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J.F. Waterhouse and T. Riipa

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"HARDWOODS FROM SOFTWOODS?"

John F. Waterhouse & Tiina Riipa[*]

Institute of Paper Science and Technology

[*]Enso-Gutzeit Oy, Varkaus, Finland

ABSTRACT

Softwoods, were investigated as a replacement for a hardwood pulp. Refining, formation, surface properties, and stiffness were important pulp and base paper requirements considered.

The creation of "hardwoods" from softwoods is based on the concept of fiber cutting, and was achieved using a device equipped with a set of parallel blades to produce a fiber length distribution similar to that of hardwoods. In practice it is anticipated that a disk or conical refiner operating as a "cutting" refiner would be used.

We have found that cut softwoods can act as "hardwoods", but their performance is somewhat limited by coarseness differences.

INTRODUCTION

Occasionally, there arises situations where hardwoods are in short supply or unavailable. There is also a growing concern about the future availability of hardwoods in this and other countries. It is well known that certain grades of paper are highly dependent upon hardwoods, especially printing and writing papers. It has always seemed sacrilege to want to deliberately "cut " softwood fibers to improve sheet formation and surface characteristics of these grades. A preferred strategy is to use a blend of hardwood and softwood to produce the desired properties. An advantage of this strategy is cost savings which usually results from increased hardwood utilization.

In the event that hardwoods are in short supply and only softwoods are available the only choice may be to obtain hardwood from softwood by "cutting". This poses three questions: 1. How might softwoods be "cut" to produce a hardwood type fiber? 2. What are the papermaking characteristics of "cut" fibers? and 3. How well does the "cut" fiber perform when compared with a natural hardwood? This paper briefly reviews the literature and speculates about the answer to the first two questions. While a specific case study involving Scandinavian softwoods and a hardwood is used as an example to answer the third question.

1. How might softwoods be "cut" to produce a hardwood type fiber?

Various means have been used to produce "cut" fibers for laboratory investigations including: guillotining, fractionating, fibers from different growth rings, and synthetic fibers of different length. This approach guarantees that fiber length reduction is the only change occurring. According to Page's review (1) there are many effects associated with refining and fiber length reduction is one of them. It has been argued that fiber length reduction may occur by "cutting" (shear forces) or tensile failure. Giertz (2) argues that under normal refining strong fibers are more likely to fibrillate than rupture whereas weak fibers, i.e., those degraded in the pulping process are more likely to undergo tensile failure. Changes in fiber coarseness (fiber splitting) may also be desirable, but presumably more difficult to accomplish. According to Hietanen and Ebling (3) this is difficult with fibers of high fibril angle, whereas, fibers having a 0° fibril angle are more readily split, e.g., hemp fibers.

In both laboratory and production refining, changes in fiber length distribution will be dependent on the fiber characteristics, e.g., initial fiber length distribution, coarseness, and viscoelasticity; and refiner operating variables, e.g., refiner type, tackle design, consistency, pH, temperature, and speed. Changes in fiber length distribution may also be accompanied by more subtle damage to the fibers (3).

In Nordman and Laininen's (4) investigation of fiber cutting they found that the type of beater significantly affected changes in fiber length distribution. Furthermore, in mixed refining of hardwood and softwood pulps the hardwood was protected by the softwood. Differences in fiber length distribution were also found to be dependent on the pulping and bleaching conditions used. For a birch pulp beaten for 60 minutes in a Jokro mill the sulphate process gave the least reduction in fiber length followed by the unbleached sulphite and bleached sulphite. These changes could possibly be explained by differences in their viscoelastic behavior as proposed by Page (5), i.e., the sulphate fibers are more viscoelastic and can absorb more energy during refining than the more elastic sulphite fibers.

Two models for describing the refining action of commercial and laboratory bar type refiners are Specific Edge Load, and the other involving the number and intensity of impacts. Generally, these models account for plate design, consistency, speed, power, and throughput. According to the recent review by Baker (6), a balance between cutting and fibrillation can be achieved with 1. a fairly course-barred filling with a shallow angle, 2. Medium specific energy input, and 3. Refining at about 4% consistency.

Although the above refining conditions could possibly result in a significant reduction in average fiber length, they probably would not be sufficient to transform a softwood fiber length distribution into a hardwood fiber length distribution, at least not without incurring significant fiber damage and a large reduction in freeness. A high specific edge load, i.e., wide bars with sharp edges, low speed, consistency, and temperature, are conditions favorable to "cutting". The authors, however, are not aware of any published results on "cutting" fibers on a commercial scale, and therefore it is difficult to say if the desired effects can be produced with a conventional refiner using these conditions.

2. What are the papermaking characteristics of "cut" fibers?

This question has been studied in one form or another by a number of researchers (7)-(12). We are primarily concerned with the impact of fiber length and coarseness differences on refining, water removal, and property development.

- Refining -

In this study we have separated the effects of fiber length reduction and refining. We would therefore expect the refining of "cut" softwoods to be similar to the refining of hardwoods. Generally hardwoods refine at a faster rate than softwoods, and require a lower specific edge load if the tear-tensile performance is to be maximized, since tear is strongly dependent on fiber length (8),(10), although the conventional wisdom of tear failure has recently been challenged by Page (13).

- Water Removal -

Drainage behavior is primarily dependent on fines production. In addition to fiber length, coarseness, morphology, and pulp viscosity, are other factors which can influence fines production. Water removal as determined by water retention value (WRV) is an important papermaking variable. It is presumed that fiber length reduction alone would not significantly change WRV. However, a reduction in fiber length might lead to greater fines production and internal fibrillation, and hence higher WRV's.

- Property Development -

Differences in the performance of hardwoods and softwoods are well known, and are generally accounted for by differences in fiber length, coarseness, and chemistry. Some of these performance differences are descriptive, while others can be explained using theoretical-empirical models.

The objective of the experimental program which follows was to determine if "cut" Scandinavian pine or spruce could be used as a substitute for Scandinavian birch. There are many considerations which go into the formulation and making of a printing and writing grade paper, and our investigation was only a part of a larger overall program. Unfortunately time constraints did not allow us to look at blend optimization including the impact of filler on both optical and mechanical properties. Although our "cutting" procedure is not a real world situation it nevertheless provides useful insight into the potential of fiber "cutting" as one means of solving hardwood substitution problems.

EXPERIMENTAL

The three Scandinavian never dried bleached kraft pulps used in this study were: Pine (*Pinus Silvesteris*), Spruce (*Picea Abies*), and Birch (*Betula Verrucosa*). The average properties of these pulps are given in Table 1.

