RELATIVE DENSITY, EQUILIBRIUM MOISTURE CONTENT, AND DIMENSIONAL STABILITY OF WESTERN HEMLOCK BARK[1]

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ABSTRACT

The measurement of western hemlock bark samples from three coastal sites in British Columbia revealed that inner bark relative density (0.382) is less than that of the adjacent sapwood (0.413) and markedly less than that of outer bark (0.463). The equilibrium moisture content of the inner and outer bark are equivalent at both 70 and 30% relative humidity, and slightly higher than that of the sapwood.

The generally higher shrinkage of bark compared with wood is the result of bark cell collapse during drying. In the outer bark, some collapse or crushing takes place in the standing tree. This compacting of tissue reduces the shrinkage of outer bark relative to the inner bark. The actual shrinkage per unit change in moisture content of the inner bark is the same as that for the sapwood. The outer bark appears to be more dimensionally stable. The longitudinal shrinkage of both inner (2.9%) and outer (2.2%) bark is markedly greater than that of the sapwood (0.1–0.2%).

Keywords: Inner bark, outer bark, specific gravity, shrinkage, western hemlock.

INTRODUCTION

Currently, the major use for western hemlock (*Tsuga heterophylla* [Raf.] Sarg.) bark in British Columbia is hog fuel. As raw material demands increase in the future, economics may force the utilization of residues for higher-value products. One obvious use to consider, since bark generally becomes available in a particulate form, is in a particleboard (Maloney 1973). As methods are developed to use bark in this or in other building materials, data on its physical properties become increasingly important so that performance of the material can be predicted. Smith and Kozak (1971) have reported values of moisture content and specific gravity for the inner and outer bark of thirteen conifers and six hardwoods, including western hemlock. There are apparently no available published data on the equilibrium moisture contents (EMC) nor the amount of related shrinkage from the green condition for western hemlock bark.

This paper reports the results of measurement of western hemlock bark properties. Properties measured were: initial moisture content; relative density; equilibrium moisture content at 70 and 30% relative humidity; and shrinkage from the green condition to equilibrium with 70, 30 and 0% relative humidity. Measurements were made on inner and outer bark separately and, for comparative purposes, on sapwood samples obtained immediately adjacent to the bark.

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METHODS

Three sites were selected for study to represent the geographical range of large-scale, commercial, coastal sawtimber production areas: southern Vancouver Island, the B.C. Lower Mainland near Vancouver, and the North Coast near Terrace. Details of material selection and sampling methods were presented by Bramhall et al. (1977).

Briefly, ten stems from each site were selected to represent typical sawtimber from the particular region. Disks were taken at three height positions: stump height, top of the first 24-foot log, and at the merchantable top of the stem (6-inch dob). These height positions are referred to hereafter as butt, middle, and top. Wood with bark attached was obtained from three circumferential positions of each disk. These samples therefore represent bark from commercial, mature, western hemlock sawtimber of coastal British Columbia.

Samples were obtained during the dormant season, so that bark would remain intact on the wood during handling and sample preparation. From each of the nine samples per tree, single wafers of varying thickness, but as thick as the tissue would allow, were sawn from the outer and inner bark, after reducing outside dimensions to 20 × 20 mm in the tangential and longitudinal directions. Cubes 20 mm on a side were cut from the outermost sapwood radially adjacent to the bark samples. Thus, ninety samples of each tissue type were measured from each of the three geographic sites. Samples of sapwood, inner and outer bark from any given sampling location were approximately matched as to origin from related cambial initials.

Green weight (to the nearest 0.1 milligram), volume (to the nearest 0.001 cm^3 using water immersion) and radial, tangential, and longitudinal dimensions (to the nearest 0.01 mm using a micrometer) were obtained, before all samples were placed in a constant temperature and humidity cabinet, at 70% relative humidity (RH) and 40 C. These conditions were maintained until the outer bark, the slowest to come to equilibrium, had reached a constant weight. Weights and dimensions were then recorded, and the procedure was repeated for the conditions 30% RH and 40 C, and finally oven-drying at 105 C.

