MORPHOLOGICAL AND BARK STRENGTH CHARACTERISTICS IMPORTANT TO WOOD/BARK ADHESION IN HARDWOODS

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ABSTRACT

Dormant season wood/bark adhesion was determined for twenty-four hardwood species using a previously described Instron testing machine method. Wood/bark adhesion was compared, using simple and multiple correlation techniques, with bark specific gravity, inner bark strength, bark toughness, wood specific gravity, wood toughness, percent bark fibers, and percent sclereids. Wood/bark adhesion was found to be positively correlated with percent bark fibers, bark toughness, and inner bark strength. Wood/bark adhesion was negatively correlated with percent sclereids in the bark. Morphologically, it appeared that the presence of fibers increased inner bark strength, sclereids decreased inner bark strength, and inner bark strength had a major influence on wood/bark adhesion. A multiple correlation comparison employing wood toughness and inner bark strength accounted for 69% of the wood/bark adhesion encountered.

Keywords: Bark, phloem, morphology, hardwoods, sclereids, fibers, bark strength, bark toughness, specific gravity, adhesion, wood.

INTRODUCTION

As more and more companies turn to whole-tree chipping as a way of maximizing per acre fiber yield, efficient handling of bark and the problems associated with bark becomes imperative. Species-to-species, tree-to-tree, and within-tree differences in bark are considerable. This variation has made it evident that a single best solution to the bark problem could not be developed and that additional knowledge was needed regarding differences in adhesion between wood and bark of the various pulpwood species.

The bark anatomy of common North American pulpwood species has been described by Chang (1954). Several investigators (Wilcox et al. 1954, 1956; Schutt 1960; Fobes 1957) have discussed the influence of cambium activity and the number of newly formed xylem and phloem cells on ease of peeling. However, little has been done to critically examine morphologically what structures are destroyed in separating wood and bark, either during the "peeling season" or at times when wood/bark adhesion is high. Similarly, little attempt has been made to explain the reasons for differences between species in wood/bark adhesion during the growing season or the dormant season.

With this in mind, a program was established to systematically characterize the bark of the most important hardwood North American pulpwood species. The objectives were to: (1) measure accurately dormant and growing season wood/bark adhesion for twenty-four hardwoods and (2) examine species and seasonal morphological differences in the failure zone in an attempt to correlate morphological differences with measured wood/bark adhesion. In an earlier paper, Fiscus (Harder) et al. (1983), the test developed for measuring wood/bark adhesion was described. In this paper, differences found in wood/bark adhesion among the

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various hardwoods and the simple and multiple correlations run to determine those factors important in bark adhesion are described.

METHODS AND MATERIALS

Sampling techniques were described in a previous paper by Fiscus (Harder) et al. (1983). Briefly, they involved removing a disk or wedge-shaped sample from a tree and preparing small ($^3/_{16}$- × $^3/_{16}$- × $1^1/_4$-inch) tabs that incorporated both wood and bark from the disk or wedge. The tab then had a cut made through both the wood and bark sides with the two cuts overlapping. The distance between the two cuts was $^1/_8$ inch, the bottom of the two cuts overlapped 0.010 inch, and the surface area of the wood/bark interface was 0.0234 square inch or 0.151 square cm. The specimens were mounted in an Instron tester and adhesion was measured using shear parallel to the grain. The specimens were then examined using light and scanning electron microscopy to determine where failure had occurred. The anatomical structure of the bark was examined in additional specimens to determine what cell types, structure, and degree of cell differentiation were important in wood/bark adhesion.

Preliminary wood/bark adhesion measurements conducted throughout the year for six hardwood species made it possible to limit subsequent measurements to twice during the year. This resulted in the establishment of a standard procedure involving collections from a minimum of two trees during the dormant season and a similar two-tree collection during the growing season. The trees selected were forest-grown trees 7 to 9 inches (18 to 23 cm) in diameter; they varied for most species from 20 to 60 years in age, depending on species growth rate. Growing season sampling was discontinued after measurements were completed on nine species, when little variation was encountered in adhesion values (245–628 kPa). Growing season failure zones quite consistently were located in the cambium zone or in the newly formed and only partially lignified xylem elements just inside the cambium zone. The wood/bark adhesion values utilized are average values based upon two to five trees.