The fiber length of the softwood pulps was reduced as follows. A handsheet having a basis weight of 300 g/m^2 was formed in a Noble and Wood handsheet former, and after couching was cut into 1 inch wide strips. These strips were then cut on a small press as shown in Figure 1. The cutting head consisted of a series of parallel blades with spacers in between to give a spacing of approximately 1 mm. The effectiveness of the cutting procedure on the length weighted distribution is shown in Figures 2 and 3. The shift in fiber length distribution for the spruce is shown in Figure 2, where we see that the average fiber length has been reduced by "cutting" from 2.03 mm to 0.97 mm. The length weighted distributions of "cut" pine and spruce are compared with birch in Figure 3, and we note that there is still some long fiber present, i.e., around 5% to 10%, but this was considered to be acceptable.

TABLE 1 PROPERTIES OF SCANDINAVIAN PULPS.

PROPERTY	PINE	SPRUCE	BIRCH
KAPPA NUMBER	27.3	25.8	15.9
COARSENESS mg/m	0.13	0.14	0.09
FIBER LENGTH mm	2.03	1.86	0.78
FIBER WIDTH μm	39 (10)	29 (13)	19 (11)
CELL WALL THICKNESS μm	7 (3)	5 (2)	4 (2)
NUMBER OF FIBERS PER GRAM	3.79 x 10^6	3.84 x 10^6	14.2 x 10^6

(number in parenthesis are standard deviations)

The refining of the pulps was carried out in a PFI mill at 10% consistency using 24 gram batches. The uncut softwoods were refined over the range of 0 to 10,000 revolutions. The birch and "cut" pine and spruce pulps were refined over the range of 5000 and 1500 revolutions, respectively. The progress of beating was monitored using Canadian Standard Freeness measurements (CSF). Tappi recommended procedures were followed for sheet making, couching, wet pressing, drying, and conditioning. However, the handsheets containing either birch, or "cut" softwoods were wet pressed at both 50 psi and 80 psi.

The Kajaani FS-100 was used to measure changes in fiber length distribution. The length weighted average fiber length is defined as follows:

$$l_{avg.} = \Sigma(n_i l_i^2)/\Sigma(n_i l_i) \qquad 1.$$

Unless otherwise noted Tappi procedures are followed in making paper property measurements. Paper thickness was measured using both hard platen and soft platen (14) procedures. Apparent density calculations were based on soft platen thickness measurements.

The difference in hard and soft platen caliper measurements was also used as a measurement of surface roughness.

$$\text{Roughness} = (HP_{cal.} - SP_{cal.})/2 \qquad 2.$$

Other measurements of roughness used were Parker Print Surf using a soft backing and a pressure of 10 Kg/cm^2, and Sheffield smoothness. Porosity was also measured using the Parker Print Surf instrument.

The IPST Formation Tester (15) was used to make mass density measurements. The aperture used was 1 mm x 1 mm and the area over which the formation measurements were made was 80 mm x 80 mm, and reproducible to within 2% or better.

In plane and out-of-plane elastic constants were determined using ultrasonic procedures developed at IPST (16),(17).

Other paper property measurements included normal span tensile properties, zero span strength, light scattering coefficient, and opacity.

RESULTS & DISCUSSION

In this section we present a comparison of the beating and handsheet properties of pine, spruce, birch, and potential hardwood pulp substitutes, i.e., "cut" pine and "cut" spruce.

Refining

Figure 4 shows the variation of freeness CSF with PFI revolutions. It is clear that the progress of refining is controlled predominantly by fiber length and coarseness. In this respect the "cut" softwoods appear to refine like the hardwood, i.e., birch. Interestingly, the "cut" spruce refines at a faster rate than either the "cut" pine or spruce as summarized in Table 2.

Table 2 Change in CSF over the Refining Range of 0 to 1500 PFI Revolutions.

TYPE	COARSENESS mg/m	INITIAL CSF ml	ΔCSF ml
BIRCH	0.09	660	153
PINE	0.13	690	180
SPRUCE	0.14	705	320

We see that the coarser the pulp the higher is the initial freeness and the greater is the drop in freeness (CSF). A higher initial CSF with increasing coarseness has been noted by Seth (8), however, no similar finding is evident in the study of Canadian hardwoods by Gurnagul, Page, and Seth (10).

The effect of refining on fiber length is shown in figure 5. We see that there is a small increase in fiber length over the refining range of 0 to 5000 revolutions. This is attributed to the removal of curl and microcompressions which were probably induced during dewatering and pulp conditioning. The "cut" pine and spruce do not show this affect, although the range of refining is much smaller (0 to 1,500 revolutions).

Fiber Strength

Zero span strength is often used as an indicator of fiber strength. The variation of zero span strength with sheet apparent density (based on soft platen thickness) is shown in Figure 6. Densification of handsheets made from uncut pine and spruce is achieved by refining, and for sheets made from the hardwood and "cut" softwoods by varying refining and wet pressing. The impact of fiber length reduction on zero span strength is clearly seen. However, this is not believed to be a true indication of fiber strength loss. According to Seth (8), fiber cutting should not change fiber strength. In fact fiber strength should increase according to Pierce's weak link theory. It is probably an artefact of zero span testing which is known to be fiber length dependent.

The increase in fiber strength with densification by refining and wet pressing could result from two effects. The improvement of fiber strength with refining could be due to fiber straightening, and the removal of microcompressions from the cell wall. There is also a component due to bonding. The apparent rise and then fall off in zerospan strength of the birch is not readily explained, although the initial increase may possibly be due to increased bonding.

Scattering Coefficient and Relative Bonded Area

Scattering coefficient is an important optical property as it relates to the opacity of the sheet and the degree to which the fibers are bonded. The variation of light scattering coefficient with sheet apparent density is shown in Figure 7, and we see that fiber length and coarseness also influence this relationship. It is noted that the birch has a larger unbonded surface area at a given level of sheet densification, followed closely by the "cut" pine and "cut" spruce. The uncut softwoods have the lowest level of scattering coefficient for a given level of densification.

Relative Bonded Area (RBA) is defined as the percentage or fraction of the total surface area which is in a bonded state. Surface area measurements can be made using either gas adsorption or light scattering. Generally there is an excellent correlation between these two measurements in spite of them being very different. The problem in determining RBA is one of determining S_0 the total surface area of the fibrous structure in a totally unbonded state. Various extrapolation procedures have been used, with varying degrees of success, to determine S_0, including density, modulus, and tensile strength (18)-(21).

