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Properties Related to drying Defects in Red Oak Wetwood

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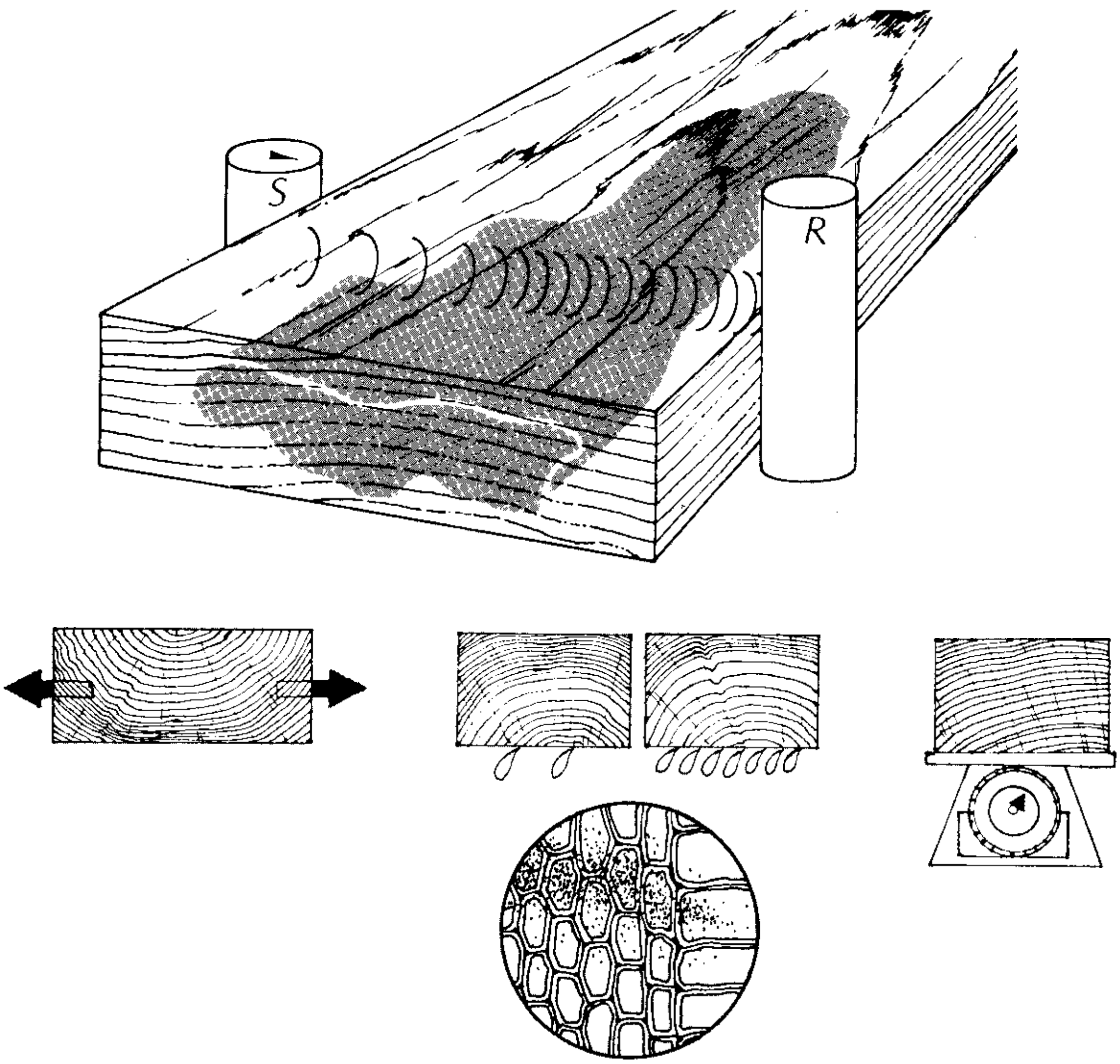

Abstract

Bacterially infected wood, called wetwood, is often not visually apparent in logs or green lumber. When dried, lumber containing wetwood is prone to develop defects. This study had two objectives: (1) to show the potential of using moisture content, green and basic density, stress wave travel time, and tensile strength across the grain as indicators of bacterial infection in green lumber and (2) to evaluate the relative susceptibility of infected and uninfected lumber to checking during drying and the level of actual drying degrade. Bacterially infected and uninfected green, flat-sawn, 1-1/8-in.-thick red oak (*Quercus* spp.) lumber was used in this study. The relative susceptibility of infected and uninfected wood to check during drying was examined by comparing tensile strength across the grain. Actual drying degrade was determined by kiln drying using a standard American schedule. Results show that moisture content and density levels are not good indicators for identifying bacterial infection. However, maximum stress wave travel time across the grain in green lumber appears to be a promising indicator of bacterial infection. Low tensile strength across the grain in bacterially infected red oak strongly indicates a high susceptibility for the lumber to check during drying. Because decreased tensile strength is indicated by increased stress wave travel time, stress wave analysis of green lumber can be a good indicator that drying defects will also develop.