Additional measurements used in conjunction with the wood/bark adhesion measurements included bark strength, wood and bark toughness, wood and bark specific gravity, percent bark fiber, and percent sclereids in the bark. Bark strength measurements were made using essentially the same procedure as used in measuring wood/bark adhesion with the exception that, when inner bark strength was being tested, the cuts in the test specimen were prepared so as to overlap in the inner bark zone. When testing the strength of the outer bark, the cuts were located to overlap in the outer bark region. Wood and bark toughness were measured by using the energy required to rupture a small bark or wood sample by bending with a force parallel to the diameter of the tree and expressed as J/m^2. The values for bark strength, wood and bark toughness, specific gravity, and percent fibers and sclereids present are average values based upon samples from two to five trees.

Specific gravity of small wood and bark samples was determined using a water displacement technique that is a modification of TAPPI Standard Method T18 m-53. To obtain percent bark fiber and sclereids, bark from breast high (4.5 feet) samples was micropulped using the procedure of Thode et al. (1961). An aliquot of the bark sample was oven-dried to provide yield data, and the rest was kept

TABLE 1. *Hardwood species containing sclerenchyma-type cells in the bark.*

Tree species		Type of elements present[a]	
		Fibers	Sclereids
Quaking aspen	*Populus tremuloides* Michx.	X	X
Eastern cottonwood	*P. deltoides* Bartr.	X	M
Black cottonwood	*P. trichocarpa* Torr. & Gray	X	M
Sugar maple	*Acer saccharophorum* K. Koch	X	X
Silver maple	*A. saccharinum* L.	X	X
Red maple	*A. rubrum* L.	X	X
Sweet gum	*Liquidambar styraciflua* L.	X	X
Paper birch	*Betula papyrifera* Marsh.	A	X
Sycamore	*Platanus occidentalis* L.	A	M
Black tupelo	*Nyssa sylvatica* Marsh.	X	M
White ash	*Fraxinus americana* L.	X	X
Green ash	*F. pennsylvanica* Borkh.	X	X
American beech	*Fagus grandifolia* Ehrh.	M	X
Shagbark hickory	*Carya ovata* (Mill.) K. Koch	X	A
Black willow	*Salix nigra* Marsh.	X	M
Northern white oak	*Quercus alba* L.	X	X
Southern white oak	*Q. alba* L.	X	X
Post oak	*Q. stellata* Wangh.	X	X
Northern red oak	*Q. borealis* Michx.	X	X
Southern red oak	*Q. falcata* Michx.	X	X
Black oak	*Q. velutina* Lam.	X	X
Pin oak	*Q. palustris* Muenchh.	X	X
Yellow poplar	*Liriodendron tulipifera* L.	X	X
Red alder	*Alnus rubra* Bong.	A	X

[a] X = present, M = present in minor numbers, A = absent.

in a wet state and put through a series of screens, including 60-mesh, 100-mesh, 150-mesh, and 200-mesh. The fractions that stayed on each screen plus the fraction that passed through all screens were examined for the type of cellular material they contained.

RESULTS AND DISCUSSION

Bark variability

After examination of twenty-four hardwoods, it became obvious that there was significant diversity in the anatomical makeup of hardwood barks. One consistent feature was the presence of sclerenchyma (fiberlike cells and sclereids), but the proportion of these cells in the bark is apparently both species- and age-dependent. The presence of sclerenchyma-type cells in hardwood bark is summarized in Table 1.

A particular hardwood bark may contain fibers and/or sclereids, with both cell types being commonly associated with the inner bark. Fibers were found in this zone in all species except red alder, paper birch, and sycamore. Sclereids were found in all species examined except shagbark hickory. Sclereid levels were low in black cottonwood, sycamore, eastern cottonwood, yellow poplar, white ash,

TABLE 2. *Between-species comparisons of wood and bark characteristics.*

Species	Total no. trees sampled	Wood/bark adhesion[a] (kPa) Growing season	Wood/bark adhesion[a] (kPa) Dormant season	Inner bark strength (kPa)	Wood toughness (J/m²)	Usable bark fiber (%)[b]	Total sclereids (%)[c]
Quaking aspen	10	628	1,118	883	441	10	13.17
Eastern cottonwood	10	431	1,324	1,736	373	9	0.25
N. black cottonwood	3	—	1,834	1,363	294	12	0.70
Black willow	3	—	1,726	1,020	431	21	1.29
Sugar maple	10	569	990	137	1,177	3	15.88
Silver maple	4	598	1,383	333	490	6	17.27
Red maple	3	—	1,216	1,108	618	12	5.19
Paper birch	10	500	1,177	157	667	0	22.28
Sycamore	2	—	1,451[d]	598	490	0	0.03
Sweetgum	2	—	1,500	794	275	5	2.76
Yellow poplar	2	—	1,628	1,314	226	13	0.99
Black tupelo	2	—	1,324	941	549	5	0.34
White ash	2	—	2,334	1,961	667	16	1.02
Green ash	2	—	1,706	1,236	628	13	4.39
Shagbark hickory	9	373	3,001	2,452	1,451	15	0.01
American beech	3	—	912	726	1,000	0.2	24.24
Red alder	2	—	1,275	804	490	0	11.04
Post oak	3	—	1,196	667	647	4	8.30
Pin oak	3	—	1,265	1,030	628	2	10.48
Black oak	3	—	2,108	1,147	843	5	8.91
N. white oak	10	471	765	451	608	3	8.56
S. white oak	2	—	706	461	961	3	22.74
N. red oak	4	245	824	206	912	5	12.61
S. red oak	4	530	804	353	539	4	17.75