RESULTS AND DISCUSSION

Green moisture content

Average green moisture contents for sapwood and bark are given in Table 1. At all sites, the sapwood moisture content is consistently higher than that of the inner bark, which in turn is higher than the outer bark. Over all sites and tree positions, average inner bark moisture contents range from 85.9 to 126.5%. Smith and Kozak (1971) reported average inner bark moisture contents for thirteen western hemlock trees, ranging from 90 to 108% over ten tree height positions. Comparable average outer bark moisture contents range from 38.2 to 81.4%. Smith and Kozak (1971) found matching outer bark moisture contents ranging from 42 to 73%.

Figure 1 shows a strong negative relationship between the initial moisture content of the outer bark and the number of periderms in the tissue, as reported by Bramhall et al. (1977). The projection of the linear relationship to zero number of periderms yields an initial moisture content of at least 88.4%, a value similar

TABLE 1. *Average green moisture contents and relative densities of western hemlock sapwood, inner bark and outer bark samples.*

	Vancouver Island			Lower Mainland			North Coast		
	Top	Middle	Butt	Top	Middle	Butt	Top	Middle	Butt
Green moisture content, %									
Sapwood	135	139	117	160	179	160	143	152	125
Inner bark	126	118	104	122	105	105	108	92	86
Outer bark	81	48	64	55	48	57	62	38	39
Relative density									
Sapwood	0.426	0.419	0.458	0.407	0.362	0.392	0.405	0.399	0.454
Inner bark	0.404	0.390	0.400	0.361	0.365	0.377	0.380	0.377	0.386
Outer bark	0.440	0.466	0.500	0.478	0.497	0.487	0.426	0.424	0.447

to the observed average moisture content of the inner bark. Moisture within the inner bark must move towards the outer surface, where it evaporates into the atmosphere. Impermeable periderm layers retard moisture movement from the wood through the bark to the surrounding atmosphere. The greater the number of periderm layers, the greater is the restriction of outward moisture flow. Therefore, the average moisture content of the outer bark decreases. The outer parts of the bark probably contain tissues whose moisture content is actually below the fiber saturation point. Thus, shrinkage may take place in outer bark tissue in the standing tree, which will increase relative density and decrease subsequent shrinkage of that tissue.

Statistical analysis of the data presented in Table 1 reveals that the tree position effect for outer sapwood is significant or nearly significant at all geographic sites, with the lowest moisture content at the butt and the highest at the middle, with the top being intermediate. For inner bark, the highest moisture content appears to be at the top, the lowest at the butt, and the middle is intermediate. Formal significance of this, at the 95% level, is approached at two of the sites. For outer bark, the middle height position appears to have the lowest moisture content. In this case, formal significance of the height effect is attained at one site and approached at another.

Relative density

Average relative density values for outer sapwood, inner bark and outer bark are shown also in Table 1. Inner bark relative densities range from 0.361 to 0.404 over all sites and tree positions. Comparable outer bark relative densities range from 0.424 to 0.500. Whereas the agreement with the observations of initial moisture content reported by Smith and Kozak (1971) were good, considerable difference exists in the relative density data. Their average relative densities ranged from 0.405 to 0.511 and from 0.503 to 0.658 for inner and outer bark, respectively. In contrast, the ranges in average relative density do not even overlap between the two sets of observations. An explanation for this is not readily available.

A pattern of wood relative density variation with tree position is found in which the highest value is at the butt, the lowest is in the middle, and the top is intermediate. In the case of the Lower Mainland sapwood sample, the top actually