Keywords: Nondestructive testing, wetwood, red oak

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Properties Related to Drying Defects in Red Oak Wetwood

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Introduction

Wetwood develops from the infection of living trees by anaerobic bacteria. The presence of anaerobic bacterial infection by Clostridium and Erwinia sp. was verified (Ward and Zeikus 1980, Ward and others 1972). According to current information, these bacteria only attack standing trees. In red oak, the infection originates at injuries in the root collar and forms a conical pattern in the central core of the lower bole, tapering to an apex in the upper bole (Ward and Pong 1980). When sapwood is invaded and colonized by bacteria, sapwood migrates to the transition zone of sapwood and heartwood. Infection may develop in previously formed heartwood by invasion of bacteria from an adjacent infected area. Bacteria never colonize in the vicinity of the pith.

Anaerobic bacteria secrete enzymes that are able to degrade pectic substances of the compound middle lamella as well as starch, tannins, and possibly monomeric wood sugars (Schink and Ward 1984, Ward and Zeikus 1980). Consequently, chemical bonds between wood cells are weakened. The degradation is indicated by destroyed pit membranes and microcracks between the cell walls. Thus, although the secondary cell walls appear to remain intact and the wood maintains its original density, the wood's ability to withstand drying stresses is reduced (Ward and Pong 1980). Weak bonding causes a high risk for the development of checks, splits, or ring failure during drying, even under mild drying schedules. Checks may be deep surface checks, honeycomb, or end checks (Rasmussen 1961). Collapse and warp may also be more frequent and severe in infected wood (Ward and Pong 1980).

Checking of red oak wood during drying may depend on tensile strength across the grain (Youngs 1957). Bacterial infection and subsequent degradation are expected to reduce tensile strength. Reduced tensile strength across the grain also tends to cause problems in machining and gluing (Kutscha and Ethington 1962, Wengert 1990).

Moisture content tends to be greater in bacterially infected wood than it is in uninfected wood. This is often indicated by a water-soaked and dark appearance in comparison to adjacent normal wood (Ward and Zeikus 1980). However, sometimes no difference occurs in moisture content between the infected and uninfected wood (Ward and Groom 1983, Ward and Zeikus 1980).

Bacteria affect the strength of the wood when the tree is still standing. When the affected trees are subjected to stress from wind, growth, and freezing, weak bonding between the cells results in an increased risk for radial and tangential growth ring separations (Ward and Pong 1980). These separations, known as shake, often go undetected prior to wood processing.

Bacteria also create acetic acid and additional fatty acids that have a characteristic unpleasant, rancid odor (Schink and Ward 1984); propionate, butyrate, valerate, and caproate in fetid liquid were detected in bacterially infected oak (Ward and others 1969). The odor is often accompanied by a strong vinegar smell and vapors that sting the eyes. In fact, the particular odor is still considered a reliable detection criterion for bacterially infected wood. The objective information available on the identification of bacterial infection is based on culture techniques (Ward and Zeikus 1980), microscopy (Sachs and others 1974), chemical analysis of extractives (Zinkel and others 1969), and combined trace vapor detection and ion mobility spectrometry (Lawrence 1991). A promising detection technique has been developed that is based on stress wave analysis, i.e., speed of sound measurements across the grain (Verkasalo 1991, Ross and others 1992).

This paper compares the results of moisture content, green and basic density, stress wave travel time, and tensile strength across the grain, as related to drying defects (checks, splits, collapse, warp) of bacterially infected and uninfected red oak lumber. The first objective of this study was to show the potential of using these properties to indicate bacterial infection in green lumber. The second objective was to evaluate the relative susceptibility of infected and uninfected red oak to checking during drying and the level of actual drying degrade.

Experimental Methods

Materials

Thirty-two freshly cut, about 12-ft-long red oak butt logs from the Piedmont area in south central Virginia were selected as likely to contain bacterially infected wood. (See Table 1 for metric conversion factors.) The presence of bacterial infection in logs was determined at the butt end, using rancid odor, occurrence of ring shake, and dark greenish or reddish-brown discoloration as indicators (Ward and Pong 1980). The logs were grade-sawn into 1-1/8 in. thickness at a hardwood sawmill in Virginia. The 12-ft boards were cross-cut to 6-ft lengths, and these were graded according to the standard rules of the American National Hardwood Lumber Association (NHLA 1990). Only Rat-sawn boards were accepted. All boards graded No. 1 Common and some graded No. 2A, 2B, and 3A Common were accepted to make sure that enough bacterially infected boards were included. In total, 225 boards with a range in width from 4 to 11 in. were selected.

Presence of Infection

The boards were shipped to the Forest Products Laboratory in Madison, Wisconsin, where they were examined for the presence of bacterial infection. Board sections with a strong odor and obvious discoloration were classified as definitely infected; sections with a slight odor and discoloration were classified as possibly infected; sections without odor and discoloration were classified as uninfected.

A map was drawn for each green board illustrating the infected zones, grain pattern, and observable defects. An example of such a map and the criteria for evaluating grain pattern are shown in Figures 1 and 2, respectively.