Figure 8 shows the variation of tensile strength with light scattering coefficient and the degree of linearity for the various pulps is quite good. Values of S_0, by extrapolating to zero tensile strength, are given in Table 3.

TABLE 3 LIGHT SCATTERING COEFFICIENT S_0 AT ZERO TENSILE STRENGTH.

FIBER TYPE	S_0(m^2/kg)	R^2
BIRCH	45.9	0.988
PINE	41.3	0.995
"CUT" PINE	41.5	0.995
SPRUCE	38.9	0.974
"CUT" SPRUCE	35.6	0.960

One might expect that the surface area per unit weight of fiber would be inversely proportional to the square root of fiber coarseness. The above results are roughly in agreement with this prediction. We also note that the surface area per unit weight is not significantly affected by "cutting". Other researchers (19), (20) have found a non-linear relationship between light scattering coefficient and tensile strength.

Values of S_0, given in Table 3, are used to calculate values of RBA, and the variation of RBA with sheet apparent density is shown in Figure 9. Again this relationship is dependent on pulp type. Usually caliper specifications have to be met for a given grade of paper, and the name of the game is to use as little fiber as possible while satisfying property requirements, i.e., achieve properties at the lowest possible apparent density.

Strength related properties, e.g., modulus and tensile strength, can be related either to RBA (7),(19),(21), and (22), or apparent density (20),(21), and (23) as we shall consider later.

Formation, Porosity, and Surface Roughness

One of the main advantages of using a blend of softwood and hardwood pulps is to improve formation, i.e., both visual uniformity and small scale mass distribution (mass density). Measures of formation are controversial, but we adopt as our formation index the coefficient of variation of mass density, which has been proposed by Dodson (24) as a universal index of formation. This definition has the advantage that comparisons can be made with formation of an ideal random network of fibers. The coefficient of variation of mass density % CV(W) is defined by equation 3.

$$\%CV(W) = (\sqrt{variance}/mean\ grammage)*100 \qquad 3.$$

For an ideal random network of fibers it can be shown (25) that %CV(W) is given by:

$$\%CV(W) = 100\sqrt{(k*C)/W} \qquad 4.$$

where k is a fiber length dependent constant, C is fiber coarseness, and W is the mean sheet grammage. A more precise method of calculating the formation index given by equation 4 using fiber length distribution data has been proposed by Dodson (26).

The variation of formation index CV(W) with apparent density is shown in Figure 10 and predictions of formation index based on equation 4 are given in Table 4.

TABLE 4 PREDICTIONS OF %CV(W) BASED ON EQUATION 4.

BIRCH	**PINE**	**"CUT" PINE**	**SPRUCE**	**"CUT" SPRUCE**
2.83	4.16	3.6	4.32	3.7

According to Table 4 birch has the best formation potential, however, because of their greater coarseness the "cut" pine and spruce are not equivalent to the birch. Nevertheless, we see from Figure 10 that the formation of "cut" pine and spruce improves with sheet densification while the birch deteriorates. In previous work Waterhouse (15) has shown that formation can be improved by sheet densification.

Spruce potentially will yield the worst formation followed by the pine according to the predictions given in Table 4; however, according to Figure 10 pine gives a slightly better formation than the spruce.

The variation of porosity as the sheet is densified by refining is shown in Figure 11 for the various pulp types. At a given sheet density (or solid fraction) porosity is controlled by pore size distribution, which in turn is dependent on fiber coarseness and the amount of fines generated by refining. We note that for a given level of densification, particularly above a density of 0.8 g/cm^3 that the "cut" softwoods result in a more open or porous sheet. Since much less refining is needed to achieve this level of densification the more porous sheet is attributed to a lower fines content. Even so, the "cut" spruce develops surface area more rapidly than the "cut" pine (as has already been noted), and this is reflected in a lower porosity. The birch is intermediate in porosity to the "cut" and uncut pine and spruce.

Three methods were used to measure surface roughness namely the average difference in hard and soft platen calipers, Parker Print Surf @ 10 kg/cm^2 using a soft backing, and Sheffield Smoothness.

The variation of roughness, based on hard and soft platen caliper measurements, with apparent density is shown in Figure 12. The results are not very consistent, nevertheless, the "cut" softwoods do show, surprisingly, an increase in surface roughness. Changes in Parker Print Surf and Sheffield Smoothness with densification are relatively small, and the average values are given in Table 5.

Table 5 Summary of Average Smoothness Values

SPECIES	PARKER PRINT SURF	SHEFFIELD SMOOTHNESS
BIRCH	6.9	306
PINE	7.4	360
"CUT" PINE	7.3	357
SPRUCE	7.4	356
"CUT" SPRUCE	7.4	362

These measurements show that birch gives a potentially smoother sheet than either of the two softwoods, and, furthermore, "cutting" does not produce any significant improvement in surface roughness. The extent to which these trends will hold if the sheet is calendered is not known.

Elastic and Failure Properties

According to the theory of Seth and Page (27) the in-plane elastic modulus of paper is given by:

$$E_p^* = E_f^*/3\ [1 - (w(n_k+1)/L\ \mathrm{R.B.A})(E_f^*/2G_f^*)^2] \qquad 5.$$

where E_p^*, E_{f*}, G_f^*, w, L, n_k, and R.B.A. are paper specific modulus, fiber specific modulus, fiber transverse specific shear modulus, fiber width, fiber length, the number of kinks or crimps in the fiber across which the load cannot be transmitted, and relative bonded area. The expression in parenthesis describes the effective load transfer between the fibers in the network.

The out-of-plane specific modulus Ez^* is also given by the following equation (28):

$$Ez^* = Ez_f^*\ \mathrm{R.B.A.} \qquad 6.$$

where Ez_f^* is longitudinal transverse fiber modulus.

The in-plane and out-of-plane longitudinal elastic constants, measured ultrasonically, are shown in Figures 13 and 14. We see, as predicted by equation 3, that the in-plane elastic constant is fiber length dependent. Both the birch and the "cut" softwoods yield a lower in-plane elastic constant. In a blend situation the loss in modulus and thus flexural stiffness, at a given level of densification, would not be significantly affected by fiber "cutting". In this instance the "cut" softwoods and birch are approximately equivalent in performance.

The out-of-plane longitudinal elastic constant Figure 14 is slightly lower for the birch and the substitute "hardwoods" for a density less than 0.8 g/cm^3.

