RELATION OF COMPARATIVE DIFFUSION RATES OF OAK RAY AND SURROUNDING TISSUE TO CHECK FORMATION

W. T. Simpson
U.S. Department of Agriculture, Forest Products Laboratory,
Madison, Wisconsin 53705

(Received 29 January 1973)

ABSTRACT

The rate of radial moisture diffusion in desorption was determined for both the ray tissue and the surrounding tissue of white oak, northern red oak, and cherrybark oak. In all these species, radial moisture diffusion was found faster in ray tissue than it was in the surrounding tissue. The relationship of this phenomenon to surface checking during drying is discussed.

Additional keywords: Quercus alba, Q. rubra, Q. falcata var. *pagodalfolia,* desorption, seasoning, check formation.

INTRODUCTION

The objective of this study was to compare rates of radial moisture diffusion in broad ray tissue and in surrounding tissue. The comparative rates are of interest from the standpoint of moisture sorption, particularly drying quarter- and flatsawn lumber. It is generally known that flatsawn lumber dries faster than does quartersawn. The axial direction of ray tissue is oriented perpendicular to the plane of the wide face of flatsawn boards. Thus, if ray tissue passes moisture faster radially in a board than does the surrounding tissue, or "prosenchyma," this could be part of the reason flatsawn lumber dries faster than does quartersawn. To simplify terminology, the tissue surrounding the broad ray tissue will be referred to as "prosenchyma," although it does contain longitudinal parenchyma and uniseriate rays (see Schniewind 1959). The terms "radial" and "tangential" direction will refer to the axes of the whole tree for both types of isolated tissue.

A more important reason for interest in comparative rates is the relationship to drying stresses and surface checks.

On the basis of structural level, Schniewind (1960) has classified drying stresses into three orders. The first-order stresses are confined to a single cell, and are due to unequal shrinkage of the different cell-wall layers. The second-order stresses are developed within discrete types of tissues because of unequal shrinkage between adjacent types of tissue, i.e. between earlywood and latewood or between ray tissue and prosenchyma. The third-order stresses are developed within regions of a board because of gross moisture gradients.

Surface checks are usually attributed to tangential tensile stresses on the surface in the early stages of drying when the moisture gradient is quite steep, and would thus be considered caused by third-order stresses. In species with large and numerous rays, like oak, surface checks usually occur around a broad ray end on the tangential face of a flatsawn board and quite often occur within the ray tissue itself (Gaby 1963; Panshin and deZeeuw 1970). Superimposed on the third-order stresses are the second-order stresses that result from differential shrinkage between ray tissue and prosenchyma. Several investigators (Clarke 1930; Morschauser 1954; Schniewind 1959) have shown that ray tissue shrinks less in the radial direction than does prosenchyma. This is readily apparent on the tangential face of any oak board that has been surfaced before drying—the ray ends protrude from the surface after drying. Schniewind (1966) has noted this effect as a problem in finished products made from red alder.

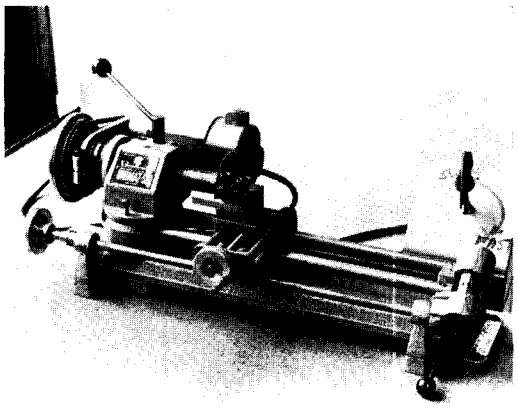

FIG. 1. Circular saw used to cut specimens from ray and surrounding tissue (prosenchyma).

Schniewind and Kersavage (1961) have shown that these second-order stresses do exist during drying, and that they cause radial compression in the ray tissue and radial tension in the prosenchyma.

Although the second-order radial stresses are probably involved in the mechanism of check formation, it would seem that tangential stresses are also important. By using models, Schniewind (1963) found evidence that tangential stresses do exist in both ray tissue and prosenchyma during drying. At room temperature the ray tissue is in tangential tension, the prosenchyma, in tangential compression. At 104 C he found that these stresses were reversed in his model, which he attributed to differences in thermal expansion.