Table 1—SI conversion factors

English unit	Conversion factor	SI unit
board foot	0.002	cubic meter (m^3)
degree Fahrenheit (°F)	(°F - 32)/1.8	Celsius (°C)
foot (ft)	0.3048	meter (m)
inch (in.)	25.4	millimeter (mm)
pound per square inch (lb/in^2) (stress)	6,894	pascal (Pa)
pound per cubic foot (lb/ft^3)	2,767	kilogram/cubic meter (kg/m^3)

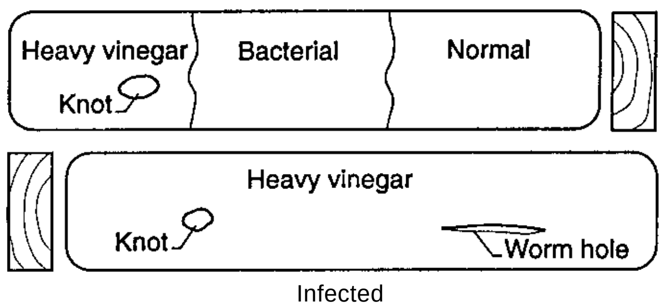

Figure 1—Example of a board map.

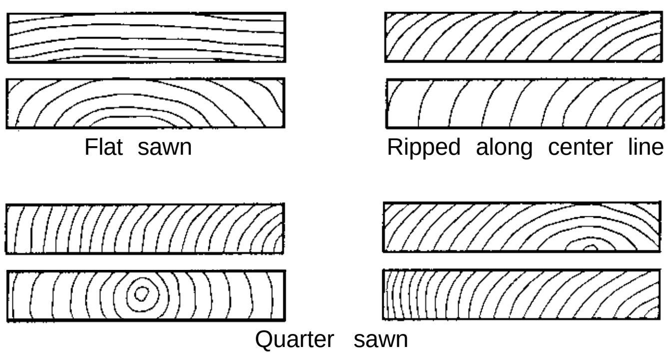

Figure 2—Criteria for evaluating grain pattern in red oak lumber.

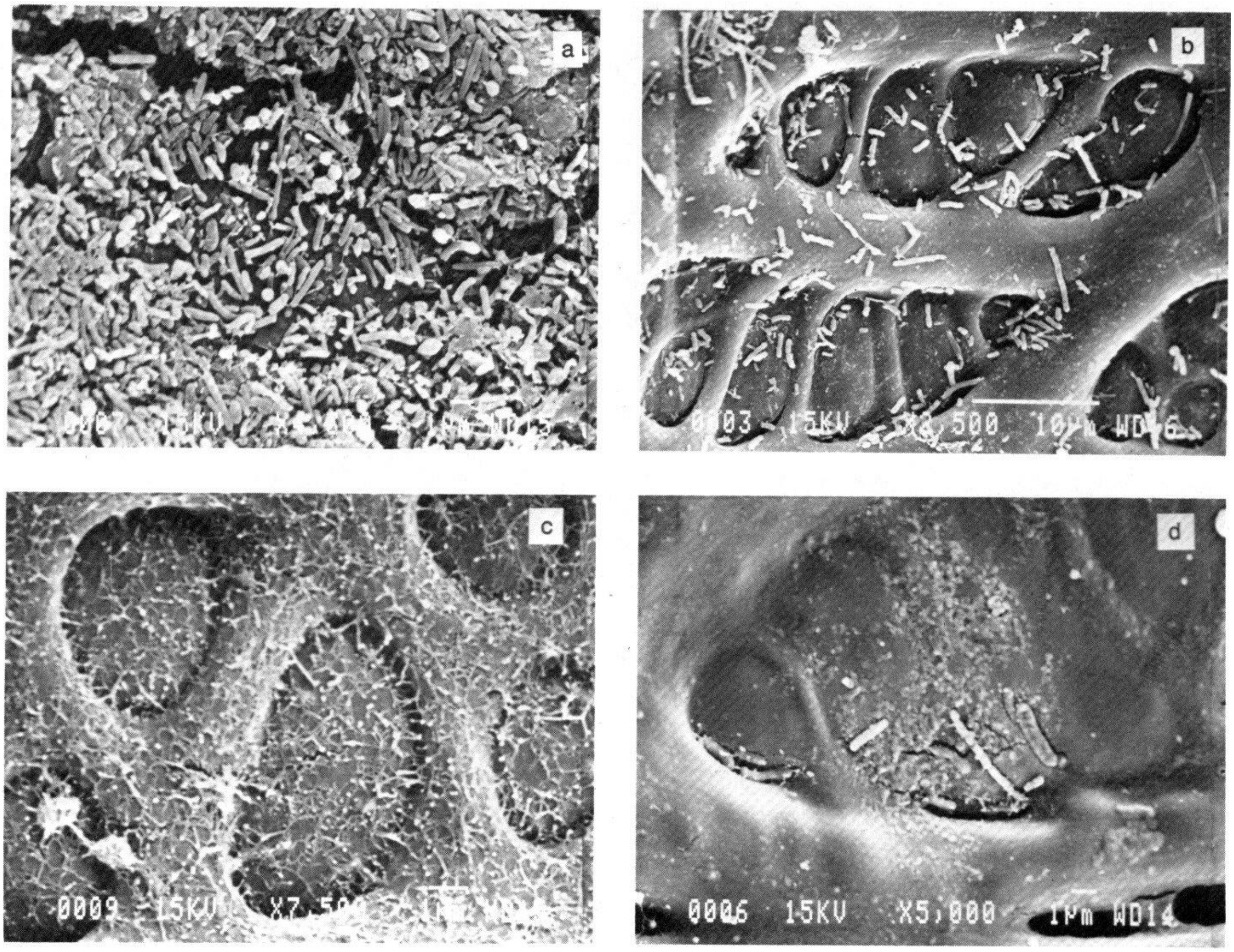

Figure 3—Bacteria in red oak heartwood: (a.b) heavy infections; (c,d) cracks and slime on vessel wall.