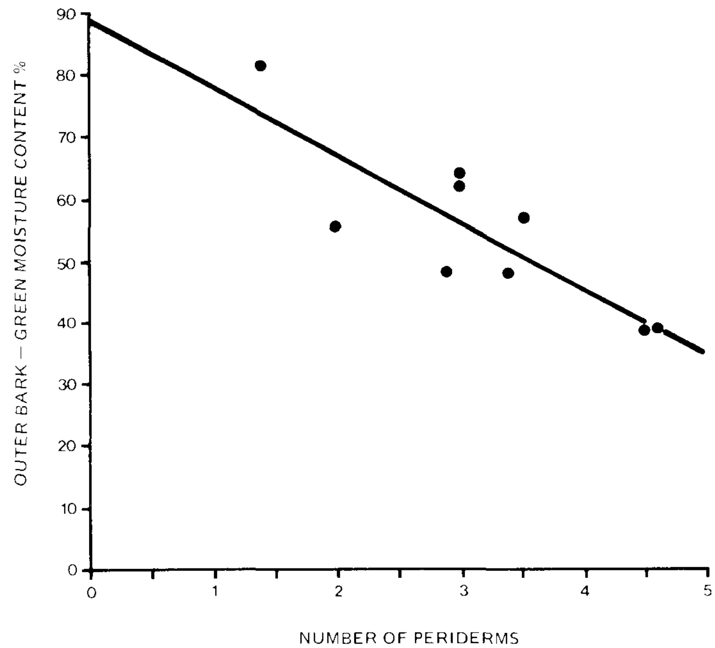

FIG. 1. Relationship between the average number of periderm layers in the outer bark and the green moisture content of that tissue. Data points are geographic site averages.

had the highest relative density. This general pattern of relative density change with tree position has been reported before for western hemlock by Kellogg and Keays (1968). Average inner bark relative density is, in general, less than that of the wood and shows no significant pattern of change with tree position.

Outer bark has markedly greater relative density than inner bark. Several factors must contribute to this increase. First, the expanding periderm causes crushing of the outer bark cells and, second, the loss of moisture from the outermost bark tissue must result in shrinkage and may result in cell collapse. We speculate that the high moisture content of inner bark and the small size of the pit openings

TABLE 2. *Average equilibrium moisture contents at 70 and 30% relative humidity and 40 C for western hemlock outer sapwood, inner bark, and outer bark samples.*

Tissue type	Equilibrium moisture content, % at 70% RH and 40 C		
	Vancouver Island	Lower Mainland	North Coast
Outer sapwood	14.2	14.4	14.2
Inner bark	16.3	15.5	17.1
Outer bark	15.9	16.2	16.4
	Equilibrium moisture content, % at 30% RH and 40 C		
Outer sapwood	6.0	5.6	5.9
Inner bark	8.3	6.7	8.4
Outer bark	9.1	8.7	9.4

TABLE 3. *Average green to oven-dry shrinkage (%) of western hemlock outer sapwood, inner bark, and outer bark samples.*

		Radial			Tangential			Longitudinal		
		Top	Middle	Butt	Top	Middle	Butt	Top	Middle	Butt
Outer sapwood	Vancouver Island	5.2	5.5	5.4	8.4	9.1	8.2	0.1	0.1	0.2
	Lower Mainland	4.9	4.5	4.2	8.0	8.0	7.6	0.1	0.3	0.3
	North Coast	4.7	4.8	5.1	7.4	8.2	7.6	0.1	0.0	0.1
	Average	4.9	4.9	4.9	7.9	8.4	7.8	0.1	0.1	0.2
Inner bark	Vancouver Island	14.0	13.9	14.4	15.7	15.8	16.2	2.3	2.3	2.4
	Lower Mainland	17.4	15.2	13.9	15.6	18.8	18.0	2.5	2.5	2.6
	North Coast	13.6	15.4	14.7	21.1	18.7	17.5	3.5	3.8	3.7
	Average	15.0	14.8	14.3	17.5	17.8	17.2	2.8	2.9	2.9
Outer bark	Vancouver Island	11.6	7.8	8.9	3.6	5.6	5.5	2.7	2.0	2.2
	Lower Mainland	9.8	6.8	7.2	4.5	5.5	5.7	2.7	2.2	2.1
	North Coast	10.2	6.9	7.4	4.9	5.4	5.4	2.5	1.7	1.9
	Average	10.5	7.2	7.8	4.3	5.5	5.5	2.6	2.0	2.1

(Bramhall and Kellogg 1979) make collapse a probable occurrence. The relative density gradient with stem position, which develops in the outer bark, is formally significant at one site; however, relative density of the outer bark from the top position is consistently and significantly lower than that from the butt. Development of this gradient must result from a differential degree of influence of one or both of the factors suggested. Analyses of the bark tissue characteristics and distribution by Bramhall et al. (1977) have shown that both inner and outer bark thickness and number of periderm layers differ significantly between top and butt samples. Development of increasing numbers of periderm layers may increase the amount of cell crushing due to periderm growth, as well as isolate the outermost outer bark layers from the source of moisture so that shrinkage of the tissue can take place during dry-weather conditions.