For densities higher than 0.8 g/cm^3 the birch and uncut softwoods show a reduction in out-of-plane modulus. In previous work (23) a reduction in out-of-plane modulus at high densities has been found. Interestingly, the "cut" pine does not show a similar reduction in modulus. This fall off in out-of-plane modulus with densification is attributed to a more planar alignment of the fibrils affectively lowering the fiber longitudinal transverse modulus Ez_f^*. A good correlation has been found (22) between out-of-plane modulus and z-directional strength, and, therefore, we would not expect that the delamination resistance of the sheet would be impaired by the substitution of "cut" softwoods.

The variation of tensile strength with light scattering coefficient is shown in Figure 8 and was used to estimate total unbonded surface area of the various pulps as shown in Table 3. From Figure 8 we also note that, for a given strength level, the scattering coefficient is highest for the birch, while the "cut" fibers yield the lowest values. According to Figure 15, at a given level of densification, the "cut" softwoods yield a sheet which is much weaker than those made from either the uncut softwoods or birch.

Now Page's equation (7) for tensile strength T is written as follows:

$$1/T = 9/8Z + 12A\rho g/bPL(R.B.A.) \qquad 7.$$

Where Z, A, P, b, L, ρ, and g are zero span strength, fiber cross sectional area, perimeter, interfiber bond strength, fiber length, cell wall density, and gravitational constant, respectively.

Using equation 7, and assuming that only fiber length is changed by "cutting", we can calculate the change in tensile strength as result of fiber length reduction at constant R.B.A. as follows:

$$1/T(L_2) = (9/8Z)(1-L_1/L_2) + (1/T(L_1))L_1/L_2 \qquad 8.$$

where $T(L_1)$ and $T(L_2)$ are the tensile strengths at fiber length L_1 and L_2, respectively. Using the results shown in Figures 6, 9, and 15 we find for a bonded area of 60% that the tensile strength of the softwoods are reduced by cutting from approximately 80 Nm/g to 55.6 Nm/g for the spruce, and from approximately 75 Nm/g to 48.8 Nm/g for the Pine. The actual value of 56 Nm/g is approximately the same for the pine and spruce and is in quite good agreement with the predicted values.

By comparison the tensile strength of the birch is almost equal to the softwoods at 60% R.B.A. despite having only half the average fiber length. This implies that the birch has a higher bond strength b than the softwoods whether "cut" or not. The higher bond strength is mainly attributed to a lower coarseness, although differences in fines content may also be a factor.

The above result also tends to confirm that the apparent reduction in zero span due to cutting (see Figure 6) is not real.

CONCLUSIONS

It has been found that "cut" softwoods can approach the performance of hardwood. In our experiments "cut" pine and spruce were compared with birch. At medium to high levels of handsheet densification the scattering coefficient of the "cut" pine and spruce approached that of the birch as did the in-plane elastic properties. Tensile strength was significantly reduced by "cutting" as predicted by the Page equation.

"Cutting" of the softwoods, and handsheet densification, also improved formation, which approached that of the birch. Furthermore, "cutting" resulted in a more porous sheet as measured by Parker porosity. Birch produced the smoothest sheet, and no improvement in softwood smoothness was found by "cutting".

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Figure 1 Fiber "Cutting" Apparatus.

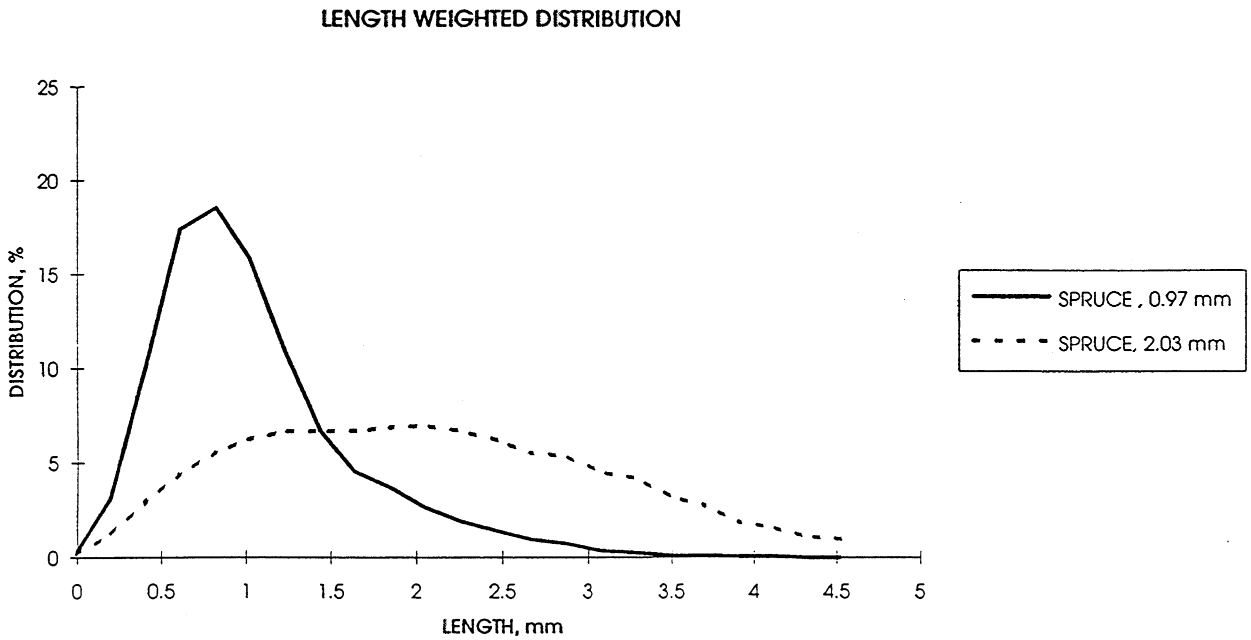

Figure 2 Effect of "Cutting" on Fiber Length Distribution of Spruce.