The degree of infection in each board was estimated to the nearest 10 percent of board volume. Boards with more than 70 percent definitely or possibly infected wood were classified as bacterial; boards with 30 to 70 percent definitely or possibly infected wood were classified as mixed; boards with less than 30 percent definitely or possibly infected wood were classified as normal.

Of the 225 boards, 84 were classified as bacterial, 63 as mixed, and 78 as normal. When giving the lumber grades, the indices were 1 for FAS, 2 for SEL, 3 for No. 1 Common, 4 for No. 2A and 2B Common, and 5 for No. 3A Common; the mean grade indices were 2.56, 2.31, and 2.06 for bacterial, mixed, and normal boards, respectively. Wilcoxon rank sum test showed a significant (p = 0.041) difference in the grade index between bacterial and other boards.

The presence or absence of bacterial infection was confirmed by scanning electron microscopy (SEM) (McGinnes and others 1974, Sachs and others 1974) on 50 small specimens cut from the butts of boards with and without infection. The severity of the infection was evaluated visually. Severe infection was indicated by large localized bacterial populations (Fig. 3a), moderate populations throughout the sample (Fig. 3b), and distinct cracks and slime on cell wall (Fig. 3c,d). Mild infection was indicated by less abundant bacteria but also by abundant tyloses in vessels (Fig. 4a,b).

Specimens from all boards classified as bacterial had severe bacterial infection. In 17 percent of specimens from the mixed classification (30 to 70 percent infected), no infection was observed, and most of those remaining specimens showed only mild infection. Specimens from normal (less than 30 percent infected) boards showed no sign of bacterial infection or only traces of infection.

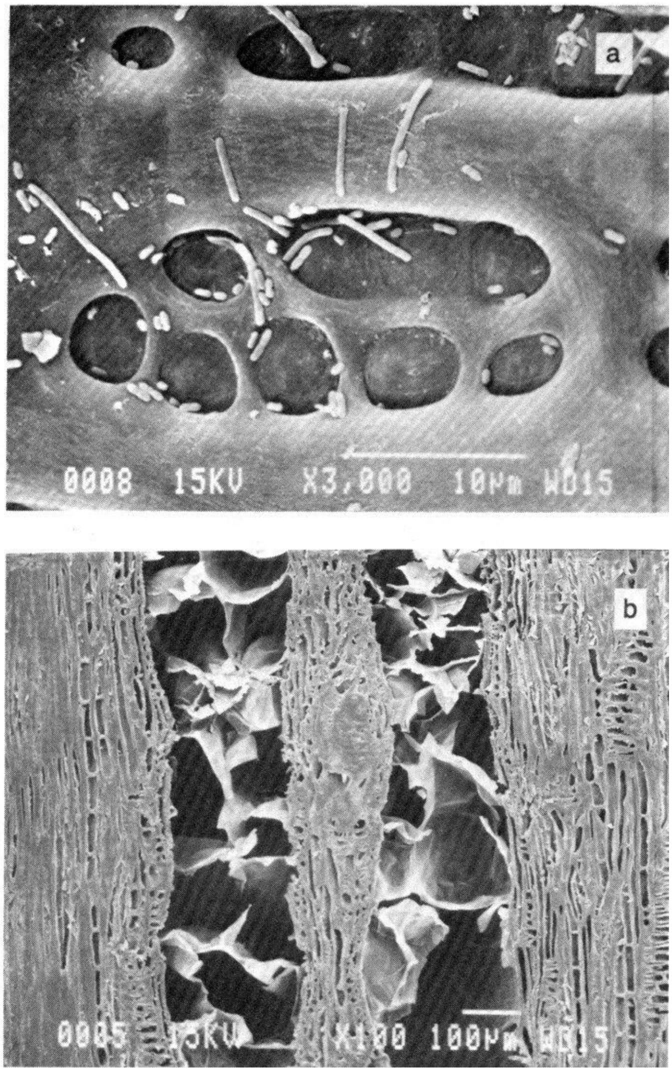

Figure 4—Relatively mild bacterial infections in red oak heartwood, characterized by (a) few bacteria and (b) abnormally abundant tyloses in vessels.

Measurement of Wood Properties

A 1-in. sample from along the grain was cut from the butt and top end of each board to estimate the average moisture content, green density, and basic density. (Basic density is based on ovendry weight and green volume.) Moisture content and density of each sample were determined by gravimetric techniques. The results may have underestimated the true moisture content in the board, because board ends are apt to lose moisture more rapidly than is the center of the board when exposed to drying conditions.