[a] Total number of trees sampled. Dashes mean that adhesion was not measured for those species during the growing season. Adhesion values are averages of two to five trees.
[b] Usable bark fiber is the amount of fiber retained on the 60- and 100-mesh screens when bark samples were micropulped and screened. Average of two trees.
[c] Total sclereids is the amount of sclereids found in the total bark sample when micropulped and retained on 60- and 100-mesh screens. Average of two trees.
[d] Samples failed in tensile.

black tupelo, and black willow. Seven different species of oak were examined, including red and white oaks from both the southern and northern United States. All contained both fibers and sclereids in their inner bark and sclereids and minor amounts of fiber in their outer bark. Thus, bark cell composition is relatively similar for the commercial oaks. Noticeable distinctions can be made between red and white oak barks, but these are related to the arrangement of the phloem cells and to the morphology of the outer bark or rhytidome.

Wood/bark adhesion measurements

Dormant season wood/bark adhesion is the important parameter associated with debarking problems, and dormant season values were measured for twenty-four hardwoods. As a result of the measurement data taken and observations made of the failure zone, it became clear that, for hardwoods, dormant season wood/bark adhesion was related to inner bark strength and inner bark morphology.

Hardwood dormant season wood/bark adhesion varied from 3,006 kPa for

TABLE 3. *Simple correlations between hardwood wood and bark characteristics.*[a]

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Wood/bark adhesion (1)	1.0	−0.09	−0.05	0.59**	−0.56**	0.40	0.72**	0.78**	0.83**
Wood specific gravity (2)		1.0	0.64**	−0.29	0.36	0.73**	0.32	0.16	−0.11
Bark specific gravity (3)			1.0	−0.48*	0.50	0.62**	0.26	0.20	−0.22
% Bark fibers (4)				1.0	−0.60**	−0.03	0.51*	0.45*	0.68**
% Sclereids (5)					1.0	0.20	−0.38	0.41*	−0.68**
Wood toughness (6)						1.0	0.65**	0.63**	0.29
Bark toughness (7)							1.0	0.92**	0.68**
Bark strength[b] (8)								1.0	0.76**
Inner bark strength (9)									1.0

[a] Values from 0.404 to 0.515 significant at 0.95 level of probability (*). Values greater than 0.515 significant at 0.99 level of probability (**).
[b] Average of inner and outer bark values.

TABLE 4. *Variables important in estimating hardwood wood/bark adhesion.*

Independent variables	Standard PRC[a]	F-test[b]	R^{2c}
I. % Fibers	0.1534	0.802	
Wood toughness	0.1301	1.092	
Inner bark strength	0.7064	18.38	0.70
Regression equation W/B adhesion = $541.5 + 13.95(X_1) + 0.239(X_2) + 0.655\ (X_3)$			
II. Wood toughness	0.1315	0.764	
Inner bark strength	0.615	46.04	0.69
Regression equation W/B adhesion = $579.79 + 0.1942(X_1) + 0.7615(X_2)$			
III. % Fibers	0.1143	0.465	
Inner bark strength	0.7497	20.66	0.69
Regression equation W/B adhesion = $692.7 + 10.39(X_1) + 0.695(X_2)$			
IV. % Fibers	0.659	15.34	
Wood toughness	0.228	1.89	0.43
Regression equation W/B adhesion = $715.44 + 59.87(X_1) + 0.418(X_2)$			

[a] Standard partial regression coefficients reflect the relative contribution of the several independent variables to the regression equations.
[b] F-test for significance of regression coefficients; values greater than 4.3 are significant at 95% level of probability.
[c] R^2 values greater than 0.36 are highly significant when the number of variables, k = 2; 0.43 values are required when k = 3 (Eq. 1).