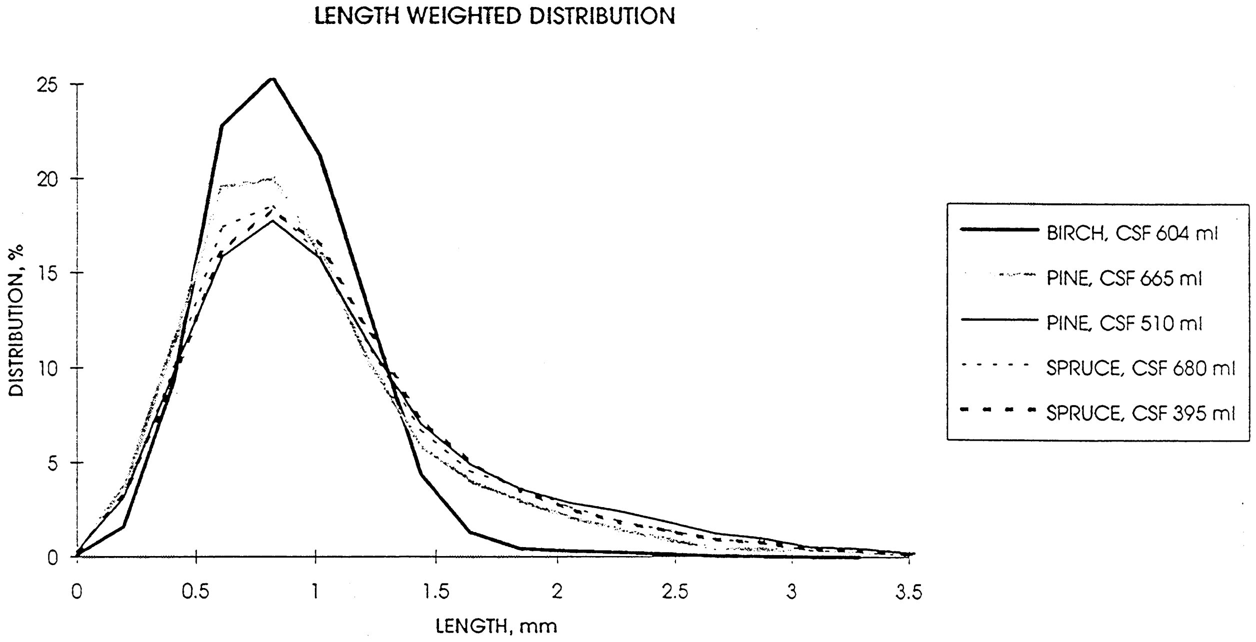

Figure 3 Comparison of "Cut" Softwood Pulps and Birch.

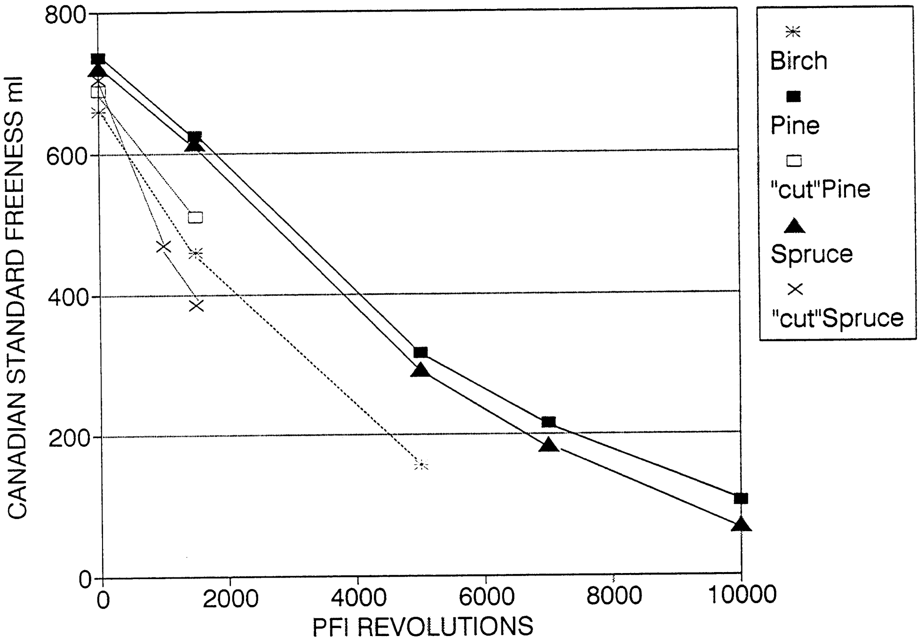

Figure 4 Freeness Development with PFI Revolutions.

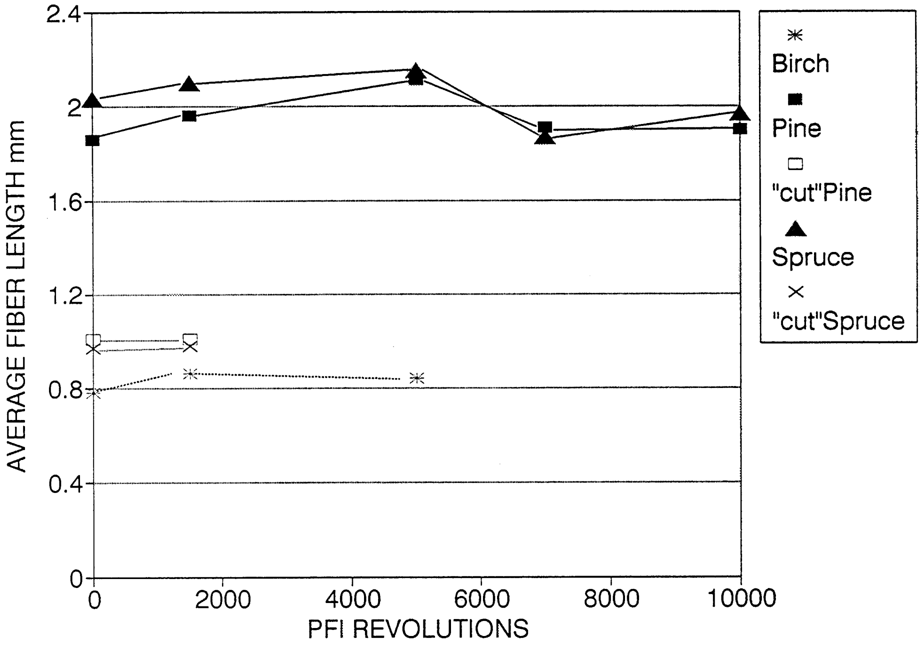

Figure 5 Effect of PFI Refining on Average Fiber Length.