Stress wave travel time across the grain for each board was measured at points located at 1-ft intervals along the board length. If an observable defect (knot, cross grain, check, split, decay, pith) was noted at the point of measurement, an extra measurement was taken at

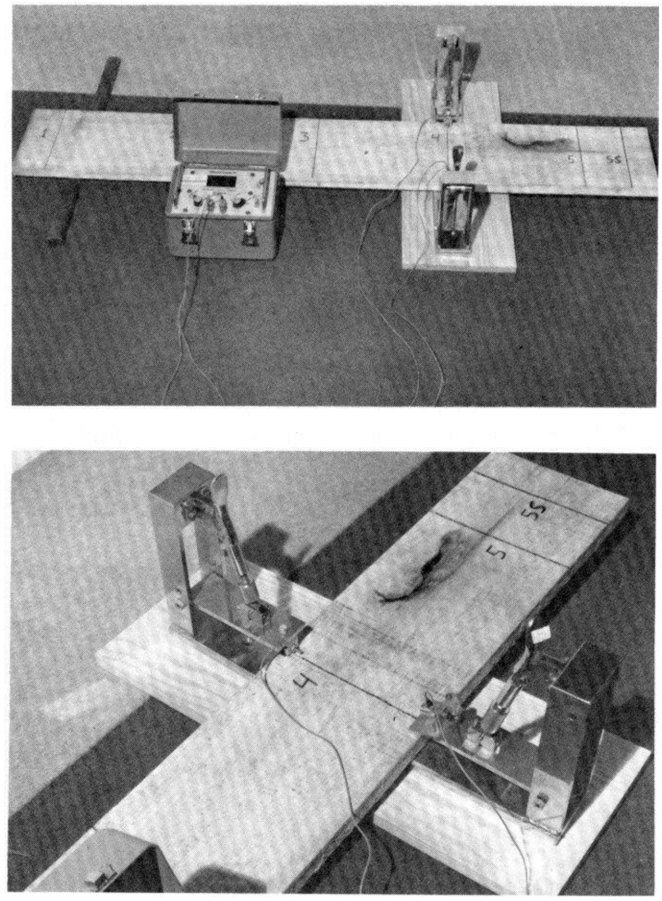

Figure 5—Experiment setup used to measure stress wave travel time.

the closest point judged visually free from defects. Stress wave travel time was measured between points 0.25 in. from the edge of the board. Stress waves were induced with an impact hammer, and transit time was measured with a commercially available timer. The accuracy of timing was ±2μs, or 0.1 to 1 percent (Fig. 5).

Tests on tensile strength across the grain were performed on 244 specimens free from visible checks, splits, knots, and decay. These specimens were cut from a subsample of 40 boards and had the following dimensions: 1 in., radial; 0.5 in., longitudinal; and at least 5 in., tangential wood direction. The tests were performed with a Rhiele[1] universal test machine using a loading rate of 0.025 in./min. The location and roughness of the failure plane were visually observed, and failures were classified as follows:

[1] The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

1 = Strictly along a wood ray (tension failure)

2 = Roughly across the specimen, through several parallel wood rays (incomplete tension failure)

3 = Strictly along earlywood and latewood interface (shear failure)

4 = Combination of 1 and 3 (combined tension and shear failure)

Kiln Drying

After selecting the material for tensile strength tests, the remaining 185 boards were kiln dried. We used a 1 to 1.5 × 10^3 board foot steam-heated kiln, following the schedule T4D2 (Rasmussen 1961). The average air velocity through the stacks was 355 ft/min, with a range from 310 to 410 ft/min. Drying took 28 days (638.5 h).

Natural and drying defects are given in the Appendix. Only the obviously drying-induced external and internal defects and their severity were recorded after the experiment. End checks, splits. collapse, and warp were examined on full-size boards after drying and were compared to the initially recorded initial defects in the green lumber. The boards were then cross-cut at the points of stress wave analysis. Observed surface checks, internal checks (honeycomb), ring failure, and collapse, and their severity were recorded as drying defects if no defect was present prior to drying. The degraded board volume was estimated to the closest 10 percent, considering only the external and internal checks, splits, and ring failure, and severe collapse. We used the criterion that the smallest usable board would be 3 in. wide by 2 ft long—the smallest acceptable cutting in the lumber grade No. 3A Common.

Results

Moisture Content, Green Density, and Basic Density

Moisture content, green density, and basic density values of the boards are exhibited in Table 2 by category of bacterial infection. The average values for all boards were close to the reported average values for northern and southern red oak (Forest Products Laboratory 1987): heartwoods usually have green moisture content levels of 80 and 83 percent; normal green densities of 63 and 60 lb/ft^3; and normal basic densities of 35 and 33 lb/ft^3, respectively. Consistent with the results from prior research (Ward and Pong 1980), no significant difference was observed in these variables among the categories of bacterial infection.

Table 2—Moisture content, green density, and basic density of red oak lumber

Category of bacterial infection	Boards (number)	Moisture content (percent)	Density (lb/ft^3) Green	Basic[a]
Bacterial	84	85.8	66.2	35.8
Mixed	63	84.5	66.4	36.2
Normal	78	84.8	65.3	35.5

[a] Based on ovendry weight and green volume.

Thus, it was not possible to identify bacterial infection using density or moisture content measurements.

