lower, and the increase in tear strength upon refining is also slower than that from four-ply. However, the peak tear strengths occur at somewhat higher tensile strengths. The four-ply peak tear strengths are significantly higher than the single-ply peak tear strengths. After the peak, the single-ply tear strength may decrease more slowly with refining and, at high tensile strengths, the single-ply tear strengths are either similar to or somewhat higher than the four-ply strengths, as indicated in Figs. 2 and 3.

The single- and four-ply tear indices in these and subsequent figures were measured with 200 gf and 800 gf pendulums, and the results are means of 10 and 5 tests respectively. The pulps were beaten in a PFI mill. In hardwoods, the single-ply tear strengths are also lower than those from four-ply, but the increase in tear strength with refining is faster. At high tensile strengths, the single-ply strengths once again are either similar to or higher than the four-ply strengths, as shown in Fig. 4. Thus,

4. Single- and four-ply tear index-tensile strength plots for a commercial dried bleached kraft pulp of Canadian prairie aspen



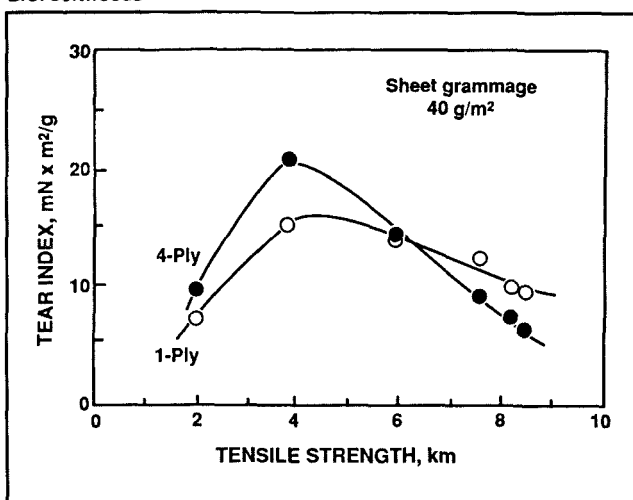
softwood pulps appear more forgiving of refining when assessed by the single-ply test than when assessed by the four-ply test. For instance, in Fig. 2, when the tensile strength of the pulp doubled from 4 km to 8 km upon beating, the four-ply tear index dropped by 45%; however, the loss in single-ply tear index was only 15%. Hardwood pulps, on the other hand, develop tear strength faster with refining based on the single-ply tear tests.

The fact that the tear index in general depends on the number of plies torn simultaneously has been known since 1922 (5), and it has been confirmed over the years by several other researchers. The mechanisms responsible for this are not completely understood. Therefore, at present, it is not possible to predict how the discrepancy between single- and multi-ply tests for a specific pulp will vary with the number of plies, or the degree of bonding in the sheet. This can only be determined experimentally. What is clear, however, is that the discrepancy is different for different pulps and exists even for mechanical pulps, as shown in

1. Comparison of tear strengths of a laboratory-made papermaking-grade spruce TMP

C.S.F.	110 mL
Tensile strength	3.82 km
Stretch	2.02 %
Tear index (1-ply)	7.27 mN × m ² /g (std. dev. 0.243)
Tear index (4-ply)	8.69 mN × m ² /g (std. dev. 0.328)

5. Single- and four-ply tear index-tensile strength plots for 40 g/m² sheets made from a commercial dried bleached kraft pulp of interior B.C. softwoods



6. Single- and four-ply tear index-tensile strength plots for 80 g/m² sheets made from a commercial dried bleached kraft pulp of interior B.C. softwoods