If tangential tension exists in ray tissue during drying, it is due either to the third-order stresses caused by gross moisture gradients in the piece or to the second-order stresses caused by restrained tangential shrinkage of the two types of tissue. The rays are an integral part of the piece, and during drying, their shrinkage potential becomes restrained shrinkage, which is in effect strain that can cause fracture. It is possible that ray tissue shrinks more tangentially than does prosenchyma. Schniewind (1959) measured the tangential shrinkage in California black oak of both ray tissue and tissue free of broad rays. He found shrinkage values, from green to oven-dry, of 6.6% for ray tissue, 5.2% for earlywood free of broad rays; and 7.9% for latewood free of broad rays. If only the total amount of shrinkage is involved, this suggests that in earlywood the ray tissue is restrained from shrinking tangentially; therefore, it is stressed in tension, whereas in latewood the ray tissue is compressed tangentially.

However, more than just total shrinkage should be considered. The rate of shrinkage could be even more important than that of total shrinkage. There are a number of possible combinations of amount and rate of shrinkage of the two types of tissue. For example, if the total tangential shrinkage of ray tissue between two moisture contents is both less and occurs more slowly than that of the prosenchyma, the ray tissue cannot be strained in tension by this mechanism during drying. Other combinations of amount and rate of shrinkage could lead to shrinkage restraint and to the development of tangential tensile stress in the ray tissue at some time during drying.

In this study, the radial moisture diffusion rate of both ray tissue and prosenchyma was determined for three oak species.

PROCEDURE

Radial desorption-time curves were determined for both ray tissue and prosenchyma of the heartwood of white oak (*Quercus alba* L.), northern red oak (*Quercus rubra* L.), and cherrybark oak (*Quercus falcata* var. *pagodalfolia* Ell.). All specimens were taken from a single flatsawn board of each species. Each board was surfaced to approximately ¼-inch thickness, then cut into many pieces ¼ inch long along the grain. The individual specimens of ray tissue and prosenchyma were cut from these pieces, so that they measured approximately ¼ inch radially and longitudinally. The tangential thickness was limited by the tangential dimension of the rays, and varied from about 0.008 inch for some of the thinnest cherrybark oak rays