Stress Wave Travel Time

Wood, identified as definitely infected, had longer average stress wave travel time across the grain than did possibly infected or uninfected wood (Table 3). The difference was statistically significant, even though the absolute difference was only 25 to 26 μs/ft. The results for full-size boards followed the same pattern: bacterial boards had longer travel times than did mixed and normal boards. The largest difference was 60 μs/ft for the average maximum travel time, indicating that the highest observed stress wave reading in a board was the most feasible to identify bacterial infection.

Tensile Strength Across the Grain

The variation in tensile strength between individual specimens was large, ranging from 9 to 976 lb/in^2. Tensile strength across the grain was 41 percent less in definitely infected specimens than in possibly infected and uninfected specimens (Table 4), a considerably larger difference than the 24 percent difference reported by Hart and others (1984). The extremely low tensile strength values were probably due to unidentified small checks or incipient ring failures.

Lengthy stress wave travel time across the grain corresponded with low tensile strength (Table 3). This further supports the correlation of stress wave travel time and bacterial infection.

Failure along one or several wood rays, interpreted as tension failure by Bodig and Jayne (1982), was the usual failure pattern in possibly infected and uninfected specimens (Table 4). In connection with this failure pattern, low tensile strength probably indicates susceptibility to checking during drying. Failure along an earlywood-latewood interface or a combined failure along that and a wood ray, both of which strongly indicate shear failure, was common among

Table 3—Stress wave travel time based on individual and full-size board readings

	Category of bacterial infection	Travel time (μs/ft) Average	Average maximum[a]
Individual readings	Definitely	319	—
	Possibly	294	—
	Uninfected	295	—
Full-size board	Bacterial	323	377
	Mixed	297	316
	Normal	298	316

[a] Average of maximum travel time for each board; —, not applicable.

Table 4—Average stress wave travel time, maximum tensile stress, and Failure pattern distribution of test specimens

Category of bacterial infection	Speci-mens (number)	Stress wave travel time (μs/ft)	Maximum tensile stress (lb/in^2)	Failure pattern[a] (percent) 1	2	3	4
Definitely	139	338	440	63	10	14	13
Possibly	37	295	711	78	11	3	8
Uninfected	68	289	772	76	19	0	5

[a] 1 = strictly along a wood ray; 2 = through several parallel wood rays, 3 = strictly along earlywood-latewood interface; 4 = combination of 1 and 3.

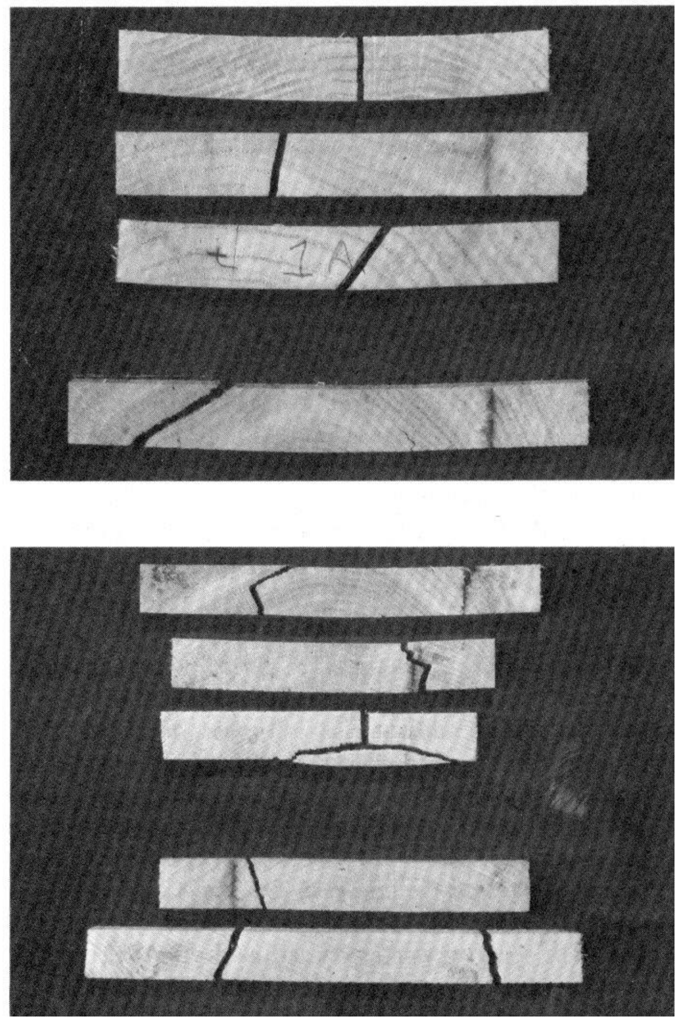

Figure 6—Different failure patterns in tests on tensile strength across the grain.

definitely infected specimens. Low tensile strength in connection with this failure pattern probably indicates susceptibility to ring failure during drying.

Weak wood tended to fail along an earlywood-latewood interface, in contrast to the tendency of strong wood to fail along a wood ray. Tensile strength of the specimens with the first failure pattern was only 326 lb/in^2, compared to 628 lb/in^2 for the specimens with the second failure pattern. The various failure patterns are exhibited in Figure 6.