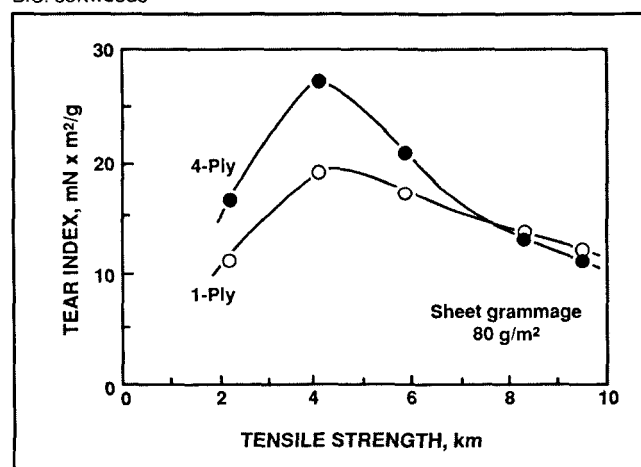


Table I. For a given pulp, the discrepancy varies with sheet grammage, as shown in Figs. 5 and 6. Here, the two sets of sheets were made at similar consistency to minimize variation due to formation. We can, nevertheless, speculate on the mechanisms involved in the discrepancy.

The multi-ply tear strength may be different from the single-ply tear strength because of the nature of the tear. Being essentially a layered structure, paper always splits when torn in the Elmendorf mode. This is because tearing in this mode occurs under out-of-plane loading. The extent of splitting depends on the sheet grammage, the degree of bonding in the sheet, and on the number of plies torn simultaneously (3, 6). The extent of splitting cannot be predicted, and its contribution to tear work is difficult to assess. In the single-ply test, splitting is allowed to proceed freely; however, it is arbitrarily restricted in the multi-ply test.

Multi-ply tear strength may be higher because of the work dissipated in bending the interlocked plies and in overcoming friction between the plies and between their

torn edges (7). The multi-ply tear strength may also be higher because of effects related to the tearing rate (8). If the rate of tear propagation is slower in a multi-ply test, fibers are more likely to pull out than break; more work is consumed to pull a fiber out of the sheet structure than to break it (9). At high bonding and in dense sheets, the four-ply tear strengths converge, as in Fig. 3, or even fall below the single-ply tear, as in Fig. 2, possibly because the tear path is constrained by interlocked plies in the four-ply test. This may lead to a higher ratio of fiber breakage to pull out. A higher proportion of fiber breakage should lower tearing resistance (9). A decrease in tear strength with increased number of plies for well-bonded sheets has previously been observed (3, 10, 11).

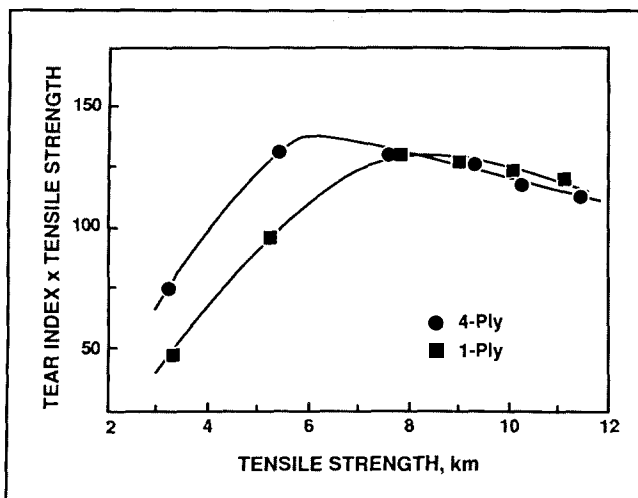
For each pulp in Figs. 2-4, there is a point where the single- and four-ply tear-tensile plots cross. Near these points, there is a range of bonding levels for which the tear strengths are similar. If the furnishes for commercial papers are bonded to levels which are close to the crossover points for the two tear tests, the effect of the number of plies torn on tear index of paper will not be apparent. It is not surprising, therefore, that many previous studies made on commercial papers, including ours (12), failed to recognize the effect of plies.