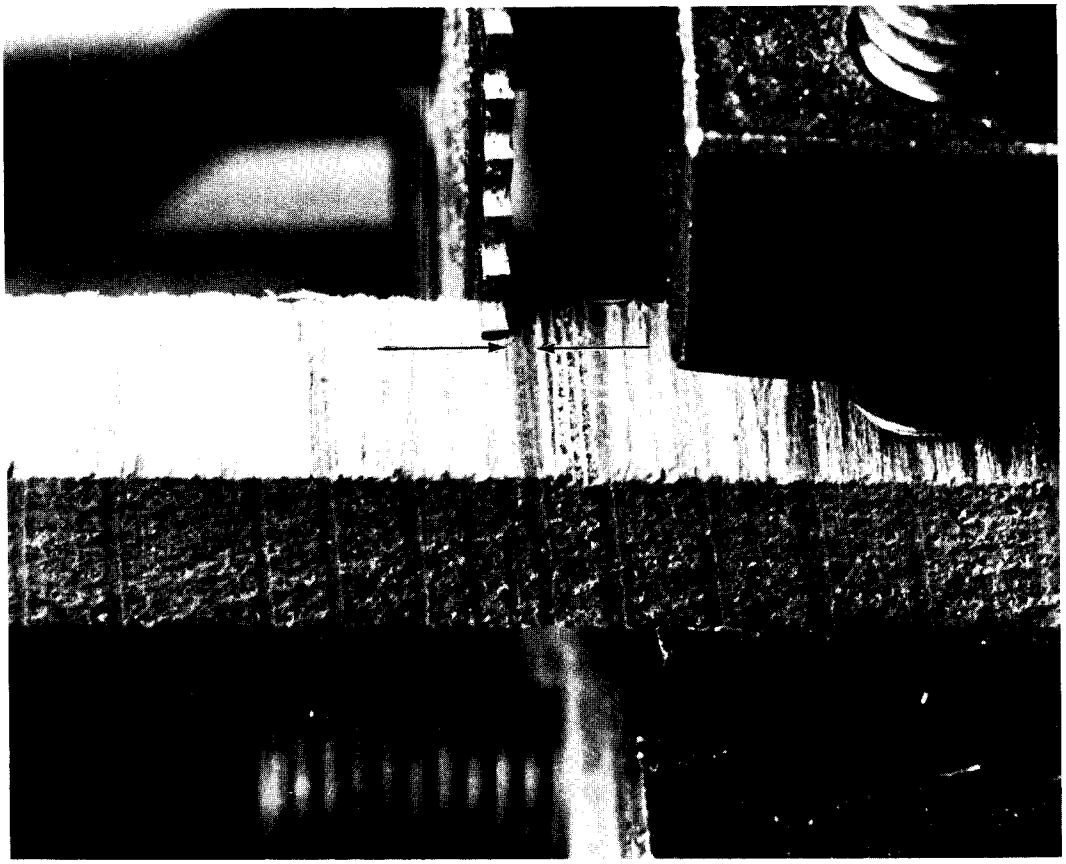

FIG. 2. Close-up of specimen and saw blade showing alignment of the blade with the edge of the ray (shown by arrows) tissue.

to about 0.015 inch for some of the thickest white oak rays. The prosenchyma specimens were cut to fall within this thickness range. Both types of tissue were cut on a small circular saw (Fig. 1) with a 2½-inch-diameter metal-cutting blade that left the surfaces quite smooth. The pieces were positioned in a holder mounted on a carriage that could be moved in two directions in relationship to the blade. The holder could be swiveled on the carriage so that the piece could be lined up with the blade parallel to the edge of a ray (Fig. 2).

After cutting, the specimens were conditioned at 45% relative humidity and 25 C. All but the tangential faces of each specimen were then coated with three coats of aluminum paint so moisture movement would be confined to the radial direction. Separate tests showed three coats of this paint were an effective vapor barrier within the time limits of these desorption tests. The specimens were then clipped with a template and razor blade to 0.17 inch in the radial direction so that the length of the diffusion path would be the same for all specimens. The specimens were reconditioned in desiccators over distilled water to establish a high initial moisture content before starting the desorption tests.

It would have been very difficult to maintain the specimens in their original green condition throughout all of the processing steps necessary to arrive at the finished specimen. Thus it was decided that the conditioning to 45% relative hu-

TABLE 1. *Rate of desorption for ray tissue and surrounding tissue (prosenchyma) of oak*

Replicate	Prosenchyma[a]		Ray tissue[a]	
	$t_{0.5}$ (min)	$\bar{D}$ ($cm^2 sec^{-1} \times 10^6$)	$t_{0.5}$ (min)	$\bar{D}$ ($cm^2 sec^{-1} \times 10^6$)
		WHITE OAK		
A	97.7	1.56	52.5	2.91
B	113	1.35	81.3	1.87
C	118	1.29	47.9	3.19
Average	110	1.40	60.6	2.66
t = 4.05*, 4 degrees of freedom				
		RED OAK		
A	126	1.21	42.7	3.57
B	166	0.92	39.8	3.83
C	100	1.53	32.3	4.72
Average	131	1.22	38.3	4.04
t = 4.75**, 4 degrees of freedom				
		CHERRYBARK OAK		
A	102	1.49	32.3	4.72
B	138	1.10	37.1	4.12
C	144	1.06	33.9	4.50
Average	128	1.22	34.4	4.46
t = 7.09**, 4 degrees of freedom				

*Denotes significant difference between ray tissue and prosenchyma at 98 percent confidence level.

**Denotes significant difference between ray tissue and prosenchyma at 99 percent conference level.

[a] $t_{0.5}$, time for one-half of desorption to occur; $\bar{D}$, integral diffusion coefficient.

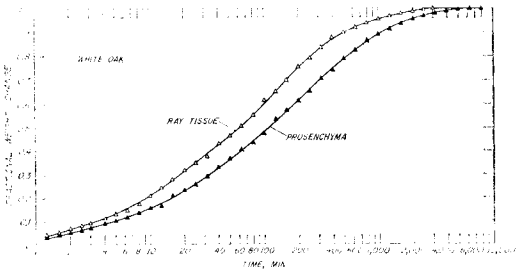

FIG. 3. Relationship of fractional weight change to time for ray and surrounding tissue (prosenchyma) of white oak.