Drying Defects

At the locations of stress wave measurement, drying defects typical for bacterially infected red oak were found in 40 percent of the definitely infected wood, 22 percent of the possibly infected wood, and 20 percent of the uninfected wood (Table 5). Ring failure and honeycomb were more frequent and the defects were more severe in definitely infected wood. The frequency of collapse was relatively low, and no significant difference was observed between the categories of bacterial infection. The development of collapse was probably caused by high initial moisture content and wood capillarity rather than bacterial infection (Rasmussen 1961, Siau 1984).

Of the bacterial boards, 87 percent had at least one drying defect, and it was severe in 44 percent of these boards (Table 6). Defects were present in 57 percent of the mixed boards and 50 percent of the normal boards, but defects were much less severe than those in the bacterial boards. The defects appeared to be concentrated to limited sections in boards, mainly near the butt ends. The average percentage of board volume degraded during drying was high (22 percent), indicating the severe drying conditions. Drying degrade

Table 5—Occurrence of drying defects at locations of stress wave measurements

Drying defect	Bacterial infection (percent)[a]			
	Definitely	Possibly	Uninfected	All
Any defect	39.9	21.8	20.0	29.0
Light	11.5	10.6	9.3	10.5
Medium	16.8	6.8	7.2	11.3
Heavy	11.5	4.4	3.6	7.2
Honeycomb	16.5	5.3	7.5	10.6
Light	1.6	0.8	1.5	1.4
Medium	8.9	1.9	4.8	5.8
Heavy	6.0	2.7	1.3	3.5
Surface checks	14.0	6.5	7.5	9.9
Light	2.2	1.9	1.5	1.9
Medium	9.2	3.4	4.3	6.0
Heavy	2.7	1.1	1.8	2.0
Ring failure	27.2	9.1	8.0	16.2
Single, near surface	7.4	4.2	4.3	5.6
Single, throughout	9.8	2.7	2.0	5.3
Multiple	10.0	1.5	1.8	5.1
Collapse	9.8	6.8	6.1	7.7
Light	8.9	6.8	5.8	7.3
Medium	0.9	—	0.3	0.5
Heavy	—	—	—	—

[a] Total number of readings: definitely, 374; possibly, 249; uninfected, 368; all, 991.

in bacterial boards was 36 percent, double that of the degrade in mixed boards (18 percent) and almost triple the degrade in normal boards (13 percent). The relative difference between the categories of bacterial infection matched well with the results of Ward and Groom (1983), but the absolute level of drying degrade was higher in the study reported here.

Warp, which is due to the shrinkage differentials between radial, tangential, and longitudinal wood directions, is often related to grain pattern, board width, and the occurrence of juvenile and tension wood (Wengert 1990). In the study reported here, bacterial boards developed considerably more warp (73 percent) than did mixed boards (53 percent) and normal boards (38 percent) during drying (Table 7). Cupping was the most common type of warp, especially in bacterial boards. Although only flat-sawn lumber was accepted, the result may be partly attributable to the fact that bacterial wood tended to be located near the log core where grade sawing yields lumber with an increased curved-grain pattern. The minor difference in board width, 5.54, 5.47, and 5.43 in. for the bacterial, mixed, and normal boards, respectively, did not contribute significantly to the difference in warp. Drying defects related to bacterial infection are illustrated in Figure 7.

Table 6—Proportion of boards with a drying defect

Drying defect	Bacterial infection (percent)			
	Bacterial	Mixed	Normal	AU boards
Any defect	87.3	56.9	50.0	64.9
Light	12.7	12.1	17.2	14.1
Medium	30.2	27.6	17.2	24.9
Heavy	44.4	17.2	15.6	26.0
Honeycomb	49.2	29.3	26.6	34.0
Light	4.8	5.2	3.1	4.3
Medium	25.4	13.8	12.5	17.3
Heavy	19.0	10.3	11.0	12.4
Surface checks	42.9	29.3	26.6	33.0
Light	9.5	6.9	4.7	7.0
Medium	22.2	19.0	14.1	18.4
Heavy	11.1	3.5	7.8	7.6
Ring failure	57.1	29.3	20.3	35.7
Single, near surface	11.1	10.3	9.4	10.3
single, throughout	14.3	10.3	4.7	9.7
Multiple	31.8	8.6	6.3	15.7
End checks and splits	41.1	25.2	24.8	30.5
Butt	34.9	17.3	17.2	23.2
Top	9.5	10.3	9.3	9.7
Collapse	22.2	15.5	21.9	20.0
Light	17.5	13.8	20.3	17.3
Medium	4.8	1.7	1.6	2.7
Heavy	—	—	—	—

[a] Number of boards: bacterial. 63; mixed, 58; normal, 64: all boards 185.