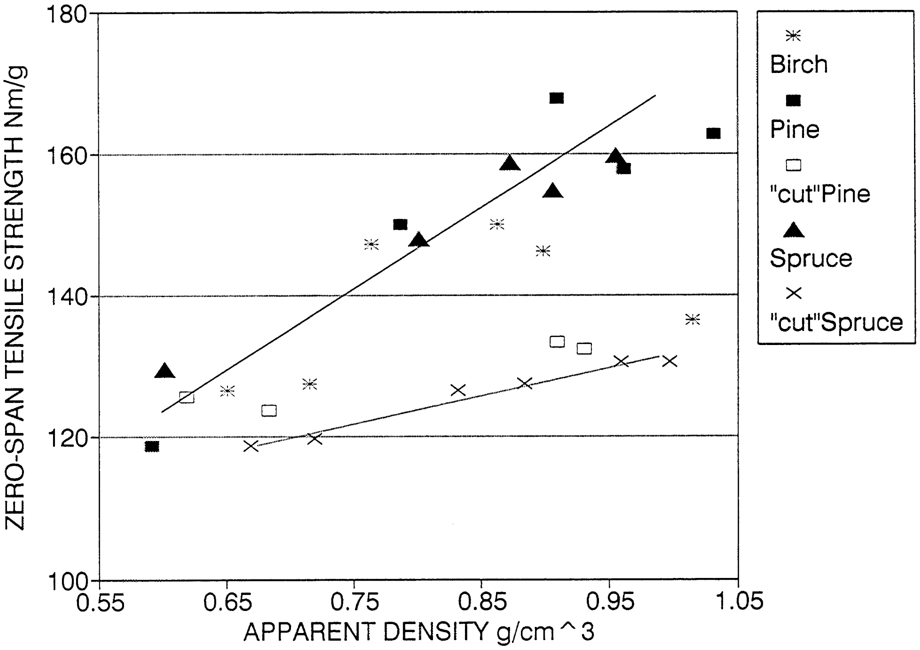

Figure 6 Variation of Zero Span Strength with Apparent Density.

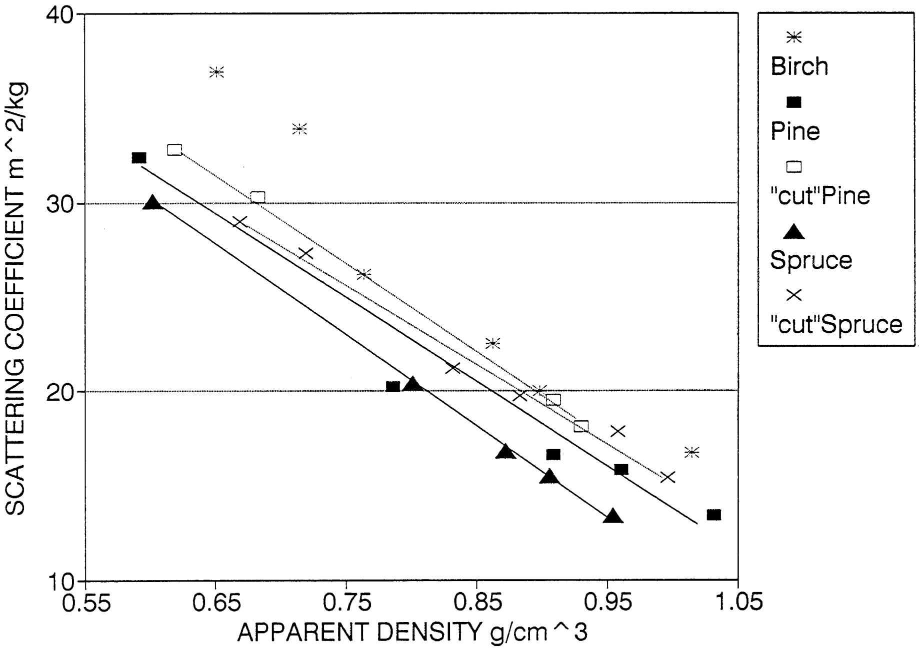

Figure 7 Variation of Scattering Coefficient with Apparent Density.

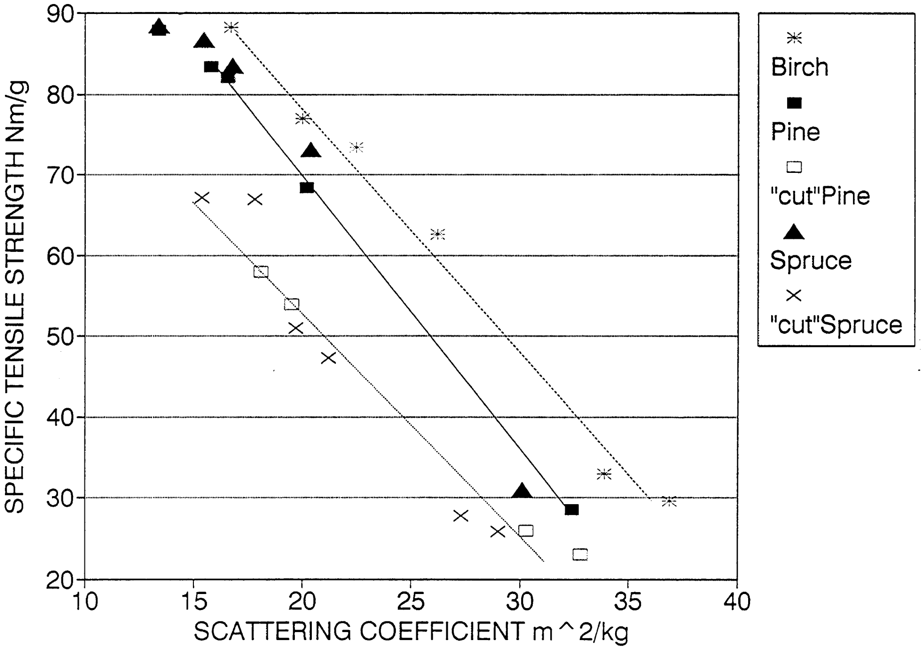

Figure 8 Variation of Specific Tensile Strength with Scattering Coefficient.

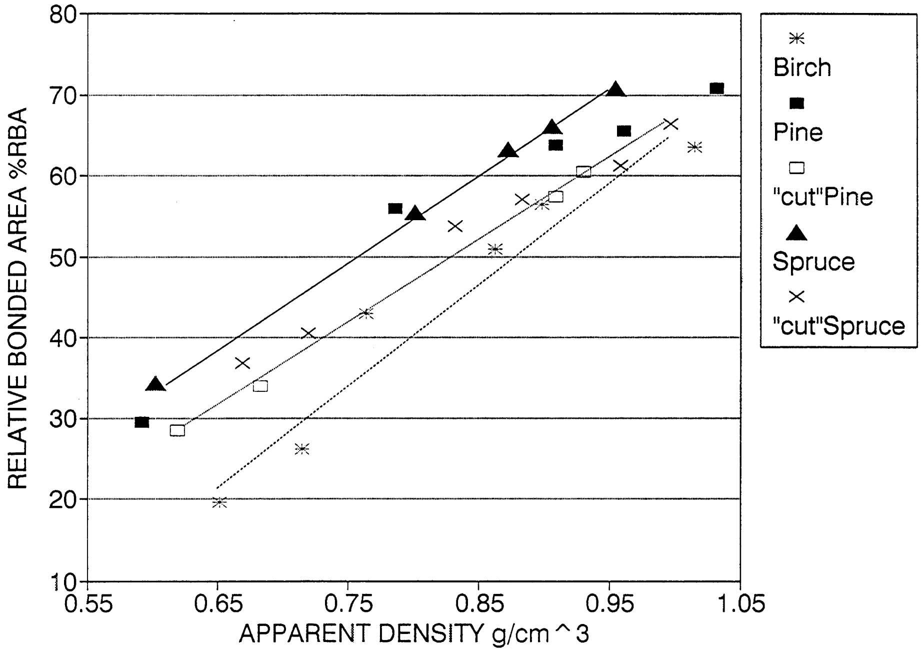

Figure 9 Variation of Relative Bonded Area with Apparent Density.