Equilibrium moisture content

Average equilibrium moisture contents of wood and bark samples from the three sites are shown in Table 2. The values obtained differ very little between sites at both 70 and 30% relative humidity.

Inner and outer bark samples differ little in equilibrium moisture content, but are consistently higher than the sapwood at both relative humidity levels. Values reported here compare very closely with those obtained by Wilhelmsen (1969) for *Pinus sylvestris* and *Picea abies*. Fraser and Swan (1979) have found the total extractive contents of fresh western hemlock bark from five trees at the University of B.C. Research Forest to be 34 and 33% for outer and inner bark, respectively. Wangaard and Granados (1967) demonstrated that for wood increasing extractive contents reduced equilibrium moisture content, particularly above 60–

70% relative humidity. Below this level, the sorption isotherms of extracted and unextracted wood coincided very closely. The higher equilibrium moisture contents found for the inner and outer bark, despite the high extractive content, may be the result of the relative humidity levels at which the observations were made and a basic greater sorptive nature of the bark.

Shrinkage

The average green-to-oven-dry shrinkage values of outer sapwood and bark samples from all three sites are shown in Table 3. The values obtained for western hemlock wood are in close agreement with the published average of 5.4 and 8.5% for radial and tangential shrinkage, respectively (Jessome 1977). Longitudinal shrinkage of wood is relatively constant for normal wood of different species and the values obtained of 0.1–0.2% are as expected.

The transverse shrinkage of inner bark is large relative to that of wood. The average ratio of tangential to radial shrinkage in the wood is 1.64, while that of the inner bark is 1.19. An even greater difference in shrinkage behavior is exhibited by the outer bark, where the ratio of tangential to radial shrinkage is actually 0.60. The average tangential shrinkage of the outer bark is only 5.1%. The periderm layers appeared to exert a considerable restraining action on the tangential shrinkage of the outer bark.

The longitudinal shrinkage of both inner and outer bark is markedly greater than that for the wood. Overall averages are 2.9 and 2.2% for inner and outer bark, respectively.

In general, stem position effects are small for the sapwood and inner bark material. In the case of the outer bark, it appears that material from the top position has significantly greater radial and longitudinal shrinkage, and significantly less tangential shrinkage, than the outer bark from the middle or butt positions.

There is little evidence of site differences for the shrinkage of either sapwood or outer bark. However, the tangential shrinkage of inner bark from Vancouver Island is significantly lower than that from the other two sites.

The average radial shrinkage values of the wood, inner bark and outer bark samples for each site at three moisture-content levels are plotted in Fig. 2. The same information for tangential shrinkage is plotted in Fig. 3. Linear regressions were fitted to the plotted points. The greater radial shrinkage of both inner and outer bark, compared with that of wood over the entire range of the data, is clearly seen in Fig. 2. Of greater significance is the fact that the slopes of the three shrinkage curves are not significantly different. This means that for a given change in moisture content, within the ambient equilibrium moisture content range, the radial shrinkage of both inner and outer bark of western hemlock does not differ from that of the sapwood. In effect, the dimensional stabilities of these materials under ambient conditions are the same.

A similar condition exists in comparing the tangential shrinkage of inner bark and sapwood in Fig. 3. However, the tangential dimensional stability of the outer bark is considerably greater than that of the wood. This greater stability in the tangential direction would be offset, as far as its contribution to volumetric shrinkage is concerned, by the considerably greater longitudinal shrinkage of the bark.