shagbark hickory to 706–765 kPa for white oak. The relationships that exist between hardwood dormant season wood/bark adhesion and bark strength and morphology were examined by running a series of simple and multiple correlations between wood/bark adhesion and wood specific gravity, bark specific gravity, percent bark fiber, percent sclereids, wood toughness, bark toughness, total bark strength, and inner bark strength. Table 2 summarizes parameters important to understanding wood/bark adhesion, and Table 3 summarizes the simple correlation matrix involved. Hardwood wood/bark adhesion was found to be positively correlated with percent bark fibers, wood toughness, bark toughness, inner bark strength, and inner plus outer bark strength. Wood/bark adhesion was negatively correlated with the percent sclereids in the bark. Several multiple correlations were run in an effort to determine those variables that would be most useful in estimating wood/bark adhesion. Percent bark fiber, wood toughness, and inner bark strength proved to be the most useful of the variables investigated. Bark toughness was also highly correlated with wood/bark adhesion but was not used in the final multiple correlation because it was correlated with several of the other parameters.

Table 4 summarizes the data for the four most promising multiple correlation comparisons. Based upon F-tests and R_2 values, comparison II, using wood toughness and inner bark strength, turned out to be the most useful. Use of the variables percent fibers and inner bark strength, comparison III, also provided a useful estimate of wood/bark adhesion. The relative importance of the independent variables can be determined by comparing the standard partial regression coefficients (Snedecor and Cochran 1967). When this is done, it becomes apparent that inner bark strength is several times as important as the other independent variables in estimating wood/bark adhesion.

Morphologically, the presence of fibers increases inner bark strength, and when sclereids are present, bark strength is usually lower. Inner bark strength, in turn, has a major influence on dormant-season, hardwood wood/bark adhesion. The multiple correlation comparison employing wood toughness and inner bark strength accounts for 69% of the wood/bark adhesion variation encountered. Use of inner bark strength alone provides almost as much information about wood/bark adhesion as the sample correlations (Table 3) demonstrate.

Failure zone examination studies

Bark, particularly that of hardwoods, is rather complex, and, apparently, several factors influence its adhesion to wood. As stated under bark variability, fibers were found in all species examined except red alder, paper birch, and sycamore (and minor levels in American beech). The presence of fibers tends to increase adhesion during the dormant season, whereas the presence of sclereids has a negative influence on wood/bark adhesion. Species lacking or having few sclereids (like eastern cottonwood, black cottonwood, yellow poplar, shagbark hickory, white ash, sycamore, black tupelo, and black willow) uniformly had high adhesion values, the most extreme example being shagbark hickory, which had the highest adhesion values of any species examined. Figure 1 illustrates the seasonal variation in wood/bark adhesion for sugar maple. This adhesion pattern is typical of that usually found in all samples examined throughout the year, with failure during the growing season occurring in the newly formed xylem initials just inside the cambium zone and during the dormant season in the inner bark. In addition, ray "pull-out" areas are evident in the August 10 collection. Shown in Fig. 2 is an example of adhesion in the oaks, again with growing season adhesion failure in the area of the cambium zone and newly formed xylem initials and dormant season adhesion failure occurring in the inner bark.

There are instances where the prediction of wood/bark adhesion for previously little-utilized species is desirable. Through a thorough understanding of bark morphology, it appears that difficult-to-debark species (high wood/bark adhesion) can be identified. This requires information on the presence of fibers and sclereids and the distribution of these sclerenchyma cells in the inner bark as well as a measure of inner bark strength and wood toughness. Several species seem to be exceptions to the rule that fibers increase wood/bark adhesion and sclereids decrease adhesion. These exceptions are the reason there is a low multiple correlation ($R^2 = 0.41$) when only percent fibers and percent sclereids are used to predict wood/bark adhesion. Explanation of the reason for exceptions like silver maple and white birch will require additional examination of the inner bark cell characteristics.

Simple and multiple correlation investigations indicate wood/bark adhesion can be estimated satisfactorily using information on inner bark strength and wood toughness. This suggests that there are alternate methods of identifying difficult-to-debark species. At present, at least one organization is utilizing wood/bark adhesion data to determine drum barker dimensions. Direct measurement of wood/bark adhesion appears to be a practical measurement technique and a useful research tool.