Table 7—Percentage of warped boards

Type of warp	Percentage of boards			
	Bacterial	Mixed	Normal	Average
Cup	47.6	25.9	14.1	29.2
Bow	12.7	20.7	12.5	15.3
Twist	3.2	3.5	6.3	4.3
Crook	1.6	0	3.1	1.6
Combined	8.0	3.5	1.6	4.3
Total	73.1	53.6	37.6	54.7

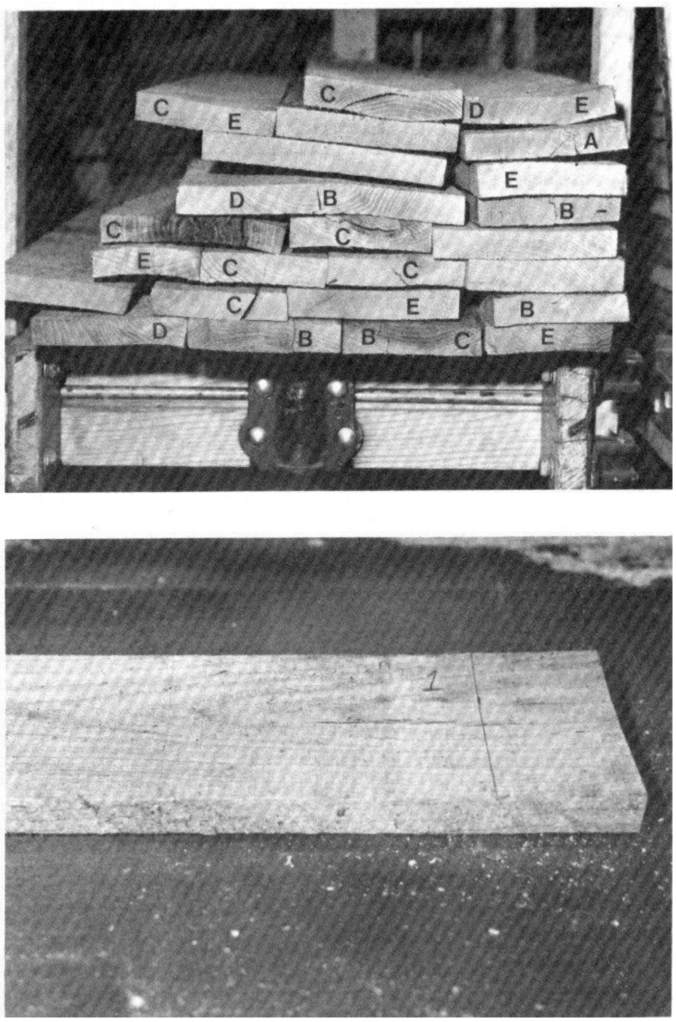

Figure 7—Drying defects related to bacterial infection in red oak lumber: A = deep surface check, B = honeycomb, C = ring failure, D = collapse, E = warp (cup).

Discussion

A limiting factor in evaluating the results of this study was the uncertainty of establishing the presence of bacterial infection by odor and discoloration. Although we were able to estimate the extent of bacterial infection in a piece of lumber, it was difficult to establish the presence of infection at a particular location. Although the inspection of samples by SEM tended to confirm our classification, it provided no definite verification because sample size was small and specimens were taken from board butts only.

Conclusions

Neither moisture content nor density appears to have potential for identifying bacterial infection. On average, moisture content may be somewhat greater in bacterially infected red oak compared to uninfected red oak, but the difference is not enough for identification and board separation.

Maximum stress wave travel time across the grain in green lumber is a promising indicator of bacterial infection. However, in practice, a certain amount of incorrectly identified boards cannot be avoided. An increase in moisture content generally results in an increase in stress wave travel time (Ross and Pellerin 1991); however, the small difference in the moisture content in green lumber in the study reported here did not significantly hamper the interpretation of the stress wave results. Because maximum travel time gives better results than does board average travel time, several observations along the full-board length are needed for a proper identification. Defects in green boards may cause errors in the identification of bacterial infection by stress wave analysis. However, preventing drying defects is the ultimate objective, and green board defects are likely to result in drying defects. In our study, most types of defects in green boards tended to cause a board to be identified as infected even if no infection was present. Also, only knots caused a reading of uninfected in an infected board.

The low tensile strength across the grain in bacterially infected red oak wood strongly indicates a high susceptibility to check during drying. Because decreased tensile strength is indicated by increased stress wave travel time typical for infected wood, stress wave analysis of green boards can be expected to indicate the development of drying defects as well.

Acknowledgments

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Appendix- Code System

The following was used to classify natural and drying defects in red oak boards.

Natural Defects

Knot,

- Large knot, greater than 1.0 in. diameter
- Medium knot, 0.25 to 1.0 in. diameter
- Small knot, less than 0.25 in. diameter

Hole

- Knot, hole, loose knot
- Large worm hole, ant gallery, decay hole
- Pin hole, tiny worm hole

Hark pocket (included bark with or without callus, pin knots)

- Large, width greater than 1 in.
- Medium, width 0.25 to 1.0 in.
- Small, width less than 0.25 in.

Wane (greater than 25 percent of thickness)

Pith

Splits, radial separations, shake

Ring failure

Discoloration

Fungal

Drying Defects

Surface checks

- Light, in less than 10 percent of surface width
- Medium, in 10 to 30 percent of surface width
- Heavy, in more than 30 percent of surface width

Honeycomb

- Light, in less than 20 percent of cross-section
- Medium, in 20 to 50 percent of cross-section
- Heavy, in more than 50 percent of cross-section

Ring failure

- Single separation near board surface
- Single separation throughout the board cross-section
- Multiple separations

End checks and splits

- Light, in less than 20 percent of cross-section
- Medium, in 20 to 50 percent of cross-section
- Heavy, in more than 50 percent of cross-section

Collapse

- Hardly observable
- Clearly observable
- Severe