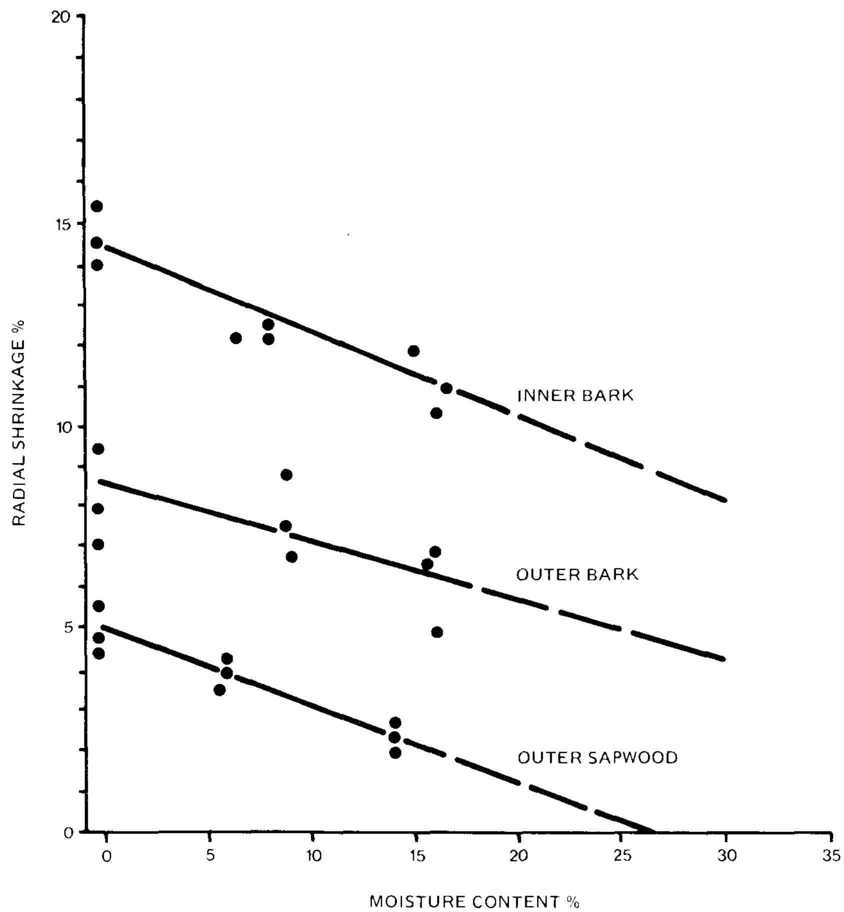

FIG. 2. Radial shrinkage as a function of moisture content for outer sapwood, inner bark, and outer bark of western hemlock. Data points are geographic site averages.

Therefore, one could anticipate that products made from bark would not differ greatly from wood in their dimensional stability.

Fiber saturation point

Little information exists in the literature on estimates of the fiber saturation point of bark. Martin (1968) estimated the average fiber saturation point of the outer bark of several coniferous and deciduous tree barks to be about 25%. This estimate was based on the equilibrium moisture content values determined after exposure to a saturated atmosphere. In contrast, Wilhelmsen (1969), using the porous-plate technique, obtained estimates of the fiber saturation point of inner and outer bark of *Pinus sylvestris* of 165 and 70%, respectively.

Another method of estimating the fiber saturation point is to determine the intercept of the linear shrinkage-moisture content relationship with the moisture content axis. Using this method on the shrinkage-moisture content relationship