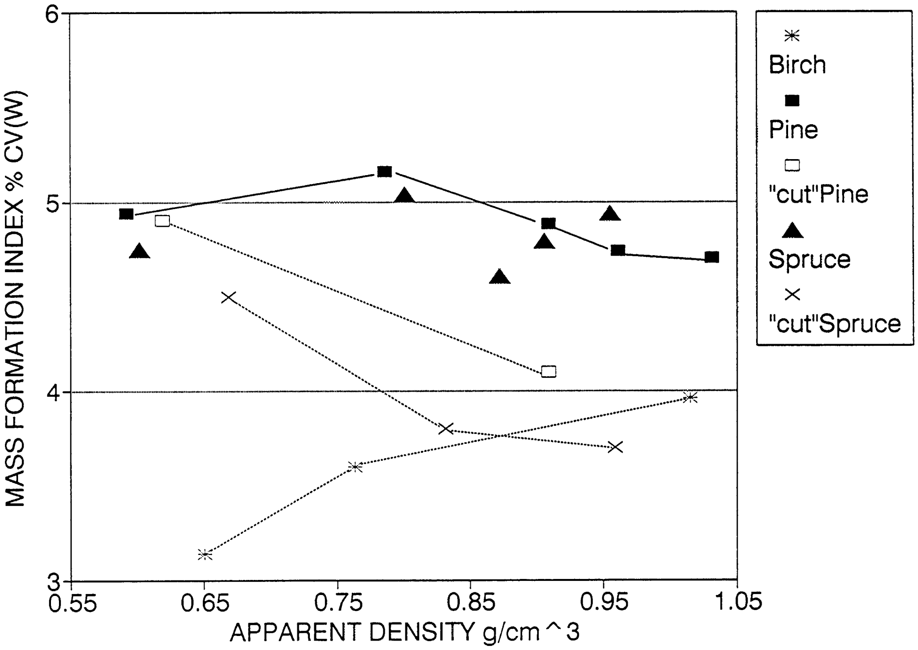

Figure 10 Variation of Mass Formation Index with Apparent Density.

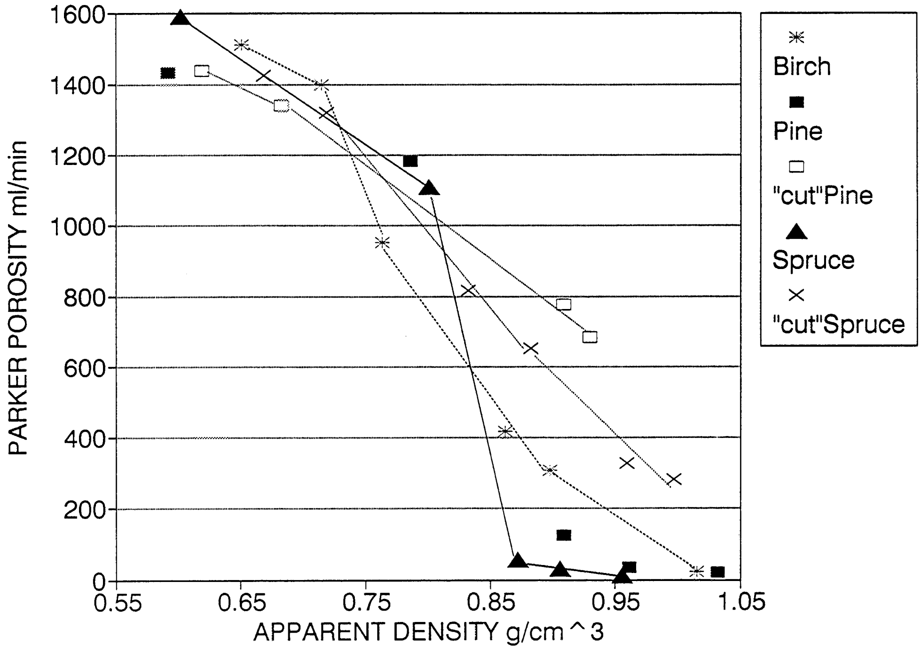

Figure 11 Variation of Parker Porosity with Apparent Density.

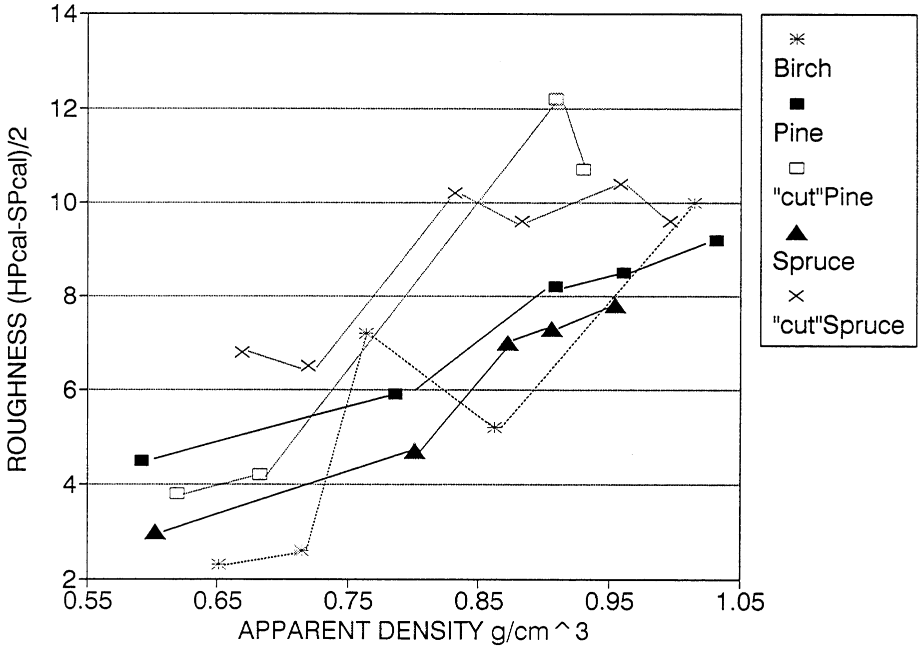

Figure 12 Variation of Roughness with Apparent Density.