Conclusions

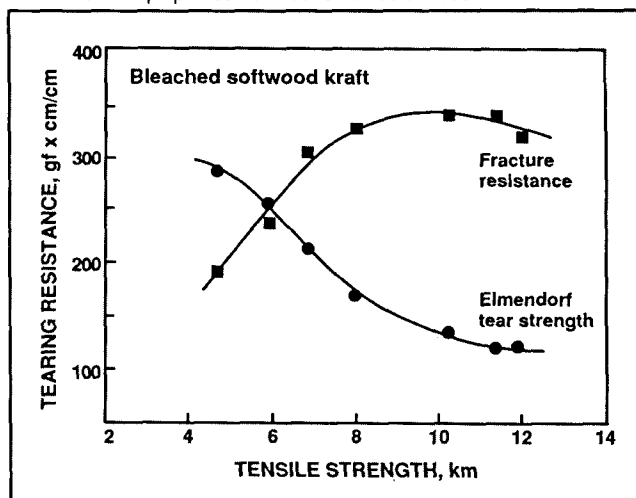
Tear strength is an important specification for pulps, as well as for paper and board products. For a given paper, the Elmendorf tear index has been regarded as a characteristic of the sheet. Unfortunately, not only does it depend on the number of plies torn simultaneously, but the discrepancy between single- and multi-ply results also depends on the furnish itself and varies with the degree of bonding in the sheet. Consequently, single- and multi-ply tear-tensile plots give different perspectives of a pulp's response to refining and to other papermaking treatments. This can have important implications for characterizing pulps, depending on whether a single- or multi-ply test is used.

Tensile and tear strengths are two important mechan-

7. Product of tensile strength and tear index as a function of tensile strength for the data of Fig. 3



8. Comparison of four-ply Elmendorf tear strength and fracture resistance as shown by Seth and Page (13) for a commercial dried bleached kraft pulp of eastern Canadian softwoods



ical properties of paper. Tensile strength determines the ability of a sheet to withstand in-plane stress. Tear strength, on the other hand, indicates a sheet's ability to resist tear propagation initiated by flaws such as cracks. Depending on how the tearing forces are applied, there are several ways to propagate a crack in a paper sheet. In manufacturing and in converting operations such as coating and printing, paper fails in a mode in which the tearing forces are applied in the plane of the sheet. In the Elmendorf mode, the tearing forces are applied out of the plane of the sheet. This mode of crack propagation does not simulate most end-use failures (11, 13).

Also, the Elmendorf tear strength of long-fibered pulps, after an early peak, decreases rapidly with an increase in fiber-fiber bonding in the sheet, as shown in Fig. 1. At the same time, the tensile strength and other sheet mechanical properties increase greatly. This apparent contradiction has cast doubt on the relevance of the Elmendorf tear strength for characterizing the end-use performance of a sheet (11). In spite of these drawbacks, the Elmendorf test is widely used because it is easy to carry out.

Furthermore, a multi-ply test is done presumably because it tends to reduce splitting and, for some papers, can make the rupture zone in the Elmendorf test appear more like the rupture zone encountered in end-use failures in which, in general, paper does not split (3). If the reason for using multiple plies in the Elmendorf test is to make an out-of-plane tear failure resemble an in-plane tear failure, then this practice is difficult to justify, given the uncertainties due to plies noted above and also that the resistance of paper to tearing is different in different tearing modes (13).

Fracture resistance determines the resistance of paper to tearing in a mode in which the tearing forces are applied in the plane of the sheet (13). At present, the methods available for measuring fracture resistance (14, 15) are complicated and time consuming. Until alternative, simpler methods for measuring fracture resistance become available, it would be prudent to keep the

limitations of the Elmendorf test in mind when relating its results to end-use failures.

As long as the Elmendorf tear test continues to be used, several arguments can be made in favor of the single-ply test. The test measures directly the out-of-plane tearing resistance of a paper sheet, which Elmendorf originally intended (16); that is, it measures a mechanical property of a paper sheet instead of that of a pad. The test correlates with the Brecht-Imset tear test (12), which also measures out-of-plane tearing resistance and is used by many European papermakers. It is consistent with out-of-plane single-ply tear tests as performed by modern automated paper testing equipment (17). It is comparable to other single-ply tear tests, such as the so-called in-plane tear test (11) and the fracture resistance test (13); different conclusions might have emerged had the effect of plies on test results been considered by those who compared multi-ply Elmendorf tear strengths with these tests (4, 13, 15, 18-20).