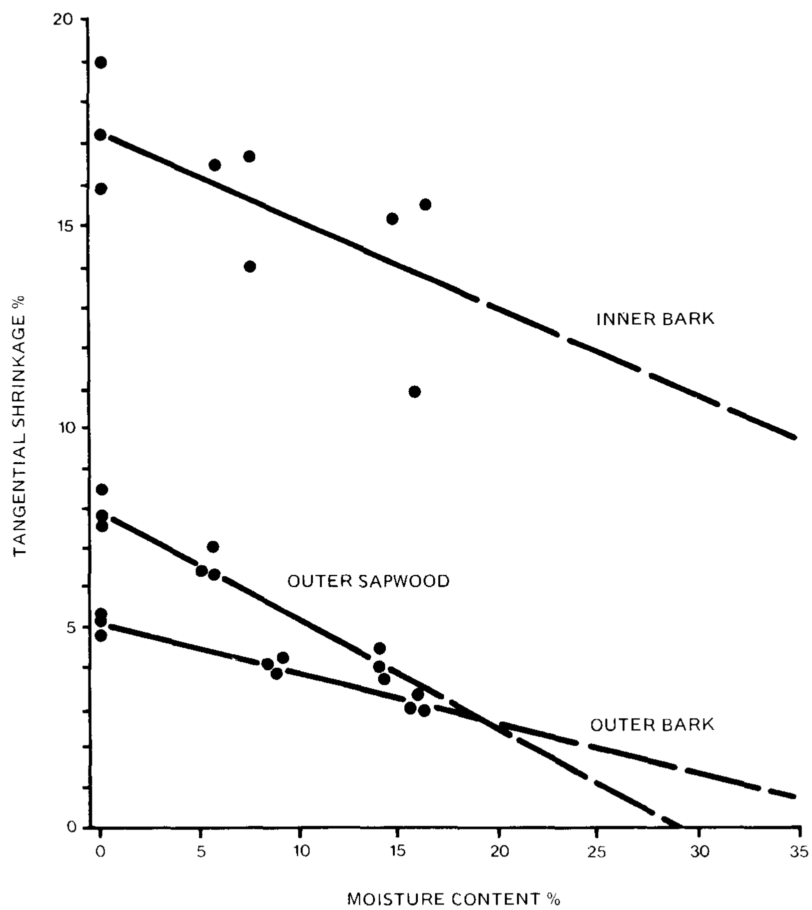

FIG. 3. Tangential shrinkage as a function of moisture content for outer sapwood, inner bark, and outer bark of western hemlock. Data points are geographic site averages.

for the sapwood samples results in estimates of the fiber saturation point of 26 and 28% for the radial and tangential shrinkage curves, respectively.

Using this same method results in estimates of the bark fiber saturation point greater than those for the sapwood. Estimates for the outer bark samples are 56 and 40% for the radial and tangential shrinkage curves, respectively. The inner bark values are even higher at 66 and 77%, respectively.

A question arises as to the correctness of those values which appear to support the estimates made by Wilhelmsen (1969). The possibility exists that collapse of the essentially unlignified cells occurred during the drying process. If this should be the case, these estimates based on shrinkage response would be too high.

Figure 4 is a scanning electron micrograph of a representative sample of air-dry inner bark. Several samples 2 cm long were surfaced in the green condition with a razor blade and then air-dried. Collapse is evident, particularly in the tangential bands of axial parenchyma and the rays. This collapse might be the

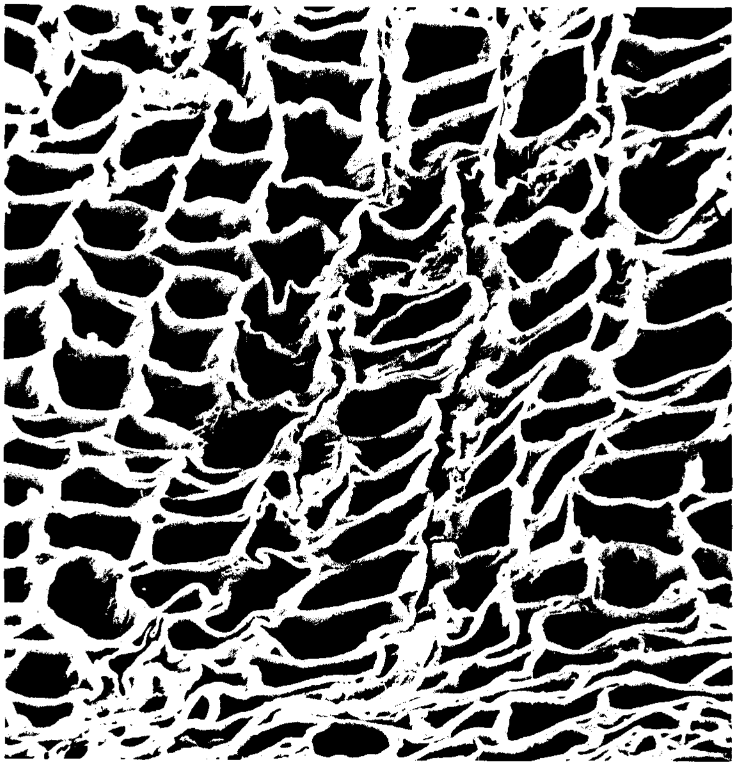

FIG. 4. Scanning electron micrograph of a cross section of air-dried inner bark; 530×.

result of either drying stresses or the compressive action of growth. If the collapsing force is the result of growth, then the collapsed cells should be evident in the green material.