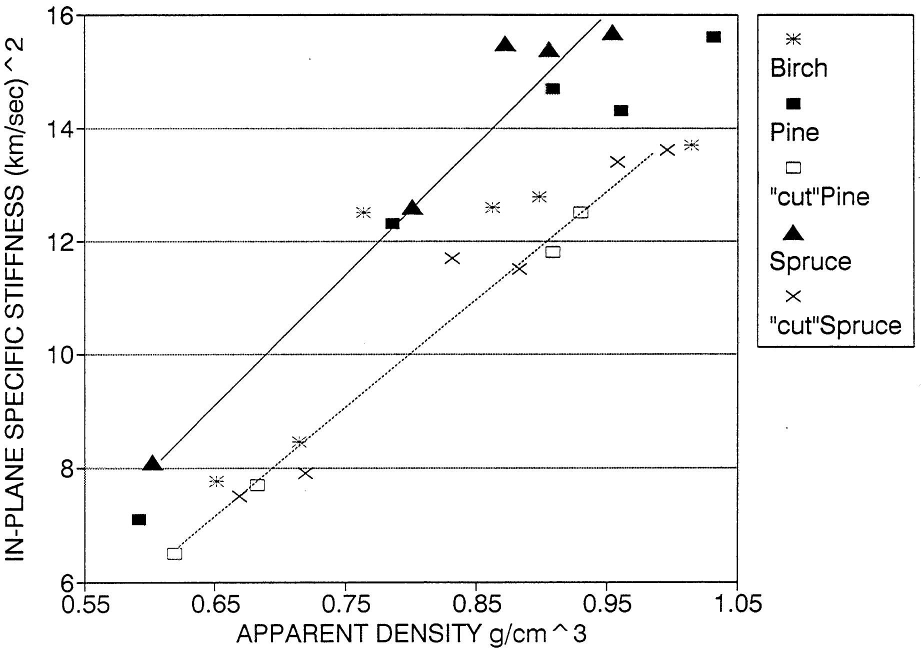

Figure 13 Variation of In-plane Specific Stiffness with Apparent Density.

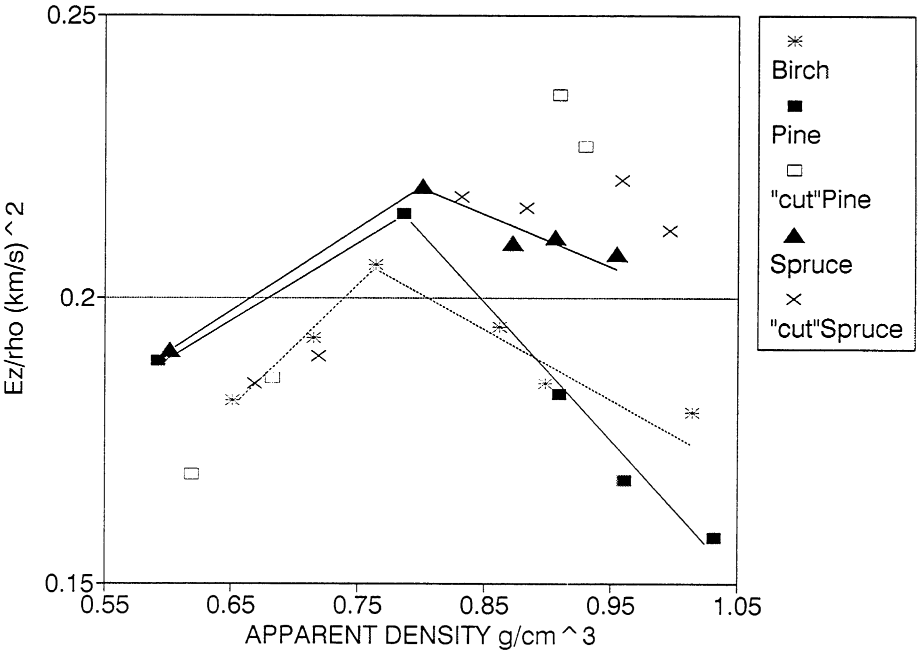

Figure 14 Variation of Out-of-Plane Specific Modulus with Apparent Density.

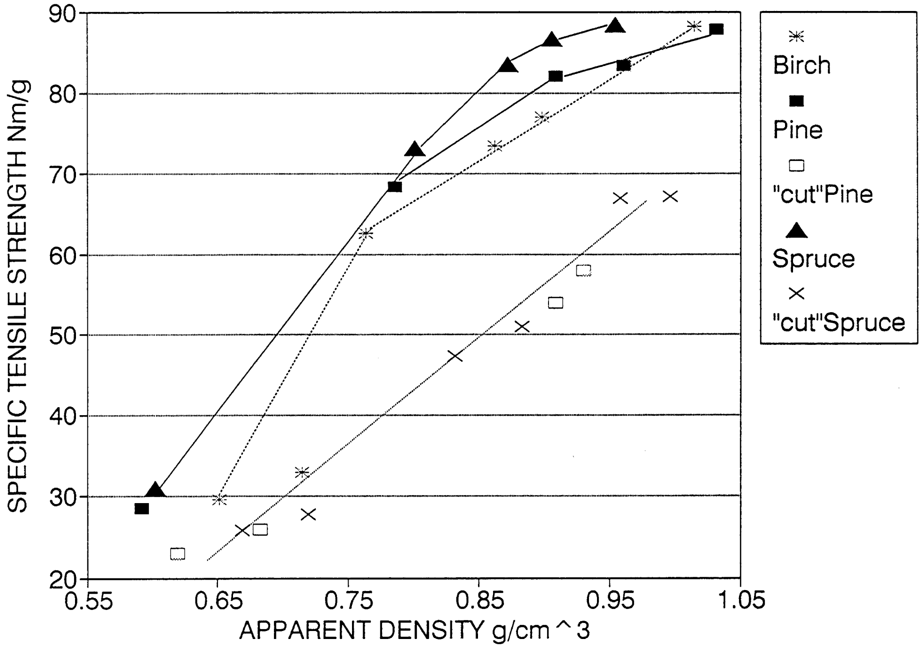

Figure 15 Variation of Specific Tensile Strength with Apparent Density.