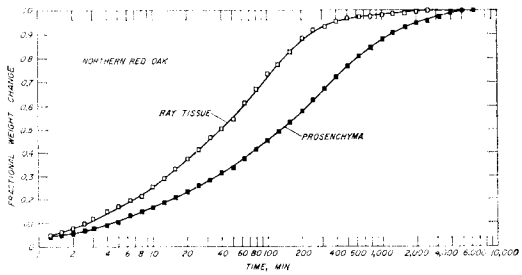

FIG. 4. Relationship of fractional weight change to time for the ray and surrounding tissue (prosenchyma) of northern red oak.

midity, which would ensure a more uniform sorption history among the specimens, would be advantageous. The possibility does exist that the initial desorption might occur at a different rate than subsequent desorptions, but it seems unlikely that this could seriously affect the comparative rates during desorption in the hygroscopic range when differential shrinkage between the two types of tissue would occur.

To resolve the small weight changes, the specimens were tested in groups of 10 on an analytical balance sensitive to 0.0001 g. The smallest total weight change was 0.005 g, therefore; the poorest resolution was 2% of the total weight change. For ease of handling, each group of 10 specimens was mounted on a piece of nonhygroscopic metal tape. Three replicates of these groups of 10 specimens were tested for each type of tissue of each of the three species.

The specimens were desorbed from equilibrium with 25 C over distilled water to equilibrium with 25 C and 45% relative humidity. Weights were taken at 0.1 increments of $\log_{10}$ (min.) for the first 9 hr, and at convenient times thereafter.

RESULTS AND DISCUSSION

The results of desorption tests are summarized in Table 1, in which the time required for one-half of the total weight change to occur ($t_{0.5}$) is given, as is the integral diffusion coefficient ($\overline{D}$). The diffusion coefficient is the integral value over the moisture content range involved, and was calculated from the equation (Crank 1956):

$$\overline{D} = (0.049)(\ell^2)/(t_{0.5}) \quad (1)$$

where $\overline{D}$ is the diffusion coefficient in cm^2 sec^{-1}; l, the length of the diffusion path in cm; and $t_{0.5}$, the time in seconds required for one-half of the total sorption change to occur.

The differences between the desorption half times ($t_{0.5}$) of ray tissues and prosenchyma were tested as unpaired observations with the assumption that the two populations have a common variance (Steel and Torrie 1960). The results of the t tests are included in Table 1; it seems reasonable to conclude that radial moisture diffusion is faster in ray tissue than in prosenchyma.

The relationship of fractional weight change (E) to time for each species is shown in Figs. 3 through 5. The values plotted are the fraction of the total change that has occurred at any time. Each curve is made up of points that are the average values of the three replicates at each time increment. The points greater than 9 hr were reduced to values at 0.1 increments of $\log_{10}$ (min) by the Newton method of numerical interpolation (Scarborough 1962). The ray tissue is clearly ahead at all stages of desorption.

The difference between the ray tissue desorption curve and the prosenchyma desorption curve is plotted as a function of time for each species in Fig. 6. This is the relationship in oaks that could have sig-

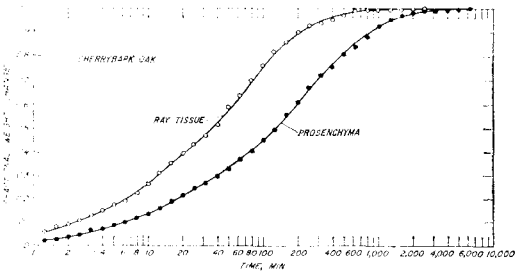

FIG. 5. Relationship of fractional weight change to time for the ray and surrounding tissue (prosenchyma) of cherrybark oak.

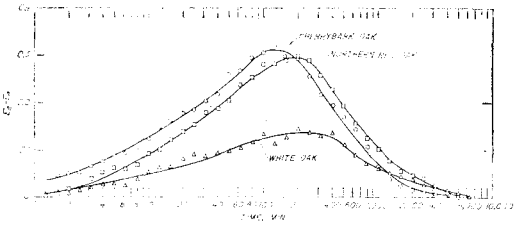

FIG. 6. Relationship of difference between the fractional weight change curve for ray tissue (E_R) and the fractional weight change curve for the surrounding tissue (prosenchyma) (E_P) to time.

nificance in the mechanism of surface check formation. The fractional change in weight is directly proportional to moisture content change, and shrinkage is approximately linear with moisture content (Panshin and deZeeuw 1970). Therefore, the fractional weight change curves in Figs. 3 through 5 have the same shape as tangential shrinkage-time curves, and if each point were multiplied by the total tangential shrinkage that would occur between the two equilibrium conditions, they would very closely represent tangential shrinkage-time curves. Similarly, the difference curves in Fig. 6 would very closely represent the difference in tangential shrinkage between the two types of tissue. Since the ray tissue and the prosenchyma are connected in whole wood, the curves of Fig. 6 would represent the tangential shrinkage that is restrained in the ray tissue.