To answer this question, several green samples of inner bark were surfaced with a razor blade and then dried in a critical-point dryer. This technique results in stress-free drying, so collapse forces should not develop. Figure 5 is a scanning electron micrograph of a surface of critical-point dried tissue prepared in the manner described. Little or no collapse is evident. The collapsing force must be due not to growth-induced stresses, but to drying stresses. The effect of this collapse on the shrinkage curves for the inner bark, shown in Fig. 2, would be to shift it vertically. This would negate the value of the curve as a means of estimating the fiber saturation point, since the value obtained would be seriously overestimated.

As the periderm layers develop and the outer bark is formed, two events take place that have an influence on the subsequent shrinkage properties of the material. First, as the periderm develops within the inner bark, compressive forces must develop that cause crushing of the existing cells, thus reducing the collapse component of the shrinkage potential. Second, as Fig. 1 illustrates, formation of periderm layers and drying of the outer tissue occur simultaneously. Under these conditions, it can be presumed that collapse will take place in portions of the

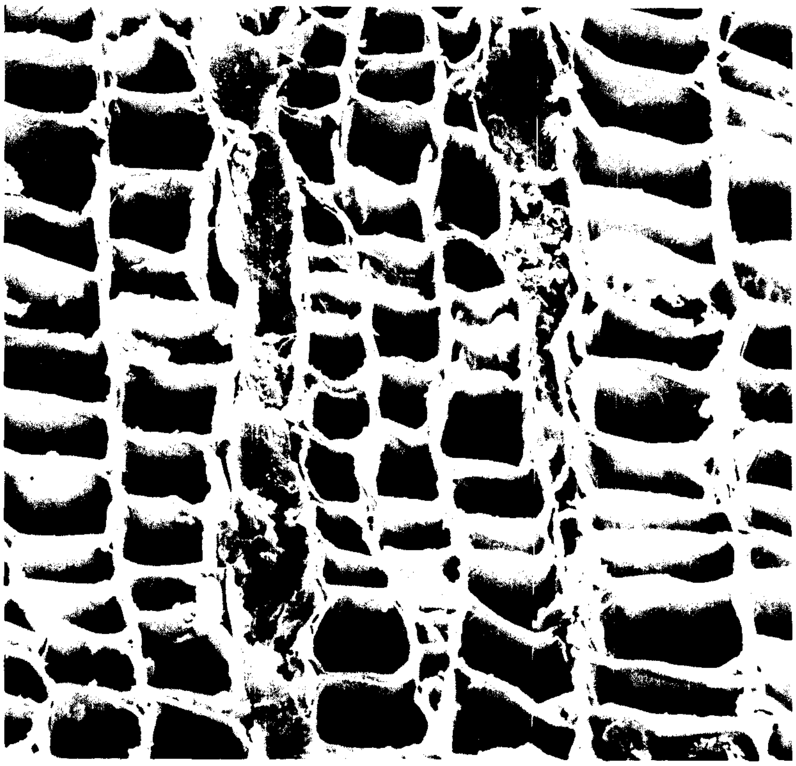

FIG. 5. Scanning electron micrograph of a cross section of critical-point-dried inner bark; 515×.

outer bark. Both of these factors will reduce the collapse and shrinkage potential of the tissue. It may well be, however, that the radial shrinkage relationship for outer bark shown in Fig. 2 may still contain a considerable collapse component.

In the case of tangential shrinkage, the expanding periderm must crush many of the cells still in the green condition. The diminished shrinkage potential, due to the removal of a large portion of the collapse potential, may explain in part the marked reduction in the tangential shrinkage of this tissue relative to the shrinkage it would have exhibited as inner bark.