CONCLUSIONS

Growing season wood/bark adhesion measurements varied from 245 to 628 kPa, and the growing season failure zones quite consistently were located in the

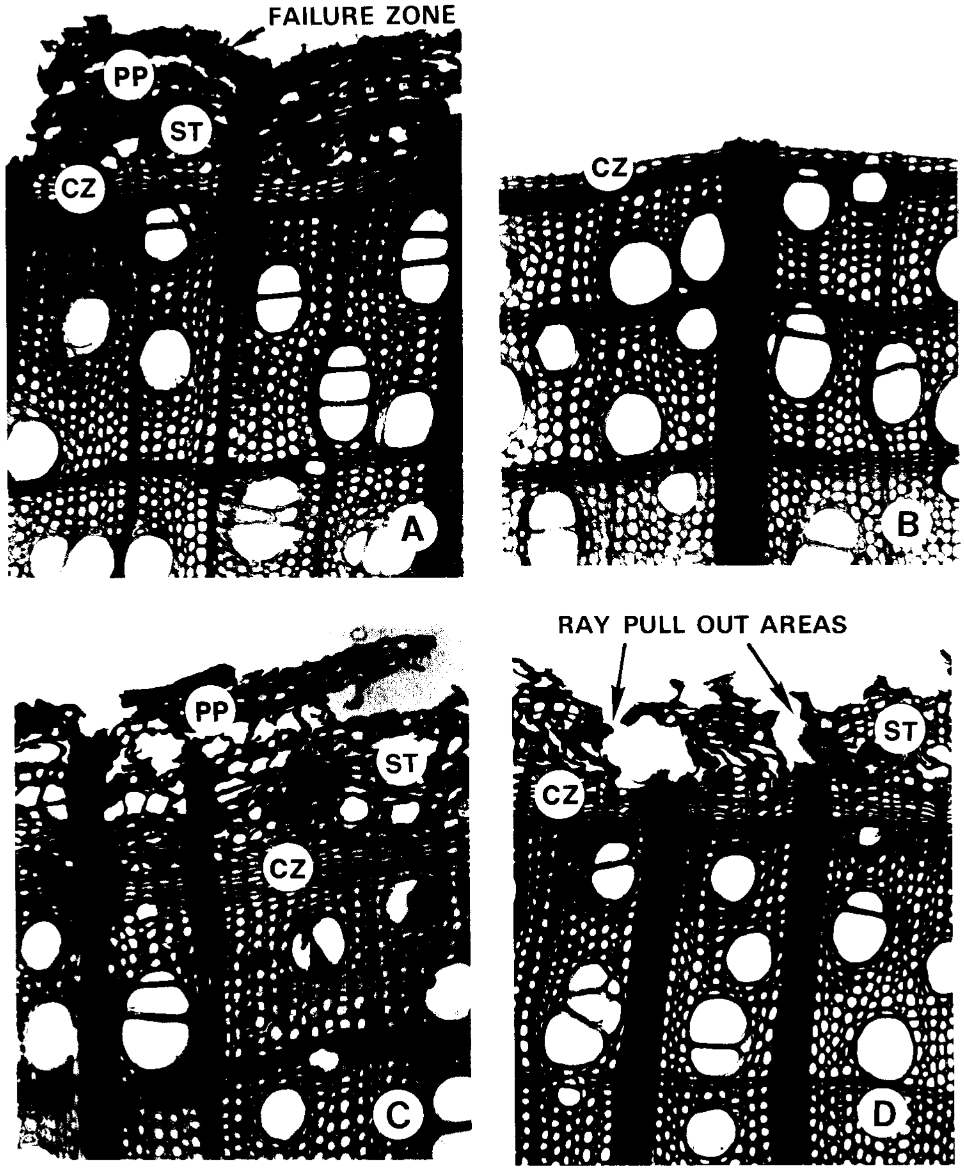

FIG. 1. Seasonal changes in the location of the zone of failure in sugar maple; A—May 18 collection, failure in phloem parenchyma and sieve tube area (PP-ST) just outside the cambium zone (CZ); B—June 1 collection, failure in cambium zone (CZ); C—August 10 collection, failure again in the PP-ST area, with failure being influenced by the "pulling out" of phloem rays.

cambium or the newly formed xylem elements just inside the cambium zone. Dormant season wood/bark adhesion measurements were greater than the growing season values and varied from 706 kPa for white oak to 3,006 kPa for shagbark hickory. Failure zones during the dormant season were located in the inner bark, and wood/bark adhesion values were influenced by the morphology of the inner bark.