Furthermore, assume that both Elmendorf tear and tensile strength are important for papermaking and in end-use of paper when softwood market chemical pulps are used as reinforcement fibers. The large apparent loss in multi-ply tear from its peak value at low tensile strengths to that at tensile strengths which are typical of industrial refining practices does not occur in the single-ply test. It has been suggested that the performance of pulps in usage appears more in agreement with tear measured by the single-ply test than with that measured by the multi-ply test (21), although any relationship between the Elmendorf tear and end-use performance has yet to be demonstrated.

An empirical strength index, the product of tensile and Elmendorf tear strengths, has at times been used to characterize pulps (22-26). For softwood pulps, this index peaks at higher beating levels with the single-ply tear test than with the four-ply test, as shown in Fig. 7. Based on this criterion, it seems beneficial to refine softwood reinforcing fibers to higher tensile strengths than those predicted with the four-ply tear test. Interestingly, this suggestion is in agreement with findings of Seth and Page

(13), who measured the fracture resistance of pulps upon beating. They showed that the fracture resistance of softwood pulp handsheets peaked at fairly high tensile strengths, and for a pulp similar to the one in Fig. 7, the fracture resistance peaked at approximately 9 km tensile strength, as indicated in Fig. 8.□

Literature cited

1. CPPA Tech. Sec., Standards D.9 and D.12.
2. TAPPI Test Methods T 414 om-88 and T 220 om-88.
3. Wink, W. A., and Van Eperen, R. H., *Tappi* 46(5): 323(1963).
4. Lyne, M. B., Jackson, M., and Ranger, A. E., *Tappi* 55(6): 924(1972).
5. Houston, P. L., *Paper Trade J.* 74(10): 43(1922).
6. Jones, H.W.H., and Gallay, W., *Pulp Paper Mag. Can.* 53(4): 115(1952).
7. Hardacker, K. W., and Van den Akker, J. A., *Tappi* 33(11): 109A(1950).
8. Sun, B. C., Wilson, J. W., and Bach, L., *Tappi* 59(10): 106(1976).
9. Staff of the Institute of Paper Chemistry, *Paper Trade J.* 118(5): 13(1944).
10. Jones, A. Y., *Pulp Paper Mag. Can.* 68(12): T631(1967).
11. Van den Akker, J. A., Wink, W. A., and Van Eperen, R. H., *Tappi* 50(9): 466(1967).
12. Seth, R. S., and Blinco, K. M., *Tappi J.* 73(1): 139(1990).
13. Seth, R. S., and Page, D. H., *Tappi* 58(9): 112(1975).
14. Seth, R. S., *Tappi* 62(7): 92(1979).
15. Uesaka, T., Okaniwa, H., Murakani, K., and Imamura, R., *Japan Tappi* 33(6): 403(1979).
16. Elmendorf, A., *Paper* 28(23): 15(Aug. 10, 1921).
17. Lachapelle, L., 1989 Newsprint Conference Proceedings, CPPA, Montreal, p. 147.
18. Brezinski, J. P., 1971 International Paper Physics Conference Proceedings, CPPA, Montreal, p. 65.
19. Lyne, M. B., Jackson, M., Ranger, A. E., and Trigg, A.R.V., in "The fundamental properties of paper related to its uses," Transactions of the symposium held at Cambridge, September 1973, edited by F. Bolam, Technical Division, BPBIF, London, 1976, p. 269.
20. Helle, T., 1979 International Paper Physics Conference Proceedings, CPPA, Montreal, p. 13.
21. DeCrease, D.W., Weyerhaeuser Paper Co., private communication, 1990.
22. Fanselow, J. R., and Fanselow, J. L., *Tappi* 43(8): 205A(1960).
23. Jayme, G., and Buttel, H., *Papier* 18(10a): 624(1964).
24. Winczakiewicz, A., *Przegląd Papier* 22(2): 35(1966).
25. Idner, K., and Kjellberg, N., *Paperi ja Puu* 71(3): 262(1989).
26. Lumiainen, J., 1990 Papermakers Conference Proceedings, TAPPI PRESS, Atlanta, p. 269.

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