SUMMARY AND CONCLUSIONS

Sapwood moisture content is consistently higher than that of the inner bark, which in turn is higher than that of outer bark. For sapwood, the lowest moisture content is found at the butt (134%), the highest at the middle (156%), and the top is intermediate (146%). For inner bark, the lowest moisture content is found at the butt (98%), the highest at the top (119%), and the middle is intermediate (105%). In the case of the outer bark, the middle height position appears to have the lowest moisture content (45%), but formal significance of the height effect is attained at only one geographic site.

The average inner bark relative density (0.382) is less than that of the sapwood (0.413) and shows no significant pattern of change with tree position. The outer bark shows a marked increase in relative density (0.463) over both that of the sapwood and inner bark.

The average equilibrium moisture content of the sapwood at 70 and 30% relative humidity and 40 C is 14.3 and 5.8%, respectively. Inner and outer bark samples differ little in equilibrium moisture content, but are consistently higher than the sapwood at both 70 and 30% relative humidity levels, averaging 16.2 and 8.4%, respectively.

Inner bark tissue is subject to considerable collapse on drying, which results in large shrinkage values relative to the sapwood. The average oven-dry radial and tangential shrinkages of the sapwood samples are 4.9 and 8.0%; the corresponding values for the inner bark are 14.7 and 17.5%, respectively. In the outer bark, some collapse or crushing has already taken place, which reduces the radial and tangential shrinkage values to 8.5 and 5.1%. The most dramatic shrinkage difference between sapwood and bark occurs in the longitudinal shrinkage. In this case, the virtually negligable shrinkage (0.1–0.2%) found for sapwood increases to 2.9 and 2.2% for inner and outer bark, respectively. There was little evidence of either a stem position or site effect on these shrinkage values.

The shrinkage of bark tissue is generally higher than sapwood. It appears that this is due largely to cell collapse. The dimensional stability of the inner bark in the observed range of relative humidities is the same as that for sapwood. The outer bark appears to be even more stable, at least in its tangential shrinkage. This greater stability would be offset by the higher shrinkage potential of bark in the longitudinal direction, but it appears that the dimensional stability of composite products made of western hemlock bark would be similar to that of wood-based products.

Estimates of the fiber saturation point of bark tissue, based on the moisture content-shrinkage relationship, are in error as a result of the large component of shrinkage related to cell collapse.

REFERENCES

Bramhall, A. E., R. M. Kellogg, R. W. Meyer, and W. G. Warren. 1977. Bark-tissue thickness of coastal western hemlock in British Columbia. Wood Fiber 9(3):184–190.

Bramhall, A. E., and R. M. Kellogg. 1979. Anatomy of secondary phloem of westerm hemlock, *Tsuga heterophylla* (Raf.) Sarg. IAWA Bulletin 4:79–85.

Fraser, H. S., and E. P. Swan. 1979. Phenolic character of sequential solvent extracts from western hemlock and white spruce barks. Can. J. For. Res. 9(4):495–500.

Jessome, A. P. 1977. Strength and related properties of woods grown in Canada. Can. Forest. Serv., East. Forest Prod. Lab., Forest. Tech. Rep. 21. 37 pp.

Kellogg, R. M., and J. L. Keays. 1968. Can. Forest. Serv., Bi-Month. Res. Notes 24(4):32.

Maloney, T. M. 1973. Bark boards from four West Coast softwood species. For. Prod. J. 23(8):30–38.

Martin, R. E. 1968. Interim volumetric expansion values for bark. For. Prod. J. 18(4):52.

Smith, J. H. G., and A. Kozak. 1971. Thickness, moisture content, and specific gravity of inner and outer bark of some Pacific Northwest trees. For. Prod. J. 21(2):38–40.

Wangaard, F. F., and L. A. Granados. 1967. The effects of extractives on water-vapour sorption of wood. Wood Sci. Technol. 1:253–277.

Wilhelmsen, G. 1969. Bark-water relationships. II. Hygroscopicity of bark of spruce, pine and birch. Norsk Skogind. 23(11):333–339.