As Fig. 6 is now drawn, the assumption is the total tangential shrinkage of the two types of tissue is the same. Whether or not this is true is unknown; thus, the magnitudes of the maximum restrained shrinkage in Fig. 6 are not exact, but the approximately 30% of total shrinkage values for northern red and cherrybark oak and the 15% for white oak are reasonable first approximations of the restrained shrinkage in the ray tissue if the total tangential shrinkages of the two types of tissue are no more different than Schniewind (1959) found for California black oak. The times of the maxima in Fig. 6 are independent of the magnitude of the total tangential shrinkage.

The discussion built around Fig. 6 is certainly an oversimplification of the mechanism of check formation and of the contribution of the faster radial diffusion in ray tissue in check formation. Differential radial shrinkage between ray tissue and prosenchyma and, perhaps more important, third-order drying stresses are involved in check formation. The time-dependent mechanical properties of the two types of tissues are also involved, as well as stress concentrations around the tips of the ray ends on the tangential face. Also, the boundary conditions for diffusion were different in this experiment than they are in whole wood. The ray tissue is then flanked by prosenchyma instead of aluminum paint, and tangential moisture transfer is possible between the two types of tissue. This does not change the validity of this hypothesized contribution to the mechanism of check formation, however, because near the exposed surface the driving force for diffusion, the moisture gradient, is very likely much steeper in the radial direction than tangentially between ray tissue and prosenchyma.

SUMMARY AND CONCLUSIONS

The results of this study show that radial moisture diffusion is faster in the ray tissue of white oak, northern red oak, and cherrybark oak than it is in the surrounding tissue. The radial diffusion coefficient of the ray tissue was 1.9, 3.3, and 3.7 times greater, respectively, for the three species than that of the surrounding tissue.

Based on this conclusion, it is hypothe-

sized that the large difference in radial desorption rates between the two types of tissue is a contributing factor in the mechanism of surface check formation in the ray ends that appear on the tangential face of flatsawn oak boards. The ray tissue dries faster than does the surrounding tissue, is restrained from shrinking tangentially, and is therefore strained in tangential tension and subject to the possibility of fracture. Other mechanisms undoubtedly contribute to surface check formation, but it is, apparently, quite possible that this previously unexplored mechanism is also involved.

REFERENCES

CLARKE, S. H. 1930. The differential shrinkage of wood. Forestry 4(2):93–104.

CRANK, J. 1956. The mathematics of diffusion. Clarendon Press, Oxford, England.

GABY, L. I. 1963. Surface checking of white oak as related to mechanical processing. For. Prod. J. 13(12):529–532.

MORSCHAUSER, C. R. 1954. The effect of rays on the differential shrinkage of red oak. J. For. Prod. Res. Soc. 4(5):280–282.

PANSHIN, A. J., AND C. DEZEEUW. 1970. Textbook of wood technology, 3d ed., McGraw-Hill Book Co., New York.

SCARBOROUGH, J. B. 1962. Numerical mathematical analysis. Johns Hopkins Press, Baltimore.

SCHNIEWIND, A. P. 1959. Transverse anistropy of wood: A function of gross anatomic structure. For. Prod. J. 9(10):350–359.

———. 1960. On the nature of drying stresses in wood. Holzforschung 14(6):161–168.

———. 1963. Mechanism of check formation. For. Prod. J. 13(11):475–480.

———. 1966. Irregularities of finished surfaces caused by unequal ray shrinkage. For. Prod. J. 16(8):66–67.

———, AND P. C. KERSAVAGE. 1961. A quantitative evaluation of second order drying stresses. For. Prod. J. 11(11):523–530.

STEEL, R. G. D., AND J. H. TORRIE. 1960. Principles and procedures of statistics. McGraw-Hill Book Co., New York.