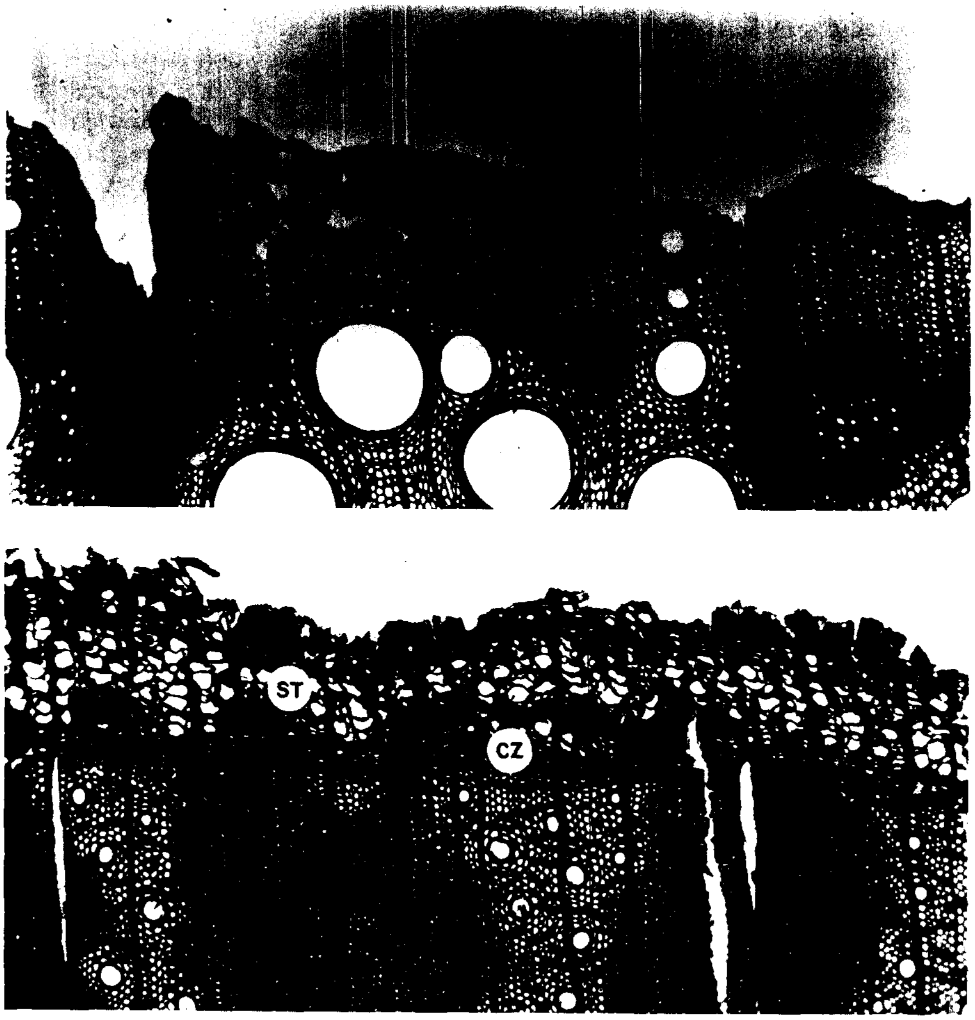

FIG. 2. Zones of failure in northern red oak are illustrated for the growing season (top) and dormant season (bottom). The growing season failure zone was located between the cambium zone and the adjacent last-formed immature xylem cells. Failure during the dormant season occurred in the inner bark, primarily between the collapsed phloem sieve tubes and the parenchyma cells adjacent to the more recently formed tangential bands of phloem fibers close to the cambium. Magnification, 75×.

Wood/bark adhesion was compared, using simple and multiple correlation techniques, with bark specific gravity, inner bark strength, bark toughness, wood specific gravity, wood toughness, percent bark fibers, and percent sclereids. Wood/bark adhesion was found to be positively correlated with percent bark fibers, bark toughness, and inner bark strength. Wood/bark adhesion was negatively correlated with percent sclereids in the bark. Morphologically, it appeared that the presence of fibers increased inner bark strength, sclereids decreased inner bark strength, and inner bark strength had a major influence on wood/bark adhesion. The multiple correlation comparison employing wood toughness and inner bark strength accounted for 69% of the wood/bark adhesion encountered. Use of inner bark strength alone provided almost as much information about wood/bark adhesion. The prediction of debarking difficulties appears possible through a thorough understanding of bark morphology. For North American hardwoods, knowledge of the presence of fibers and sclereids and the distribution of these sclerenchyma cells in the inner bark is required.

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